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FIRE TECHNOLOGY DEPARTMENT
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December 14, 2006

Dr. R. Rhoads Stephenson
Motor Vehicle Fire Research Institute
1334 Pendleton Court
Charlottesville, VA 22901

Subject: SwRI® Project No. 01.06939.01.005

Dear Dr. Stephenson:

Enclosed please find two copies of the above-referenced final report, along with photographic and video documentation. If you should have any questions or comments or if I can be of further assistance, please feel free to contact me at 210-522-5483 or by fax at 210-522-3377.

Sincerely,

Nathan Weyandt
Senior Research Engineer
Engineering and Research Section

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Enclosures: 1) 2 Final Reports
2) 1 Photo CD
3) 1 Video (DVD)

cc: Record Copy A – FTD (w/o encl. Nos. 2 & 3)
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VEHICLE BONFIRE TO INDUCE CATASTROPHIC FAILURE OF A 5,000-PSIG HYDROGEN CYLINDER INSTALLED ON A TYPICAL SUV

FINAL REPORT
Consisting of 28 Pages

SwRI® Project No. 01.06939.01.005
Test Date: September 14, 2006
Report Date: December 14, 2006

Prepared for:

Motor Vehicle Fire Research Institute
1334 Pendleton Court
Charlottesville, VA 22901

Prepared by:

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ABSTRACT

Southwest Research Institute's (SwRI's) Fire Technology Department, located in San Antonio, TX, performed a bonfire test on a vehicle to induce catastrophic failure of a 5,000-psig hydrogen cylinder installed on a typical SUV. The test was performed on September 14, 2006, for the Motor Vehicle Fire Research Institute, located in Charlottesville, VA. The objectives of this program were to assess the progression of a vehicle fire and duration of occupant tenability, and to investigate the extent of hazards associated with hydrogen cylinder rupture.

A standard SUV was modified by removing the standard fuel tank and replacing it with a 5,000-psig hydrogen cylinder (wetted volume approximately 5,370 in.^{3}). Standard safety relief devices were not installed on the cylinder as the objective was to determine the effects of failure, not the likelihood of failure. The cylinder was exposed to an underbody propane bonfire approximately 1 in. greater than the cylinder in all directions.

Measurements in the interior of the vehicle included blast pressure, temperature, and carbon monoxide concentration. Measurements on the underside of the vehicle included temperatures in the bonfire and in the vicinity of the cylinder. Interior cylinder conditions were measured with a pressure transducer. Measurements in the field surrounding the vehicle included blast pressures at various locations and distances and heat flux at one location.

Parts of the vehicle ignited shortly after the bonfire began. Black smoke was generated indicating combustion of plastic parts and tires and fiberglass from the cylinder. The flames and gases entered the passenger compartment rendering it untenable after approximately 4 min of exposure (approximately 400°F and in excess of 1 percent carbon monoxide).

The cylinder burst after being exposed to the propane bonfire for 12 min 18 sec. An estimated 12,200 Btu (12.8 MJ) in mechanical energy was released when the tank burst, and up to 209,000 Btu (220 MJ) in chemical energy was released, based on the heat of combustion of hydrogen. The cylinder failed through the bottom, destroying the automobile and bonfire pan, and launching the cylinder remains 135 ft (41 m) north of the test location.

A blast wave pressure of 20.3 psig was measured 4 ft from the vehicle and 1.8 psig was measured 50 ft from the vehicle. Limited hazards would be expected below 0.5 psig, which is estimated to occur at approximately 80 ft, based on extrapolation of the blast-pressure data. Based on shrapnel, the safe exclusion zone would be in excess of 350 ft (110 m)

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1.0 INTRODUCTION

The objectives of this program were to assess the duration of tenability of occupants in a vehicle bonfire and to investigate the hazards associated with the catastrophic failure of a 5,000-psig hydrogen cylinder when installed on a vehicle. The objectives were achieved by replacing a typical SUV's gasoline tank with a hydrogen cylinder devoid of pressure relief devices and exposing it directly to a bonfire. Measurements included interior temperature and carbon monoxide conditions to judge tenability, temperature around the vicinity of the cylinder, and blast wave pressures and a single heat flux measurement in the field around the vehicle.

The results presented in this report apply only to the materials tested, in the manner tested, and not to any similar materials or material combinations.

2.0 TEST FACILITY

Initial instrumentation preparation and verification was performed at Southwest Research Institute's (SwRI) main campus in San Antonio, TX. This included assembly of the cylinder's instrumentation and fittings as well as evacuating and filling of the cylinder.

The bonfire was conducted at SwRI's remote fire testing facility, located in Sabinal, TX. The remote facility consists of a 15-acre test field and a remote location for control and viewing of the test.

A 250-gal (950 L) propane tank was located at the remote location. Propane flowed from the tank, through a rotameter, and to a buried pipe for supplying the burner. The supply pipe ran underground from the propane supply system, stubbed out of the ground next to the steel test site, and was connected to the bonfire system via flexible hose.

The bonfire was approximately 35 × 18 in., 1 in. larger than the test cylinder in each direction. This size was chosen to provide similar conditions to those found in the standard ECE R 34.01 fire test for standard gasoline fuel tanks. The bonfire consisted of a lower pan into which the propane would flow. The lid consisted of 1-in. thick ceramic fiber, which formed an even distribution of fuel, similar to a liquid pool fire. An electric match was used to ignite the fuel remotely as the gas flow was initiated.

