MVFRI RESEARCH SUMMARY
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Research in Fire Safety for Hydrogen-Fueled Vehicles

Based on contracts with:
Southwest Research Institute
Bob Zalosh (FIREXPLO)

Fire safety issues that may be associated with hydrogen fueled vehicles were examined. Key questions include: (1) What are the surface temperature and internal pressure responses of hydrogen tanks when exposed to bonfire tests and how do these responses influence the design of the pressure relief device? (2) What are the failure characteristics of different hydrogen tank designs? (3) What is an appropriate burn test for hydrogen fuel tanks? (4) What is the extent of the risk of major vehicle fires (occupant compartment entry) from the hydrogen leakage resulting from a broken fuel line? (5) What is the influence of the location of the leakage on the risk of a major fire or explosion? (6) What are the characteristics of the most significant threats associated with hydrogen leakage? (7) What is an appropriate test to assure the safety of hydrogen fuel lines? (8) What is the nature of the most significant threats associated with hydrogen fuel tanks and fuel lines subjected to crash induced fires?

The initial project explored fire safety issues with an on-board hydrogen storage tank and attempted to address the first three questions listed in the above paragraph. The existing and proposed standards for compressed natural gas containers were used as guides.

Federal Motor Vehicle Safety Standard (FMVSS) No. 304, *Compressed natural gas fuel container integrity* requires a bonfire test. Draft International Standard ISO 15869-1, *Gaseous hydrogen and hydrogen blends – Land vehicle fuel tanks – Part 1: General requirements* also specifies a bonfire test. Both procedures expose a compressed gas cylinder at its working pressure to a 65-in. (165-cm) long bonfire.

Tests are performed with the tank manufacturers' specified fire protection system in place (e.g., a thermally activated pressure relief device). The test criteria for FMVSS 304 requires a cylinder to either not rupture during a 20-min bonfire test, or to safely vent its contents through the pressure relief device. ISO 15869-1 requires a hydrogen cylinder to vent its contents prior to rupture without a time limit of exposure.

BONFIRE TEST OF A TYPE 4 COMPOSITE HYDROGEN FUEL TANK

The high pressures required for compressed hydrogen storage have resulted in the extensive use of composite tanks. A Type 4 filament wound 5000 psi hydrogen tank suitable for automotive use was subjected to a bonfire test under an MVFRI contract with Southwest Research Institute with consulting assistance from Dr. Robert Zalosh, of FIREXPLO. [Weyandt, 2005; Zalosh 2005]. The objective was to test the tank to failure and study the properties of the tank and its contents prior to failure. The magnitude of the energy released at failure was determined. Safety measures typically required on compressed gas cylinders (pressure relief devices) were not utilized.

The Type-4 hydrogen cylinder was approximately 33 in. (84 cm) long with a 16-in. (41-cm) diameter (outer dimensions) and weighed approximately 70.6 lb (32.0 kg). The tank was comprised mainly of a high-density polyethylene inner liner, a carbon fiber structural layer, followed by a fiberglass protective layer. Each end of the cylinder consisted of a dome and an aluminum end fitting.

Figure 1. Hydrogen fuel tank in bonfire test fixture

The test setup for the bonfire test is shown in Figure 1. The hydrogen tank was supported by two insulated chains approximately 24 in. (61 cm) apart. A propane burner provided the heat source below the tank. The line burner was approximately 12 in. (30 cm) wide and had an effective length of 33-in. (84-cm). The burner length was shorter than the 65 in. (165 cm) required by the standard. This was done to determine the effect of a concentrated bonfire on the hydrogen tank. The propane burner was protected from wind with a 32 x 90 x 8-in. deep (81 x 230 x 20cm) pan.

The tank instrumentation included an internal thermocouple and pressure transducer. The flame exposure temperatures and tank surface temperatures were measured using six thermocouples. Overpressures around the tank were measured by four blast-wave pencil probes.

The composite material on the surface of the tank ignited approximately 45 seconds after the start of the bnfire exposure. After 6 minutes and 27 seconds, the cylinder failed catastrophically through the bottom, launching the 30.9 lb. (14.0 kg) main portion 270 ft. (82 m) from the test location. Blast pressures were 43 psig (300 KPa) at 6.3ft. (190 cm.) and 6 psig (41 kPa) at 21.3 ft. (650 cm.). The pressures measured did not include any effect of reflected waves that might be associated with surrounding rigid and semi-rigid surfaces. The data from the test was recorded in a report to MVFRI and a published paper. (Weyandt 2005, Zalosh 2005).

