CNG buses fire safety : learnings from recent accidents in France and Germany

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ABSTRACT

The use of CNG in bus and private vehicles is growing steadily. Recent fire accidents involving CNG buses have shown that tanks may explode though compliant with current ECE UN R110 regulation. Such a repeated scenario is certainly not acceptable having in mind the tremendous amount of energy released when a compressed tank bursts. Investigation of German and French recent cases detailed in this article highlights potential improvements in current CNG buses fire safety concepts. Among others, it includes to rely on a system-level test and expectations in combination with the current component-level test. Fire safety should not solely rely on tank behaviour when exposed to fire but also to additional and upstream fire safety barriers. Thermal fuses can not be seen any more as an ultimate option to control tank burst in case of fire.

INTRODUCTION

Over the last decade, the use of CNG (Compressed Natural Gas) in vehicles has been increasing all over Europe as a "green" alternative to conventional liquid fuels. According to the European Natural Gas Vehicle Association (ENGVA), the European CNG fleet is estimated to about 550 000 vehicles of all types (city buses, private cars…) with a prominent share for Italy (see picture below).

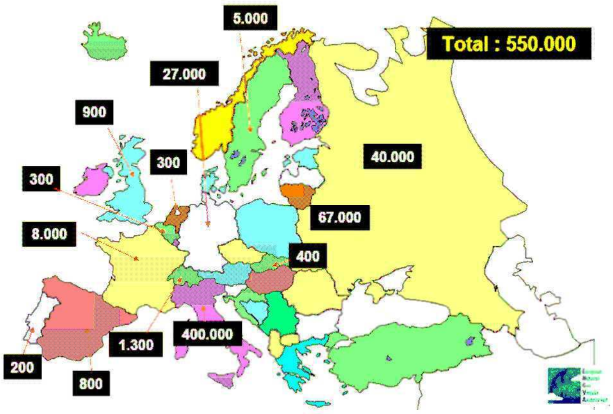

Figure 1: CNG vehicles number and distribution in Europe in 2005 (from European Natural Gas Vehicule Association)

France counts about 1600 city buses. The number of CNG vehicle will be on the rise in France, especially for private vehicles due to the introduction of CNG vehicles home refuelling apparatus.

Natural gas is stored onboard vehicles under 200 bar in metallic or composite tanks. For buses, tanks are associated in series (tank system) and located on the roof.

In comparison with liquid-fuel-powered buses, CNG buses may pause additional hazards which comprise:

- tank burst and associated pressure waves, projectiles (projection of tank fragments and other equipment) and eventually thermal effects (fire ball resulting from the combustion of released natural gas),
- jet fire and associated thermal and pressure effects,

- and finally explosive atmosphere and associated thermal and pressure effects.

Mechanical[1] (road accident…) and thermal aggressions (onboard or nearby fire) are the main causes that may lead to any of the above hazards. Though tank burst is not supposed to happen based on existing UN ECE regulations [3], recent CNG buses tank bursts in Europe have highlighted potential deficiencies in the present fire safety concept.

Therefore, we will concentrate in this article on CNG bus fire safety issues. After introducing the CNG bus fire safety topic, we will study recent CNG bus fires in France and Germany and will extract "lessons to be learned" for CNG and other compressed fuels such as hydrogen.

CNG BUS FIRE SAFETY STRATEGY

Fire onboard buses may be caused by internal or external factors. Internal factors include events such as electrical short circuits, excessive temperature of bus components including the braking system, the turbo-compressor, the exhaust pipe… in combination with combustible materials including polymeric materials, oil, dust and debris… . Experience shows that fires usually start in the engine compartment [9].

As far as external causes are concerned we can mention human error during maintenance (use of open flames…), vandalism and propagating fires from nearby vehicles or infrastructure.

The most unwanted event in case of CNG bus fire is the burst of one or more of the compressed storage tanks located on the roof of the vehicle. Tank burst is definitely not a tolerable option having in mind the tremendous amount of mechanical and chemical energy released in the course of this event.

