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Hydrogen Fuel Tank Fire Exposure Burst Test

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ABSTRACT

A fire exposure test was conducted on a 72.4 liter composite (Type HGV-4) hydrogen fuel tank at an initial hydrogen pressure of 34.3 MPa (ca 5000 psi). No Pressure Relief Device was installed on the tank to ensure catastrophic failure for analysis. The cylinder ruptured at 35.7 MPa after a 370 kW fire exposure for 6 min 27 seconds. Blast wave pressures measured along a line perpendicular to the cylinder axis were 18% to 25% less the values calculated from ideal blast wave correlations using a blast energy of 13.4 MJ, which is based on the ideal gas internal energy at the 35.7 MPa burst pressure. The resulting hydrogen fireball maximum diameter of 7.7 m is about 19% less than the value predicted from existing correlations using the 1.64 kg hydrogen mass in the tank.

INTRODUCTION

Hydrogen fuel tanks complying with the HGV2 draft standard [1] are required to have a Pressure Relief Device (PRD) to prevent tank rupture during fire exposure. The PRD effectiveness has to be demonstrated in a standard bonfire test. The HGV2 test standard, which is similar to the bonfire test requirement for CNG fuel cylinders in FMVSS 304 [2], involves a hydrocarbon exposure fire to a cylinder to at its service pressure (manufacturer specified tank pressure at a uniform temperature of 15°C). The tank must vent its contents down to a pressure of 0.7 MPa (100 psi) through the PRD without bursting. Unless a thermally activated PRD is utilized on the cylinder, another test must be conducted with a cylinder at 25% of its service pressure.

Although the tank PRD is intended to prevent tank rupture for most vehicle fire exposures, some fire scenarios and failure modes may render PRD protection ineffective. One such scenario is a fire that engulfs and degrades a portion of the tank without heating the PRD to its activation temperature. Other scenarios include a PRD with a plugged outlet, a defective PRD, or an improperly installed PRD.

Due to the inevitable occurrence of an ineffective PRD resulting in catastrophic failure of a pressurized hydrogen tank, it is important to investigate and understand the possible consequences of such an incident. The Motor Vehicle Fire Research Institute sponsored a program at Southwest Research Institute (SwRI) to investigate the catastrophic failure of a 34.5 MPa hydrogen cylinder under the bonfire test. Since the consequences of a non-metallic tank burst are of particular interest, the test was conducted with a Type HGV2-4 fuel tank

MAIN SECTION

TEST DESCRIPTION

The test was conducted on May 21, 2004 at SwRI's remote fire testing facility, located in Sabinal, Texas. A full description of the test is provided in SwRI's Final Report [3]. An abbreviated description follows with comparisons of key data with calculations from various empirical correlations developed for other types of tank bursts.

Tank Description

The 72.4 liter (4420 in^3) capacity 5000-psig (34.5-MPa) cylindrical tank had a high-density polyethylene inner liner, a carbon fiber structural layer, and a protective fiberglass outer layer. The cylinder's outside dimensions were approximately 0.84 m (33-in.) long with a 0.41 m (16-in.) diameter. Its ends were domes equipped with SAE threaded fittings for filling, and pressure measurement, and normally for a PRD. No PRD was used in this test.

The tank was filled with in advance with hydrogen such that its internal pressure and temperature at the start of the test were 34.3 MPa (4980 psig) and 27°C (81°F), respectively.

Figure 1. Hydrogen Tank Prior to Test

Exposure Fire

The cylinder was placed with its axis oriented horizontally over the bonfire (Figure 1). A propane fire exposure was set up using the wind-barrier pan and perforated piping shown under the tank in Figure 1. Propane flowed out of the perforations directly below the 0.84 m (33 inch) long tank.

Propane flow began at approximately 415 scfh, and was quickly increased to approximately 580 scfh for the duration of the test. This corresponds to a heat release rate of approximately 370 kW (21,000 Btu/min), assuming a 95% burning efficiency. The resultant propane fire engulfed the tank, but was somewhat asymmetrical in the 3.6 m/s (8 mph) wind, as shown in Figure 2.

