Blast Waves and Fireballs Generated by Hydrogen Fuel Tank Rupture During Fire Exposure

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ABSTRACT

Compressed hydrogen vehicle fuel tanks are required to have Pressure Relief Devices (PRDs) to prevent rupture during fire exposure. If the PRD does not actuate, because either the PRD fails or the fire does not encompass the PRD, the tank will rupture and produce a blast wave and hydrogen fireball. Tank rupture tests without PRDs have been conducted with a Type 3 tank (wrapped composites with metallic liner), and with a Type 4 tank (fully wrapped composites with a nonmetallic liner). The Type 3 tank was mounted under a Sports Utility Vehicle (SUV).

The Type 4 fuel tank test produced a rupture after about 6.5 minutes due to the gradual deterioration and burning of the resin and carbon fiber wrapping. The hydrogen pressure and temperature at tank rupture were only slightly higher than their pre-test values. Results showed that the measured blast pressures were consistent with ideal blast wave correlations based on the adiabatic expansion energy of the compressed hydrogen and tank volume. Composite fragments from the Type 4 tank were found at distances up to about 80 m from the test site.

The SUV-mounted Type 3 tank ruptured after 12.3 minutes of fire engulfment. Blast wave pressures were in agreement with published correlations providing a virtual distance was used for targets in line with the vehicle longitudinal axis. Some SUV fragment projectiles were thrown over 100 m from the original SUV location.

Introduction

Compressed hydrogen vehicle fuel tanks are required to have Pressure Relief Devices (PRDs) to prevent rupture during fire exposure. When the PRD actuates a hydrogen jet is emitted that may or may not ignite depending on the exposure fire size and location, and whether or not auto-ignition occurs. The characteristics of both un-ignited jets and hydrogen jet flames from PRD releases have been studied extensively and recently reported in References 1 and 2.

If the PRD does not actuate, because either the PRD fails or the fire does not encompass the PRD, the tank will rupture and produce a blast wave and hydrogen fireball, as well as tank fragment projectiles. The danger zone associated with the blast wave, fireball, and projectiles depends on the tank size and pressure, and the type of tank construction. The two most common types of construction for vehicle fuel tanks are the Type 3 tank composed of a fully wrapped composite with a thin metal liner, and the Type 4 tank composed of a fully wrapped composite with a non-metallic liner.

This paper describes and analyzes the results of Type 3 and Type 4 hydrogen fuel tank fire exposure tests without any PRDs, such that fuel tank failure is inevitable. The objectives of the tests were to determine the tank time-to-failure and to characterize the blast wave, hydrogen fireball, and fragment projectiles produced upon tank failure at a nominal hydrogen storage pressure of 35 MPa. The tests were sponsored by the Motor Vehicle Fire Research Institute and conducted at a remote test site operated by Southwest Research Institute (SWRI). Details of the tests are available in the two SWRI reports (3, 4), and two Society of Automotive Engineers papers (5, 6).

Test Setup

The Type 4 tank test was conducted on the stand-alone 72.4 liter tank shown in Figure 1. The 0.84 m long, 41 cm tank was fabricated with a high-density polyethylene inner layer, a carbon fiber structural layer, and a fiberglass outer layer. The tank is situated over a propane burner composed of perforated piping in a wind-barrier pan. The tank was instrumented with thermocouples and a pressure transducer. The propane exposure fire heat release rate was approximately 370 kW. Instrumentation away from the tank included blast wave pressure transducers, and high-speed video cameras. The hydrogen tank pressure was 34.3 MPa at the start of the test.

Figure 1. Type 4 hydrogen fuel tank test setup on propane burner.

The 88 liter volume Type 3 hydrogen fuel tank was installed under a typical Sports Utility Vehicle (SUV) in the place of the removed gasoline fuel tank as shown in Figures 2 and 3. The 0.84 m long tank had an aluminum inner liner, a carbon fiber structural layer, and a fiberglass outer layer. The SUV had a length of 4.5 m, a width of 1.8 m, and the tank clearance above the ground was 28 cm. The instrumentation on the SUV included thermocouples and a carbon monoxide gas sampling system and analyzer. External instrumentation included eight blast wave transducers, one heat flux transducer, an infrared camera and high-speed video cameras operating at slightly greater than 1,000 frames per second. The propane burner heat release rate was approximately 265 kW. The hydrogen tank pressure was 31.8 MPa at the start of the test.