The current safety strategy to prevent tank burst consists in fitting pressurised tanks with devices that release stored compressed natural gas as they fuse under the effect of temperature rise (fire). The melting temperature of these fuses is about 110°C. In practical terms, to prevent tank burst, internal tank pressure has to decay before the fire degrades the mechanical strength of the compressed storage. Experience shows that unprotected tank (inhibited pressure relief devices) can not survive a standard bonfire test for more than few minutes [4] & [5]. The main cause for a tank to burst is the decay of its mechanical strength and rise in internal pressure.

Therefore, pressure relief devices (PRD) should be capable of depressurising a tank within a couple of minutes. According to experience, bus tanks can be exposed to fire for about 20 to 30 minutes which is an average time frame for a bus to be burnt out[2].

Isolated compressed tank or tank systems are submitted to standardised bonfire test (component-level test according to UN ECE R110, test A15 [3]) to certify that they work in accordance with this fire safety strategy.

Though tank burst is not supposed to happen, recent CNG buses tank bursts in Europe have highlighted potential deficiencies in the existing fire safety concept.

PRESSURISED TANK BURST

Large quantity of mechanical and chemical energy are stored in compressed combustible gas storage. Sudden release of this energy in case of tank burst may cause some severe damage to the bus environment.

When a tank bursts, observation shows [4] two consecutive pressure wave propagating in the surrounding environment. The first one which is also the more severe is associated with the pneumatic rupture (gas expansion) whereas the second is caused by the combustion of the released combustible gas into the air (fire ball). It is therefore to be noticed that although the chemical energy stored is usually an order of magnitude larger than the mechanical energy, the sudden release of the mechanical energy induces greater overpressure effects.

Theoretically, the pneumatic burst of a 130 L tank at a pressure of 200 bar releases an energy equivalent to the detonation of about 1.85 kg of TNT (8.7 MJ). Windows can be broken within a 30 meters radius (50 mbar) and pressure wave induced lethality is to be foreseen within a radius of 12 meters (140 mbar). These calculations can worsen due to pressure wave reflection and pressure build up as well as to directional energy release (axial direction) due to the rupture mode of the cylindrical tank. Moreover, projectiles can also cause severe damages within a radius much larger than the one estimated above for overpressure effects. [5] shows that fragments of up to 14 kg (type IV tank filled with hydrogen at 350 bar, test conducted in open atmosphere / projectiles not hindered by bus equipment) have travelled a distance of 82 m from tank fire location. The mechanical energy released as the tank ruptured was equivalent to about 1.35 kg of TNT (6.3 MJ).

Therefore, an unacceptable event such as a tank burst induces a significant damage radius (missiles and overpressure) that goes far beyond the bus geometry. This makes a major difference with conventional liquid-fuel-buses with damage radius in case of fire limited to the bus itself (unless the fire propagates).

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[1] There is no evidence so far of any mechanically induced rupture failures of tanks in CNG service world-wide. This scenario is however plausible.

[2] It takes about 10 to 15 minutes for a bus to be fully involved in fire.

The tank may be subject to fire aggression in various ways:

- engulfing fire as combustible materials in the vicinity of the tank are burning,

- localised fire aggression (at one end of the tank) as combustible materials in the vicinity of the tank are burning,

- and finally impinging jet flame fed with high pressure natural gas.

Experience shows that fire protected tanks may not survive some of the aggressions above indicating that PRD efficiency is limited. This limitation should be acknowledged.

Indeed [4] has shown that protected tanks can not survive an impinging jet flame and will fail within a couple of minutes. As far as localised thermal aggressions are concerned we could expect thermal fuses not to be triggered and the tank to fail depending on the distance between local flames and the PRD. Finally, the less severe case for protected tank integrity which consists in engulfing flame is basically what PRD are useful for. This test is part of the certifying process of protected tanks as mentioned before.

RECENT TANK BURST ON OPERATED CNG BUSES

We can mention three CNG bus fire accidents in Europe where one of the tank did burst. The table below summarises the three cases.

