2021

Underwater Cutting Explosions

Causes / Effects / Consequences
&
Prevention

FRANCIS HERMANS

Retired Commercial Diver

May 2021

Cover photo copied from Instagram courtesy of Callum Macleod.

All my thanks to OCTO Diving for their technical assistance which enabled me to verify the accuracy of certain data mentioned in this document

OCTO Diving

Original title
Découpage Sous Eau
Causes, Effets, Conséquences
&
Prévention des Explosions

Acknowledgments:
Many thanks also to Brian Gilgeous for his help in the correct translation of this document

<u>Notes on units of measure</u>

Since the great majority of divers are still accustomed to using the bar as a unit of pressure measurement, all the data initially expressed in Pa and its multiples have for their convenience been converted into bar in this document.

Summary

Why this document? 3
THE CAUSES 5
Definition of a gas explosion 5
How does an explosion occur? 5
The confinement 6
The fuel 7
Production of hydrogen and carbon monoxide 7
Production of methane and sulphur dioxide 9
Gases present in a wreck 10
Paints and bituminous products 10
Residual gas from the use of an underwater gas cutting torch 11
Welding electrodes gases 11
The oxidizer 12
Fuel in suspension 12
Explosion domain 13
Source of ignition 14
THE EFFECTS 15
Potential energy 15
Concentration of the fuel gas mixture 15
Volume of gas charge 18
Deflagration regime 18
Detonation regime 18
Rate of explosion pressure rise 19
Water depth 20
Practice example 21
CONSEQUENCES 26
Consequences for the diver 26
Maximum peak pressure (Pm) 30
Impulse (I) 30
Prediction of the effects of peak pressure and impulse 34
Hydraulic water hammer 43
Mini - explosions (pops or bangs) 44
Pops with H_2/O_2 44
Steam explosion 47
Concrete explosive spalling 51
PREVENTION OF ACCIDENTAL EXPLOSIONS 52
General prevention 52
Prevention of explosion risks associated with welding 55
Prevention of explosion risks associated with gas torch cutting 56
Prevention of explosion risks associated with methane 56
Prevention of explosion risks linked to hydrogen 57
Prevention of explosion risks associated with cutting in a wreck 59
Prevention of explosion risks associated with a too low oxygen pressure 60
Prevention of explosion risks associated with welding gas/air mixtures* 63
Conclusions 64
Bibliography 65

Why this document?

During their cutting work, divers quite regularly have to undergo the effects of small gas explosions commonly called "pops or bang" in our technical jargon. Although the effects generated by these pops are sometimes quite painful, they can in no way be compared to those generated by explosions of larger volumes of gas which can have much more serious consequences.

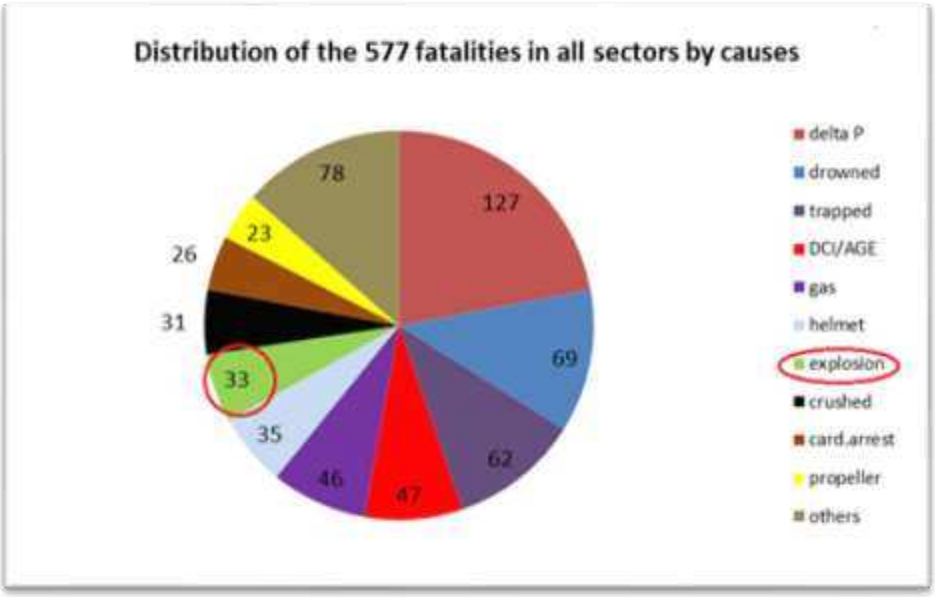

Fig. n° 1: distribution diagram of fatal accidents according to their causes (1).

If we refer to statistics established over a period of 40 years and published a few years ago, we can see that the fatal accidents due to explosions linked to underwater cutting are relatively high since no less than 33 known accidents are listed there. To this list, we must also add the dozens of serious accidents as well as incidents which had less serious consequences and for which no statistics exist.

On reading these statistics, we realise that under water thermal cutting (gas or electrodes) is a dangerous activity which presents high risks. Therefore, to limit these risks, one wonders whether it would not be prudent to replace this technique with a cold cutting method that can be done remotely while generating little or no sparks.
Various techniques (diamond wire, hydraulic shears, hydro abrasive jet) exist and are already often used, but these tools cannot be used in all situations and therefore thermal cutting is not yet ready to be stopped.

Whilst many books and documents have been written on underwater explosions, practically all of them relate only to solid explosives. When it comes to underwater gas explosions, almost nothing has been written on the subject and for the very few articles that have been published; they are unfortunately not available for everyone to view.

The purpose of this little document, which has no scientific vocation, is therefore mainly dedicated to the commercial divers in order to explain to them in a simple way, what are the causes, effects and consequences of these explosions, so that they can prevent them happening as much as possible.

THE CAUSES

Definition of a gas explosion

Whether it happens in the air or under water, a gas explosion generates a very rapid release of energy that causes an almost instantaneous increase in temperature accompanied by a sudden expansion of the medium in which it occurs.
The faster this transformation takes place, the more the resulting medium is in overpressure.

How does an explosion occur?

We are generally taught that to trigger an explosion, we must bring together the 3 elements which are included in the fire triangle.

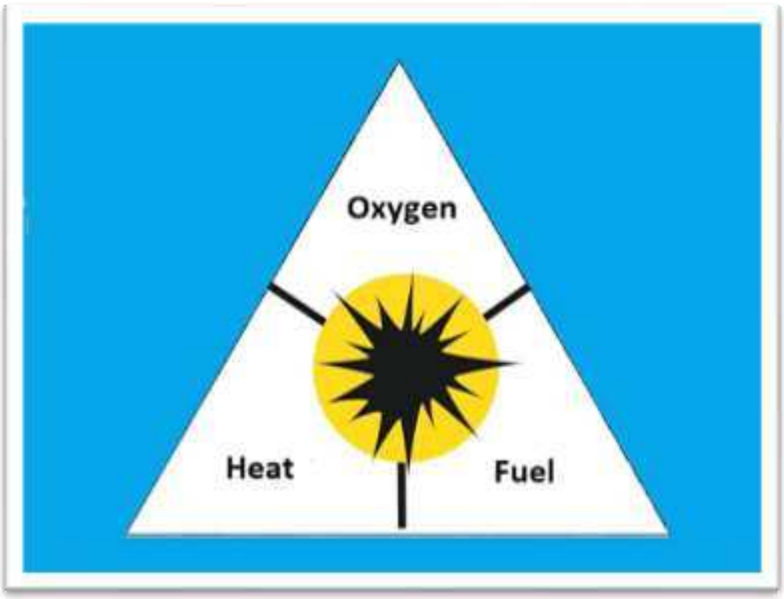

Fig. n° 2: The fire triangle.

These 3 elements are the presence of:

- an oxidizer
- a fuel
- a source of ignition.

While it is true that the mere presence of these 3 elements is enough to start a fire, it will not be the same to automatically start an explosion.
To explain the triggering of an explosion, we use instead a hexagonal shape diagram in which we see that six conditions must be met simultaneously and that as soon as one of the conditions is no longer present, the risk of explosion then becomes zero.

As we can see in fig. n° 3, the three initial conditions to generate a fire; the oxidizer, the fuel and the ignition source are always present, but it is also necessary that the fuel / oxidizer mixture is confined in any enclosure in the form of a gas mixture in suspension and that the concentration thresholds in oxygen and fuel are conducive to explode.

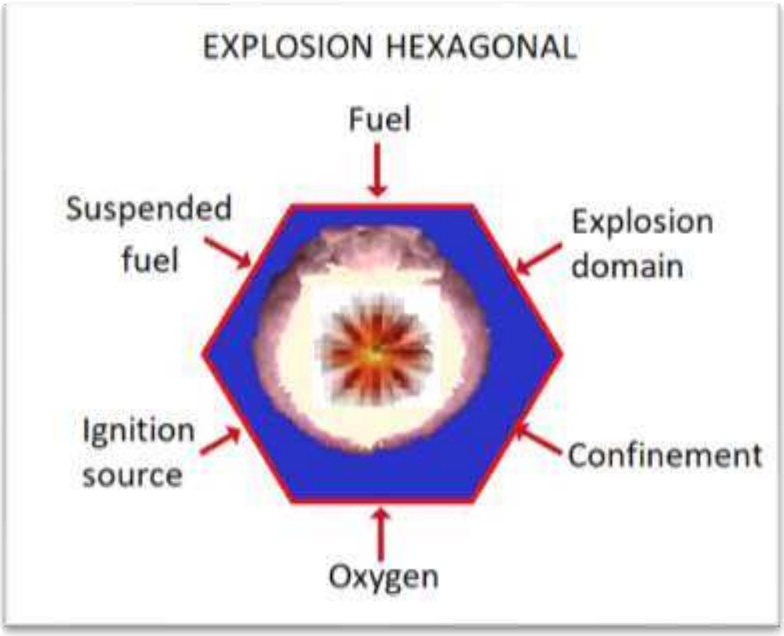

Fig. n° 3: Hexagon of explosion.

Let us take in detail the six conditions listed in this hexagon of explosion.

The confinement

In this instance, confinement means here a space in which gases can accumulate.
Under water, this type of closed place can be encountered in a very large number of circumstances and can appear as soon as the residual cutting (or welding) gases cannot or no longer freely rise to the surface.

We can meet these confinements in:

- wrecks
- sealed piles
- pipelines
- IPN profiles and various angles pieces
- sheet pile slots
- the cuts made below the bottom level
- marine growth
- others

The fuel

With regard to our underwater explosions, the fuel is always present in gaseous form and may originate from:

- the gases generated by the cutting itself (hydrogen (H_2), carbon monoxide (CO);
- the gases generated by organic decomposition in certain silt (methane (CH_4), sulphur dioxide (H_2S);
- the gases generated by the hydrocarbons still present in the wrecks and various enclosures (fuel vapours, various solvents);
- the gases generated during the cutting coming of certain paints and bituminous products (CO);
- the unburned residual gases when using an underwater cutting torch (MAP, Propane (C_3H_8), Hydrogen (H_2), Acetylene C_2H2, gasoline vapours);
- the gases generated by the welding electrodes. (H_2 / CO / CH_4).

Production of hydrogen and carbon monoxide

With a density of 0.071 g/l (at 0 ° C), hydrogen is the lightest of gases, it is colourless, odourless, but above all it is the most flammable of all known substances.

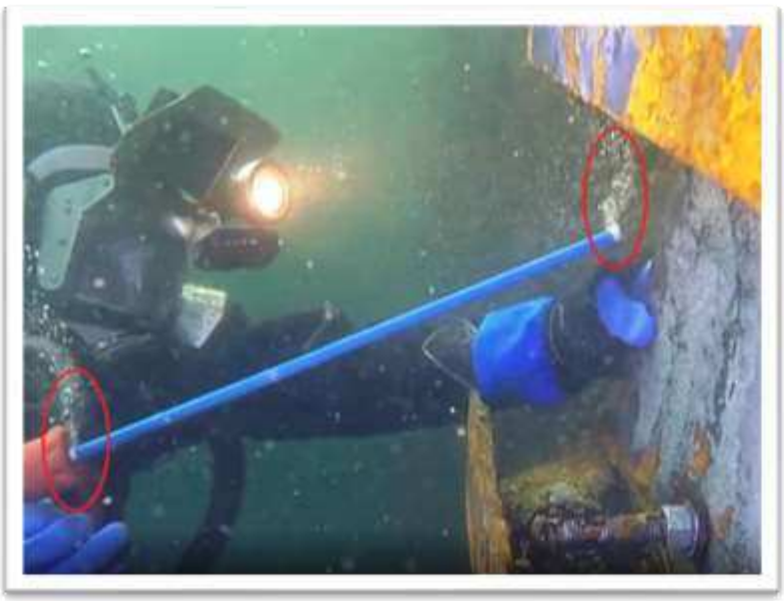

Fig. n° 4: Formation of H_2 by electrolysis (2).

Fig. n° 5: Formation of H_2 by thermolysis (3).

During cutting, hydrogen is generated under water on the one hand by the electrolysis of sea water (practically no electrolysis is met in fresh water), but also and mainly by thermolysis (vaporization) of water (4) which then causes the fragmentation (cracking) of the water molecules into oxygen and hydrogen atoms.

Fig.n°6: Spontaneous ignition of the produced gases (H_2/CO/other) (5).

If we refer to what is mentioned in most of our commercial diving manuals, this hydrogen production during cutting is (and without giving numbers) quite high. However, some studies (6,7,8,9) and analyses of the residual gases emanating from underwater cutting indicate that the percentage of this gas found in the residual gases is generally lower than the lower explosive limit (see LEL description on page 13).

This is due to the fact that the amount of hydrogen generated by the cutting of each cubic centimetre of steel is quite low (+ / _ 8 ml) (10), but also because part of the gas produced by both electrolysis that by thermolysis ignites spontaneously near the source as soon as it comes into contact with an incandescent slag.

CAUTION, this does not mean that explosions caused by hydrogen are not possible. Indeed, it would seem that in practice and during a gas cloud explosion in the open air, a freshly contained explosive mixture is sometimes characterized by a non-uniform composition in which we can then meet various concentrations of the mixture, some of which can be explosive (11).
It is therefore not impossible that the same situation can also be encountered underwater.

For what concerns the CO, it has a density of 0.968 g/l. It is also a very explosive gas produced during cutting, but its proportions are generally quite low (12).

Production of methane and sulphur dioxide

Methane (density of 0.55g/l) is a fuel resulting from the fermentation of organic animal or plant matter which can appear in certain types of anaerobic sludge (containing no or very little oxygen). Its presence is far from rare and it is sometimes revealed by the rise of small bubbles of completely odourless gas on the surface of the water.

Fig. n° 7: Presence of methane gas in the silt of a river (13).

If these small bubbles percolate inside a structure without being able to rise freely to the surface such as in a wreck, piles, or any other structure on which cutting or welding work must take place, they can mix with ambient air or with the oxygen present in the residual cutting gasses and thus become a highly explosive mixture.

Sulphurous hydrogen (density 1.19 g / l) is an extremely toxic gas, characterized by a very strong smell of rotten eggs. It is also flammable and like methane, it is produced by the microbial breakdown of organic material in the absence of oxygen.
It can be found in sewage wastewater or some marshes and although it seems rarer also at sea, according to the accounts of some divers.

Gas present in a wreck

This type of structure very often conceals hydrocarbons and various solvents in its hidden parts (hold, paint lockers) and / or difficult to access.

Paints and bituminous products

Certain paints and / or bituminous products such as those covering metal sheet piles or certain piles can decompose into flammable gas under the action of a flame. Fortunately for the diver, as with the formation of hydrogen, some of the gas produced ignites immediately on contact with incandescent slag at the start of the ascent.

Fig. n° 8: Formation of flammable gases (14).

Residual gas from the use of an underwater gas cutting torch

When cutting with an underwater gas torch, it is frequently observed whether it takes place just below the surface of the water and regardless of the type of fuel used, that flames burn on the surface of the water. This is due to the fact that the gases issued from the torch are not always completely burned and then ignite through contact with an incandescent slag.
The same situation can be encountered at depth and the diver can then see (if visibility permits) small pockets of unburnt gas ignite above their cut.
In some circumstances, just as in the case of electrical cutting, these gases do not encounter any incandescent slag and then ascend to the surface or to an enclosed space where they can then confine themselves and create a dangerous situation.

Fig. n° 9: Ignition of unburned gases (15).

Welding electrodes gases

Whatever the purpose of their use (welding or cutting), the combustion of this type of electrode generates via their coating and depending on their diameter, a significant amount (1.8 to 2.8 litres / electrode) of various flammable gases (H_2/CO/CH_4) (16) which, if confined, can then mix with the oxygen present in the gases exhaled by the diver.

Fig. n° 10: Flammable bubble stream generated by a welding electrode (17).

The oxidizer

Whether the cutting is performed using an oxy-arc or ultra-thermic electrode or using a gas cutting torch, these two types of method always use oxygen.
This will allow, on the one hand, to carry out the combustion of the metal and on the other hand, thanks to the action of the pressure jet, to eliminate and drive these oxides out of the kerf. To carry out this flush, a fairly high cutting pressure is generally used (4 to 7 bars normo) which, depending on the type of electrode used, generates a more or less significant consumption of oxygen (18). Yet of all the volume sent through the electrode or through the torch nozzle, only a small amount of the total volume of oxygen is burned during the oxidation of iron (19). Clearly, this means that a certain amount of (pure) oxygen is found in the residual gases.
In other working situations such as welding or cutting with a welding electrode which does not use oxygen, the air exhaled (+/- 18% O_2) by the diver may also be the oxidizer responsible for an explosion.

Contrary to popular belief, pure oxygen, even when confined, does not burn or explode on contact with a flame.

Fuel in suspension

Once trapped in an enclosed space, for an explosion to occur, the flammable mixture must be in suspension, that is, it must be present in the form of gas or gas vapour. A cut made in the liquid mass of a hydrocarbon should therefore not cause its ignition. But in practice it should not be forgotten that the incandescent slag produced by the cutting of the containment wall will be carried towards the surface of the liquid by the flow of residual gases where they could be brought into contact with flammable vapours.

Explosion domain

In order for it to ignite and then explode the concentrations of the mixture composed of oxygen (or air) and any fuel or gas vapour must be within the limits of an explosive range expressed as a percentage of flammable gas. This range is defined on the one hand by the lower explosive limit (LEL) and on the other hand by the upper explosive limits (UEL).

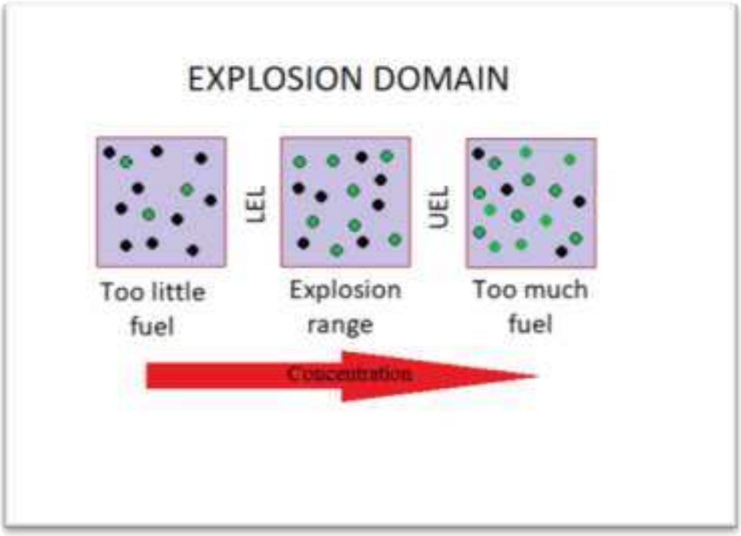

Fig. n° 11: Explosivity range.

