Shooting Gas Cylinders to Prevent Their Explosion in Fire

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***Abstract*—** Gas cylinders in general, and particularly cylinders containing acetylene, constitute a great potential danger to fire and rescue services involved in salvage operations. Experiments show that gas cylinders with acetylene, oxygen, hydrogen, CNG, LPG or CO2 may blow after short exposition to heat with very destructive effect as fragments of blown cylinder may fly even several hundred meters. In the case of acetylene the explosion may occur also several hours after the cylinder is cooled down. One of the possible neutralization procedures that in many cases may be used to prevent explosions is shooting dangerous cylinders with rifle bullets. This technique is used to neutralize acetylene cylinders in a few European countries with great success. In Poland research project "BLOW" was launched in 2014 with the aim to investigate phenomena related to fire influence on industrial and home used cylinders and to evaluate usefulness of the shooting technique. All together over 100 gas cylinders with different gases were experimentally tested at the military blasting grounds and in shelters. During the experiments cylinder temperature and pressure were recorded. In the case of acetylene that is subjected to thermal decomposition also concentration of hydrogen was monitored. Some of the cylinders were allowed to blow and others were shot by snipers. It was observed that shooting hot cylinders has never created more dangerous situations than letting the cylinders to explode spontaneously. In a great majority of cases cylinders that were punctured with bullets released gas in a more or less violent but relatively safe way. The paper presents detailed information about experiments and presents particularities of behavior of cylinders containing different gases. Extensive research was also done in order to select bullets that may be safely and efficiently used to puncture different cylinders. The paper shows also results of those experiments as well as gives practical information related to techniques that should be used during shooting.

***Keywords*—**fire, gas cylinders, neutralization, shooting.

I. Introduction

GAS cylinders that are commonly used both in industry and many households constitute a serious danger in the case of being exposed to high temperatures that occur during fires. Essentially the danger is twofold. The cylinder may blow due to overpressure throwing numerous and usually very heavy and sharp shrapnel with high kinetic energy and if the gas is flammable or explosive also a fireball may be created.

Some of the portable gas cylinders are equipped with overpressure safety valves (for example many of CO_2 cylinders and all containers with Liquefied Natural Gas -LNG). Unfortunately, it is not always advisable to use the safety valves in portable cylinders because in many cases unexpected ejection of gas from the valve can be very dangerous in itself. This is true especially in the case of highly flammable or toxic gases.

Cylinders with acetylene bring still another serious threat which is the possibility of delayed explosion. Cooling down cylinders containing compressed gases like for example oxygen, hydrogen, Liquefied Petroleum Gas - LPG, argon or air leads to rapid decrease of pressure to the safe level. Of course material of the cylinder may be degraded (especially in the case of laminated cylinders) and thus less strong, but construction of the cylinders accounts for this so it is **relatively safe** to handle **a cooled down** gas cylinder removed from fire.

The case of acetylene (C_2H_2) is, however, very different. If acetylene is compressed over 15 kPa or heated over 180ºC the decomposition of acetylene may start according to the equation (1). This is an exothermic reaction so if it occurs in a confined space it leads to a further increase of temperature and pressure resulting in a violent burst of the cylinder. To prevent explosion acetylene gas is dissolved in liquid acetone for safe storage and usage. The cylinders are also filled with porous material that helps to suppress decomposition processes.

$$C_2H_2 \rightarrow 2C + H_2 \tag{1}$$

The decomposition process may start during the heating of the acetylene cylinder and continue inside porous filler also after the outer surface of the cylinder is cooled down. If it happens, the cylinder becomes a time bomb that may explode much later. Consequently, all acetylene cylinders exposed to excessive heat must be treated in a special way. The classic way is to cool the cylinder by water spray for one hour and monitor its surface temperature for up to 24 hours [2], [3]. During rescue operations involving acetylene cylinders it is necessary to implement a 200 m radius Hazard Zone. This procedure is very cumbersome and in many cases it also disturbs rescue operations around the cylinder. According to [3] it is possible to reduce the Hazard Zone after initial cooling of the cylinder provided that temperature of the cylinder is periodically monitored. Often, in order to cool the cylinder with water it is necessary to send firefighters very close to the dangerous cylinder(s) exposing them to risk of serious injuries or death as even a "cold" cylinder may blow surprisingly.

