Chapter 8
Tools and Techniques for Plug and Abandonment

8.1 Casing Cut and Removal Techniques

In permanent P&A, establishment of a rock-to-rock barrier is a requirement. There are situations where the annular barrier behind casing is not qualified or there is no annular barrier. Therefore, full access to the formation shall be obtained. Different techniques have been utilized by the petroleum industry such as cut-and-pull, casing milling, and section milling. Some new techniques have been suggested some of which are in use and others are in development. Such techniques include perforate-wash-cement, upward section milling, melting downhole completion, and plasma-based milling. This chapter will present these techniques, briefly.

8.1.1 Cut-and-Pull Casing

In permanent P&A operations, there are situations where there is only a poor annular barrier or no annular barrier at all. When there is a long length of uncemented casing, a cut-and-pull operation can be the necessary option. In this operation, a circumferential cut is made of the casing, above a casing coupling, and then a spear is engaged inside the casing to pull the casing out of hole. The spear can be engaged hydraulically. For the traditional method, the pulling force is provided by the working unit through the workstring to the bottom hole assembly. However, the advancement of cut-and-pull techniques provides a new generation of tools, downhole hydraulic pulling tool anchors, to create large amounts of pulling force without fully engaging the working unit pulling capacity. As an example, by use of 1 psi hydraulic power, 300 psi is generated by the downhole hydraulic pulling tool anchors [1].

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Ideally, the cut-and-pull operation is a single trip. However, there are challenges associated with it, which may require multiple trips. Such challenges are settled barite behind casing, scale depositions, collapsed formation, or unknown bond strength of the poor casing cement. Therefore, pipe retrieval requires high pulling capacity. The pulling capacity can be beyond the working unit or workstring capacity. It can also compromise the stability of the facility (i.e. working unit or platform). Therefore, multiple trip are performed by cutting the casing into short lengths. During casing pulling operations when the casing is moving, debris may fall down around the casing causing it to get stuck and even be irretrievable. Multiple trips expose personnel to several cut-and-pull operations and increases the risk of HSE issues. In addition, the retrieved pipe needs to be handled safely and disposed off properly.

The casing cut can be done using explosives, chemicals, mechanical cutters or using abrasive cutters. Regardless of which type of cutting technique is used, usually the cut is performed when the casing is under tension. Some of the challenges associated with explosive cutters are transportation, handling and storage, uncertainties related to eccentricity or stand-off of the device and damage of the outer casing, dispersion of force from the device, and shape of the resulting cut. Radial cutting torches, which use thermite derivatives to melt casing radially, can cut the casing partially or cut the pipe behind casing. Chemical cutters utilize chemicals which react with steel. Bromine triflouride is an example of such a chemical which is extremely hazardous for surrounding and personnel with irreversible health effects. The efficiency of chemical cutters can be affected by the presence of scale, poor spray pattern, or eccentricity of casing. Mechanical cutters are either electrical pipe cutters (see Fig. 8.1) or hydraulic pipe cutters (see Fig. 8.2). One of the advantages of mechanical cutters is the centralizer which holds the cutter in the pipe center and the risk of damaging the outer casing due to eccentricity is reduced.

For abrasive cutting techniques, abrasive cutting particles are injected into a water jet and wear away the production tubing, casing, drill pipe or drill collar. As this technique has advantages for cut and removal, especially wellhead cut and removal, the subject is covered in more detail, later in this chapter.

Fig. 8.1 Mechanical pipe cutter which is powered electrically. (Courtesy of Baker Hughes)

Fig. 8.2 Mechanical pipe cutter which is powered hydraulically. (Courtesy of Schlumberger)

8.1.2 Casing Milling

In this operation, casing is milled when a length of casing needs to be removed. Such circumstances may include slot recovery or sidetracking. The process of opening a window is typically done by a mill, however, milling with the use of an abrasive fluid jet has been studied [2]. In a P&A operation the required length is usually longer than required for sidetracking. Therefore, typically a section casing milling operation is carried out.

8.1.3 Casing Section Milling

One of the main reasons limiting the use of rigless P&A operations is poor casing cement or uncemented casing. For conventional practice, a window is section milled and the operation is called *section milling*. The aim of section milling is to grind away a portion of casing and cement. While section milling the casing, the hole needs to be kept clean by removal of produced swarf and other debris. The term *swarf* is used for metal fillings or shavings created by the milling tool during the casing removal process. The opened window needs to be under-reamed to expose new formation. Then, a cement plug is placed. Section milling is a time consuming operation and difficult to execute safely and efficiently. The current rate of milling

Table 8.1 Section milling data gathered during P&A operation of a well on the NCS

Casing size	Milling fluid	Length of window	Type of cutters	Number of runs	Milling rate	Weight of removed metal
13 3/8-in.	KCl based polymer fluids or MMH based fluids	164 ft	Tungsten carbide	1–2	8.5 ft/h	72 lbm/ft

operations for 7-in. casing is typically around 7–9 (ft/h), with additional time taken for tripping, hole cleaning and cleaning of BOP cleaning. The operation increases risk and introduces different challenges. The fluids designed for section milling must have sufficient weight and viscosity to suspend and transport swarf to surface while keeping the opened hole stable. Sometimes, the required viscous profile of the designed fluids increases the ECD to exceed the fracture gradient, resulting in breaking the formation. This phenomenon may lead to fluid loss and subsequently swabbing and loss of well control. Presence of fluid loss also causes poor hole cleaning and risk of packing off the Bottom Hole Assembly (BHA) which can lead to sticking of the milling or under-reaming BHAs. Section milling is also affected by the location of casing couplings and casing accessories such as centralizers and scratchers. With current milling tools, there is a risk of splitting and buckling the casing, which effects performance and the ability to successfully mill the required interval. Swarf and skimmed casing, and debris can also damage the BOP and effect its functionality. At surface, the transported swarf must be separated and captured by use of handling equipment. Swarf needs to be handled and disposed off properly and as it has sharp angular surfaces, it introduces HSE challenges. Swarf therefore requires a special handling system with trained personnel who need to be equipped with protective equipment. The milling operation requires the use of a drilling rig which is costly. As the cutting tool is worn out after only some feet of milling, frequent trip out and in is often required, which is time consuming. An additional limitation of section milling is generated vibrations. Table 8.1 shows the milling data gathered from a well on the NCS. Due to challenges associated with conventional milling operations, some techniques or methods have been suggested as alternative solutions. These techniques include upward milling, PWC, melting the downhole completion and plasma-based milling.

8.1.4 Upward Milling

Section milling is a proven technique which gives full access to the original formation for creating a rock-to-rock barrier. However, swarf transportation to surface and swarf handling on surface are time consuming and costly operations which are associated with HSE risks. If swarf could be left behind in the wellbore, section milling without swarf to surface, the section milling technique could be more efficient. Upward milling is a new form of section milling technique where the milling operation is performed while moving upward, cutting the swarf into small bits, where the swarf falls down into the wellbore. This system consists of a taper mill, auger section, section mill, emergency release disconnect, jet sub, left-hand rotating mud motor, drill collars, torque isolation assembly, spring loaded pads, spiral stabilizer, and intensifier [3, 4]. Figure 8.3 shows the main tools of upward milling bottom-hole assembly, from top (component 1) to bottom (component 11).

The key components of the upward section mill assembly are shown in Fig. 8.3. At the bottom of the planned milled window, the assembly opens its knives and creates the cut through the casing. Then, it mills upward to the desired depth, and finally retracts the knives at the top of the window. In conventional milling, the knives are retracted when pulling the workstring upward. However, the retraction mechanism for knives in the upward milling method is challenging as the knives cannot retract through upward movement.

Emergency release disconnect—This is a designed weak link in the system to release the assembly if the knives do not retract or the BHA becomes stuck. By over-pulling the workstring, the designed weak link is activated and the BHA is

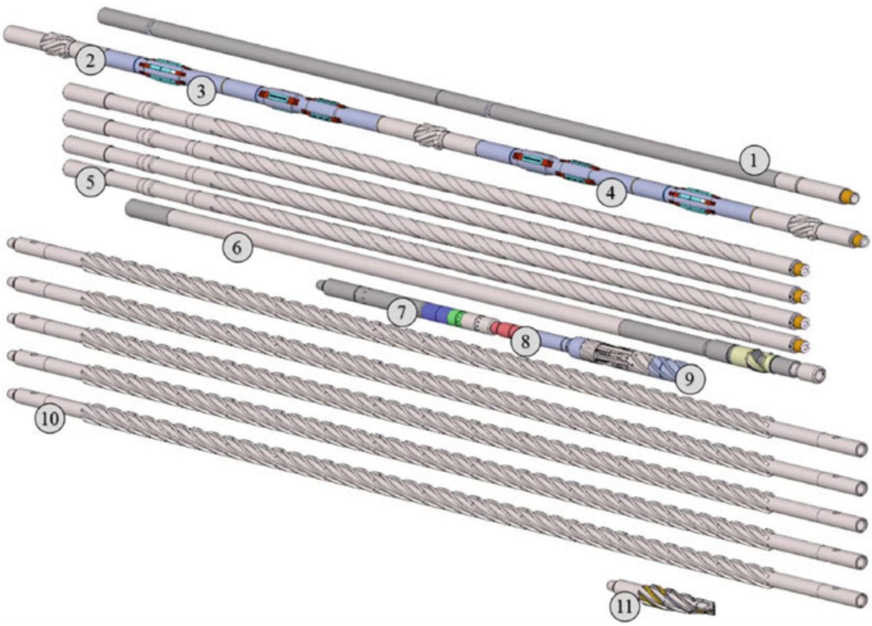


Fig. 8.3 Main components of an upward milling BHA without swarf to surface; (1) intensifier, (2) spiral stabilizer, (3) spring loaded pads, (4) torque isolator, (5) drill collars, (6) left-hand mud motor (7) jet sub, (8) disconnect, (9) section mill, (10) auger section, and (11) taper mill [3]

Table 8.2 Advantages and possible limitations of upward milling technique

Advantages	Possible limitations
• No HSE issues related to swarf handling • Time and cost efficient • No steel as part of permanent barrier	• High inclination can affect the swarf movement to the well leg

released. However, this is a last option to release the BHA. Other scenarios such as reciprocating the workstring to retract knives and pushing the knives to the bottom of window are tested prior to activation of the release disconnect feature.