Figure 2 Exposure Fire Engulfing Tank

Fiberglass on the outer surface of the tank began burning approximately 45 sec into the test. The internal cylinder temperature and pressure slowly increased during the exposure.

Instrumentation and Cameras

Hydrogen pressure and temperature within the cylinder were monitored with a 140 MPa (20,000 psig) pressure transducer, and a 1.6 mm ($^{1}/_{16}$-in.) diameter inconel-sheathed Type K thermocouple. Three additional thermocouples measured temperatures on the cylinder surface and 20 cm (8 in.) above the cylinder.

Blast-wave pressures were measured with four piezoelectric blast-wave pressure probes mounted on a steel rod at the elevation of the cylinder's axis (Figure 3). Three probes were located perpendicular to the axis of the cylinder, at distances of 1.9 m (76 in.), 4.2 m (166 in.) and 6.5 m (256 in.) from the center of the tank. The remaining probe was located just off the axis of the cylinder; approximately 4.2 m (166 in.) from the center of the cylinder, placing it equidistant as the second pressure probe perpendicular to the cylinder.

Figure 3. Blast wave transducer

Instrument signal wiring was run to a Yokogawa WE 7000 high-speed data acquisition system located approximately 30 m (100 ft) from the test site. A fiber optic cable connected the data acquisition system to the control computer located in a remote-monitoring building.

A wireless video camera was placed near the test site to monitor the event. The video signal was captured and recorded at the remote-monitoring building.

A Jade high-speed infrared camera was used to capture the radiation emitted by the hydrogen fireball after cylinder failure. The camera is sensitive from 3 to 5.2 microns (mid-wave IR) and uses a MCT (mercury cadmium telluride) based focal plane array sensor cooled with a thermoelectric cooler. IR Video was captured at 200 frames per second using the ALTAIR PC-based analysis and reporting software.

A Phantom v5.0 high-speed black and white video camera was used to capture the development of the fireball following cylinder rupture. This high-speed video was captured at 1000 frames per second, producing a recording that starts 0.135 seconds prior to cylinder rupture and ends about 6 seconds after.

CYLINDER AND BLAST PRESSURES

Thermal degradation of the cylinder wall caused the cylinder to rupture after 6 min 27 sec of fire exposure. The hydrogen pressure and temperature at failure were 35.7 MPa (5180 psig) and 39°C (103°F). Failure occurred as a large hole in the bottom hemi-cylinder.

Ideal blast wave energy, E, associated with the internal energy of an ideal gas in a vessel of volume, V, failing at a pressure, P_1, is [4]:

$$E = \frac{(P_1 - P_0)V}{(\gamma_1 - 1)} \qquad [1]$$

where P_o is the ambient pressure and γ_1 is the ratio of the constant pressure to constant volume heat capacities at burst conditions. The value of γ for hydrogen at STP is specified as 1.41 in Reference 4 and 1.383 in Reference 5. At 35.7 MPa, the calculated blast-wave energy is between 6.3 MJ and 6.7 MJ, depending on the value of γ_1.

The Redlich/Kwong equation provides a more accurate equation of state for hydrogen at high pressures. The isothermal expansion energy for this equation is given by the definite integral:

$$E = \int_{V1}^{V2} \left(\frac{nRT}{V - nb} - \frac{n^2 a(T)}{V(V + nb)} \right) dV \qquad [2]$$

where: T is temperature, n is the number of moles, R is the ideal gas constant (units consistent with E, n, V, and T), a and b are parameters independent from volume, V1 is the internal volume of the cylinder, and V2 is the final volume (assumed to be standard volume of 3.62 lb of hydrogen at STP).

Evaluation of Equation 2 results in an expansion energy of 6.5 MJ, i.e. midway between the values calculated from Equation 1 with the two cited values of γ_1.