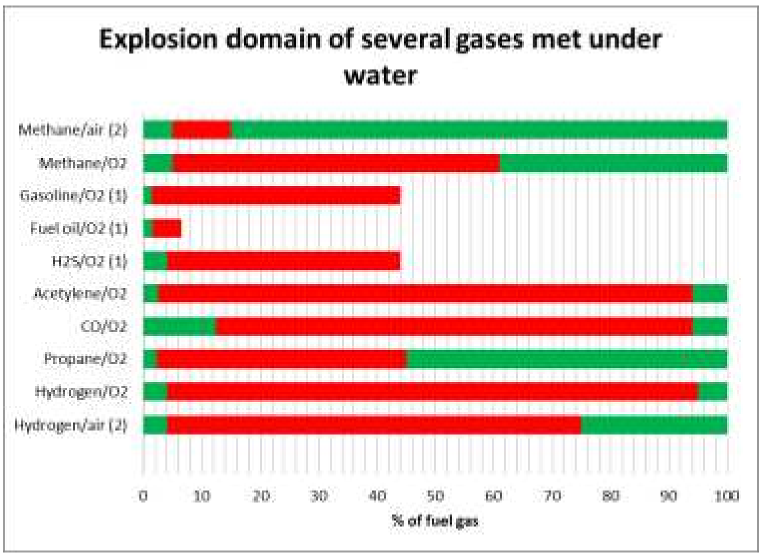

Fig. n ° 12: Explosive range of gases likely to be encountered under water.

(1) Data not available with oxygen, but the explosive range is certainly higher than the values mentioned in the graph.
(2) In a situation that may be encountered during welding.

Below this LEL, there is too little combustible gas in the mixture to trigger ignition, while above this UEL there will be too little oxygen in the gas mixture to trigger the explosion.

However, not all flammable gases have the same explosive range and for the same gas it varies depending on the oxidizer (oxygen or air).

Source of ignition

In order to ignite, the gas mixture must receive a minimum ignition energy (MIE). This minimum ignition energy is generally defined in micro joule and varies depending on the concentration of fuel gas with oxygen as well as the type of gas mixture.

For most combustible gases, this minimum energy is between 100 and 300 µJ, but for acetylene and hydrogen at their stoichiometric concentration this value drops to 17 µJ, which means that these 2 gases are extremely sensitive to inflammation.
With regard to underwater works, these values are only indicative because the ignition of a gas mixture pocket will occur either by direct contact with the flame of a gas cutting torch, or by contact with an incandescent slag droplet whose energy will vary according to its size, but which will always be greater than the minimum energy necessary to trigger the explosion process.

Besides this first source of ignition, the gas mixture can also ignite if its self-ignition temperature is exceeded.
This situation could possibly be encountered during welding work on a structure behind which there is a pocket of gas / air mixture.
Depending on the thickness of the plate, it could rise in temperature and thus reach and exceed this critical temperature.

Presumably, only the 4 gases listed in table n° 1 could be concerned.

Table n ° 1: Self-ignition temperature of some gases.

Gas	Gazole	H_2S	H_2	CH_4
Self-ignition in °C	250°	260°	500°	535°

THE EFFECTS

The effects produced by an underwater gas explosion will depend on a number of factors such as:

- the potential energy of the mixture considered ;
- the percentage of fuel gas present in the mixture ;
- the volume of the gas charge ;
- the rate of explosion pressure rise ;
- the depth of water.

Potential energy

All the fuel gases mentioned above store a certain amount of energy in their molecules which will be released during the explosion. This content is either expressed in specific mass energy, i.e. in Megajoule per kilo of gas (MJ / kg), or in volume energy density, i.e. in Mega joule per m³ of gas (MJ / m³).

Table n ° 2: Potential energy of some fuel gas / oxygen mixtures.

Gas	hydrogen	methane	propane	acetylene	CO	TNT
E (MJ/kg)	119,89	55,5	50,3	50,2	22,7	4,184
E (MJ/m³)	10,05	23,53	29,44			6,92
TNT eq	28,65	13,26	12,02	11,9	5,42	

By observing table n ° 2, we see that hydrogen has a mass energy much higher than other gases and even than TNT which is a very powerful military explosive since by comparing the figures we can read that 1 gr of hydrogen is equivalent to 28.65 g of TNT (20). One might therefore think that in our case the underwater explosion of a mixture H_2/O_2 is much more dangerous than that of a mixture CH_4/O_2 which has a specific mass energy and a much lower TNT equivalent.

This is not the case, however, because during a cutting related explosion, the diver is always confronted with the ignition of a certain volume of the gas mixture and not to a certain mass (weight). Clearly this means that the explosion of a mixed volume containing for example 50 litres of methane (1.17 MJ) will have a higher energy than an explosion of the same volume of hydrogen (0.50 MJ). This is explained in particular by the fact that hydrogen is a much lighter gas than methane and therefore the number of grams present in this 50 l pocket is lower.

Concentration of the fuel gas mixture

When we look at Figure n° 12, we realise that most of the LIE are around 4 – 5 % while the LSE varies much more.

If we take the H_2/O_2 mixture as an example, we see that the explosive range is between 4 and 95 %. Does this then mean that as soon as 4 % hydrogen is reached there will be an explosion? To answer this question, we can refer on the tests results which were carried out outside the water in explosion vessels of varying volumes (2.8 to 2000 dm³) (21).

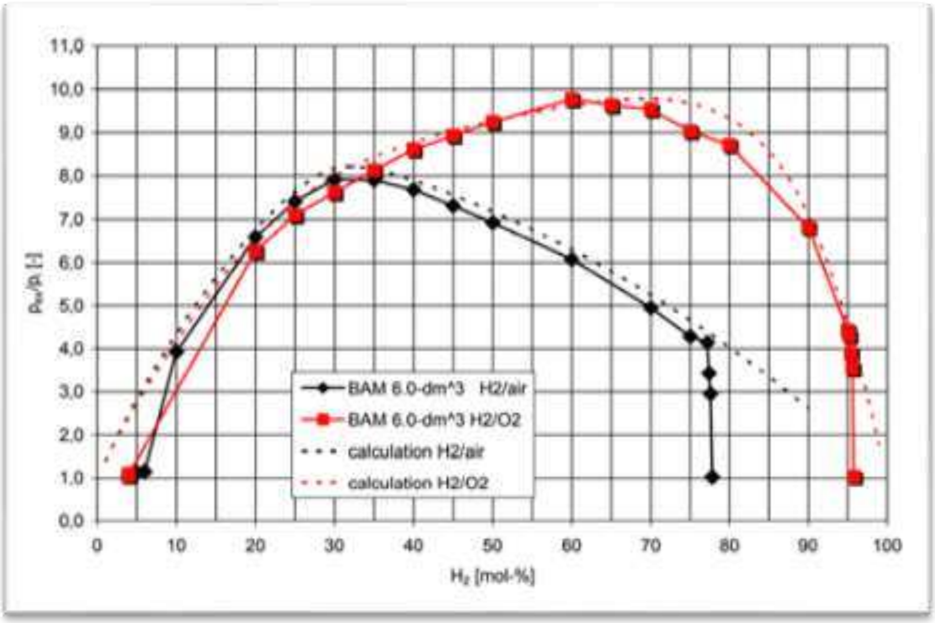

Fig. n° 13: Explosion pressure of a 6 litres gas as a function of the percentages of an H_2/O_2 and H_2/air mixture at the initial pressure of 1 bar at 20 ° C (21).

If we look at the explosion profiles in figure n° 13, then we can confidently say that the answer to the question posed above is no.

From 4 % hydrogen there will be a reaction with oxygen in the form of a "flash over" but without any sign of overpressure. A slight rise in pressure will start only from 8 % hydrogen, and then accelerate from 12 %.

We also note that the more the percentage of fuel gas increases, the more this explosion pressure (Pex/Pi) will increase until it reaches a maximum when the ideal mixture (stoichiometric mixture in which all the oxygen as well as all the fuel is burned) is reached. Then the explosion pressure will begin to drop until the upper explosive limit is reached and prevents any explosion.

Regarding the H_2/O_2 mixture, we can see that this ideal concentration is around 66/34 % and drops to 29/71 % for an H_2/air mixture.

The results published in Figure n° 13 have been established from tests carried above water, and one might therefore wonder whether they are valid for underwater gas explosions. On the basis of what is written in our various manuals, the answer remains very vague because, as mentioned at the beginning of the document, we have so far had no reference on this subject with regard to pressure measurements taken under water.

To ensure this, the author has therefore and thanks to the technical collaboration of the company OCTO Diving, carried out in a tank filled with water, a series of tests on vessels containing from 4 to 133 ml of H_2/O_2 mixture at ratios ranging from 5 to 100 %. The results obtained during these tests give a curve profile comparable to that of the H_2/O_2 mixture in this same figure.

In view of these results, it is therefore logical to assume that this pressure rise profile remains the same regardless of the volume of gas concerned.

Fig. n° 14: Tests tank for the H_2/O_2 mixtures.

Fig. n° 15: Explosion intensity measurement on a 35 ml sample at 95/5 %.

For the other types of mixture described in figure n° 12, the ideal concentration is generally considered to be +/- in the middle of the explosive range.

Volume of the gas charge

The volume of the charge will have a very strong influence on the decomposition mode of the gas mixture and therefore on the intensity of the explosion. Two decomposition regimes can be encountered:

- the deflagration, which is the most common regime and which generally appears during the explosion of a gas volume not exceeding a few tens of litres ;
- the detonation which is a much faster decomposition regime, but which can only occur under certain conditions.

Deflagration regime

In this propagation mode, the flame front moves at a speed lower than the sound of the concerned medium. This deflagration speed varies greatly depending on the type of fuel gas but also for the same type of fuel depending on its concentration with oxygen or air.
Thus, if we take for example a mixture of H_2/O_2, we may encounter two different deflagration regimes.
From 8 to 12 % volume, we observe a slow deflagration of about 25 m/sec without significant pressure rise and which can be heard under water in the form of a «POUF» without much intensity.
Then from 12 % a rapid deflagration will appear in which the flame front at the stoichiometric concentration can reach a speed of about 500 to 600 m / sec and instantly raise the pressure to between 7-16 bars (22). This will result in the creation of a pressure wave which will develop in front of the flame front and then continue to propagate in the water.

With the other fuel / oxidiser mixtures that may concern us and which all have a sound propagation speed lower than hydrogen, the deflagration speed and the associated overpressures will generally be lower.

Detonation regime

When the volume of explosive gas is trapped in a larger cavity (> 100 litres) (23) and at the condition that the percentage of fuel gas is greater than 15 % (24), the explosion can then pass to another mode of propagation that is detonation. Here the pressure wave is transformed into a shock wave which together with the flame front moves in the gas mixture at a supersonic speed which can then be of the order of 1000 to 2000 meters / second and reach a much higher explosion pressure.

Although the mechanism of the deflagration-detonation transition is still not fully understood, it is however admitted that it can only be triggered if the ignition energy of the gas charge is high and the flame front have enough space ahead of it to be able to accelerate its propagation speed beyond 500 m / sec and thus catch up with the pressure wave (25).

Rate of explosion pressure rise

Another important characteristic that will influence the effects of an underwater explosion is the rate of pressure build-up. This speed (dP / dt) which characterizes the time interval between the ignition and the appearance of the maximum pressure is expressed in bars / s.
It is variable according to each combustible gas or vapour as well as the volume, form of containment and point of ignition. The more vertical its profile, the faster the rate of increase and the more violent is the explosion.

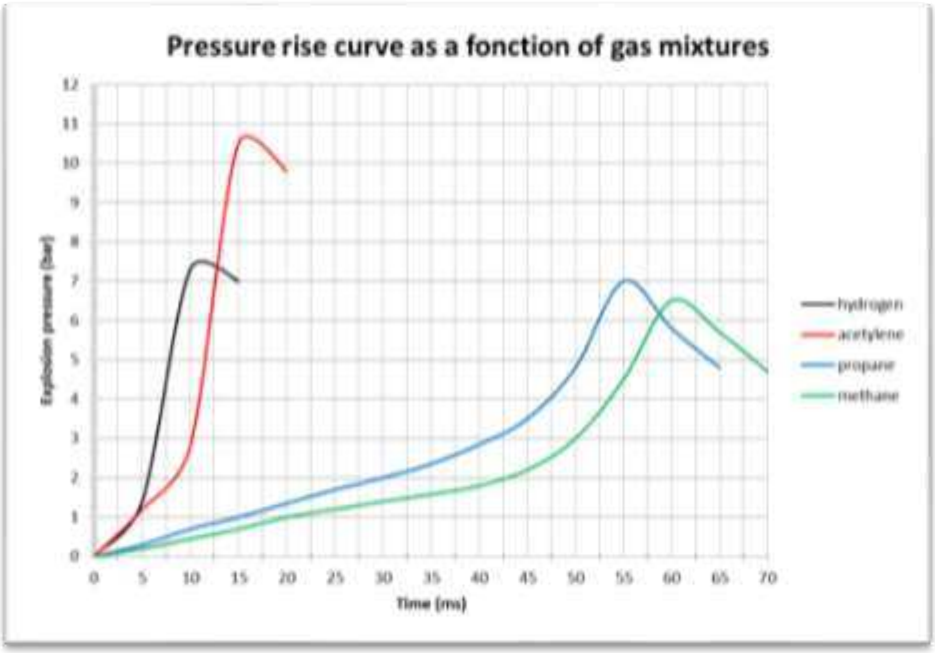

Fig. n ° 16: dP/dt profile of various fuel gases.

Looking at these four profiles, we would be tempted to think that this does not correspond with what has been said about the potential energy of fuel gases since we can notice on the graph above, that the profile of hydrogen for instance is much more vertical than that of methane and therefore its effects are more violent. This is indeed the case because if we compare the effects produced by the explosion of these two gases against a diver, we can say that in the first case the effects will be identical to those of a very sharp and very short punch while that with methane the effects will be comparable to those of a more powerful but slower blow.

For those of the readers who have some notions or experiences with explosive substances, one could compare these two profiles with what are the shattering capability and the power of an explosive which are two terms which define how the available energy is released. For example, a high explosive will release all of its energy and raise the detonation pressure in an extremely short time, which will allow very hard materials to be shattered. On the contrary, a lower bulk strength explosive will release its energy and build up pressure more slowly which will then have a more heaving effect that will allow to fracture volumes of softer material but in larger quantities.

As we will read later in this document, under water, the greatest bodily injuries encountered by the divers are generally due to the duration of the pressure wave and not to its peak pressure.

Water depth

Based on laboratory tests, it has been found that an increase of the relative pressure inside the containment (thus also of water depth) generates a slight increase of the explosion pressure (26), but at the same time it decreases the rate of explosion pressure rise.
In addition, the relative pressure also has a slight influence on the explosive range as it shrinks with depth.

Table n ° 3: Reduction of the explosive range of an H_2/O_2 mixture depending on the depth (27).

Water depth (m)	L.E.L % H_2	U.E.L % H_2
surface	4	95,2
50	4,6	94,6
100	5	94,2
200	5,4	94,2

Practice example

Now that we have described what were the six conditions necessary to trigger an explosion, let's take this same hexagonal diagram to study a concrete case in which the diver is going to cut a vertical tube whose upper part is closed by a concrete plug.
The tube was driven decades ago in a muddy soil containing methane gas and unfortunately this gas percolated through the tube and about 30 litres are now confined under the concrete.
To perform his cutting, the diver planned to use ultra-thermic electrodes.

So initially before the cutting begins, 2 conditions are already in place.
The confined space (closed tube) and the fuel gas (+ / _ 30 litres of methane).

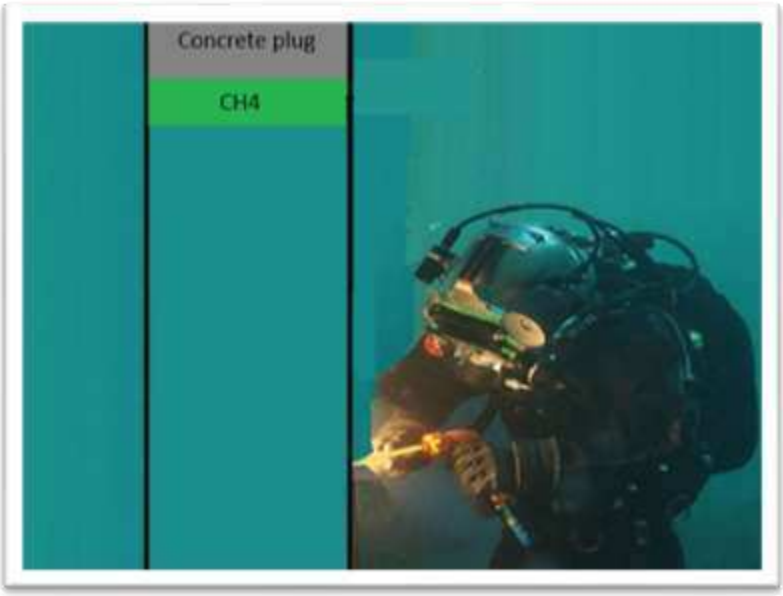

Fig. n° 17: Initial situation (28).

Then, as soon as the diver initiates his electrode and pierces the tube, some of the oxygen will be used to burn the steel while a large amount of unburned oxygen will be found in the residual gases (O_2/H_2/CO/etc.) which will go up in the tube where they will be confined under the concrete and immediately mix with methane.

Given the high flow rate of the jet passing through the cutting electrode, it will then only take a few seconds to add about twenty litres of residual oxygen and now pass the CH_4/O_2 mixture + other gases from the too rich area to the area within the explosive range.

As can be seen in figure n° 18, five of the conditions that could lead to the ignition of the gas pocket are now fulfilled.

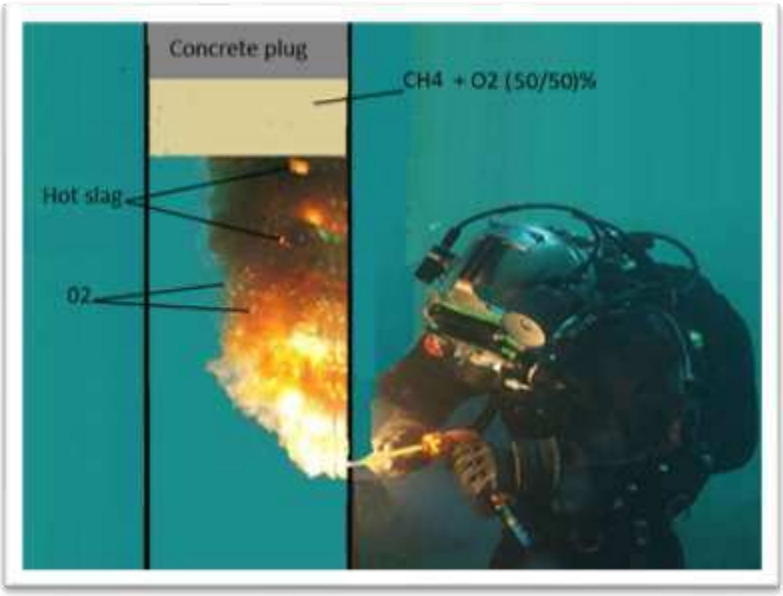

Fig. n° 18: Start of cutting (29).

While enriching the methane pocket with oxygen, this residual gas flow will also carry some of the glowing slag in its wake. The heavier slags will quickly fall to the bottom where they will continue to produce some hydrogen bubbles, but the lighter ones will continue to rise while gradually cooling on contact with water.
Under normal conditions, the cooling time of an incandescent slag until it reaches a temperature below the self-ignition temperature of most gases that concern us (+/- 500 ° C) is about 10 seconds (30), which in plain language and knowing that the speed of ascent of these gas bubbles is about 35 cm per second (31) means that they can ignite a pocket of confined gas up to a distance of about 3.5 m from the source.

