

Some Things to be Learned from the “Other” Compressed Gas Fuel System

Henry E. Seiff

Clean Vehicle Education Foundation

Copyright © 2008 CVEF

ABSTRACT

Compressed natural gas vehicles were first commercialized after World War II in Italy. There are now seven million CNG vehicles on the road worldwide. The first US CNG vehicle “incident” in our files dates to 1984. “Those who cannot learn from history are doomed to repeat it” (1), so this paper will explore a few of the things to be learned from CNG vehicle history that can help assure the safety of compressed hydrogen tanks and fuel systems.

A LITTLE BACKGROUND INFORMATION

Compressed natural gas as a motor vehicle fuel has been around for a long time.

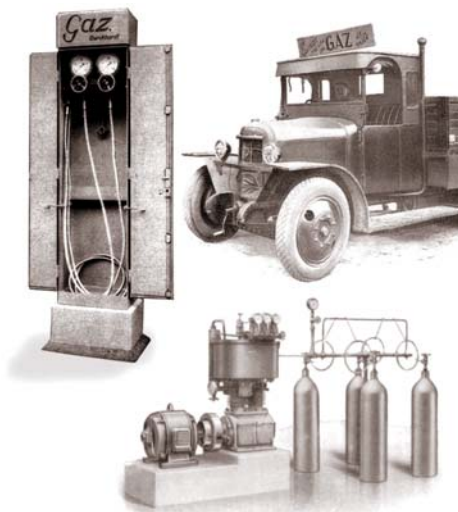


Figure 1: Historic CNG vehicle and equipment (2)



Figure 2: 1932 Chrysler "Ironsides" powered by a Mogas Natural Gas System (3)

Although low in number in the United States, worldwide there are seven million natural gas vehicles (NGVs) on the road today and a target of 50 million for 2020 (4). Natural gas vehicles offer some major advantages, such as:

- they use zero petroleum
- they are inherently cleaner burning than gasoline or diesel
- they produce around 25% less Greenhouse gas
- the fuel is less expensive on an energy equivalent basis

and some disadvantages:

- the fuel system costs more to produce
- the fuel system takes up more space and weighs more for the same driving range
- there is a limited natural gas fueling infrastructure in place

Interestingly, the safety record of natural gas vehicles has proved to be as good as, if not better, than petroleum-powered vehicles. (5)

It is also interesting, but not surprising, that the advantages and disadvantages of natural gas (which is almost all methane) as a vehicle fuel are similar to those of hydrogen. Four-fifths of the atoms in a natural gas molecule are

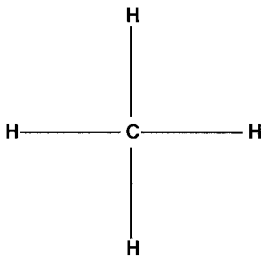


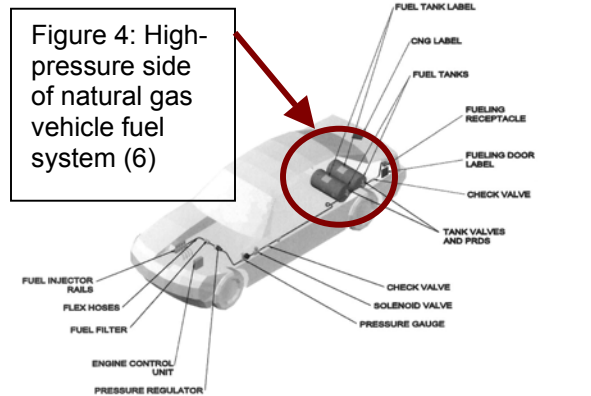
Figure 3: Natural gas molecule is 4/5 hydrogen.

hydrogen and vehicular natural gas is most often transported in high-pressure cylinders, just like hydrogen.

So, given that “those who cannot learn from history are doomed to repeat it,” what can be learned from 60 or more years of experience with natural gas vehicles, particularly, what can be learned from our experience with compressed natural gas fuel systems, which are likely to be very similar to compressed hydrogen fuel systems if and when hydrogen-powered vehicles become popular?

