

CNG and Hydrogen Vehicle Fuel Tank Failure Incidents, Testing, and Preventive Measures

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ABSTRACT

Compressed Natural Gas (CNG) vehicle fuel tank design, fabrication, and testing standards are intended to minimize tank failures. The various standards for both CNG and hydrogen cylinders are reviewed here with an emphasis on the fire exposure testing conducted in accord with the standards and the tests conducted to determine the consequences of pressurized tank failure. Field experience with CNG fuel cylinders and anecdotal descriptions of the reported tank damage and tank failure incidents are also described to demonstrate that several cylinder failures have occurred because the exposure fire did not actuate the cylinder Pressure Relief Devices. Possible revisions to fuel tank fire exposure testing and to tank thermal protection and inspection to prevent future incidents are recommended.

1. INTRODUCTION

The worldwide population of Natural Gas fueled vehicles has been growing at an annual rate of 31% since 2000, reaching about 7 million vehicles in June 2007 (1). In the United States, there were 147,000 natural gas vehicles in June 2007, with an annual growth rate of about 4% (1). The overwhelming majority of the U.S. natural gas vehicles use Compressed Natural Gas (CNG) fuel tanks.

Although there were only a few hundred hydrogen fueled vehicles in the U.S. in 2007, Department of Energy funding and research programs are intended to advance the technology and refueling infrastructure to the point that many more hydrogen fueled vehicles will be built in the next few years. Several of the automobile companies have also announced commitments to develop new few cell vehicles with hydrogen on board storage. For example, Honda says its FCX Clarity fuel-cell car is production-ready, but it requires a hydrogen infrastructure that does not exist yet (2).

Both CNG and hydrogen are stored on board in cylindrical pressure vessels. The following four types of cylinders have been used.

- **Type 1** container is a metallic non-composite container.
- **Type 2** container is a metallic liner over which an overwrap such as carbon fiber or fiberglass is applied in a hoop wrapped pattern over the liner's cylinder sidewall.
- **Type 3** container is a metallic liner over which an overwrap such as carbon fiber or fiberglass is applied in a full wrapped pattern over the entire liner, including the domes.
- **Type 4** container is non-metallic liner over which an overwrap such as carbon fiber or fiberglass is applied in a full wrapped pattern over the entire liner, including the domes.

CNG on-board containers are usually rated for storage¹ at 3,600 psi (24,821 kPa, 248 bar). Most hydrogen cylinders are rated for storage at 5,000 psi (34,450 kPa, 345 bar), but some new hydrogen cylinders are rated for 10,000 psi (68,900 kPa, 690 bar) storage. Compressed flammable gas on-board storage at these high pressures requires comprehensive standards for container design and construction and ability to withstand various anticipated abuses and other extreme exposures. The following section provides a summary of the container standards and associated testing requirements that have been developed for these applications. The emphasis is on the current requirements for withstanding fire exposures.

2. CNG Fuel Tank Standards and Test Requirements

FMVSS 304

U.S. federal requirements for CNG vehicle fuel tank integrity are described in FMVSS 304 (3). The stated purpose of FMVSS 304 is “to reduce deaths and injuries occurring from fires that result from fuel leakage during and after motor vehicle crashes.” The FMVSS 304 container requirements, which were developed based on the ANSI standard NGV2 (4), include ambient temperature pressure cycling tests without leakage, a hydrostatic burst test, and a bonfire test. The hydrostatic burst pressure is required to be at least 2.25 times the cylinder service pressure for non-welded cylinders, and at least 3.5 times the service pressure for welded containers. There are also detailed cylinder labeling requirements in FMVSS 304.

The bonfire test described in FMVSS 304 and in DOT TP304-03 (5) requires that two CNG tanks be tested, with one filled to 98% of its service pressure and the second tank filled to 24% of its service pressure. Each cylinder is positioned horizontally above a 1.65 m (65 inch) long burner or flame bed. Since most CNG cylinders are equipped with a thermally actuated Pressure Relief Device (PRD) next to the cylinder valve, the test has specific requirements for the cylinder and PRD location above the burner, as shown in Figures 1a and 1b. Cylinders shorter than 1.65 m are situated over the centerline of the burner, but cylinders longer than 1.65 m are situated such that the PRD(s) and valve are not directly exposed to the burner flame. The PRD on the short cylinder shown in Figure 1a is required to be shielded from the burner flame by surrounding it with a box made of steel plate (5). If the cylinder is

¹ Cylinder pressure ratings are specified in terms of a settled service pressure, which is defined as the filled container gas pressure at a uniform temperature of 21 °C, i.e. after any compressive heating, associated with gas filling, has been dissipated.

protected with thermal insulation instead of a PRD, it is positioned symmetrically with its center directly above the center of the burner.