3.0 TEST SETUP

A sport utility vehicle was chosen as the test vehicle, due to its popularity and ease of instrumentation and modification for testing. The vehicle (shown in Figure B-1) was roughly 178 in. long and 70 in. wide with 11 in. of ground clearance. With the exception of the metal hood, rear hatch, and framework, the vehicle was comprised mostly of plastic panels and components.

The gasoline fuel tank and filters were removed from the underside of the vehicle, and the fuel lines were drained of residual gasoline. Additional fluids were drained, including engine coolant, and brake and transmission fluids.

SwRI acquired a single 5,000-psig (34.5-MPa) Type-III hydrogen cylinder for this program. The cylinder was approximately 33 in. (84 cm) long with a 16 in. (41 cm) diameter (outer dimensions) and its wetted volume was approximately 5,370 in.^{3} (88.0 L) (shown in Figure B-2). The cylinder was comprised mainly of an aluminum 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 with female SAE threads. One end was plugged, and the opposite was used for connection to gas handling equipment and a pressure transducer. All fittings and instrumentation installed on the cylinder were rated for a minimum of 5,000 psig.

3.1 Instrumentation

Tenability on the interior of the vehicle was evaluated by temperature and carbon monoxide measurements. One Type "K" thermocouple (TC) was located above the driver seat, and another was located in the middle of the rear passenger compartment. Both were at the approximate level of the headrests.

A gas sample was drawn from near the driver-side head rest, through stainless steel tubing, to a remotely-located infrared gas analyzer. The analyzer was calibrated for carbon monoxide prior to testing. The delay time of the analyzer was measured as 24 sec, and the response time of the analyzer is stated as less than 30 sec. Graphical data shown in Appendix A has been adjusted for the delay time.

The hydrogen cylinder was instrumented with a strain-gauge type pressure transducer to monitor its conditions during the test. The pressure transducer had a range of 0-15,000 psig (103 MPa), a reported accuracy of ± 15 psig, and a response time of approximately 3 ms. The area around the cylinder was instrumented with seven 24-ga Type "K" TCs. Three TCs were located directly under the cylinder in the bonfire – one in the center and one between the center and each of its ends. These locations are similar to those specified in FMVSS 304 [1]. One additional TC was installed next to the valve connection, and three TCs were located at the longitudinal center of the cylinder at the front, rear, and top.

Blast-wave pressures were measured with eight blast-pressure pencil probes. Four probes were located at the vehicle's rear at 4, 8, 16, and 32 ft away. Two probes were located off of the vehicle's driver side at 8 and 16 ft. One probe was located 50 ft from the vehicle's driver-side-rear corner, and a final probe was located in the vehicle's driver seat. The blast pressure probes consisted of piezoelectric transducers of various ranges enclosed in an aerodynamic pencil-shaped housing. The sensors have a rise time of less than 4 μs and an accuracy of ± 0.5 percent. Data from the sensors was continually logged in a buffer at a rate of 25 kHz, and data was saved automatically upon a rise in pressure.

A single heat flux transducer was located 50 ft from the vehicle's driver-side-rear corner, next to one of the blast-pressure probes. The heat flux transducer was an uncoated thin-film Type "E" thermopile-based sensor. The transducer was calibrated at approximately 11.5 W/cm^2 and had a reported response time of 17 μs.

Data was logged on a high-speed data acquisition system. Slow speed data, which included the TCs, cylinder pressure, and carbon monoxide concentration, was logged and saved at a rate of 0.5 Hz throughout the entire exposure. The high-speed blast-wave pressure transducers and heat flux transducer were logged at a rate of 40 kHz throughout the test. The acquisition system was set up such that 1.25 sec of data would be saved to a file upon a sufficient rise in pressure. A fiber optic cable connected the data acquisition system to the control computer located at the remote monitoring location.

A 30-fps thermal imaging camera with a wavelength response of 8 to 14 μs was used to view and record the size and shape of the vehicle explosion. A high-speed camera was used to capture the event at greater than 1,000 frames per sec. Documentation also included two standard video views and digital photographs. Figure 1 depicts the instrumentation layout.

4.0 EXPERIMENTAL PROCEDURE

The test was performed for Motor Vehicle Fire Research Institute on September 14, 2006, at SwRI's Fire Technology Department remote site. The hydrogen cylinder was filled to 5,000 psig (34.5 MPa) with laboratory hydrogen one day prior to the test. Once the cylinder was full, the needle valve opening was capped to prevent the accidental release of hydrogen. The cylinder was then transported to the test site for installation. The cylinder was installed into the cavity resulting from the removal of the gasoline fuel tank, and supported by two metal straps approximately 1 in. wide, such that the bottom of the cylinder was approximately 9-$^1/_2$ in. (24 cm) above the surface of the ground.

All instrumentation was connected and verified prior to the test. All cameras were set up and focused on the vehicle, and video and data acquisition were initiated. Wind speed averaged 12 mph from the southeast, ambient temperature was approximately 88°F (31°C), and relative humidity was 56 percent.

The initial test exposure was initiated, but aborted within 3 min due to an obstructed propane line. Visual observations showed no significant damage to the cylinder.

