Tactical depressurization of hydrogen containers with civilian rifle and ammunition

Gehandler J.[1,*], Lönnermark A.[1,*], Runefors M.[2] , Madsen D.[2], Egardt E.[3]

[1] *RISE Research Institutes of Sweden, Safety Research, Borås, Sweden.*
[2] *Lund University, Division of Fire Safety Engineering, Lund, Sweden.*
[3] *Swedish Civil Contingencies Agency (MSB), Karlstad, Sweden.*
**Corresponding author's email: jonatan.gehandler@ri.se*

ABSTRACT

There can be situations, for example if gas containers have been damaged in a vehicle crash, when the fire and rescue service would like to depressurize the gas containers through shooting with a civilian rifle. Modern high-pressure hydrogen containers are designed for a working pressure of 700 bars. This means that they have a very thick and strong shell made of composite material. At the same time the fire and rescue service only have access to civilian rifles and ammunition that can be bought for hunting purposes. Thus, tactical and safe depressurization of hydrogen containers is a big challenge. RISE have, together with the Södra Älvsborgs Fire and Rescue Services (SÄRF), Swedish Civil Contingency Agency, and Lund University conducted shooting tests of gas tanks mounted on a hydrogen gas vehicle and three stand-alone hydrogen gas tanks. The shooting tests were conducted at Remmene shooting field in Sweden. Thirteen shooting tests with hydrogen tanks placed in favouarable positions were performed. Out of these, only four tests were succesful in puncturing the individual gas tank in a single shot. Furthermore, two unwanted events occurred; one rupture (after 7 shots) and two powerful jets (after 20 and one shot respectively). This shows that further development and research is required in order to develop a method to safely depressurize high pressure hydrogen tanks.

KEYWORDS: Depresurization, puncture, hydrogen, civilian rifle, shooting, winchester.

INTRODUCTION

With the projected increase in hydrogen vehicles in the coming years, more such vehicles can be expected to be involved in traffic accidents. In some accidents, there might be situations when the gas containers have been damaged, making it too dangerous to tow these vehicles from the scene without first depressurizing the containers. One technique, that has been successfully applied in Sweden over several decades to depressurize gas containers, is by using rifles. This technique has primarily been developed for use in industrial fires with gas containers filled with, for example, acetylene for welding. However, the technique has also been applied in a few recent accidents involving CNG-vehicles [1, Runefors].

When it comes to research on how this can be effectively and safely performed, a few tests on the penetration of CNG containers [1, Runefors] and industrial containers [2, Hora et al.] can be found in the literature, but the number of experiments is very low. Also, modern high-pressure hydrogen containers are designed for a working pressure of 700 bars. This means that they have a very thick and strong shell made of composite material making them difficult to penetrate.

Only one study on the penetration of such high yield containers has been found in the literature, and that is from a study by U.S. Army [3, Paczkowski et al.]. However, they primarily used military-grade ammunition with armour piercing capabilities. Such ammunition is not available on the civilian market and, therefore, not for the fire and rescue services. The only ammunition used in the study that is available on the civilian market was the 7.62 Ball, and this was found to not be able to penetrate the tanks. Therefore, no guidance on the selection of combination of rifles and ammunition for the fire and rescue service when depressuzing hig-pressure hydrogen containers can be found in the literature.

Therefore, to fill this gap, RISE Research Institutes of Sweden have, together with the Södra Älvsborg fire and rescue services (SÄRF), Swedish Civil Contingency Agency, and Lund University conducted shooting tests of gas tanks mounted on a hydrogen gas vehicle and three stand-alone hydrogen gas tanks. The first steps have been taken to develop a safe method to depressurize high-pressure hydrogen tanks using civilian rifles and ammunition.

