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TACTICAL DEPRESSURIZATION OF HYDROGEN AND CNG TANKS USING RIFLES AND OTHER PROJECTILES

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ABSTRACT

After a tank has been exposed to crash violence, or an external fire, it might, in some situations, be judged dangerous to move the vessel due to the risk of a sudden tank rupture. Therefore, Swedish rescue services have a long history of using rifles to penetrate and therefore depressurize the vessels. In this paper, some first steps on providing guidance on the selection of ammunition and required stand back distance are presented. The results indicate that a stand back distance on the order of 100 m is required and that the standard 7.62 Ball should only be used for composite CNG-tanks, while stronger ammunitions are needed for steel and composite hydrogen tanks. However, more research is required to provide a more solid scientific underpinning of the tactic guidance.

1.0 INTRODUCTION

With the introduction of more and more vehicles with gaseous fuels, the risk of those vehicle being involved in traffic accidents is steadily increasing. In some situations, the pressure vessel might be affected by the crash forces or an external fire so that the structural integrity of the vessel is cast into doubt in the case the vehicle is towed from the scene. This will result in a situation known to the fire service as a “static unstable” situation where the consequences will not increase over time by itself, but small perturbations on the system might lead to rapid escalation. These situations are characterized by that the commander has time to assess different options and dispatch new resources to the scene but at the same time put high demands on that the measures taken are appropriate and will not escalate the situation.

Static unstable situations involving pressure vessels have a long history in Sweden to be dealt with by depressurization using rifles to penetrate the vessel and release the pressure. This technique was developed in the 1970s and 1980s and has since regularly been used where a pressure vessel, or its valve, has been damaged. Depressurization can also be needed for vessels that have been overfilled with condensed gas or containing a gas prone to decomposition and self-heating (primary acetylene).

The technique has primarily been used in industrial complexes, but after an incident in 2016 in Gothenburg [1] where two firefighters were injured after a vessel rupture at a CNG-bus fire, work to transfer the technique to road traffic was initiated at the Swedish Civil Contingencies Agency (MSB). Experiments were planned to take place later in 2016, but before these were executed, another CNG-vehicle accident occurred in Katrineholm [2], in this case, a garbage truck.

The accident in Katrineholm was not fire-related, but instead, a spontaneous tank rupture occurred soon after refilling. The accident investigation concluded that the most probable cause was mechanical degradation of the tank due to repeated minor collisions [2]. When the fire service arrived, they concluded that the primary vessel rupture could have damaged the remaining three vessels in the rack and, therefore, they should be depressurized at the scene before towing. A rescue shooter was recruited to the scene and used a rifle to penetrate the tanks. Two of the tanks slowly released their contents with an unignited jet, while the third tank ruptured, throwing both primary and secondary fragments over the shooter located 100 m from the truck.

The latter is of specific interest since the CNG-tanks are required, under ECE R110 rule A.15, to withstand a 7.62 mm projectile (which was the same used in this case) without rupture. The reason could be that the vessel was damaged from the rupture of the neighbouring vessel.

Figure 1. (*Left*) Picture from the bus fire where two firefighters were injured after vessel rupture in Gothenburg in 2016. (*Right*) Picture from the garbage truck accident where a rifle was used for depressurization, at the moment of tank rupture.

These events, together with other similar events, illustrated the need for systematic research to evaluate different techniques and provide guidance for this type of depressurization. A review of the literature has resulted in two publications on the subject, one report from U.S. Army [3] and one scientific paper from three Czech researchers [4].

In the Czech paper, the type of vessels tested was unclear, and the number of trials was very small. The U.S. Army report aimed to investigate the potential consequences of an attack on a gas vehicle rather than being a method for planned depressurization. However, the results were still relevant and are included in section 3.1.

This paper aims to expand the experimental data on tactical depressurization and present a discussion on the selection of ammunition and adequate standoff distance for the shooter. Also, a brief discussion on other alternative techniques for tactical depressurization is presented, and one potential technique (shaped charge) is also tested.

The paper should be seen as a first step since there is a need for a larger number of experiments and also experiments that account for additional parameters such as internal pressure. Therefore, more research is needed to provide detailed tactical guidance for the rescue services.

2.0 METHODS

2.1 Experiments

Experiments with rifles were performed using three different kinds of ammunition and two different rifles, which are presented in the Table below. Bullet velocity was measured using a chronometer from LABRADAR.

Table 1. Used ammunition, rifles and the measured bullet velocity.

Ammunition/Calibre	Rifle	Measured bullet velocity
7.62 Ball	Haenel RS8	821 m/s
.308 Winchester	Haenel RS8	768 to 769 m/s
300 WINMAG	Remington 700P	920 to 1029 m/s

Pictures of the two rifles used and the position of the shooter can be found in Figure 2.

