Survey of underwater cutting of metals

(document prepared by Dr. F. Goldberg)

1. INTRODUCTION

Underwater cutting techniques have become increasingly important due to the great interest shown in natural resources in the sea, on the continental shelf and the ocean floor. The rapidly growing activities in structural work and repairs of offshore drilling and production equipment have increased the demands for efficient and safe cutting techniques and equipment.

The primary objective of this paper is to give a summary of underwater cutting methods for metals at present being used as well as of recent developments in this field. The safety aspects of underwater cutting are dealt with in a separate paper, (document I-606-77) "Safety code of practice for underwater thermal cutting."

2. OXY-FUEL GAS CUTTING

2.1. History

Underwater flame cutting was first performed in 1908 in Germany using a standard oxy-acetylene blowpipe as used in air. The standard cutting nozzle proved to be difficult to use since the surrounding water quickly annulled the necessary preheat. It was also difficult to maintain the precise nozzle-to-work distance required. Nevertheless, a limited amount of cutting was done for several years at depths down to 8 m. The major breakthrough in underwater oxy-fuel gas cutting took place in 1925 where the US Navy developed an oxy-hydrogen blowpipe with an outer shroud of compressed air, used for salvage operations. Although detailed modifications have been introduced over the years to this blowpipe, it still forms the basis of present-day underwater oxy-fuel cutting blowpipes.

2.2 Cutting mechanism

The cutting mechanism is the same as in air. The steel is preheated to the ignition temperature by an oxy-fuel flame and a high velocity jet of oxygen is directed onto the preheated metal. The oxygen jet causes an exothermic reaction, oxidizing and melting the steel. The oxygen jet also blows away the oxides and the melt, thus forming a kerf.

2.3 Description of blowpipe

The additional design requirement of the underwater blowpipe is that provision must be made for maintaining a gas bubble around the cutting tip to avoid the water from reducing the preheat effect of the flame. Two basic types of oxy-fuel cutting blowpipes have been developed for underwater use : one relying on a jacket of burnt gases for shielding and the other using a jacket of compressed gas.

The latter one is more commonly used and a schematic outline is shown in fig. 1 (1). The gas bubble

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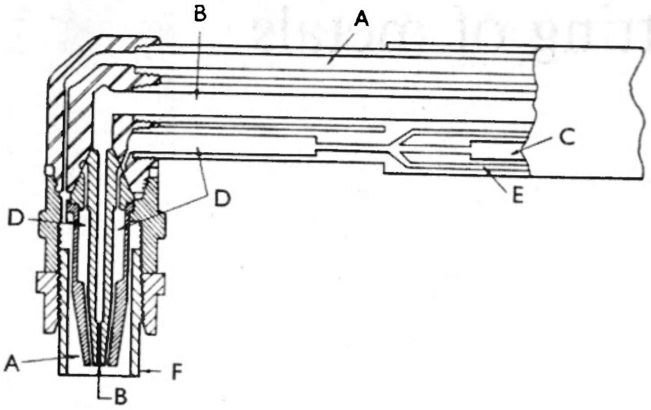


A—AIR
B—OXYGEN CUTTING JET
C—OXYGEN
D—MIXED OXYGEN AND HYDROGEN
E—HYDROGEN
F—SHIELDING CUP

Fig. 1. Schematic outline of oxy-fuel cutting blowpipe.

consists normally of compressed air, oxygen or nitrogen which is ejected around the tip, shielding the cutting nozzle in a gas bubble. The gas-shield stabilizes the flame and at the same time displaces the water from the cutting area. The gas-shield is at the same time used as a spacer device and is adjustable so that the tip can be held at the correct distance from the workpiece. This is essential for underwater work where the blowpipe is employed under adverse lighting conditions and a diving suit restricts the freedom of movement of the operator. Slots in the shield are provided to allow burned gases to escape to the surface.

A short blowpipe is used to reduce the recoil from gas-jet against the surrounding water.

2.4. Requirements for gases used

The critical requirements for the gases used at underwater pressures are non-liquefaction and chemical stability.

2.4.1 *Acetylene*

Acetylene is suitable to use in shallow water (<5m) because its flames have a good stability and are of higher temperature than hydrogen or propane or other hydrocarbons. At greater depths acetylene cannot be used due to the risk of explosion caused by acetylene decomposition and flash backs.

2.4.2 *Hydrocarbons*

Propane, and similar hydrocarbons, can be used down to depths of 20 to 50 m depending on water-temperature. The vapour pressures of these gases are strongly influenced by the temperature. See Table 1.

2.4.3 *Hydrogen*

Hydrogen is the most commonly used fuel gas for underwater cutting. It may be used down to depths below 1000 m. In order to overcome the rapid dissipation of heat and hydrostatic pressure, oxy-hydrogen underwater cutting blowpipes require a pressure of about 13 bar for hydrogen and 5 bar for oxygen. Additional pressure to compensate for depth must be applied at approximately 0.1 bar/m depth and 0.1 to 1.2 bar per 10 m length of hose.

2.4.4. *Liquid fuels*

Liquid fuels can be used under water but were only employed in rare instances prior to and during World War II. Oxy-petrol and oxy-naphta underwater cutting blowpipes are very efficient but the hazards involved prevent their common use in underwater cutting today. In 1962 a new blowpipe for oxygen-petrol was described (2) and good results at depths of 60 m were reported.

2.5. Ignition techniques

Gas blowpipes can be ignited above water and lowered to the operator, but this is not practicable at depths greater than 9 m (3,4). The flame can be ignited under water by a spark between two carbon electrodes in a suitable lighter. There are also blowpipes provided with an additional small flame called a "match" which is ignited on the surface. This flame is small and therefore not dangerous. When the diver is ready to start cutting, the "match" flame ignites the preheat flame of the cutting nozzle. This type of blowpipe, which is patented in Italy, is safe as well as economical (20).

With the oxy-petrol blowpipe developed by Jansen (2) the flame is normally ignited above the water. Although underwater ignition is possible, this not recommended because of possible ignition of vapours above the water surface.

2.6. Applications

The oxy-fuel cutting process is generally used for cutting mild steels, low-alloyed steels and materials which are readily oxidized. It is not very suitable for

Table 1. Depth for liquefaction of various fuel gases at bottom water temperatures.

GAS	T°C	Depth (m)
Hydrogen	0	app. 1400
Ethylene	0	410
	4	425
Ethane	0	230
	4	255
Propane	0	37
	4	44
	10	54
Butane	10	5
MAPP	0	35

Table 1 shosw the liquefaction depths of some fuel gases. For hydrogen it is not true liquefaction depth but the depth at which density of the gas approaches that of the liquid.

corrosion-resistance steels or for non-ferrous metals except titanium.