Drill collars—As reaming is a part of the operation, it is important to ensure that the torque isolation assembly remains inside casing. Therefore, drill collars are installed above the left-hand mud motor.

Intensifier—This is a hydraulic spring to increase the impact force while enabling smooth load transition from the applied over-pull, at surface, to the knives, downhole, when milling upwards.

Left-hand mud motor—Right-hand rotation upward milling increases the risk and chance of unscrewing casing collars, especially at intervals where uncemented casing exists. Therefore a left-hand motor provides the downhole left-hand rotation and the required torque for the section mill and auger. A design feature for such a motor is high-torque and low-speed. This type of motor may be used in combination with coiled tubing to carry out rigless P&A operations.

Jet sub—To divert the flow of mud to the annulus while allowing swarf and cuttings to fall down the well, a jet sub is used below the left-hand mud motor. The main function of the jet sub is to avoid circulating fluid along the knives, if it is out of control and the swarf and cuttings might move upward and cause serious challenges and risks. The nozzle design and nozzle configuration are important to open the knives and generate enough force for milling. The nozzles are designed for different flowrates and fluid densities.

Torque isolator assembly—This is used to minimize the heavy vibration which occurs during section milling, especially upward section milling. By using such a component, axial movement and a continuous torsional constraint are provided.

Auger—In order to improve the process of swarf movement into the rat hole and prevent bridging, auger sections are used (see Fig. 8.3). Casing inside diameter, auger outside diameter, fluid flowrate, density of fluid and system operational procedures are some of the parameters considered during the design process of the auger and which affect the efficiency of it.

Taper mill—Swarf and cuttings can bridge across the cut-out and block the path for other swarf to fall down the wellbore. A taper mill is installed below the section mill to clean out such swarf bridges.

When milling upwards, to prevent backing-off of casing collars, a left-hand rotation is necessary. It can be facilitated either by a left hand mud motor or by left-hand workstring to surface. An alternative flow path is also a requirement as swarf or cuttings need to be deposited below the milled section. Table 8.2 presents advantages and possible limitations of the upward milling technique.

8.2 Perforate, Wash and Cement Technique

8.2.1 Concept Behind the Technique

Generally speaking, this technique was first taken into use in the 70's to establish annular barrier whereby casing is perforated, washed and cemented [5]. Briefly, a perforation gun is run to the barrier depth where there no cement or poor cement behind casing. The casing is perforated, Fig. 8.4, and the gun is either left in hole or retrieved. In the next step, a washing tool is Run in Hole (RIH) and washes the annular space behind the perforated casing to remove the debris, settled mud and mud film [6, 7]. The washing process is carried out downward and a several times to obtain fresh formation. At surface, removed metal and debris can be seen and monitored on shakers which gives better control of the washing process. When washing is completed, an integrity test is performed to check the quality of washed and removed zone. If the integrity test is successful, the washing tool may either be left below the bottom perforations to function as a mechanical foundation for the

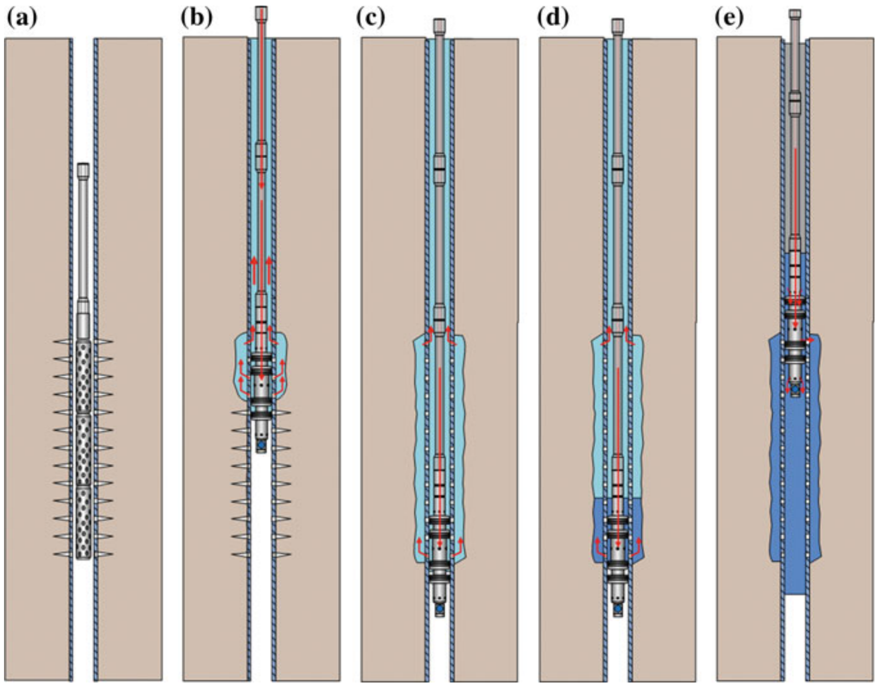


Fig. 8.4 Perforate and wash part of PWC technique; **a** casing is perforated, **b** washing tool is RIH and washes the annular space behind the perforated interval, downward, **c** BHA is placed below the bottom perforations, **d** spacer is pumped and work string is pulled, upward, **e** spacer is extended above the top perforations. (Courtesy of Archer Oiltools)

Fig. 8.5 Perforation gun and washing tool are RIH in single trip. (Courtesy of Archer Oiltools)

cement plug, which is placed in the next step, or it is used as BHA for the cementing stage. For the washing tool to serve as a foundation, a packer is incorporated in the tool and once activated, stays in place. For the next step, spacer is pumped through the perforations. To do so, a new BHA may be used if the wash tool has already been released after the washing process. While pumping spacer, the work string is pulled out of hole. The process is known as pump-and-pull. The spacer is placed below the bottom perforations and extended to above the top perforations.

Nowadays, the perforation gun and washing tool are run in a single trip and when perforating is completed, an activation mechanism is engaged and drops the gun into the well rat hole. The single trip method saves time (Fig. 8.5).

For the next step of the operation, the BHA is placed below the bottom perforations and cement slurry is pumped, Fig. 8.6. After pumping some volumes to remove the spacer around the BHA, work string is pulled out of hole while pumping cement. The pumping of cement is continued with the calculated rate while pulling the work string with an optimal speed until cement and BHA reach above the top perforations. The BHA needs to be pulled out of the cement plug, to at least two stands above the top of cement. Then the well must be circulated to get clean.

One of the challenging parts of the PWC technique is the washing operation. The goal of washing is to remove any materials present behind the perforated casing. Wash fluid, which is a modified water-based fluid, should be pushed through the created perforations, and transport any materials presents out from the annular space. Currently, there are two different methods of washing: swab cup tool and jet tool. In the swab cup method, rubber plastic cups are installed below and above the injection nozzle present on the BHA, Fig. 8.7. Cups create a seal between casing and the work string and prevent the washing fluid traveling in the annular space between the casing and tool, Fig. 8.8a. In this way, wash fluid penetrates through the perforations into the annulus behind the casing and moves upward.

The jet tool method uses a jetting tool to wash and clean out debris by spraying wash fluid, Fig. 8.8b. The angle of jet nozzles and the exit velocity of wash fluid play an important role in the success rate of the washing technique. Centralization of the jet tool while washing could be a concern while for the swab cup tool, the cups partly act as a centralizer. Table 8.3 presents field data from a P&A operation where the PWC technique was used.

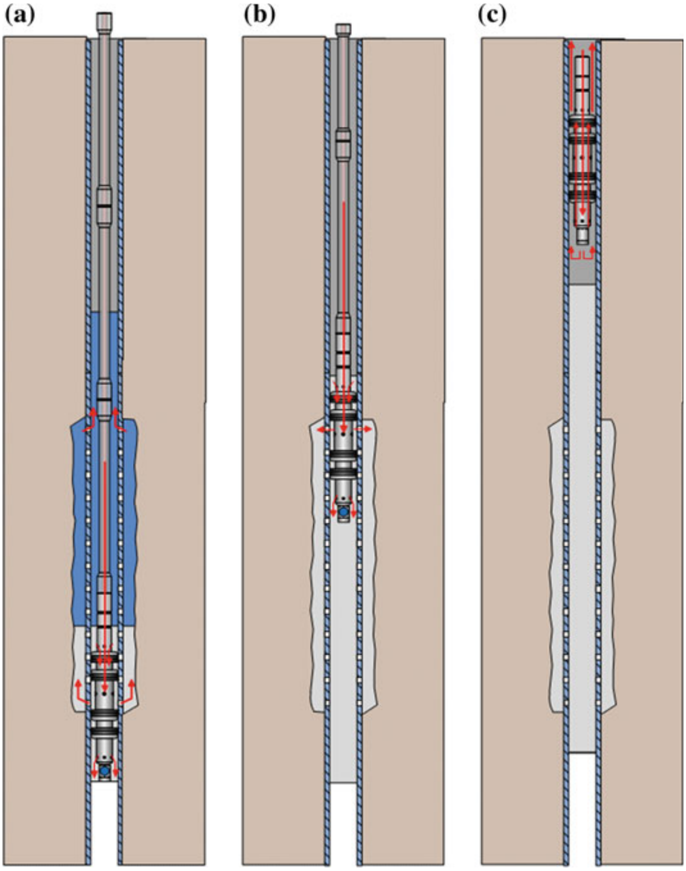


Fig. 8.6 Cementing part of PWC technique; **a** BHA is placed below the bottom perforations, pumping few volumes of cement, **b** pump-and-pull while cementing, **c** pump cement and circulate out the cement in BHA, pull the BHA out of cement, at least 2 stands above top of cement. (Courtesy of Archer Oiltools)