Although the burner fuel and flame heat release rate are not prescribed in FMVSS 304, there are prescriptions for the gas temperatures exposing the cylinder. Three thermocouples are installed 1 inch (2.54 cm) above the bottom of the cylinder, equally spaced along a line parallel to the cylinder longitudinal axis. The average gas temperature measured with these thermocouples must be at least 430 °C within five minutes from flame ignition.

The CNG container must successfully withstand exposure to the bonfire flame for at least 20 minutes, or until the gas contents of the container are vented via the PRD to a pressure less than 100 psig (689 kPa), as measured with a pressure transducer.

NGV2

The ANSI NGV2 standard (4) requires several other tests in addition to the pressure cycling, hydrostatic burst pressure test, and bonfire test required by FMVSS 304. These additional tests include drop testing with various cylinder orientations, bullet penetration tests to demonstrate that the cylinder will not fragment, and environmental exposure tests. The latter include temperature extreme exposures and corrosive liquid exposures. Newhouse et al. (6) and Trudgeon (7) have provided summaries of these tests and minimum acceptable results.

ISO 11439

The NGV2 standard was the starting point for the development of the ISO 11439 international standard for NGV fuel tanks (8). Besides specifying various abuse and environmental exposure tests, ISO 11439 provides cylinder design guidance including more detailed specifications on the ratio of the minimum burst pressure to the service pressure and the minimum fiber stress ratio for various types of fibers in Type 2, Type 3, and Type 4 cylinders. It also requires the cylinder manufacturer to specify the intended service life in years, and to demonstrate that the cylinder can withstand pressure cycling for a minimum of 1,000 cycles per year times the specified service life. ISO 11439 also requires that the maximum allowable flaw or defect size be detectable by cylinder Non-Destructive Examination.

NGV and CNG Fuel System and Component Tests

The National Highway Traffic Safety Administration (NHTSA) requires U.S. NGVs to be crash tested in accord with FMVSS 303 to verify that vehicle fuel system leakages in crashes do not exceed specified limits equivalent to those for gasoline fueled vehicles. ANSI standard PRD1 specifies minimum requirements for PRDs, while ANSI NGV3.1 specifies requirements for other fuel system components. Chapter 4 of NFPA 52-2006 (9) specifies NFPA requirements for NGV fuel system pressurized components, including requirements for ten particular components to be listed or approved. CGA C-6.4 (10) provides information and procedures for the periodic visual examination and inspection of natural gas (and hydrogen) vehicle fuel containers which are certified to meet the ANSI NGV2 standard.

3. Hydrogen Fuel Tank Standards and Test Requirements

Due to the relatively small number of hydrogen fueled vehicles currently on the roadways, there are not yet any NHTSA regulations for hydrogen fueled vehicles that would be the equivalent of FMVSS 303 and 304. However, the following consensus national and international standards for hydrogen vehicle fuel containers and fuel systems are currently under development.

ISO/DIS 15869.2 (11) is the draft ISO standard for hydrogen fuel tanks. It was originally drafted as an equivalent to ISO 11489 for CNG tanks (including a similar bonfire test) with special requirements for hydrogen material compatibility and for hydrogen permeation testing. When ISO/DIS 15869.2 was balloted by ISO, it did not pass by one vote. One of the negative votes was by the U.S. delegation, partly because ISO/DIS 15869.2 conflicted with the U.S. draft standard for hydrogen fuel systems, the new SAE J2579 (12). One important difference between the approach in SAE J2579 and the NGV2 approach is that SAE J2579 is intended as a vehicle fuel system standard for vehicle OEMs whereas NGV2 is a tank standard developed primarily for the vehicle aftermarket.