A VEHICULAR COMPRESSED GAS FUEL SYSTEM PRIMER

This paper concentrates on the high-pressure cylinder and related items, particularly the cylinder and the pressure relief device normally used to protect against cylinder rupture in a fire.



The safety of CNG cylinders is assured by Federal Motor Vehicle Safety Standard 304 (7), as well as ANSI/CSA NGV2 (8), the industry standard generally adhered to in the US, which is somewhat more stringent than FMVSS 304. Hydrogen cylinder safety standards are being written by both CSA and SAE at this time.

Four types of cylinders are normally used for vehicular compressed gas fuel (8):

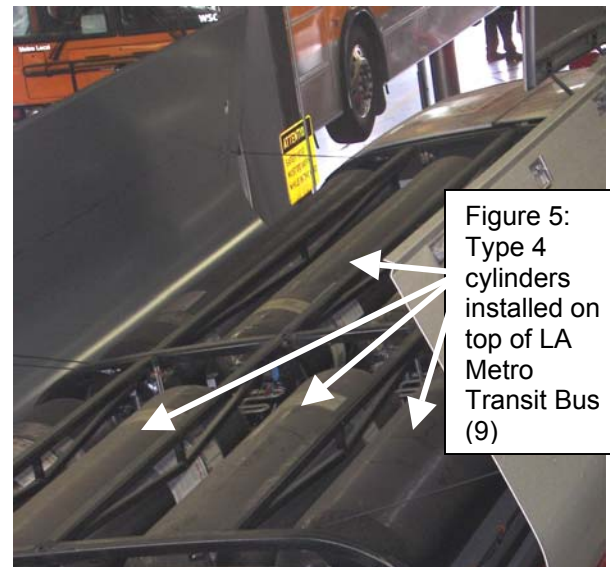
Type 1 – Metal

Type 2 – Resin impregnated continuous filament with metal liner with a minimum burst pressure of 125% of service pressure. The container may be either hoop-wrapped or full-wrapped.

Type 3 – Resin impregnated continuous filament with metal liner. The container may be either hoop-wrapped or full-wrapped.

Type 4 – Resin impregnated continuous filament with a non-metallic liner.

Type 1 steel cylinders are the least expensive and the heaviest. They are generally used on CNG vehicles in the developing world. Type 3 and 4 cylinders, wrapped with fiberglass and/or carbon filament, are the lightest and most expensive cylinders. Because of their relatively light weight (1/4 – 1/2 the weight of an equivalent steel type 1 cylinder), they are generally used in the US on OEM natural gas vehicles, such as transit buses and are the type of cylinders normally considered for vehicles operating on compressed hydrogen.



The service pressure of vehicular CNG cylinders worldwide is normally 200 Bar (3,000 psi), although most US CNG vehicles operate at 250 Bar (3,600 psi). Since hydrogen must be compressed to much higher pressures to provide a sufficient amount of energy in a reasonable space, pressures of 350 - 700 Bar (5,000 – 10,000 psi) are being considered.

The standards under which CNG cylinders are built assure that they will withstand at least 2.25 times service pressure and “leak before burst” (LBB) if punctured or cycled. In particular, the standards require that the cylinder shall not rupture after having been “penetrated by an armor piercing bullet with a diameter of 7.62 mm” (§18.11, ANSI/CSA NGV2-2000) or when subjected to a minimum of 11,250 cycles at 125% of service pressure (§12.5.2.1). They also undergo a number of other tests to assure safety, such as an accelerated stress rupture test, a drop test, and exposure to various corrosive environmental fluids.