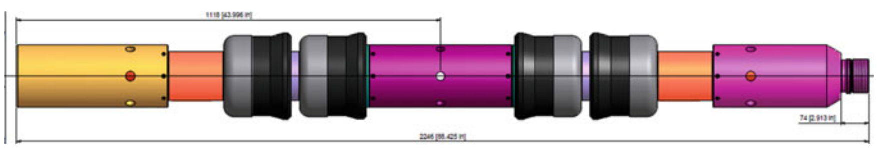


Fig. 8.7 Swab cup tool used in PWC technique. (Courtesy of Archer Oiltools)

When pumping cement slurry through the perforations, the cement should fill the annular space behind the perforations. Displacement efficiency of spacer and placement of cement is a strong function of exit velocity and inclination of the casing, Fig. 8.9. The displacement efficiency, during washing and cementing, is a

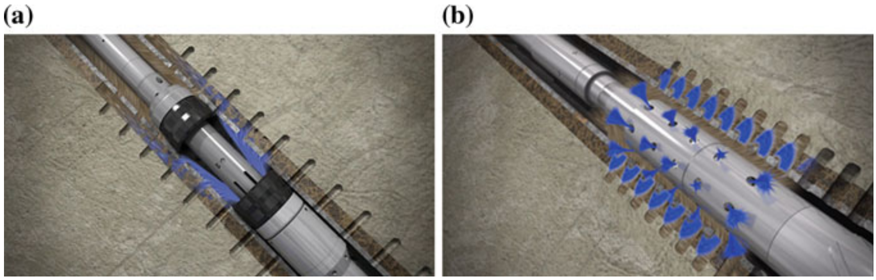


Fig. 8.8 Washing tools for PWC technique; **a** swab cups create a seal inside casing and force the wash fluid into perforations, **b** jet tool sprays the wash fluid through perforations. (Courtesy of Hydrawell AS)

Table 8.3 Field data obtained from a P&A operation on the NCS where PWC technique has been used

Casing size	Length of window	Wash tool	Number of trip in	Perforation size	Perforation phasing	Weight of removed metal	Inclination	Used time
9 5/8-in.	164 ft	Swab cups	Single trip	>1-in.	NA	2%	63°	36 h

concern and matter of research. More theoretical and experimental work should be performed to understand the mechanisms involved. To improve the cement placement and force cement through the perforations, different tools have been designed. Creating a cyclone effect is one of the suggested methods, Fig. 8.10.

There are advantages and possible limitations for the PWC technique, Table 8.4. Lack of qualification methods are the most challenging limitations. With current technologies, to qualify a PWC job, the cement inside the casing is drilled out and casing cement placed during the PWC job is logged by employing sonic logs. However, holes created during perforating challenge the reliability of logging data, in addition to uncertainties associated with sonic logs and the interpretation of logging data in general. If the annular barrier is qualified, cement is placed inside the casing and when the cement has set, it is pressure tested and tagged.

8.3 Explosives to Establish Annular Barrier

In P&A, establishing the annular barrier is one of the main challenges. In order to overcome the challenge, it has been suggested to use explosives for expanding the casing to create a seal or foundation for the annular barrier to be placed on. The amount of explosive to be used, is selected in such a way that the casing will be ballooned but not ruptured. The challenge is to select the correct amount of explosive

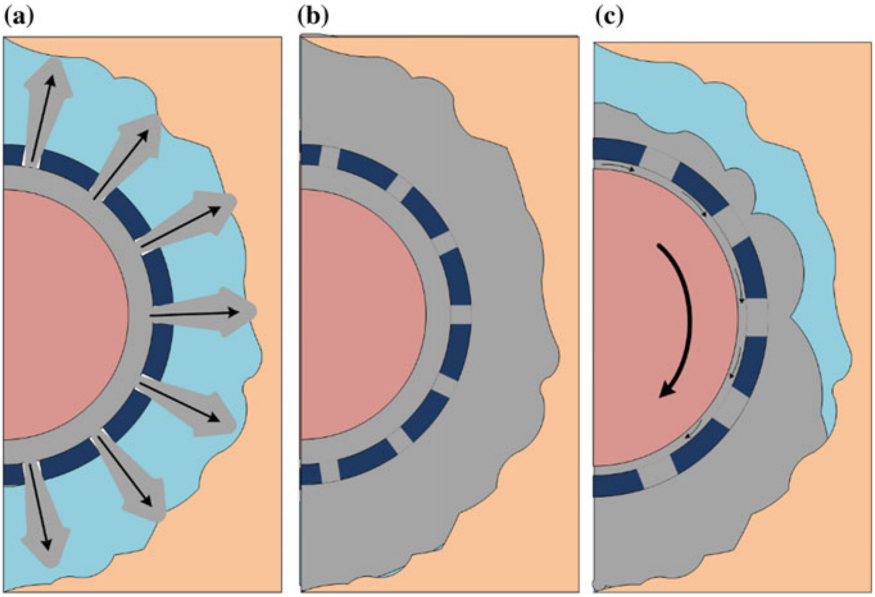


Fig. 8.9 Cementing of perforated casing in PWC technique; **a** cement is pumped through perforations, **b** the ideal cement job to be expected, **c** due to inefficient displacement and inclination cement slurry may not be able to fully displace spacer

Fig. 8.10 Creating a cyclone effect for a better cement placement for PWC technique. (Courtesy of Hydrawell AS)

required as the casing string may not have its original thickness due to corrosion. This technique has been lab and yard tested but today has not been applied in the field.

Table 8.4 Advantages and possible limitations of PWC technique

Advantages	Possible limitations
• Time and cost effective technique • No milling is required • Metal is left in place	• Effectiveness of washing must be verified • No convenient qualification tool or technique to verify established annular barrier • Effective perforation size and phasing need more theoretical and practical investigation • Casing eccentricity during washing and cementing

8.4 Melting Downhole Completion

One of the challenges associated with P&A of wells is removal of the downhole completion to create a rock-to-rock barrier, also known as a cross-sectional barrier. Retrieval of downhole completion exposes personnel to HSE risks, increases the operational time, and carries cost associated with proper handling and disposal of the retrieved equipment. Therefore, a possible solution is to leave as much metal as possible downhole. But the presence of downhole completion at the required depth for the barrier is another challenge to be considered. One possible solution that may solve the issue and create a permanent barrier could be to melt all of the downhole completion and create a rock-to-rock barrier. For this method, the downhole completion and surrounding formation are melted in a controlled manner by use of thermite. In a thermite reaction, aluminum alloys and iron oxide (rusted steel) react and extreme amount of heat is generated. The oxygen required for the reaction is provided by the iron oxide [8]. Consider the reaction of thermite and the reaction mechanisms in Chap. 4.

The use of thermite for cutting tubing, drillpipe and bottomhole assemblies has already been employed in the field [9]. When considering melting the downhole completion and creating a barrier by modifying in situ materials, the barrier verification might be a challenge as discussed in Chap. 9.

8.5 Plasma-Based Milling

8.5.1 Concept Behind the Technology

During permanent plug and abandonment of Oil and Gas wells, the presence of the production tubing introduces challenges associated with logging cement behind the production casing, and cutting and pulling or section milling part of the production casing. Therefore, in conventional P&A methods, the production tubing needs to be retrieved, which is time consuming, costly and associated with risk. The limitations with cutting and pulling casing revolve around two main issues, the ability to effectively cut and retrieve casing and the manual handling of pipe at the surface. Current technology generally requires at least two BHA runs, one with a cutting assembly to cut the pipe at the required depth, then an additional run to retrieve (fish) the pipe above the cut. There are tools available that allow cutting and pulling in one run but a significant time reduction is not yet achieved. Many situations exist which make the pipe unrecoverable, even if the cut is fully successful. In such cases, section milling may be necessary. Challenges introduced by section milling have already been discussed in this chapter. The challenges related to section milling are proliferated by the type of production facility and working unit used for P&A. For offshore P&A activities, rigless P&A utilizing LWIV is a goal. The reason is a significant reduction of daily rental cost. Plasma-based technology may address some of these challenges. The development of plasma-based milling technology for through tubing well abandonment might be a potential solution. Generally speaking, plasma-based milling technology aims to disintegrate steel into small particles and transport the particles to surface [10].

8.5.2 Scientific Background of the Technology

In 1920's, Irving Langmuir described a fundamental state of matter which, unlike the other three fundamental states of matter, does not freely exist, where an ionized gaseous substance becomes highly electrically conductive. In this state, the behavior of matter is dominated by long-range electric and magnetic fields. In 1928, Irving coined the term "plasma" for the new matter state. Lightning and fire are examples of plasma. Plasma can be produced artificially by subjecting some gases to a strong magnetic field or by heating them [11, 12]. The most common gases used for generation of plasma include: air, argon, nitrogen, hydrogen and carbon dioxide. A Plasma jet can be used for different processes such as plasma cutting, plasma arc welding, plasma spraying, etc. Plasma cutting is a process of cutting an electrically conductive material utilizing an accelerated jet of superheated electrically ionized gas, plasma, having a large kinetic energy [12]. Figure 8.11 shows a schematic of a thermal plasma DC torch based on a cathode ionizing a gas stream.

