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ON THE RISK OF A PRESSURE VESSEL EXPLOSION INSIDE ROAD TUNNELS

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ABSTRACT

Biogas and hydrogen are two renewable fuels that are needed in a transition from fossil fuels. Biogas and hydrogen tanks are equipped with a melt fuse that should release in the event of fire. However, on a few occasions, both nationally and internationally, the tank failed and the high pressure compressed gas was released instantaneously causing a pressure vessel explosion. If the explosion occurs inside a tunnel, the problems related to the pressure wave will be even more challenging, so the question whether the rescue service should be allowed to enter the tunnel has been raised, in particular with regards to the risk of hearing impairment. The Swedish civil contingency agency (MSB) takes such a stance. However, there are many uncertainties and assumptions that lead to such a decision that may need to be further discussed. It is argued that the limit value of 200 Pa is too low for such short and rare source of noise that a pressure vessel explosion is, and that such a decision also must consider the low likelihood of occurrence. A distinction should be made between pressure limits that has an immediate damaging effect and those which causes hearing damages from long-term exposure.

Keywords: CNG, biogas, hydrogen, pressure vessel explosion, tunnel, safety distance, firefighting, rescue service.

1. INTRODUCTION

Biogas and hydrogen are two fuels that are needed in a decreased use of fossil fuels, transition towards cleaner fuels, and lowered green-house gas emissions. These vehicle fuel tanks are equipped with a melt-fuse, a thermally activated pressure relief device (TPRD), that should release the gas in the event of fire before a pressure vessel explosion occurs. However, a pressure vessel explosion in the event of fire has occurred twice in Sweden, and several times internationally. The reason that often have been put forward is a local fire that does not heat the TPRD, or that extinguishing media cool the TPRD. RISE have been investigating CNG tanks exposed to local fire exposure [1] and extinguishing [2] in field experiments.

The Swedish civil contingency agency, MSB, are considering to recommend very strict measures for rescue service interventions of gas vehicles in road tunnels in a future guideline. This is mainly due to the risk of hearing impairment in the event of pressure vessel explosion, by which the entire tunnel tube is considered a "prohibited area", regardless of tunnel length if there is a risk of a pressure vessel explosion. In the event of a tunnel incident, this decision would be taken by the local rescue leader as soon as a gas vehicle is confirmed on fire. This is of great importance to the Swedish Transport Administration, as a rescue intervention is part of the tunnel safety concept. MSB bases its conclusions on work carried out at Lund University [3]. The purpose of this paper is to explore the reasonableness of MSB's future recommendations regarding requirements for rescue operations in tunnels with gas vehicles. In particular, the following factors will be analyzed.

- How likely a CNG or hydrogen pressure vessel explosion is.
- How a pressure wave propagates in a tunnel, considering vehicle and tunnel characteristics.
- Pressure magnitude limits used in literature.

- An occupational health perspective for firefighters' hearing.
- A decision and risk theory perspective.

2. REVIEW

2.1. The risk for a pressure vessel explosion in the event of fire

As was stated in the introduction, RISE have investigated whether a local fire exposure and extinguishing can cause a pressure vessel explosion. In total 15 field experiments were conducted, either with a local fire source [1] (see left hand of Figure 1) or extinguishing with water [2] (see right hand side of Figure 1).

Figure 1. Left: small fire pan (i.e. local fire exposure) below CNG steel tank. Right: application of water onto CNG composite tank with widespread fire pan below the tank. (Photo: RISE)

Only one of the 15 tests led to a pressure vessel explosion; a CNG composite tank filled to 150 bar that was exposed to the local fire exploded after 20 min, see Figure 2. While application of water was efficient at cooling the TPRD and thus put it out of operation, the water also cools the tank and for the different types of tanks that were tested, this did not lead to a tank rupture. Water was applied for 20 min. The tests show that it is difficult to create the necessary conditions to reach a pressure vessel explosion. In many real situations, fires will only result in a local exposure for a limited period of time, and application of water will often result in that the fire is extinguished. Despite, as was stated in the introduction, a pressure vessel explosion in the event of fire has occurred, e.g., twice in Sweden during the last 20 years during which Sweden has had about 50000 CNG vehicles [2].

Figure 2. A pressure vessel explosion.

2.2. Pressure wave propagation

The pressure wave propagation is commonly studied using empirical methods and numerical simulations. Baker et al. [4] has developed a methodology for evaluating physical bursting of a sphere in the free space using data fitting from numerical calculation, comparing with measurement, and solving one-dimensional shock wave equation together with blast scaling law. By specifying the initial tank volume and pressure, tables can be looked up, and the tank rupture explosion overpressure versus distance can be obtained. For example, Molkov and Kashkarov [5] applied the empirical method developed by Baker et al. for estimating pressure wave correlations for a stand-alone hydrogen tank rupture. It is possible to apply Baker et al's empirical method to tunnel condition by introducing a factor for considering the congestion of the tunnel geometry. It is then important to be aware of the uncertainty of this factor of congestion.