To avoid potential rupture, cylinders must be protected with pressure relief devices. Despite their name, these PRDs must be designed to protect against fire, not excessive pressure (although some PRDs protect against both). The logic behind this is two-fold:

- 1- The fueling dispenser has at least two levels of overpressure protection, so it is relied on to assure that the cylinder is not over pressurized during fueling. This leaves a vehicle fire as the only reasonable way a cylinder might experience excessive pressure.
- 2- When exposed to a fire, the gas in Type 1 (all metal) cylinders could be expected to increase in pressure as it heats up and vent through a **pressure** relief valve before a cylinder ruptured. However Types 2-4, especially Types 3 and 4 cylinders, would likely have their strength compromised by the fire before the pressure increased enough to vent through a pressure relief valve. Therefore they must be protected by a temperature sensitive PRD.

Both the government (FMVSS 304) and industry (ANSI/CSA NGV2) CNG cylinder standards provide for a bonfire test to assure that the PRD operates properly. The industry ANSI/CSA PRD1 (10) standard sets other safety

requirements of PRDs used on CNG vehicles. A hydrogen version of PRD1 (HPRD1) is currently under development by the industry.

In addition to these design and test requirements to assure natural gas vehicle safety, cylinders and their accompanying fuel systems should undergo a detailed safety inspection at least every three years or 36,000



Figure 6: CNG cylinder label with inspection requirements (11)

miles or when they have been involved in collisions, accidents, fires or other damage (ANSI/NGV2 §§4.1.4 & 4.1.5) Specific inspection procedures are provided in the Compressed Gas Association’s pamphlet C-6.4, supplemented by the cylinder manufacturer’s own inspection instructions. There are a number of ways of providing the “qualified” inspectors required by CGA C-6.4, the best known being the CSA inspector qualification test (12), which now provides over 500 certified inspectors nationwide.

As some of the discussion above indicates, the natural gas vehicle industry has been extremely concerned about safety in the US. In fact, there has been only one fatality in the US caused by the natural gas fuel system of a vehicle! So there is a lot of safety information from the manufacture and operation of those vehicles, which may be applicable to hydrogen-powered vehicles.

NATURAL GAS VEHICLE “INCIDENTS”

The Clean Vehicle Education Foundation and its predecessor organization, the Natural Gas Vehicle Coalition, run a voluntary NGV incident reporting program in order to learn from incidents involving NGVs. This has allowed us to improve NGV codes and standards to assure higher levels of vehicle safety over the years. To date we have details of 76 incidents since 1984, primarily in the US, as well as information on 44 cylinder failures worldwide (13) since 1976, plus a number of other overseas incidents (Contact the author for a summary list or details on these incidents). Learning from domestic and overseas incidents and incorporating the information in US NGV codes and standards helps ensure this enviable safety record.

SOME THINGS THE NGV INDUSTRY HAS LEARNED WHICH APPLY TO HYDROGEN VEHICLES

Some of the issues which the natural gas vehicle industry has seen which the hydrogen vehicle industry can learn from follow.

VEHICLE CYLINDERS CAN GET OVER PRESSURIZED AND RUPTURE – An obvious concern of any industry dealing with high-pressure compressed gas is over pressurization of a gas cylinder (or any other part of the system) which could lead to cylinder failure, or in the worst case, cylinder rupture.

The NGV industry assigns the responsibility to avoid over pressurization to the dispenser at the fueling facility. The vehicle system has no protection against over pressurization as such (the Pressure Relief Device on the vehicle is required to protect against fire, although some devices may also protect against over pressurization).

NFPA 52 (Vehicular Fuel Systems Code) (14) (§8.6.3) requires that “An overpressure protection device...shall be installed in the fueling transfer system to prevent overpressure in the vehicle.”

ANSI/NGV4.1 (NGV Dispenser Systems) (15) requires two overpressure protection systems. Section 1.11.4 on overfill protection requires: “Each dispensing system shall be fitted with a

safety valve set to relieve pressure no more than...” 125% of service pressure “...to prevent cylinder over pressurization.” And §1.4.2 requires: “A pressure relief valve shall be located downstream of the overfill protection system to prevent over-pressurization of the vehicle storage vessels.”

And yet there have been cases where the dispenser protection has failed to keep vehicle cylinders from being over pressurized and rupturing.