Downhole conditions and materials imply that, the plasma-based milling technology cannot utilize state-of-the-art conventional plasma torch technology. The most important difference compared to conventional plasma torch technology is that the electrical arc with temperatures of tens of thousands of degrees Kelvin heats the surface of target material directly. In addition, its radiation component is also more efficient, with minimalized heating of intermediate gas. The intermediate gas flow in conventional plasma torches reduces the efficiency of heat transfer into the rock. Moreover, the arc creates area-wide, relatively homogeneous heat flow from a spiral arc on the whole surface for a high-intensity disintegration process.

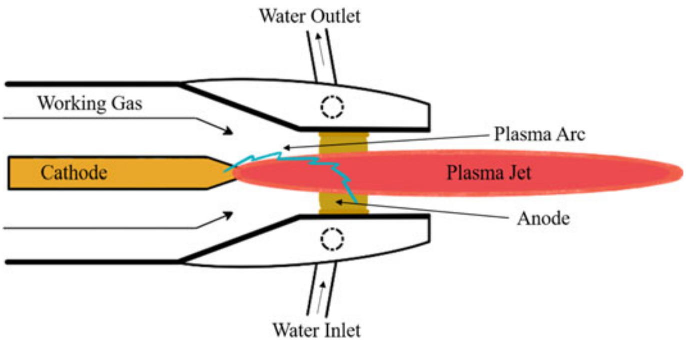


Fig. 8.11 A non-transferred plasma cutter based on hot cathode

Figure 8.12 shows a process of tubing and casing section milling using plasma-based tools. The tool is deployed through the tubing to the target zone where the plug is to be set (Fig. 8.12a). The electric arc is ignited, plasma is created and the tool moves upwards while milling the tubing (Fig. 8.12b). After tubing milling, the tool is moved back to its starting position and then removes casing and cement layers (Fig. 8.12c). After the removal of both tubing and casing, the tool is pulled out of hole (Fig. 8.12d). The section is then ready for cement plug placement (Fig. 8.12e).

The combination of a high temperature large cross-section plasma torch and rotating electric arc is another generation of plasma generators, which might be an effective tool for casing milling. The process using plasma technology is based on a mixture of hybridized plasma, chemical and thermochemical processes resulting in fast metal degradation and removal. The main process responsible for the rate and effectivity of steel degradation and removal is high temperature oxidation supported by melting and evaporation. Nowadays, several studies and techniques deal with the effect of water steam and temperature on the steel removal rate for a wide range of input parameters. One can conclude that temperature and heat transfer were found to be the key factors in increasing the constant rate needed for the required thermo-chemical and thermo-physical processes. The proportional contribution of the processes results in a steel removal effect, which varies with changing temperature and brings the following basic features [10]:

- The oxidative part of the targeted steels' structural degradation is an exothermic process - i.e. it supplies additional energy for all steel removal sub-processes.
- Oxidation and evaporation rate of steel raises with increasing plasma temperature, power density through the unit area at the plasma-steel interface and plasma enthalpy.
- Oxidation and evaporation rate of steel is most efficient in water steam and air-steam mixtures from an energetic point of view (in comparison with other industrial gases).
- There is a narrow temperature window in the range of 3055–3390 °C where enthalpy liberated from oxidative processes raises by a factor of 3. It means that

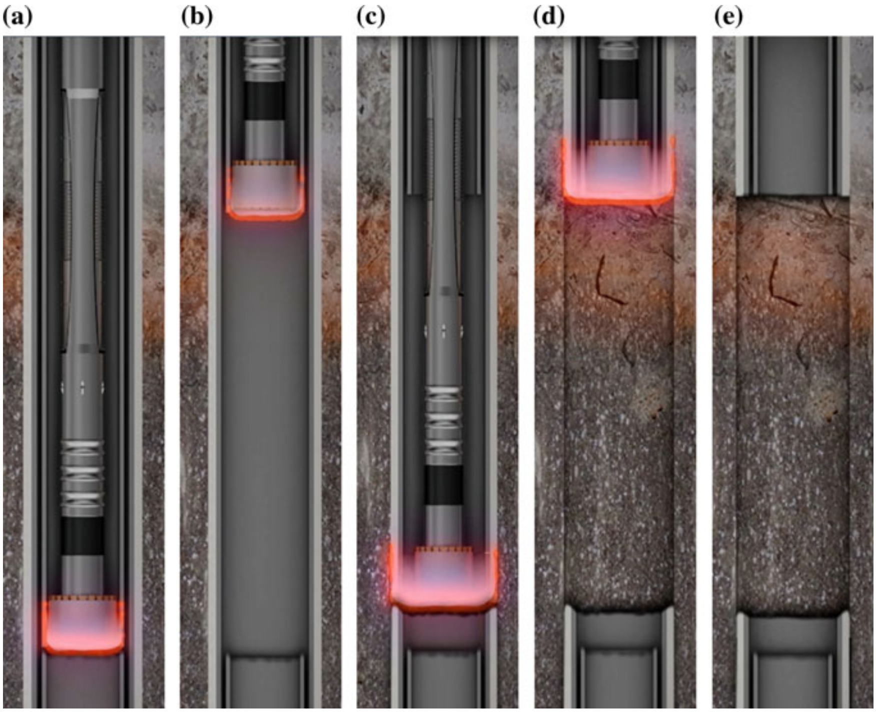


Fig. 8.12 Casing section milling of tubing and casing with plasma-based tool. (Courtesy of GA Drilling)

three times more energy is supplied to the steel removal processes without increasing external power of the plasma generator. This window should be valid for all types of steel alloys since at such high temperatures all the compounds are in gaseous phase.

- Above a steel surface temperature of 6100 °F, a total dissociation and evaporation occurs. Plasma particles impact on the steel surface in the form of active ionic atoms resulting in metal etching effect. It is important not to forget that oxidation is still active during melting and evaporation processes.

Because of steel oxidative processes, a large amount of energy is released during oxidation reactions and recycled to the steel removal processes. In closed vessel conditions, the total energy consumed for steel removal is at least by 30–40% lower than the theoretical value needed for steel melting. Penetration rate is a strong function of total power put into the steel degradation processes and the environment [10, 13]. Theoretically, by increasing input power the steel removal rate should be increased slightly linearly up to its saturation point, which can be obtained only by experimentation.

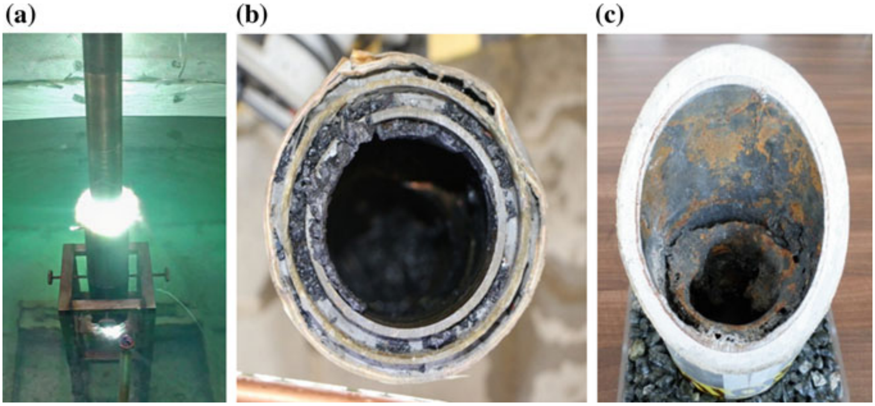


Fig. 8.13 **a** Plasma-based tool entering a multistring casing sample; **b** upper view on the sample after the experiment; **c** sample after diagonal section in order to reveal obtained steel-cement removal [14]

Figure 8.13 shows a plasma-based tool, which is acting on a mono-structure multistring casing sample whereas casing cements support the casings. As shown in Fig. 8.13, the inner casing and cement layer have been completely removed on the chosen section. Experiments have proved that a 3.5-in. tool is capable of milling a wide range of casing sizes including 4½-in., 5½-in. and 7-in. [14].

Scaled testing in pressures up to 1450 psi has been reported. Based on the challenges associated with section milling challenges, several parameters like ROP, steel types and cuttings types from plasma milling processes have been analyzed. Experiments carried out at different boundary conditions show that the efficiency of cutting steel can be characterized, empirically, by one special parameter. This parameter, ε, describes the energy needed for total removal of a mass of steel under the physical conditions. The parameter, ε, *h*as a statistical character as it summarizes the liberated energy coming from exothermic iron oxidation processes and the real electric energy supplied to the plasma generator. Therefore, it is evident that ε is always lower than the consumed electric energy. It was also found that ε is dependent on the degree or type of steel oxidation and hydrodynamic circumstances [14]. In order to determine the ROP, testing with a plasma generator has been carried out on two types of steels: carbon steel S355 and alloy steel with 20% Cr and 12% Ni. The value of ε is calculated from [14]:

$$\varepsilon = \frac{U \times I \times t}{m} \tag{8.1}$$

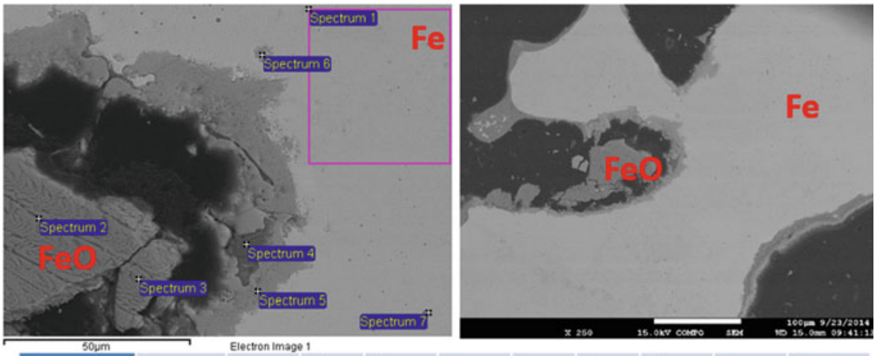
where $U \times I$ is the electrical power to plasma generator, m is the mass of the removed steel from the sample plate, and t is the time of the process.