Date	Location / Country	Fire cause	Accident location	Time before burst
12 May 2003	Saarbrücken / Germany	Oil deposit close to hot gear box (engine room)	Bus depot	15 minutes
1st August 2005	Montbéliard / France	Short circuit (engine room)	Street (village exit)	20 minutes
8 November 2005	Bordeaux / France	Vandalism (Molotov cocktail in passenger compartment)	street	10 minutes

Table 1: Summary of the three studied bus fire accidents

THE SAARBRÜCKEN ACCIDENT: DESCRIPTION AND LEARNING

Description [2] & [6]

The fire started on a CNG articulated bus in the engine compartment (back of the bus). When the fire took off at 3:00 pm, the bus was parked in a depot along with other CNG articulated buses. Each articulated bus was fitted with 10 CNG type III PRD protected tanks of 172 L each and filled with natural gas at a pressure of 200 bar.

Figure 2: Side picture of a bus similar the ones that burned (from [6])

On-site first responders tried to put out the fire without success and then called the local fire brigade that arrived on the scene at 3:09 pm.

The fire propagated from the back of the first bus to another articulated bus parked in a row at 1.5 meters behind. At 3:09 pm the fire is well developed inside the depot and violent explosions occur. These explosions are caused by the release through actuated PRDs, mixing and later combustion of natural gas inside the depot. Both buses have been burnt out whereas the other ones have been extracted from the depot before they caught fire. The first bus burnt from the back to the front. The second bus burnt the opposite way.

Figure 3: View of the fire once it was under control (from [6])

19 of the 20 CNG tanks exposed to the fire did behave as expected. The stored gas was released through PRDs hence preventing tanks from exploding. Each tank was fit with two boss mounted PRDs (one on each boss). All 38 PRDs did open at about 110°C as expected for the 19 tanks.

It went a different way for one of the tanks mounted on the second bus whereas the fire was "under control". The tank burst about 15 minutes after the fire started. A large tank fragment was propelled in the tank axial direction. It broke through a nearby wall (hole at 3 meters from ground level) flew through the air and damaged another wall located 25 meters further and ended up its journey on the roof of a bus parked in a nearby depot. The tank that burst was the first in the row when looking at the bus from the front (tank n°1). The fire was put out at 4:30 pm. Nobody was injured.

Figure 4: Destroyed bus with red arrows pointing (from right to left), tank n°3, hanging tank n°2 and hole through which tank n°1 flew (from [6])

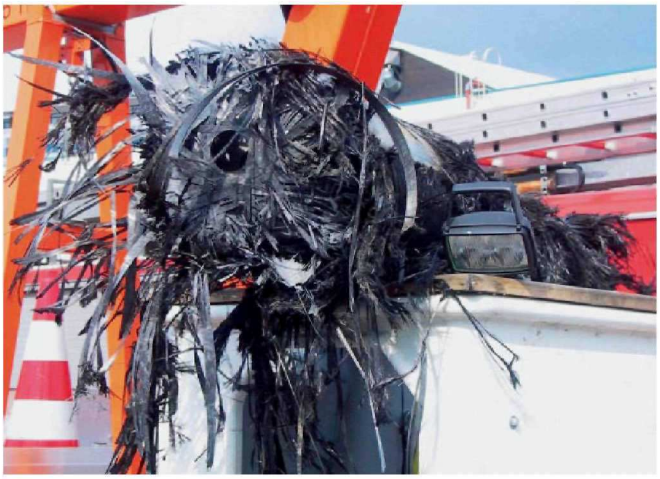

Figure 5: Remains of tank n°1 after it landed (from [6])

One should notice that tanks were isolated one from the other. The emptying of one tank through its PRDs did not cause adjacent tanks' pressure to decay.

Investigation lead to the following explanations. Tank n°1 burst for two concomitant reasons:

- on one hand it suffered a local fire stress when a fire-induced short-circuit triggered the opening of a roof door mounted nearby tank n°1 (Picture 6). Flame broke through this opening and heated up tank n°1 in its middle part,

- on the other hand, PRDs mounted on tank n°1 did fail to open, hence preventing the tank from depressurising. Investigation concluded that failure to open was caused by an insufficient heat up of the PRDs that did not melt completely. The protective cover mounted on the top of tanks contributed to prevent sufficient heat to reach the PRDs.