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Although in the majority of studies and manuals the waiting period of 24 hours after cooling is considered to be necessary to ascertain that acetylene cylinder is safe to handle, some studies indicate also that one hour cooling and one hour observation is adequate [4].

One of the solutions to lower the explosion risk of gas cylinders subjected to fire is to use a rifleman to puncture the cylinder by shooting it with rifle bullets. This paper describes experiments and findings of several test campaigns performed in Poland within the project BLOW.

Although acetylene cylinders were the main concern, also explosions and shooting procedures for neutralization of cylinders with other gases were investigated. Most of the studies limit the shooting neutralization technique to single cylinder with acetylene, the exception being [5] where also oxygen, hydrogen and propane cylinders were being shot.

The authors decided that in order to get more general information for firefighters it is necessary to test several compressed gases and try to shoot multiple cylinders. During fire it may be difficult to properly recognize different cylinders and intentional or unintentional shooting bottles with other gases may occur. What is more, it is common have in bigger enterprises to gas cylinders batteries that contain 4, 6 or 8 cylinders interconnected by pipes and built in to the special cage. Besides the acetylene following gases were also used during the experiments: hydrogen, oxygen, LPG, methane, LNG, and CO_2.

II. MEASURING SYSTEM AND FIREARMS

A. Instrumentation

All tests were carried out on military shooting and blasting grounds so the instruments had to be proofed for harsh weather conditions. In Fig. 1 general layout of the system is presented. The system was composed with two units. The first unit located close to the gas cylinder was equipped with pressure sensor, temperature sensors and hydrogen sensor (for description see subchapter II.B). The unit contained also steering valves for gas torches that were used during some of the tests to heat gas cylinders. Gas torches operated on propane and bottles that supplied them with gas were preheated by electric heaters to prevent freezing. The second unit was positioned in tranche at the safe distance of 200 m from the test cylinder. This unit was equipped with data acquisition system, remote detonator to ignite fire around the test cylinder and high speed camera. The rifleman was positioned few meters from the unit.

B. Hydrogen sensor

According to equation (1) decomposition of the acetylene leads to release of hydrogen and carbon, so monitoring of hydrogen concentration in gas samples may be used as a reliable indicator of decomposition process. Unfortunately, in field conditions it is rather difficult to measure the concentration of hydrogen in hydrogen-acetylene mix.