METHOD

Test objects

Three different designs of compressed hydrogen gas containers for passenger car usage were used in the shooting tests. Two tanks (103 l and 50 l) mounted on a Hyundai ix35, and 3 stand-alone hydrogen tanks (52 l) from a Hyundai Nexo. The ix35 vehicle tanks were filled with a mixture of methane and hydrogen to a pressure of 700 bar. The reason was that the vehicle was accidently filled with methane at a refueling station which was the reason for decomissioning the vehicle and making it avaliable for testing. The vehicle was before the tests refuelled (to 700 bar) with hydrogen. The small ix35 tank had a material thickness of 30 mm. The big ix35 tank had a material thicknes of 50 mm. Of the stand-alone tanks, two were exposed to fire such that the TPRD released and they were thus empty and damaged by fire at the time of shooting. The third stand-alone tank was not exposed to any fire and was filled with hydrogen to a pressure of 410 bar at the time of shooting. The stand-alone tanks had a material thickness of 30 mm. All tanks were composite tanks with a plastic container that is wrapped in carbon fibre reinforced polymer composite material (Type 4). All tanks were fitted with valves and a TPRD at one end.

The fire and shooting tests were conducted at Remmene shooting field in Sweden, 30th of august and 1st of September 2021, see Fig. 1. The ix35 passenger car was tilted unto its side and fixed unto the ground with metal bars to keep it steady, see Fig. 2 (left) The stand-alone gas cylinders were fixed approximately 0.7 m above ground level on metal bars, see Fig. 2 (right).

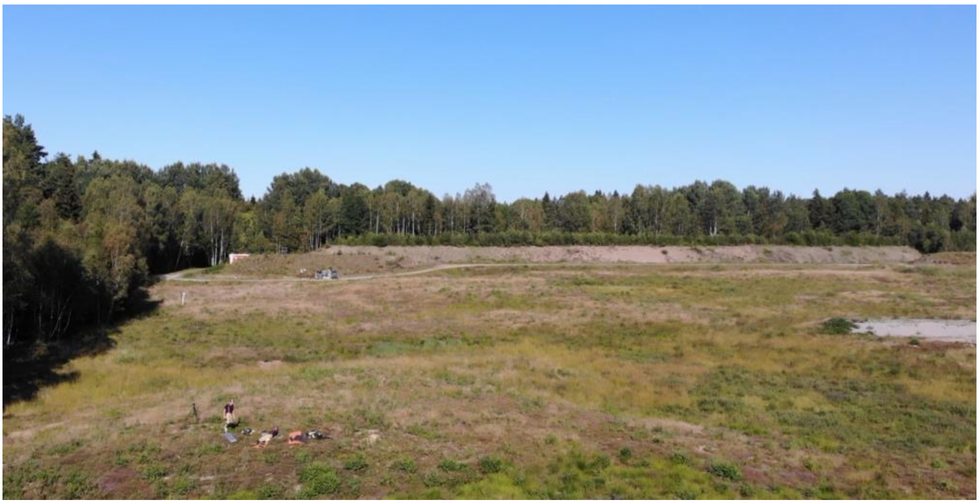

Fig. 1. Shooters (in the foreground) and the hydrogen vehicle (120 m away) at Remmene shooting field. (Photo: Marcus Aronsson, SÄRF)

Rifle, ammunition and balistic calculations

A pre-condition for the shooting tests was to use civilian weapons that can be bought for hunting purposes in class 1 according to the The Swedish Environmental Protection Agency (Swedish EPA) publication NFS 2002:18 [4]. This is the highest class where the pre-conditions of the derived rifle and ammunition allow for hunting of the largest species in Sweden, i.e. mooses, bears etc. Different rifles and ammunition were tested. Balistic calculations of bullet speed were based on the Pejsa model[1] using the software tool JBM ballistics.

