Fire Protection Strategy for Compressed Hydrogen-Powered Vehicles

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ABSTRACT

Virtually all major automotive companies are currently developing hydrogen-powered vehicles. The vast majority of them employ compressed hydrogen tanks and components as a means of storing the fuel onboard. Compressed hydrogen vehicle fuel systems are designed in the same way as compressed natural gas vehicles (NGV), i.e. the high pressure (up to 70 MPa) fuel is always contained within the system under all conditions, with the exception of vehicular fire. In the event of a vehicle fire the fuel system is protected using a non-reclosing thermally activated pressure relief device (PRD) which safely vents the contents.

Hydrogen fuel system PRDs are presently qualified to the performance requirements specified in draft hydrogen standards such ANSI/CSA HPRD 1 and EIHP Rev. 12b. They are also qualified with individual fuel tank designs in accordance with the engulfing bonfire requirements in various published/draft tank standards such as CSA B51 Part 2, JARI S001, SAE TIR J2579, ANSI/CSA HGV 2, ISO DIS 15869.2 and EIHP Rev. 12b. Since 2000 there have been over 20 documented NGV tank failures in service, 11 of which have been attributed to vehicle fires.

This paper will examine whether currently proposed hydrogen performance standards and installation requirements offer suitable fuel system protection in the event of vehicular fires. A number of alternative fire protection strategies will be discussed including:

i. The requirement of an engulfing and/or localized fire test for individual tanks, fuel systems and complete vehicles;
ii. The advantages/disadvantages of point source-, surface area- and/or fuse-based PRDs
iii. The use of thermal insulating coatings/blankets for fire protection, resulting in the NON-venting of the fuel
iv. The specification of appropriate fuel system installation requirements to mitigate the effect of vehicular fires.

1.0 INTRODUCTION

1.1 Background

The experience with compressed natural gas vehicles (NGVs) provides a window into a future of fuel cell vehicles using compressed hydrogen fuel systems. There are now over 5,500,000 NGVs in the world - some OEM and most after-market conversions. Since the year 2000, there have been over 20 failures of NGV tanks on-board vehicles. The single largest cause of these failures (over 50%) was fire.

Some of the fire failures could be attributed to slow reacting pressure relief device (PRD) designs, but the majority of failures was caused by localized fire effects where the flame exposure was at a location on the tank remote from the PRD location. These CNG cylinder fire failures have occurred on OEM passenger vehicles, as well as OEM transit buses.

PRDs do not tend to activate unless they are exposed directly to a high heat source, or direct flame impingement. There is currently no requirement in NGV PRD standards for PRDs to exhibit any minimum activation time in the chimney test (exposure to hot gases).

1.2 Current Fire Testing Requirements

All NGV or draft compressed hydrogen vehicle tank standards worldwide only specify a bonfire test of a tank where the fire source is a standard 1.65m length. This fire length is derived from a U.S. DOT fire test developed in the 1970's for application to composite air-breathing cylinders of relatively small size.

The history of NGV tank failures has shown that this standard 1.65m fire test is inadequate for the larger pressure vessels used as fuel tanks on-board passenger vehicles, trucks and, especially, transit buses.

1.3 The Need for Alternative Fire Protection Strategies

While it would seem obvious that the industry should reduce the size of the fire used in bonfire tests, there is a reluctance to do so because (a) industry would have to agree on the dimensions and temperature profile of the smaller fire source, and (b) it would make current PRD designs inadequate for fire protection purposes, i.e. they would only work if they were placed in (or in very close proximity to) the fire. The industry may need to explore alternative fire protection methods.

2.0 NGV FIRE PROTECTION EXPERIENCE

2.1 A Brief History of NGVs

The large-scale use of NGVs in North America began in the early 1980's. This development was promoted by gas utilities as a means of increasing sales of natural gas. The technology used to convert gasoline vehicles to operate on compressed natural gas (CNG) was primarily of Italian origin, where the large scale use of NGVs had earlier commenced in the 1960's. The standards developed in North America for NGV designs were based on a combination of the Italian experience and industrial high pressure gas requirements.

In the early 1980's there was no requirement in Italy for vehicle fuel storage systems to be equipped with PRDs. The philosophy in Italy was that in the event of a vehicle fire, the pressure would be released through the numerous fittings and parts involved in the fuel system. However, this opinion was based on fires typically occurring within the engine compartment where the pressure regulator and fill receptacle were located, and not on the fire being concentrated in the location of the fuel tank at the rear of the vehicle. In addition, since the fuel tanks were made exclusively of steel, it was believed this type of design had sufficient resistance to thermal effects to withstand a fire of the duration typically experienced by a vehicle. At the time, Italy had experienced several NGV fires without rupture of the pressurized fuel system.