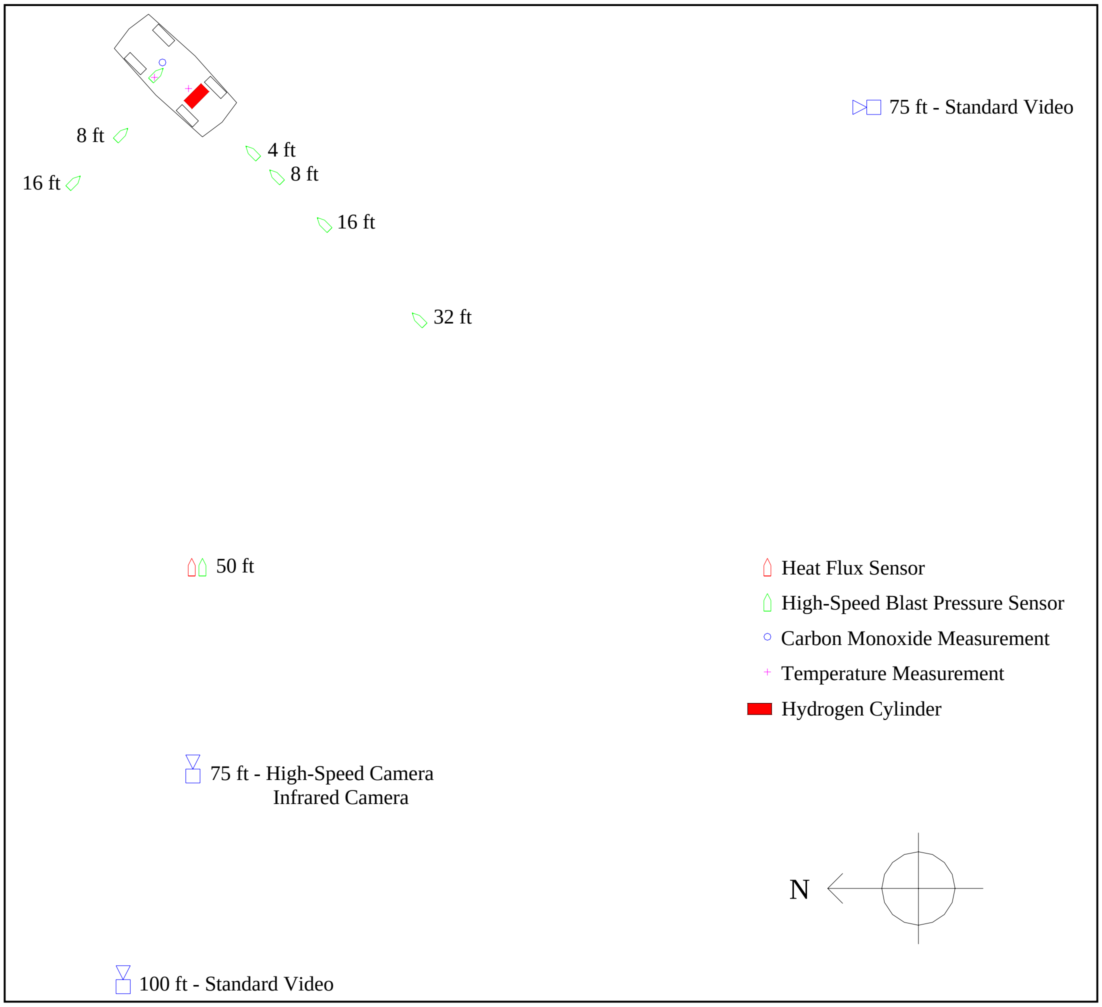


Figure 1. Instrumentation Layout.

The internal cylinder pressure at the beginning of the formal test exposure was 4,620 psig (31.8 MPa). The propane flow was started and ignition was initiated by means of the electric match. Propane flow was held at approximately 415 scfh (195 slpm) for the duration of the test. This corresponds to approximately 15,000 Btu/min (265 kW), assuming a 95 percent combustion efficiency. Flame exposure temperatures on the underside of the cylinder rose in excess of 1200°F (650°C) within 3 min and eventually reached 1400°F (760°C), as shown in Graph A-1. This is well in excess of the minimum temperatures specified in FMVSS 304 of 800°F (427°C).

5.0 RESULTS

Combustion of the composite material and plastic vehicle components began within 20 sec of ignition, as evidenced by the appearance of black soot. The internal pressure of the hydrogen cylinder remained fairly constant during the exposure. The pressure transducer failed at approximately 1 min 24 sec into the test, at which time the cylinder pressure had not changed from its initial value.

The cylinder had been exposed to the fire for 12 min 18 sec when it lost its integrity and failed catastrophically. Graphical depiction of the test data is provided in Appendix A. Photographic documentation of the test is provided in Appendix B.

Temperatures on the interior of the vehicle initially remained low, but increased to untenable levels at approximately 4 min, exceeding 400°F at approximately 4 min 10 sec, as shown in Graph A-2. The carbon monoxide concentration slowly increased to over 100 ppm starting at 3 min 20 sec of exposure. The concentration increased to over 1 percent in less than 1 min (4 min 18 sec of exposure), saturating the instrument.

The hydrogen cylinder failed after 12 min 18 sec of exposure, destroying the burnt remains of the automobile. The rear of the vehicle projected upwards and twisted counter clockwise and over the front half of the vehicle. As the rear of the vehicle twisted, the cylinder projected horizontally (northward) out of the top of the vehicle. The vehicle rotated clockwise about 90 degrees. A trail of aluminum liner fragments of various sizes was left in the path of the cylinder to its final resting place, 132 ft north of the explosion.

Cylinder failure was apparently due to deterioration of the carbon fiber layer directly in the exposure area. Once sufficiently weakened, the remaining carbon fiber and aluminum cylinder could not withhold the internal cylinder pressure. Post-test investigation found no evidence of melted aluminum prior to cylinder rupture.