Figure 2. Shooter position (left) and rifles (right)

The 308W is the commercial implementation of 7.62 Ball, and they are therefore essentially identical except when it comes to chamber pressure, where the 308W accepts higher chamber pressure which is associated with a higher bullet velocity. The reason for including both versions is to investigate the influence of bullet velocity on the outcome. The 300 WINMAG also has the same projectile diameter but significant higher velocity, which is an advantage for deeper penetration in hard targets.

The reason behind the chosen calibres is that CNG-tanks, according to A.16 in UN ECE R110, should be tested for penetration with a 7.62 mm calibre bullet at 20 MPA ± 1 MPA shot in with an impact angle of 45°. During the test, there should be no sign of fragmentation. This indicates that this bullet should not cause tank rupture to use in most situations. It should, however, be noted that tank rupture still has occurred in practice on several occasions, but this might be due to that the tank was damaged in the crash. In the parallel legislation for hydrogen, UN ECE R134, the authors have been unable to locate the same requirement, but it is assumed that keeping small calibres will minimize the risk of tank rupture.

In total, 13 different vessels were tested, and 39 shots were attempted. Among the vessels, 8 were type 1 (steel), 2 were type III (carbon-fibre composite with steel or aluminium inside), and 3 were type IV (carbon-fibre composite with plastic liner). The vessels were exposed to 24, 7 and 8 shots, respectively. The results are also complemented with results adopted from the US Army report [3].

As an alternative to depressurization using rifles, shaped charges (SC) were used. These are normally used for the disposal of visible mines and unexploded ordnance by the military. The principle behind a shaped charge is that, after ignition, a detonation wave deforms a cone-shaped metal liner in the front of the device, producing a metal ray travelling in the order of 5,000-10,000 m/s [5]. A schematic and a picture of a shaped charge is presented in Figure 3. The charge used was manufactured by SAAB under the model name SM-EOD 33 with a standoff distance of 125 mm.

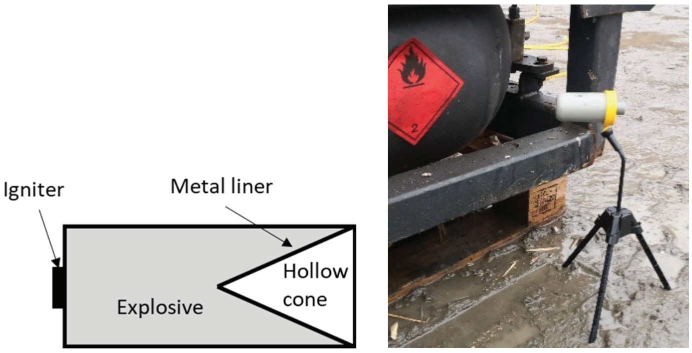

Figure 3. Schematic and picture of a Shaped Charge (SC)

The shooting tests were performed at Bofors Test Center (BTC) in Karlskoga from a distance of 107 m ± 2 m. The shooter was placed behind a ballistic shield and under a steel roof for extra protection. The weather was rainy and 3-5°C with a relative humidity of 91-95%.

2.4 Calculation of hazard distance

As described in section 1, the depressurization has occasionally resulted in tank rupture despite that vessel should be tested to withstand penetration with a 7.62 mm projectile. Therefore, the shooter needs a significant hazard distance not to be injured by a potential rupture. To evaluate the need for standoff distance, calculation of pressure effects from vessel rupture was performed using the model developed by Molkov and Kashkarov [6].

The model includes two parameters, where α is related to the mechanical energy stored in the vessel and β is related to feedback from the energy released by combustion (if the release is ignited). If the vessel is located in the open air, α is 1, while it is 1.8 if located close to the ground. In theory, α should be 2 if the ground is treated as a smooth rigid plane, but the reduction is due to energy lost due to deformation of the ground. The second parameter, β, which is related to chemical energy released, is experimentally determined to be approximately 0.052 since only a limited part of the chemical energy contributes to the pressure wave. There is also a version for under-vehicle rupture where more mechanical energy is lost (α=0.12), but a larger portion of the chemical energy released contributes to the blast wave (β=0.09). In this paper, overpressures and impulses for all three situations (open-air, ground and under-vehicle) were calculated. For hydrogen, ignition is assumed to occur since the high ignitability of hydrogen results in that most releases are ignited [7], and this is also suggested in the paper where the model was introduced [6]. For the vessels containing CNG, ignition is assumed not to occur, or, if ignited, the combustion is assumed not to influence the blast pressures. This is due to that the model, to the authors' knowledge, has not been calibrated and validated for CNG and the significantly lower flame speeds of CNG compared to hydrogen indicate that a lower proportion of the chemical energy is released in the same time scale as the blast wave propagates. Also, the practical experience from CNG-tank ruptures is that they often do not ignite. In the Gothenburg accident described in section 1, the rupture even extinguished the fire that caused the rupture [1].