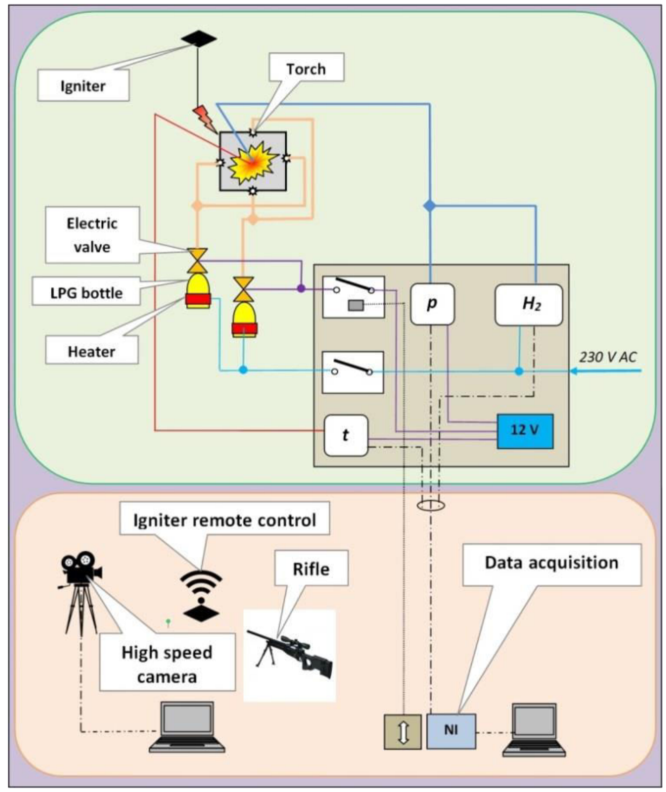

Fig. 1 Layout of the measuring system used during experiments

Most of the commercial hydrogen sensors, due to the principle of their operation, cannot work in the environment where gas mix contains acetylene and vapors of acetone. To overcome this problem a special ultrasonic meter was designed and constructed at the Technical University of Gdańsk (TUG). The sound speed in hydrogen is very high (1207 m/s) and in acetylene it is rather low (323 m/s) so the sound speed in the mix of those two gases is very sensitive to the concentration of hydrogen - more hydrogen means higher speed of sound. Sound speed in gases is relatively easy to measure with ultrasonic sensors. The simplest way is to use an ultrasonic distance meter that shows distance from the sensor to the sound reflective surface of the test tube filled with gas. Such a meter is usually calibrated for sound speed in the air so it shows false distance when sound speed is different. When true distance to the reflective surface is known it is possible to calculate actual speed of sound in gas mix by simple calculations based on those "false" readings. The instrument constructed at TUG is shown in Fig. 2.

The instrument was calibrated by gas mixes containing known concentration of hydrogen. The calibration revealed that precision of measurements is very good and the system may be used to measure even low concentrations of hydrogen (less than 1%) The meter was equipped with a set of filters that removed black carbon and vapors of acetone and prepared to be connected via pressure regulator and pipe to the test cylinders. In order to reduce acetylene consumption a small electric operated valve was also installed in front of the meter so it was possible to sample the gas mixture at arbitrarily set intervals.

Fig. 2 Hydrogen sensor constructed at TUG

C. Firearms used during experiments

Choice of the rifles for the experiment was based on their availability for Police and Military Personnel in Poland. The idea was to test rifles shooting bullets of the most common calibers so in the case of emergency any SWAT team or military sniper team could be used. Unfortunately, in Poland there are no regulations that legalize the use of firearms by civilians or firemen during firefighting operations, despite a relatively big number of firearms being in possession of private persons like hunters and sport shooters.

Definitely the most popular rifle caliber in Poland and in most European countries is .308 Winchester (or its military equivalent 7.62x51 NATO). Less popular but better suited for shooting in difficult conditions (longer distance, strong wind, thicker gas cylinders walls) is caliber .338 Lapua Magnum that is very popular at the special forces and among long range sport shooters. Both calibers were used in the initial stage of the experiments to establish their potential towards puncturing the gas cylinders. It must be mentioned that gas cylinders designed to store acetylene and LPG have rather thin steel walls, while cylinders for oxygen, hydrogen, methane or CO_2 have very strong and thick walls and bottoms.

Two rifles of different construction were used. They are described in Table I and show in Fig. 3.

TABLE I
RIFLES USED DURING EXPERIMENTS

-	Rifle 1	Rifle 2
Caliber	.308 Winchester	.338 Lapua Magnum
Manufacturer	Oberland Arms	Sako
Model	OA-10	TRG42
Barrel length	640 mm	690 mm
Riflescope	S&B Police Marksman II	US Optics SN3
Magnification	5-25	5-25

It must be mentioned that armed forces and Police use extensively also small bore firearms of caliber .223 Remington (5.56x45 NATO) that are capable of puncturing gas cylinders but the resulting holes are of a very small diameter (at about 5 mm) that do not release the pressure quick enough.

During the initial test several types of ammunition were tested to find out which one is the best for puncturing gas cylinders. Full Metal Jacket (FMJ) as well as Match, hunting (soft-point), Armor Piercing (AP) and tracers were used.

Fig. 3 Rifles tested during field experiments

All FMJ and Match bullets as well as tracers were capable of puncturing the walls of gas cylinders if bullets hit central region of the cylinder, but efficient zone was evidently bigger for bullets cal. .338 Lapua Magnum - see Fig. 4. Bullet hitting cylinders outside the efficient zone have not penetrated the sidewall and in a few cases they ricocheted. In the case of LPG cylinders all bullets were going through both walls of cylinder while hitting cylinders with other gases the bullets were stopped inside the cylinders. Hunting bullets (like Lapua Naturalis) were not able to puncture gas cylinder walls except LPG bottles so **they should not be used** to neutralize gas cylinders. AP bullets in most cases were passing through both walls of cylinders with exception of oxygen bottles where they oxidized passing through oxygen and burnt completely inside the cylinders.