In 2000 one cylinder mounted in the bed of a pickup truck ruptured, apparently from over pressurization. It is speculated that multiple failures of pressure regulating and relief systems allowed the dispensing of 6000 psi gas, into 2400 psi cylinders. The force of the rupture propelled the cylinder through the roof of an adjoining bowling alley. Luckily the bowling alley was unoccupied at the time so there were no injuries from the incident.

Also in 2000, a vehicle refueling appliance (a small dispenser) failed, allowing the over pressurization and rupture of a CNG cylinder on a delivery truck being fueled in Montreal, Canada. There were also no injuries from this incident.

Lesson for compressed hydrogen vehicles: Consider whether vehicle tanks should also provide protection against over pressurization.

PHYSICAL OR CHEMICAL ABUSE CAN DAMAGE CYLINDERS – CNG cylinders built to ANSI/NGV2 standards must pass tests to assure they can stand up to physical and chemical abuse. Section 18.8 requires withstanding a 1.83 m (6 foot) drop test such as might happen if a cylinder fell from a forklift. Section 18.4 requires an “environmental test” in which the cylinder is first impacted, then exposed to five different types of corrosive fluid, including sulfuric acid. This last test was added when some cylinders failed in service after battery acid in a truck bed leaked onto cylinders and failed the fiberglass overwrap from stress corrosion cracking.

The environmental test was added to the NGV2 standard in 1998 but some older cylinders are still in use. The first US fatal accident attributed to the CNG fueling system happened in May 2007, when an older add-on tank on a

SuperShuttle van ruptured during fueling. It appears the failure was due to acid exposure on the tank during a previous accident.

Since the 1995 edition, NFPA 52 (§6.3.2.1) has required that “fuel supply containers shall be protected with a means to prevent damage that can occur due to road hazards, loading, unloading, direct sunlight, exhaust heat, and vehicle use including accidental cargo leakage.” However in August 1996 a cylinder on a Los Angeles transit bus, apparently built to an earlier standard, ruptured due to physical damage. “Since the rupture all of the buses have been equipped with shields to protect the cylinders (which) they did not have before the rupture” (NGV News, August 1997).

In 1994 and 1996, prior to the environmental test requirement in NGV2, two cylinders ruptured from exposure to battery acid. And, as mentioned above, another older cylinder recently failed from this cause and killed the man fueling the vehicle in May of 2007.

Lesson for compressed hydrogen vehicles: Cylinders must be designed to protect against corrosive agents, road debris, and other types of foreseeable damage. Alternatively cylinders must be mounted in the vehicle to avoid these types of potential damage.

CYLINDERS/FUEL SYSTEMS NEED INSPECTION – In September 2003, in Scarborough, Ontario (a suburb of Toronto) a cylinder ruptured during fueling of a Dodge Ram van which had been converted to CNG in 1994. “Apparently the cylinder failed during fueling at substantially under its rated 3000 psi (200 Bar). The driver said he had smelled gas for a long time but hadn’t gotten around to checking the source. It was reported that there was massive external corrosion on the tank and there was no evidence of it having been inspected.” (16)



Figure 7: Dodge van after cylinder rupture (17)

As discussed above, the natural gas vehicle industry advises cylinder users to routinely have a detailed visual inspection at least every 36 months and FMVSS 304 requires the cylinder label to state that “This container should be visually inspected after a motor vehicle accident or fire and at least every 36 months or 36,000 miles, whichever comes first, for damage or deterioration.” On the Dodge van, the Canadian cylinder registration required an inspection every three years. (18)

A detailed visual inspection, conducted per the Compressed Gas Association pamphlet C-6.4 (Methods for External Visual Inspection of Natural Gas Vehicle Fuel Containers and Their Installations) (19) referenced in the industry container standard, ANSI/CSA NGV2, includes inspection of much of the CNG fuel system, not just the fuel container. Therefore these inspections find gas leaks, PRD or fuel line damage, and many other potential problems before they lead to an incident. Periodic CNG fuel system inspections are no different from brake, headlight or tire inspections in their ability to help ensure safe vehicle operation.