The internal temperature and pressure of the hydrogen at the time of failure was 103°F (39°C) and 5,180 psig (35.7 MPa), respectively. It is necessary to locate pressure relief devices (PRD's) such they experience the same, or worse, fire as the tank. Redundancy may be prudent also.

A typical compressed hydrogen tank, when exposed to a bonfire, presents safety challenges. The consequence of a rupture is catastrophic. In our test, blast pressures of 6 psi were measured 21 ft away from the tank, and debris was propelled more than 250 ft. At the time of tank rupture, the pressure inside the 5,000 psig tank had only increased by 180 psi and the temperature had risen only to 103 ^{o}F. The test results suggest that bonfire protection and pressure relief sensing for hydrogen Type 4 hydrogen will require some sophistication.

VEHICLE-LEVEL FIREWORTHINESS TEST OF A TYPE 3 HYDROGEN FUEL TANK

Testing of hydrogen fuel tanks by Southwest Research Institute was continued under a second MVFRI funded research project. The second test was a bonfire test of a Type 3 hydrogen fuel tank [Weyandt, November 2006]. The purpose of this test was to perform a vehicle-level fireworthiness test. A second purpose was to determine the consequences from a vehicle-mounted hydrogen tank if the Pressure Relief Device (PRD) does not vent the tank(s). A third purpose was to compare the fire characteristics of Type 3 and Type 4 hydrogen tanks.

The test vehicle was a popular SUV. The conventional gasoline tank was removed and the vehicle was fitted with a Type 3 (aluminum liner) hydrogen tank holding about 2 Kg of hydrogen at 5000 psig. The tank did not have a PRD. The vehicle and surroundings were instrumented with several video cameras, IR and high-speed cameras, blast probes, many thermocouples, and a CO sensor and thermocouple in the driver's position to assess tenability. The vehicle just prior to the test is shown in Figure 2.

Figure 2. Instrumented test vehicle

Figure 3. Fireball from tank burst

The initializing fire was a propane burner (265 kW) which burned until the hydrogen tank burst. The burner pan size was approximately one inch larger that the tank in each dimension.

The fire was initiated and portions of the vehicle became involved (plastic body panels, tires, and then the interior). The temperatures on the underside of the cylinder quickly rose in excess of 1200 ^{o}F (650 ^{o}C). Measurements inside the vehicle showed that the driver's position space became untenable (CO > 1% and temperature > 200C^{o}) in about 4 minutes. The internal tank pressure remained fairly constant during the first 9 minutes, at which time the pressure transducer failed. The fire continued and grew and the hydrogen tank burst after 12 minutes. The fireball is shown in Figure 3.

The mechanical impulse from the tank burst did extensive damage to the vehicle, and parts of the vehicle were scattered as far as 350 feet. A large portion of the tank landed 135 feet away. Overpressures of 2 psi were measured at 32 feet, and thus the exclusion radius for no overpressure damage (0.3 psi) is about 150 feet.

Based on analysis of the video and thermocouple data, it is very likely that a PRD mounted at either end of the tank in this test would have been thermally actuated and prevented the tank from bursting.

Observations from the Tank Fire Tests

The pressure relief device (PRD) in hydrogen tanks must work to prevent catastrophic rupture of the tank when exposed to a bonfire. The PRD must be highly reliable.

The Type 3 hydrogen tank mounted in the vehicle lasted about twice as long as the Type 4 tank tested using an FMVSS 304-like bare tank bonfire test. It is not known whether the longer time to burst was due to the different tank or to the partial protection provided by the vehicle. The pressure rise in the both the Type 3 and the Type 4 tanks was only a small fraction of the rated pressure and would not be useful in activating a (PRD). The strategy for implementing pressure relief may require sophisticated sensing.

One of the key decisions a firefighter must make is what constitutes a safe distance to keep the public away from a fire with a compressed gas tank. The test results provide some data on this subject. Since vehicle fires occur in both crash and non-crash conditions, the exposure of the fuel tank to a vehicle interior fire is much more frequent than reported in crash data. A vehicle level fire test is appropriate in order to assure the PRD functions in this common fire scenario.

A vehicle-level fireworthiness test appears to be a feasible way of assessing occupant tenability and of allowing the vehicle designer the maximum flexibility to optimize the system from a fire progression point of view. In addition to our single test, GM conducted 11 well-instrumented vehicle burns on pre-crashed vehicles. The results are summarized in [Tewarson 2005, Vol. I]. Such a test could be applied to a vehicle independent of fuel used (gasoline, diesel, CNG, or hydrogen – compressed, liquid, or hydride). The underbody pool fire simulation is a very severe test and tenability will likely be limited to a few minutes. A similar test could also be developed to simulate the more common underhood fires resulting from frontal impacts. Under these more frequent fire conditions, the fuel tank must vent safely and not pose a hazard to rescue personnel.