Fig. 4 Zones of efficient hit for the acetylene cylinders; solid line - efficient zone for FMJ, Match bullets and tracers, dotted line - efficient zone for AP bullets

Big advantages of Armor Piercing bullets are the much larger efficient zones where hit leads to puncture of the cylinder and their ability to puncture cylinder also in its upper region (valve area) and through its bottom part. Unfortunately, AP bullets constitute also some extra danger as the gas container is not usually able to stop them so they leave it and may be dangerous even at long distance away.

III. RESULTS OF EXPERIMENTS

A. Acetylene cylinders

Several cylinders with acetylene were tested during the experiments. The cylinders were heated with gas torches, otherwise by burning gasoline or firewood. Some of the experiments were carried out long enough to get the cylinder blown by the internal pressure and in other cases the cylinders were shot through by the rifleman before their spontaneous explosion. Statistical data about the results are presented in Table II.

TABLE II
RESULTS OF EXPERIMENTS WITH ACETYLENE CYLINDERS

-	Spontaneous blow	Neutralized by shot
Number of cylinders tested	13	8
Av. number of debris	1	1
Max. distance travelled by debris	64	0
Av. distance travelled by debris	24	0
Max. pressure when blown/neutralized	39	31
Min. pressure when blown/neutralized	28	19
Av. pressure when blown/neutralized	32	28
Av. fireball diameter	15	-
Av. jet-fire length	7	3

Exploding acetylene cylinders do not create separate debris but get ruptured on lesser or greater length - see Fig. 5. Such a ruptured cylinder may travel a relatively long distance. Although during the experiments the longest distance travelled by acetylene cylinder was only 64 m, during an earlier pilot study the longest observed distance was 146 m. When acetylene explodes spontaneously the fireball has usually considerable diameter over a dozen meters - see picture from high speed camera in Fig. 6. The character of the fireball is very much dependent on the degree of acetylene decomposition that occurred before the explosion.

Fig. 5 Fully ruptured acetylene cylinder

Shooting acetylene cylinder prevents its spontaneous blow and is a very efficient way of neutralization. When the cylinder is punctured with the bullet the escaping acetylene creates a 2-3 m long jet fire that is much less dangerous than it would be in the case of an explosion of the cylinder - see Fig. 7. Occasionally, probably depending on the degree of the decomposition, the stream of gas escaping the cylinder is not lit, even by a tracer bullet. It must be stressed, that a single hole created by the bullet may not be enough to prevent the blow of the cylinder, especially if the decomposition of acetylene is well advanced, therefore it is necessary to shoot the cylinder three times at least.

Fig. 6 Fireball during acetylene cylinder explosion (distance between triangle markers is 10 m)

Fig. 7 Jet-fire after puncturing acetylene cylinder

In Fig. 8 time histories of pressure and H_2 concentration in acetylene cylinder heated by four torches (each of 50 kW power) are presented. The figure shows that at about 4 minutes after the start of heating H_2 concentration increases rapidly and at about one minute later the cylinder is blown by gas pressure.

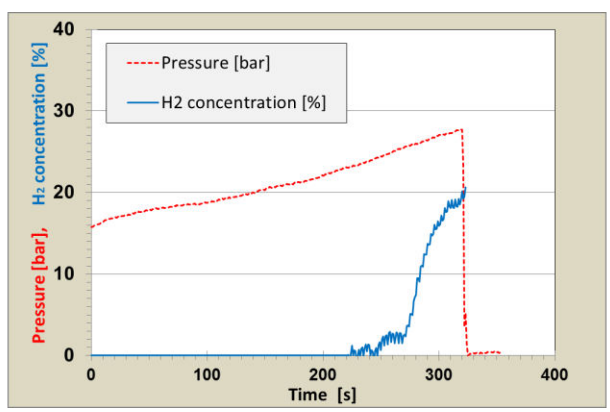

Fig. 8 Time history of pressure and H2 concentration in acetylene cylinder heated by four gas LPG driven torches