2.2 Industrial Gas Cylinder PRDs

In North America the use of PRDs was required based on the practice used in the industrial gas cylinder industry. North American NGV regulations required that vehicle fuel storage systems be equipped with PRDs that complied with the CGA S-1.1 standard. The PRDs defined in the CGA

S-1.1 standard were not specifically designed for NGV service conditions and as a result, a number of in-service failures occurred.

The commonly used burst disk/fusible metal device required the combined action of heat and elevated temperature to activate, i.e. the burst disk would rupture after the fusible backing metal had melted due to exposure to elevated temperatures. Unfortunately, the temperature and pressure variations that were typical of NGV service caused premature leakages due to fusible metal creep and fatigue of the burst disk. In addition, these combination PRDs were unable to protect partially filled fuel tanks from fire effects. This latter failure mode prompted the NGV industry to use thermally activated PRDs (no burst disk).

2.3 Pressure Relief Valves

The concept of using reclosing pressure relief valves (PRV) on each vehicle fuel system was considered as a means of providing overpressure protection onboard vehicles in addition to the use of thermally activated PRDs. The driving force for the use of reclosing PRVs was due to the possibility that vehicles could fill on a cold day, then park indoors and warm up, increasing the pressure and causing a vent to occur. In this case, a reclosing PRV would prevent the entire fuel tank contents from venting into an enclosed space. However, it was feared that the PRVs could become unreliable when used in NGV service conditions, and once opened they may not properly reclose. In addition, more advanced filling control systems have been introduced into NGV service to account for temperature conditions during fill. Currently, the NGV industry primarily uses non-reclosing thermally activated PRDs to protect fuel tanks from vehicle fires.

2.4 Development of a PRD Performance Standard

Following the introduction of newer thermally activated PRD designs in the 1990's, there were nevertheless many cases of premature activation occurring. Causes of these failures included internal corrosion of components, creep of fusible metals, and damage of internal components due to ice formation in the vent line. These incidents prompted the development of a performance-based standard for NGV PRDs in 1998 (ANSI/IAS PRD 1). Since its publication, the number of unintended releases of PRDs has decreased dramatically.

2.5 Recent NGV Tank Failures

Since 2000 there have been over 20 documented NGV tank failures in service, 11 of which have been attributed to vehicle fires. Of these 11 incidents, the evidence suggests that the majority of the PRDs failed to activate. In many cases the failure mode was related to a lack of heat directed at the PRD due to a localized fire. The effect of a localized fire on the structural integrity of the fuel tank is the one critical failure mode requiring additional consideration in the development of future codes and standards for both NGV and compressed hydrogen fuel systems.

3.0 HYDROGEN VEHICLE FIRE PROTECTION STRATEGIES

3.1 A Strategy Based on NGV Experience

The fire protection strategy for compressed hydrogen vehicle fuel systems is based on the experience of the NGV industry, i.e. with the use of a non-reclosing thermally activated PRD. Hydrogen fuel system PRDs are presently qualified to the performance requirements specified in draft hydrogen standards such as ANSI/CSA HPRD 1 and EIHP Rev. 12b. Both of these documents include tests derived exclusively from the NGV PRD requirements in ANSI/IAS PRD 1.

Hydrogen fuel system PRDs are also qualified with individual fuel tank designs in accordance with the engulfing bonfire requirements in various published/draft tank standards such as CSA B51 Part 2 (published), JARI S001 (published), SAE TIR J2579 (draft), ANSI/CSA HGV 2 (draft), ISO DIS 15869.2 (draft) and EIHP Rev. 12b (draft).

3.2 The Effect of a Higher Working Pressure

Hydrogen fuel systems can operate at pressures up to 70 MPa. Due to the strength-to-weight limitation of all-metal (Type 1) and metal hoop-wrapped (Type 2) tank designs at such high pressures, hydrogen vehicles typically employ tanks constructed with a fully-wrapped composite metal liner (Type 3) or plastic liner (Type 4). The insulating characteristics of the fully-wrapped composite material is such that minimal heat is transferred to the contained gas when Type 3 and 4 tanks are exposed to a fire. This attribute coupled with the fact that compressed hydrogen experiences a lower pressure rise with temperature compared to CNG, strongly reinforces the design principle that "pressure" activated relief devices cannot safely protect pressurized hydrogen fuel systems from the effects of fire.