Fig. n° 19: Rise of incandescent slag.

Unfortunately for the diver in our example, the distance between the cut and the gas pocket is less than 3.5 meters and so as soon as one of the glowing slag comes into contact with the gas mixture, it will immediately heat up a small volume of surrounding gas at ignition temperature and the resulting laminar combustion will then cause a rise in temperature as well as a slight increase of the pressure.

These hot products will in turn heat up the surrounding layer to their ignition temperature resulting in a further increase in pressure. This in turn will increase the burning velocity and the rate of pressure rise; it's the beginning of the EXPLOSION.

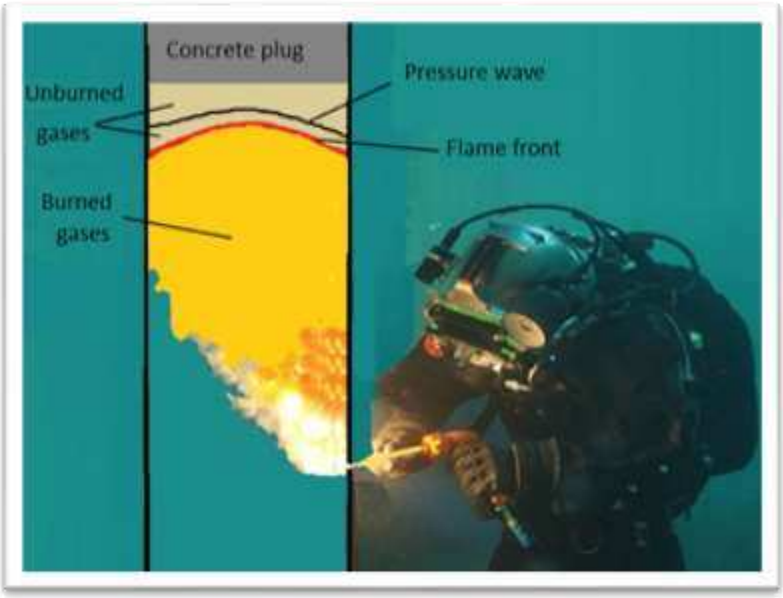

Fig. n° 20: Start of the explosion (32).

What happens next, as we have seen above, depends on certain parameters, including the volume of gas trapped in the cavity and the shape of the cavity.
If we go back to our example, we can safely say that with a volume of gas of +/- 50 litres, the mode of decomposition of the gases will still be done according to a deflagration regime and in this case the continuation of the explosion process will consist in generating gases burned at a very high temperature that can reach 2900°C (33).
This will in effect create a pressure wave that will develop ahead of the flame front and then continue its propagation into the water and at the same time instantly increase the initial volume of the gas pocket by a factor of 3 to 6 (34-35) which will then exert a strong compression on the surrounding water.
During this phase of expansion, the gas pocket confined inside the tube will expand to its maximum volume while at the same time the internal pressure will decrease until it becomes very quickly below the hydrostatic pressure, hence a reversal of the process.

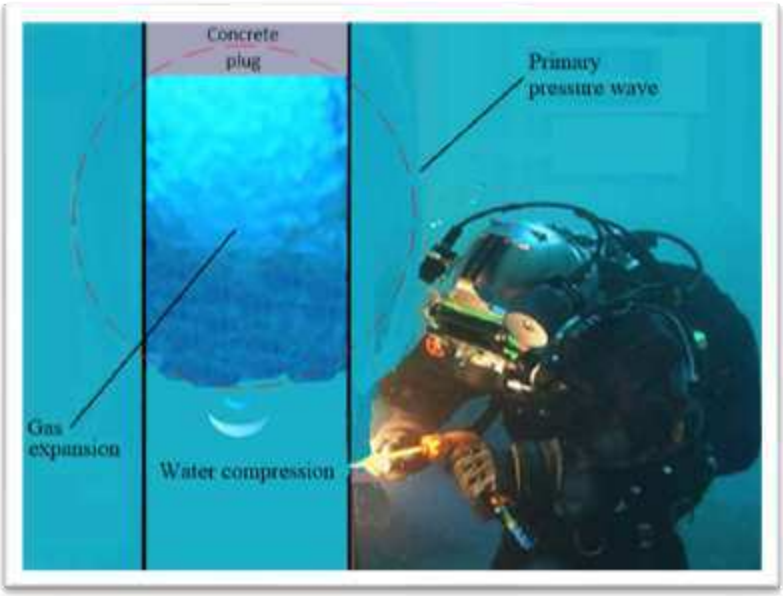

Fig. n° 21: Expansion of the gasses (36).

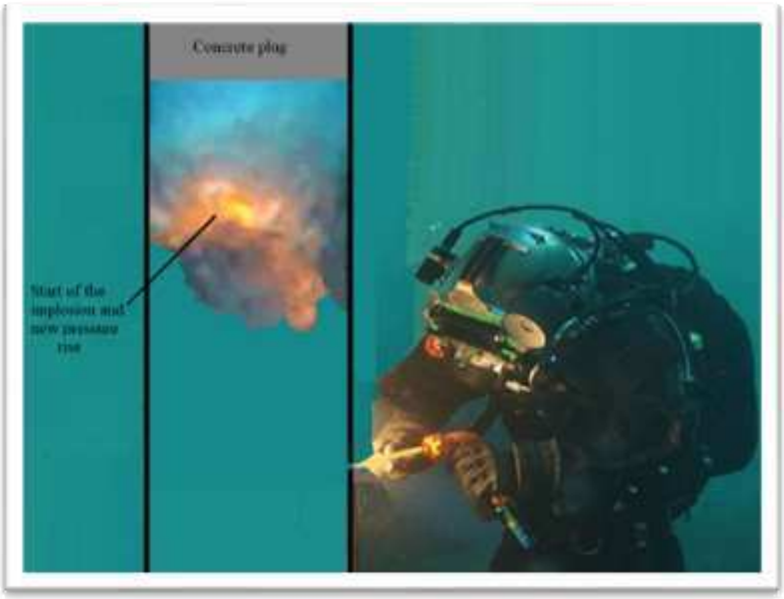

Fig. n° 22: Beginning of the implosion phase and new pressure build-up of the gas bubble (37).

The bubble implodes until it reaches a smaller volume where the pressure increases again resulting in a new expansion and so on until the gas bubble no longer has enough energy.

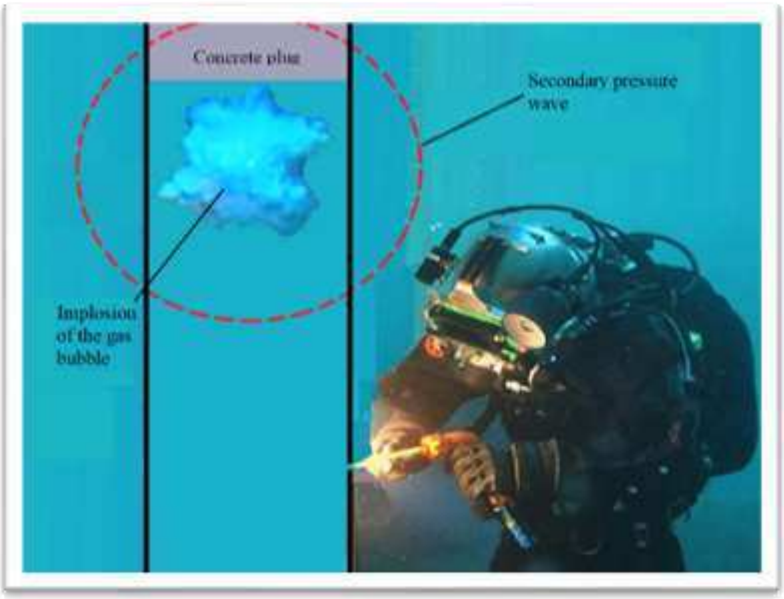

Fig. n° 23: End of the implosion and creation of a new pressure wave (38).

CONSEQUENCES

Consequences for the diver

At the beginning of the document we saw that explosions linked to underwater cutting were responsible for a very large number of accidents. How can this be explained?
As we will read in the following pages, three different effects resulting from the explosion can be responsible for the bodily injuries suffered by the diver, but to better understand them it is necessary to first make a comparison between the explosion on the surface of a certain quantity of explosive and the explosion under water of this same quantity.
If we look at the two graphs below which each represent the pressure profile corresponding to the explosion of a charge of 1 kg of TNT, we can see that the two attenuation curves have practically the same profile, but if we take a closer look, we can notice that there is a very strong difference in the pressure peaks, since we can read that at a distance of 1 meter from the explosion, that representing the underwater blast is about 80 times higher than the explosion above water.

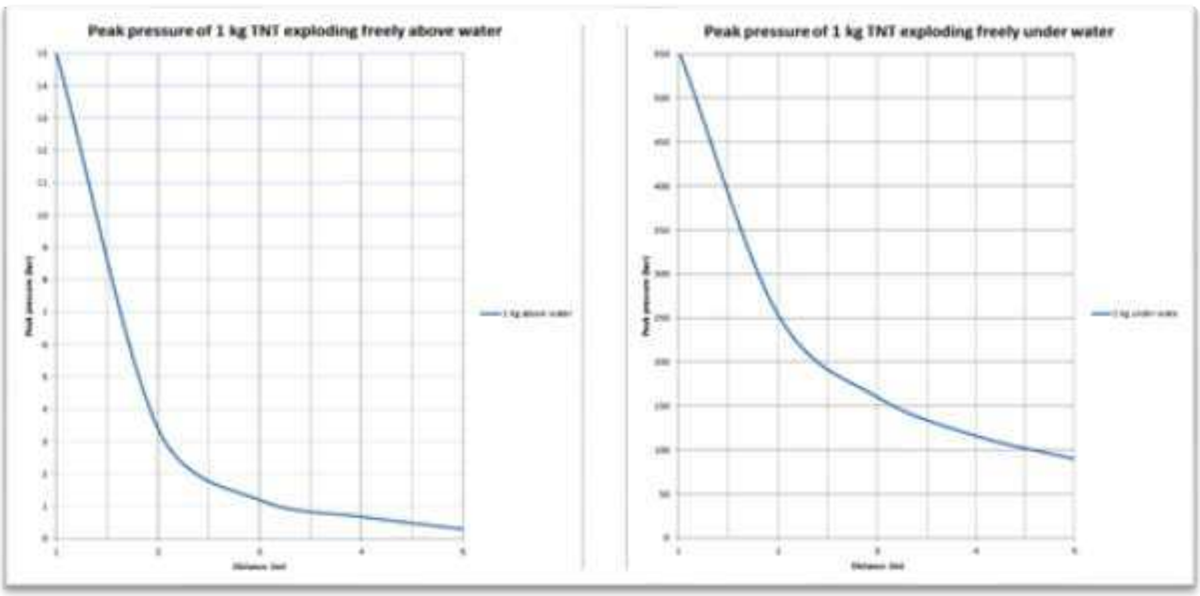

Fig. n ° 24: Peak pressure comparison of a charge of TNT exploding above and under water.

The reason is due to the fact that water is about 800 times denser and 10,000 times less compressible than air and therefore during an underwater explosion, the surrounding liquid will not absorb the energy delivered by the explosion as quickly as in the air.
This has for consequence that the incompressibility of the water will on the one hand generates a much higher suppression (pressure peak), but this shock wave of greater intensity will also propagate over a much longer distance and is therefore more dangerous than an explosion in the open air.

Conversely, looking at figure n ° 25, we observe that there is a noticeable difference between these two media because they show that for the same quantity of explosive, the duration of the primary shock wave in the water is shorter (+/- 2 ms) than that generated by an air wave (+/- 6.5 ms). This characteristic is important because it allows divers to withstand higher pressures than those produced by an explosion out of water.

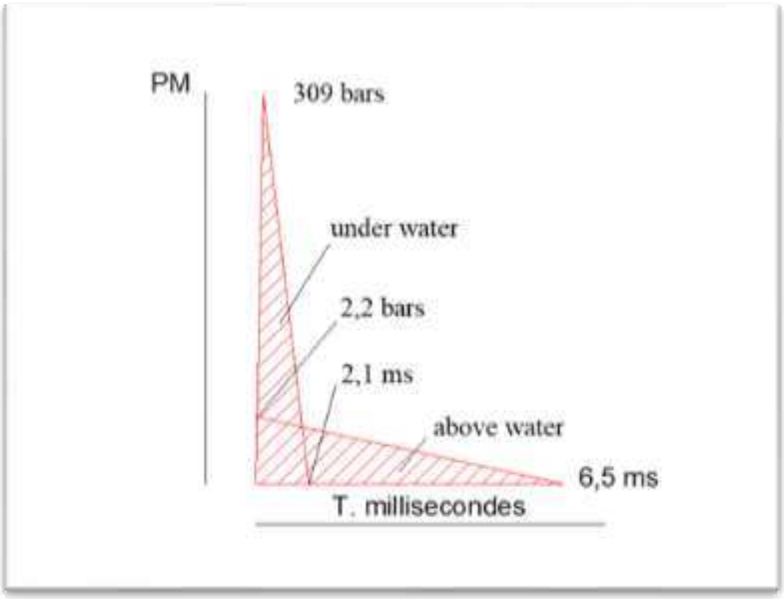

Fig. n ° 25: Comparison of pulse duration in and out of the water of a charge of 1 kg Paxit at 1.5 m distance (39).

As far as we are concerned, we are not dealing with a solid explosive but with a gaseous composition. However the effects generated under water by these will be more or less similar and therefore to understand them well let us refer to figure n° 26 on which its juxtaposed the images of the underwater explosion of a balloon filled with an ideal mixture of propane / oxygen (40) and below the explosion profile of a 133 ml bubble of ideal mixture of H_2/O_2 (41).

If we analyse this figure what do we see?

Following the ignition of the mixture (1), the flame front propagates in the gases and causes the latter to explode which has the effect of increasing the pressure almost instantaneously (2) and at the same time generates a pressure wave which will immediately propagate in the water at a speed of about 1500 m / s.
Because of the high temperatures (+/- 2900°C) prevailing in the burned gases, the propagation of the flames is accompanied by an expansion (3-6 times the initial Ø) of these gases (3-4) which will force water towards the outside until the moment when, due to the inertia of the water, the gas pressure inside the bubble becomes lower than the hydrostatic pressure (5). This then causes the water to collapse on the bubble resulting in a further rise in pressure and

the creation of a new pressure wave (6-9). The same process then repeats itself until the pressure returns to equilibrium (9-13).

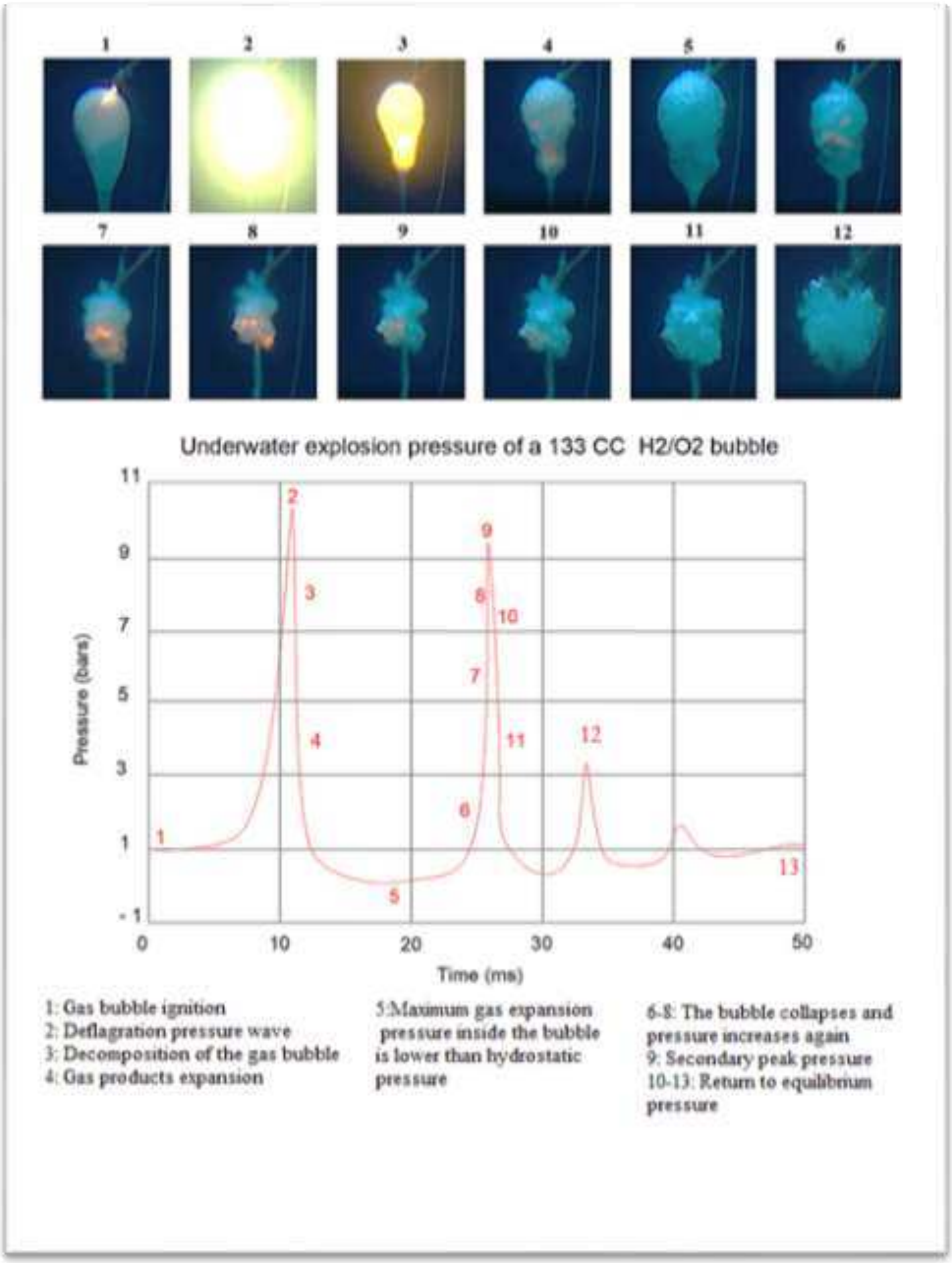

Fig. n ° 26: Underwater explosion of a balloon filled with a stoichiometric mixture of propane / oxygen and below the explosion profile of a bubble of 133 ml of ideal mixture of H_2/O_2.

During this explosion, we can see that there is creation of three pressure waves, the first (primary pressure wave (2)) is initiated by the deflagration of the gas pocket, while the following two (9, 12) are caused by the contractions associated with the implosion of the gas bubble.

As they leave the periphery of the gas pocket, these pressure waves will propagate spherically through the water at a speed of about 1500 m / s. in the form of a compression wave of positive value.

Three situations can then be encountered:

- if no obstacle (interference) is encountered, these waves will gradually lose some of their energy until they are balanced with the hydrostatic pressure (A);
- if they encounter an obstacle, they will depending on the acoustic impedance of the environment encountered either be transmitted through this interface with or without loss of a certain amount of energy (B);
- or be entirely reflected towards the source while passing from the compression wave to a negative tensile wave (C).

As will be seen later in this document, these 3 types of configuration have an important role in the effects that the pressure waves will have on the diver.