Typically, puncturing a gas cylinder with bullets is used only for single, separated bottles. The present authors decided, however, that it is important to test if the procedure may be used also in the case of industrial batteries of cylinders containing 4, 6 or 8 cylinders interconnected by a system of tubes and valves. All together four experiments with cylinder batteries were performed. The results indicate that although it is possible to shoot through cylinders visible from the shooting positions, it is not possible to neutralize all cylinders as some of them are always shadowed by the ones in the front. What is more, if the battery is not strongly anchored the first shot and the resulting strong gas recoil may destabilize the battery so it falls making consecutive shots even more difficult, if not impossible.

Consecutive shots must be made very quickly as the acetylene leak from one of the cylinders speeds up the decomposition processes in other cylinders in the battery due to the gas flow and at the same time burning acetylene increases temperature of the battery rapidly. When shooting to four cylinder batteries the authors always managed to neutralize two or three cylinders before the rest of them exploded. It means that the overall effect of the neutralization was positive, however, not ideal. Fig. 9 presents the result of neutralization of four cylinder acetylene battery. Two cylinders were successfully punctured but other two ruptured (exploded). Two of the cylinders were thrown away from the frame and one of them landed 42 m away.

Fig. 9 Battery of cylinders after neutralization; a - the frame with one ruptured cylinder and two punctured cylinders, b - ruptured cylinder found 42 m away

B. Oxygen cylinders

Explosions of cylinders containing compressed oxygen are very dangerous because the cylinders tend to produce big and very sharp shrapnel and oxygen itself is a very active oxidizer. Experiments with oxygen cylinders were carried out in a similar manner to the ones in the case of acetylene. Statistical data about the results are presented in Table III.

TABLE III
RESULTS OF EXPERIMENTS WITH OXYGEN CYLINDERS

-	Spontaneous blow	Neutralized by shot
Number of cylinders tested	3	4
Av. number of debris	3	1
Max. distance travelled by debris	198	48
Av. distance travelled by debris	101	31
Max. pressure when blown/neutralized	329	262
Min. pressure when blown/neutralized	262	164
Av. pressure when blown/neutralized	294	202
Av. fireball diameter	-	-
Av. jet-fire length	-	5

Exploding oxygen cylinders may create shockwaves with considerably high air pressure (10 kPa at the distance of 8 m) what is equivalent to 0.5 kg of TNT. Typically, the cylinder is thorn to 2 - 3 pieces that are heavily deformed by the blast - see Fig. 11. Blast of the oxygen cylinder does not create fireball unless there is flammable gas, dust or liquid close to the cylinder.

Fig. 10 Shrapnel created during the blast of oxygen cylinder that was thrown 146 m from the place of explosion

Neutralization of the oxygen cylinders by shooting them with rifle bullets is possible but not as safe as shooting acetylene cylinders. The danger is related to specific behavior of the cylinder when it is punctured by a very energetic bullet. Energy of the bullet hitting and puncturing the oxygen cylinder is transformed to heat that locally increases temperature of the steel in the area of the puncture. The increase of temperature is enough to start rapid oxidation of the steel and as a result a small rocket engine is created. This engine has enough thrust to move the cylinder and start to rotate it vigorously- see Fig. 11. Of course the rotation of the cylinder depends on the position of the puncture - the further from the center of gravity - the more rotation. Observations by this authors indicate that fast rotations of the cylinder may sometimes have a positive effect on the neutralization process as in some cases the cylinder nearly hoovers over the ground without moving away. Unfortunately, when the rotating cylinder hits the ground or any rigid obstacle it bounces off in a direction that is difficult to predict. Nevertheless, even a heavily bouncing cylinder does not fly more than 50 m from the place where it was hit by the bullet while very sharp and heavy shrapnel created by cylinder blast can fly a four times longer distance.

Oxidation process of the cylinder wall around the bullet hole that acts as rocket engine burns steel so the hole diameter increases from initial 6-8 mm to 70 - 80 mm.

Fig. 11 Oxygen cylinder rotating after hit by bullet

Fig. 12 Burned off whole that was initiated by the bullet and enlarged by oxidation

C. Hydrogen cylinders

During the experimental campaign 6 cylinders with compressed hydrogen were tested. Statistical data about the results are presented in Table IV.