The Reference 4 procedure for doing ideal blast wave calculations involves calculating the nondimensional radius, $\bar{R}$, for each target distance, r, using the equation for a ground level (hemispherical) release:

$$\bar{R} = r \left(\frac{P_0}{2E} \right)^{1/3} \qquad [3]$$

If $\bar{R}$ is less than 2, calculations of blast wave pressures, P_s, involves first calculating an initial radius and corresponding maximum blast pressure to account for near-field deviations from ideal blast wave correlations.

Values of $\bar{R}$ and P_s for the two outermost blast transducer locations and a value of 2E of 13.4 MJ are shown in Table 1. The measured pressures are 18% to 25% less than the calculated pressures.

Table 1

Calculated and Measured Blast Pressures

r (m)	$\bar{R}$	Calculated P_s (kPa)	Measured P_s (kPa)
4.2	0.656	111 (16 psig)	83* (12 psig)*
6.5	1.01	50 (7.4 psig)	41* (6 psig)*

*Pressure measured at location perpendicular to cylinder axis.

The pressure measured at r = 4.2 m located near the cylinder axis was 62 kPa (9 psig), 33% lower than the corresponding value normal to the axis. This is consistent with results from other non-spherical vessel bursts described in Reference 4.

Pressure signals from all four blast wave transducers are shown in Figure 4. The closest transducer (at r = 1.9 m West) recorded a peak pressure of 43 psig (300 kPa).

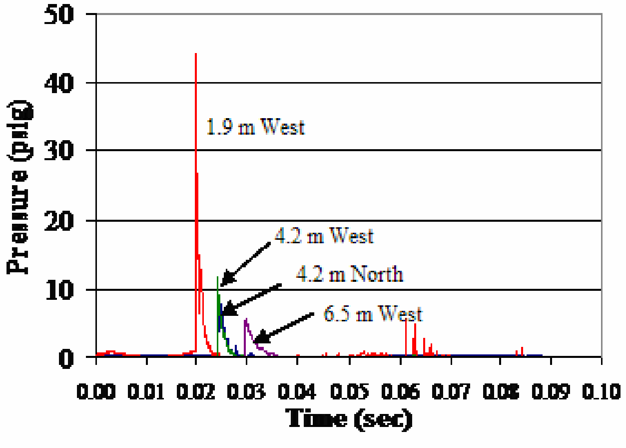

Figure 4 Blast pressures measured at four locations.

FIREBALL

Figure 5a-d is a sequence of four images of the fireball formed upon cylinder rupture. It starts as a rapidly expanding flame, with a height/diameter ratio of about 1/3 in the first image. It reaches its maximum diameter of about 7.7 m (25 ft) in the second image. The flame has a more spherical shape in the third image, and has lifted off the ground in the fourth image about 1 second after cylinder rupture.

Figure 5a Fireball 10 msec after rupture.

Figure 5b Fireball 45 msec after rupture.

Figure 5c Fireball 107 msec after rupture.

Figure 5d Fireball 997 msec after rupture.

One striking feature of the first three fireball images is the sharply varying luminosity of the flame. Presumably the inhomogeneous flame is caused by different fuels burning. Besides the hydrogen, there are polyethylene decomposition products and fragments of carbon fibers. The IR camera images also revealed large variations in flame temperature, with the highest temperatures occurring near the periphery.

Hord [5] has reported the following simple empirical equation for predicting the hydrogen fireball diameter D_f, based on tests with rocket propellants.

$$D_f \approx 7.93 W_f^{1/3} \qquad [4]$$

where D_f is in meters, and W_f is the weight of hydrogen fuel in kilograms. With a weight of 1.64 kg (3.62 lb_m), the calculated fireball diameter is 9.36 m (31 ft). Thus, the observed fireball maximum diameter of 7.7 m (25 ft) is approximately 19% less than the value predicted from Eqn 4. The precise observed diameter varies only slightly among the images recorded by the various cameras, but the limited spectral range of the IR camera may have prevented observation of gaseous combustion products radiating in the UV and short wave IR portions of the spectrum.