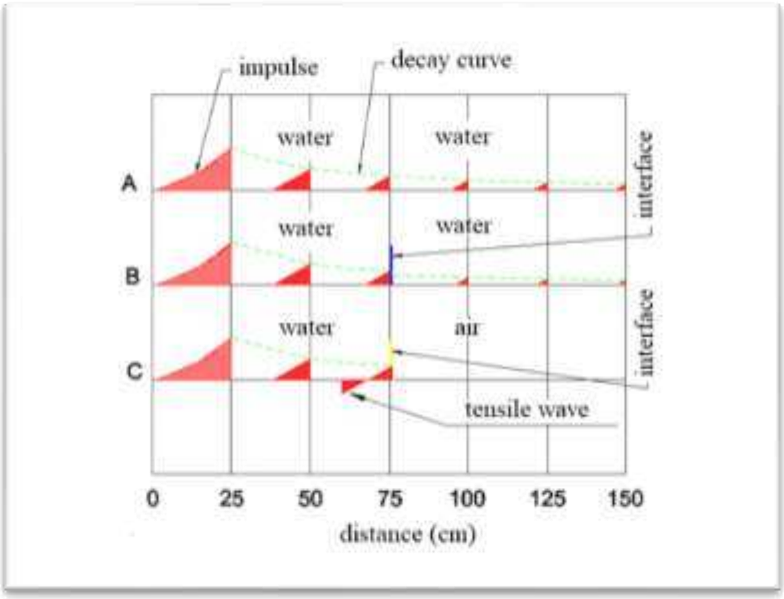

Fig. n ° 27: In water progression of pressure waves generated by the explosion of a very small charge of TNT (1 g).

The physical characteristics that define this pressure wave are:

- the maximum peak pressure (Pm) ;
- impulse (I) ;
- the attenuation constant (Θ) ;
- the energy flux density (U) ;
- the particle velocity (P).

These 5 characteristics are useful to know if working with explosives, but as far as we are concerned, only the maximum peak pressure (Pm) and the impulse (I) will be used in this document to measure the severity of the damage.

Maximum peak pressure (Pm)

The peak pressure of a shock wave is the maximum level of overpressure over ambient pressure. By convention, the primary pressure wave is generally considered to be the peak pressure.
It is usually expressed in bar, psi or kPa.

Impulse (I)

The impulse is a fairly complex characteristic to determine, but it can be defined as the product of the average pressure of the overpressure peak multiplied by its duration.
It is usually expressed in Pascal-second (Pa-s), kilopascal millisecond (kPa-ms), or in psi-ms.

As one can imagine, the pressure wave generated by an underwater explosion conveys a greater or lesser amount of energy that may, depending on its duration, cause more or less serious damage or injury that may even in some cases be lethal.

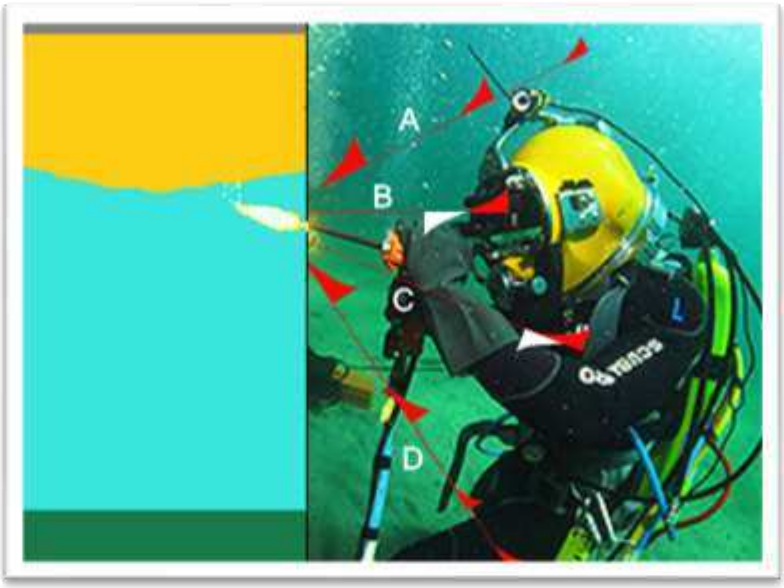

Fig. n° 28: Effect of pressure waves on the diver (42).

If we take the example of the figure above and analyse the path travelled by this pressure wave we see:

- In A, no obstacle is encountered, the wave will continue to progress towards the surface by losing its energy until balancing with hydrostatic pressure.

- In B, the pressure wave hits, crosses the helmet window and then encounters the air or gas mixture contained in the helmet.
  As this air has a much lower acoustic impedance (0.000429) than that of water (1.489), a large part of the energy will be reflected and move again in the opposite direction while passing from a compression wave to a tensile wave, that can then in certain cases cause the glass to break (incident that occurred sometimes with constant volume hoods which were fitted with a smaller glass pane).
  The part of the energy transmitted through the helmet (or the band mask) can also create sinus damage and more commonly cause the eardrum to rupture.
- In C, the pressure wave hits the chest. It passes through the diving suit, which depending on the nature of the type of material (neoprene or rubber) absorbs a very small amount of the energy delivered.
  It then passes through the skin and encounters the various hollow organs and lungs which also have a low acoustic impedance. As a result, between 28 and 49 % (43) of the wave is reflected with again a phase change that will create small cracks and a spalling in the alveolar tissue and the gastrointestinal system.

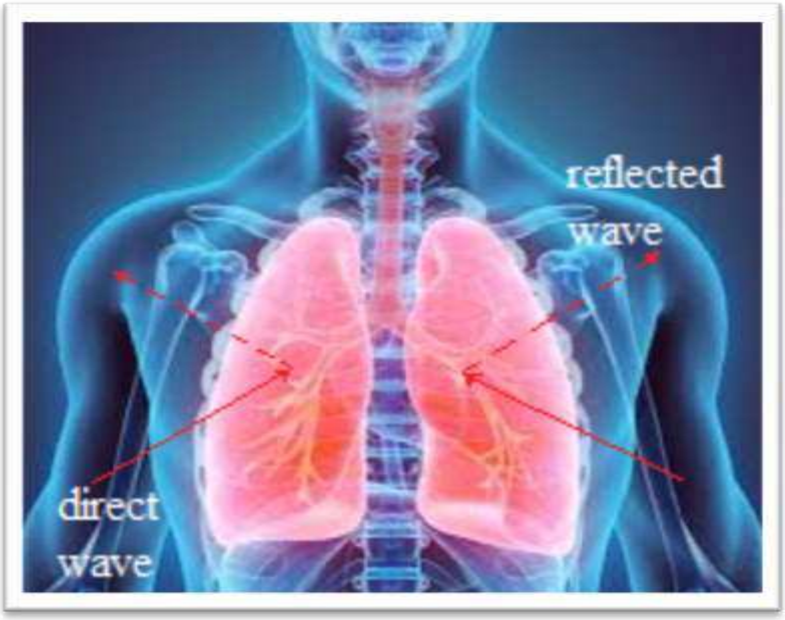

Fig. n ° 29: Waves reflection on the lungs and hollow organs (44).

- In D, the pressure wave meets the lower limbs and other parts of the body made up of water, fat, muscles. Since all of these substances have an acoustic impedance close to that of water, the pressure wave will pass through them without being reflected and generally without causing damage.

As for the bones, they also have a fairly low acoustic impedance and therefore part of the pressure wave is reflected with the unpleasant consequence of more or less strong tingling sensations, as well as more or less painful blows on the fingers.

These same pressure waves can also be reflected from the bottom and from the surface.

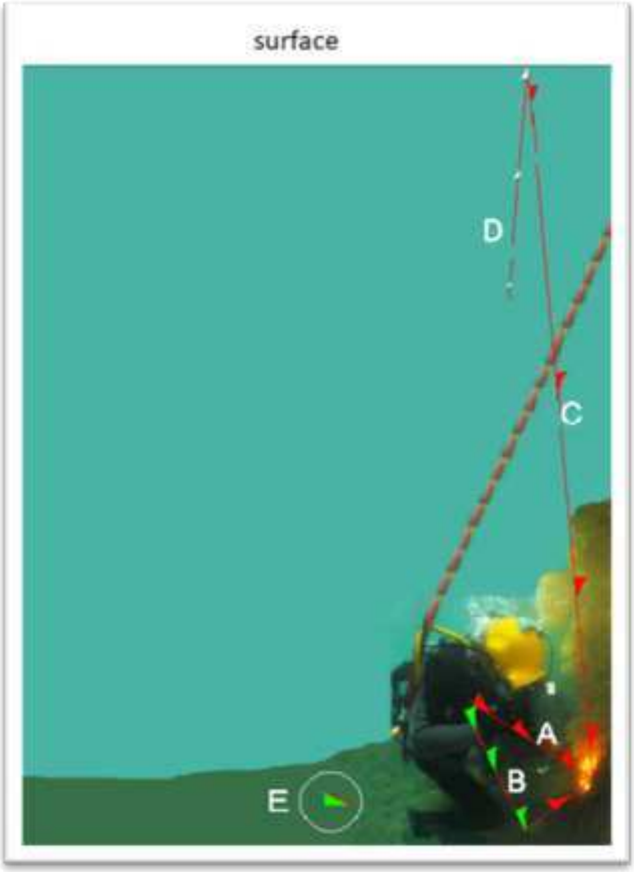

Fig. n° 30: Surface and bottom wave's reflexion (45).

As shown in Figure n° 30, in addition to the incident wave (A) that will directly strike the diver, he may also be struck by a reflected wave that will depending on the nature of the terrain be more or less absorbed by the bottom (B). On a muddy or sandy ground, the pressure wave will be almost entirely absorbed, but if the diver cuts on a hard ground such as a concrete floor, it will then be reflected by the bottom and arrive against the diver a few microseconds after the incident wave and their two effects can then cumulate with the consequence of lengthening somewhat the duration of the impulse (E). Finally, the part of the wave that goes to the surface will reflect on it and return to the bottom in the form of a tensile wave having a negative pressure. In theory, since it is now a tensile wave, it could have a beneficial effect because instead of cumulating its effects with the incident wave, it would have been able to cut part of the impulse and therefore make its effects less harmful. In reality this is less likely (unless the cutting is done in very shallow water) because the peak pressure will quickly decrease and disappear before reaching the diver again.

As can be seen, underwater explosions generate a greater or lesser amount of energy that can cause damage to structures but also injure or kill nearby swimmers or divers.
The first divers who were able to realise the power of underwater explosions were probably the brothers Charles and John Deane (the creators of our profession) who under the direction

of Colonel Pasley began to implement underwater charges of gunpowder during work on the *Royal George* in 1829 (46).
It was then not until 1916 to find a first study carried out by the medical staff of the Royal Navy describing the injuries generated by the explosion of mines or depth charges (47).
The other studies on the effects of underwater explosions then only resumed in 1941. The first consisted of evaluating the effects of the explosions on volunteers swimming on the surface, as well as on animals (non-volunteers), and then very quickly the various navies also started to do this type of study on immersed divers.
The classic scenario of the tests generally consisted in detonating a charge of a given size and depth and gradually approaching the volunteers to the source in order to know the tolerance thresholds and thus be able to establish models making it possible to calculate the safety distances from the explosion of a given charge.
For the underwater burners, these safety distances are obviously not of much interest because the diver will unfortunately always be positioned very close to the source of the explosion, that is to say generally between a few centimetres and less than 3.5 - 4 meters from it.
On the other hand, it is interesting to know the effects generated on the diver by the shock wave as well as the tolerance thresholds in relation to it.

Table n° 4: Subjective comment from a diver exposed to a 5lb (2.27kg) charge of TNT (Wright et al, 1950) (48).

Range	Sensations	Estimated Shock Levels	
meters	Subjective comments	Pm (bar)	I (bar-ms)
33.5	Sound of intense bang.	11	5.17
30.5	Intense bang. Mild blow on chest.	12	5.86
27.4	Severe blow on chest.	13.4	6.55
24.4	Blow on head and torso. Body shaken. Brief paralysis of arms and legs.	15.1	7.24
22.9	Violent blow. Brief paralysis of limbs. Substernal pain for 1/2 to 1 hour.	16.5	7.58
21.3	Violent blow. Temporary paralysis of limbs. Substernal pain lasting several hours. Aural damage. Tongue lacerated. Mask blown off. Mild concussion.	18	7.93

Table n° 5, mentions the conclusions of the US Navy which were published as early as 1970 in its diving manual, and which are still relevant in their current manual.

Table n° 5: Injury potential of an underwater TNT blast (US Navy Diving Manual, 1970) (49).

Peak pressure (PM) (bar)	Peak pressure (PM) (kPa)	Effects
>138	> 13800	Death Certain
34.5 - 138	3450 - 13800	Likely to cause death or severe injury
3.45 – 34.5	345 - 3450	Likely to cause injury
< 3.45	< 345	Unlikely to cause injury.

The two tables above refer to effects produced on divers by the explosion of TNT charges that are high explosive that have a detonation process as a mode of transformation, which is not the most common decomposition regime for a gas explosion.

To get an idea of the feeling with a deflagrating product, we can base ourselves on tests which were carried out in 1993 with two types of bold guns and for which the divers declared that a pressure wave with an overpressure peak of 1 bar compared to the ambient pressure was absolutely not a problem, but that from an overpressure of 3.5 bars and an impulse of 500 Pa.sec (5 bar.ms), the effects at the level of the ear became extremely annoying and forced the divers to work at arm's length (50).
As can be seen, this 3.5 bars overpressure is very close to the threshold for the appearance of a risk of injury mentioned in the US Navy table.

Prediction of the effects of peak pressure and impulse

Is it possible to predict the peak pressure and the impulse values of an underwater acoustic wave?
For a solid explosive, the peak pressure (Pm) and the impulse (I) of a charge exploding in open water can be easily calculated using an empirical formula.
One of the most used to calculate the peak pressure of a TNT charge exploding in open water is that of Cole (51):

$$Pm = K (W^{1/3}/R)^{A}$$

Where:

Pm = peak pressure (bar)
K= explosive scaling constants (555 for the TNT)
W= the charge weight (kg)
R= the range between the charge and the target (m)
^{A} = decay constants (1.13 for the TNT)

With regard to the calculation of the impulse the formula of Aarons (52) is also widely used:

$$I = 6 \times 10^{3} W^{0.63} R^{-0.89}$$

Where:

I = impulse (Pa.s)
W= the charge weight (kg)
R= t he range between the charge and the target (m)

So, if we use these two formulas to calculate the effects of an explosion of 1 g of TNT on a diver located 1 meter away, we would have:

$$Pm = 555\,(0.001^{1/3}/1)^{1.13} = 46 \text{ bars}$$
$$I = 6 \times 10^{3}\ 0.001^{0.63}\, 1^{-0.89} = 77.29 \text{ Pa.s}$$
That to say: 0.00077 bar.s or 0.77 bar.ms

If we compare these figures with the values mentioned in tables 4 and 5, we see that in this case, it would be the peak pressure that would cause the most damage since the expected effects would be likely be to cause death or severe injury.
Obviously, these formulas are related to solid explosives, but with regard to an explosion linked to a gas charge, no such formula seems to exist to calculate these two characteristics in the case of an underwater explosion.
If we refer to what was written above, it would seem that the explosion pressure during an underwater gas deflagration would be between 7 and 16 bar in function of the type of gas.

But what about this pressure at a given distance from the explosion?

To be able to answer it, it is first necessary to convert this gas charge into TNT equivalent.
We have seen in table n° 2 that for a mass of 1 g, most fuel gases have a TNT equivalent comprised between 5.42 and 13.26 g of TNT, while for hydrogen this equivalent is equal to 28.65 g of TNT. As this last gas is the one that often causes us the most problems during our cutting, we will continue our simulation with this one.

Knowing that 1 g of hydrogen represents, according to an ambient temperature between 0°C and 20°C, a volume of 11.2 l to 12 l of gas, it is then possible to convert using an Excel spreadsheet, a given volume of ideal gas mixture (66.6% H2/33.4% O2) in a TNT equivalent.
By then modifying the constants K and ^{A} in the COLE formula we can then make this formula correspond to the (only) actual data currently available on the net which correspond to the measurements recorded during the underwater explosion of gas charges of 133 CC of H_2/O_2 in a test tank (53).

The result of this conversion can be seen in the figure below.

In addition to the actual profile for this 133 CC charge, figure n° 31 also has two additional attenuation profiles to verify if the modified Cole formula is consistent.
As this appears to be correct, it is now possible to calculate the peak pressure of various volumes of gas pockets and check their attenuations according to the distance of the explosion.

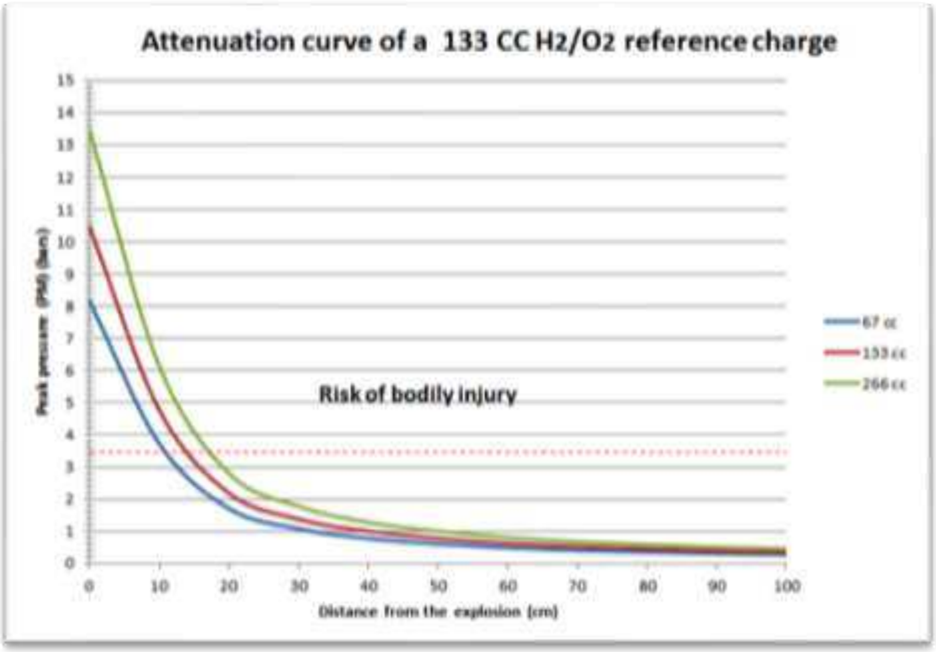

Fig. n° 31: Peak pressure and theoretical attenuation of 2 gas charges compared to the real curve of a 133 cc gas charge.

If we take into account the pressure limit of 3.5 bars up to which there is no risk, we can realize by consulting figures n ° 31 to 33, that in the event of an explosion in a deflagration regime, all the volumes concerned exceed this limit which therefore risk causing more or less serious injuries without reaching the lethal limit of 34.5 bars since the pressure peaks would not exceed the (theoretical) limit of 16 bars.

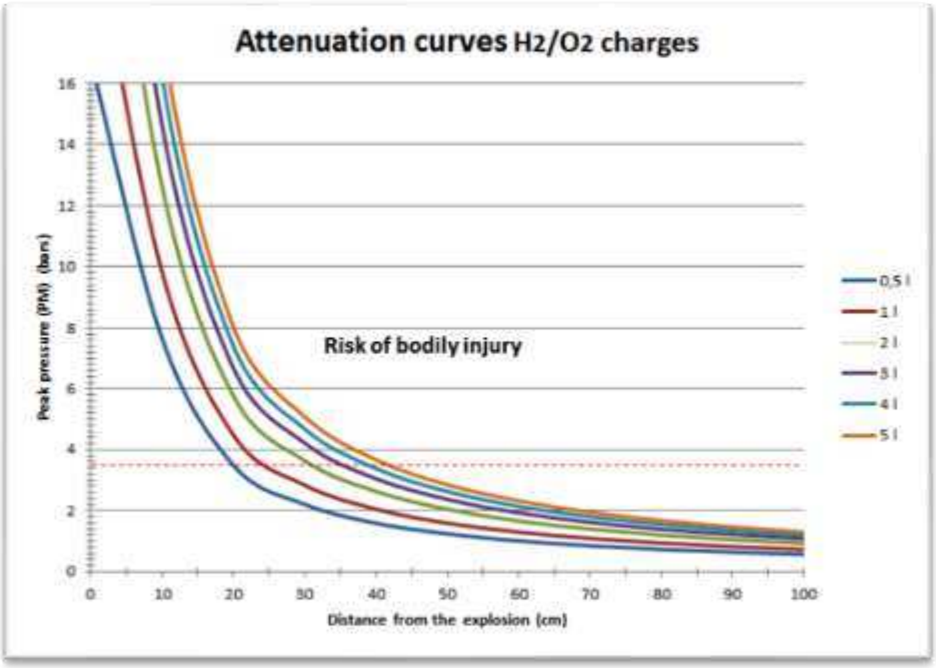

Fig. n° 32: peak pressure attenuation curves based on H_2/O_2 mixing volumes between 0.5 and 5 litres.