The optimum thickness range is from 10 to 40 mm. Thinner steel plates are difficult to cut as the surrounding water quickly cools the plates. This makes it difficult to reach the ingition temperature during the cutting operation. Thicknesses greater than 40 mm can be cut but require a sharply increased level of skill from the operator. Material as thick as 300 mm has successfully been cut under water.

2.7. Cutting data

Diagrams 1 and 2 give some typical cutting data for oxyfuel underwater cutting.

2.8. General discussion

Oxy-fuel underwater cutting, mainly using hydrogen as fuel gas, requires only light portable equipment without the necessity of generators or other electrical equipment. It obviates electrical hazards, dangers from shock and corrosion through electrolysis on divers' gear and spark formation.

Oxy-fuel cutting is also suitable for cutting off steel wires and cables because it offers less electrical hazards and less danger of damage to nearby vessels. The process has, however, a few disadvantages in that it can only be used on ordinary mild and low-alloyed steels. Stainless steel and cast iron are difficult to cut due to the oxidizing properties of these materials (5).

Non-ferrous metals (e.g. brass, copper, bronze or aluminium) can only be cut by melting. This is a slow process which produces a poor quality cut, it is restricted to steels thicker than about 10 mm, as mentioned earlier, and it requires a higher degree of skill from the operator than oxy-arc cutting. It is also a slower method than oxy-arc ; the importance of this factor depends on the working depth. The diver must also be aware of the dangers from explosions when using hydrogen formed by decomposition of water.

3. OXY-ARC UNDERWATER CUTTING

3.1. History

The oxy-arc process, originally introduced in 1915 (6,7), relies on the same basic principles as oxy-fuel, cutting but instead of a flame an electric arc is used as the primary heat source. The arc is struck from the tip of a hollow electrode through which a jet of oxygen is blown onto the workpiece. The major development work in cutting electrodes was carried out by the US Navy during World War II. The objective of this work, which was reported by Ronay in 1946(8), was to develop a safe and effective alternative to oxy-hydrogen cutting, already an established underwater salvage tool, which would eliminate the need to carry large quantities of hydrogen. The work resulted in two different types of electrodes which still form the basis of present-day cutting electrodes. These were a ceramic tubular electrode and a steel tubular electrode, which will be discussed later.

3.2. Cutting mechanism

The cutting principles for oxy-arc cutting are similar to oxy-fuel cutting but, instead of preheating with a flame, an arc is struck between a hollow electrode and the workpiece. The oxygen jet blowing through the tubular electrode has two functions, first to establish an exothermic oxidizing reaction and then to blow the

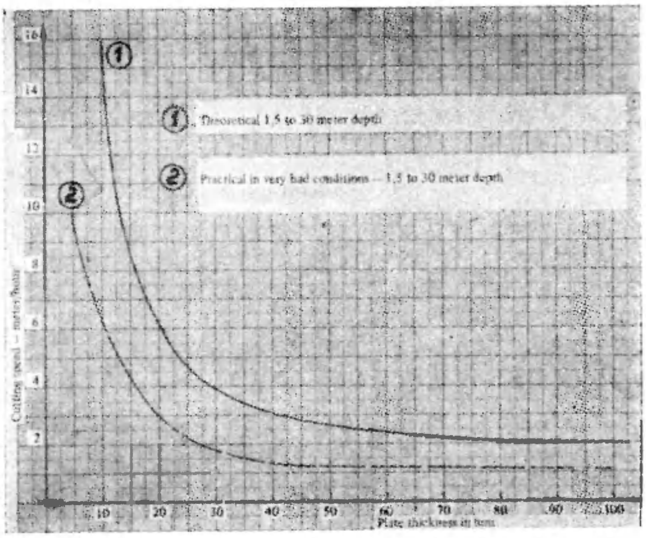


Diagram 1. Carbon steel underwater oxy-fuel cutting (H_2-C_2H_2-C_3H_8).

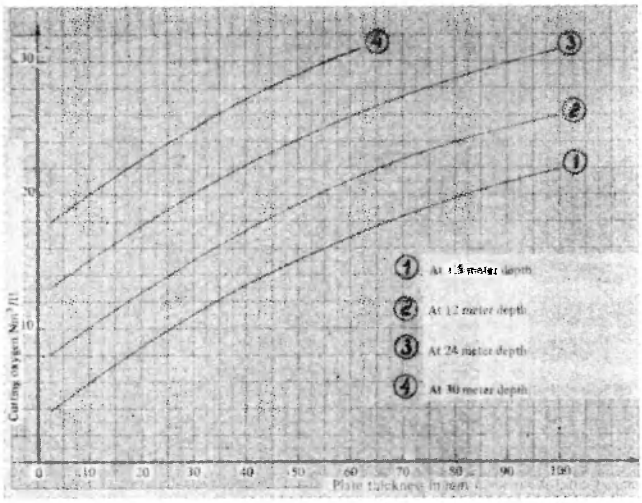


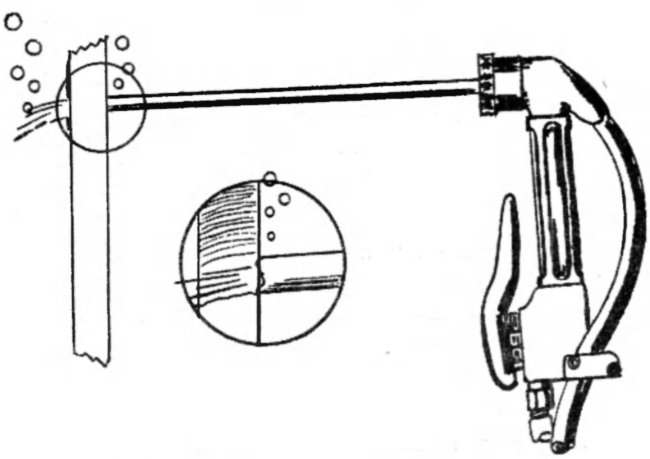
Diagram 2. Carbon steel underwater oxy-fuel cutting (H_2-C_3H_8-C_2-H_2).

molten oxides away to form a kerf. Cutting is performed directly in the water and no gas shield is required. The arc also heats the electrode which is then exposed to both heat and oxidation. In consequence the first developed electrodes were made of slowly-oxidizable materials such as brass, cast iron and carbon. As a result of the US Navy developments, the electrodes today are made from ceramics or from tubular steel with an insulating coating which also improves the arc-action. The electrodes are fastened in an electrode holder similar to those used for welding (fig. 2).