Fig. 2. The target: rear of the tilted hyrogen vehicle with the small and large tank (left) and a stand-alone tank (right) (Photo: RISE)

Test set-up

The shooters were placed on a small elevation at around 120 m distance from the target in north-east. The tank was placed with the aim that the shooter should be positioned perpendicular to the tank mantle surface. In reality this was not always achieved and deviations with up to 14° angle between a perpendicular axis from the cylinder mantle surface and shooter were estimated, see Fig. 3 and Table 1.

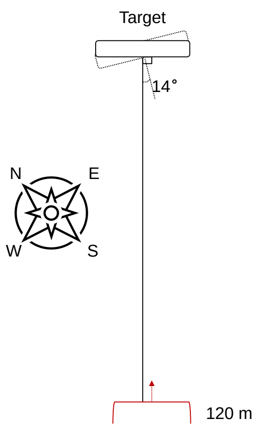

Fig. 3. The shooter was placed about 120 m from the target. The target, i.e. the gas tank, was up to 14° from its perpendicular position.

[1] https://en.wikipedia.org/wiki/External_ballistics

Table 1. Hydrogen tank shooting tests, overview

Test no.	Target	Date	Fire exposed	Distance [m]	H2 Pressure [bar]
1	50 l tank iX35	30th aug 2021	No	117	700
2	103 l tank iX35	30th aug 2021	No	117	700
3	Stand-alone 52 l tank	1st sep 2021	Yes, 22 min	127	0
4	Stand-alone 52 l tank	1st sep 2021	Yes, 5 min	127	0
5	Stand-alone 52 l tank	1st sep 2021	No	127	410
6	50 l tank iX35[a]	1st sep 2021	No	124	0
7	103 l tank iX35[a]	1st sep 2021	No	124	0

[a]Tanks were disabled and placed on the ground.

Measurements and documentation

The tests were recorded with video cameras. Bullet speed of each rifle and ammunition combination was measured with a balistic chronograph, e.g. Chrony M1, before or after the shooting. Weather data was measured or retrieved from weather stations nearby.

The pressure inside the stand-alone gas containers was measured. The free field blast pressure were measured with two pressure probes (from PCB/ICP) positioned at 5 m and 10 m distance from the tank centre, see Fig. 4. At 5 m the 137B24B probe was equiped with one piezoelectric element and at 10 m, the 137B25 probe was equipped with two piezoelectric elements, Front and Rear respectively.

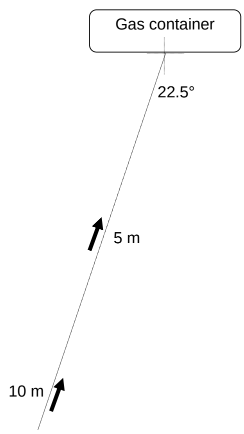

Fig. 4. Placement of free field blast pressure probes relative to the stand-alone gas tank.

RESULTS

In Table 2, the weather data are presented. In Table 3, balistic data for calculation of bullet speed are presented, and in Table 4 the results from the shooting tests can be seen. The ballistic coefficient in Table 3 of a bullet is a measure of its ability to overcome air resistance in flight. The kinetic energy of the bullet when it hits the tank surface is in the order of 250 J for all combinations in table 4.

Table 2. Hydrogen tank shooting tests, weather data

Test #	Temperature [°C]	Wind speed [m/s]	Wind direction[a]	Relative humidity [%]	Air-pressure [kPa]
1 & 2	21	1,5	NE	47	100.9
3	18	1	N	50	102.4
4	19	1	NW	45	102.4
5	20	1	NW	47	102.3
6 & 7	20	1	NW	47	102.3

[a]N=North, NW= North West, NE=North East.

Table 3. Inner and outer ballistic data.