Various parts of the cylinder, vehicle, and bonfire system were strewn about the test site in all directions, up to 350 ft away. Figure 2 shows the location of the major components found around the test site. The main portion of the cylinder, thrown approximately 132 ft northward, weighed approximately 105 lb (48 kg). The portion of steel thrown approximately 350 ft southward of the test location weighed approximately 5 lb (2.3 kg).

Heat flux data peaked at approximately 66,000 Btu/ft^{2}hr (21 W/cm^2), followed by a rapid decrease to zero in 0.003 sec. An unreasonably large, single-point peak that followed, is presumed to the noise caused by the blast wave.

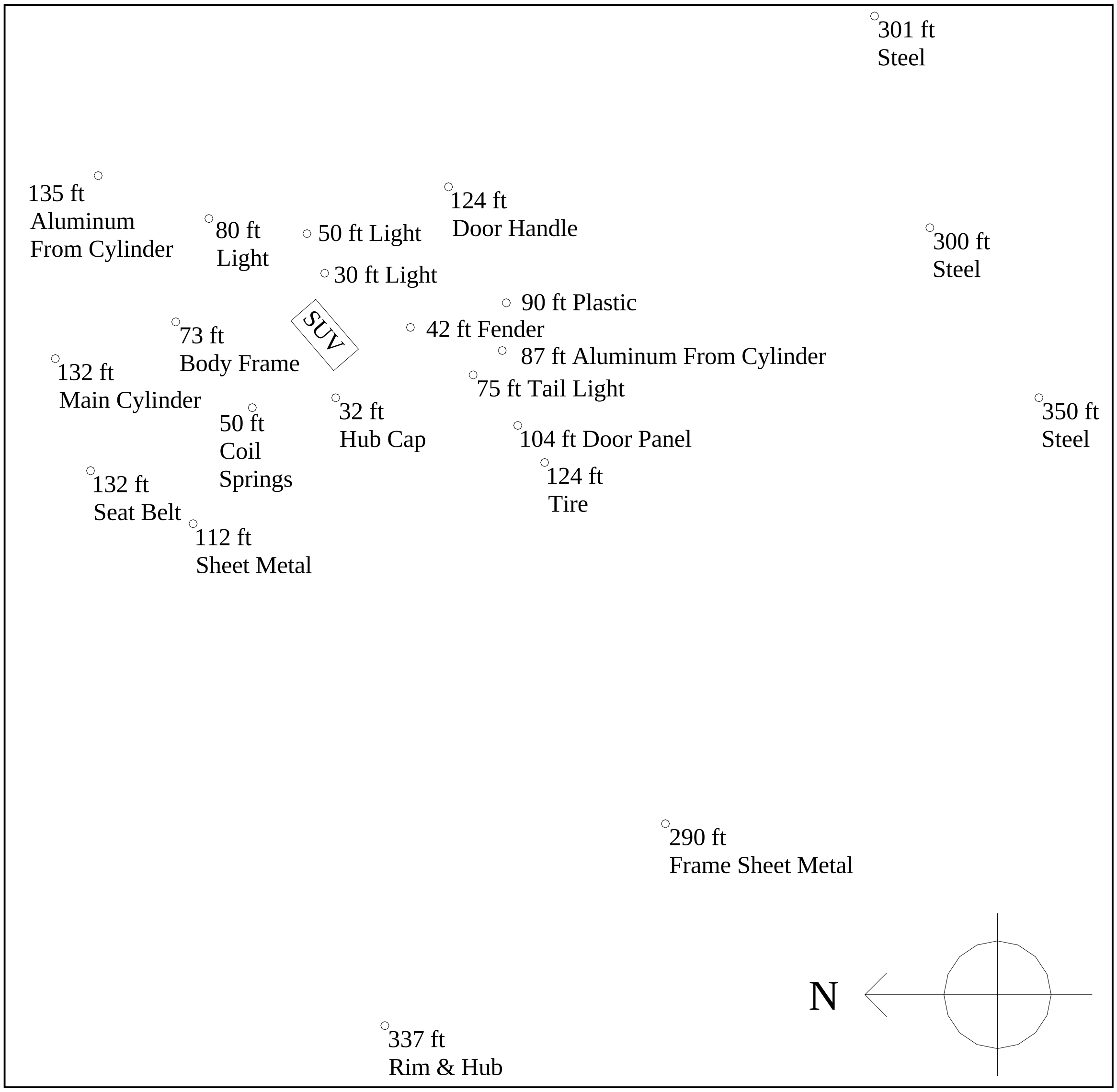


Figure 2. Locations of Various Parts Following Explosion.

The visible fireball from the hydrogen released, as recorded by the high-speed video camera, was initially a hemispherical shape, 80 ft (24 m) in diameter. It then rose into the air as it transformed into a shrinking sphere. The fireball observed with the infrared camera was approximately 80 ft (24.4 m) in diameter. However, the fireball image from the infrared camera was observed for a longer duration compared to the same image size and angle from a standard camera (approximately 4 sec, compared to approximately 2 sec).