3.3. Electrodes

3.3.1. *Steel tubular electrodes*

Steel tubular electrodes can have two types of covering : a flux covering applied by either extrusion or dipping and a wrapped covering of plasticized cellulose tape. In either case it is also protected with lacquer for waterproofing. This protects the electrodes from absorbing water that might lead to cracking or fracture during heating. The flux on a covered cutting electrode is a source of easily ionized compounds which lead to arc stability, supplement the gaseous barrier around the arc and help to insulate it from the surrounding water. The covering is designed so that it melts away more slowly than the tubular steel core, thus resulting in a cup on the end of the electrode. This makes it possible to cut by holding the covering in contact with the metal, thus facilitating operations under difficult conditions and ensuring the proper arc gap.



Fig, 2. Oxy-arc cutting blowpipe.

A typical steel tube covered electrode is 355 mm long with external and internal diameters of 8 mm and 3 mm respectively (fig. 3).

3.3.2. *Ceramic tube electrodes*

Ceramic electrodes are formulated to be highly refractory, resistant to oxidation and to have good electric conductibility.

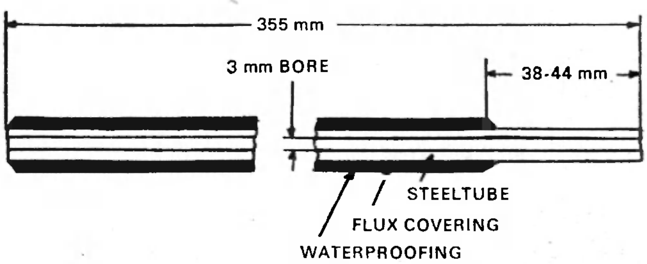


Fig. 3. Typical steel tubular electrode for underwater oxygen-arc cutting.

The standard size for a ceramic tube electrode is 200 mm long, approximately 14 mm outer diameter with a 3 mm bore.

During manufacture the electrode is baked at high temperature to make it less brittle and is further reinforced by a sprayed steel covering approximately 0.8 mm thick. One end of the electrode is ground to a diameter of 13.5 mm for a length of approximately 32 mm to from the grip end and the rest of the electrode is given an insulating waterproof warp. This electrode was developed with two principal advantages in mind. First, the ceramic electrode does not react readily with oxygen at high temperaure and has a much longer life than the steel electrode. This minimizes the number of electrode changes required for a given cut length. The second advantage is its light weight, an important factor when supplies are air freighted. In the latest types of ceramic electrodes, the refractory oxides have been superseded by silicon carbide.

3.3.3. *Carbon electrodes*

In the UK, carbon electrodes have been developed for oxy-arc underwater cutting. They consist of a carbon tube with dimensions approximately 230 mm long, 10 mm diameter and 1.6 mm bore. They are metal plated, usually with copper, and are fitted with a brass contact tip. For insulation they also have a protective covering. The same electrode can be used for cutting steel thicknesses up to 100 mm. The carbon electrodes can also be used for cutting cast iron, copper and brass etc. (4).

3.4. Operating data

The following typical operating data for the different types of electrodes when cutting mild steel are valid :

Covered steel electrodes

T	Cutting speed mm/min	O_2 cons. per m cut	O_2 bar*	Electrodes cons/m	Cut : burnoff ratio
6	650	0.23 m^3	1.3	0.31 kg/7 pcs	1.5
12	500	0.28	2	0.42 gk/10 pcs	1.0
18	450	0.32	3	0.42 kg/10 pcs	
25	375	0.37	4	0.48 kg/11 pcs	0.75

*Add 0.1 bar per m water depth and 0.1 to 0.2 bar per 10 m length of hose.

Ceramic electrodes

T	Cutting speed mm/min	O_2 bar	Cut : burnoff ratio
6	325	1.3	20
12	254	2	15
25	200	4	5

Carbon electrodes

T	Cutting/speed mm/min	Cut : burnoff ratio
12	305	12

Although the steel electrode gives a faster cut at all metal thicknesses, the ratio of cut length/burnoff is considerably higher for the ceramic and carbon electrodes. This difference is particularly significant on thin plate. When the time spent in changing electrodes is accounted for, the length of cut achieved over a considerable time can be greater with ceramic electrodes. As seen in fig. 4(8) the approximate break-even point lies at 19 mm thickness. Beyond this thickness the steel electrode is more efficient, even accounting for the

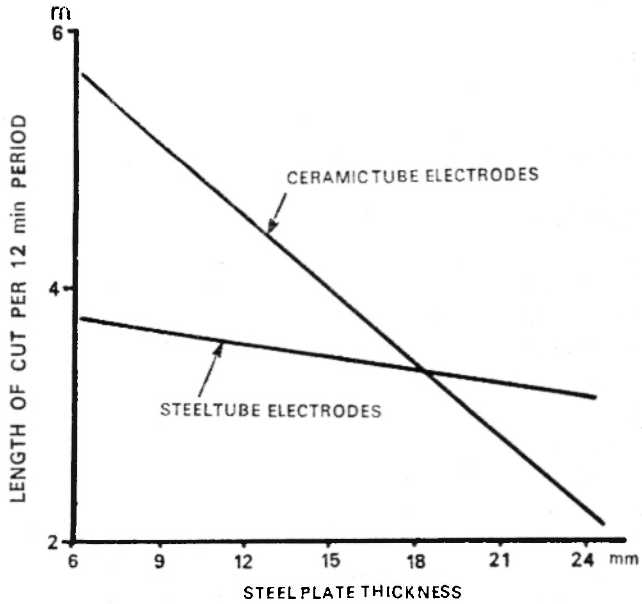


Fig. 4. Comparison of cutting rates for a 12 minute cutting period between steel tube electrodes and ceramic tube electrodes.