Figure 2 is a schematic diagram of the fuel system addressed in SAE J2579. The dashed line designates the boundary of the hydrogen storage system, which includes the PRD, the container isolation valve and the fill check valve. The standard includes requirements for minimum hydrogen leakage in crash tests analogous to those in FMVSS 303 for CNG and FMVSS 301 for gasoline fuel systems. There is also a currently ill defined vehicle level fire exposure test. According to the chair of the SAE committee responsible for SAE J2579, since the details of the test requirements and methods of verification are currently undergoing verification testing, the document will be issued as a SAE Technical Information Report rather than a standard.

Chapter 5 of NFPA 52-2006 describes NFPA requirements for vehicle hydrogen fuel systems in a manner that is consistent and equivalent to the Chapter 4 requirements for CNG vehicle fuel systems. One special requirement in Chapter 5 is the designation of specific metals and alloys that are not compatible with high pressure hydrogen storage.

4. CNG Cylinder Failure Incidents

Overall, there apparently have been relatively few CNG cylinder failure incidents in the U.S. Newhouse et al. (6) report that there were eight cylinder ruptures in the nine year period from 1993 through 2001. The U.S. NGV population increased from near zero to about 100,000 vehicles during that time, corresponding to an average annual vehicle population of about 50,000 vehicles. Thus, the approximate frequency of cylinder ruptures during this period is about one rupture per 56,000 cylinder-years.

The relatively small number of CNG cylinder failures is remarkable in view of the field abuse to which vehicle installed cylinders have been subjected. Newhouse et al. (6) report that their company's Type 3 cylinders had not experienced a rupture as of 2002 despite numerous crash, impact, and vehicle fire incidents. The incidents described by Newhouse et al. include CNG tanks striking a bridge with a force that sheared off part of the structural support wrap as shown in Figure 3. Even with this damage, subsequent burst pressure testing revealed that the degraded tank could satisfy the FMVSS 304 burst pressure requirements for a new tank.

According to Newhouse et al. (6), three of the eight CNG cylinder ruptures prior to 2002 were caused by glass fiber stress corrosion cracking due to [battery] acid exposure. Four

other tanks ruptured due to severe physical tank damage, and one tank failed due to over-pressurization.

There have been several fire incidents resulting in CNG cylinder PRD actuation and subsequent cylinder depressurization. Figure 4 is an aerial overhead image of one such incident involving a transit bus. As in most such incidents, the PRD actuation resulted in the gas jet being ignited by the exposure fire (in this case an engine fire) and resulting in a jet flame.

Since 2001, there have been at least two CNG cylinder ruptures due to fire exposures that did not cause PRD actuation. In September 2002, a cylinder located behind the rear seat in a Ford Crown Victoria ruptured because flame from the interior of the vehicle impinged on the cylinder without exposing the cylinder PRD. According to the NHTSA incident investigation (NHTSA Action Number EA03001), the direct flame impingement on the cylinder “compromised the hoop strength of the natural gas cylinder, thus allowing the cylinder to fail prior to the PRD releasing at its designed temperature.” Figure 4 is an example of a composite cylinder (not the one in this incident) with localized flame impingement damage. Since then, Ford has developed an insulator to protect the cylinder from direct flame impingement from the vehicle interior. Ford has been installing these insulators behind the back seat of CNG fueled Crown Victoria vehicles.

A similar incident occurred in a CNG fueled Honda Civic in Seattle in March 2007. According to the Seattle Fire Department (13), an arsonist set fire to a row of parked vehicles in an outdoor lot. Seattle firefighters responding to the fire were 50 to 75 ft (15 to 23 m) away from the Honda and approaching it with a handline when the CNG tank exploded and rocketed. Figure 6 shows the burned remains of the Honda Civic, and Figure 7 shows the remains of the Type 4 CNG tank about 100 ft away from the Honda. Other large debris from the Honda was found 75 to 90 ft (23 to 27 m) away from the vehicle. Fortunately, nobody was injured in this incident. Since this incident, the fire NHTSA and Honda investigations have led to Honda installing insulators between the back seat and the CNG tank (NHTSA Action Number: PE07028), as Ford did with the CNG fueled Crown Victoria.