A functional correlation has been reported between the steel removal rate (*SRR* [kg/h]) and plasma voltage *U* [V], current intensity *I* [A], plasma torch efficiency *h* [0–1] and net energy requirement per unit mass of removed steel ε [MJ/kg]:

$$SRR = \frac{U \times I \times 3.6 \times 10^{-3}}{\varepsilon} \times h \tag{8.2}$$

In real casing conditions, in a water environment at low pressures, the value of ε is found to be in the range of 3–4 MJ/kg. When considering power output 250 kW, plasma torch efficiency 70% and net energy requirement per unit mass of removed steel 3 MJ/kg, the value of SRR is 210 kg/h [14]. This value means ROP 2.0–4.5 m/h for 9 5/8-in. casing section milling (depending on the wall thickness). This ROP is comparable to present-day section milling techniques, however the real difference is the fact that the plasma-based tool is able to mill various casing dimensions (as well as multiple strings) using one tool. This means a reduction in tripping and a significant increase in overall productivity.

For S355 steel, scanning electron microscopy (SEM) analysis clearly indicates the dominant presence of iron (II) oxide in the cuttings, Fig. 8.14. Structural analysis proved a heterogeneity between the formed oxidized and diffusive metallic layers in the cuttings. This resulted in differences in the thermal expansion coefficients of metal-oxide systems at the border of metallic and oxide layers. Therefore, hydrodynamic removal of such weakened multilayers could be realized relatively easily. In the



Spectrum	In stats.	O	Na	Al	Si	K	Ca	Mn	Fe	Total
Spectrum 1	Yes	1.26							98.74	100.00
Spectrum 2	Yes	43.60	1.47	6.94	14.36	1.41	1.61	2.61	28.00	100.00
Spectrum 3	Yes	40.06	0.28	1.23	12.99	0.25	0.48	4.67	40.05	100.00
Spectrum 4	Yes	46.90	1.74	11.08	15.98	2.22	2.22	1.17	18.69	100.00
Spectrum 5	Yes	35.04							64.96	100.00
Spectrum 6	Yes	20.47							79.53	100.00
Spectrum 7	Yes	25.11			6.91			14.34	53.63	100.00

Fig. 8.14 Samples of SEM image and EDX analysis of cuttings' material formed during plasma-based steel removal process of S355. (Courtesy of GA Drilling)

case of alloy steel, the aforementioned differences in thermal expansion properties of metal-oxide multilayers are significantly higher due to a higher grade of chemical heterogeneity in the microstructure. Figure 8.14 shows samples of SEM image and Energy-dispersive X-ray spectroscopy (EDX) analysis of cuttings´ material formed during plasma-based steel removal process of S355 steel.

Apparently, the plasma-based technology is capable of removing carbon steel as well as steel alloys without significant obstacles. Recently, plasma milling in a high-pressure environment has been presented. Subsequently, the following topics associated with the plasma-based milling process of production tubing and/or casing were researched [15]:

- Radial reach of plasma to cement in a high pressure (HP) environment up to 6000 psi
- Effect of the water-based fluids on the milling process in HP of 3600 psi
- Effect of the Oil-Based Mud (OBM) on the milling process in HP of 3600 psi
- Tests of possible damage to casing when milling eccentric tubing in HP of 3600 psi.

Cement removal at pressures of up to 42 MPa using electrical plasma has been tested at laboratory scale. In the case of implementation for either water-based or oil-based fluids, no interference effects on the milling process are reported but due to the presence of drilling fluid contaminating the cement, the removal process seems to be enhanced. The degradation is increased due to different thermal conductivity of present materials. Likely, chemical reactions with a plasma-forming medium are more significant and drilling fluid degradation is stronger or drilling fluid is flushed by the dynamics of implementation of the plasma forming medium into the process. In addition, it is possible to retrieve data of increased electrolysis when the process takes place in a "muddy" environment. The electrolysis level increase is different for WBM and OBM. This gives an important input to the knowledge regarding the structure of the milled casing.

Experimentally it has been shown that plasma-based milling technology can remove production tubing with control line and clamps. Since control line removal is a challenge using conventional technologies, this ability is another advantage.

A well documented advantage is related to the production of small particles instead of swarf. Figure 8.15a shows a typical example of cuttings collected from the casings after the milling processes. Using a sieve analysis, the size distribution of cuttings after drying was evaluated, Fig. 8.15b.

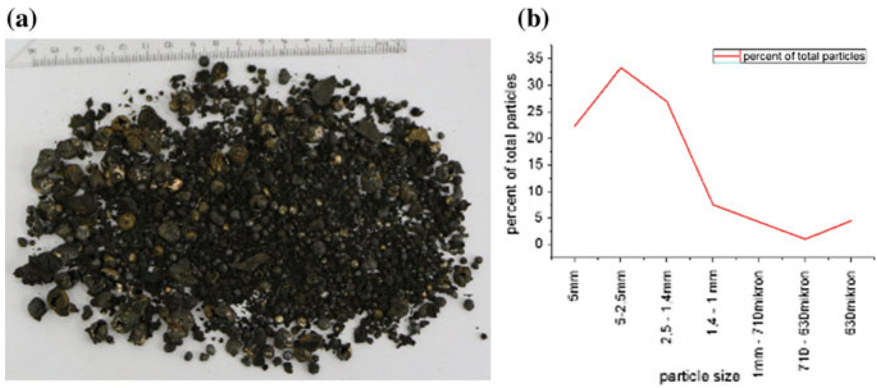


Fig. 8.15 **a** Cuttings generated during plasma milling processes in water environment (scale in mm); **b** cuttings size distribution [16]

The smaller particles are formed from small fragments of oxidized particles with an irregular shape. A fraction of bigger particles contains a larger number of globular particles having smooth surfaces. The ratio of cement particles is approximately the same for each size group. SEM-EDX analysis has been carried out for each size groups and it has been concluded that oxidation processes penetrate the steel volume. Figure 8.16a shows spherical particles identified as a ferrite material with small amounts of oxygen in the structure. Higher content of oxide is shown in the dark parts on the particles. Figure 8.16b, c show a visible inner structure of the oxide fragment. Advantages and possible limitations of plasma-based milling technology are listed in Table 8.5.

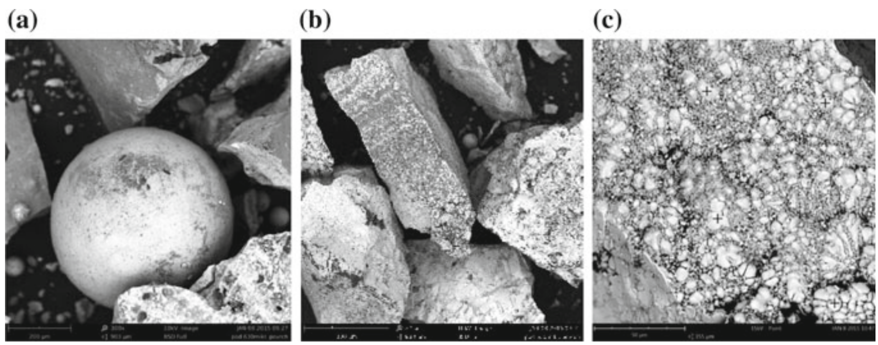


Fig. 8.16 **a** Spherical cutting particle having feritic structure; **b** and **c** SEM photo of oxidized cuttings surface. (Courtesy of GA Drilling)

Table 8.5 Advantages and possible limitations of plasma-based milling technology

Advantages	Possible limitations
• Rigless operation as the system is designed as a coiled tubing deployed solution • High milling ROP and subsequently cost effective • No swarf generation • Non-contact approach which improves reliability by minimizing the wear and tear of the tool or challenges associated with sticking • Fully automated coiled tubing milling process goes hand in hand with the enhanced safety of operational staff • No need to remove Christmas tree	• Not field proven yet and therefore, not commercially available • The Plasma Bit requires a purpose-built CT-reel conveyed umbilical • Ability to deliver sufficient electric power with transfer lines

8.6 Wellhead Cut and Removal

For a P&A operation, in Phase 3, the wellhead needs to be handled safely and efficiently. Depending on the well location and the corresponding authority regulations, the wellhead can be cut and removed or left in place with a cover protection. Considering deep or ultra-deep subsea wells, wellhead cut and removal may not be necessary as there might be no other activities (e.g. the fishing industry) in the area. However, it is a common practice to cut, below the baseline, and remove wellhead of land and platform wells.

Wellhead cut and removal can become a complex and costly operation, especially for subsea wells as a mobile offshore drilling unit, not necessarily a drilling rig, needs to be employed. Experience shows that the total time spent on mechanical wellhead removal of a subsea well can take between 6 and up to 40 h though a typical operation may take approximately 19 h. Therefore, it is necessary to consider wellhead cut and removal and its impact on the AFE. Different types of wellhead cutting are available including explosive cutting, hot cutting, mechanical methods, abrasive methods, and laser cutting. Some of these techniques are already in use whereas others are a relatively young state of the art technology. These technologies are explained in this section.