Rifle, bullet	Projectile weight [g]	Balistic coefficient
Remington 700 .308W 580 mm barrel 1:12 twist, Sako Powerhead Blade	10.5	0.39[a]
Remington 700 .308W 580 mm barrel 1:12 twist, Barnes Vor-Tx	10.9	0.47[b]
Antonio Zoli .300 WM, 510 mm barrel twist unknown, Winchester Supreme Elite	11.7	0.527[c]
Sauer 202 .300 WM, 600 mm barrel 1:11 twist, Barnes Vor-Tx	10.7	0.442[d]

[a]www.sakosverige.se/ammunition/solida-kulor/powerhead-blade
[b]www.raytrade.com.au/products/category/EYMMVAGC-centrefire-rifle-ammunition/BB308W2--barnes-vor-tx-308-win-168gr-ttsx-bt-cartridges
[c]www.ableammo.com/catalog/ammo_charts/Winchester_Ammunition_Ballistic.pdf
[d]www.raytrade.com.au/products/category/EYMMVAGC-centrefire-rifle-ammunition/BB300WM2--barnes-vor-tx-300-win-mag-165gr-ttsx-bt-carts

Table 4. Hydrogen tank shooting tests, results

Test #	Target	Rifle, bullet	Measured speed at 1.8 m [m/s]	Calculated speed at target [m/s]	Impact
1	50 l tank iX35	Remington 700 .308W, Powerhead Sako	888	800	Started to leak after 3 shots. Rupture after 7 shots
2a	103 l tank iX35	Remington 700 .308W, Powerhead Sako	888	800	No leaking after 8 shots
2b	103 l tank iX35	Antonio Zoli .300WM, Winchester Supreme Elite	953	884	No leaking after 6 shots (of which 4 where clustered)
2c	103 l tank iX35	Remington 700 .308W, Powerhead Sako	888	800	Gas jet after 7 shots
3a	52 l tank (fire exposed)	Remington 700 .308W, Barnes Vor-Tx	833	756	2 shots, one penetration
3b	52 l tank (fire exposed)	Sauer 202 .300WM, Barnes Vor-Tx	893	808	2 shots, one penetration
4a	52 l tank (fire exposed)	Remington 700 .308W, Barnes Vor-Tx	833	756	Penetration at first shot
4b	52 l tank (fire exposed)	Sauer 202 .300WM, Barnes Vor-Tx	893	808	Penetration at first shot
5a	52 l tank	Remington 700 .308W, Barnes Vor-Tx	833	756	Penetration at first shot. Minor leakage.
5b	52 l tank	Sauer 202 .300WM, Barnes Vor-Tx	893	821	Penetration at first shot. Major jet flame with blast wave.
6a	50 l tank	Remington 700 .308W, Barnes Vor-Tx	833	758	No penetration. Bullet entered 9 mm into the tank.
6b	50 l tank	Sauer 202 .300WM, Barnes Vor-Tx	893	810	No penetration. Bullet entered 29 mm into the tank.
7a	103 l tank	Remington 700 .308W, Barnes Vor-Tx	833	758	No penetration. Bullet entered 13 mm into the tank.
7b	103 l tank	Sauer 202 .300WM, Barnes Vor-Tx	893	810	No penetration. Bullet entered 15 mm into the tank.

Test #1 and #2 on the hydrogen vehicle with pressurized tanks

The combination of rifle and ammunition was not very succesfull in these first two shootings on the big and small iX35 tanks. At the same time, these tanks were very challenging to penetrate, see Fig. 5 & Fig. 6. All the hits from the Remington 700 rifle was contained in a surface with a diameter of 33 mm, indicating that a high level of accuracy can be achieved at the used distance. For the Antonio Zoli rifle (Test #2b) the accuracy was worse, only the first 4 shots were clustered. Most likely the barrel was heated from the 4 first shots resulting in a worse shooting. Therefore the shooters switched back to the Remington 700 rifle (Test #2c). From the sound recording of a video camera placed nearby the vehicle, a squezing sound is clearly heard indicating leaking gas after three shoots in test #1. Unfortunatley the only camera that was available for test #2 was the drone which did not record any sound. However, according to the shooters (who also heard the leaking gas in test #1, it was not leaking until the gas jet (see Fig. 5 right hand side) apeared after 19 clustered shots.