In May 2007 a fatal CNG fuel tank rupture occurred in Carson, California. The rupture occurred as the cylinder was being refueled with CNG. According to the CBS News account of the incident (<http://cbs2.com/local/Carson.Gas.Tank.2.531822.html>), the CNG fueled van had been in an accident three weeks earlier, and had just been returned to the driver from the repair shop the night before he was killed. This information raises obvious concerns about the fitness of the CNG cylinder that may have been damaged in the collision.

Since the U.S. population of CNG fueled vehicles is only about 2% of the worldwide population, it is instructive to also briefly review CNG cylinder failure incidents outside the U.S. There have been several anecdotal accounts of fire induced CNG cylinder ruptures in India, and at least one rupture during refueling in Thailand. However, the Thailand incident was due to the illegal use of an acetylene cylinder for CNG, and the details of the Indian CNG tank and PRDs (if any) are not available. A more comprehensive description of CNG cylinder failure incidents in Europe was recently reported by Perrette and Wiedemann (14).

Perrette and Wiedemann (14) describe three fire induced CNG cylinder failures aboard buses in Germany and France. CNG cylinders in Europe are qualified in part based on the same type of bonfire exposure test required by FMVSS 304 and NGV2. The failed CNG cylinder in Germany was a PRD protected Type 3 cylinder with a fill volume of 172 liters and a fill pressure of 200 bar (2900 psi). An engine fire starting in one articulated bus spread to a second bus in a depot, resulting in fire exposure to a total of 20 roof mounted CNG

cylinders. The double PRDs on all but one of the cylinders actuated at or around their 110°C actuation temperature. The 20th tank ruptured about 15 minutes after the fire started. The ruptured tank rocketed through the depot wall, leaving the hole and charred bus shown in Figure 8. The inside of the un-actuated PRD is shown in Figure 9.

The two French CNG bus fires described by Perrette and Wiedemann (14) occurred on buses equipped with nine roof mounted Type 4 CNG tanks rated for 200 bar service pressure. One fire started in the bus battery and eventually spread through the bus, including the roof. One cylinder ruptured 20 minutes after ignition as it was exposed to a combination of the fire through the roof hatch and the jet fire from an adjacent cylinder with an actuated PRD. The main fragment from the ruptured tank was found on the roof of a house about 30 m from the bus. There was some minor blast damage as far as 60 m from the bus. The second French bus fire was started by vandals throwing a Molotov cocktail into the bus passenger compartment. One roof mounted cylinder ruptured after exposure to the fire that spread to the roof through the roof hatch.

These incidents demonstrate that catastrophic, sometimes fatal, cylinder ruptures can and do occur, and that even more vigilance is needed. The fire exposure incidents in which the cylinder PRDs did not actuate raise concerns about the adequacy of the bonfire test configuration in FMV304 and NGV2. One possible revision would be to conduct smaller exposure fires directed toward the center of the cylinder, away from the PRDs. Another option would be to conduct vehicle fire tests instead of isolated cylinder fire exposure tests.

5. Hydrogen Cylinder Rupture Testing

Although there have not yet been any reported hydrogen cylinder ruptures on hydrogen fueled vehicles, hydrogen cylinders are susceptible to the same failure modes as CNG cylinders. Since these include failure of the cylinder PRD to actuate in a fire, it is useful to determine the consequences of hydrogen cylinder rupture resulting from fire exposure. Two tests have been conducted with Motor Vehicle Fire Research Institute funding in order to determine those consequences. Descriptions of those tests have been reported by Zalosh and Weyandt (15, 16, and 17). The following is a brief summary.

Both tests were conducted with propane burner fires under cylinders filled with hydrogen at a pressure of 32 to 34 MPa (4600 to 4900 psi) without PRDs. One test was conducted with a 72 liter Type 4 cylinder by itself, while the second test was conducted with an 88 liter Type 3 cylinder installed under a Sports Utility Van as shown in Figure 10. The Type 4 cylinder ruptured after 6 minutes 27 seconds of fire exposure. The burner flame ignited the SUV (see Figure 11) before the Type 3 cylinder ruptured after 12 minutes 18 seconds of fire exposure. In both cases, the cylinder wraps prevented the hydrogen temperature and pressure from increasing significantly above their pre-test values.