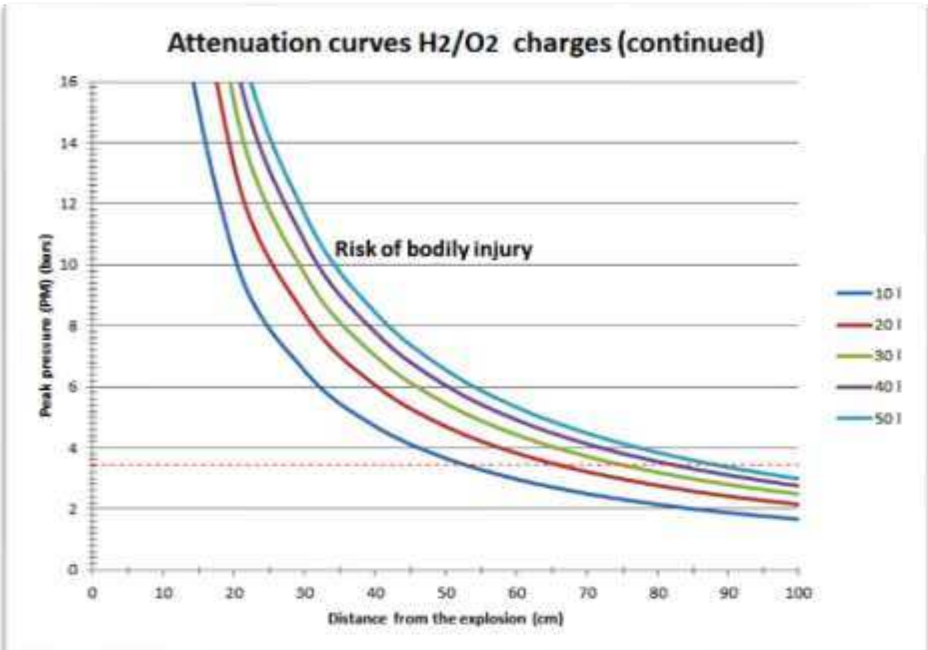

Fig. n° 33: peak pressure attenuation curves based on H_2/O_2 mixing volumes between 10 and 50 litres.

So how can we explain all these unfortunate deaths linked to the explosions?

The cause could then be due to a transition from the deflagration regime to a detonation regime which can in theory occur if the confined gas has a sufficient gas volume (> 100 litres) to allow the flame front to increase its speed of combustion.
In this case, the peak pressure could reach values much higher than those of a deflagration and then quickly reach a pressure exceeding the limit of 34.5 bars as illustrated in figure n° 34 in which we find the attenuation profile of a gas charge of 100 litres which decomposes in detonation mode.
In this same figure, in addition to the curve of this 100 litres gas charge, the attenuation profile of a 1 pound TNT charge (0.453 kg) as well as that of a 8 ft³ (226 l) gas charge of H_2/O_2 mixture is shown.
These two curves have been added to the graph to allow the reader to understand what is said in the very good video produced by ADCI (54) on the risks associated with cutting under water, in which it is indicated that the energy generated by the explosion of a volume of 226 l of hydrogen is identical to that of the explosion of a TNT load of 0.453 kg.
Although the specific energy delivered by the two explosions is close to 1.89 MJ (H_2) / 1.61 MJ (TNT), it is nevertheless noted that the pressure peaks generated in the water by these two different types of charge are despite everything quite distant.

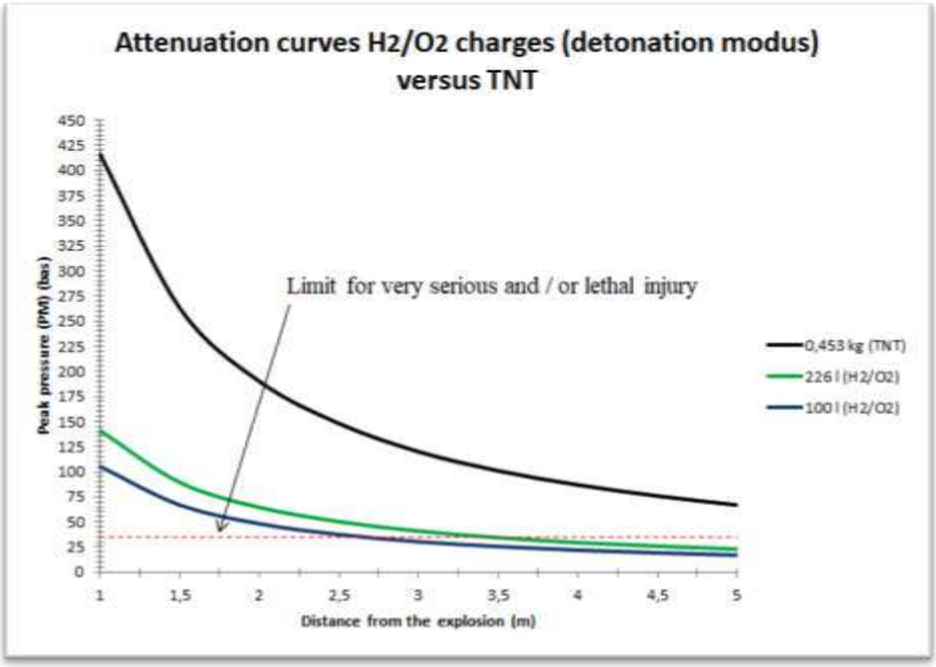

Fig.n ° 34: Peak pressure attenuation curves in the event of a detonation regime.
(By convention the horizontal axis representing the distance is for solid explosives, always started at the distance of 1 m).

If the serious or fatal bodily harm is not due to the peak pressure, then it is usually related to the impulse.

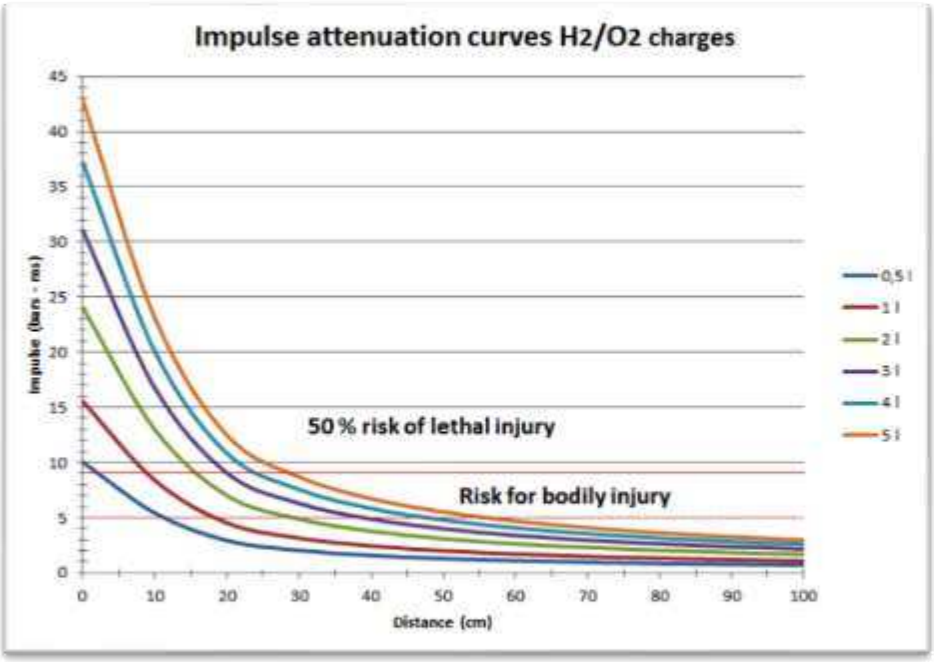

Fig. n ° 35: Impulse attenuation curves as a function of the volume of the H_2/O_2 mixture.

To calculate the energy of an impulse generated by the explosion of a gas charge, one could be tempted to proceed in the same way as for the calculation of the peak pressure, that is to say by modifying certain parameters of Aarons' formula.

Unfortunately, no data that can be used to make comparisons seems to be available on the net concerning the impulses generated by the explosion of gaseous charge under water, therefore to establish the curves published in figure n ° 35 only the TNT equivalent of each H_2/O_2 bubble volume was used.

As mentioned earlier in this document, during an underwater explosion, the severity of the injuries may be due to the peak pressure, but also and especially to the duration of the impulse against the diver.
If we look at figures n° 36 and 37, we can see that the explosion generated by the explosion of a gas bubble of 133 CC of H_2/O_2, has a pulse duration longer than that caused by the detonation of its equivalent TNT and is therefore likely to generate serious damage to the diver.

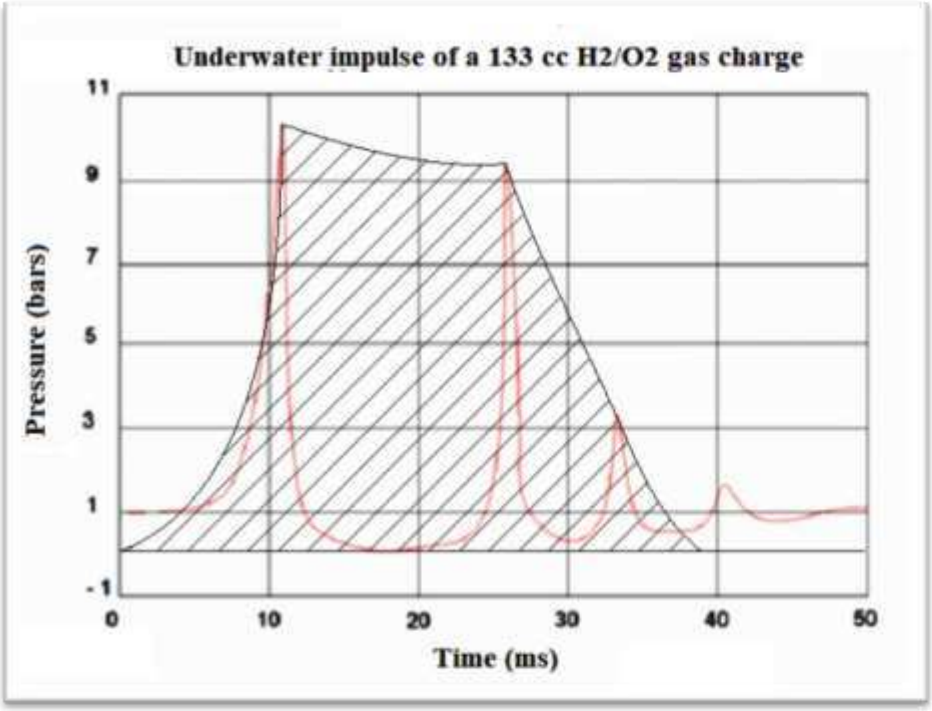

Fig. n° 36: Gas charge impulse profile of 133 CC of H_2/O_2 mixture (TNT eq 0.22 g).

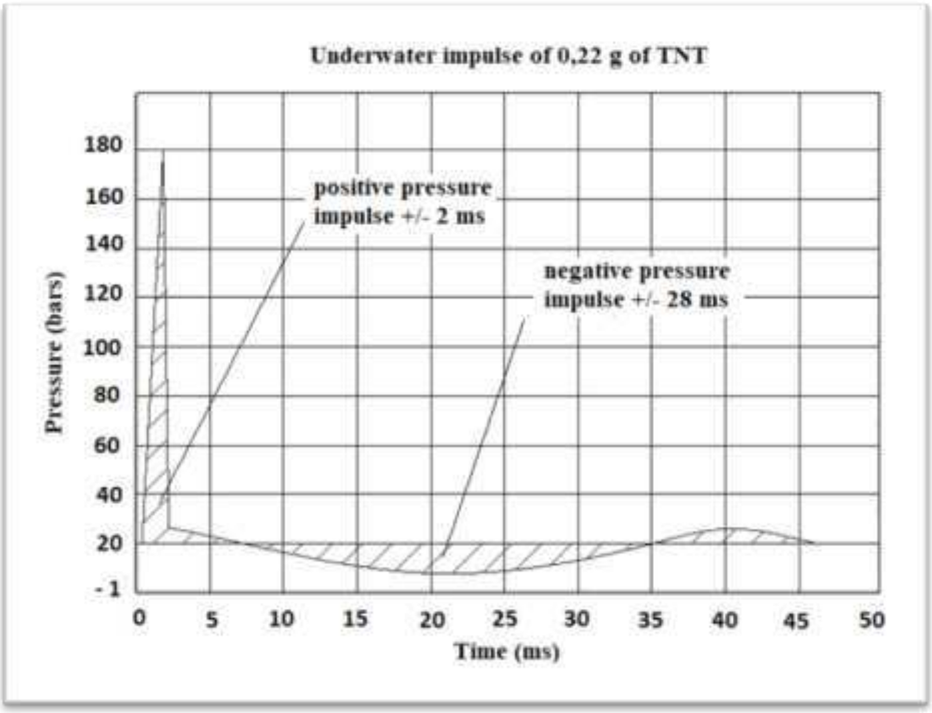

Fig. n ° 37: Impulse profile of the explosion of a 0.22 g TNT charge.

To fully understand the phenomenon, it should be known that when a shock wave comes into contact with a structure, it will exert a certain pressure on it for a few milliseconds which will have as consequence to make the structure vibrate according to its natural frequency.
During this brief period of time the structure will absorb the energy of the impulse for half a period of its natural frequency which can in some cases cause damage.

For clarity, we shall illustrate this with an example.

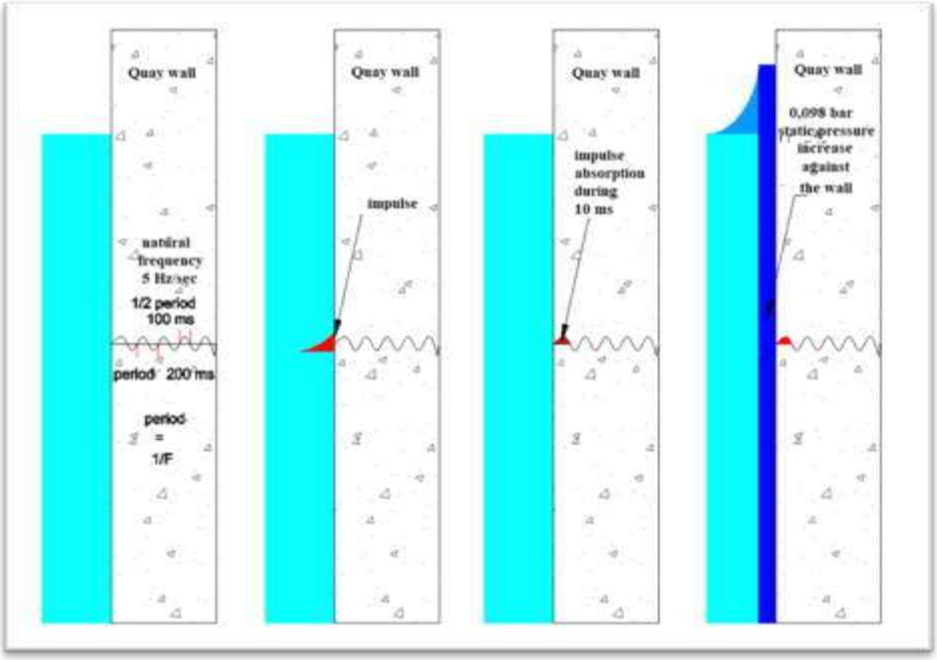

Fig. n° 38: Impulse and increase of the static pressure against a quay wall.

Suppose that a quay wall with a natural frequency of 5 Hz (period 200 ms) is subjected to the effects of an explosion of 15 kg of explosive located 15 meters away and in which the shock wave has an impulse pressure of 9.86 bar.ms (55).
This wall will therefore absorb this impulse for half a period of its natural frequency that is to say for 100 ms.
This means that the static pressure exerted against the quay wall will then be equivalent to:

$$9.86 / 100 = 0.098 \text{ bar}$$

This corresponds to the pressure of a wave of 0.98 m applied during a period of 100 ms.

What is valid for a submerged structure is also valid for the human body because all the organs also have their own natural frequency which means that we can also do this type of calculation.

Suppose therefore that during his cutting, a diver is subjected to the effects of an explosion of a gas pocket of 5 l of H_2/O_2 mixture while he is about thirty centimetres from it.

By examining graphs n° 32 and n° 35, we see that at this distance, the diver will experience a peak pressure of about 5 bars, therefore well below a pressure liable to generate serious damage, but at the same time the impulse of this pressure wave will be about 8.69 bar.ms which it is already well in the critical zone.
If we take as a reference the lungs whose natural frequency is about 45Hz (56) we can then calculate that they will then absorb the energy of the impulse for about 22.22 / 2 that is to say +/- 11 milliseconds.
This means that the static pressure exerted against the lungs will then be equivalent to:

$$8.69 / 11 = 0.79 \text{ bar}$$

This corresponds to the instantaneous pressure of a wave of 7.9 m during a period of 11 ms.
As is known, a diver is able to withstand very high pressure provided that it is applied gradually. On the other hand, in the event of an instantaneous overpressure, the air (gas) contained in the lungs and other hollow organs will be subjected to this same instantaneous compression, which could then cause irreversible damage.

Hydraulic water hammer

Another important phenomenon generated during an underwater explosion that must be taken into account is the hydraulic ram. Contrary to what is sometimes said, this effect has nothing comparable with the effects generated by a hollow charge, which is a device specially designed to focus the shock wave produced by the explosion towards a specific point (57).
In the case of the water ram, the shock wave has no influence on its propagation because it is only created by the almost instantaneous expansion of the burnt gases which will then compress the surrounding water for a few milliseconds.
Because of the incompressibility of water, the effects produced against the diver may be more or less serious and will be related to the type of confinement as well as to the volume of the gas charge. If we take as an example the case of figure n° 39, in which the diver makes a cut in a pile, we see that at the time of the explosion, the water is instantly pressurized (E). Because of the confinement created by the metal wall, the water will then have only one escape: pass through the hole created by the electrode (F).

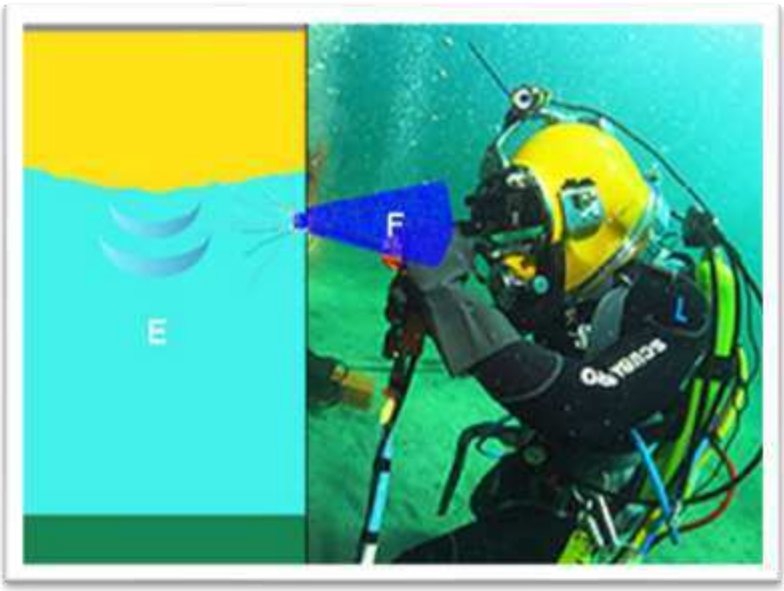

Fig. n° 39: Water hammer.