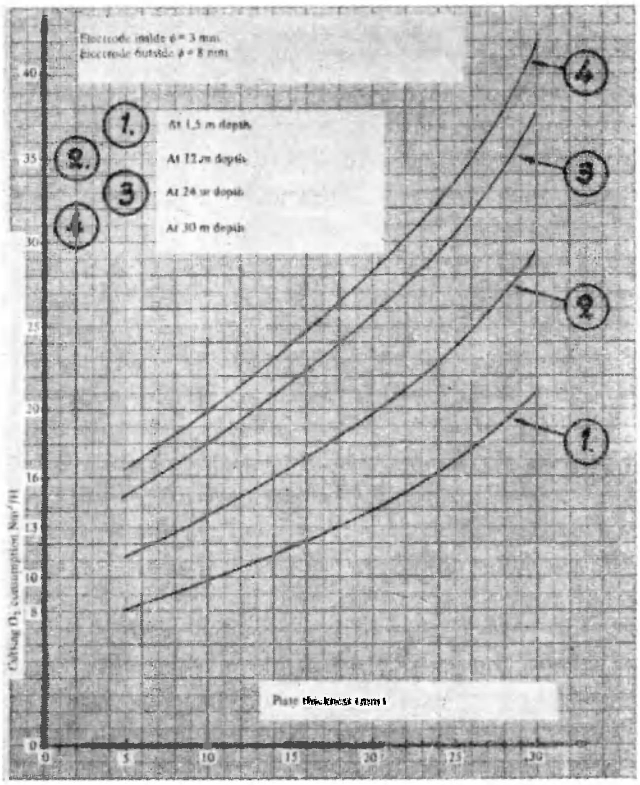


Diagram 3. *Oxy-arc underwater cutting of carbon steel.*

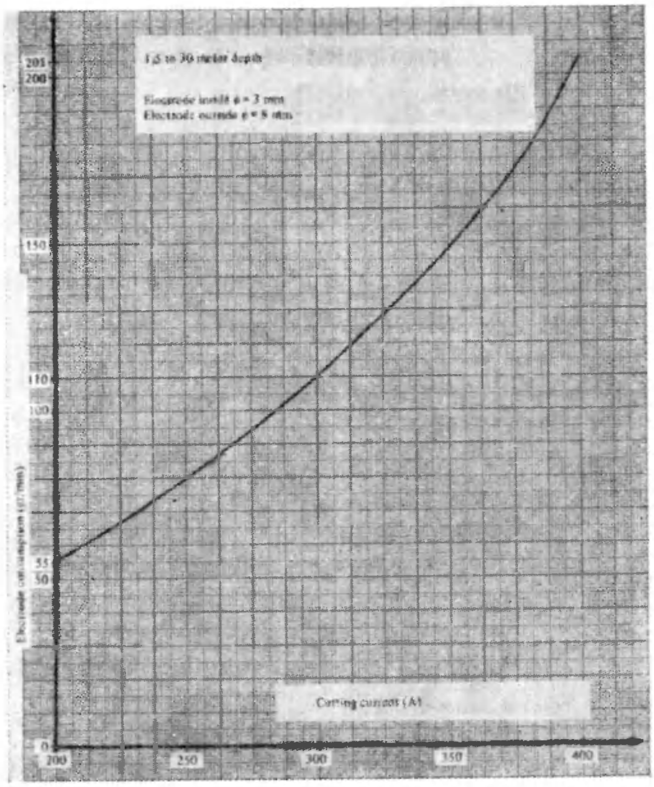


Diagram 4. *Oxy-arc underwater cutting of carbon steel.*

higher frequency of electrode changes. Diagram 3 shows the oxygen consumption for steel electrodes in relation to material thickness and depth and diagram 4 shows electrode consumption in relation to the cutting current.

3.5. Application

The oxy-arc underwater cutting process is today the most commonly used. Even with little skill and poor visibility the operator can cut both easily oxidized material such as mild steel and low-alloyed steel and also stainless steel, cast iron, copper or aluminium. In the latter materials, the cutting operations mainly melt the material which is why the cutting is slower and needs more skill by the operator. The steel tube electrode produces a narrow cut which makes it difficult to inspect for complete severance. Ceramic tubes produce a wide cut which is easily tested for complete severance but the cut is not as clean and smooth as when produced by a steel electrode. The ceramic electrode is shorter and permits the operator to cut when access is restricted. The quality of the cuts is generally too rough for welding without surface dressing.

The oxy-arc cutting process is suitable for cutting under water ferritic structures up to 40 mm thickness. The method, can be extended with difficulty to greater thicknesses.

3.6. Oxy-arc gravity cutting

Oxy-arc gravity cutting is a special mechanized underwater cutting technique developed in Japan (11). The equipment is very similar to standard gravity welding equipment but the welding electrode is replaced by a tubular steel electrode through which oxygen is blown (fig. 5).

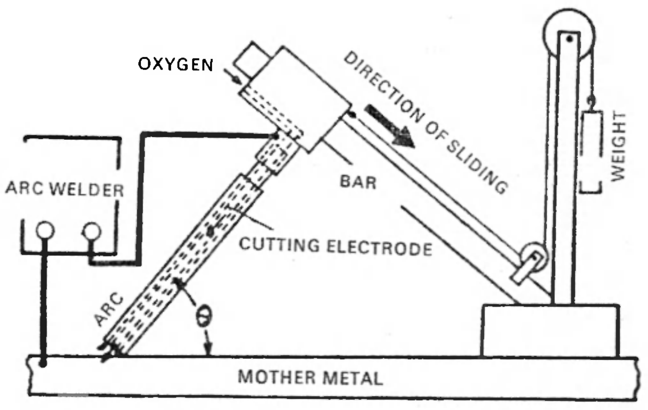


Fig. 5. Schematic view of oxy-arc gravity cutting.

The advantage of this technique is that the electric hazards are eliminated as the operator does not need to be under water when the equipment is operating. The equipment which can only be operated in the horizontal position is easy and quick to set up and keeps the electrode and arc steady to produce a relatively good cut surface quality.

The cutting speeds are claimed to be high : 250 mm/min in 100 mm thickness and 600 mm/min in 40 mm thickness.

3.7. General discussion

The oxy-arc underwater cutting technique is easy to operate and can be used to cut most metals and all thickness.

The main disadvantage, which applies to all electric-arc-under-water techniques, is the danger of electric shocks and the pipe is light and easy to handle and the consumables are cheap.

The main advantage, which applies to all electric-arc underwater techniques, is the danger of electric shocks and the electrolytic production of oxygen/hydrogen mixtures, especially in sea water. Another disadvantage is that there must be close cooperation between the operator and an assistant above water to switch the current on and off when the electrodes are replaced. This frequent change of electrodes is also a negative factor. The electric power supply unit needed is also too heavy to be carried around in a small boat.

Despite these disadvantages, the oxy-arc cutting method is today the most widely used.

4. METAL-ARC CUTTING

4.1. Basic principles

This cutting technique uses the same equipment and consumables as underwater manual metal-arc welding (MMA), the difference being that metal-arc cutting needs much higher current densities.

The cutting action is merely one of melting produced by the electric arc, there being no exothermic reaction or gaseous blast to eject the molten metal. The molten metal is pushed out of the kerf by the electrode in a short slow sawing motion which requires good operator skill.

4.2. Equipment for metal-arc cutting

4.2.1. *Cutting with covered electrodes*

The recommended power source for metal-arc cutting is a 400 amp DC generator. As in oxy-arc cutting, an AC power source can be used, but is dangerous and requires 10% larger currents.

Practically any type of covered, welding electrode can be used, provided that it is waterproofed. A 4.8 mm diameter electrode with 300 amp and 40 volts can cut out steel plates up to 6.4 mm thickness. For thicker material the use of 4.8 mm or 6.4 mm diameter electrode with a 400 amp generator at 40 volts is recommended.