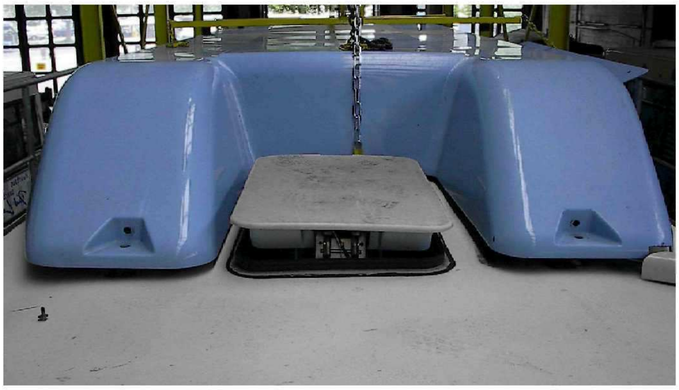

Figure 6: Roof opening ahead of tank n°1 (from [6])

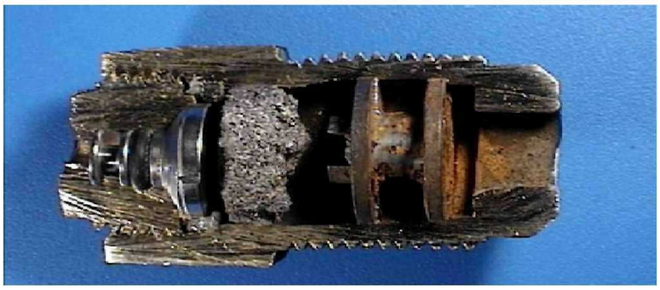

Figure 7: Example of one closed PRD from tank n°1. Picture shows that the metal fuse did not have time to melt completely (from [6])

<u>Learnings</u>

This accident confirmed that boss mounted PRD on both side of a bus tank is not an ultimate protection if pressurised tanks are exposed to localised fire (sunroof or any other opening underneath or nearby the tanks): PRD may fail to work in time.

In that case PRDs did not fail because they froze[3] but because flames heat did not reach them fast enough. Therefore, a tank system that survives a bonfire test may not survive in a real life situation, similarly a fuse that works correctly in test condition may operate differently in real life conditions. Indeed, as the bonfire test only focuses on the tank system and does not consider the entire vehicle, it misses synergetic effects induced by the association of tank system and the vehicle. This remark underlines that tank fire protection and bus fire safety can not rely only on the performance of isolated protected tank systems.

Further developments of the current "bonfire test" are necessary in order to consider the entire vehicle as suggested also by [7] & [8]. Besides, any opening underneath or nearby the tank must be avoided (or be sealed and fire resistant). Finally, PRD performance and potential failures should be further investigated including

[3] PRD freezing has also been observed in the past. It is known to be the consequence of a competing effect between the heat from the fire and the cooling down from expanding gas.

appropriate location that does not shield them from heat or allow them to freeze. As far as freezing is concerned, new PRDs exist with fuse made of glass-cylinders containing expanding liquids. Glass brakes up at 110°C and completely free the release orifice with no possibility of PRD reclosure.

THE MONTBÉLIARD ACCIDENT: DESCRIPTION AND LEARNING

Description

A 12 meter CNG bus was in daily commercial service on the 1st of August 2005. This bus was equipped with nine 126 L, 200 bar working pressure type IV CNG tanks. Each of the nine tanks was fitted with one thermal fuse located alternatively on the right or on the left side of the bus. There were two other thermal fuses located respectively ahead and behind the tank system. These two fuses are supposed to open before the fire reaches the tank system (from the front or the rear of the bus).

One single valve isolates the entire tank system from downstream components which means that when the valve is closed the tanks remained connected one to the others. The only way to isolate one tank from the others is to shut down its manual valve. Gas release deviators pointing upwards are mounted on the PRDs outlet in order to discharge CNG in the upward direction.