The mechanical energy released is equivalent to the work on the surrounding environment by the expanding gasses, assuming ISO thermal expansion:

$$E = \int PdV$$

where: E is energy,

V is Volume, and

P is Pressure

The pressure for the work must be written in terms of volume, which can be calculated using the Redlich/Kwong equation [2], giving the definite integral:

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

where: T is temperature (555°R),

n is the number of moles (2.01– obtained from volume and pressure in the cylinder),

R is the ideal gas constant (units consistent with E, n, and T–1.99 Btu/mol°R),

a and b are parameters independent from volume (303 and 0.292, respectively),

V1 is the internal volume of the cylinder (3.11 ft^3), and

V2 is the final volume (estimated as 812 ft^3 by the volume of n moles of hydrogen at STP).

Solving this integral results in a mechanical energy release of approximately 12,200 Btu (12.8 MJ).

Table 1 lists the maximum blast-wave pressures obtained and the associated times. Note that their relative times are accurate, but that there is no significance of the zero time. The following graph taken from the Society for Fire Protection Engineers (SFPE) Handbook [3] outlines the ideal blast pressures of TNT and estimates some representative effects of various overpressures.

Table 1. Blast Pressures and Associated Times.

	Rear 4 ft	Rear 8 ft	Rear 16 ft	Rear 32 ft	Side 8 ft	Side 16 ft	West 50 ft	Driver Seat
Pressure - psig (kPa)	20.3 (140)	8.1 (56)	4.3 (30)	2.0 (14)	11.6 (80)	10 (69)	1.8 (12)	0.5 (3)
Arrival Time (s)	0.848000	0.850550	0.856500	0.869250	0.848625	0.853325	0.883000	0.845050

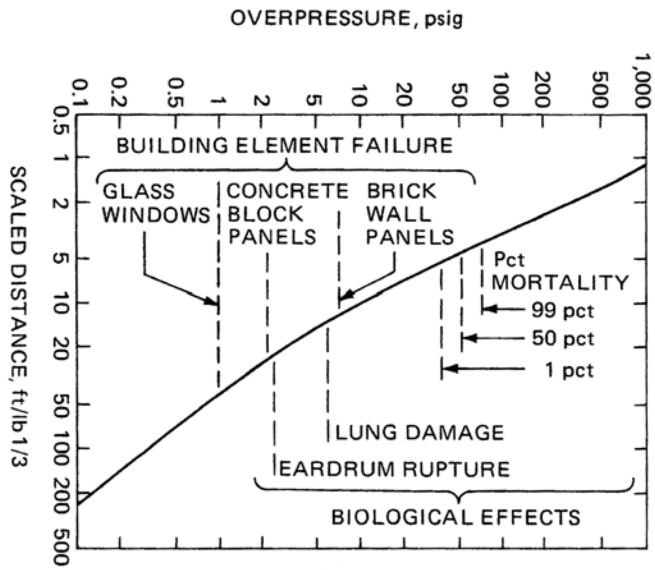


Figure 3. Ideal Blast Wave Overpressure vs. Scaled Distances [3].

The pressure obtained at 16 ft on the driver side of the vehicle, oriented on the longitudinal axis of the cylinder, was 2.3 times higher than the respective location to the rear of the vehicle, oriented on the cylinders radius. This is likely due to the manner in which the cylinder failed, projecting itself to the north, above where the "side" pressure transducers were located.

The velocity of the blast wave was estimated by dividing the distance between the in-line pressure transducers by the time at which the blast wave first reached them. This results in a velocity of 1570 ± 50 ft/sec between the first and second west pressure transducers, a velocity of 1344 ± 50 ft/sec between the second and third pressure transducers, and a velocity of 1250 ± 50 ft/sec between the third and fourth transducers. These velocities are approximately 38 to 10 percent faster than the speed of sound in air, which is approximately 1140 ft/sec (347 m/s) at the ambient test temperature. The velocity measured on the driver side of the vehicle, equivalent to the location of the second and third transducers to the rear of the vehicle, was 1700 ft/sec.

6.0 CONCLUSIONS

The interior of the vehicle became life threatening (untenable) due to interior temperatures, shortly after 4 min of cylinder exposure. Asphyxiation due to carbon monoxide on the interior of the passenger compartment would be a threat at approximately the same time.

Both the mechanical and chemical release of energy from the catastrophic failure of a cylinder would have a devastating effect on an automobile and its passengers, but in this case did not occur until 8 min after the passenger compartment had already become untenable. By this time, the majority of the vehicle was engulfed in the fire; at this point, visible warnings of the hydrogen cylinder on the exterior of the vehicles may have become unrecognizable.

Failure of hydrogen cylinders must be prevented to avoid its major effects on the surroundings, emergency response personnel, other motorists, pedestrians, buildings, *etc*.

In this experiment, a properly working temperature-activated pressure relief device located on the cylinder presumably would have been activated to prevent rupture. However, in the most extreme case, a pressure relief device might prove ineffective when a cylinder is exposed to a localized source of heat or flame, although more time may be required for catastrophic failure to occur. The incorporation of one or multiple layers of thermal insulation with a debris shield might delay or prevent catastrophic failure of a compressed hydrogen cylinder exposed to a flame source as observed in this test.

Certain test standards, including FMVSS 304 (written for compressed natural gas), contain a minimum integrity requirement of 20 min, in lieu of activation of a pressure relief device. Although at this time the interior of the automobile would already have become untenable from a modest-sized fire, devastating effects could still result on the exterior of the vehicle. Test data suggests that the blast wave could cause eardrum rupture approximately 50 ft from the event (2 psig), and could break windows approximately 65 ft from the event (1 psig). Data further suggests that harmful fragments could damage property or personnel approximately 350 ft from the event.