Table 2. Summary of parameters used in the calculations of the pressure wave from tank rupture.

	Rupture in the open	**Rupture close to the ground**	**Rupture under vehicle**
Mechanical energy coefficient (α)	1	1.8	0.12
Chemical energy coefficient (β)	0.052 (hydrogen) 0 (CNG)	0.052 (hydrogen) 0 (CNG)	0.09 (hydrogen) 0 (CNG)

Since the depressurization of the vessel is a planned work for the rescue shooter, in contrast to accident scenarios with a given probability, no negative impact on the firefighter can be accepted. Therefore, the safety criteria employed in the current study needs to be more stringent compared to a typical risk analysis. This results in that information on tolerable pressure and impulse are scarce in the literature.

One of the most sensitive organs for overpressures are the eardrums, known to rupture at pressures around 16.5 kPa [8]. Loss of hearing can, however, occur at lower pressures, and the Swedish armed forces state that the maximum tolerable peak overpressures acceptable for their soldiers are only 200 Pa [9]. There are sophisticated methods for the impact of blast overpressures on the ear, for example, the AHAAH [10], but, after discussions with a researcher in acoustics [11], a sound pressure analogue could be employed, albeit conservative.

A 200 Pa overpressure can be translated into a sound pressure of approximately 140 dB(A) and, given that a good earplug can reduce the sound pressure with 30 dB(A) and good earmuffs with 34.9 dB(A), the maximum tolerable peak overpressure with earplugs is 6.3 kPa and with earmuffs 11.2 kPa. The two types of protection can also be used in combination even if the exact level of sound pressure reduction is difficult to assess [12], but since other, non-ear related, types of problems typically arise in the range of 30-50 kPa, only a reduction of 8-13 dB(A) is needed to reach this level. For a shooter, it can be expected that the individual uses earmuffs and dual protection can be prescribed if needed.

Regarding non-ear related blast wave injuries, a recent PhD-thesis [13] have reviewed a range of different potential impacts of blast pressures on humans and concluded that injuries to the CNS (Central Nervous System) were the one that occurred at the lowest pressures and impulses. The thesis combined a large number of experiments, and those are presented as dots in Figure 1 together with two other sources found in the literature, namely Courtney [14] and Bowen [15].

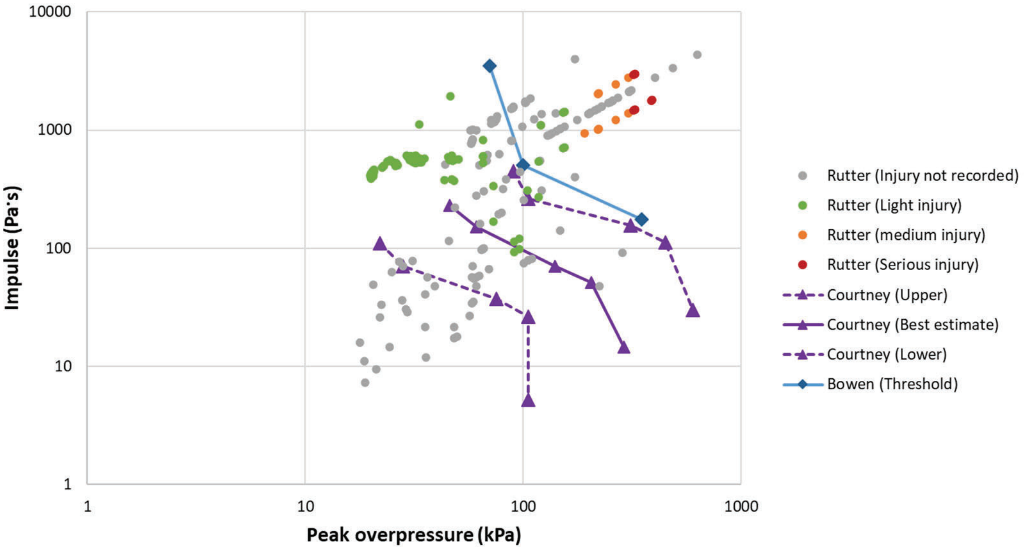

Figure 4. P-I plot of three different sources of limits for CNS-injuries

Rutter [13] suggests a criterion containing all grey dots (where the level of injury is not known), which results in a very low acceptable criteria of 17.7 kPa and 7.2 Pa·s, respectively. This appears not to be in agreement with previously published sources, and, therefore, the mean line by Courtney is used in this study. However, this is complemented by a point at low peak overpressures that contain all the green dots.