RESEARCH IN HYDROGEN LEAKAGE FROM BROKEN FUEL LINES

A ruptured fuel line is a possible hazard in a vehicle crash. A 2004 study [Parsons Brinkerhoff, 2004] suggested that hydrogen leakage rates in the range of 24 g/min and 48 g/min were credible. These leakage rates were used as the basis for the MVFRI research in fuel line leakage that was conducted under contract by Southwest Research [Weyandt 2006]

Two types of leakage were examined. The first type (delayed ignition) permitted the leaked gas to accumulate for a period of time before ignition occurred. The second type examined the consequence of immediate ignition and a fuel fed flame at the location of the fuel line rupture.

Two leakage locations were also examined. One location was on the underside of the vehicle along the driver's side frame rail, near the center of the vehicle, consistent with the vehicle's original gasoline fuel line. The other location was where the original fuel line bent upward into the engine compartment with the nozzle pointed toward the underside of the hood.

Measured data included temperature and heat flux on the bottom side of the vehicle, temperature on the interior of the passenger compartment, and four temperatures in the interior of the engine compartment. During the post-release (delayed) ignition tests, pressures were also measured; one measurement was made on the interior of the engine compartment, and another on each side of the vehicle's perimeter.

Series 1 Tests: Underside Mid-body Delayed Ignition

Release durations were started at a nominal 1 second and doubled up to a nominal 128 –sec release. A flow of 48 g/min was chosen to provide the maximum expected leakage rate. The measured blast pressures generally increased with leakage duration, but remained at low levels. The maximum overpressures measured in the occupant compartment and outside the vehicle were less than 0.19 psi and occurred after a 128 release at a flow of 48 g/min.

Series 2 Tests: Under-hood Delayed Ignition – High Flow Rate

Release rates and durations were as in the Series 1 tests. The hydrogen release was in the engine compartment with the hood closed.

Blast wave pressures were significantly higher in Series 2 tests than in Series 1. The highest pressures were consistently obtained inside the engine compartment. Engine compartment over-pressures ranged from 0.14-psig (2-sec duration) to 3.2-psig (64-sec duration) at this location. The next highest pressures were obtained at the front of the vehicle (up to 2.08 psig) followed by the passenger and driver sides, and finally the rear of the vehicle. Most tests resulted in little to no damage to the vehicle. The overpressure during the 64-sec duration leak caused deformation of the hood and loosening of the passenger side fender. The damage is shown in Figure 4. Several pressures in excess of 1 psig were recorded for releases of 8 sec or greater duration.

Figure 4. Damage to vehicle during series 2 leakage tests

Series 3 Tests: Under-hood Delayed Ignition – Low Flow Rate

Release rate for this series of tests was 24 g/min and durations were as in the Series 1 tests, but extended to 265-sec. The hydrogen release was in the engine compartment with the hood closed. Pressures measured in Series 3 tests were rather insignificant. The highest pressures were consistently obtained within the engine compartment, but none of the pressures exceeded 0.05 psig.

Series 4 Tests: Engine Compartment Jet Fire Tests

The 48-g/min hydrogen jet-fires in Series 4 impinged directly on the underside of the hood of the engine compartment in all but the first test. The thermocouple in the direct path of the jet-fire recorded a temperature above 2200°F in each test. Temperatures on the underside of the vehicle did not increase appreciably. In a test with the hood open, the visible jet fire appeared to reach 16 in. outside of the engine compartment, for a total length of approximately 32 in. from the nozzle. A test with hood open is shown in Figure 5 and with hood closed is shown in Figure 6.

Figure 5: Fuel line leakage – hood open

Figure 6: Fuel line leakage – hood closed

After a jet fire of 5.2 sec, the liner on the underside of the hood ignited. After the 9.8-sec duration jet fire, a plastic harness showed obvious deterioration, there was a hole in the hood liner, and the exterior of the hood showed slight warping and paint bubbling. After a 17.8-sec duration burn, the plastic harness was completely consumed, copper wires were severed, and the exterior of the hood was discolored with more warping and paint bubbling. See Figures 7 and 8.