4.2.2. *MIG-cutting*

Instead of covered electrodes, a continuous wire with a shielding gas has been used with a conventional MIG-welding unit as an experimental technique (fig 6). The resulting cuts suffer from two major drawbacks. There is a tendency for molten metal to flow around the arc and form bridges between the severed edges with production of much dross. Recent developments in Japan have overcome these difficulties by using a high pressure water jet instead of shielding gas to blow away the molten metal. A detailed description is given in chapter 5.

4.3. Applications

The operator who has mastered the "sawing" technique can part almost any metal, regardless of composition or thickness, provided a proper power source is available. The cutting speed obtained in cutting mild steel plates, however, is substantially slower than that with oxygen-arc.

The technique has two areas of application where it has a marginal advantage over the more common oxy-arc technique. It is more controllable on steel plate with thicknesses of less than 6 mm and many operators claim that it is preferable for cutting non-ferrous materials at all thicknesses.

5. METAL-ARC CUTTING WITH CONSUMABLE ELECTRODE AND WATER JET

5.1. Cutting principle and application

The principle of underwater cutting using a consumable electrode and water jet technique is shown in fig. 6 (12). The method has been developed in Japan at the Government Industrial Research Institute of Sikoku. As seen in fig. 6, the method is very similar to metal-arc gas-shielded cutting (MIG), but by using a high-pressure water jet the molten metal is efficiently dispersed, leaving a clean cut surface and little dross. Because the cutting action is principally one of melting, the method is applicable to both ferrous and non-ferrous metals. Since the process uses a continuous wire as the consumable electrode, the need for the frequent electrode changes is eliminated and thus productivity is high. The process does not suffer from hazards any more severe than those usually encountered with wet underwater welding techniques.

5.2. Cutting data and discussion

The experiments described using this method(12) have been carried out in shallow water (0.2 m depth) with mechanized torch-transport. Under these conditions the process has been capable of producing both straight cuts and bevelled cuts with high speed and surface quality.

Table 2 shows some cutting data. Although the torch has not yet been tried manually, two factors render it suitable for manual use. The torch is efficiently cooled by both the surrounding water and the water jet and can therefore be made light, even for currents up to 1200 A.

Mechanized trials have produced successful cuts over a wide range of torch/workpiece distances, which would suggest that the process will be tolerant to the variations in this parameter which will evidently arise with a diver working under adverse conditions.

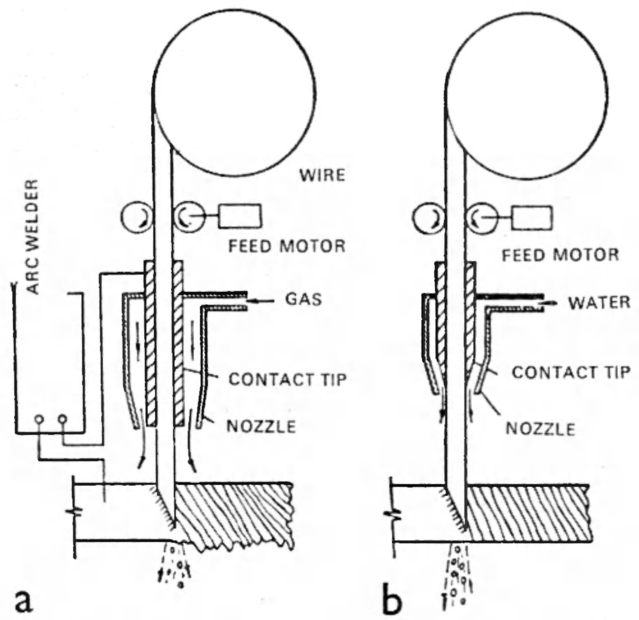


Fig. 6. Principles of MIG cutting (a) with gas shielding (b) with water jet

Table 2. Cutting data for consumable electrode water-jet cutting.

Thickness mm	Current A	Speed cm/mm	Voltage V	Kerf width (mm) Top	Kerf width (mm) Bottom
9	500	40	25-30	2.8-3.2	3.0-4.5
	1000	150			
16	600	30	25-30	2.8-3.2	3.0-4.5
	1000	90			
20	600	30	28-33	3.0-3.5	3.5-5.0
	1000	60			
30	1000	25	30-35	3.0-3.5	3.7-5.5

Stainless steel

Thickness mm	Current A	Speed cm/mm	Voltage V	Kerf width (mm) Top	Kerf width (mm) Bottom
12	600	50	35	1.8-2.0	2.0-4.5
	1200	140	40		
20	700	45	35	2.3-2.8	4.0-5.0
	1200	90	40		
30	1200	55	40	2.3-2.8	4.5-5.5
40	1200	35	45	2.3-2.8	4.5-6.0

6. PLASMA-ARC CUTTING

6.1. Basic principles

A standard plasma-arc cutting torch has a central tungsten electrode (cathode) recessed within a nozzle which has a small orifice at its end. Gas is passed

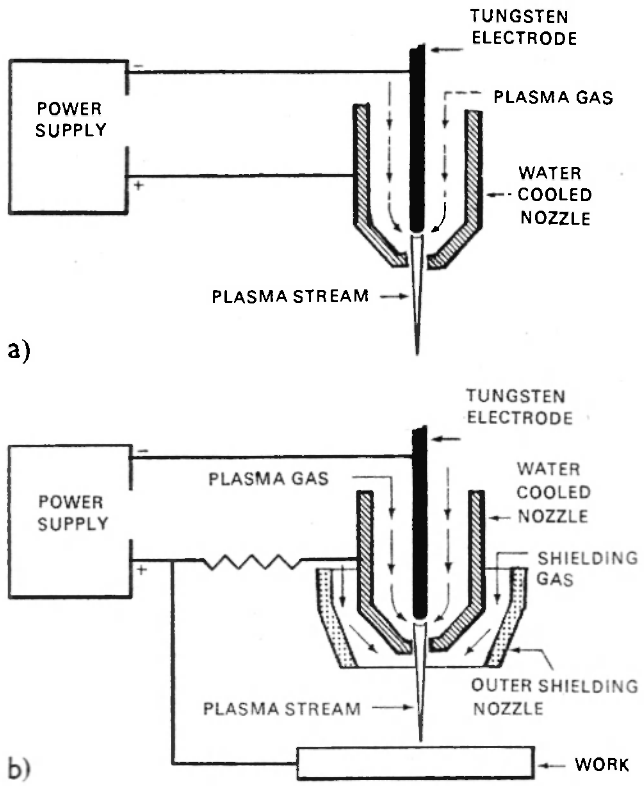


Fig. 7. Schematic diagram of (a) non-transfered plasma arc system and (b) transfered plasma arc system.

through the annular channel between the nozzle and the cathode and emerges through the orifice. When the arc is struck between the electrode and workpiece ionized gas is blown through the orifice to form a constricted plasma-jet. The difference between plasma welding and cutting is that cutting uses higher currents and gas flow rates. The plasma-jet melts all materials instantly and is blown out of the kerf. It can therefore be used for both mild steel and stainless steels without difficulty. When cutting stainless steels, the oxides, which obstruct oxygen cutting, are also melted and vapourised by the plasma-jet. Plasma torches may be designed for the transferred or for the non-transferred arc system. In the former, the arc is struck between the cathode and the workpiece ; this is the method most directly applicable to the underwater cutting of metals. The non-transferred arc is struck between the electrode and the nozzle and the plasma flame is blown through the orifice in the nozzle (fig. 7).