An additional hazard from tank rupture is fragment projectiles. There are several models available to predict throwing distance (see for example [16]), but many assumptions are needed, for example, regarding number, weight, shape of fragments, and still, the level of precision can be expected to be limited. Therefore, no calculations on throwing distance are performed within the scope of this paper, but the issue is assessed qualitatively and probability-based in section 4.3.

The vessel sizes and pressures for different vehicles used in the calculations are based on a market survey performed by the authors in 2020 [17]. The vehicles, of different types, with the largest single tank, is presented in Table 3.

Table 3. List of size and pressure of single largest tank for different vehicle types and fuels.

Case	Fuel	Vehicle type	Volume	Pressure	Vehicle model
A	Hydrogen	Car	104 litres	700 bar	Hyundai ix35 FCEV
B	Hydrogen	Bus	312 litres	350 bar	Solaris Urbino 12 Hydrogen
C	CNG	Car	89 litres	230 bar	Daimler B200 NGT
D	CNG	Truck	100 litres	230 bar	Volvo
E	CNG	Bus	375 litres	230 bar	MAN

3.0 RESULTS

3.1 Results for rifles

The results from the experiments within the scope of this paper is presented in Table 2. This is also complemented by data adopted from the experiments performed by U.S. army [3] in Table 3 to cover more types of tanks and ammunition.

Table 2. Penetration tests for CNG-tanks

			Vessel type (CNG)			
		Bullet Velocity	Type I	Type III	Type IV	Type IV
Impact angle			90°	90°	90°	45°
Ammunition	7.62 Ball	821 m/s	7 of 12	-	2 of 2	4 of 5
	308W	768 to 769 m/s	-	2 of 2	-	-
	300WM	920 to 1029 m/s	6 of 6	2 of 2	1 of 1	-

Table 3. Penetration test for hydrogen tanks (adopted from U.S. Army [3])[1]

		Vessel type (Hydrogen)		
		Bullet Velocity	Type III	Type IV
Ammunition	7.62 Ball	~850 m/s	-	0 of 2
	7.62 AP[a]	~850 m/s	-	2 of 2
	7.62 API[b]	~850 m/s	1 of 1	-

[a] “Armor Piercing” [b] “Armor Piercing Incendiary”

The results show that the weakest ammunition (7.62 Ball) give sufficient penetration for the composite CNG-tanks, but neither for composite hydrogen tanks nor CNG steel tanks. Increasing the velocity of the bullets (with the same type of projectile) increases the penetration rate for the steel tanks, but it has

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[1] The experimental setup was almost identical as the experiments described in section 2.1 except as slightly shorter stand-off distance (90-100 m) and a different (and unknown) rifle. The bullet velocity was not measured, and the noted velocities are according to standard specification for the ammunition. For more details, refer to the report.

not yet been assessed if this is enough to penetrate hydrogen tanks. Experiments regarding this will be performed in September 2021.

However, it seems that increasing the tensile strength of the ammunition with the application of armor-piercing (with or without incendiary) allows penetration even at lower bullet velocities, at least for the composite hydrogen tanks.

A non-orthogonal impact angle (in this case, 45°), which can be used to decrease the risk of flying debris from the tank (see section 4.3), still allow the penetration of composite CNG tanks with 7.62 Ball (and therefore likely by the other ammunitions). This has currently not been tested for hydrogen tanks or steel tanks.

From the experiments, it is also clear that the resulting holes are very different between steel and composite tanks (see Figure 5).

Figure 5. Typical holes from penetration with rifles in type I (left) and type III and IV (right) vessels

The hole sizes for type I vessels were in the order of 9 mm for 7.62 Ball and 10-12 mm for 300WM. For type III and IV, the hole sizes were difficult to measure due to the irregular pattern of the hole but were generally found to be in the order of 7-8 mm. However, it should be noted that this is the hole in the carbon fibre composite material, which might not be representative of the hole in the inner liner (see section 4.1).

3.2 Results for shaped charge (SC)

Three experiments were performed with shaped charges.

Experiment	Vessel type	Angle of impact	Result
A	Single, type III	90°	Entrance and exit
B	Single, type I	45°	Entrance and exit
C	Seven parallel, type III	90°	Hole through two vessels

As expected, the shaped charge had no problems penetrating a single vessel. In experiment C, however, which was intended to simulate a typical vessel rack at the roof of a bus, only two vessels were penetrated.