High pressure Type 3 and 4 hydrogen fuel tanks experience high gas temperature rise due to heat of compression during the fueling process. This phenomenon is particularly significant at 70 MPa working pressures, which has prompted the industry to consider pre-cooling of the hydrogen prior to fueling. These higher gas temperatures during fueling necessitate a careful consideration of PRD eutectic creep behaviour for the case of 70 MPa PRDs.

High pressure hydrogen fuel tanks are inherently safer than fuel tanks operating at lower working pressures (e.g. NGV tanks). This is due to the fact that the thicker composite wrap provides both structural and thermal damage protection. Although this benefit would suggest that high pressure hydrogen tanks are more resistant to the effects of engulfing fires compared to NGV tanks, testing has shown that all fuel tanks regardless of working pressure are highly susceptible to rapid degradation due to localized fires. Rapid-activating PRDs are critical to the protection of all such fuel tanks, but these devices alone may not be sufficient to mitigate the effect of localized fires.

3.3 Bonfire Testing of Hydrogen Tanks

3.3.1 Engulfing Bonfire Test

As discussed previously, all fuel storage tank designs must undergo a standardized bonfire test to ensure the PRD can adequately protect the tank in the event of a vehicle fire. The bonfire test is performed using a 1.65 m long fire (created with a gasoline/diesel pan or LPG burner) that produces flame impingement along the entire length of the pressurized tank. Assuming that sufficient heat is provided to the PRD, the device activates and safely vents the tank contents before the fire can weaken the structural integrity of the tank and cause a rupture.

The current engulfing bonfire test procedure is based on a U.S. DOT fire test developed in the 1970's for application to composite air-breathing cylinders of relatively small size. It does not take into account tanks that may be longer than the specified 1.65 m length. In addition, the consistency of the test procedure is somewhat suspect between test-to-test and between test lab-to-test lab. For example, diesel pan fires tend to burn hotter than LPG-fed fires (gas phase), allowing certain combinations of tanks/PRDs to perform safely in one test, but not in the other test. Finally, engulfing bonfire tests do not evaluate the tank's susceptibility to localized fires.

3.3.2 Localized Bonfire Test

If a vehicle fire is such that the tank is subjected to localized flame impingement only, i.e. no heat is provided to the PRD, the tank will rupture. A localized bonfire test, i.e. one in which a pressurized fuel storage system is subjected to a directed flame, can determine whether the system can withstand such an incident. Although no such test is currently specified in NGV or compressed hydrogen tank standards, the latest draft of SAE TIR J2579 includes the following language on the subject of localized fire tests:

> *The vehicle manufacturer should investigate potential sources of localized fires with respect to the exposure of the storage system and the release of the thermally activated PRD to ensure that the storage system will not rupture from identified fire sources (Section 5.2.6.3.2).*

The development of a localized bonfire test procedure would need to consider the size, intensity, location and length of time for the localized exposure. In addition, the industry would need to agree on whether acceptable (safe) performance is exemplified by either the tank venting its contents, or withstanding the specified length of exposure, i.e. no venting and no rupture after 30 minutes (for example).

In order to meet the "vent" requirement of a localized bonfire test, tanks would require a zonal network or array of PRDs covering its entire surface area. Alternatively, a fuse network designed to conduct heat to a remotely situated PRD could be employed to ensure venting. The "no vent" condition could be met through the use of either thermally insulating coatings or thermal encapsulation of the fuel system.

3.4 Thermal insulation of Hydrogen Fuel Systems

The concept of thermally insulating a pressure vessel from the effects of both engulfing and localized fires involves the application of a thin layer of ceramic material (or other heat resistant coating) to the outer surface of the composite wrap. While the outer surface can sustain flame temperatures exceeding 800°C, the inner surface of the coating (outer surface of the reinforcing composite wrap) experiences temperatures below 200°C. Figure 1 shows a fire test conducted on a composite tank coated with a sprayed ceramic insulating material. Figure 2 is a photograph showing the intact condition of a composite tank wrapped with a ceramic blanket after having been exposed to an intense localized fire for 45 minutes.

An alternative method of imparting fire protection to the fuel tanks would be to encapsulate the entire fuel system in a protective shell consisting of a thermally insulating foam. This concept is illustrated in Figures 3 and 4. Protective encapsulation not only imparts fire protection but also provides an additional level of impact protection to the fuel system. This may allow tank designers to reduce the amount of reinforcing composite material which could reduce the cost and weight of future hydrogen fuel storage systems.

3.5 Hydrogen Fuel System Installation Requirements

A review of NGV fuel system installation codes and standards such as CSA B109 and NFPA 52 reveals a single common requirement with respect to vehicular fire protection, i.e. manufacturers must ensure that the PRD is in the same physical compartment as the fuel tank it is protecting.