7.0 REFERENCES

[1] FMVSS 304. Chapter 49, Code of Federal Regulations Part 571.304 (49 CFR 571.304), *Standard No. 304, Compressed Natural Gas Fuel Container Integrity*. 2000.

[2] Abbott, M. M., J. M. Smith, and H. C. Van Ness. *Introduction to Chemical Engineering Thermodynamics*, 6th ed. McGraw-Hill, 2001. pp. 91 – 100.

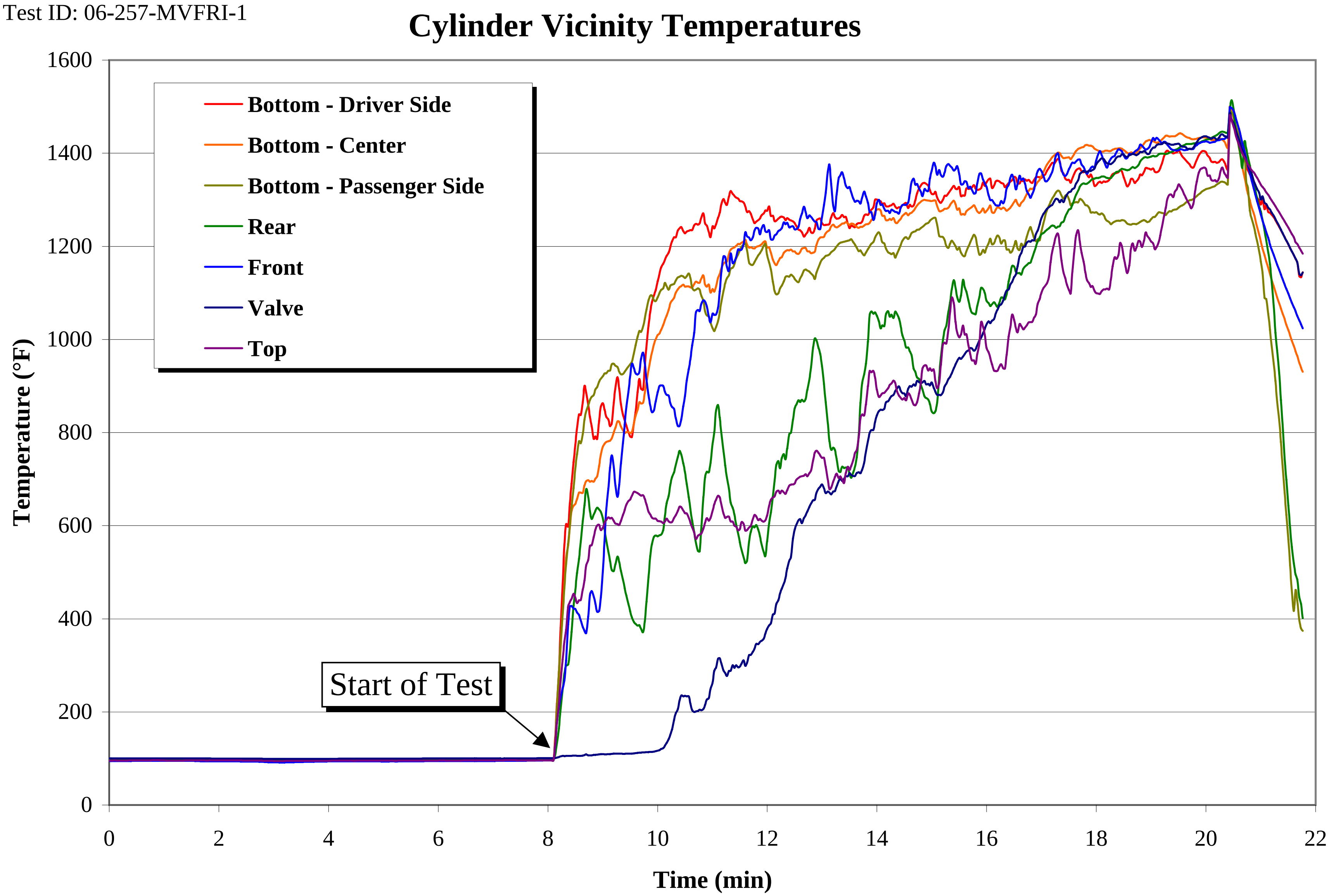
[3] Society of Fire Protection Engineers. *The SFPE Handbook of Fire Protection Engineering*, 2nd ed. National Fire Protection Association, 1995. pp. 3-326 - 3-327.

APPENDIX A

GRAPHICAL TEST DATA

(CONSISTING OF 6 PAGES)

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.005
Test Date: September 14, 2006
Test ID: 06-257-MVFRI-1