6.2. History

Underwater plasma cutting technology is now (1976) becoming commercially available. Extensive studies are being carried out at several research laboratories around the world, where limited experiments have shown plasma cutting to work well under water.

The first documented practical use of underwater plasma cutting was carried out in the USA and Italy in connection with dismantling nuclear components in nuclear reactor tanks. The components were cut at depths varying from 1 to 7 m using standard plasma torches slightly altered for underwater use.

The advantages of using plasma cutting in the nuclear tanks were many. The process is easy to automate, shape cutting can be carried out with proper remote control and cutting speeds are high. The cutting gas-jets creates turbulence in the water, which washes the gas and traps very fine as well as large particles of metal and oxides, and thus reduces the release of radioactive material to the air. In maintenance work the water rapidly oxidizes and quenches molten metal from the kerf, limits its travel and thus prevents spatter damage to system components.

In Trino (Italy), the thermal shield of the pressurized water reactor was dismantled. The shield was a hollow cylinder 3 m diameter with a thickness of 76 mm. Due to radiation the shield had to be cut underwater and was split up in 39 strips. The cutting was carried out vertically upwards, the cutting speed being 250 mm/min with 210 volts and 982 A. The cut groove was 13 mm. No difficulty was experienced in depths of 7 m but the influence of the surrounding water required nearly twice the power used for cutting in air.

In the Soviet Union research with plasma cutting under-water has also been carried out. Special torches were developed for both fresh water and salt water (13). One interesting detail of this development was that the torch cooling was not recirculated but is fed through an annular nozzle concentric with the plasma orifice to provide a flow of fresh water around the arc. In addition to minimizing current leakage this is claimed by Madatov to give more favourable conditions for arcing and to improve visibility by suppressing bubble formation. Successful tests were carried out at 5 and 10 m depths.

Studies of the plasma arc behaviour at lower depths have been carried out in a deep water simulator at the Royal Armament Research Development Establishment in Great Britain (14). Plasma cutting has successfully been carried out at simulated depths of 370 m. This indicates that the plasma-arc cutting techniques seems to be very suitable for deep-water cutting applications, for which today very few cutting methods are available.

Moss et al (a14) also found that the effect from ambient water pressure on an arc is reflected in the arc voltage (fig. 8).

6.3. Safety aspects

Before manual underwater plasma cutting becomes a practical proposition, the electrical safety aspects will require a careful study. The only systematic study so far reported was conducted by Madatov (13). Voltage measurements were made between various limbs of a dummy clad in diving gear when using the OPPR-1 torch in salt water, with an open circuit voltage of 180 V and leakage currents of up to 70 A. The maximum potential difference of 14 V was observed between the right hand and the right boot of the dummy. On this basis it was concluded that underwater plasma cutting is safe provided the torch is properly insulated. However, much more detailed study will be required before plasma cutting can be considered a viable manual technique for underwater cutting.

6.4. Applications

As mentioned earlier, the practical use known so far of underwater plasma cutting has been in connection with the maintenance of nuclear reactor components. Laboratory experiments around the world have, however, shown that underwater plasma cutting will be an important underwater cutting process in the future.

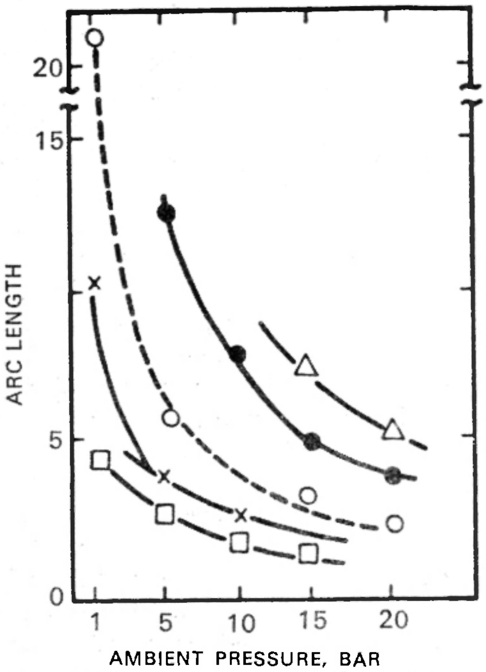


Fig. 8. Arc length as function of ambient gas pressure and voltage.

The reason for this is the lightness and compactness of the torch, the possibility to cut manually or by remote control, the possibility of use for cutting both ferrous and non-ferrous metals and even non-metallic materials when used with a non-transferred arc. The cutting speed is said to be 3 to 8 times greater than that achieved with oxy-arc cutting.

Underwater plasma cutting may also give interesting advantages over plasma cutting in air. Thin sheets of metal submerged in shallow water (about 20 mm) can easily be plasma cut practically without distortion. Other advantages in the workshop are the reduced noise-level and flash from the arc and also reduced ultra-violet radiation forming ozone and nitrous gases.

7. EXPLOSIVE CUTTING

7.1. History

Explosives have been used for many years in underwater salvage operations. The most common technique has been the use of contact demolition charges which, as the name implies, involves the use of bulk explosives fastened to the structure in question. The size and placing of the charges is largely a matter of experience. The cut or tear produced is extremely irregular and there is an obvious danger of damage to adjoining components and structures. When, as in many salvage operations, this is of little consequence, the technique is adequate.

During the last 20 years explosive cutting has, however, developed into an established cutting technique and is a sophisticated and precise means of underwater cutting. This is due to the development of shaped charges.

7.2. Principle of shaped charges

The basic shaped charge consists of a specially selected explosive contained in a metal sheath made from a soft metal such as copper, aluminium or lead (fig. 9). Upon initiation the metal liner collapses and is projected towards the workpiece as a high velocity jet of metallic particles. The particles converge along a line which concentrates impact energy on a relatively small area of the target.