According to Hord [5], the hydrogen fireball duration, t_f, can be estimated from

$$t_f \approx 0.47 W_f^{1/3} \qquad [5]$$

Equation 5 predicts a fireball duration of approximately 0.6 seconds.The observed fireball duration was about 2 seconds from the high-speed camera and about 4.5 seconds on the IR camera record. More recent fireball duration correlations described in References 4 and 6 suggest that Equation 5 is only applicable to momentum-dominated fireballs, whereas buoyancy dominated fireball durations are better correlated by:

$$t_f \approx 2.6 W_f^{1/6} \qquad [6]$$

The calculated fireball duration using Equation 6 with 1.64 kg of hydrogen is 2.7 seconds, which is in much better agreement with the observed duration in this test.

PROJECTILES

The largest projectile formed upon cylinder rupture was found smoldering 82 m (270 ft) east of the original test location (Figure 6). The projectile weighed 14 kg (31 lb_m), approximately 43% of the original cylinder weight.

Figure 6 Top half of tank with residual fire

The two plastic cylinder dome liners, weighing 2.0 kg (4.3 lb) each, were found approximately 49 m (160 ft) northeast of the original cylinder location. One of the domes is shown in Figure 7. A 1.6 kg (3.6 lb) cylindrical piece of liner was found 33.6 m (74 ft) from the test site.

Figure 7 Cylinder dome end cap projectile.

The total weight of the four main recovered projectiles was about 61% of the original cylinder weight of 32.0 kg (70.6 lb). Another 2.1 kg (4.6 lb) of small debris (polyethylene pieces and carbon fibers) was also recovered. The remaining 32% of the original mass presumably burned during the exposure fire or was dispersed as very small projectiles (including soot) and unburned carbon fibers.

CONCLUSION

A 370 kW fire exposure of a 72.4 liter Type HGV-4 cylinder without a PRD, pressurized to 34.3 MPa with hydrogen, resulted in sudden cylinder failure after 6 min 27 seconds. Measured blast pressures were 18% to 25% less than the values calculated from ideal blast wave correlations, using a blast wave energy of 13.4 MJ.

The hydrogen fireball formed upon cylinder rupture had a diameter of 7.7 m, 19% less than the value estimated from the hydrogen mass of 1.64 kg in a previous correlation. Comparison of the blast wave and fireball measurements with literature correlations indicate that the correlations provide a slightly conservative representation of the hazards associated with the rupture of Type IV (non-metallic) hydrogen cylinders.

Smoldering projectiles from the cylinder were found at distances of 34 m to 82 m from the original cylinder location. The total weight of the recovered projectiles was about 68% of the original cylinder weight.

These results demonstrate how crucial it is for effective and reliable PRDs to prevent fire- induced hydrogen cylinder rupture and the accompanying fireball, blast wave, and projectiles. Furthermore, the minimal hydrogen pressure and temperature increases inside a Type IV cylinder during exposure fires present additional challenges to the design and installation of effective PRDs and thermally actuated vents for these cylinders compared to those used on metal cylinders.

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REFERENCES

1. HGV2 Draft, “Basic Requirements for Compressed Hydrogen Vehicle Fuel Containers,” NGV2/HGV2 Technical Advisory Group on Development of

Standards for Natural Gas Vehicle and Hydrogen Vehicle Fuel Containers, December 2003.

2. "Laboratory Test Procedure for FMVSS 304, Compressed Natural Gas (CNG) Fuel Container Integrity," National Highway Traffic Safety Administration TP-304-03, December 8, 2003.
3. Weyandt, N., "Analysis of Induced Catastrophic Failure of a 5000 psig Type IV Hydrogen Cylinder," Southwest Research Institute Report for the Motor Vehicle Fire Research Institute, 2004.
4. *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs,* AIChE Center for Chemical Process Safety, 1994.
5. Hord, J., "Is Hydrogen Safe," NBS Technical Note 690, 1976.
6. Beyler, C., "Fire Hazard Calculations for Large, Open Hydrocarbon Fires," p. 3-306, *SFPE Handbook of Fire Protection Engineering*, Society of Fire Protection Engineers and National Fire Protection Association, 3rd Edition, 2002.

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