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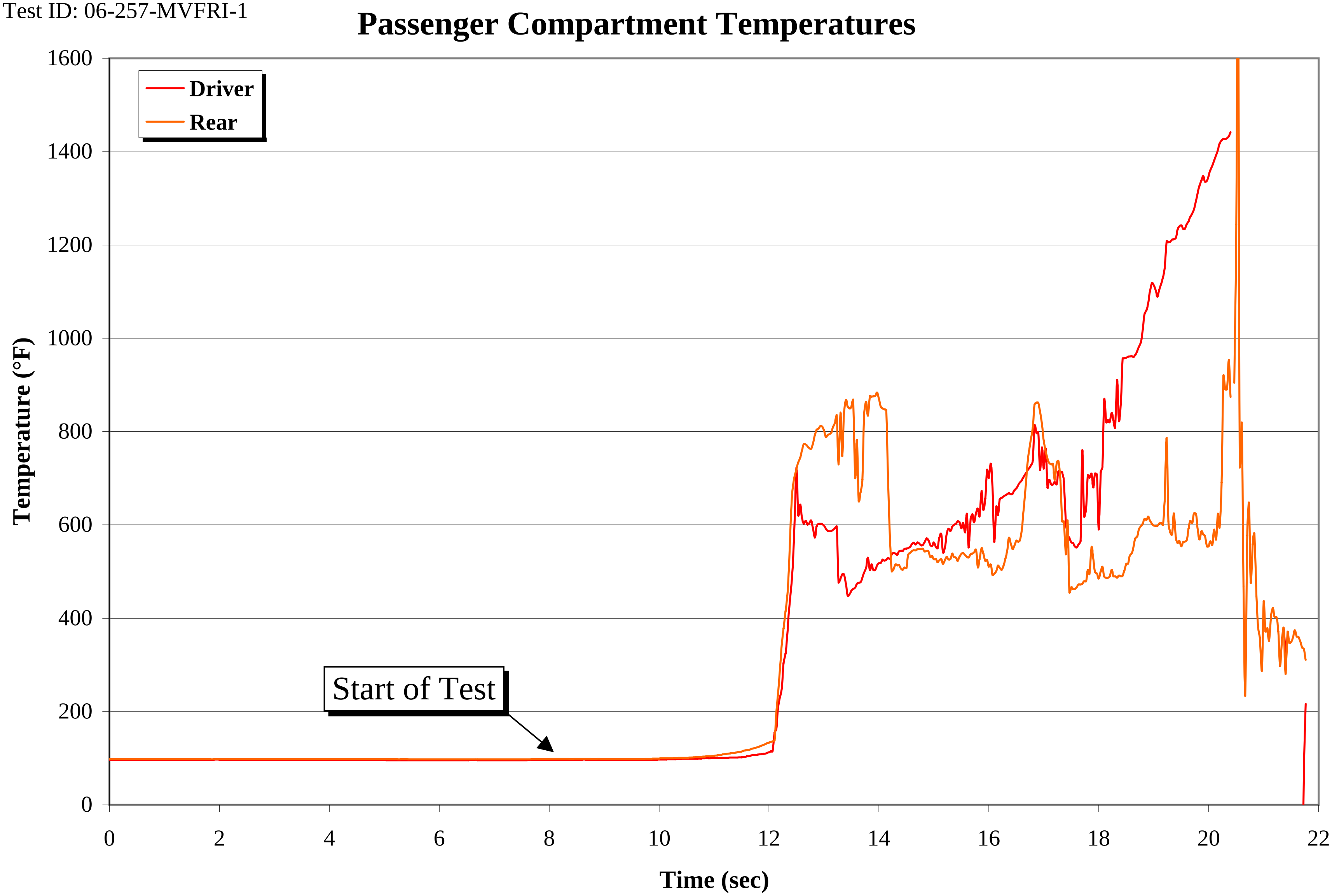

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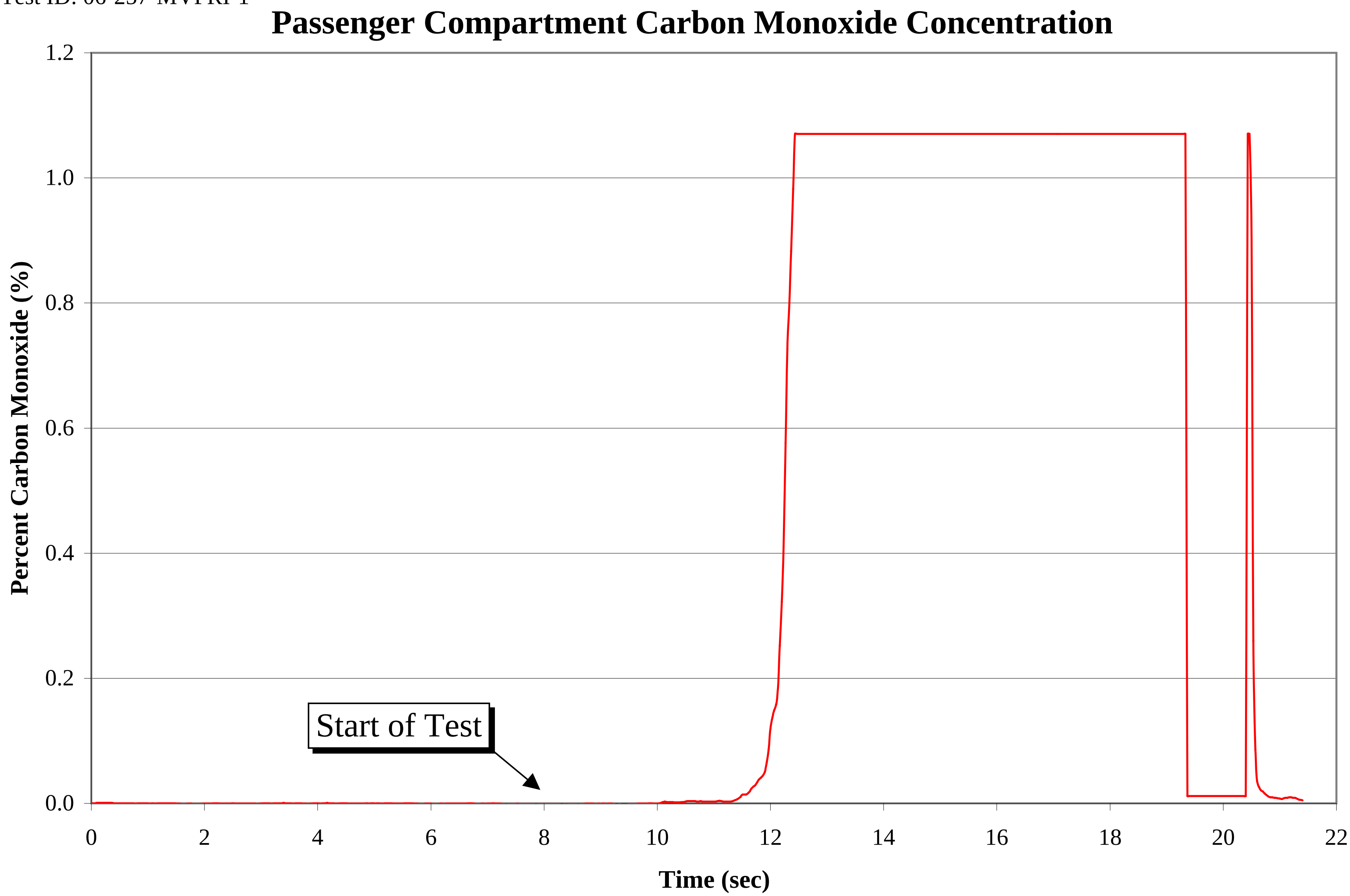