Spontaneous explosion of hydrogen creates big and very sharp shrapnel that have considerable kinetic energy. During experiments only one cylinder exploded so it is difficult to interpret the data in a statistical way. Maximal distance travelled by the debris is not representative as the debris buried into the ground closely to the explosion place (see Fig. 13). Its energy was enough to make it fly much further if the direction of fly were different. The authors speculate that free flying debris of hydrogen cylinder fly in a similar way to oxygen cylinder.

TABLE IV
RESULTS OF EXPERIMENTS WITH HYDROGEN CYLINDERS

-	Spontaneous blow	Neutralized by shot
Number of cylinders tested	1	5
Av. number of debris	2	1
Max. distance travelled by debris	21	0
Av. distance travelled by debris	13	0
Max. pressure when blown/neutralized	290	240
Min. pressure when blown/neutralized	290	164
Av. pressure when blown/neutralized	290	203
Av. fireball diameter	10	-
Av. jet-fire length	-	6

Fig. 13 Explosion of hydrogen cylinder; the arrow indicates place where big shrapnel buried into the ground.

Neutralization of hydrogen cylinders by shooting them with rifle bullets is a straight forward and relatively safe procedure as the jet fire has only 4 - 8 m length and the cylinder is not changing its position - see Fig. 14.

Fig. 14 Jet fire associated with shooting hydrogen cylinder.

D. Methane cylinders

Cylinders with methane (Compressed Natural Gas - CNG) are also build to withstand very high pressure (like oxygen and hydrogen cylinders). Data about the results of measurements are presented in Table V.

TABLE V
RESULTS OF EXPERIMENTS WITH METHANE CYLINDERS

-	Spontaneous blow	Neutralized by shot
Number of cylinders tested	1	4
Av. number of debris	3	1
Max. distance travelled by debris	>500	3
Av. distance travelled by debris	250	1
Max. pressure when blown/neutralized	459	430
Min. pressure when blown/neutralized	459	313
Av. pressure when blown/neutralized	459	390
Av. fireball diameter	20	-
Av. jet-fire length	-	10

Spontaneous explosions of methane cylinders create very large fireballs and shrapnel may reach very high speed that allows for a very long fly. One of the debris that was created during explosion of one of the cylinders moved over 500 m and was not found as it was lost in the forest. According to high speed camera registration this shrapnel was of a size of a cowboy's hat and looked like a rotating propeller. The shrapnel is visible in Fig. 15 that visualizes the first phase of methane cylinder explosion. The second phase is visualized in Fig. 16.

Fig. 15 Explosion of methane cylinder; the arrow indicates big shrapnel that moved over 500 m.

Fig. 16 Fireball associated with methane cylinder explosion.

Neutralization of methane cylinders by shooting them in all cases prevented explosion and dangerous fragmentation, however, jet fires were violent and reaching up 10 m lengths (see Fig. 17).

In opinion of this authors neutralization of methane cylinders by shooting lowers the risk related to the explosion as it prevents shrapnel and reduces danger of the fireball.

Fig. 17 Jet fire developed after hitting methane cylinder with bullet.

E. LPG cylinders

LPG cylinders are probably the most common gas containers in households of many countries including Poland. LPG is used for heating, for grills and in many vehicles as alternative fuel. In the case of Poland about 15% of cars (and nearly 100% of taxis) are equipped with LPG systems. Systems used in vehicles are very well protected against risk of explosion but other cylinders that are portable, like the most common 11 kg bottles and smaller ones, have no safety valves of any type. Due to this, LPG cylinders received special attention during implementation of project BLOW. Data about the results of measurements are presented in Table VI.