Lesson for compressed hydrogen vehicles: Periodic fuel system safety inspections can help ensure safe vehicle operation.

PRDs SOMETIMES LEAK - PRDs (pressure relief devices) are routinely used with CNG containers to protect against rupture during a fire. They sense high temperature and vent the high-pressure gas before the fire can compromise the tank strength and allow it to rupture. Vehicular hydrogen tanks, which generally operate at a higher pressure than CNG, also use PRDs.

Two types of problems can occur with PRDs in service. A type 1 failure, where the PRD fails to properly vent the gas during a fire, is likely to be more serious, potentially allowing the tank to rupture. A type 2 failure, the unintended venting of the PRD during normal vehicle operation, can also cause serious problems.

Normally a type 2 failure causes only the loss of the gaseous fuel into the atmosphere, and is an inconvenience to the operator. But a leaking PRD can also occasionally lead to a serious fire as it did in an Akron, Ohio bus garage in 1999. In this case, there were two preceding leaks,

one two weeks before and one seven hours before the leak which led to the fire (20).

Although it is not known exactly why the PRDs leaked in Akron, the cause of a similar incident about the same time in State College, PA is known. In that case and in others, moisture got into the PRD vent tube, froze and, as it expanded, damaged the PRD. Although vent caps are normally used to prevent this, and some CNG bus users drill “weep holes” to allow water to drip out, this problem continues, although at a much decreased rate.

Lesson for compressed hydrogen vehicles: With the potential for high volumes of compressed hydrogen vehicles on the highways, type 2 failures, where PRDs vent unintentionally, must be eliminated or at least minimized.

PRDs DON'T ALWAYS PROTECT AGAINST FIRES, ESPECIALLY LOCALIZED FIRES – ANSI/CSA PRD1 (§1.2) contains a warning that “Pressure relief devices may not prevent rupture of a container under all conditions of fire exposure. When the heat transferred to the container is localized, intensive, and remote to the relief device, or where the fire builds extremely rapidly, such as in an explosion, and is of very high intensity, the container may weaken sufficiently to rupture before the relief device operates, or while it is operating.” This, or a similar warning, will likely be carried over to the standard for compressed hydrogen PRDs.

In September 2002 a CNG cylinder on a Ford Crown Victoria police vehicle awaiting decommissioning “exploded during a fire” in a holding lot. “It was concluded that a direct flame (from the interior of the vehicle) onto the cylinder (located behind the rear seat in the car) compromised the hoop strength of the natural gas cylinder, thus allowing the cylinder to fail prior to the PRD releasing at its designed temperature.” (21)

On March 26, 2007, an arsonist torched 12 vehicles in a Seattle, WA city government holding lot. All the vehicles were damaged or destroyed including a CNG Honda GX, whose fuel tank exploded in the fire. The tank was apparently compromised by fire moving from the back seat area onto the center of the cylinder, which was protected by a PRD at one end.



Figure 8: Honda CNG vehicle after fire and cylinder explosion (22)

Lesson for compressed hydrogen vehicles: Although PRDs normally successfully protect CNG cylinders from explosion in vehicle fires, there are cases where present designs may not protect from localized fires. This could become a more serious concern if high volumes of compressed hydrogen vehicles on the highways using Types 2, 3, and 4 cylinders, are not protected by more advanced fire-sensing systems.

FIBER-WRAPPED CYLINDERS ARE EXPENSIVE: - A major expense for compressed natural gas or compressed hydrogen vehicles is the pressure vessels or cylinders used to hold the fuel. A ball-park estimate of the cost of various types of eight gasoline-gallon equivalent (gge) 250 Bar CNG cylinders is (23):

Type 1 - \$375

Type 2 - \$580

Type 3 - \$1022

Type 4 - \$1022

For compressed hydrogen far higher pressures and/or larger cylinders would be needed to hold an equal amount of fuel energy. This may be balanced against expected high efficiencies of fuel-cell vehicles, however.