Fig. 5. The rupture of the small tank (left, test #1), and the puncture of the big tank (right, test #2). (Photo: Marcus Aronsson, SÄRF)

Fig. 6. Punctured big tank (left, test #2) and ruptured small tank (right, test #1). (Photo: RISE)

Test #3 and #4 on fire exposed tanks at low pressure

In these tests, the fire had caused the TPRD to release. In test 3a and 3b, two shots were required for penetration. In test 4a and 4b, one shot was enough for penetration, which was captured on video as there still was some gas left in the container, see Fig. 7.

Fig. 7. A small jetflame following the penetration on the first shot in 4a (left) and 4b (right). (Photo: RISE)

Test #5 shooting on pressurized unexposed stand alone tank

The impact from shooting #5a on the pressurized stand-alone tank resulted in a small leakage. The pressure dropped from 408 bar to 407 bar in 5 s. Shoting #5b resulted in a violent release, see Fig. 8. The hole from shooting #5a measured 6 mm and from shooting #5b it was 13 mm, see Fig. 9. The fast release resulted in a blast wave that is seen in Fig. 10 - 12 below.

Fig. 8. A sequence of pictures showing the penetration on the first shot in #5b, from left to right.

Fig. 9. Two successful penetrations at first shot; one big hole to the left (#5b that resulted in a large jet flame) and a small to the right (#5a that resulted in minor leakage). (Photo: RISE)

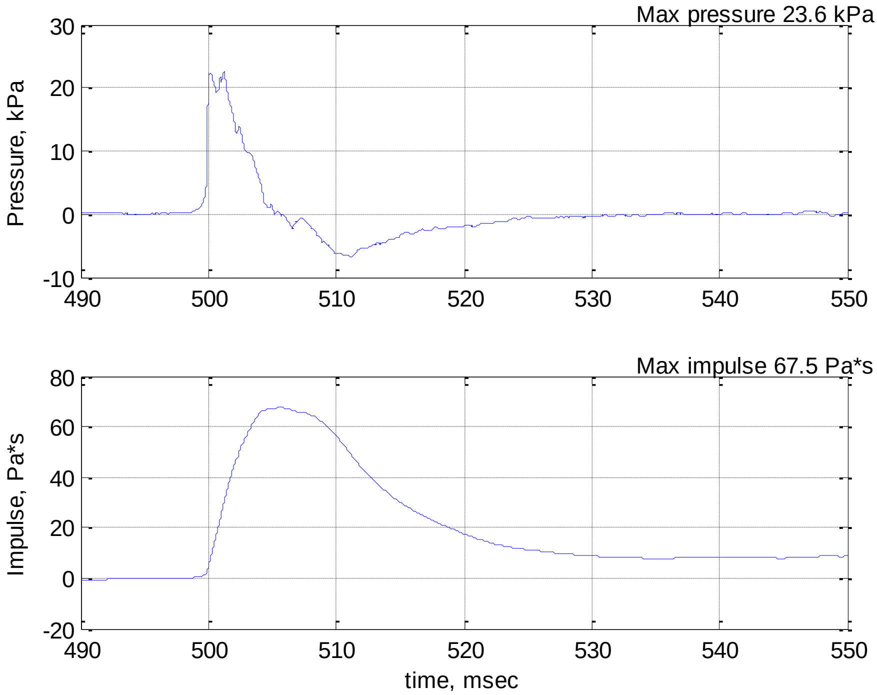

Fig. 10. Blast wave at 5 m distance, 137B24B sensor.