3.3 Results from the calculation of hazard distance

As described in section 2.4, peak pressure and impulse was calculated using three different analytical models. One model was developed for open-air ruptures, one was for ruptures close to the ground, and the last was specifically for vessels under cars. For hydrogen, ignition was assumed to occur and affect the pressure wave according to the model. For CNG, it was assumed that the released content did not ignite or that the influence on the pressure wave was negligible. Calculations were performed for several different types of vehicles, and representative results for cars is presented in Figure 6.

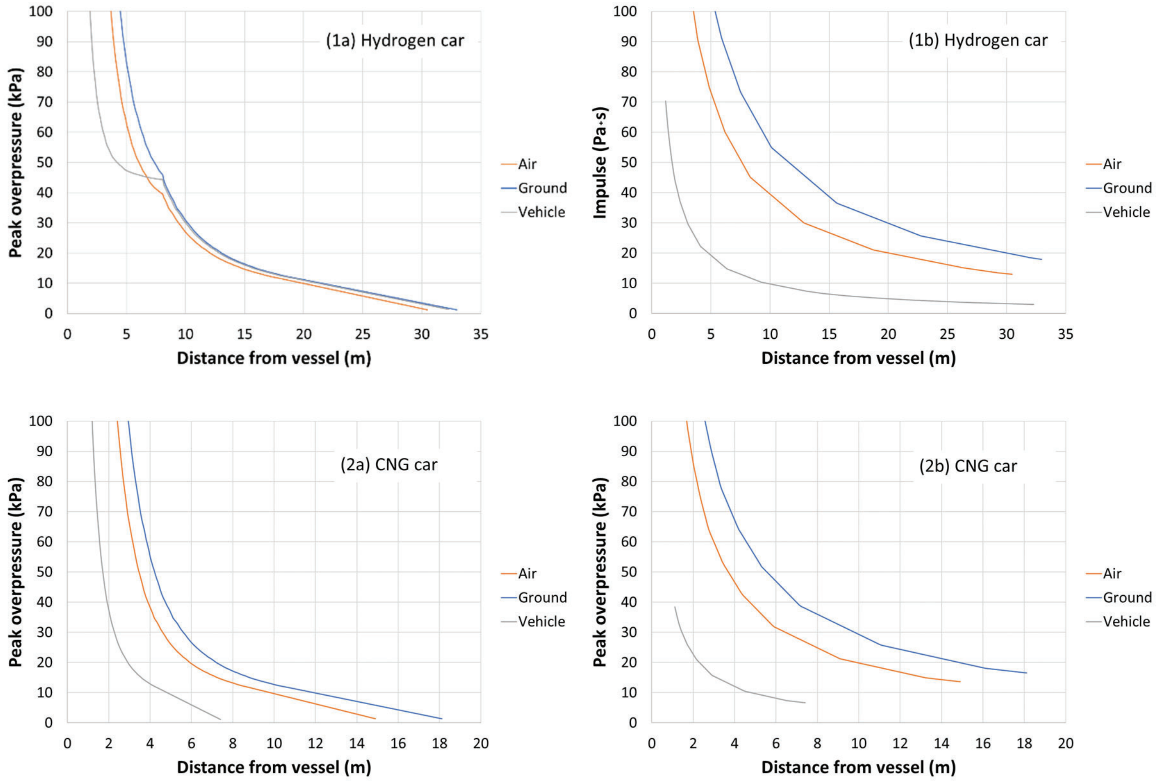

Figure 6. Peak overpressure and impulse from hydrogen and CNG car using three different models.

In Figure 6, it can be seen that the model for rupture close to the ground give the highest pressures, but generally, the difference is only a few meters. Therefore, the ground model is consistently used in the remainder of this paper, which is slightly conservative.

The results for all included vehicles (see Table 3) are presented in the P-I diagram in Figure 7, together with the tenability criteria defined in section 2.4.