The Type 4 hydrogen cylinder primary remains were found about 82 m away from the burner. The largest fragment of the Type 3 hydrogen cylinder was found about 41 m away from the burner. These fragments are shown in Figures 12a and 12b. Note the similarity to the ruptured Type 4 CNG cylinder from the Seattle fire (Figure 7). SUV fragments from the second test were found at distances up to 107 m away from the original SUV location.

Representative blast pressures measured in both tests are shown in Figure 13. The ideal blast wave pressures calculated for blast energies of 13 MJ and 15 MJ are also shown in Figure 13. The blast energies were calculated from hydrogen isothermal expansion from the

tank rupture pressure as described by Zalosh (16). The agreement with the data demonstrates the viability of blast wave calculations based on the cylinder pressure and volume.

Hydrogen fireballs resulted immediately after cylinder rupture in both tests. The fireball maximum diameter was 7.7 m in the cylinder only test, and about 24 m in the cylinder-under-SUV test. The larger fireball diameter in the SUV test indicates that the SUV fire at the time of cylinder rupture also contributed to the fireball.

The results of these tests suggest that the danger zone associated with hydrogen cylinder rupture extends to a radius of roughly 100 m from the hydrogen vehicle. In order to protect personnel and structures within this danger zone, it is important to develop additional cylinder rupture prevention measures.

Recommended Additional Cylinder Failure Prevention Measures

The cited accounts of CNG Type 3 and Type 4 cylinder failures from fire exposure in the area away from the PRD demonstrate that an additional thermal barrier is needed for these cylinders. The need for such barriers is not accounted for in the current standard bonfire tests, because the exposure flame extends over too large a length of the cylinder. It is necessary to revise or augment the current bonfire test with a more local exposure fire, such as a jet fire, that only heats a much smaller area of the cylinder.

Two vehicle manufacturers have decided to use vehicle installed thermal insulators to provide cylinder protection for fires originating within the vehicle. Another approach would be to use thermal coatings or wraps for the cylinders themselves. Many different types of intumescent and spray-applied coatings are available commercially and used for protecting metal tanks and structures. Research would be needed to determine their compatibility, cost, and longevity when applied to composite cylinders.

A third possible approach for local fire exposures would be to use linear heat detectors in conjunction with a cylinder vent valve. The linear heat detector would be wrapped around the cylinder, such that cylinder/detector surface temperatures (or rates-of-temperature-rise) above the detector set point would initiate a signal for a vent valve to actuate. Fusible links or spot detectors are currently used to actuate cylinder venting on some European CNG buses, but the locations of these fusible links or spot detectors did not provide sufficient coverage to prevent cylinder rupture in at least one of the reported European incidents (14).

The current practice and FMVSS 304 and NGV2 requirements for periodic cylinder visual inspection to detect degraded strength needs to be supplemented by a more reliable testing or inspection method. Chamberlain's analysis (18) of crack growth in metal cylinders shows that small subsurface defects such as micro cracks generated during typical manufacturing procedures can sometimes be exacerbated by stress corrosion and fatigue to the point that unstable crack growth leads to CNG cylinder failure. He recommends more extensive use of acoustic emission and other Non-Destructive Test (NDT) methods to detect large sub-surface defects that would not be seen in visual inspections. Since Chamberlain's analysis was limited to Type 1 cylinders, it would be helpful to analyze the benefits and potential effectiveness of more widespread use of these NDT methods for Type 2, 3, and 4 cylinders. It would also be useful to extend the Chamberlain analysis to hydrogen cylinders, accounting for potential hydrogen embrittlement effects.

