International Conference on Hydrogen Safety, Piza Italy, September 2005

FIRE SAFETY OF HYDROGEN-FUELED VEHICLES: SYSTEM-LEVEL BONFIRE TEST

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ABSTRACT

The European Community requires a vehicle-level bonfire test for vehicles using plastic fuel tanks for conventional fuels (ECE R-34, Annex 5). A similar test could be applied to hydrogen-fueled vehicles. It would test a realistic vehicle with its complete fuel and safety systems. An advantage of such a test is that the same test could be applied independent of the hydrogen storage technology (compressed gas, liquid, or hydride).

There are currently standards for bonfire testing of a bare Compressed Natural Gas (CNG) tank and its Pressure Relief Device (PRD). This standard is FMVSS 304 in the U.S. and ISO 15869-1 in Europe. Japan has a similar standard. It requires that a bare tank and its associated PRD be subjected to a propane flame for 20 minutes. The tank must either survive or safely vent its contents. No modern composite wound tank is expected to survive for 20 minutes – so this is not a tank test but really a PRD test. The test procedure requires the PRD to be shielded from direct impingement of the flames – but the shield is not well specified. If it shields the PRD too well, the PRD will not activate and the tank will burst. This paper describes the results of a CNG and a hydrogen tank burst from such tests. The mechanical energy released is enormous. It is simply unacceptable to allow the tank to burst – the PRD and venting system *must* work. Organizations in the U.S, Europe, and Japan are in the process of modifying the CNG tank bonfire test for compressed hydrogen storage.

A bare tank with a single PRD is *not* a good simulation of a hydrogen fuel *system* installed in an actual vehicle. There will usually be multiple tanks plumbed together at either the tank pressure or at the intermediate pressure (after the pressure regulator). There may be more than one PRD. The tank may be shielded (from debris) or insulated to protect it from an underbody pool fire. Also the heat transfer from the simulated pool fire (propane flame) will be very different when mounted in a vehicle versus the bare tank test. A vehicle-level pool fire test will alleviate these problems.

It is therefore recommended that the bare tank test be replaced by or augmented with a vehicle-level bonfire test similar to ECE R-34, Annex 5.

1. INTRODUCTION

Various governments and the automotive 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 U. S. Department of Energy (DOE) has a large effort in several offices. The U.S. government 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, The U. S. Council for Automotive Research (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, 2].

The U.S. 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) in the USA. 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 [3].

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 (CAFE)
- International harmonization of codes and standards

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 [3, 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 [4] 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 28 grams 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 PRDs attached. The tank is exposed from below to a propane flame of unspecified power (kW), but the thermocouple temperatures below the tank must be above a given minimum. The tank must either survive for 20 minutes or safely vent the contents before the tank bursts. FMVSS 304 was 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.

NHTSA will begin this year 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 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. 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.

3. HIGH PRESSURE CYLINDER TESTS

3.1 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 the Southwest Research Institute (SwRI). 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. Powertech Labs Inc. in British Columbia, Canada also performs many FMVSS 304 tests. They have tes ted several hundred tanks over the past 5 years and had about 10 failures where the tank burst [5].

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 SwRI 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

The tank burst 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.

3.2 Compressed Hydrogen Gas Cylinders

MVFRI contracted with SwRI to apply a FMVSS 304-like test to a 350 bar (5000 psi) compressed hydrogen tank [6, 7]. 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 (a PRD) was 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 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. That is one reason why PRDs need to be thermally actuated - not pressure activated. 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.

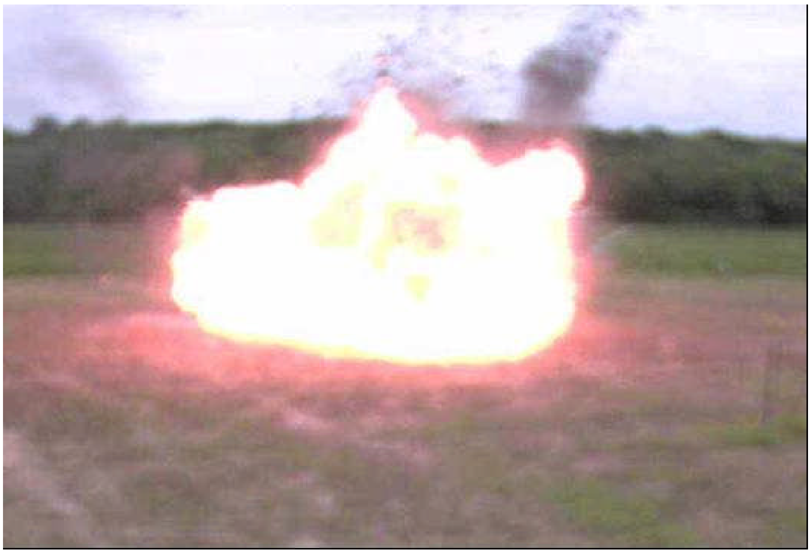

Figure 2. Hydrogen Tank Burst in FMVSS 304-Like Test

The bursting of the tank resulted in a large fragment (14 Kg or 44% of the original mass) being propelled to 44 meters altitude and landing about 82 meters away from where it started. Some other fragments were never found. The blast pressures were 296 KPa (43 psi) at 1.9 meters from the centerline of the tank (the 50% fatality level is ca 344 KPa (50 psi)). At 6.4 meters the overpressure was 41 KPa (6 psi). This will cause some eardrum ruptures. Windows start breaking at 7 KPa (1 psi). Again, the conclusion is that the fuel tank system must be protected from fire damage and must not be allowed to burst.

It is 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 350 or 700 bar), or they might be plumbed together after the pressure regulators at an intermediate pressure (typically ca 1030 KPa (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).

Another advantage of a vehicle-level test is that one could also make use of active systems (electronic sensors and controls) to sense a fire and vent the contents of the tank. Active sensing, if used, should be in addition to the passive protection provided by a PRD.

4. PROPOSED VEHICLE SYSTEM-LEVEL TEST

A way to resolve these problems is to perform 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, 2, 8, 9]. 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 system) 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 [9] staged pool fires with spilled gasoline of various quantities (the amounts were unspecified). 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 was a continuing source of gasoline, or if the vehicle catches fire and continues the fire 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 SwRI [10]. We tested to tank failure because we wanted a quantitative measure of tank performance – not just a pass/fail qualitative result. 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 X 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, X, be? Ideally, one would choose 20-minutes as used in FMVSS-304. That would 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. Such 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 thus 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 damaged tank. This should be done remotely. One implementation would be to use a normally-closed squib valve which could be remotely triggered using a coded signal (RF or IR). Such a de-fueling system would also be desirable on any high-pressure compressed gas 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 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 [3]. 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.

An FMVSS 304-like test may still be desirable for a tank with an *in-tank* pressure regulator with an integral PRD. It is important that the PRD activate quickly. Such a test would demonstrate that the PRD sensing element can quickly heat up to release the gas. The in-tank regulator itself plus the tank boss and dome represent a thermal heat sink which could prevent or delay actuation of the PRD. For hydrogen storage systems using an external PRD, there is not an obvious reason to continue with the FMVSS-304 type of test.

5. 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 gasoline fuel tanks. It will test real vehicles in a pool fire situation and is more realistic than a bare tank with PRD test. It should be able to be applied independent of the technology used for hydrogen storage.

6. REFERENCES

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