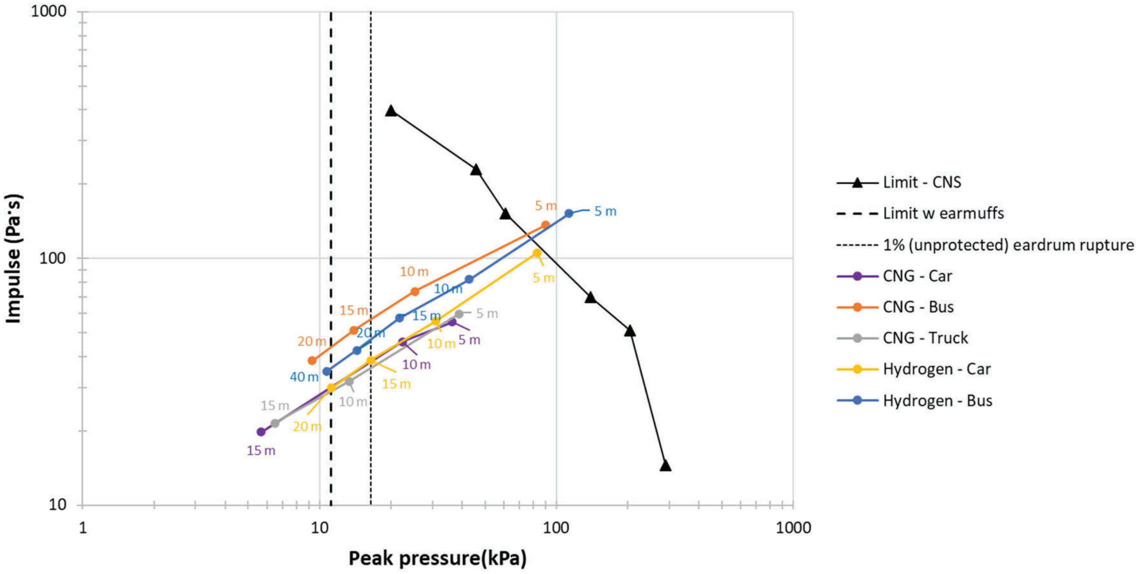

Figure 7. P-I curve for blast wave from rupture of different tanks at different distances with tenability criteria.

In Figure 7, it can be seen that, given that the shooter has earmuffs (which they need for the sound from the shot), it is safe to be 15-40 m from the vehicle, depending on vehicle type.

4.0 DISCUSSION

4.1 Impact of vessel type and pressure

The experiments indicated that holes in type III and IV vessels would be in the order of 7-8 mm. This is slightly larger but the same order of magnitude as the dimensions reported by manufacturers based on their standard test, which was 6.3 mm and 5.5 mm for Hexagon type IV and ULLIT, respectively. This would indicate that the blowdown time to 1% of the original pressure would be in the order of 35-75 s for the largest tank (hydrogen bus) using the expanded and under-expanded jet models [7]. However, this is at odds with the result from both the actual accident in Katrineholm and the experiments by U.S.-army [3] where blowdown times in the order of 5-20 minutes were identified.

A possible explanation for the large deviation is that the hole in the inner liner is significantly smaller or that the high pressure in the vessel might deform the inner liner so that it partly blocks the hole. This needs to be further investigated in the future, but it stresses the importance that it is verified that the vessel is depressurized before attempting to remove the vehicle or vessel. This could be either performed by measurement or additional punctations.

Type I vessels gave repeatable results in the order of 10-12 mm. However, given the large dimension of the hole, the source strength will be substantial. If tank restraints are damaged, the tank might propel and damage nearby equipment. A more rigid projectile with the same energy of impact should result in a smaller diameter of the hole and thus smaller reaction forces.

4.2 Impact of projectiles

The results showed that the weakest ammunition (7.62 Ball) could only penetrate CNG-steel-tanks. For composite hydrogen tanks, 7.62 AP (and API) was found to be able to penetrate, while for CNG-composite-tanks, ammunition of type 300WM and 308W could penetrate. If 300WM and 308W could penetrate composite hydrogen tanks, and vice versa, has currently not been tested, but such tests is planned for September 2021.

However, in one case where three bullets were thought to have penetrated and depressurized a vessel, the bullets had actually got stuck in the vessel material and, when the vessel was disposed of, the personnel responsible for disposal ended up in a flammable cloud. This stress the importance of sufficiently strong ammunition to achieve a reliable penetration. Strong ammunition also leaves room for the shooter to not be perpendicular to the vessel but rather at a 45-degree angle which reduces the risk of the shooter being exposed to flying debris.

Strong ammunition refers both to the velocity of the bullet but also to the tensile strength and weight of the projectile. In the experiments performed in the current study, the focus was on velocity while the US Army study [3] instead varied the tensile strength of the bullet. The weight of the bullet is primarily of relevance for bullet velocities over 1000 m/s [5], which is approximately the upper bound of the ammunitions tested.

The intent of using a shaped charge was to be able to depressurize an entire rack of vessels often placed on the roof of busses, typically consisting of seven parallel vessels. However, the results indicated that only two of the seven vessels were penetrated, and, therefore, the (slight) increase in performance, generally, cannot compensate for the need to place the charge next to the vessel. It can, however, be useful in some situations when it is not possible to achieve a visual on the vessels at the recommended 100 m or when stray bullets might induce unacceptable risk.

