PROPOSED VEHICLE-LEVEL BONFIRE TEST FOR HYDROGEN-FUELED VEHICLES

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1. Introduction

The government and industry are seriously performing R&D on hydrogen fuel cell vehicles. Work is being done internally by all the major auto makers. In addition, the DOE has a large effort in several offices. The Administration has committed to spending $1.7 B on these efforts over a 5-year period starting in FY 2004. Part of the program is being performed jointly with the US auto industry in a partnership between DOE, USCAR, and several energy companies.

There are many challenges ahead in terms of developing a vehicle which will have adequate range, durability, and acceptable cost. Safety is also an important topic because of the flammability and potential explosion hazard with hydrogen [1].

The government and USCAR are working toward a commercialization decision by 2015. Working backwards, there is an interim milestone to have draft safety codes and standards in place by 2010.

This paper is focused on vehicle safety standards which are the responsibility of the National Highway Traffic Safety Administration (NHTSA). NHTSA has recently published a 4-year Hydrogen Vehicle R&D Plan which has been published for public comment. The plan and the public comments on it are available in [2].

The plan includes a series of tasks under the topics:

- Component level testing
- Onboard refueling system performance testing
- Full vehicle performance testing
- Corporate Average Fuel Economy (CAFÉ)
- International harmonization of codes and standards

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The comments on the plan were supportive and showed a willingness to cooperate and share data. Many of the comments urged the use of science-based performance standards – not design standards; and several also emphasized that the vehicle should be tested at the system (whole vehicle) level.

Major comments from MVFRI on the plan included:

- Determine H_2 leak limits by experiment – not by selecting the same energy release rate as with gasoline in Federal Motor Vehicle Safety Standard (FMVSS) 301
- Improve the FMVSS 304 bonfire test
- Pressure Relief Devices (PRDs) also need a standard
- Gather accident data on natural gas (NG) and hydrogen vehicles
- Tanks may be weaker in crashes at less than full pressure

The author believes that safety information should be openly available and shared. We are all in this together. A serious accident by one will reflect badly on all. In the NHTSA docket [2, document 19] BMW stated "The issue of safety in the use of hydrogen should always be treated in the same way along commonly agreed lines, not as a competitive feature distinguishing one company from another."

2. Background

NHTSA has the 300 series of standards that deal with post-crash safety issues. These standards [3] relate to fire and electrical (battery) safety. FMVSS 301 is a fuel system integrity standard. It requires three crash tests (front, side, and rear), followed by rolling the vehicle around its longitudinal axis. Fuel leakage is limited to 1 ounce per minute. FMVSS 302 relates to the flammability of materials inside the passenger compartment. FMVSS 303 relates to vehicle-level tests of Compressed Natural Gas (CNG) vehicles and is similar to FMVSS 301. FMVSS 304 is a bonfire test of a bare CNG tank (if insulation is part of the cylinder system, then it is included in the test) with its Pressure Relief Device(s) (PRDs) attached. The tank must either survive for 20 minutes or safely vent the contents before the tank bursts. FMVSS is based on the industry standard NGV-2. ISO Standard 15869-1 is also similar. FMVSS 305 relates to electric and hybrid vehicle batteries (high voltage) and ensures electrical isolation from the vehicle and limits electrolyte leakage. It is does not deal with fire, smoke, or ignition sparks from the battery.

In FY 2005 NHTSA will begin to do R&D in order to establish a set of safety standards that will apply to hydrogen-fueled vehicles. One approach is to modify the existing 300-series of standards to make them applicable to hydrogen. Another approach is to make a new set of standards for hydrogen-fueled vehicles. NHTSA will also be working with Japan and Europe to harmonize standards. This paper is primarily focused on the fire safety of vehicles containing high-pressure compressed hydrogen tanks.

NHTSA plans to do something similar to FMVSS 304 for hydrogen tanks and their PRD system. A draft standard (HGV-2) using this approach is being developed by CSA-America.

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3. High Pressure Cylinder Tests

Compressed Natural Gas Cylinders

Several testing facilities routinely perform the FMVSS 304 bonfire test on CNG tanks. The author is familiar with the testing at one facility. Over the last several years they have done over 30 FMVSS 304 tests. They have had two tests where the PRD did not activate and the CNG tank burst.