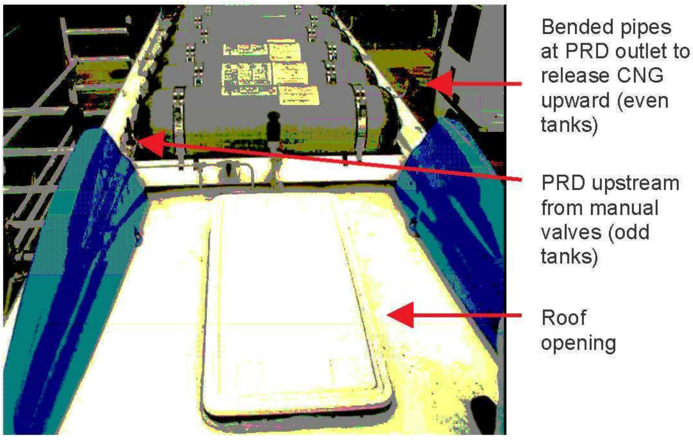

Figure 8: Top view of a CNG bus of a similar type to the one that caught fire (tank cover has been removed for taking the picture)

CNG tanks were full as the bus was just starting its working day. At 06:15 am, the driver saw an alarm signal on the dashboard indicating “no battery charging”. He then called his central office that suggested to turn off the engine in order to reset the electronics. He tried but did not succeed to switch off the engine and finally drove away as suggested by the central office. Few kilometres later, as the bus was leaving the city center, the driver witnessed an abnormal heavy smoke rising from left side of the motor room and smelled something burning. He stopped the bus at the village exit and evacuated the 3 passengers. He then tried to put off the fire with the onboard extinguisher by injecting the chemical agent through the motor room ventilation grids (as prescribed). He did not succeed to put off the fire. As the fire rapidly propagated, he called the fire brigade at 6:27 am. Then, the driver saw the PRDs opening progressively from the rear to the front of the bus as the fire was propagating.

By the time the fire brigade arrived at 6:40 am, the fire had propagated to the entire bus. Firemen rapidly set a safety perimeter. As they arrived on the scene, they witnessed jet flames pointing upwards (about 5 meters high and more) and a shorter one pointing horizontally. These jet flames were fed by PRDs releases.

Firemen stood at a safe distance in front of the bus and tried to cool down the tank system with water spray. 10 minutes later at 6:51 am, the front cylinder exploded causing slight and directional damages to the environment within a distance of 100 m. Damages were caused by tank debris (tank n°1 damaged the roof of an adjacent house after a 30 m fly) and overpressure (poster frame unhooked and damaged sliding shutters 60 m away from explosion). As it burst, tank n°1 also propelled the adjacent tank to the other side of the road (10 m away). The tank n°1 ruptured in large pieces whereas carbon fiber could be found as far as 150 m away. Tank n°1 valve and associated fuse have not been found after the accident. Bursting noise could be heard at a 5 km distance. Firemen did not report any noticeable fireball though they felt a transient heat. Nobody was injured.

Figure 9: Side view of the bus with tank n°3 hanging (Courtesy SDIS 25)

Figure 10: Top view of the bus (Courtesy SDIS 25)

Figure 11: Tank n°1 after burst (Courtesy SDIS 25)

Figure 12: Tank n°2 propelled on the other side of the road (Courtesy SDIS 25)

Investigation took place and some realistic explanations can be put forward:

1. Excessive depressurisation time or no depressurisation at all for tank n°1:
   - PRDs which were mounted on the bus were not of a fast release type since they were fitted with a 1.5 mm flow limiter orifice in order to comply with an ancient French draft regulation dated from 1996 (before ECE R110 took over) that required emptying time to be comprised between 25 to 35 minutes. This surprising timeframe which is not compatible with bus fire kinetics was deemed to mitigate gas releases through PRDs in confined spaces like tunnels or parking structures,

   - Since tanks are not isolated one from the others the pressure drops evenly in the entire tank system. However, if one tank is manually isolated from the others, its internal pressure will not drop unless its sole thermal fuse is actuated (single thermal fuse located upstream from manual valve for odd tanks like tank n°1 and located on the bottom boss of the tank for even tanks). The tank n°1 manual valve may have been voluntarily shut off in order to use its gas content as a back up.

2. Localised thermal aggression that caused tank mechanical strength to weaken and tank to burst:
   - The fire broke through the roof opening located 20 cm ahead of tank n°1 and caused a severe localised thermal stress in the middle part of tank n°1,

   - A horizontal jet flame may have come from tank n°2 PRD release and also caused a severe localised thermal stress to the bottom of tank n°1. This abnormal horizontal jet flame is a possibility since on one hand firemen witnessed horizontal jet flames and on the other hand PRD outlet deviators (on even tanks) have been found pointing horizontally when investigating bus remains. Deviators may have collapsed during the fire or some times before due to vibrations or other operational constraints.