Recent NGV tank failure experience suggests that localized fire is the single-most critical unresolved failure mode in the industry. Although the development of a localized fire test for inclusion in future hydrogen vehicle fuel system standards will likely mitigate this failure mode, it is recommended that future hydrogen vehicle fuel system installation standards also draw attention to this issue. At a minimum, future hydrogen vehicle fuel system installation standards should draw attention to the potential for localized fires and recommend that vehicle designers prevent localized fires impinging on vehicle fuel tanks. In fact, the requirement may involve a careful balance between mitigating flame impingement on the fuel tank while at the same time ensuring the PRD is not shielded.

4.0 SUMMARY

The fire protection strategy for compressed hydrogen vehicle fuel systems is based on the experience of the NGV industry. Hydrogen tanks are protected from fire effects through the use of non-reclosing thermally activated PRDs.

The standardized engulfing bonfire test procedure is purely arbitrary, provides inconsistent results, and does not consider the possible effect of localized fires.

The development of a localized bonfire test, i.e. one in which a pressurized fuel storage system is subjected to a directed flame, can determine whether the fuel system can withstand such an incident.

A number of fire protection strategies are available to hydrogen fuel system designers, namely:

(a) Network/array of point source PRD protection across the surface area of the tank
(b) Fuse device designed to conduct heat to a remotely situated PRD
(c) Thermally insulating coatings or encapsulating fire resistant foam

Hydrogen vehicle fuel system installation standards should draw attention to the potential for localized fires and recommend that vehicle designers prevent localized fires impinging on vehicle fuel tanks. This requirement may involve a careful balance between mitigating flame impingement on the fuel tank and ensuring the PRD is not shielded.

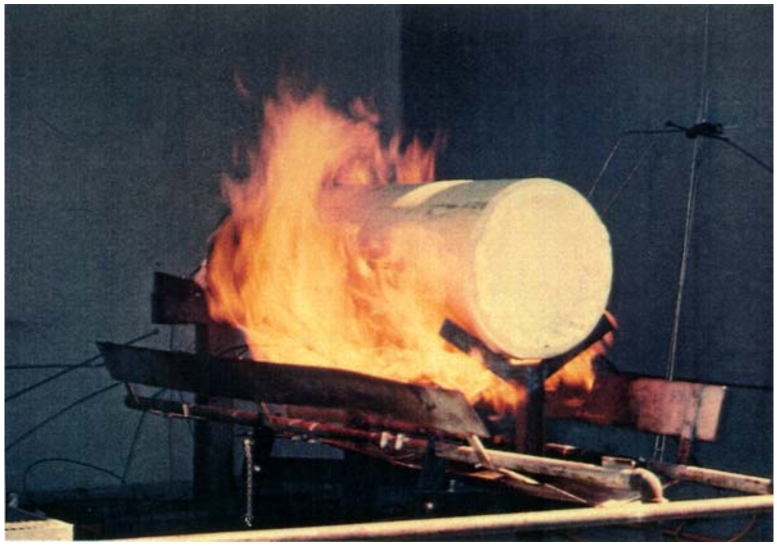

Figure 1: Fire test conducted on a composite tank coated with a sprayed ceramic insulating material.

Figure 2: Photograph showing the intact condition of a composite tank wrapped with a ceramic blanket after having been exposed to an intense localized fire for 45 minutes.

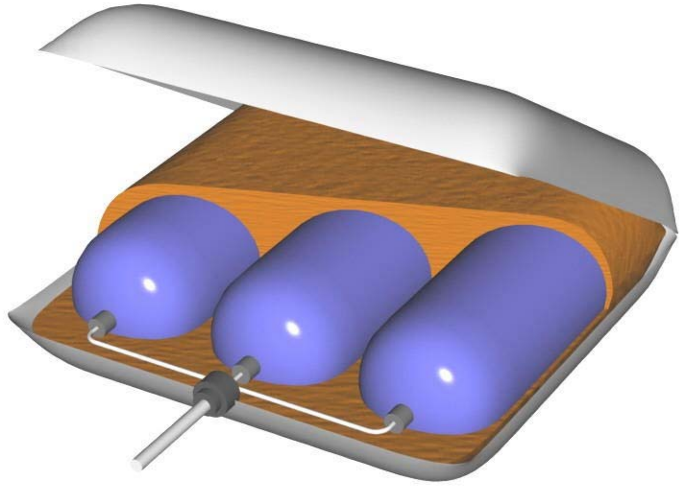

Figure 3: Schematic of proposed encapsulated fuel system.

Figure 4: Protective shell encapsulating a fire resistant foam can impart fire protection and an additional level of impact protection to the fuel system.