7.3. Applications

Shaped charges have been developed for a wide variety of applications which range from straight line cuts in plate, through hole cutting, to the complete

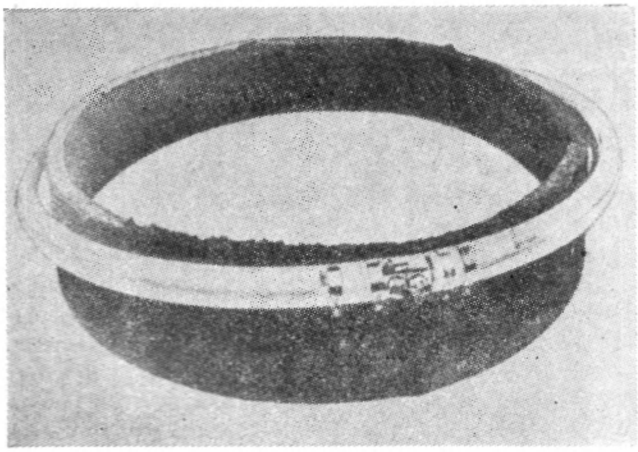


Fig. 9. An explosive charge in shaped metal sheath.

severance of standard geometrical forms. Of particular interest to the offshore oil industry is a series of shaped charge cutters designed for cutting tubular sections from either outside or inside. This is the case when cutting off conductor pipes and casing left after an oil well has been abandoned offshore. These have to be cut at or below sea-bed level and a shaped explosive charge is claimed to be the quickest and most efficient method of cutting, saving a day or more in rig time.(15). When possible, the pipe is cut from inside by lowering a charge into it. The required explosives are calculated from the internal diameter of the pipe and its wall thickness. A suitable canister to hold the charge is selected to fit the diameter of the bore of the pipe. The charge is primed and lowered into the pipe to the required depth of cutting. The rig is then free to move away leaving the conductor pipe in position. The charge is detonated from a small boat and a dive is made to ensure satisfactory cutting.

When the conductor pipe has a very narrow bore, an internal charge alone cannot be used. The alternative is to use a ring-shaped charge which is slipped around the outside of the pipe, combined with an internal charge.

The technique can also be used for pile cutting using "hi-velocity gelatin" (Nitroglycerine) in shaped containers. Careful placing of the charges permits control of the direction of fall of the pile.

Where the possibility of accidental damage is an extreme problem a curtain of air bubbles can be used to attenuate the shock-wave and thus protect adjacent components.

Charges have been developed which will cut 100 mm thick steel plates, 150 mm diameter steel cables and concrete piles up to 1.2 m diameter with 38 mm thick steel casings. The shaped charge has two main advantages over the contact demolition charge : it produces a much more precise cut and, because the explosive is used efficiently for cutting, the risk to adjoining structures is much less severe.

8. THERMIC LANCE

8.1. Principle

The thermic lance consists basically of a steel tube packed with steel rods. Oxygen is blown down the centre of the tube and when the exhaust end of the tube is externally preheated to red heat, the steel burns exothermically at a sufficiently high temperature to maintain a continuous process and to melt-cut other materials, both metallic and non-metallic. If the material is readily oxidizable, such as mild steel or low-alloyed steel, the metal melts due to the heat from the lance and from the exothermic reaction between the oxygen coming through the lance and the steel. This results in a quickly cut hole. If the material does not oxidize readily (e.g. concrete, brick or brass) the material is melted and flows or is blown away by excess oxygen (16). As the thermic lance produces a hole, a series of holes must be made close together, allowing the bridges between the holes to collapse in order to produce a cut.

8.2. Equipment

Commercial thermic lances are packed with mild steel rods to produce a more intense source of heat. The oxygen flows in the spaces between the wires. Common types of lances have a nominal bore of 9.5 mm to 21 mm and are about 3 m long. The lances are screwed into a lanceholder fitted with a gas flow control valve. The holder is conventionally connected by hose and pressure regulator to cylinders of oxygen. The sizes of holes produced iwth 9.5 mm and 19 mm diameter lances are about 38 mm and 73 mm diameter respectively (17).(+)

8.3. Applications

The thermic lance is not widely used for cutting steels below 40 mm thick under water. However, it is used on very thick sections not easily cut by other processes. An example of this type of operation is the

(+) See doc. IIS/IIW-472-75 Welding in the World (Vol. 13, No. 3/4, 1975).

cutting of ship stern frame castings. The technique has also been extensively used for cutting concrete and is perhaps the best available method for cutting reinforced concrete under water.

8.4. Safety aspects

Although not an electrical cutting method the process does have its hazards. The reaction of unburnt oxygen with dissociated hydrogen produces so-called "steam explosions" which can be sufficiently severe to be a hazard to the diver. This is one of the principal factors limiting the use of the process in modern deep-diving applications (1). It is also recommended to use a flash-back arrestor on the lanceholder to prevent molten products being blown backwards and igniting the hose.

9. MECHANICAL CUTTING

9.1. Principle

The principle of mechanical cutting under water is the same as in air ; rotating milling cutters, single tool lathe-type cutters or grinding discs are used. These types of cutters have been used for many years under water with standard types of pneumatically or hydraulically driven motors converted for underwater use.

9.2. Applications

As mechanical cutting operations are very slow by comparison with thermal cutting processes, they are mainly used only when high quality cuts are demanded. This is the case when bevelling surfaces before welding. At present mechanical cutting is the only means of producing precise welding bevels on an existing pipeline under water. Fig. 10 shows an example of a milling type cutter. A chain tensioning system is used to traverse a high speed rotating milling cutter around the pipe. Various shapes of cutting wheel can be inserted to give a variety of cut shapes ranging from a simple square cut to complex welding bevels.

9.3. Fluid power driven systems

The use of fluid power driven systems under water is limited to the depth to which the fluid power can be transmitted from the surface.

Most hydraulic tools adapted for underwater use are powered by oil lines from the surface and are limited to a depth of 45 m (18). As the depth increases, hydraulic lines become necessarily larger in diameter and create handling problems both above and below the surface. Also increased input power is required at the pump to overcome line losses.

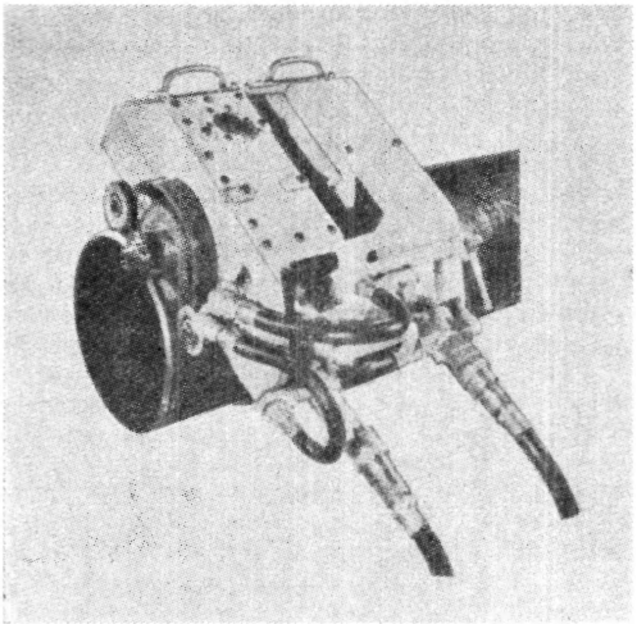


Fig. 10. An underwater hydraulic milling type cutter.