Figure 2 Instrumented SUV with Type 4 Hydrogen Fuel Tank

Figure 3 Type 4 Fuel Tank Mounted on SUV and over Propane Burner

Fire Development and Tank Failure

After about 45 seconds of fire exposure to the stand-alone Type 4 tank, there was an appearance of black soot, indicative of the burning of the tank composite layers. The internal cylinder temperature and pressure increased only marginally from 27^{o}C to 39^{o}C and from 34.5 MPa to 35.7 MPa during the 6 min and 6 min, 27-second fire exposure that culminated in catastrophic tank rupture.

In the Type 3 tank and vehicle test, black soot from tank and vehicle component burning was observed after only 20 seconds of fire exposure. As the fire spread to additional components on the vehicle under the influence of the 5.4 m/s wind, the flame size increased accordingly as shown in Figure 4a, 4b, and 4c. The tank internal pressure remained constant, at least until the pressure transducer failed after 1 min 24 seconds of fire exposure. The tank failed catastrophically 12 min 18 seconds after the exposure fire was ignited, i.e. after about twice the time-to-failure of the Type 4 tank.

Figure 4a. SUV and tank fire exposure and spread to left rear wheel-well at about 2 minutes.

Figure 4b. SUV and tank after about 4 minutes of exposure fire.

Figure 4c. SUV and Type 3 tank after about 9 minutes of exposure fire.

Thermocouple and carbon monoxide readings within the vehicle indicate that flame penetrated into the vehicle interior after about 4 minutes of exposure fire. Therefore personnel escape or rescue would have had to be accomplished within that time period to be successful.

Blast Wave Pressures

Blast wave pressures measured at four locations in Test 1 with the stand-alone Type 4 tank are shown in Figure 5. Peak pressures varied from at a high of 300 kPa at a distance of 1.9 m, to a low of 41 kPa at a distance of 6.5 m. The pressures were highest in a direction perpendicular to the longitudinal axis of the tank.

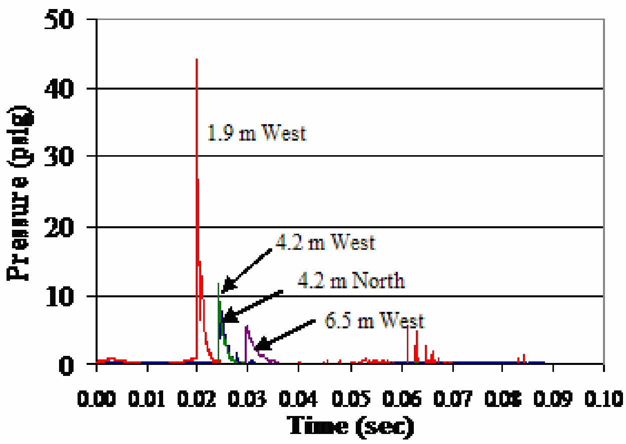

Figure 5 Blast pressures measured when the Type 4 tank burst in Test 1.

Blast pressures measured in the SUV and Type 3 tank test varied from a high of 140 kPa at a distance of 1.2 m, to a low of 12 kPa at a distance of 15 m. In this test, blast pressures were higher in a direction perpendicular to the SUV longitudinal axis, i.e. in a direction parallel to the fuel tank longitudinal axis.

Peak blast pressures from both tests are plotted as a function of distance from the tank in Figure 6. The curves in Figure 6 denote the pressure vessel rupture blast wave correlations based upon the Baker et. al methodology described in References 7 and 8. The correlations are in the form

$$\frac{P_s}{P_a} = f\left[\left(\frac{P_b}{P_a}\right),\left(\frac{\gamma_g M_a T_g}{\gamma_a M_g T_a}\right),\left(\frac{r P_a^{1/3}}{E^{1/3}}\right)\right] \qquad [1]$$

where P_s is the blast wave peak pressure (gauge) at a distance r from the vessel, P_a is atmospheric pressure, P_b is the vessel burst pressure, γ_g and γ_a are ratio of specific heats of the gas in the vessel and air, respectively, M_a and M_g are the molecular weights of air and the gas in the vessel, and E is the blast wave energy associated with gas expansion upon pressure vessel rupture.