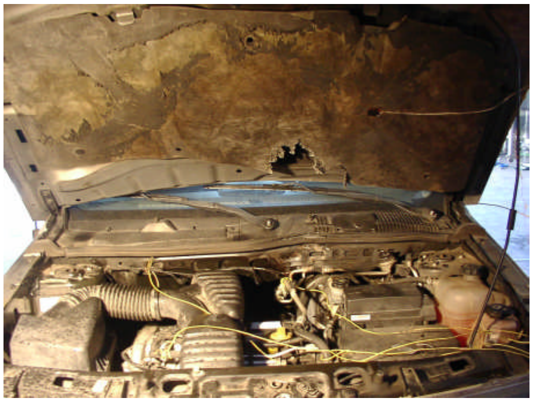

Figure 7: Hood damage – underside

Figure 8: Hood damage - outside

Series 5 Tests: Underside Mid-Body Jet-Fire Tests

The 48-g/min jet-fires in Series 5 tests impinged along the frame, fuel lines, and into plastic support components as shown in Figure 9. Minimal damage occurred to the vehicle in this series. The jet-fire quickly destroyed the delicate combination Thermocouple/heat flux sensor in its direct path and it only intermittently measured the jet-fire temperature of about 2200°F.

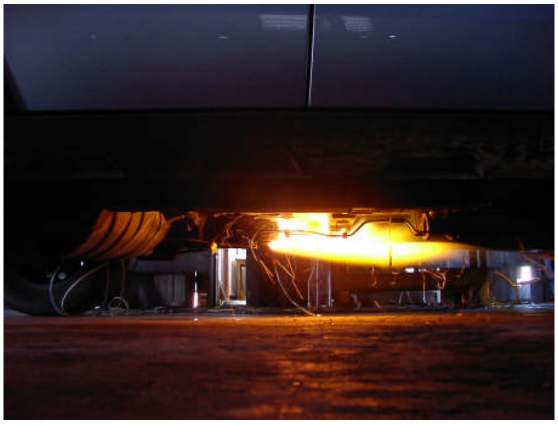

Figure 9: Leakage flame during test

Figure 10: Residual flame after test

Even in the shortest duration test, the fuel lines were red hot and the plastic support brackets continued to burn following the test as shown in Figure 10. For longer jet-fire durations, the fuel lines remained red hot for a longer period. After the final duration of 33 sec, the plastic bracket had been mostly consumed, but no other damage around the vehicle was evident. Peak heat fluxes measured in Series 5 tests were about 3600 Btu/ft^{2}hr (11 kW/m^2).

Observations from Fuel Leakage Tests

Only minor overpressures (less than 0.25 psig) were measured from releases on the underbody of the vehicle, and for the low flow rate (24-g/min) releases in the engine compartment. These pressures are not considered high enough to cause bodily harm or window breakage. Overpressures nearest the underbody release remained relatively constant with increased duration due to the lack of confinement areas for hydrogen accumulation. At longer durations, the overpressure on the interior of the engine compartment did increase for the underbody releases, although not enough to cause any apparent damage to the vehicle.

Higher overpressures were measured at all locations with high-flow (48-g/min) releases of hydrogen in the interior of the engine compartment. This is due to the fact that the peak concentration obtained during this type of release (27% hydrogen) is only slightly less than the stoichiometric mixture (30% hydrogen) [Underwriters Laboratory] . A pressure in excess of 3 psig was experienced in the engine compartment. This pressure, measured during ignition of the 64-sec duration release, caused significant physical damage to the hood of the vehicle. For this test condition, pressures on the order of 2 psig were experienced on the perimeter of the vehicle near the ground. The SFPE Handbook of Fire Protection Engineering estimates threshold pressures for glass breakage at approximately 1 psig, and for eardrum rupture at approximately 2 psig [SFPE, 1995]. However, the highest overpressures measured at the base of the car would be expected to dissipate to levels of minor discomfort after several car lengths.

Damage to the vehicle was minimal for the majority of tests and consisted mainly of burnt plastic components. Temperatures for short-duration delayed-ignition tests were higher in the location of the release, whether on the underside of the vehicle or in the engine compartment. Temperatures for longer duration delayed-ignition tests, however, were consistently higher in the engine compartment, where more hydrogen could accumulate. Heat flux data followed the same trend as temperature data.

High temperatures were evident in the areas of the hydrogen release, and in areas such as the engine compartment, in which the hydrogen could collect. However, these temperatures were brief in the delayed ignition tests, and insufficient to ignite surrounding exterior components. In the jet-fire tests, temperatures and heat fluxes were obviously of a magnitude and duration that could cause severe burns or ignite most plastic components. The extent of a jet-fire hazard would ultimately depend on the size, location, and direction of leak. At no time, however, was there a significant rise of temperature in the passenger compartment of the test vehicle.

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