There is an enormous amount of *mechanical* energy stored in these high pressure tanks which is released in milliseconds. Of course the chemical energy in the tank is much more (or we couldn't afford to pump up the tank) but the combustion of the flammable gases takes place over a much longer period – ca 2-10 seconds. In one of the tests at the aforementioned facility, substantial damage was done to steel plates, railroad ties, and I-beams in the test structure. Figure 1 shows the debris from a CNG tank burst inside the test structure. It is simply unacceptable to allow a tank to burst.

Figure 1. CNG tank explosion during FMVSS 304 test

Why did the tank burst? It was because the PRD did not open and vent the contents. One of the flaws of the FMVSS 304 test is that the PRD is required to have a shield to prevent direct impingement of the flame – but the nature of the shield is not well specified. In other words, the PRD was protected by the shield, but the tank was not – and thus the tank burst. One could argue that the presence of the shield is "conservative" in that it makes the activation of the PRD more difficult. But it also shows that the geometry of the system and the location of the fire relative to the tank and PRD are very important.

FMVSS 304 is primarily a PRD test. It really doesn't test the tank because no modern composite tank is likely to survive for 20 minutes of fire exposure.

Compressed Hydrogen Gas Cylinders

MVFRI contracted with SwRI to apply a FMVSS 304-like test to a 5000 psi compressed hydrogen tank [4, 5]. The objective was to test the tank to failure and study the properties of the tank and its contents prior to failure. In addition, the magnitude and characteristics of the energy release at failure were determined. For this reason safety measures typically required on compressed gas cylinders (PRD's) were not utilized.

A propane flame was used similar to FMVSS 304. The test was conducted at a remote hazardous test area. Instrumentation included tank and flame temperatures, tank pressure, pencil-probe blast sensors, and visual and IR video coverage. The tank tested was a type-4 (plastic inner liner) composite tank.

The composite material on the surface of the tank ignited approximately 45 seconds into the test. After 6 minutes and 27 seconds, the cylinder catastrophically failed (see Figure 2). The type-4 tank is a very good thermal insulator, so the pressure and temperature internal to the tank increased by a negligible amount. The tank failed because it was weakened by the fire exposure. The tank burned through near the bottom - which is closest to the fire source.

Figure 2. Hydrogen Tank Burst in FMVSS 304-Like Test

The bursting of the tank resulted in a large fragment (14 Kg or 44% of the original mass) being propelled to 145 feet altitude and landing about 270 feet away from where it started. Some other fragments were never found. The blast pressures were 43 psi at 6.3 feet from the centerline of the tank (the 50% fatality level is ca 50 psi). At 21 feet the overpressure was 6 psi. This will cause some eardrum ruptures. Windows start breaking at 1 psi. Again, the conclusion is that the fuel tank system must be protected from fire damage and must not be allowed to burst.

Reflection on this problem makes it clear that tank fire safety is a vehicle *system* issue. A bare tank test with an attached PRD will never simulate a real vehicle configuration. Most hydrogen vehicles will have several tanks. They might be plumbed together at tank pressure (say 5000 or 10,000 psi), or they might be plumbed together after the pressure regulators at an intermediate pressure (typically ca 150 psi). There may be several PRDs because of the number of tanks and/or the desire for redundancy. It is really important that the PRD(s) be exposed to the same, or a more severe, fire as the tank. SwRI suggested that it might be prudent to insulate or shield the tank from the exposure fire (but one must make sure that the PRDs are readily exposed).

4. Proposed Vehicle System-Level Test

A possible way to resolve these problems is to do a bonfire test at the vehicle level. The Europeans have been doing such a test (ECE R-34 Annex 5) for conventionally-fueled plastic fuel tanks for many years [1, 6, 7]. This test is not required in the US, but it is believed that the vast majority of plastic fuel tanks used in the US are qualified by this test. The ECE R-34 test was developed for gasoline and diesel-fueled vehicles – but a modern composite tank for compressed CNG or hydrogen is also a "plastic" tank – so why not apply a similar test.

The ECE R-34 test exposes a complete vehicle (or a vehicle "buck" – which is essentially one-half of the vehicle containing the fuel tank) to a gasoline pool fire. The gasoline is contained in a pan of specified dimensions. The vehicle is exposed to the full heat flux for one minute, and then a ceramic screen is slid over the pool fire to reduce the heat flux for a second minute. The tank is said to "pass" the test if the tank survives without leaking for two minutes.