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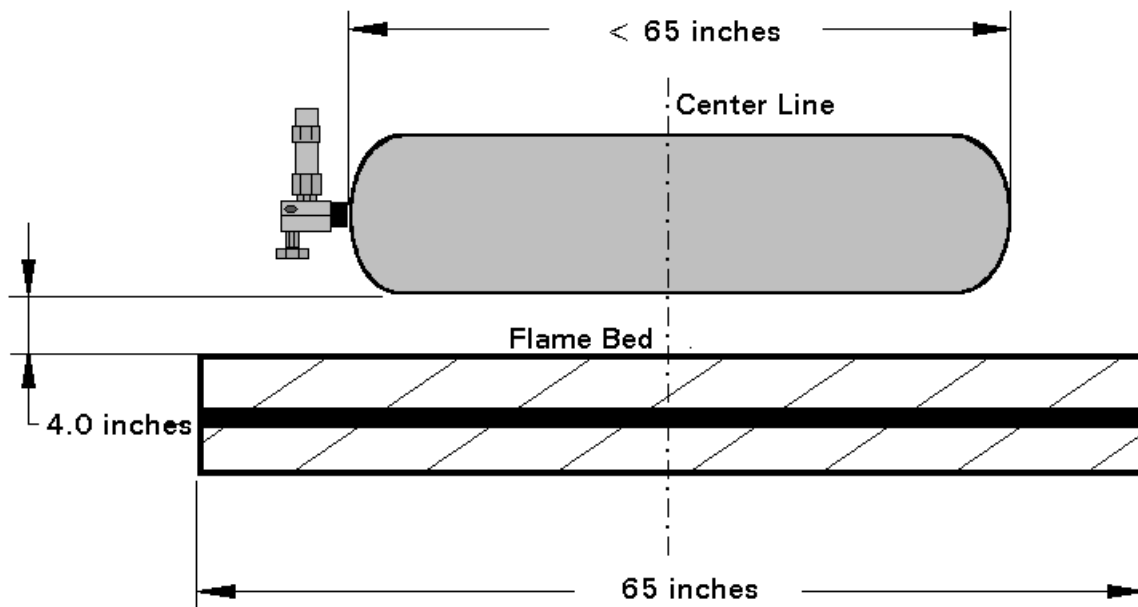


Figure 1a FMVSS 304 Bonfire Test for CNG cylinder shorter than 65 inches. From (5)

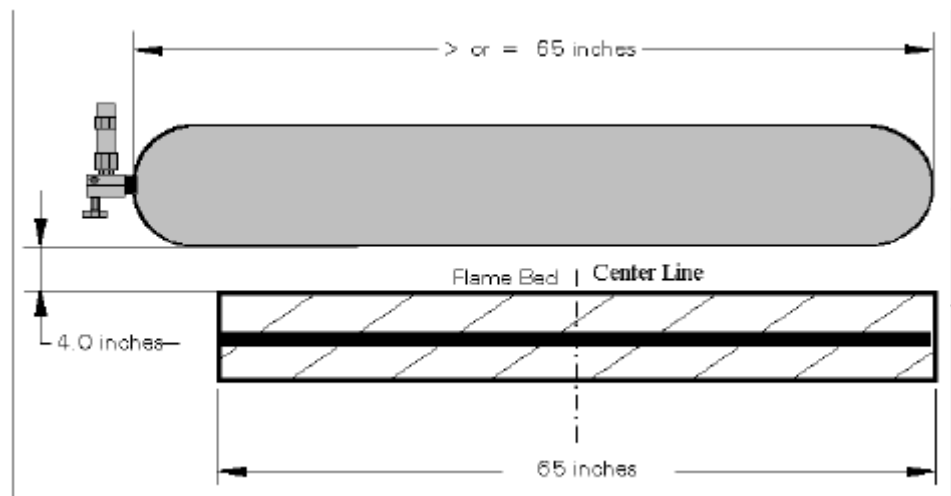


Figure 1b FMVSS 304 Bonfire test for CNG cylinder longer than 65 inches. From (5)