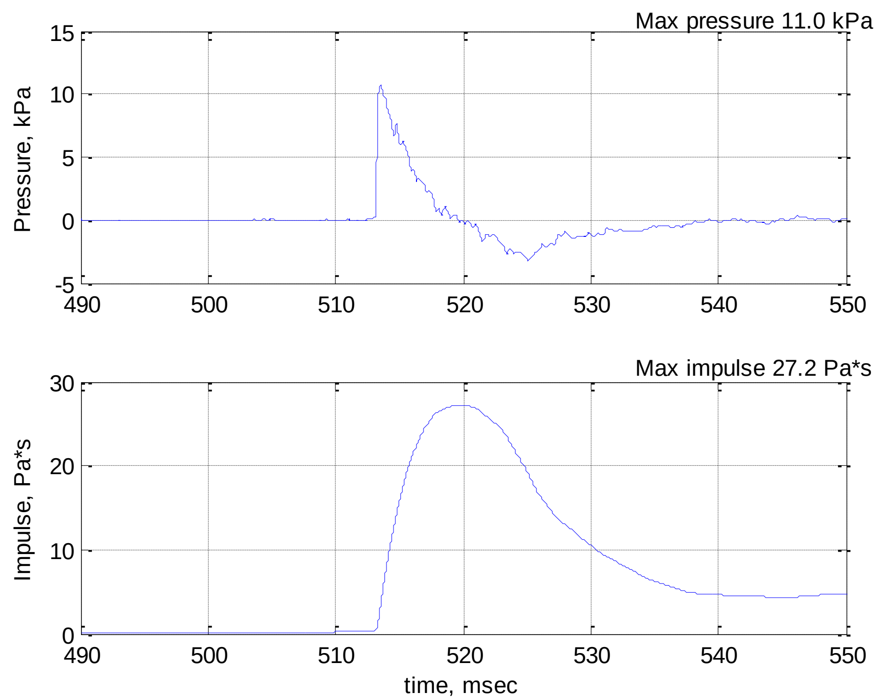

Fig. 11. Blast wave at 10 m distance, 137B25 Front sensor.

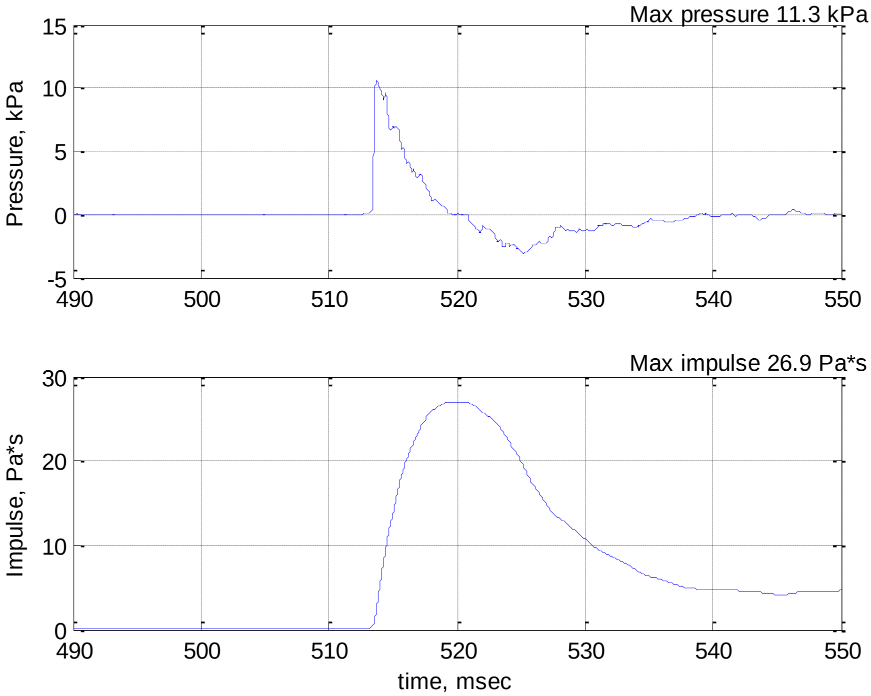

Fig. 12. Blast wave at 10.1 m distance, 137B25 Rear sensor.