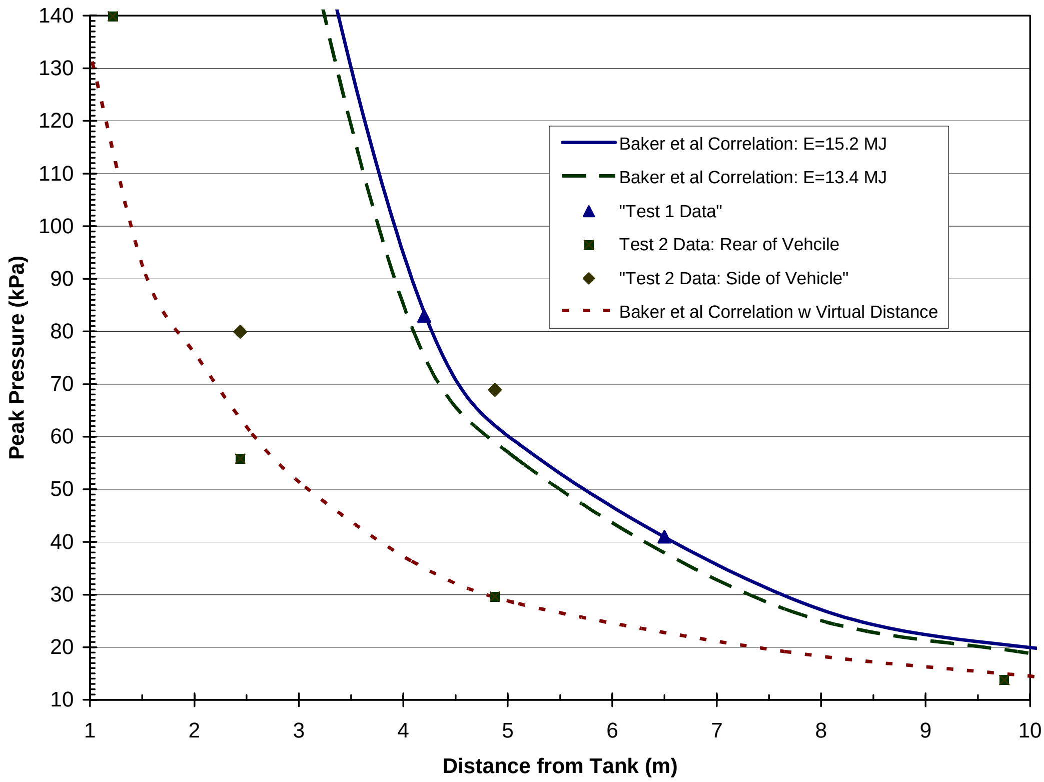

Figure 6 Blast pressures versus distance from fuel tank center.

The values for E for these hydrogen tank burst tests have been calculated from the following equation for the $\int_{v_1}^{v_2} p\,dv$ for isothermal expansion of an Able-Noble gas.

$$E = nRT_1 \ln\left(\frac{P_1}{P_a}\right) \qquad [2]$$

and

$$n = \frac{V}{b + RT_1/P_1} \qquad [3]$$

where n is the number of moles in the pressure vessel, R is the universal gas constant, T_1 is the gas absolute temperature, P_1 is the tank burst pressure (P_b), V is the tank gas volume, and b is the constant in the Able-Noble Equation-of-State. The best-fit value of b for hydrogen for temperatures in the range 223-423 K and pressures up to 200 MPa is b = 15.84 cm^3/mol (9). Using this value and Equations 2 and 3, values of E of 15.2 MJ and 13.4 MJ were obtained for Tests 1 and 2, respectively. The corresponding values of E reported in References 3 and 4 using a Redlich-Kwong equation-of-state for hydrogen are 12.9 MJ and 12.4 MJ.