4.3 Hazard distances

Since tactical depressurization is planned work, the requirements for safe execution are extensive. The optimal result of the depressurization is a hole in the same scale as the ammunition, and if this happens, the vessel content will be orderly released into a flammable cloud or possibly a jet flame (if ignited). Generally, the risk of harm will be within the order of 10th of meters. A more hazardous outcome is a tank rupture which, as described above, also occurred on several occasions.

The tank rupture will impose two different risks, where one is the pressure wave from the expanding gas, and the other is the vessel fragmentation which induces missile effects. For the gas expansion, hazard distances were calculated in section 3.3 and was found to be below 40 meters and often below 20 meters.

There are several models for missiles effects available (see [16]). However, the level of uncertainty is large and typically, many assumptions are needed, for example, on the number of fragments, fragment weights and shape and presence of tumbling. Therefore, the assessment in this paper is primarily based on experience from actual events. A limited review of 25 vehicle accidents published in [17] revealed 18 accidents with tank ruptures, and the throwing distance was reported in 7 cases. In all but one of those cases, the throwing distance was below 50 meters. In the remaining case (garbage truck in Indianapolis, USA in 2015), parts of the vessels were thrown 400 m.

It should, however, be noted that all accidents were for CNG-vehicles which typically have the maximum pressure in the order of 230 bar. Hydrogen vehicles can have pressures up to 700 bar, and experiments on an SUV have resulted in fragments being found 107 m from the vehicle [6].

A standoff distance of approximately 100 m has been found to be a purposeful distance to achieve a good hit by an experienced shooter with a large degree of certainty. At this distance, however, there is a slight risk of being hit by a fragment, but, assuming the laying shooter occupies 0.6x2 meters, the risk of a direct hit is only $3.82 \cdot 10^{-5}$ per fragment or only one hit in approximately 26’000 fragments. This is based on a uniform distribution of throwing distance from 0-100 meters.

Also, the throwing distance depends on attack angle, and the largest throwing distances is generally along the vessel centre axel or perpendicular to this axle since fragment tend to travel orthogonally to the surface [18] and, therefore, it might be a good option to places the shooter at a 45-degree angle. The results in this study show that it is possible to achieve penetration at this angle, but the result become more sensitive to the exact point of impact of the bullet, so it put high requirements on the shooter to hit the centre line of the vessel. Any deviation from this will lead to that the bullet slips of the vessel without punching any hole.

Based on the analysis above, it can generally be seen as safe for the shooter to be 100 m from the vehicle. If this distance is not possible to achieve, and rifle depressurization is still regarded as the best option, it might in some situations be possible to reduce this distance by using a 45-degree attack angle and/or a ballistic shield.

4.4 Other techniques

In this paper, only depressurization using projectiles from rifles or shaped charges have been investigated. However, several other options might be useful in some situations. One is local heating of the thermally activated pressure relief device (TPRD) up to the activation temperature (usually 110°C). The benefits are that the resulting hole size is known in advance and results in a rapid depressurization. The negative aspects are primarily due to that the personnel need to be close to the damaged vessels during the mounting, and they are then exposed to risk in the event of an unexpected rupture or release.

A remote-controlled robot that can pierce the vessel and lead the gas to a flare has been discussed since it migrates the need for any personnel to be in close proximity to the vessels before depressurization and can also be used in confined spaces. The main problems with this approach are reaching the vessels (e.g. on the roof of a bus) with the robot and also that the power electronics need to be rated for an explosive environment.

A third option could be a remote-controlled rifle which can be easily built with a fixed rack and an expandable hose that push the trigger. However, depending on the rig, it might, in some situations, be difficult to hit the intended location, and personnel still need to go reasonably close to the vehicle.

The fourth and last identified alternative technique is using other types of explosives. This approach was tested in Paczkowski et al.[3] where a C4-charge was used. The approach was successful in depressurizing the vessel, but the explosive led to substantial fragmentation, which might pose a danger to the surrounding area. Also, personnel need to mount the explosive on the vessel.

5.0 CONCLUSION

The results presented in this paper should be seen as a first attempt to investigate the influence of different parameters on the outcome of tactical depressurization of vessels using rifles and shaped charges. More research is needed to investigate the influence of, for example, pressure on effective orifice diameters for type III- and IV-vessels. Also, larger data sets are required for both the number of shots and the number of different vessels since variation between vessels of the same type can be expected.

However, some guidance for practice can still be given based on the limited investigation in this paper.