8.6.1 Explosive Cutting

Explosive technology has been used for control of blowing wells, removal of conductors for well abandonment, removal of platform piling for salvage, and the removal of debris which may present a hazard to navigation and the fishing industry [17]. In this technique, shaped charge cutters are used to produce slot type cuts rather than producing holes in a classical manner. In the classical manner, conical lined shaped

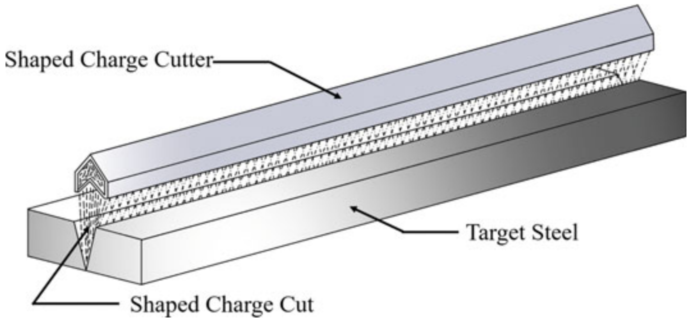


Fig. 8.17 Drawing of a shaped charge cutter and the provided cut in the steel target [17]

charges are used to produce perforations when completing oil and gas wells. The principal of charge cutters and conical shaped charges are the same but the charge cutters provide a linear cutting action (see Fig. 8.17). To create a cut in circular geometries (such as pipes and wellheads) circular cutters, which consist of two 180° hermetically sealed charges, are used (see Fig. 8.18). The circular charges can be used inside or outside circular geometries.

Generally, an explosive cutter system consists of three main parts: command unit, detonator, and charge. The command unit sends a signal via a shielded electrical cable to a detonator, and the detonator initiates the charge directly or via a cortex link. There are some advantages and possible limitations associated with use of explosive cutting for wellhead cut and removal, Table 8.6 (Fig. 8.19).

Fig. 8.18 Inside circular cutter [17]

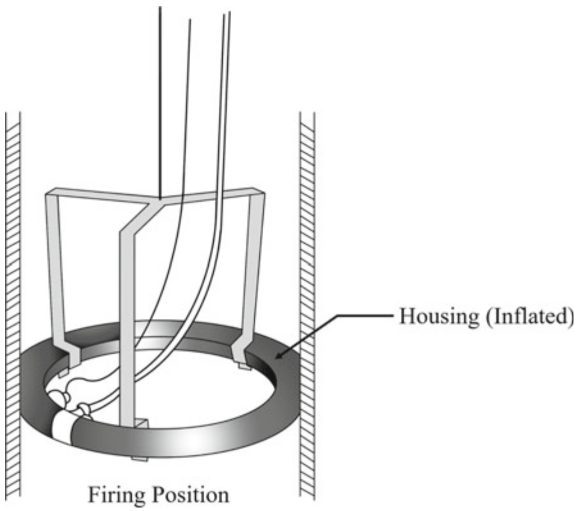


Table 8.6 Advantages and possible limitations associated with use explosive cutting for wellhead cut and removal

Advantages	Possible limitations
• Easy to handle and install • No limitation in size of cut • Fast cutting performance	• No guarantee of the completion of the cut • No control on cutting stages • Restrictions imposed by some authorities for wellhead cutting (environmental concerns) • Due to unclean cut, the removal process of wellhead could be difficult • Associated safety issues

Fig. 8.19 Schematic presentations of unclean cut created by explosives. (Courtesy of Blast Design)

8.6.2 Hot Cutting

The petroleum industry is familiar with different hot cutting methods including oxygen-gas cutting, oxygen-arc cutting, thermic lance, plasma arc cutting, pyrotechnic cutting, and flame jet cutting. The hot cutting technique for land-based and underwater (wet) cutting is almost the same. However, due to presence of water, a gas pocket needs to be created between the torch and target. One main reason to create the gas pocket is that water dissipates the heat more than air and the cut efficiency is dramatically reduced. General advantages and possible limitations of hot cutting are listed in Table 8.7.

In the flame cut process, an oxygen-fuel flame burns in the gas pocket and heats a spot on metal. A jet of pure oxygen, which is located in the center of the heating flame, blows against the spot on the metal to oxidize it with pure oxygen. As the torch is moved, the cut is formed [18]. Hydrogen is the prime fuel gas used for underwater cutting. The oxygen-acetylene flame is another type of flame which generates more heat compared to the oxygen-hydrogen flame. The flame equipment is bulky and requires added skills. In addition, it will only cut through steel and cannot cut through stainless steel nor nonferrous metals such as aluminum, and bronze. This lack of cutting ability is due to the low degree of oxidation of such materials. The flames cut efficiency is a function of water depth. Therefore, the technique is not used as it was used in the old days. The advancement of arc cutting technology has resulted in reduced use of flame cutting.

The arc cutting technique is almost similar to the flame cut but instead of a flame, a plasma arc is the source of heat. The arc heats the metal and oxygen is blown through the electrode to oxidize the metal. Compared to the flame cutting technique, arc cutting is faster and easier to handle and use. However, it can only cut through carbon or alloy steel. A variation of arc cutting is plasma-arc cutting.

The plasma-arc cutter generates a large amount of heat which acts on a spot on the steel surface. A gas flow blows away the molten metal, Fig. 8.20. The plasma-arc is able to cut through thick metal devices with high speed. It can cut through steel, aluminum, copper, and stainless steel alloys, cement and multiple casings.

Table 8.7 Advantages and possible limitations of hot cutting

Advantages	Possible limitations
• Easy to handle and install • Full control at all cutting stages • No limitation in size of cut • Guarantee of the complete cut	• Requires diver or ROV • Restrictions imposed by some authorities for wellhead cutting (environmental concerns) • Poor cutting performance • Associated safety issues with regards to explosion of fuels and gases

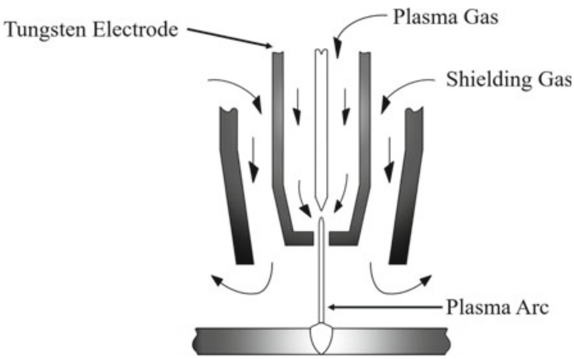


Fig. 8.20 Plasma-arc cutting of steel [18]

8.6.3 Mechanical Methods

Generally speaking, mechanical cutting methods have limitations specially when there is no cement in the annular space between conductor and casing string. The lateral movement of one string creates a challenge for cutting the next string. Mechanical cutting is divided into different categories including diamond wire cutting system, milling cutter, sawing (guillotine saw), and grinding.

8.6.3.1 Diamond Wire Cutting System

The system utilizes a series of machines, which are operated remotely, to create external cuts. The system uses a diamond embedded wire (e.g. a chain saw-like mechanism) to cut. The cutting operation can be done on steel, concrete or composite materials. A diamond wire cutting system consists of a clamping frame, cutting frame with wire driving pulleys and motor, wire feeding system, wire tensioning system, umbilical assembly, and diamond wire cable. As the cutting operation is mechanical, there is no operational limit concerning water depth. In addition, environmental-friendly, full control of the cutting operation, no limitation in size of cut, and fast cutting performance are other advantages of the system. One of the main limitations of this system is that only external cuts can be performed (see Fig. 8.21) [19]. In addition, the wire can get stuck when unstable structures are cut. These types of cutter make the cut above the baseline, seabed or ground, which is less of interest.

8.6.3.2 Milling Cutter

In milling cutting, a hydraulically actuated cutter is activated to create the cut while rotating (see Fig. 8.2). The mechanical cutter is equipped with carbide-tipped tungsten blades. When attempting multiple cemented casing strings, the blades may be worn out and trips in and out are required. Eccentricity of the inner string can result

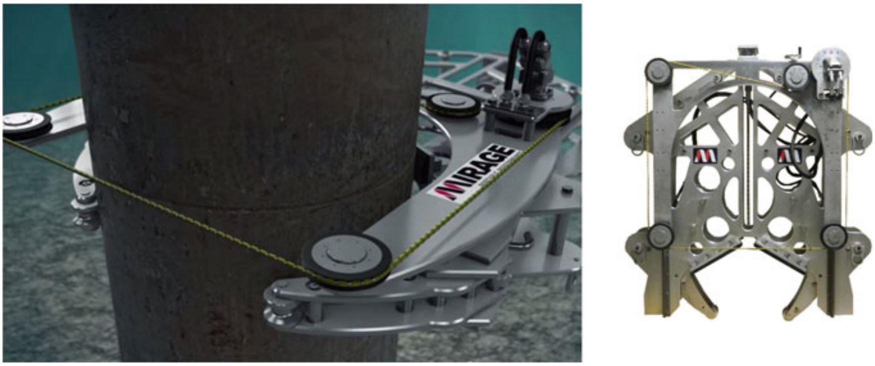


Fig. 8.21 Diamond wire saw. (Courtesy of Mirage Machines)

in an incomplete cut. This method is easy to handle, with fast cutting performance. However, a large amount of swarf is generated which needs to be handled. Replacing the blades can be time consuming, and the risk of over-torque may result in a tool stuck in the well.