Test #6 and #7 shooting on empty iX35 tanks

As the iX35 tanks apeared to be stronger, the rifle and ammunition used in test #5 was tested on the empty small and large iX35 tanks from test #1 and #2. No penetration at first shoot was achieved which confirm that the iX35 tanks were stronger and more difficult to penetrate. The same rifle and ammunition (Sauer 202 .300 WM, Barnes Vor-Tx) that caused a sudden release in test #5 penetrated deepest into the iX35 tanks.

DISCUSSION

Method

Depressurization of gas storage tanks in a safe and verified way is hard to achieve for vehicles with hidden fuel tanks. Nevertheless, it is the most suitable method we have to secure the working environment for staff working at accidents where potentially weakened gas tanks might occur. The available literature on this topic is scarse. This paper handles a series of tests of different combinations of rifles and ammunition to puncture exposed hydrogen fuel tanks of different types in a favorable orientation. The storage tanks have in all tests been placed to optimize the shooting conditions. In test #1-#2, the vehicle had been tilted and the protective plastic plate beneath the storage tank had been removed to expose the tanks. In test #3-#5, the storage tanks were placed as standalone objects in a favourable shooting orientation. This was also the case in Test #6-#7, where the tanks in Test #1-#2 were removed from the vehicle and placed on the ground. Standing at an accident scene, where the deformed vehicle is still standing on four wheels, makes the depressurization more difficult and also more difficult to verify if the shot punctured the tank or not. Nevertheless, as the experience in this matter is scarse, the performed tests in this study give valuable information of appropiate measures to the ongoing work to secure the working environment for staff working at accident sites.

The shooting distance in the order of 100 m is a trade off between safety, weather conditions, effects of the ammunition and accuracy in shooting (Runefors et al., 2021). In fact, the actual distance of these tests is within what eventually could be the distance of flying debris. Stronger means, as more powerful rifle/ammunition, would make it possible to increase the distance between the shooter and the gas tank, and thereby increase the safety.

The tanks were hit by three different bullets from two different types of rifles, The two rifle types, 0.308 Winchester and 0.300 Winchester Magnum are commonly used for hunting of the largest species and therefore the most appropiate arms for puncture of high pressure containers with a thick and strong shell. This rifle and ammunition combination has shown until now to be suitable means for puncturing gas tanks at scenes of accidents.

Ammunition for hunting purposes are designed to penetrate and expand as it enters the flesh of the animal. The expansion leads to a larger wound canal that shortens the suffering of the animal. This expanding design for hunting purposes is desribed as mandatory in The Swedish Environmental Protection Agency (Swedish EPA) publication NFS 2002:18. Unfortunately, the expanding property takes the power of the penetrating ability that is desired in the performed tests of this study. The chosen ammunition, 0.308 Powerhead, 0.308 Barnes Vor-Tx, 0.300 Barnes Vor-Tx and 0.300 Winchester Supreme Elite, have all bullets made to expand to fulfill its purpose in a hunting situation.

When the results were analysed, it was realized that hearing was the best indicator of minor leakages. From the visual video camera or IR-camera it was not possible to detect minor leakages. However, on video recordings with sound in the vicinity of the tank (within 10-15 m), a squezing sound is clearly heard after some of the hits. The shooters at a distance of 120 m could sometimes also hear the squezing sound, but at more safe positions, e.g., at 600 m or behind proteciton, no sound from leakages could be heard. In real shooting situations, the rescue service should be equipped with a live or similar so that they can know when the tank begins to leak so that further shooting can be avoided.