The developers of the ECE R-34 Annex 5 test [7] staged pool fires with spilled gasoline of various quantities (unspecified amounts). They observed that the fire was very intense (flames 1-2 m high) for about 1 minute. Then the flames subsided and were mostly gone by 1.5 minutes. Thus they chose a 2-minute test with a screen in place for the second minute. Of course, the fire could burn considerably longer than 2 minutes if there is a continuing source of gasoline, or if the vehicle catches fire and continues the exposure to the fuel tank.

A 2-minute period is probably long enough for an uninjured person to get out of the vehicle. It is clearly *not* long enough if the vehicle occupants need to be extricated by emergency response personnel. Figure 3 shows a vehicle buck undergoing the ECE R-34 bonfire test.

Figure 3. ECE R-34 Bonfire Test

MVFRI sponsored ECE R-34 Annex 5 tests of plastic gasoline fuel tanks at an independent testing laboratory [8]. We tested to tank failure because we wanted a quantitative measure of tank performance – not just a pass/fail qualitative answer. We found significant differences due to tank geometry and placement, and whether the tanks were shielded. This is a system-level test.

For hydrogen it is proposed to expose a complete vehicle to a simulated underbody pool fire. For air pollution and safety reasons it is suggested that the gasoline pool fire of ECE R-34 be replaced by a propane planar flame (diffused through sand) of equivalent energy release rate (e.g., about a 300 kW fire). The geometry of the tanks, PRDs, and plumbing should be identical to that of the intended production vehicle.

As in FMVSS 304, the tank should either survive for 20 minutes, or the tank should safely vent its contents before bursting. Safe venting should be defined as either no ignition, or if the gas ignites, that it not spread the fire to other portions of the vehicle.

How long should the fire exposure time be? Ideally, one would choose 20-minutes as used in FMVSS-304. That would certainly allow enough time for emergency responders to extricate injured or entrapped passengers in a large percentage of the cases. However, the vehicle might be fully engulfed, and the vehicle passenger compartment become untenable, well before this time. To help answer this question, MVFRI plans to do additional testing and monitor the temperatures and CO levels in the passenger compartment for tenability.

Experiments need to be done to determine the duration of the exposure fire for this proposed vehicle-level bonfire test. Ideally we should try for 20 minutes. The point of untenability will probably occur in the 5-10 minute range and may be the practical limit.

If the vehicle bonfire test is terminated *before* the PRD activates, the vehicle is in a hazardous condition. There must be a method to safely remove the hydrogen (de-fuel) from the potentially damaged tank. This should be done remotely. One implementation would be to use a normally-closed squib valve which can be remotely triggered using a coded signal (RF or IR). Such a de-fueling system would also be desirable on any hydrogen vehicle that is involved in a serious real world crash - with or without a fire.

Since the fire performance will be very much vehicle design and geometry dependant, this vehicle-level test is much preferred over a bare tank test like FMVSS 304. Several of the NHTSA docket comments on their 4-year R&D plan also recommended performance-based, system-level tests [2]. Note that this proposed test should be equally applicable to any hydrogen storage method (compressed gas, liquid, or hydride). This proposed test could either replace or be in addition to a FMVSS 304-like test for a H_2 tank and PRD.

5. Fuel System Integrity (FMVSS 301)

The current standard for conventionally fueled-vehicles allows a maximum leak rate of one ounce per minute of gasoline (or diesel). Several people have proposed basing the allowable *hydrogen* leak rate to deliver the same energy release rate as that for gasoline [9]. FMVSS 303 is similar to 301 and is applied to CNG vehicles.

NHTSA has acknowledged that the allowable leak rate for gasoline was set at the lowest level that was practical to measure. It was *not* based on any experimental fire testing related to how long an occupant could survive before the passenger compartment became untenable.

Hydrogen, as a gas, is relatively easy to measure, and we could probably detect a much smaller leak. On the other hand, hydrogen is buoyant and has a rapid diffusion rate – so it might be possible to allow a larger release and still be safe.

It is suggested that the allowable leak rate be based on hydrogen leak tests, with ignition, and with specification of the desired survival time for occupants of the vehicle. This would then result in a standard based on the science of fire spread from the ignition source (a small hydrogen flame) until the whole vehicle is involved.

MVFRI intends to sponsor additional tests to examine the ignition of known masses of hydrogen under the vehicle, and also ignited flames from steady leaks. This may shed additional light on how to modify FMVSS 301 (or 303) for hydrogen.