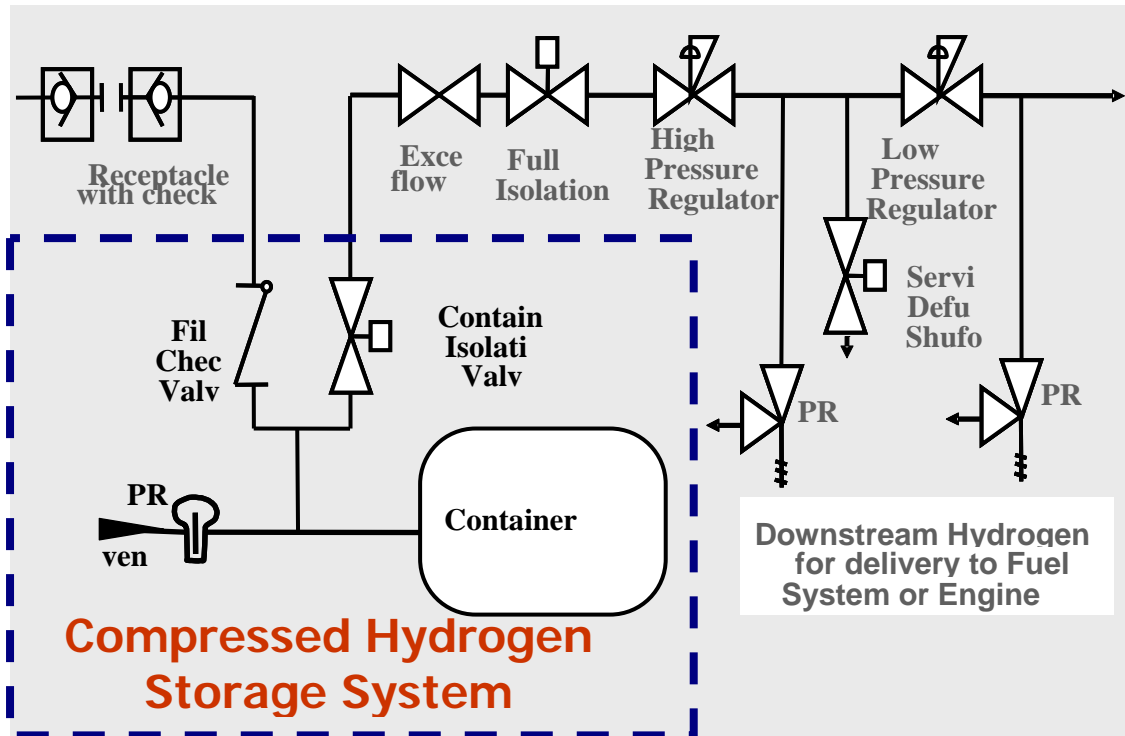


Figure 2 Hydrogen Fuel System in SAE J2579



Figure 3 Type 3 cylinder damaged by bridge impact (from Newhouse et al.)



Figure 4 Bus fire causing CNG tank PRD actuation

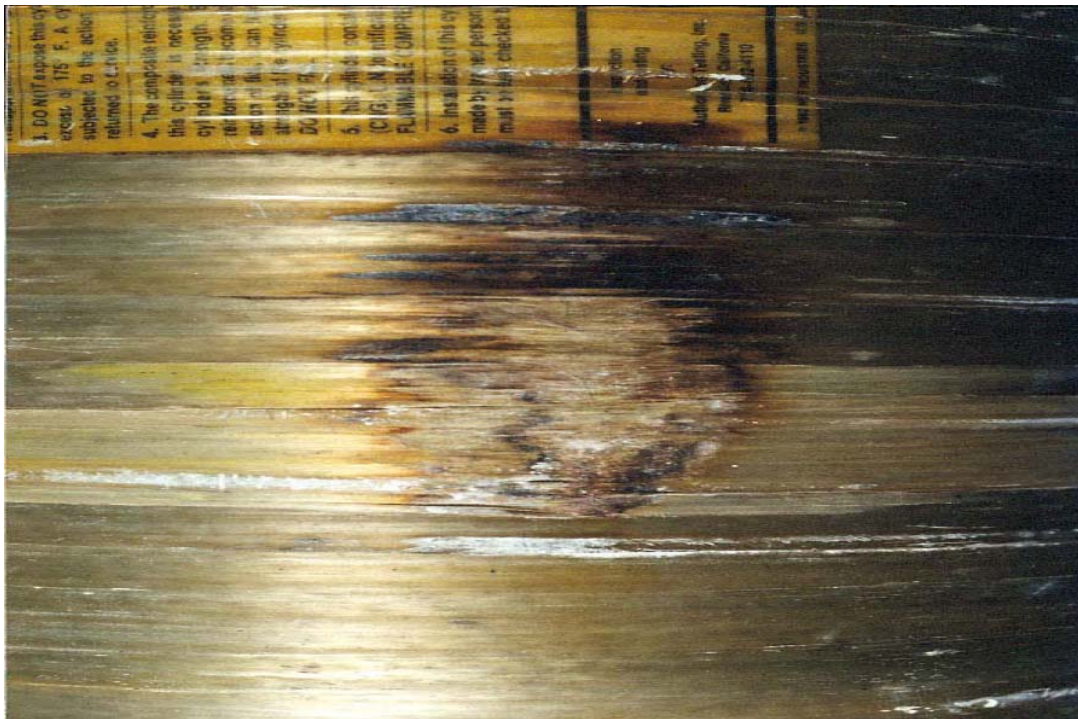


Figure 5 Composite overwrap with localized burn damage.