More efforts have been focused on applying detailed 1-dimensional (1-D) and 3-dimentional (3D) numerical tools for estimating consequences of a pressure vessel explosion. Li [6] developed an in-house 1-D code for simulating gas tank ruptures in tunnels. Runefors [3] used a commercial 3-D Computational Fluid Dynamics (CFD) code to do similar tasks, and found that the differences in explosion overpressure at different distances were within 10% between the results and Li's work [6]. A correlation for blast wave decay after hydrogen tank rupture in a tunnel fire was obtained by performing CFD simulations involving turbulence and combustion [7]. CFD simulations using a simplified method [8] by ignoring turbulence and combustion with substantial lower computational cost, was also performed using an open-source code OpenFOAM for the same tunnel geometry and scenario as in [7]. The simplified method showed quantitative agreement with RISE CNG tank rupture experiment [1]. An explicit dynamic code Autodyn was also used to simulate tank rupture at ro-ro space, which is similar to tunnel conditions [9]. Assumption of an analogy between gas tank rupture and TNT explosion was taken although this needs further verification.

As an example of the pressure wave propagation from a pressure vessel explosion, a single-lane tunnel with a width and height of 5.5 m and 4.5 m, respectively, and a length of 150 m is used. Figure 3 shows a comparison between the calculated explosion overpressures versus distance by Ulster [7] and RISE [8] for an 86 L tank filled with 700 bars hydrogen. The tank is exposed to fire so that the temperature increase to 395 K and 945 bar pressure at the time of tank rupture (the plastic is burnt away so that the composite lose its strength). It is worth noting that in the work of Ulster, 11% of chemical energy from burning of hydrogen is included in the simulation, whereas only the physical tank burst is simulated in the RISE model. Such difference in the model results in a lower overpressure at far-field, i.e., 30 m from the tank centre but reasonable agreement with Ulster's simulation results in the near-field. The far field difference is likely attributed to the combustion of the hydrogen. The discontinuity of the fourth sampling point in the figure is due to that the RISE 3D CFD model considers the detailed tunnel geometry, and that the pressure waves are interacted and magnified close to the ceiling of the tunnel at about 4 m distance and tunnel height.

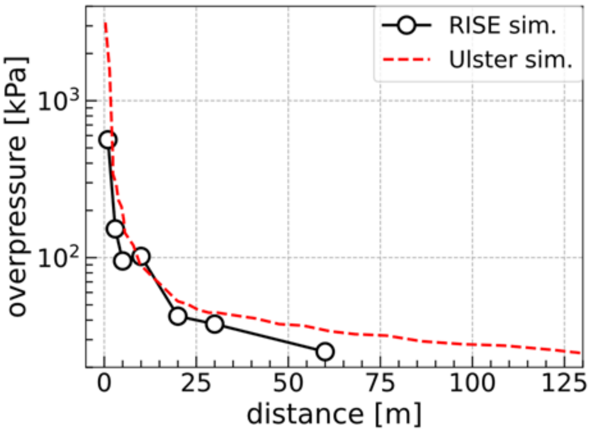

Figure 3. The pressure wave propagation along a tunnel following a pressure vessel explosion.

It is known that the pressure wave from a pressure vessel explosion decreases along the tunnel. The pressure wave may also decrease with number of objects in the tunnel. Therefore, simulated pressures without objects tends to be conservative compared to reality.

2.3. Pressure wave impact on firefighters

Different injury criteria are used by different organizations depending on the damage level on humans and on buildings. Pressure-impulse diagrams are commonly used for specifying the damage criteria for buildings based on experience gained during the second world war [4]. Here, we focus exclusively on the damage level of humans. The Swedish Civil Contingencies Agency (MSB) accepts a maximum pressure wave of 200 Pa to avoid hearing impairment [3]. This corresponds to a sound pressure level (SPL) of 140 dB, which is comparable to the 135 dB, which is level that is allowed by the Swedish Work Environment Authority as the peak value.[1]. Overpressures of 13.8 kPa, 34.5 – 48.3 kPa, and 137.9 – 172.4 kPa were proposed by Jeffries et al. [10] as thresholds for temporary loss of hearing, 50% probability of eardrum rupture and 50% fatality from lung hemorrhage, respectively. Similar values were found in Ref. [11] with thresholds for 50% probability of eardrum rupture and 50% fatality from lung hemorrhage being 43.5 kPa and 140 kPa, respectively.