As seen earlier in this document, the explosion pressure inside the pile is generally between 7 and 16 bars. This means that in the present case the diver then risks being confronted with a water ram of several bars in which the pressurized water jet which passes through the burned hole can then reach a high propagation speed comprised between +/- 37 at 56 meters per second (58).
It seems that it is this phenomenon that is at the origin of the degradation or tearing of the helmet in some of the accidents encountered.
As a reminder, it is also this type of event that is at the origin of the death of a Japanese diver in 2012 (59).

Mini - explosions (pops or bangs)

What has been written in the preceding pages describes in particular the explosions of gas charge more or less important in volume which generally lead relatively serious or even fatal bodily injuries.
There is also another series of explosions which are generally encountered at the kerf level. These are mini-explosions that are generally called “pop” or “bang” by divers.

The origin of these small explosions may be due to:

- the ignition of small pockets of H_2/O_2 mixture, which, for example, have been confined under the sand, in the mud or in various type of soil, or even in the structure itself, such as in a sheet pile slot;
- a vapour explosion;
- an explosive concrete spalling.

Pops with H_2/O_2

In the jargon of commercial divers, no threshold defines the boundary between a mini-explosion and an explosion per se and the choice between the words “pop” or “bang” in place of the word “explosion” is not well defined.

For the author, this threshold should be established according to the risk of bodily injury and the term "pop" should only be used for small gas explosions which do not present a risk to the burner.
Whenever there is a risk of bodily injury, we should call it an explosion.

When a mini-explosion occurs, it is often the knuckles of the fingers that suffer the effects because they are usually quite close to the source.
On the other hand, the helmet (head) and torso are in principle at least twenty centimetres from the source, which is then sufficient to avoid the harmful effects caused by the deflagration of these small volumes of gas.
On the other hand, as soon as this volume of gas increases, one can by consulting figure n ° 40 realize that the risk of bodily injury becomes real at this distance as soon as the volume of the gas bubble reaches and exceeds 500 ml.
The author therefore believes that from such a volume of gas it is preferable to speak of an explosion and no longer of pop.

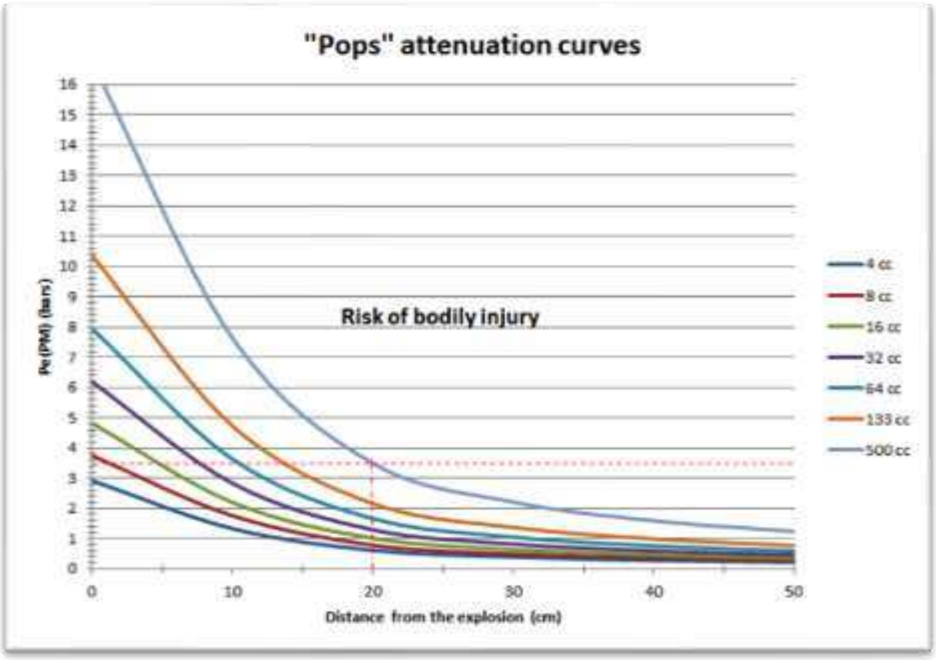

Fig n° 40: POPS attenuation curves.

As far as the origin of these small explosions is concerned, it has not yet been determined with certainty, because the residual gases resulting from the cutting generally contain a high percentage of oxygen which prevents the hydrogen from reaching the limit of 12 % which initiates an explosion, or even reaching its lower explosive limit of 4 %.

How then to explain these mini-explosions?

With regard to pops happening in sheet pile slots, it is known that the diver generally tends to push into them with his electrodes in order to be certain that they are completely cut.

We can therefore think that at the end of the combustion of its electrode a small pocket of oxygen remains confined in the upper part of the recess.
It is enough then that some incandescent slag also fell in the bottom of this small cavity to generate enough hydrogen by vaporization of the water to create a sufficiently flammable mixture which can then explode when igniting a new rod.

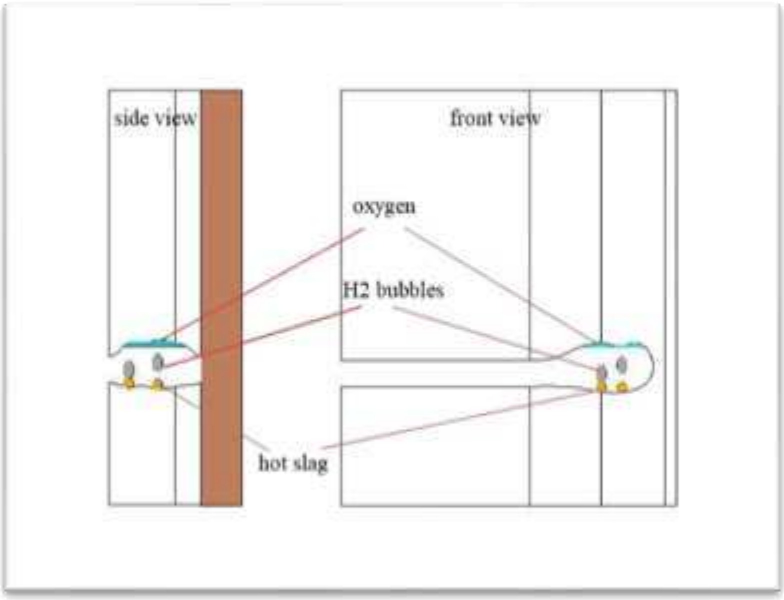

Fig. n° 41: Explosive bubble formation in a sheet pile slot (initial state).

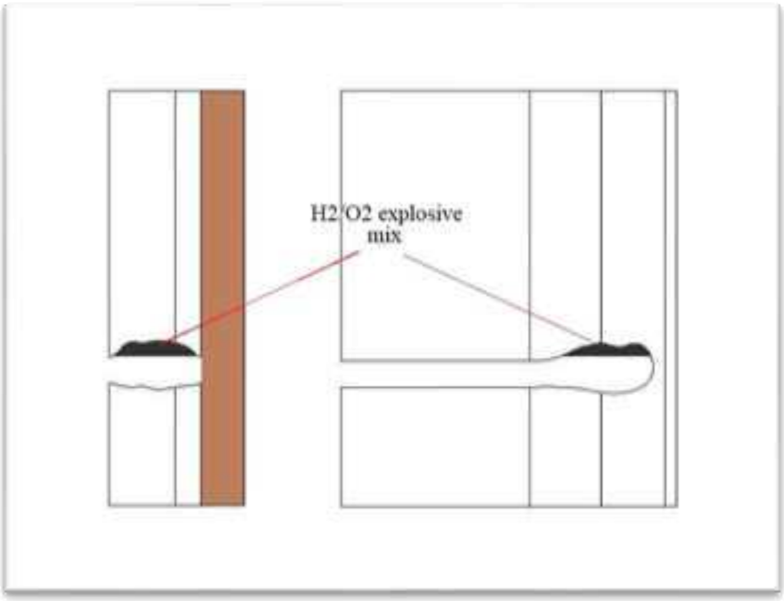

Fig. n° 42: Explosive bubble formation in a sheet pile slot (final state).

With regard to the “pops” which occur under loose soil, this becomes even more difficult to explain because even if this is done at a slower ascent rate, it is more than likely that the residual gases will slowly percolate through these various materials.

One of the possible explanations would be that here too, at the end of the combustion of the electrode, the last incandescent slag will continue to produce hydrogen for a few seconds while mixing with the last residual oxygen bubbles trapped in the ground and would then also create a small bubble of explosive gas.

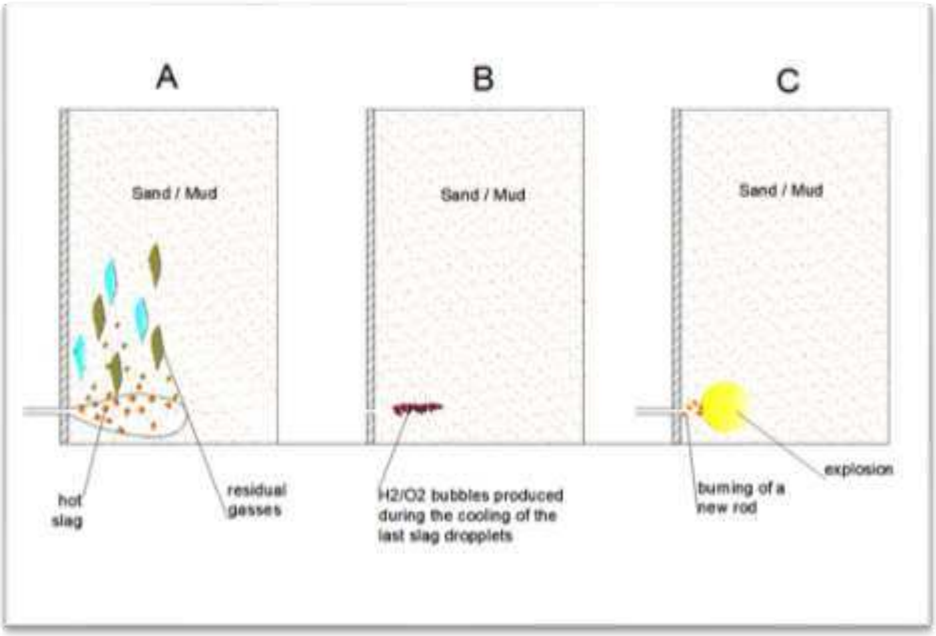

Fig. n° 43: Explosive bubble formation under the sand or mud.

Steam explosion

Another hypothesis put forward by certain scientist would be that these mini-explosions are not due to the explosion of an H_2/O_2 pocket, but rather would be linked to a steam explosion.

Although this is in principle possible with carbon steels (60), this type of explosion is however encountered more frequently when cutting so-called exotic metals such as zinc, aluminium, certain type of bronze, and even stainless steel.

Fig.n°44: Steam explosion during the cutting of an inox propeller blade (61).

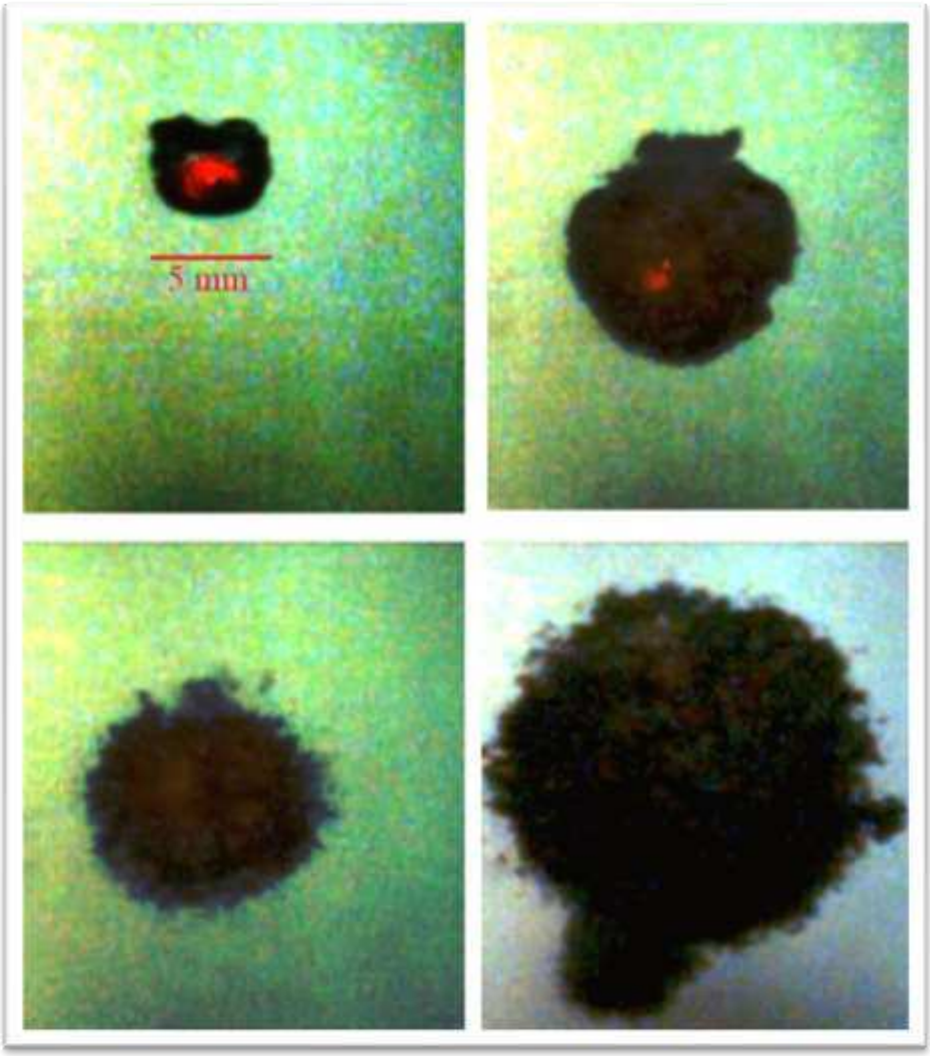

Fig. n° 45: Steam explosion of an incandescent ball (62).

What triggers this type of reaction is not yet well known, but it would seem that it is the contact of the incandescent slag with a cold liquid which would cause the explosive fragmentation (nucleation) of the slag (63) according to the mode described in the figure n ° 46, that is to say that when the liquid slags of exotic metals are ejected from the cut by the jet of oxygen, they are as soon as they come into contact with water and just like carbon steels, almost instantly enveloped by a film of water vapour (Leidenfrost effect).

Inside these pockets, the water molecules trapped between the glowing core and the vapour membrane will crack within milliseconds, causing the H_2 and O_2 atoms to separate. The oxygen will then immediately oxidize the slag while the hydrogen will expand its membrane to its breaking point and thus be able to escape to the surface in the form of a small bubble of flammable gas (A).

As a result, for a few microseconds, the surface of this metal ball will again be in contact with water, which most of the time will cause the creation of a new vapour membrane.

The same cycle is then repeated for a few seconds until the temperature of the slag no longer allows the chemical reaction (64).
But it seems that sometimes following a triggering event, for example a pressure wave or a spontaneous self-triggering, the reaction following the rupture of the vapour membrane is not the same (B).

This can then lead to the fine fragmentation of the molten droplet with at the same time the formation of small spikes at the periphery of the slag which will have the effects of instantly increasing the contact surface with the water and then causing a small shock wave (C-H) which in turn can destabilize the vapour films of the surrounding slag and thus trigger a larger chain reaction as shown in the figure below.

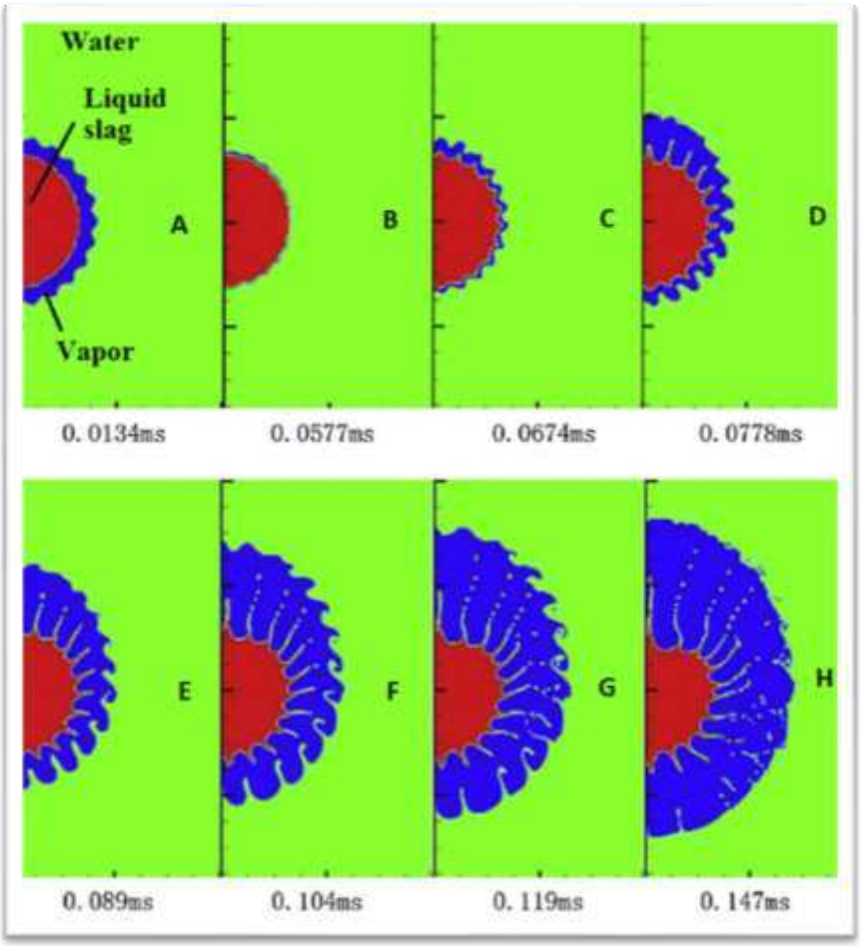

Fig.n ° 46: Simulation of a vapour explosion generated by the fragmentation of a liquid slag droplet (65).

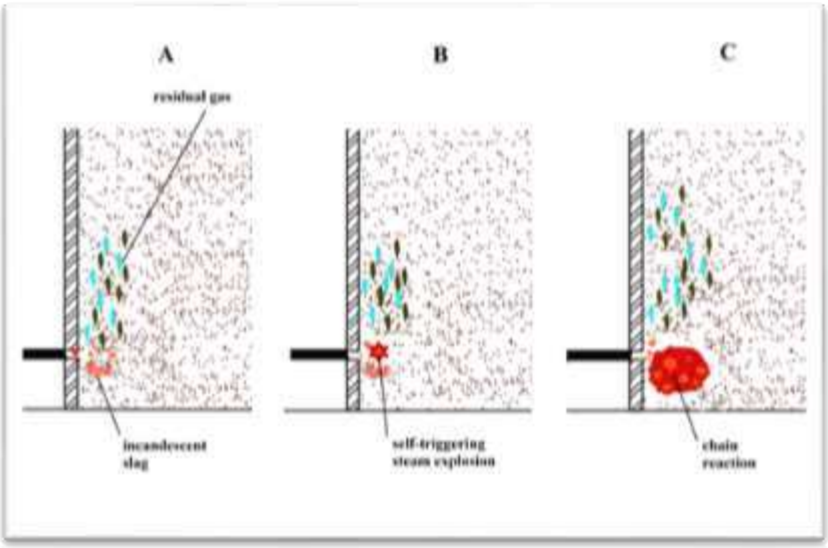

Fig. n° 47: Hypothesis of a vapour explosion of an incandescent slag with chain reaction on the surrounding slag droplets.