As for the fire cause, experts concluded that it was an electrical failure of the alternator system located on the left side of the engine room.

Out of the 11 PRDs mounted directly on tanks, 3 have been lost during the accident: the one mounted ahead of tank n°1, the one mounted on tank n°1 (plus its manual valve) as well as the thermal fuse of tank n°2. It is therefore not possible to conclude on any failure of these thermal fuses[4] such as:

- Insufficient heat up of PRDs to melt the fuse (like in Saarbrücken),
- Freezing of PRDs,
- misuse of manual valve n°1,
- or any failure of the deviator mounted on tank n°2.

<u>Learnings</u>

Some learnings are common with the German case and some others are specific. First of all, it is advisable to avoid roof openings unless they can offer a fire resistance at least equivalent to that of the roof as well as any design that may cause tanks to suffer from localised thermal stress in a fire scenario.

Then, it is advisable that tank complete emptying take place within few minutes after the PRD opened. In that case, detailed study should be undertaken for accidental release of natural gas inside confined spaces like tunnel or parking structures as explosion may occur.

[4] Thermal fuses were of the same type as those involved in the Saarbrücken accident.

The PRD outlet must be so designed that the fire jet can only point upward and can not in any circumstances impinge a nearby tank.

Finally, both accidents have shown that first responders did not manage to put out the fire. This may suggest that early response fire fighting means or procedures are not appropriate for an efficient action. However, heavy fire fighting capacities will never be available within the first couple of minutes. Automatic or manually actuated fire suppression systems located in the engine compartment should therefore be envisaged in order to effectively control fire development. Automated or manually actuated fire suppression systems in the engine room where fires are most likely to start are of a primary relevance for CNG buses. These systems may be highly relevant having in mind that somehow vulnerable compressed gas cylinders are mounted on the bus roof in a design that severely expose tank cylinders to the fire.

THE BORDEAUX ACCIDENT: SHORT DESCRIPTION AND LEARNING

The bus concerned by this later accident is exactly of the same type as the one we have just presented in the Montbeliard case though accidental circumstances are different. On the 8th of November 2005, at 6:50 pm, vandals deliberately threw a Molotov cocktail inside the passenger compartment at the rear of the bus. At that time the remaining pressure inside the storage system was estimated between 100 and 70 bar. Witnesses reported that the fire propagated rapidly and soon broke through the roof panel mounted 20 cm ahead of tank n°1. Tank n°1 burst within 10 minutes after fire broke out and before the fire brigade arrived. Horizontal jet flames were also witnessed meaning that PRD release deviators did also collapsed. Finally, firemen reported various moderate deflagrations. Damages were limited and nobody was injured as a result of this accident.

Figure 13: View of the bus after the fire (courtesy bus manufacturer)

Figure 14: View of tank n°1 that exploded (one half)

Figure 15: View of the bus from the inside (tank n°2)

Figure 16: View of the bus from the inside (tank n°2)

Learnings from the Montbéliard and Saarbrücken cases also fully apply to this one. However, we can also, in that specific case, underline the vulnerability of buses when submitted to vandalism as fire propagates very rapidly: tank n°1 exploded before the fire brigade arrived. A fire suppression system located in the engine room as suggested above would have been of no use in this specific case. Therefore, additional fire safety measures should be thought of as discussed in the next paragraph.

PROPOSED REVISIONS OF FIRE SAFETY STRATEGY FOR CNG BUSES

Up to now, fire safety and associated tank burst control measures as suggested in ECE R110 concentrate on tank system protection using PRDs. This strategy necessitates PRDs to be both highly reliable and to be efficient in various types of compressed tank fire stresses whether homogeneous or localised. Though none of the bus presented above were ECE R110 compliant (they were put in service before ECE R110 was promulgated), experience discussed in that article has proven the safety strategy that consists in focussing on tank systems not to be always appropriate. Fire safety for CNG buses should rely on more sensible principles as those applied on a usual basis whenever managing risk i.e. prevent, limit and mitigate consequences.