It is clear that a very conservative limit (200 Pa corresponding to 140 dB) is used by MSB, compared to other limit values found in literature. It is argued that for rare explosions that last for less than one second, higher values (e.g., 13.8 kPa) recommended in other papers may be more appropriate. This would for instance yield a safety distance in the order of 50 – 100 m in Runefors' [2] simulations, instead of that the whole tunnel is prohibited area.

2.4. An occupation health perspective

An initial literature search about hearing protection for firefighters shows that firemen have an apparent risk of hearing disorder. This is mainly attributed to high noise-levels in their daily work environment such as the siren in the fire truck and noise from equipment, e.g., water pumps. The literature search could not find other, more rare events such as pressure vessel explosions to be a reason for hearing disorder among firemen [e.g., 12]. At the same time, it is clear that more could be done to improve firefighter's hearing health, e.g., through the use of hearing protection devices (HPD) that are integrated with the radio and helmet, and through programmes that monitor and limit exposure to noise.

It appears that hearing impairment indeed is an occupational health issue for firefighters, however, the main contributors, according to literature, are from ordinary noise sources rather than extreme events such as explosions.

2.5. A decision and risk theory perspective

If we, as most philosophers, would believe the Scottish philosopher David Hume (1711–1776), we cannot derive an ought from an is. The level of safety, e.g., for firefighters during intervention inside a tunnel, is a normative question. Such issues are studied within normative ethics and there are primarily two ethical thought patterns that are used to justify decisions, namely, deontology and utilitarianism [13].

Within deontological ethics the core idea is that there are certain rules or duties which must not be violated, regardless of the consequences of adhering to these rules or duties. At least these consequences play a subordinate role. For instance, an authority could claim that firemen should

[1] https://www.av.se/halsa-och-sakerhet/buller/krav-vid-olika-bullernivaer/

not be exposed to noise levels above 200 Pa. A strict adherence to a deontological principle, may ultimately lead to the banning of all risky activities, and may infringe on the same values set out to be protected, which may cause more risks than it could possibly prevent [13].

Utilitarianism is about specifying the advantages and disadvantages of each alternative and choosing the alternative with the greatest net advantage. Another way to phrase this is to maximize the utility. Thus, one can argue that enough safety is achieved if the overall utility is maximized [13]. Most decision theories are based on the idea that the choice depends on the probabilities of various consequences and their utility, or value, to the decision-maker. Risk is most often understood as a combination of consequences and probability. A utilitarian approach highlights, not only the consequences side of risk, but also the probabilistic side of risk.

Based on these two thought patterns, the soundness of decisions can be debated. If one would, for example, require that firefighters under no circumstances should be exposed to noise levels above 200 Pa, this would, for instance, require that they could not go near burning trucks (truck tires can explode in the event of fire resulting pressures in the order of 5 kPa [8]), and most likely no fires at all since most vehicles and facilities contain pressure vessels of various kinds, that may explode. It appears that a strict adherence to the deontological limit 200 Pa for the firefighting profession seem unrealistic. Thus, a utilitarian basis for such decisions seems more plausible, this would give weight to the very low likelihood of occurrence of a tank rupture (in Sweden, once per year and 500 000 CNG vehicles and much less probable inside tunnels). Besides, an intervention whereby the fire is extinguished (with or without fixed firefighting systems) lowers the risk further. This decision, whether an intervention is worth the risk, is made at each incident scene by the rescue leader, and in rescue service guidelines by the MSB.

3. SUMMARY AND CONCLUSION

This paper presents preliminary investigations of the risk to firefighters from a pressure vessel explosion inside a tunnel. This is analyzed from five perspectives:

- How likely a CNG or hydrogen pressure vessel explosion is.
- How a pressure wave propagates in a tunnel, considering vehicle and tunnel characteristics.
- Pressure magnitude limits used in literature.
- An occupational health perspective for firefighters' hearing.
- A decision and risk theory perspective.

It is argued that the low likelihood of occurrence is an important risk-reducing factor, in particular in the event of sprinkler activation or manual fire extinguishing, which further lowers the risk of a pressure vessel explosion. There are many assumptions and uncertainties in pressure wave propagation simulations inside tunnels and real experimental data are lacking. It is argued that a pressure limit for this type of event should be in the order of 10-20 kPa, and that this event has little to do with an occupational health perspective which concerns ordinary noise sources such as siren and equipment. If firefighters would not be allowed to be exposed to higher pressure waves than 200 Pa, it would be difficult to perform the profession of firefighting. A distinction is necessary between pressure levels that has an immediate damaging effect and those which causes hearing damage with long-term exposure. At the same time, more could be done to improve firefighters' hearing, e.g., the use of HPD and programmes to monitor and limit noise exposure.

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