The blast pressure data for Test 1 agrees quite well with the correlation using the 15.2 MJ calculated value for E. However, all but one of the data points for Test 2 are significantly over-predicted using the Test 2 calculated E of 13.4 MJ. This over-prediction of the SUV-mounted tank data suggests either that the vehicle absorbs a large fraction of the blast energy, or delays the formation of an ideal blast wave. The lower curve shown in Figure 6 was developed using the same 13.4 MJ E value, but with the actual distances to the blast wave probes supplemented by a distance equal to half the SUV length (2.25 m). This lower curve provides a good fit to the data in a direction directly behind the vehicle. It does under-predict the data in a sideways direction from the vehicle.

Hydrogen Fireball Size and Radiant Heat Flux

The hydrogen fireball produced upon the Type 4 tank rupture in Test 1 is shown in Figures 7a and 7b. The maximum fireball diameter of 7.7 m occurs at the time of the Figure 7a image. The burning projectile at the top of the fireball is also apparent in Figure 7a. The fireball has lifted off the ground by about 1 second as in Figure 7b.

Figure 7a Fireball 45 msec after tank rupture in Test 1.

Figure 7b. Fireball 997 msec after tank rupture in Test 1.

The hydrogen fireball produced in the SUV-mounted tank test (Test 2) is shown in Figures 8a and 8b. There is a large burning fragment projectile jetting up from the top of the fireball in Figure 8a, and many small oblique projectile trajectories in Figure 8b. The maximum fireball diameter in Test 2 was 24 m, i.e. about three times as large as the fireball produced in Test 1.

Figure 8a. Hydrogen fireball about 70 msec after tank rupture in Test 2.

Figure 8b. Hydrogen fireball about 170 msec after tank rupture in Test 2.

The fireball durations, as determined from the IR camera images, were about 4.5 seconds in both tests. The duration determined by the high-speed visible range cameras were about half the duration viewed from the IR cameras.

The peak radiant heat flux measured in Test 2 at a distance of 15.2 m from the tank was 210 kW/m^2. Neglecting the atmospheric absorption over such a short path length, the relationship between radiant heat flux, q", and fireball surface emissive power, E_{FB}, is

$$q'' = F_{21}\, E_{FB} \qquad [4]$$

The fireball-to-target view factor, F_{21}, for the case of the fireball and target both being at ground level, is (Reference 8, p.209):

$$F_{21} = \frac{D_{FB}^{\ 2}}{(2L)^2}$$

where D_{FB} is the fireball diameter, and L is the distance from the center of the fireball to the target. In this case, $F_{21} = 0.62$, and E_{FB} calculated from Equation 4 is 339 kW/m^2.

Tank and Vehicle Fragments and Projectiles

The largest tank projectile fragment in Test 1 was the 14 kg top half of the tank shown in Figure 9. It was found 82 m away from the original tank location. Other smaller fragments were found closer to the original tank location.

Figure 9. Large fragment from cylinder in Test 1.

The remains of the SUV in Test 2 are shown in Figure 10. A large tank fragment found 41 m from the SUV is shown in Figure 11. Fragment projectiles from the SUV landed at distances up to 107 m from the original SUV location.

Figure 10. Vehicle remains after Test 2.

Figure 11. Large tank fragment from Test 2.

Conclusions

Fire engulfment of Type 3 and Type 4 hydrogen tanks pressurized to about 34 MPa without Pressure Relief Devices have resulted times-to-tank failure of 12 min 18 sec, and 6 min 27 sec, respectively. Blast wave peak pressures generated upon tank failure can be predicted using previously published correlations for pressure vessel bursts, but the predictions need to account for the directionality of the blast wave, i.e. greater pressures in a direction perpendicular to a stand-alone tank, or in a direction perpendicular to the vehicle for a vehicle mounted tank.

Fireballs produced upon fuel tank rupture have maximum diameters in the range 8 to 24 m, and have flame emissive powers of about 340 kW/m^2. Tank fragments from a stand-alone tank failure are projected to distances up to about 82 m. Vehicle fragment projectiles can travel distances over 100 m.

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