Figure 6. Remains of Honda CNG vehicle from March 2007 fire in Seattle.



Figure 7. Ruptured cylinder remains from Honda Civic GX fire in Seattle.



Figure 8 Burned CNG bus with arrow pointing to hole in depot wall (from Perrette and Wiedemann)

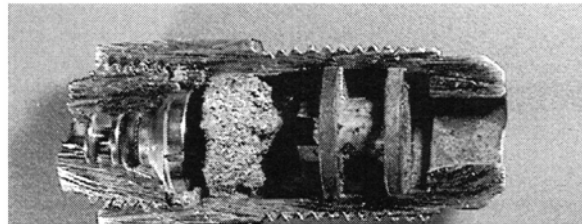


Figure 8 Un-actuated PRD on bus cylinder that ruptured (from Perrette and Wiedemann)



Figure 10 Burner below Type 4 cylinder under a SUV (from Zalosh)



Figure 11 Fire 9 minutes after ignition under hydrogen cylinder (from Zalosh)



Figure 12a Type 4 hydrogen cylinder fragment (from Zalosh)



Figure 12b Type 3 hydrogen cylinder fragment (from Zalosh)

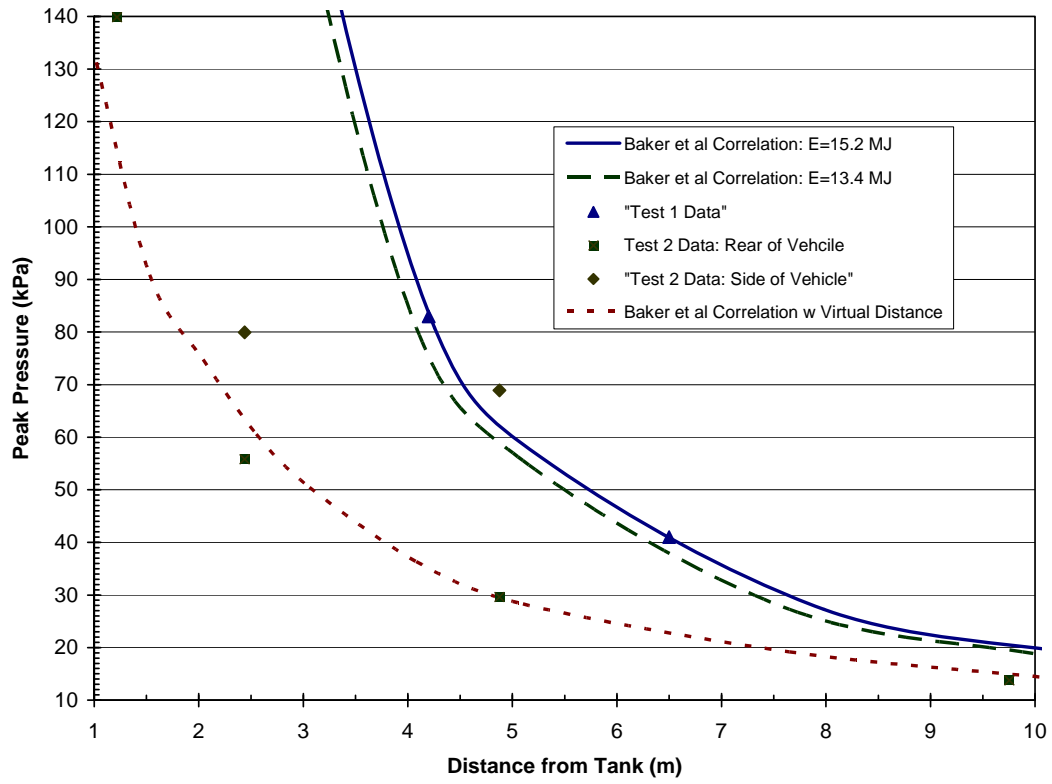


Figure 13 Cylinder blast wave pressures versus distance from cylinder (from Zalosh)