Although Type 1 all steel cylinders are often used for CNG vehicles in the developing world, some consider them too heavy for use on OEM NGVs or hydrogen vehicles in the US. However, all of cylinders have been used on OEM CNG vehicles, but Types 3 or 4 are generally talked about for hydrogen vehicles, probably because of their lower weight, especially when 350 to 700 Bar pressures are considered.

The relatively high cost of compressed gas cylinders has to do with:

- High costs of fiber overwrap, especially carbon fiber
- low (compared to normal automotive production numbers) production volumes
- slow formation times for cylinder liners
- slow and expensive fiber winding methods.

Lesson for compressed hydrogen vehicles: Lower cost manufacturing processes and materials must be found to substantially lower the cost of cylinders for hydrogen automotive vehicles to be competitive in the marketplace.

HIGH-PRESSURE CYLINDERS HAVE A LIMITED LIFE AND NEED PERIODIC SAFETY INSPECTION – We are used to seeing high pressure cylinders being used for welding, or holding medical gases in hospitals or even dentists’ offices. These are normally “DOT” cylinders (built to Department of Transportation regulations) which require periodic hydrostatic testing for safety. They are generally the all steel type 1 cylinders, which are inexpensive, extremely heavy and almost “bullet proof.” The lighter-weight, more expensive and higher technology type 3 or 4 cylinders likely to be used on hydrogen-powered vehicles will have a limited life and likely also require periodic safety inspection.

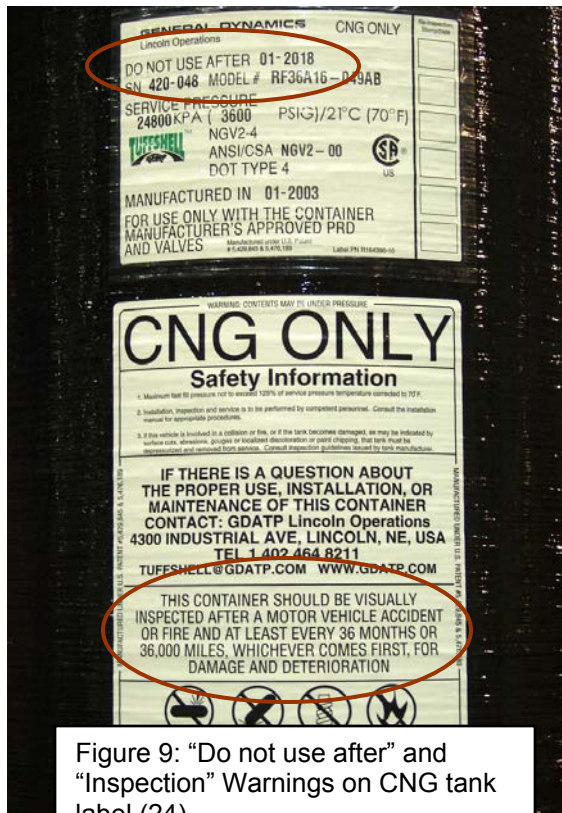


Figure 9: “Do not use after” and “Inspection” Warnings on CNG tank label (24)

Compressed natural gas cylinders in the US carry a notice that they should be inspected after an accident or fire and every 36 months or 360 thousand miles, whichever comes first. They also have a limited life, and carry an expiration date, after which they should be replaced.

Two potential problems are the possibility of moving cylinders, pressure relief devices, and other fuel system components from one vehicle to another and enforcing the “end of life” date on the cylinders. Although both those in the automotive industry working on CNG and hydrogen vehicles are strongly opposed to allowing components from one vehicle to be moved to another vehicle (such as using components on a scrapped vehicle to repair another damaged vehicle), there is no clear way to avoid this potential danger. The concern is that “donor” components used in this manner might not be safe to use on the “recipient” vehicle.