According to some studies, the explosion pressure of these small balls barely a few mm in diameter is related to the temperature of the molten droplets and reaches its maximum pressure peak around 2100 ° C (66). Generally this pressure peak is between 20 and 30 bars, but it can sometimes reach the 500 bars. Fortunately for the diver this pressure drops very quickly and no longer reaches a few bars within 5 cm of the drop (67).
This type of vapour explosion is rather unknown within the burners community, but it could explain the origin of some of the mini-explosions that the diver sometimes encounters when cutting large pieces in which gases cannot be confined, such as an anchor chain, propeller shaft or even (maybe) that of certain "pops" when cutting sheet piles.

Fig. n° 48: Possible vapour explosion by accumulation of incandescent slag in front of a sheet pile slot (68).

Concrete explosive spalling

When a metal structure is pressed against concrete, it is common during cutting to be confronted with small explosions. These have nothing to do with the formation of a small pocket of explosive gas. These explosions are due on the contrary to the fact that the concrete surface is subjected successively and for a few seconds to a very high temperature followed by rapid cooling which then generates a violent reaction which generally results in a small explosive spalling of its surface.
This same type of spalling explosions can also be met when gravel is present behind the structure to be cut.

Fig. n° 49: Concrete explosive spalling (69).

Whatever the origin (gas, steam, concrete), the effects produced by these « pops » are much less damaging to the diver than an explosion, but they can still be VERY painful.

How to protect yourself from them?

By we would suggest following the recommendations in the next chapter.

PREVENTION OF ACCIDENTAL EXPLOSIONS

General prevention

- Never start a cutting work without first having carried out a detailed analysis of ALL the risks likely to be encountered on the project (70).
- On the same project, perform a Last Minute Risk Analysis (LMRA) every day before resuming work to ensure that the risk situation on the site has not changed.
- Before using the cutting equipment, check that it is in perfect working order.
- In order to avoid the deterioration or the explosion of the cutting torch, check in particular the state of the "flash arrestor" before each cutting.
- To avoid burns and limit the pops effects on your hands, never cut without gloves.
- To limit the effects of an explosion on the head, preferably use a diving helmet rather than a band mask.
- To limit the effects of an explosion on the chest, preferably use a neoprene dry suit rather than rubber one.
- Before starting a cut, always make sure you are in the right position and at the right place.
- Before starting to cut, always make sure that the residual gases can escape freely to the surface.
- If the residual gases cannot escape freely to the surface, first make evacuation holes where they could accumulate.

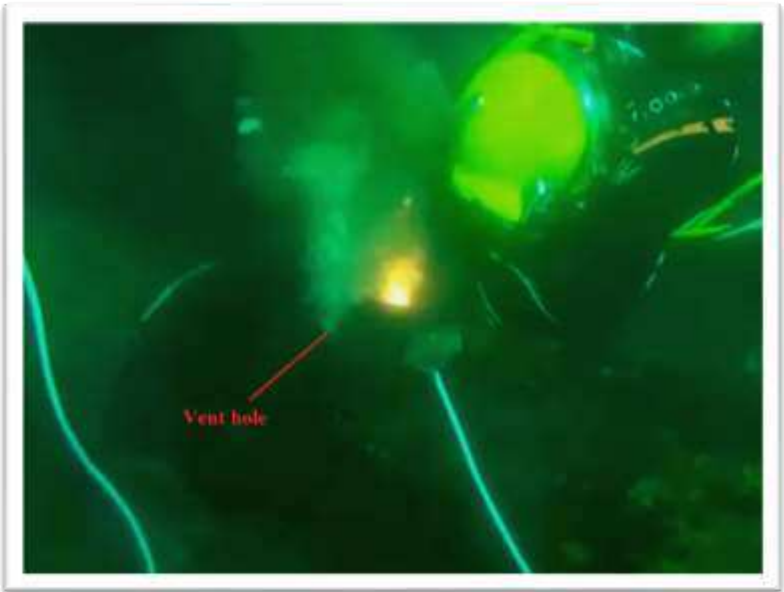

Fig.n° 50: Evacuation hole in the upper part of a pipeline (71).

- During the cutting of any wall (tube, bulkhead, sheet piles, etc.) behind which residual gases may accidentally accumulate, and whatever the cutting technique used (pushing or dragging the electrode), avoid standing in front of the cut so that in case of an explosion, you do not have to suffer the effects of a possible water ram.

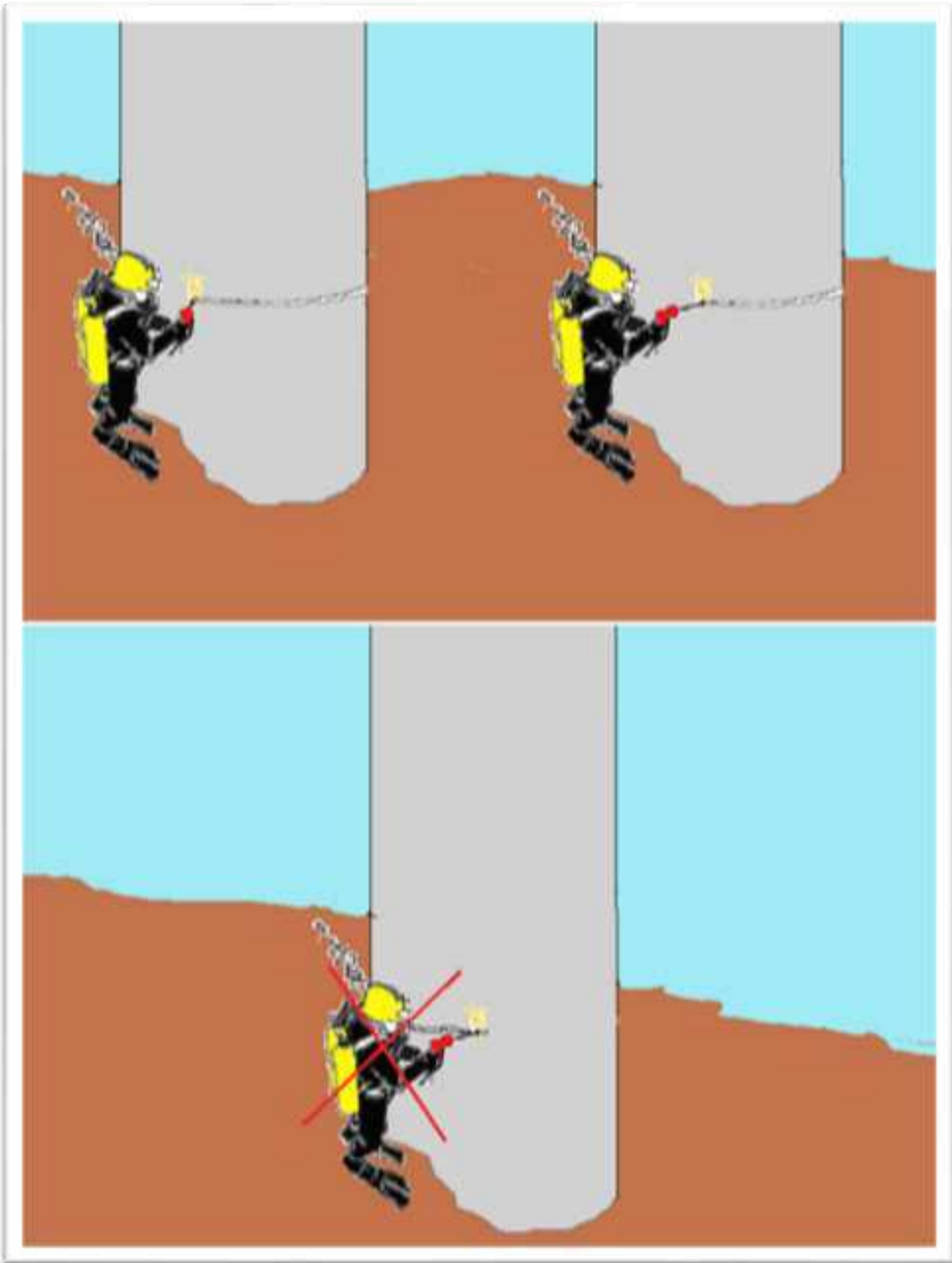

Fig. n° 51: Drag or push the rod but avoid staying in front of the cut.

- Whatever the cutting technique used (pushing or dragging the rod), avoid standing against the wall of the structure because in the event of an explosion, the pressure wave will pass directly from the metal wall into the body with a higher rate of progression than passing through water.

Fig. n° 52: Avoid being in contact with the structure (72)

- As the pressure peak decreases almost exponentially, try to get as far away from the cut as possible (at 30 cm the pressure has decreased by about 85 %). This will allow, in the event of an explosion of small volumes of gas less than 2 litres, to remain below the dangerous limit of 3.5 bars (see figure n° 32).

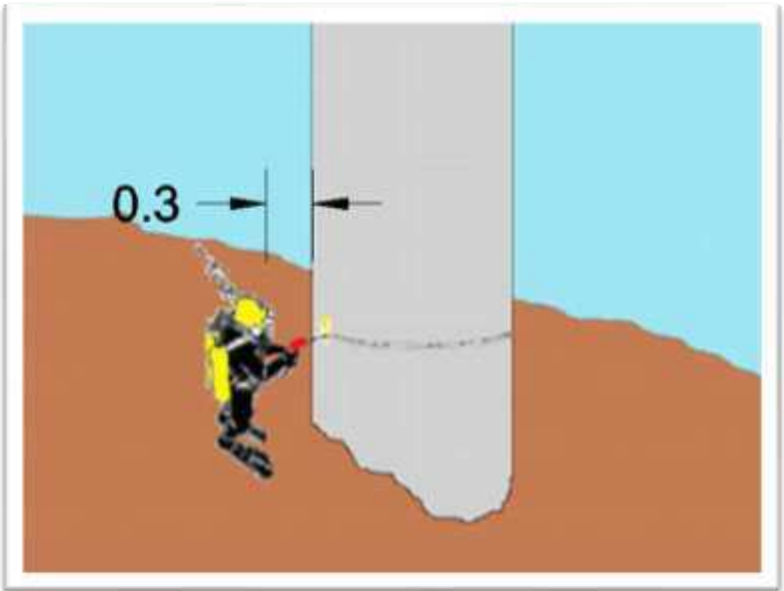

Fig. n° 53: Staying away from the cut reduces the intensity of the peak pressure.

- When cutting vertically, always start the cut from the top to avoid an accumulation of explosive gases.
- Never cut a pipeline without first receiving written confirmation that it has been purged of all flammable products and is now filled with water.

Prevention of explosion risks associated with welding

- Never weld against a structure without first making sure that no flammable substance is behind the wall.

Fig.n° 54: Result of an anode welding against a (rotten) pile containing methane under slight pressure (73).

- In the event of welding (or cutting with the welding electrode) under an overhang and near it, ventilate regularly for a few seconds using the free flow in order to dilute the flammable gases generated by this type of electrode (* see page 63).

Fig. n° 55: Risk of explosion of the welding + diver exhaled gases (74).

Prevention of explosion risks associated with gas torch cutting

- In order to limit the production of unburnt gas at the torch outlet, respect the pressure setting prescribed by the manufacturer. Too high a fuel gas pressure compared to the recommended pressure will not only produce more unburned gas, but will also cause the torch to function poorly with frequent risk of extinction.

Prevention of explosion risks associated with methane

- When cutting a pile sealed by a concrete plug or by any other material, or on any other closed structure driven in or resting on a muddy bottom, ALWAYS suspect the possible presence of methane.
- If there is ANY doubt about the presence of this flammable gas in a confined area, remove them by making evacuation holes at the highest point of the accumulation using a drill or a core drill, while taking care to regularly stop the rotation of the tool in order to cool the bit and thus prevent it from reaching the self-ignition temperature of the gas.
- Never use a grinder to make these vents because the rapid rotation of the disc can generate sparks that can trigger an explosion (75) if in addition to flammable gas, air is also present in this confined space.

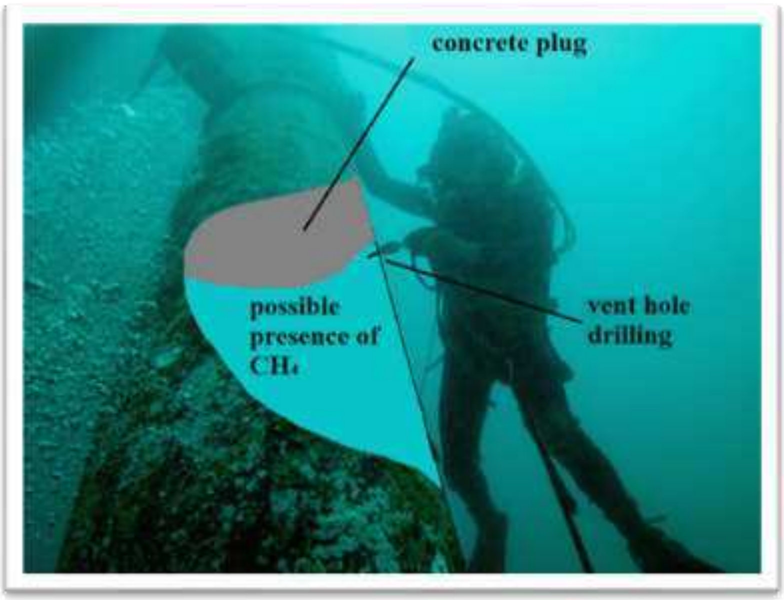

Fig. n°56: Vent holes drilling (76).

- If suspect gas was present and after it has been evacuated, ventilate the area thoroughly with compressed air and then collect a sample of the residual gas for an explosive analysis before starting cutting.

Prevention of explosion risks linked to hydrogen

- When cutting in seawater, the formation of hydrogen by electrolysis is much greater than in fresh water. To limit the production of this gas at both ends of the electrode, cut off the current when you plan to interrupt cutting for more than a few seconds.

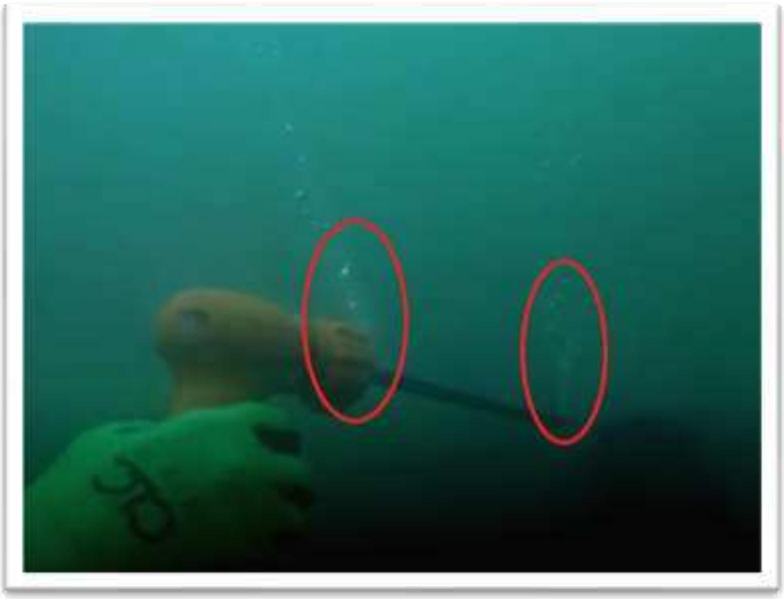

Fig. n° 57: Formation of H_2 by electrolysis (77).

- When cutting under an overhang (wreck or other), cut preferably without current (cold). This makes it possible to stop the electrolysis production of H_2 at the torch side and therefore reduces the % of this gas in the mixture created with the exhaled gases (air or nitrox).

Fig. n° 58: Cutting hot = H_2 formation at the rear side of the rod (78).

- When cutting under a overhang (wreck or other) in addition to the other safety measures, preferably use ultra-thermic electrodes instead of oxy-arc rods because the latter do not allow cutting without current (cold) and on the other hand because of the higher current intensity they use, produce more hydrogen by electrolysis on the torch side (as a reminder at the front of the electrode, the production of H_2 by electrolysis ceases as soon as the electric arc is created) (79).

Fig.n° 59: Cutting inside a wreck or under an overhang (80).

- Make sure that the power is off and give a little oxygen flush before introducing the new electrode. This will prevent an electric arc from occurring between the collet and the end of the electrode and igniting a possible bubble of explosive mixture that would be formed in the head of the torch.
- To minimize pops or small explosions when cutting below the bottom level or when loose material is behind the cut, try as much as possible to remove such material before starting to cut. If this is not possible, then perform a small moderate pressure air flush in the kerf and / or the slot (blow gun, pneumo) before starting a new electrode. This will dilute any small hydrogen bubbles that may have formed around the slag after an interruption in cutting or when changing the electrode.

- In the event of cutting below the bottom level or when loose materials are at the back of the cut, stop cutting for a few seconds as soon as a "rumble" is heard because this usually announces the arrival of a « bang ».

Fig. n°60: Smooth cut flushing (81).

Prevention of explosion risks associated with cutting in a wreck

Thermal cutting (rods or burning gas torch) of wrecks is probably the work technique that generates the most accidental explosions because this type of structure conceals many places where various flammable products can be trapped. As these explosions are the cause of many serious accidents and deaths, this type of cutting by divers is now strongly discouraged and therefore an alternative method should preferably be used (diamond wire).

If this is not the case, an in-depth study of the plans of the wreckage must be carried out in order to identify the various risk areas and thus be able to determine the position at which the evacuation and ventilation holes must be made. Here too, to avoid the risk of explosion, all the first evacuation holes must be made with a tool that does not generate sparks.

Prevention of explosion risks associated with a too low oxygen pressure

During electrode cutting (ultra-thermic / oxy-arc) and under normal conditions of use, the percentage of unburned oxygen present in the residual gases is relatively high and, according to published studies, generally exceeds 97 % (5 - 8).

Fig.n° 61: Ultra-thermic cutting with a significant rise of unburned oxygen into the residual gases (82).

On the other hand, this percentage of oxygen present in the residual gases can decrease if for one or another reason the cutting pressure (and therefore the flow rate) is reduced below the pressures prescribed by the manufacturer.

Fig.n° 62: Oxy-arc cutting with a limited rise of unburned oxygen into the residual gases (83).

Not only does this decrease the performance of the electrode, but it will therefore indirectly increase the percentage of hydrogen present in the residual gases.

This risk is then particularly present when the diver uses oxy-arc electrodes, because already in normal condition of use and due to its design, this type of electrode consumes as can be seen in figure n° 63, less oxygen than an ultra-thermic rod, and therefore less unburned oxygen is present in the gases which rise to the surface.