- A standoff distance of 100 m is usually a good balance between shoot accuracy and risk for the shooter from flying debris.
- Regarding ammunition, 7.62 Ball should only be used for composite CNG-tanks. For steel tanks and composite hydrogen tanks, stronger ammunitions are needed – either higher velocity or projectiles with higher tensile strength.
- For composite hydrogen tanks, 7.62 AP/API can be used, and for steel tanks, 300WM and 308W has been verified. If 300WM and 308W can be used for composite hydrogen tanks will be tested in the near future.
- A shaped charge can be useful when the line of sight cannot be achieved, but the increase in penetration capability is limited compared to a regular bullet.

Finally, it can be noted that the technique for depressurization described in this paper is not only useful for accidents but also to reduce the risks after experiments where a vessel might have been damaged during the experiment.

6.0 REFERENCES

1. Hagberg M, Lindström J, Backlund P (2016) Olycksutredning - Band i gasbuss i Gnistängstunneln, Göteborg 12 juli 2016 ["Accident investigation - Fire in a gas bus in Gnistängstunneln, Gothenburg July 2016"; in Swedish]. Greater Gothenburg Rescue Services

2. MSB (2017) Tryckkärlsexposion i biogasdriven sopbil - Olycksutredning ["Tank rupture in a biogas-fueled trash truck"; in Swedish]. Report MSB1099, Swedish Rescue Services Agency

3. Paczkowski B, Maslach D, Radiwon M, Caito S, Centeck K (2017) Compressed Hydrogen Storage Cylinder Ballistic and Explosive Test Results. United States Army Tank Automotive Research, Development and Engineering Center (TARDEC)

4. Hora J, Karl J, Suchý O (2016) Pressure cylinders under fire condition. Perspect Sci 7:208–221 . https://doi.org/10.1016/j.pisc.2015.11.035

5. Andersson K, Axberg S, Elisasson P, Harling S, Holmberg L, Lindén E, Reberg M, Silferskiöld S, Sundberg U, Tornérhielm L, Vretblad B, Westerling L (2009) Lärobok i Militärteknik, vol. 4: Verkan och skydd ["Textbook in military technology, vol. 4: Effect and protection"; in Swedish]. Swedish Defence College

6. Molkov V, Kashkarov S (2015) Blast wave from a high-pressure gas tank rupture in a fire: Stand-alone and under-vehicle hydrogen tanks. Int J Hydrogen Energy 40:12581–12603 . https://doi.org/10.1016/j.ijhydene.2015.07.001

7. Molkov V (2012) Fundamentals of Hydrogen Safety Engineering. Free download eBook, www.bookboon.com

8. Richmond DR, Yelverton JT, Fletcher ER, Phillips YY (1989) Physical correlates of eardrum rupture. Ann Otol Rhinol Laryngol 140:35–41

9. SAF (2017) Reglemente - Am- och minröj - Skyddsåtgärder ["Regulations - Ammunition and mine clearance - Protective measures"; in Swedish]. Swedish Armed Forces

10. Prince RG, Kalb JT (2018) The Philosophy, Theoretical Bases, and Implementation of the AHAAH Model for Evaluation of Hazard from Exposure to Intense Sounds. ARL-TR-8333, US Army Research Laboratory

11. Gelbe D (2020) Personal communication, June 3rd, 2020

12. Berger EH (2001) Extra Protection: Wearing Earmuffs and Earplugs in Combination. Audiol Online August 6:

13. Rutter B (2019) Pressure versus impulse graph for blast-induced traumatic brain injury and correlation to observable blast injuries. Missouri University

14. Courtney MW, Courtney AC (2011) Working toward exposure thresholds for blast-induced traumatic brain injury: thoracic and acceleration mechanisms. Neuroimage 54:55–61

15. Bowen LG, Fletcher ER, Richmond DR (1968) Estimate on man’s tolerance to the direct effects of air blast. Report DASA 2113, Headquarters Defense Atomic Support Agency

16. van Doormal JCA., van Wees RMM (1996) Rupture of vessels. In: van den Bosh CJH, Weterings RAPA (eds) CPR 14E, Methods for the calculation of physical effects, 2nd ed. Gevaarlijke stoffen, pp 138–147

17. Runefors M (2020) Zonindelning vid räddningsinsatser mot fordon med alternativa bränslen - Beräkningsunderlag ["Zoning distances when responding to vehicles with alternative fuels - Calculations"; in Swedish]. MSB-rapport 1620, Myndigheten för Samhällsskydd och Beredskap (MSB)

18. Van Der Voort MM, Weerheijm J (2013) A statistical description of explosion produced debris dispersion. Int J Impact Eng 59:29–37 . https://doi.org/10.1016/j.ijimpeng.2013.03.002