6. Pressure Relief Device Standard

A standard for hydrogen PRDs is being developed by CSA-America [10]. It covers many topics such as: General Requirements, Design Qualification Testing, Inspection and Acceptance Testing, Production Batch Testing, and Marking. There are many detailed requirements under each of these topics.

The author reviewed this draft standard. Major suggestions for improvement included:

- Activation time may need to be faster
- Document the rationale for all the numerical values quoted in the standard
- Mark distinctively from NG PRDs
- Vendors should also have quality plans

The draft standard calls for an activation time of 3 minutes at 110 C. It does not discuss faster activation times at higher temperatures. It may take up to 5 minutes for the hydrogen to vent depending on the amount of fuel being vented (one tank vs. several, full or near empty). Since the tank we tested burst in 6.5 minutes, it may be necessary for the PRD to activate more quickly.

The CSA standard has many quantitative values (numbers) relating to temperature ranges, pressure ranges, number of pressure cycles for fatigue testing, and many others. The basis for choosing these numbers should be documented, perhaps in an Appendix, because 25 years from now no one will remember why a specific parameter was chosen.

It may also be desirable to have standards for other high-pressure components such as the pressure regulator, valves, piping, and sensors.

7. Hydrogen Leaks Inside Buildings

The California Fuel Cell Partnership sponsored a study by Parsons-Brinkerhoff [11, 12] on hydrogen releases from vehicles in buildings. The four types of buildings studied were: a below-ground parking facility, an above-ground parking facility, a residential 2-car garage, and an auto maintenance facility.

Assumptions for the study were that a hydrogen leak would be limited to 20 CFM, and that hydrogen sensors in the wheel wells would ensure that the hydrogen was quickly shut off by a solenoid valve at the tank. The resulting hydrogen plume was modeled using a computational fluid dynamics code. It was also assumed that there were no ignition sources within 2 feet of the vehicle.

For the assumptions made, the study concluded that no additional ventilation requirements would be needed in these 4 types of facilities.

The report states "None of the recommendations presented in this report are ready for implementation." Additional work needs to be done before building codes can be developed. The computer modeling needs to be independently validated and documented. Ignition sources in and around the vehicle need to be considered. Most importantly, other leak scenarios need to be analyzed. In particular there could be high-pressure gas leaks from an inadvertent PRD release, or from a PRD which works as designed and vents to protect the tank. The probability of an inadvertent PRD release may be low, but it is *not* zero. There may also be other possibilities for leaks in the high-pressure portions of the system.

The goal of not requiring modifications to buildings is laudable. Whether that can be achieved is unclear at this time. If building modifications are required for hydrogen vehicles this will constitute another major infrastructure problem that will have to be overcome.

8. Conclusions

A vehicle-level bonfire test has been proposed which is similar to the ECE R-34 Annex 5 test used in Europe for plastic fuel tanks. It will test real vehicles in a pool fire situation and is preferable to a bare tank with PRD test. It should be able to be applied independent of the technology used for hydrogen storage.

The allowable post-crash leak rate for hydrogen should be based on vehicle flame spread tests and not on the energy equivalent to gasoline.

The draft PRD standard has been reviewed and several suggestions made.

More research needs to be done on hydrogen leaks in buildings (confined spaces).

9. Curriculum Vita and Contact

R. Rhoads Stephenson has a PhD in Mechanical Engineering from Carnegie Mellon University. He spent 36 years at Caltech's JPL and worked in both the energy and space areas. He is now retired and a consultant to MVFRI. In the mid-70's he headed an assessment of advanced automotive power plants which was funded by a grant from Ford [13]. The study included an assessment of all kinds of heat engines as well as alternate fuels, electrics, hybrids, and fuel cells. He was head of R&D for the National Highway Traffic Safety Administration (NHTSA) from 1978 to 1981.

For the last three years he has been a consultant to the Motor Vehicle Fire Research Institute (MVFRI). This institute is sponsoring ca $ 4M of crash-induced auto fire safety research. Our program and results can be found at: www.mvfri.org

Dr. Stephenson is a member of DOE's Hydrogen Safety Review Panel (HSRP) and the National Research Council's review of the FreedomCAR program. He has also organized 4 sessions on auto fire safety for the April 2005 SAE World Congress.

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9. References

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