8.6.3.3 Sawing (Guillotine Saw)

Guillotine pipe saws are designed for cold cutting and the most common type is reciprocating hydraulic driven saws with automatic feeding (see Fig. 8.22). This type of cutters can perform both on dry and wet environments and the operation can be controlled remotely [20]. Guillotine saws perform external cuts and their blade can get stuck when unstable constructions are subjected to cutting. These type of cutters are fast in cutting but they cut the pipe above the baseline, seabed or ground.

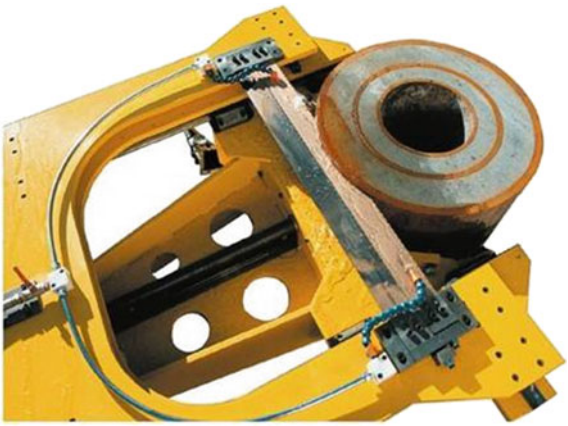


Fig. 8.22 Guillotine saw performing surface sectioning. (Courtesy of Oceaneering)

8.6.3.4 Grinding

Grinding is a type of mechanical machining where a cutting tool removes layers of the target material. The cutting tool is significantly harder than the target material. The electrochemical grinding cutting system is one type of grinding system. An electrochemical grinding cutting system consists of pumps, Direct Current (DC) generators, drive unit and manipulator, umbilical, and the cutting tool. Grinding cutters are environment friendly, safe and reliable with no limitation in size of cut. In addition, the cutting stages are under full control. However, it is a hot work method, slow process and vulnerable to casing compression.

8.6.4 Abrasive Methods

Abrasive methods have long been used in industrial and manufacturing processes to create cuts through rock, steel, and reinforced concrete [21]. Abrasive methods used in the petroleum industry to create cuts are categorized as sand cutting and abrasive water jet cutting. This categorization is based on the pressure used to create the cut. In a sand cutting technique, a high volume of particles are pumped at low pressure; however in abrasive water jet cutting, a low volume of solid particles are pumped at high pressure [22].

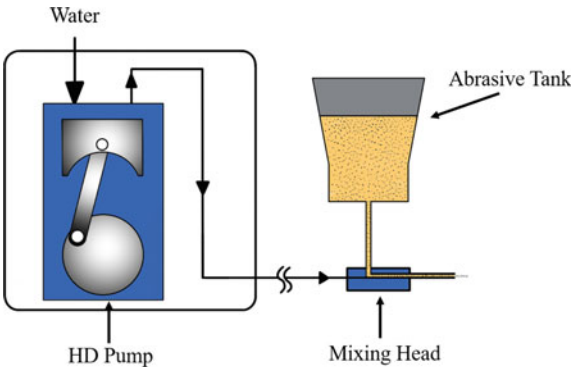
8.6.4.1 Sand Cutting

The process of tubing erosion caused by high-velocity sand has been a known well integrity issue. Development of mobile, high-pressure, high-horsepower pumping equipment, and controlling the rheological behavior of sand slurry resulted in sand cutting techniques in the 1960's [23]. In this technique, a fluid which contains abrasive solids is pumped through a set of nozzles with high differential pressure. The differential pressure is typically between 14 and 28 (MPa) with a flowrate between 350 and 450 (l/min). When the abrasive solids pass the nozzles, pressure is converted to kinetic energy and consequently high velocity is imparted to the solids. The solids with high velocities impact on casing, cement or formation and erode the target material in an organized pattern. Figure 8.23 shows the principle of sand cutting equipment. The equipment includes a high-pressure pump, blender unit with sand catch tank, hydroblast tool, and cutter heads with nozzles. The cut performance depends on nozzle differential pressure, sand concentration, nozzle stand-off distance and back-pressure.

The theoretical power available in the jet stream at the exist of nozzle may be expressed as [24]:

$$Power = QWh \tag{8.3}$$

Fig. 8.23 Principle of a sand cutting unit



where Q is the flowrate of the sand-fluid mixture in ft^3/s, W is the specific weight of the sand-fluid mixture in lb/ft^3, and h is the drop in pressure head across the jet nozzle in ft.

Setting the weight of sand-fluid mixture consists of weight of sand and fluid:

$$W = W_s + W_f \tag{8.4}$$

where W_s is the weight of sand per ft^3 of sand-fluid mixture and W_f is the weight of carrier fluid per ft^3 of sand-fluid mixture.

By substituting Eq. (8.4) in Eq. (8.3) gives:

$$Power = Q\left(W_s + W_f\right)h \tag{8.5}$$

It can be assumed that during sand cutting, the energy imparted to casing and cement by jet stream is due to presence of sand and the energy of carrier fluid is negligible. So, W_f can be set at zero. Therefore, energy per unit of time or power imparted by sand in the jet stream is given by:

$$Power = QW_s h \tag{8.6}$$

The flowrate, Q, of the nozzle can be expressed as:

$$Q = AV \tag{8.7}$$

where V is the velocity of jet stream in ft/s and A is the area of nozzle orifice in ft^2. By substituting $V = \sqrt{2gh}$, then Eq. (8.7) can be written as:

$$Q = A\sqrt{2gh} \tag{8.8}$$

Substituting Eq. (8.8) in Eq. (8.6), the power can be given as:

$$Power = A\sqrt{2gh}W_s h \tag{8.9}$$

Or

$$Power = AW_s\sqrt{2g}\left(h^{3/2}\right) \tag{8.10}$$

The pressure head can be expressed in term of pressure drop and weight of the sand-fluid mixture as:

$$h = \frac{P}{W} \tag{8.11}$$

where P is the pressure drop in lb/ft^2. Therefore, substituting Eq. (8.11) in Eq. (8.10) gives:

$$Power = W_s A\sqrt{2g}\left(\frac{P}{W}\right)^{3/2} \tag{8.12}$$

Example 8.1 Assume that a sand cutter, with single nozzle, is used to cut a casing. The pressure drop across the nozzle increased from 1,000 to 2,000 psi. Calculated the theoretical cutting power of the sand-fluid stream.

Solution The theoretical cutting power varies with the 3/2 power of the pressure drop across the jet nozzle. Therefore, for constant values of A, Ws and W, increasing the pressure drop across the jet nozzle from 1,000 to 2,000 psi increases the cutting power of the sand-fluid stream by $2^{3/2} = 2.83$ times.

Sand cutting is an environmentally friendly technique, which is economical, fast and powerful. But it is difficult to monitor the progress and requires large volumes of sand or slag. Cutting multistring casing is also challenging. Therefore, abrasive water jet cutting has been developed.

8.6.4.2 Abrasive Water Jet Cutting

Abrasive Water-Jet Cutting (AWJC) technique uses high pressure at the nozzle but low volume of sand-fluid. The pressure at the nozzle ranges from 48 to 250 (MPa) and the flowrate ranges from 40 to 100 (l/min). The principle of AWJC technique is the same as sand-cutting, which means utilizing the kinetic energy of abrasive particles carried by a carrier fluid in a high velocity jet to erode the target material. Velocity of particles and distribution of abrasive particles within the carrier fluid are important parameters for the efficiency of the cutting process. One of the challenges associated with abrasive cutting is blockage of the nozzle by oversized grit particles. To minimize the risk, a certain flow is kept at all times to prevent blockage of the nozzle. In addition, Polymeric additives are optionally used to suspend the particles

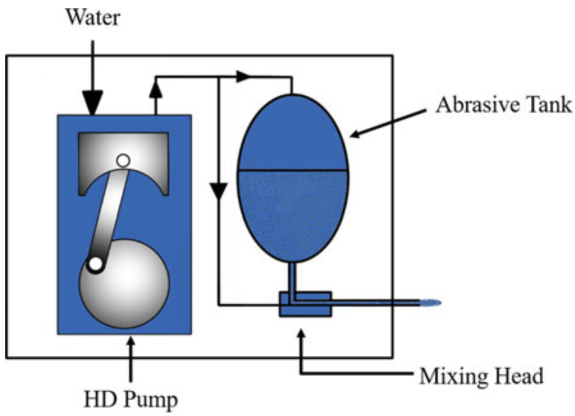


Fig. 8.24 Principle of an AWJC

in the carrier fluid and minimize the grit segregation rate if surface equipment fails and the pumping operation is halted.

A conventional AWJC unit consists of a cutting tool, manipulator, abrasive mixing or dispensing unit, high pressure water pumps, air compressors, hydraulic power unit, control panels, and cut monitoring systems (Fig. 8.24). The manipulator controls the positioning and movement of the nozzle. Presence of water in the interval of nozzle and target material reduces the efficiency of cutting by taking the kinetic energy of particles. Therefore, air compressors are used to blow air and create an atmosphere around the jet. Creating the atmosphere around the nozzle is more challenging where the cut depth increases.

During wellhead retrieval operation, the cutting tool is lowered into the well, centralized and anchored at the required depth. The AWJC unit can be placed on a vessel or MODU for offshore activities. The abrasive fluid is pumped to the nozzle by a water pump which is usually diesel engine driven. The cutting progresses as the manipulator rotates the nozzle. The AWJC technique offers a cold cutting solution, shock free cutting action, no torque between tool and target material, and proven remote operation. However, the size of topside support equipment, limited control over the reach,[1] volume of abrasive require on board, and the required number of crew to operate are some of the limitations of AWJC technique.

When considering the rate of penetration of abrasive cutters, power and velocity of the jet stream are the contributing parameters. Therefore, power equations and velocity equations are reviewed as follows.