State periodic motor vehicle inspections (PMVI) might be used to ensure that these transplants never occur, but at present only 18 states, the District of Columbia and Puerto Rico have PMVI in place and the number is decreasing. Another potential solution is to provide for free exchange of cylinders and other components when inspection is needed. Such a system is in place in Italy where fuel tax money is used to pay for replacement of cylinders at mandatory inspection periods.

Lesson for compressed hydrogen vehicles: - A way must be found to either make compressed hydrogen cylinders and fuel systems safe for the life of the vehicle, or to ensure they are inspected periodically to ensure improper components are not “transplanted” and that the system remains safe.

REFERENCES

- (1) George Santayana, *The Life of Reason*, Volume I, *Reason in Common Sense*, (Wikiquote, http://en.wikiquote.org/wiki/George_Santayana)
- (2) European Natural Gas Vehicle Association (www.engva.org), private communication
- (3) <http://www.mogassales.com/Corporate/ironside.htm>

(4) Top ten countries for NGVs (International Association for Natural Gas Vehicles, www.iangv.org)

<u>Position</u>	<u>Country</u>	<u>Number of NG Vehicles</u>
1	Argentina	1,650,000
2	Pakistan	1,550,000
3	Brazil	1,425,513
4	Italy	432,900
5	India	334,820
6	Iran	263,662
7	Columbia	203,292
8	USA	146,876
9	China	127,120
10	Ukraine	100,000

(5) Clean Vehicle Education Foundation Technology Committee Bulletin, "How Safe are Natural Gas Vehicles?", <http://www.cleanvehicle.org/committee/technical/PDFs/Web-TC-TechBul2-Safety.pdf>

(6) Schematic done for CVEF by Powertech Labs, Surrey, British Columbia, Canada. www.powertechlabs.com.

(7) 49 CFR 571.304 (Compressed Natural Gas Fuel Container Integrity), available from <http://www.access.gpo.gov/nara/cfr/cfr-table-search.html>

(8) ANSI/CSA NGV2-2000 (Basic Requirements for Compressed Natural Gas Vehicle Fuel Containers) available from CSA, www.csa-america.org

(9) Photo by author.

(10) ANSI/CSA PRD1 (Basic Requirements for Pressure Relief Devices for Natural Gas Vehicle Fuel Containers) available from CSA, www.csa-america.org

(11) Photo courtesy of Lincoln Composites, Lincoln, NE, www.lincolncomposites.com.

(12) www.csa-america.org/advisory_service/ngv_certification/

(13) "Known In-Service Failures of NGV Cylinders (Since 1976)," Powertech Labs, Inc., Surrey, British Columbia, Canada. www.powertechlabs.com.

(14) National Fire Protection Association, NFPA 52 (Vehicular Fuel Systems Code) available from NFPA, www.nfpa.org

(15) ANSI/NGV4.1 (NGV Dispenser Systems) available from CSA, www.csa-america.org

(16) *NGVCommunications*, weekly member newsletter of the Natural Gas Vehicle Coalition, September 12, 2003.

(17) Case Study, Natural Gas Fuel Cylinder Failure, Leland Shields, www.vehiclefireinvestigation.com/hybridalternative/hybridalternative12b.html

(18) "Natural Gas Fuel Cylinder Failure on 03/09/03," fact sheet was prepared by Charonic Canada Inc. in conjunction with Powertech Labs Inc. and the Ontario Technical Standards and Safety Authority.

(19) CGA C-6.4 (Methods for External Visual Inspection of Natural Gas Vehicle Fuel Containers and Their Installations), available from the Compressed Gas Association, www.cganet.com

(20) Akron Beacon-Journal, December 30, 1999.

(21) NHTSA Office of Defects Investigation Recall web site. Recall campaign number 03V472000.

(22) Photo from "Firefighter Near Miss," City of Seattle Fire Department Operations Division, May 9, 2007.

(23) Private communications.

(24) Photo courtesy of Lincoln Composites, Lincoln, NE, www.lincolncomposites.com.

CONTACT

Hank Seiff, P.E.
Director of Technology
Clean Vehicle Education Foundation
hseiff@cleanvehicle.org
1-703-534-6151