To provide hydraulic power at depths greater than 45 m a compressor is located on the sea floor near the work site. Operated by electricity supplied by cables from the surface the unit improves the efficiency of the diver by shortening the length of compressor to tool hose and by increasing the pressure available to actuate the tools.

The use of totally bottom supported systems is still in the concept stage, but presents no new ideas from the hydraulic power source point of view (18).

9.4. Pneumatic power drive systems

Most pneumatic tools adapted for underwater use are operated by a pressurized gas (usually air) supplied from the surface. The depth limitation is about 50 m due to back pressure. Apart from back pressure the tool will lose pressure due to the long lengths of pipes involved. If the exhaust can be piped back to the surface the depth limitation of the tool is the length of pipe available.

9.5. Electric power tool system

A properly designed electric tool could overcome many of the disadvantages of the pneumatic and hydraulic systems. The problems of complete insulation, motor starting and speed variations have, however, first to be overcome. Battelle Research Institute have, under the sponsorship of the US Navy, built an electric system, thought to be the first power tool designed specifically for underwater use. The 200 W underwater electric tool was built so that the major components, stator and rotor, were open to the water, isolated from the electric current and constructed of corrosion resistance materials. To simplify construction and reduce weight, the gear-box was left open to the water. The advantages of this design are that it is small and light, there are no seals, and therefore the motor is not affected by changes at various working depths.

This electric tool was successfully operated in 1969 in both salt and fresh water, but further research is required. An improvement would be to use a brushless DC motor. This would be more efficient than an AC motor and would permit better control of tool speeds. Since DC motors can operate directly from batteries, divers could be freed from entangling cables.

Electric cutting tools can in theory be used at depths of a few hundred meters. (19).

10. SUMMARY OF UNDERWATER CUTTING PROCESSES

Method	Present depth experience, m	Applications	Merits	Limitations
Oxy-gas				
Oxy-acetylene	13	Not used	Higher flame temperature than oxy-hydrogen	Acetylene unstable above ~2 bars
Oxy-hydrogen	100	Ferritic materials up to 40 mm thick. Can be extended to 300 mm thick with difficulty	Fuel gas with most favourable vapour pressure properties. Simple, easily maintained, portable equipment.	Theoretical depth limitation of 1400 m. Requires considerable skill. Relatively slow
Oxy-MAPP	1	Not used	Lessened sensitivity to nozzle/workpiece distance	Lower flame temperature than oxy-hydrogen. Handling difficulties
Oxy-petrol	100	As for oxy-hydrogen	Easy storage of liquid fuel at pressure	Need for heater to vapourise fuel prior to ignition
Oxy-arc				
Tubular steel electrodes	150	Ferritic materials up to 40 mm. Can be extended to greater thicknesses with difficulty	Simple portable equipment. Easily used technique	Need for frequent electrode changes. Rough cut surfaces
Ceramic tubular electrodes	~120	Ferritic materials up to 40 mm. Can be extended to greater thicknesses with difficulty	Simple equipment. Easily used technique. Lightweight electrodes. Good for restricted access	Brittle electrodes. Slower than tubular steel electrode

Method	Present depth experience, m	Application	Merits	Limitations
Manual metal arc	60	Cast iron, austenitic steels and non-ferrous materials	Uses same equipment as MMA 'wet' welding	High skill requirement. Very slow
Explosives Demolition Charges	Unknown	Salvage	Simple, remote handling	Very rough cuts. Danger to adjacent structures.
Shaped charges	~90	Cuts on pipelines, cables, I-beams, hole-cutting, etc. Thicknesses up to 100 mm	Simple, remote handling. Fast, little support facilities required. No skill required	Limited to simple geometric configurations. Need for care with adjacent structures
Mechanical cutting	180	Bevelling of pipelines	Accurate machining of weld preparations. Mechanised, therefore no manual skill required other than setting up	Limited to simple geometrical shapes such as pipelines. Very slow
Arc plasma Transferred arc	4 (reactor components)	Cutting, gouging and bevelling of all metallic materials up to 75 mm thick	High speed, accurate, clean cut 2-5 times faster than oxy-arc. Requires no electrode changing	High voltages used constitute severe electrical hazard for manual operation. Further development work required
Non-transferred arc	None	Cutting of non-metals		High power requirements
Thermic lance	~60	Thick metal sections. Concrete	Simple, cheap equipment. Ability to cut almost anything	Very rough cuts. Danger of 'steam explosions'
Consumable electrode with water jet	1	All metals up to 60 mm thick	Simple, equipment and consumables. Capability of mechanised bevel cuts	Questionable visibility. Further development required for both mechanised and manual operation

11. Effects of Depth on Feasibility of Underwater Cutting Processes

Process	Comment
1. Oxy-hydrocarbon	Limited to depth at which hydrocarbon liquefies
a) 70% propane 30% butane	16.5 m (4°C), 21.3 m (10°C)
b) propane	44 m (4°C), 54 m (10°C)
c) ethane	1255 m (4°C)
d) methane	179 m (0°C) (+)
e) MAPP	35 m (0°C)
2. Oxy-hydrogen	Limited to depth at which hydrogen liquefies. (+)
hydrogen	1400 m
3. Oxy-arc	Limited to depth at which Oxygen liquefies (+)
oxygen	4410 m
4. Thermic lance	As oxy-arc
5. Plasma-arc	Limited to depth at which arc gas liquefies. (+)
a) nitrogen	5090 m
b) argon	3570 m
c) hydrogen	1400 m
6. Metal-arc	Arc length depends on ambient pressure and voltage which indicate a limitation not known today. 5 mm arc length is obtained at 30 m depth with 50 Volts 200 m depth with 100 Volts (This relation is not linear) Fig. 8
7. Power cutting	
a) pneumatic	Limited to a depth of 30 m by handling problems with compressed air pipe.
b) hydraulic	With surface hydraulic support limited to 45 m. With surface electrical support and hydraulic pump and drive unit underwater no depth limitation.
c) electric	No obvious depth limitation.

+ Not true liquefation ; depth at which density of gas approaches that of the liquid.

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MEMBERS TO NOTE

From the number of circulars and communications that are being returned to the institute's office, it appears that many members omit to keep the institute posted whenever there is a change of address.

All members are requested to remember to intimate the Superintendent, The Indian Institute of Welding, 48/1 Diamond Harbour Road, Calcutta 700 027 promptly of any change of address so that communications intended for them do reach them in time.