Power Equations—In AWJC technique, the rate of penetration of hydraulic jet is proportional to power or energy of the jet at the interface of abrasive fluid and the target. The energy of jet stream is decreased with distance from the nozzle exit. As the distance between the nozzle exit and point in question increases, the energy diminishes to a value equal to the threshold cutting power. So the phenomenon can be expressed as:

[1]Reach is the cut length.

$$\frac{dL}{dt} = K_p(P_L - P_{th} - P_{losses}) \quad \left[\frac{\text{ft}}{\text{s}}\right] \tag{8.13}$$

where dL is the distance between the nozzle exit to point in question in [ft/s], P_L is the power contained in the jet stream at the point L in [(ft-lb$_\mathrm{f}$)/s] or [hp], P_{th} is the threshold cutting power in [(ft-lb$_\mathrm{f}$)/s] or [hp], P_{losses} is the hydraulic losses caused by casing, cutting restriction, and back-pressure in [(ft-lb$_\mathrm{f}$)/s] or [hp], and K_p is the constant of proportionality for power equation in [1/lb$_\mathrm{f}$] which is obtained from experimental data.

The power contained in the jet stream at point L distance from the nozzle exit is expressed as:

$$P_L = \frac{1}{2}\bar{m}_L \overline{V}_L^2 \quad \left[\frac{\text{ft} - \text{lb}_\text{f}}{\text{s}}\right] \tag{8.14}$$

where $\bar{m}_L$ is the mass rate of jet stream in [lb$_\mathrm{m}$/s] and $\overline{V}_L$ is the jet velocity at the distance L in [ft/s]. Due to diffusion of the jet stream with distance, the mass rate is proportional to the initial mass rate at the nozzle exit. The mass rate is also proportional to the ratio of nozzle diameter to distance of point in question from the nozzle exit. Therefore, the mass rate is expressed as:

$$\bar{m}_L = C_m \bar{m}_0 \frac{D}{L} \quad \left[\frac{\text{lb}_m}{\text{s}}\right] \tag{8.15}$$

where $\bar{m}_0$ is the initial mass rate at zero distance in [lb$_\mathrm{m}$/s], D is the nozzle opening diameter in ft, or in., L is the distance from nozzle exit to the point of question in ft., or in., and C_m is an empirical dimensionless constant ($C_m = 5.2$). The jet stream velocity at distance L is proportional to initial velocity of the stream at the nozzle exit and to the ratio of nozzle diameter to distance of point in question from the nozzle exit. Therefore, the velocity equation is expressed as:

$$\overline{V}_L = \frac{C_v \overline{V}_0 D}{L} \quad \left[\frac{\text{ft}}{\text{s}}\right] \tag{8.16}$$

where $\overline{V}_0$ is the initial velocity of the jet at the nozzle exit in [ft/s], and C_v is an empirical dimensionless constant ($C_v = 6.4$). Substituting Eqs. (8.16) and (8.15) in Eq. (8.14) gives:

$$P_L = \frac{C_m C_v^2 \bar{m}_0 \overline{V}_0^2 D^3}{2gL^3} \tag{8.17}$$

where g is the conversion constant in $\left[\frac{\text{lb}_m - \text{ft}}{\text{lb}_f - \text{s}^2}\right]$. From continuity equation, it can be written:

$$\bar{m}_0 = \rho A V_0 \tag{8.18}$$

where A is the area of nozzle and can be written as:

$$A = \frac{\pi D^2}{4}$$

and

$$\overline{V}_0 = \sqrt{2g \frac{\Delta P}{\rho} 144} \tag{8.19}$$

By substituting Eqs. (8.18) and (8.19) into Eq. (8.17), it gives:

$$P_L = \frac{B D^5 (\Delta P_0)^{\frac{3}{2}}}{L^3 \rho^{1/2}} \quad B = 3\pi C_m C_v^2 (2g)^{\frac{1}{2}} \tag{8.20}$$

where ΔP_0 is the pressure differential across the nozzle in [psi], and ρ is the sand-fluid density in [lb_m/ft^3]. Combining Eqs. (8.20) and (8.13) will result:

$$\frac{dL}{dt} = K_p \left(\frac{B D^5 (\Delta P_0)^{\frac{3}{2}}}{L^3 \rho^{1/2}} - P_{th} - P_{losses} \right) \left[\frac{\text{ft}}{\text{s}} \right] \tag{8.21}$$

Velocity Equations—The rate of penetration *dL/dt*, of the hydraulic jet is proportional to the velocity of abrasive fluid at the interface of the fluid and the target material. So, the rate of penetration in terms of velocity can be expressed as:

$$\frac{dL}{dt} = k_v' \left(V_L - V_{th} - \Delta V_{bp} \right) \left[\frac{\text{ft}}{\text{s}} \right] \tag{8.22}$$

where V_L is the velocity of abrasive fluid at the interface of the fluid and target material in (ft/s), V_{th} is the threshold velocity or the minimum velocity required to create the cut in (ft/s), ΔV_{bp} is the velocity of loss of the jet resulting from the return flow of the abrasive in (ft/s), and k_v' is the constant of proportionality for the velocity equation and is obtained experimentally

By substituting Eq. (8.16) into (8.22):

$$\frac{dL}{dt} = k_v' \left(\frac{C_v \overline{V}_0 D}{L} - V_{th} - \Delta V_{bp} \right) \tag{8.23}$$

By rearranging Eq. (8.23) and solving for dt:

$$dt = \frac{k_v L dL}{C_v \overline{V}_0 D - L V_{th} - L \Delta V_{bp}} \quad [\text{s}] \tag{8.24}$$

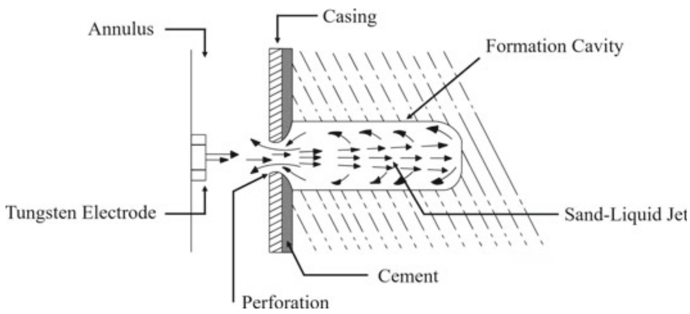


Fig. 8.25 Abrasive cut process for a cemented casing

where k_v is reciprocal of $k_v^{'}$ So, the integration of Eq. (8.24) yields [23] (Fig. 8.25):

$$t = k_v \left[\frac{C_v \overline{V}_0 D}{(V_{th} + \Delta V_{bp})^2} ln_e \left(\frac{C_v \overline{V}_0 D}{C_v \overline{V}_0 D - \left(V_{th} + \Delta V_{bp}\right) L} \right) - \frac{L}{\left(V_{th} + \Delta V_{bp}\right)} \right] \tag{8.25}$$

The research work conducted by researchers shows that the threshold cutting velocity is directly proportional to the hardness of target material:

$$V_{th} = cH \tag{8.26}$$

and

$$H \propto \frac{1}{L_{max}} \tag{8.27}$$

whereas

$$L_{max} = \frac{C_v D \overline{V}_0}{V_{th} + \Delta V_{bp}} = \frac{C_v D \overline{V}_0}{cH + \Delta V_{bp}} \tag{8.28}$$

where c is the proportionality constant, V_0 average fluid velocity of the jet at the nozzle exit in (ft/s), L_{max} is the maximum penetration in (ft), H is the relative abrasion hardness of material and is proportional to the reciprocal of the maximum penetration.

When considering AWJC, although casing back-pressure and size of opening created by the jet cutter have a significant effect on the cut efficiency, the effect of hydraulic jet stand-off, effect of sand concentration, and communication effect of materials by induced fractures or formation permeability are important parameters.

Advantages of AWJC includes but are not limited to fast cutting performance compared to the other cutting methods, environmentally friendly and no special permission is required to conduct it, and no torque between the tool and target. However, the drawbacks are limited control on the reach (cut length), cutting efficiency decreases with water depth, large volume of abrasive fluid is required on board, large topside spread compared to the other cutting methods, and number of crew to carry out the operation.

8.6.5 Laser Cutting

Light Amplification by Stimulated Emission of Radiation, broadly known as Laser, was coined by Gordon Gould in 1957. Generally speaking, lasers are devices which convert different kinds of energy to electromagnetic beams of monochromatic and coherent waves. Monochromatic means the output electromagnetic waves have a single output wavelength or in other words it means one color output. Coherent means that all the waves are in phase with one another. The generated waves span through the different regions including gamma, X-ray, ultraviolet, visible light, infra-red, microwave, and radio waves.

If the generated stream of electromagnetic beams have high enough energy, then they can create a cut on steel and rock samples. However, high-powered laser technology is required for such operations. The intensity of a laser beam depends on the wavelength of the beam. Common components of a laser are active medium, energy input (known as pump source), and feedback (laser cavity). An electron is pumped into a highly excited state and transit to a metastable region. As the electron loses its energy to return to its initial conditions, it generates photons in different directions. This process is known as spontaneous emission.

The efficiency of a laser cutter depends on several laser properties including discharge type, peak power, wavelength, average power, intensity, repetition rate, and pulse with the discharge type [25–27]. The laser discharge can be pulsed or continuous. In pulsed discharge type, the optical power appears in pulses for a certain period of time at some repetition rate. However, in continuous type of discharge, the optical power appears continuously.

The main challenge associated with the utilization of laser cutters at downhole conditions is the presence of wellbore fluids. Downhole fluids are opaque, near-opaque, or even dark which are not conducive to laser cutting.

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