Therefore, the following measures should be technically investigated:

- fire prevention by limiting and controlling engine temperature, by limiting combustible materials in the engine compartment and by cleaning up any accumulated oil or other combustible debris,
- fire detection including periodic maintenance of installed detection systems,
- fire suppression either automatic (fire detectors) or manually actuated,
- fire propagation control by segregating the engine compartment from the passenger compartment and of course the CNG storage with at least ½ hour fire resistant material. This ½ hour rating should give sufficient time for the fire brigade to arrive to set up a safety perimeter and to deploy significant fire fighting capacities before the fire has propagated to the gas storage.

As far as CNG tanks are concerned additional measures to those mentioned above should apply. These measures could mainly consist in further limiting tank exposure to fire by coating tanks with thermal shield materials or by designing a ½ hour fire resistant roof. PRDs should be extensively tested. It is advisable to locate them on both ends of each tank with no means for released gas to impinge on a nearby tank. Regarding PRD response time, discussion should take place on the appropriateness for early PRD opening in a fire scenario having in mind natural gas explosions it may cause in confined environment. Systematic and early release might be a delicate choice. We would, if confined releases are an issue, favour the strategy that considers PRD opening (fast flow) as an ultimate safety option if the others have not been sufficient to prevent severe tank exposure.

In parallel, we would expect a fire protected tank with inhibited PRD to be able to withstand fire exposure for at least 15 minutes in order to give sufficient time for firemen to arrive on the accident scene and to set up a safety perimeter.

This type of test should also be standardised as a complementary test to the bonfire test with PRD protected tanks that rather investigates the effectiveness of the PRD to prevent tanks from bursting rather than the tank itself. Limitation of the current bonfire test are well described in [7] & [8].

On a more general basis, component-level tests as prescribed by ECE R110 though useful are not sufficient as they may miss synergetic effects between the bus and the tank system. A system-level fire strategy is highly advisable to prevent any more tank from bursting. Therefore, in combination with proposed measures, a complementary system-level bonfire test is also highly advisable in order to evaluate the safe behaviour of a CNG bus when submitted to a engine room or passenger compartment fire.

TODAY CNG BUSES AND TOMORROW… CH2 BUSES

Lessons learned from CNG buses are entirely applicable to future compressed (CH_2) hydrogen buses since storage technology is similar though storage pressure is significantly higher (350 bar for CH_2 buses). As innovative technologies, we would hope that inherently safe fire safety principles will be incorporated into their design.

EC has recently submitted a draft regulation for hydrogen vehicles. This component-level based regulation based on a draft UN ECE document was open for suggestions. HySafe partners made the comment that a system-level based document with performance requirements on the system configuration would be more appropriate.

Finally, fire safety strategy on buses might not be appropriate for cars. Indeed, whereas a PRD release might be acceptable for buses because it takes place at a safe height and because city buses are not likely to roll over, it may not be the same for cars.

CONCLUSION

The use of CNG in bus and private vehicles is growing steadily. Recent fire accidents involving CNG buses have shown that tanks may in some explode. Such a repeated scenario is certainly not acceptable having in mind the tremendous amount of energy released when a compressed tank bursts. Though none of the bus mentioned in this article was ECE R110 compliant, this article highlighted, potential improvements in current CNG buses fire safety concepts. Among others, it includes to rely on a system-level test and expectations in combination with the current component-level test. Fire safety should not solely rely on tank behaviour when exposed to fire but also to additional and upstream fire safety barriers. Thermal fuses can not be seen any more as an ultimate option to control tank burst in case of fire though “well” located.

Reported cases did not cause any injury or severe damages. It would be a pity not to learn from these lucky cases rather than wait for something unacceptable to happen.

International regulations like UN ECE may also be accompanied with international accident reporting scheme in order to improve regulations content over time.

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E/ECE/TRANS/505 A
Rev.2/Add.109: Règlement No. 110
Prescriptions uniformes relatives à l’homologation :
- des organes spéciaux pour l’alimentation du moteur au gaz naturel comprimé (GNC) sur les véhicules,
- des véhicules munis d’organes spéciaux d’un type homologué pour l’alimentation du moteur au gaz naturel comprimé (GNC) en ce qui concerne l’installation de ces organes.

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