TABLE VI
RESULTS OF EXPERIMENTS WITH LPG CYLINDERS (11 KG)

-	Spontaneous blow	Neutralized by shot
Number of cylinders tested	3	4
Av. number of debris	3	1
Max. distance travelled by debris	134	11
Av. distance travelled by debris	117	2
Max. pressure when blown/neutralized	76	58
Min. pressure when blown/neutralized	66	5.7
Av. pressure when blown/neutralized	69	35
Av. fireball diameter	20	10
Av. jet-fire length	3	8

In Fig 18 the view on LPG cylinder after explosion at the pressure of 66 bar is presented. During this experiment a shock wave was created and the cylinder was thorn to three pieces indicated by arrows in the figure. All shrapnel traveled a distance over 100 m (see Fig. 19). Although the cylinder was heated during the experiment by two torches the blow of it did not resulted in ignition of released gas. A completely different development of the experiment was observed in the case of LPG cylinder that was heated up in a gasoline spill. This time the cylinder exploded also at 66 bar creating a fireball that had diameter of nearly 20 m - see Fig. 20 and the shrapnel were thrown over 90 m from the position of the experiment. It is interesting to notice that during this experiment no shock wave was created.

Fig. 18 Hydraulic blow of the LPG cylinder without combustion; arrows indicate shrapnel

Fig. 19 Shrapnel created during the blow of LPG cylinder (all debris gathered together)

Fig. 20 Hydraulic blow of the LPG cylinder with combustion

Shooting LPG cylinders always prevented their rupture but the cloud of released gas when ignited created a fireball of the size comparable to the fireball resulting from the cylinder rupture (see Fig. 21). The only advantage of neutralization by shooting was much less danger created by debris as there were no shrapnel. In one case the cylinder flew 11 meters powered by recoil of escaping LPG and in other cases cylinders stayed without dislocation.

Fig. 21 Fireball developed after shooting through LPG cylinder

F. Mixed acetylene and oxygen cylinders

During real life fires it is very common to find acetylene cylinders accompanied by oxygen cylinders as both gases are used for gas welding and gas cutting operations. This implies that both of them may be affected by high temperature, and what is more in certain low visibility condition. It may be difficult, if not impossible, to distinguish between cylinders with those gases. What follows, it was very important to check if it is practically possible and desired to neutralize a tandem of acetylene and oxygen cylinders that are close to each other. One such experiment was performed within BLOW project - see Fig. 22.

Fig. 22 Oxygen and acetylene cylinders before the experiment

As it was mentioned in chapter III B shooting oxygen cylinders results in lunching them to considerable heights and when in air the cylinders rotate quickly. This means that acetylene cylinder as more stable should be shot first as it will not destabilize the oxygen cylinder. In the worst case smoke and fire after hitting acetylene may shadow the oxygen cylinder making it difficult to see it from the firing position. To solve the problems with limited visibility it is recommended to get auxiliary bearings ("offset") to the target (in this case oxygen cylinder) based on the arbitrarily chosen secondary object close to the cylinder when it is still visible. If the cylinder gets undistinguishable the shooting may be performed by pointing the gun to this secondary object with previously established offset - see Fig 23.

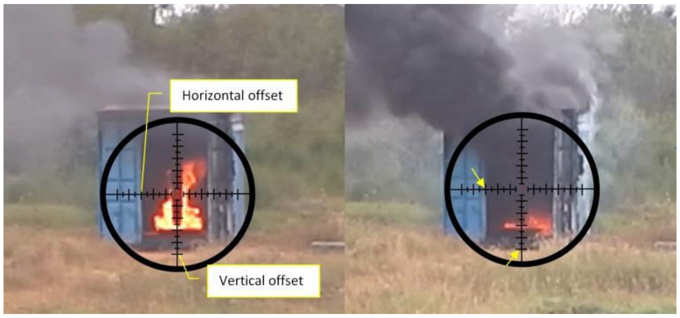

Fig. 23 Pointing the gun with auxiliary bearings (offsets)

During tests the acetylene cylinder was shot first with two shots and just a few seconds later the oxygen cylinder was shot with one AP bullet. Shooting acetylene cylinder didn't destabilized the cylinders while shooting oxygen cylinder started "the rocket engine" that moved it 92 meters away and overturned the acetylene cylinder as well. The experiment proved that it is possible to neutralize a tandem of acetylene and oxygen cylinders.

G. Carbon dioxide (CO_2) cylinders

Most of the CO_2 cylinders are equipped with overpressure safety valves that release pressure if it reaches a certain value (very often 190 bar). Unfortunately, not all cylinders are equipped with such a device and, what is more, during firefighting operations it is possible to shoot CO_2 cylinder by mistake, therefore the authors decided to investigate also this case.