Results

The gained experience from this study clarifies that the used rifles/ammunition for hunting purposes, the 308W/0.300 WM, is not in general able to penetrate the hydrogen storage tanks in one shot. Out of 13 tests, only 4 tests were succesful in puncturing the individual gas tank in a single shot. It should also be noted here that the tanks were placed in a favorable exposed position.That leaves the remaining opportunity to shoot hole-in-hole at the tanks that withstand the single shot. Shooting repeatably at the same spot gives a larger hole, that in the case of test #1 eventually led to an undesired rupture of the tank. So instead of a more controlled leakage, the tank opened in a instant explosion. It should be noted though that after analysing the videomaterial from test #1, a squezing sound was heard after three shots, indicating a leakage before the following four shots caused the rupture. The larger tank in test #2 had to be shot with even more bullets before puncture, releasing a massive outflow of gas that led to strong reaction forces on the vehicle. These reaction forces rotated the vehicle despite that it was stabilised with steel bars. Minimizing reaction forces through minor holes as the gas leaves the tank is of course of interest. There is also a need to get more knowledge of this effect on the vehicle during the discharge to avoid further implications.

It would be expected some difference between the fire arms of 0.308W and 0.300WM as the 0.300 WM has substantially higher velocity than the 0.308W together with a more favourable balistic coefficient. This was shown in test #6-#7 where the depth of single holes were measured and the 0.300WM had deeper penetration ability although it did not succed in penetrating the gas tank.

The used rifles and ammunition are, as earlier described, normally used for hunting purposes as this is the usual available means for the fire and resue service. Military ammunition with higher penetration ability (which has previously shown to be able to penetrate hydrogen tanks [3]) are normally not allowed to be handled by the municipial fire and rescue service as the ammunition for hunting purposes have shown enough penetrating properties to punture normal gas tanks as for CNG, LPG and acetylene. However, the introduction of high pressure hydrogen tanks seem to require stronger means.

The EU project HYPACTOR [6] finds that the energy of the impactor was an important factor for the reuslting damage to hydrogen composite tanks. The study used energies between 1 kJ and 10 kJ, where 1 kJ seldom damaged the tank, while higher energies, above 3 kJ often did. The energies used in these tests were in the order of 0.25 kJ, and should therefore not damage the tank. The larger mass impactor that was used in [6] does not seem to be comparable with bullets. Likely, bullets have a smaller impact area and therefore creates a greater damage at lower kinetic enrgies.

Apparently the choice of rifles and ammunition that is suitable for pressure relief of gas bottles containing CNG, acetylene and LPG can not be validated for puncturing 700 bars hydrogen gas tanks. For this, a higher penetrating effect is needed from the combination of rifle and ammunition. The Swedish Police states in their regulation RPSFS 2009:13FAP 551-3 Chapter 2 [5] that weapon license is admitted for “Udda ändamål” (Odd purposes in English), e.g., for puncturing of gas containers. In Chapter 10, it is stated that you do not need any more permit or license to buy ammunition as long as the ammunition has the same purpose as the weapon license admits. So in fact, this can be interpreted as that any ammunition might be available as long as it is needed to fulfill the purpose given in the license conditions. With this knowledge, it is important that in future applications for weapon licenses for shooting at hydrogen containers, well-founded reasons for ammunition that offers higher penetration are given.

Future project should clarify the shooting positions and complexity in puncturing hydrogen gas storage tanks as they are mounted on the vehicle. Drawings of tank installations are needed and references to what ammunition is required to penetrate tires, protection plates, fenders or what else is in the way of shooting at the tank. A large reference bank is needed as well with recommendations of ammunition required for the specific case.

CONCLUSIONS

Thirteen shooting tests with the ambition to safely depressurize high pressure hydrogen containers with civilian rifles and ammunition were performed. In these tests the tanks were placed in favourable shooting positions. Out of these 13 tests, only 4 tests were succesful in puncturing the individual gas tank in a single shot. Furthermore, two unwanted events occurred; one rupture (after 7 shots) and two powerful jets (after 20 and one shot respectively). This shows that further development and research is required in order to develop a method suitable for the municipal fire and rescue service to safely depressurize these tanks.

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