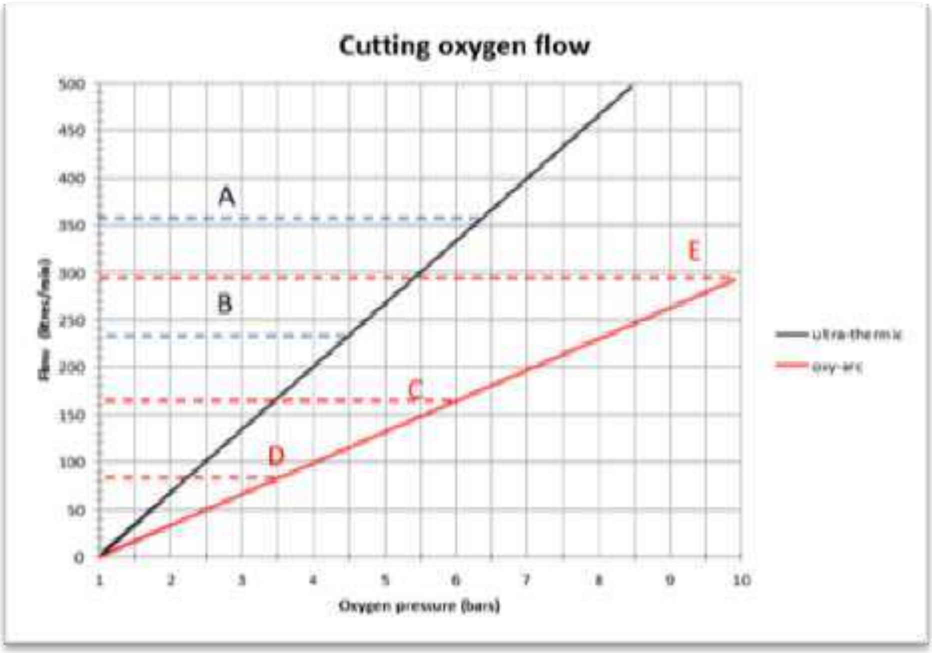

Fig.n° 63: Oxygen flow (without depth correction) in function of the rod type.

To fully understand what is described above, we can take inspiration from the following example:

Knowing that it takes +/- 3 l of oxygen to cut 1 cc of steel (iron) (84) and that this same volume of steel (1 cc) will produce by thermolysis about 8 ml of hydrogen (85), let's check what the % H_2 in the residual gas will be when a diver cuts a steel plate 35 cm long x 1 cm thick.

In our example, the diver will make 2 cuts at different pressures using a Ø 9.5 mm exothermic electrode (1.1 cm wide kerf), as well as 2 cuts using a oxy-arc electrode Ø 7.9 mm (0.9 cm wide kerf).
Finally, for comparison, the % H_2 on another 35 cm x 5 cm thick cut (1 cm wide kerf) is also calculated.

Table n° 6: % of hydrogen in function of the oxygen flow with an exothermic rod.

Cutted steel volume (cc)	O_2 pressure (surf) (bars)	Cutting Time (sec)	O_2 flow (normo) (l)	O_2 oxy reduction (l)	O_2 residual (l)	Production H_2 thermolysis (l)	% H_2 Into residual gas
35 x 1,1 = 38,5	6,4	40	360 / 60 x 40 = 240 (A)	38,5 x 3 = 116	240 – 116 = 124	38,5 x 8 / 1000 = 0,3	100 x 0,3 / 124 = 0,24 %
38,5 x 1 x 1,1 = 28,5	4,5	50	235 / 60 x 50 = 195 (B)	38,5 x 3 = 116	195 – 116 = 79	38,5 x 8 / 1000 = 0,3	100 x 0,3 / 79 = 0,38 %

Table n° 7: % of hydrogen in function of the oxygen flow with an oxy-arc rod.

Cutted steel volume (cc)	O_2 pressure (surf) (bars)	Cutting Time (sec)	O_2 flow (normo) (l)	O_2 oxy reduction (l)	O_2 residual (l)	Production H_2 thermolysis (l)	% H_2 Into residual gas
35 x 1 x 0,9 = 31,5	6	45	165 / 60 x 45 = 124 (C)	31,5 x 3 = 95	124 – 95 = 29	31,5 x 8 / 1000 = 0,25	100 x 0,25 / 29 = 0,86 %
35 x 1 x 0,9 = 31,5	3,5	70	85 / 60 x 70 = 100 (D)	31,5 x 3 = 95	100 – 95 = 5	31,5 x 8 / 1000 = 0,25	100 x 0,25 / 5 = 5 %

By comparing these two tables, we can see that with an ultra-thermal electrode of Ø 9.5 the reduction in oxygen flow will not have much impact on the percentage of hydrogen present in the residual gases.

Unfortunately, this is not the case with an oxy-arc electrode since reducing the oxygen pressure to a limit that still allows cutting can then generate a percentage of hydrogen greater than the LEL of the gas mixture.

In addition, with the latter type of electrode, the percentage of hydrogen in the residual gases can increase further depending on the thickness of the steel and the cutting speed.

Table n° 8: % hydrogen in function of the steel thickness with an oxy-arc rod.

Cutted steel volume (cc)	O_2 pressure (surf) (bars)	Cutting Time (sec)	O_2 flow (normo) (l)	O_2 oxy reduction (l)	O_2 residual (l)	Production H_2 thermolysis (l)	% H_2 Into residual gas
35 x 1 x 5 = 175	10	2 x 55 = 110	295 / 60 x 110 = 540 (E)	175 x 3 = 525	540 – 525 = 15	175 x 8 / 1000 = 1,4	100 x 1,4 / 15 = 9,33 %

*Prevention of explosion risks associated with welding gas/air mixtures

In the illustration in figure n° 55, it can be seen that in case of welding close under an overhang, the flammable gases can partly stay in the recess and possibly mix with some of the diver exhaled air. If this were the case, this mixture can then rapidly become explosive. It is not to forget that in function of its diameter a rod produces between 1,8 and 2,8 l of flammable gases which means that if all that gas stays confined in a recess, only a small volume of exhaled air will be necessary to produce a highly explosive mixture (see table below).
Luckily for the diver, this risk decreases with the increase in air volume, hence the need for regular and adequate ventilation of the area where the gas mixture may be confined.

Table n° 8: % of the flammable gases in function of the exhaled air volume.

Ø electrode	Vol. flammable gases (l)	Vol. exhaled air (normo) (l)	% of the explosive gases	Vol. exhaled air (normo) (l)	% of the explosive gases
3,2	1,8	18	100 x 1,8 / 18 = 10 %	2,4	100 x 1,8 / 2,4 = 75 %
4	2,8	28	100 x 2,8 / 28 = 10 %	4	100 x 2,8 / 3,7 = 75 %

Conclusions

As you can see from this document, cutting underwater can generate the risk of explosion, the consequences of which are sometimes fatal. This is why this technique should only be undertaken after having carried out a correct analysis of the risks that may arise and by making sure in particular that no gas accumulation can occur or is already present near the cutting or welding area.

If this risk exists, it is then imperative to evacuate the gases which are present or which may accumulate, by practicing evacuation vents and by making sure to sufficiently ventilate the concerned area with an inert gas or, failing that, with compressed air to dilute the flammable mixture and keep it below its lower explosive limit.

If despite these measures, the risk analysis shows that there is still a risk of gas accumulation, then DO NOT CUT and choose another work technique.

DIVE SAFE

Bibliography

(1) Francis Hermans, SURVEY AND ANALYSIS OF FATAL ACCIDENTS IN THE COMMERCIAL DIVING SECTOR, page 7
https://www.academia.edu/27691526/SURVEY_AND_ANALYSIS_OF_FATAL_ACCIDENTS_IN_THE_COMMERCIAL_DIVING_SECTOR

(2/3) with courtesy of Nordic Marine Service A/S Denmark
https://www.youtube.com/watch?v=RH05A0vZI6g&t=140s

(4) Hydrogen production in underwater cutting and welding
https://www.academia.edu/40566332/Hydrogen_production_in_underwater_cutting_and_welding

(5) Internet image

(6) Francis Hermans 2019, Explosiveness of the underwater residual cutting gasses. Part 1 Fresh water
https://www.academia.edu/39657695/Explosiveness_of_the_underwater_residual_cutting_gasses_Part_1_Fresh_water

(7) ANALYSIS OF GASES PRODUCED BY THREE UNDERWATER CUTTING DEVICES NAVSEA 2003 (page 8)
http://archive.rubicon-foundation.org/xmlui/bitstream/handle/123456789/3494/ADA442691.pdf?sequence=1

(8) Japanese cutting accident survey, Francis Hermans 2018 (page 14)
https://www.academia.edu/38174428/Japanese_cutting_accident_survey

(9) Determination of the feasibility of shielded metal arc welding and oxygen arc cutting at depth of 600 feet. BATTELLE MEMORIAL INSTITUTE 1969 (page 28)
https://apps.dtic.mil/dtic/tr/fulltext/u2/a076261.pdf

(10) Hydrogen production in underwater cutting and welding
https://www.academia.edu/40566332/Hydrogen_production_in_underwater_cutting_and_welding

(11) Guide des méthodes d'évaluation des effets d'une explosion de gaz à l'air libre, INERIS page 24
https://www.ineris.fr/sites/ineris.fr/files/contribution/Documents/4.pdf

(12) See in reférences 6 – 7

(13) Illustration made from an internet image
(14) Internet image

(15) Internet imaget

(16) Hydrogen production in underwater cutting and welding, page 16

https://www.academia.edu/40566332/Hydrogen_production_in_underwater_cutting_and_welding

(17) Internet image

(18) Francis Hermans, Production d'hydrogène lors du découpage et soudage sous eau, pages 19-20
https://www.academia.edu/40797576/Production_dhydrog%C3%A8ne_lors_du_d%C3%A9coupage_et_soudage_sous_eau

(19) https://forums.futura-sciences.com/chimie/859163-combustion-fer.html

(20) V. Molkov, in Comprehensive Renewable Energy, 2012 / 4.04.7 Deflagrations and Detonations
https://www.sciencedirect.com/topics/earth-and-planetary-sciences/deflagration
Fuel Cells and Hydrogen Technology /

(21) Project SAFEKINEX, Report on the experimentally determined explosion limite, explosion pressures and rates of explosion pressure rise –Part 1 : methane, hydrogen and propylene, page 7 / 63
https://www.morechemistry.com/SAFEKINEX/deliverables/44.Del.%20No.%208.pdf

(22) http://www.hysafe.net/wiki/BRHS/OFD-Chapter4

(23- 25) Les explosifs occasionnels Tomes 1 & 2 - L. Médard, 1979 Techniques & Documentations, chapitre 13 La détonation dans les gaz

(26) Project SAFEKINEX, Report on the experimentally determined explosion limite, explosion pressures and rates of explosion pressure rise –Part 1 : methane, hydrogen and propylene, page 39
https://www.morechemistry.com/SAFEKINEX/deliverables/44.Del.%20No.%208.pdf

(27) Explosion Characteristics of Hydrogen-Air and Hydrogen-Oxygen Mixtures at Elevated Pressures, Schroeder, Holtappers, page 6
http://conference.ing.unipi.it/ichs2005/Papers/120001.pdf

(28-29) Illustration made from an internet image

(30) Francis Hermans, Aide à la qualification au soudage en pleine eau, page 84
https://www.academia.edu/24993910/Aide_%C3%A0_la_qualification_au_soudage_en_pleine_eau

(31) https://www.caminteresse.fr/questions/a-quelle-vitesse-une-bulle-dair-remonte-t-elle-sous-leau-2-2/

(32) Illustration made from an internet image

(33) On the dynamics and instability of bubbles formed during underwater explosions, Suresh Menon & Mihir Lal, School of Aerospace Engineering. Page 3
https://www.sciencedirect.com/science/article/abs/pii/S0894177797100383

(34) On the dynamics and instability of bubbles formed during underwater explosions, Suresh Menon & Mihir Lal, School of Aerospace Engineering. Page 8
https://www.sciencedirect.com/science/article/abs/pii/S0894177797100383

(35) http://www.hysafe.net/wiki/BRHS/OFD-Chapter4

(36-37-38) Illustration made from an internet image

(39) Francis Hermans, Manuel de travaux de démolition par explosifs, 1989, page 258

(40) https://www.youtube.com/watch?v=Hveha7PjGeg&t=24s

(41) On the dynamics and instability of bubbles formed during underwater explosions, Suresh Menon & Mihir Lal, School of Aerospace Engineering. Page 5
https://www.sciencedirect.com/science/article/abs/pii/S0894177797100383

(42) Illustration made from an internet image

(43) Extracorporeal Shock Wave Therapy: Theory and Equipment, Scott McClure, DVM, PhD, DACVS and Christian Dorfmiiller, Dip1 Phys, page 350
https://neoshockwave.com/wp-content/uploads/2017/10/ESWT-Theory-and-Equipment.pdf

(44) Illustration made from an internet image

(45) Illustration made from an internet image

(46) The Infernal Diver, John Bevan, SUBMEX

(47) THE EFFECTS OF UNDERWATER BLAST ON DIVERS by Edward Cudahy, Ph.D. and Stephen Parvin, page 19- 20
(48) THE EFFECTS OF UNDERWATER BLAST ON DIVERS by Edward Cudahy, Ph.D. and Stephen Parvin, page 32

(49) THE EFFECTS OF UNDERWATER BLAST ON DIVERS by Edward Cudahy, Ph.D. and Stephen Parvin, page 32

50) THE EFFECTS OF UNDERWATER BLAST ON DIVERS by Edward Cudahy, Ph.D. and Stephen Parvin, page 21

(51) Francis Hermans, Manuel de travaux de démolition par explosifs, 1989, page 241

(52) The Marine Technology Directorate Ltd., Guidelines for the Safe Use of Explosives Under Water, MTD Publication 1996/101, p 38

53) On the dynamics and instability of bubbles formed during underwater explosions, Suresh Menon & Mihir Lal, School of Aerospace Engineering. Page 4
https://www.sciencedirect.com/science/article/abs/pii/S0894177797100383

(54) ADCI underwater burning video

https://videos.adc-int.org/hazards-of-underwater-burning

(55) Francis Hermans, L'Utilisation des explosifs en milieu sous-marin, 2005, page 67
https://www.academia.edu/25059029/Lutilisation_des_Explosifs_en_Milieu_Sous_Marin

(56) THE EFFECTS OF UNDERWATER BLAST ON DIVERS by Edward Cudahy, Ph.D. and Stephen Parvin, page 29

(57) Francis Hermans, L'Utilisation des explosifs en milieu sous-marin, 2005, page 30
https://www.academia.edu/25059029/Lutilisation_des_Explosifs_en_Milieu_Sous_Marin

(58) Francis Hermans, Delta P in Diving Risks and Prevention, page 6
https://www.academia.edu/36102784/Delta_P_in_Diving_Risks_and_Prevention

(59) Francis Hermans, Japanese cutting accident survey
https://www.academia.edu/38174428/Japanese_cutting_accident_survey

(60) Explosive Interactions of Core Debris with Water
https://ebrary.net/59845/engineering/explosive_interactions_core_debris_with_water

(61) Taken from the video
https://www.youtube.com/watch?v=KANigE7gMd0

(62) Taken from the video
https://www.kth.se/en/2.82572/nps/research/facilities/mistee-micro-interactions-in-steam-explosion-experiments-1.839414

(63) A REVIEW OF LARGE SCALE AND SMALL SCALE UNDERWATER THERMAL EXPLOSIONS by M. Rizk, page 3
https://apps.dtic.mil/dtic/tr/fulltext/u2/a222658.pdf

(64) Francis Hermans, Production d'hydrogène lors du découpage et soudage sous eau, page 10
https://www.academia.edu/40797576/Production_dhydrog%C3%A8ne_lors_du_d%C3%A9coupage_et_soudage_sous_eau

(65) Numerical simulation of fragmentation of melt drop triggered by external pressure pulse in vapor explosions, Yuan Zhou
https://www.researchgate.net/figure/Calculation-results-and-experiment-results-of-melt-tin-drop-fragmentation-process-with-T_fig4_257160122

(66) A REVIEW OF LARGE SCALE AND SMALL SCALE UNDERWATER THERMAL EXPLOSIONS by M. Rizk, figure n° 38
https://apps.dtic.mil/dtic/tr/fulltext/u2/a222658.pdf

(67) A REVIEW OF LARGE SCALE AND SMALL SCALE UNDERWATER THERMAL EXPLOSIONS by M. Rizk, page 38
https://apps.dtic.mil/dtic/tr/fulltext/u2/a222658.pdf

(68) Taken from the video
https://www.youtube.com/watch?v=20SokKDUlA4&t=15s

(69) Internet image

(70) Francis Hermans, L'ANALYSE DES RISQUES
https://www.academia.edu/36997989/LANALYSE_DES_RISQUES

(72) Internet image

(71) Taken from the video :
https://www.youtube.com/watch?v=8kHwGqZYOyk

(73) Taken from video
https://www.facebook.com/francis.hermans.5/videos/10213862582855659

(74)) Internet image
(75)
https://www.longstreath.com/community/incidents/?sortby=col_4&sortdirection=desc&page=10

(76) Illustration made from an internet image

(77) Illustration made from an internet image

(78) Illustration made from an internet image

(79) Francis Hermans, Production d'hydrogène lors du découpage et soudage sous eau, page 17
https://www.academia.edu/40797576/Production_dhydrog%C3%A8ne_lors_du_d%C3%A9coupage_et_soudage_sous_eau

(80) Illustration made from an internet image

(81) Illustration made from an internet image

(82) Internet image

(83) Internet image

(84) https://forums.futura-sciences.com/chimie/859163-combustion-fer.html

(85) Francis Hermans, Production d'hydrogène lors du découpage et soudage sous eau, page 15
https://www.academia.edu/40797576/Production_dhydrog%C3%A8ne_lors_du_d%C3%A9coupage_et_soudage_sous_eau

Some interesting documents on this subject

Hydrogen Safety Barriers and Safety Measures
http://www.hysafe.org/download/1200/BRHS_Chap5_V1p2.pdf

Calculating the Effect of Surface or Underwater Explosions on Submerged Equipment and Structures
https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.129.8805&rep=rep1&type=pdf

SAFE DISTANCES FROM UNDERWATER EXPLOSIONS FOR MAMMALS AND BIRDS
https://apps.dtic.mil/sti/citations/AD0766952

Explosive Shocks in Air
https://www.academia.edu/37011656/Explosive_Shocks_in_Air_pdf

GAS EXPLOSION HANDBOOK
https://www.gexcon.com/wp-content/uploads/2020/08/Gas-Explosion-Handbook-1992-version-new-front-page-2019.pdf

An Experimental Study on Melt Fragmentation, Oxidation and Steam Explosion during Fuel Coolant Interactions
https://kth.diva-portal.org/smash/get/diva2:1268247/FULLTEXT01.pdf

PREDICTION OF UNDERWATER EXPLOSION SAFE RANGES FOR SEA MAMMALS
https://www.bsee.gov/sites/bsee.gov/files/tap-technical-assessment-program/044ac.pdf

NUMERICAL SIMULATION OF AN UNDERWATER EXPLOSION BY SPH METHOD
https://academiaromana.ro/sectii2002/RomanianJournalTS/rev2016-1/RJTS-AM_2016_61_1_a6_Nastasescu.pdf

Use of weak shock theory to reproduce and extend 60-Series safe swimmer ranges from underwater explosions
https://cradpdf.drdc-rddc.gc.ca/PDFS/unc237/p804314_A1b.pdf

Guidance on Inerting for the Prevention of Explosions
http://santa.com.tr/wp-content/uploads/2019/05/CEN_TR-15281-2006-Guidance-on-Inerting-for-the-Prevention-of-Explosions.pdf

Lethal and physical injury of marine mammals, and requirements for Passive Acoustic Monitoring.
https://tethys.pnnl.gov/sites/default/files/publications/Subacoustech_2007.pdf

Underwater Explosion Phenomena and Shock Physics
http://www.am.chalmers.se/~thab/IMAC/2010/PDFs/Papers/s38p003.pdf

UNDERWATER BLAST INJURY - A REVIEW OF THE LITERATURE
https://apps.dtic.mil/sti/pdfs/AD0722666.pdf