Explosions of CO_2 cylinders that are not equipped with safety valves are very dangerous as the pressure may reach even 500 bar and the shrapnel fly up to 200 m. In Fig. 24 shrapnel that travelled 164 m and partly buried into the ground is presented. Such shrapnel constitutes serious risk, even to persons protected by heavy shields.

Fig. 24 Shrapnel created by blow of CO_2 cylinder

Experiments with neutralization of CO_2 cylinders confirmed that cylinders discharge in a safe way without rupture or dislocation.

IV. CONCLUSIONS AND RECOMMENDATIONS

Explosions of gas cylinders in fire constitute a great danger to people, animals and property. For most gases and cylinder sizes that are common in the industry, as well as, in households the shrapnel formed during cylinders blow-outs are dangerous at the distance up to 200 m. However, in some situations the debris may fly even a longer distance. What is more the explosions of bottles with flammable gases create fireballs (up to 20 m in diameter) or several meters long jet fires. While explosion risk of most gases is vastly reduced when low temperature of the cylinder is restored by cooling them, in the case of acetylene the decomposition processes that are initiated by temperature and high pressure may lead to cylinders rupture even several hours after cooling.

Direct cooling of cylinders by water spray constitutes a great danger to the firemen and rescue personnel as typically it must be performed from a relatively short distance (less than 30 m) that is from position very central in the danger zone. In the case of acetylene it is not enough to cool down the cylinder but it must be continuously cooled for one hour while the evacuation zone of 200 m must be maintained. After this process the cylinder must be monitored for its temperature for many hours.

In emergency cases the lengthy and dangerous procedures related to gas cylinder cooling by water endanger the rescue personnel that actually cools those cylinders. However, in many cases this dangerous action must be undertaken to make evacuation or rescue operations in the affected area possible. In opinion of this authors shooting dangerous cylinders with rifle bullets opens new possibilities for fast and relatively safe neutralization of the cylinders.

Properly conducted procedure of shooting cylinders does not endanger the rifleman in the case of premature explosion as he may be located quite far, even over 200 m away and at least partly shielded by objects that exist in the fire position area.

The authors never witnessed a situation when shooting cylinder of any gas would create **more dangerous** shrapnel or **bigger** fireball than spontaneous explosion of a similar cylinder, however, in many cases the danger zone was still considerable (for example in the case of oxygen cylinders that fly high after being hit by the bullet). However, one must observe that neutralization by shooting is very fast and may be done on demand so the rescue team may decide when to do it. This gives the team very good control over other activities that are related to firefighting or rescue operation. Instead of being endangered for a long time or being forced to postpone certain actions the team needs to take cover just for a few seconds when the neutralization action is performed.

Skillful riflemen are able to shoot cylinders reliably in most weather conditions from the distance of 200 m or less using appropriate ammunition (FMJ or Match bullets for less demanding shots and AP bullets for difficult shots for example through cylinders bottoms). During neutralization experiments reported in this article over 250 shots were executed and no single shot missed its target or ricocheted. Of course it is the responsibility of the rifleman to ascertain that in the unlike case of missing, or more likely, in the case of fully perforating the cylinder (both walls punctured) the bullet will not fly in dangerous direction.

In opinion of this authors the technical problems related to using riflemen to neutralize gas cylinders are less difficult than legal and organizational problems. To use a rifleman efficiently he should arrive at the incident location as soon as possible, best of all together with other rescue services. This may be achieved if the rifleman is a member of firefighters team and the rifle is carried as standard equipment in the firetruck. Swedish experience (2) shows that such a solution is possible, but it must be stressed that in Sweden generally only acetylene cylinders are neutralized by shooting. Also in Hungary neutralization of acetylene cylinders by snipers from TEK (Terrorelhárítási Központ) is frequently performed with very positive results. The aim of this article was to investigate the behavior of cylinders with other gases if they are shot on purpose or due to misrecognition. In opinion of this authors the method is efficient and safe also in the case of other (but non-toxic) gases and should be promoted.

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