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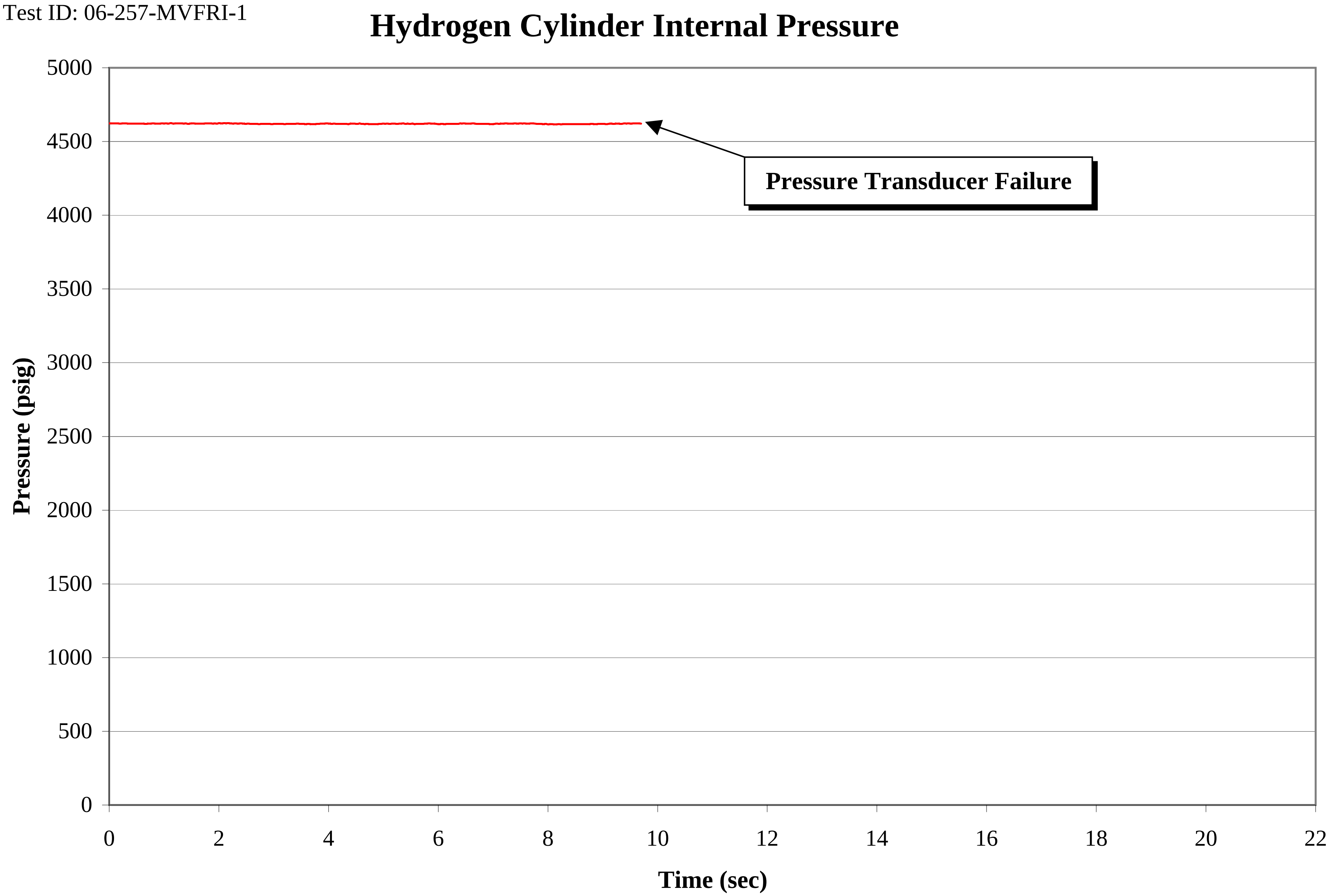

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SwRI Project No. 01.06939.01.005
Test Date: September 14, 2006
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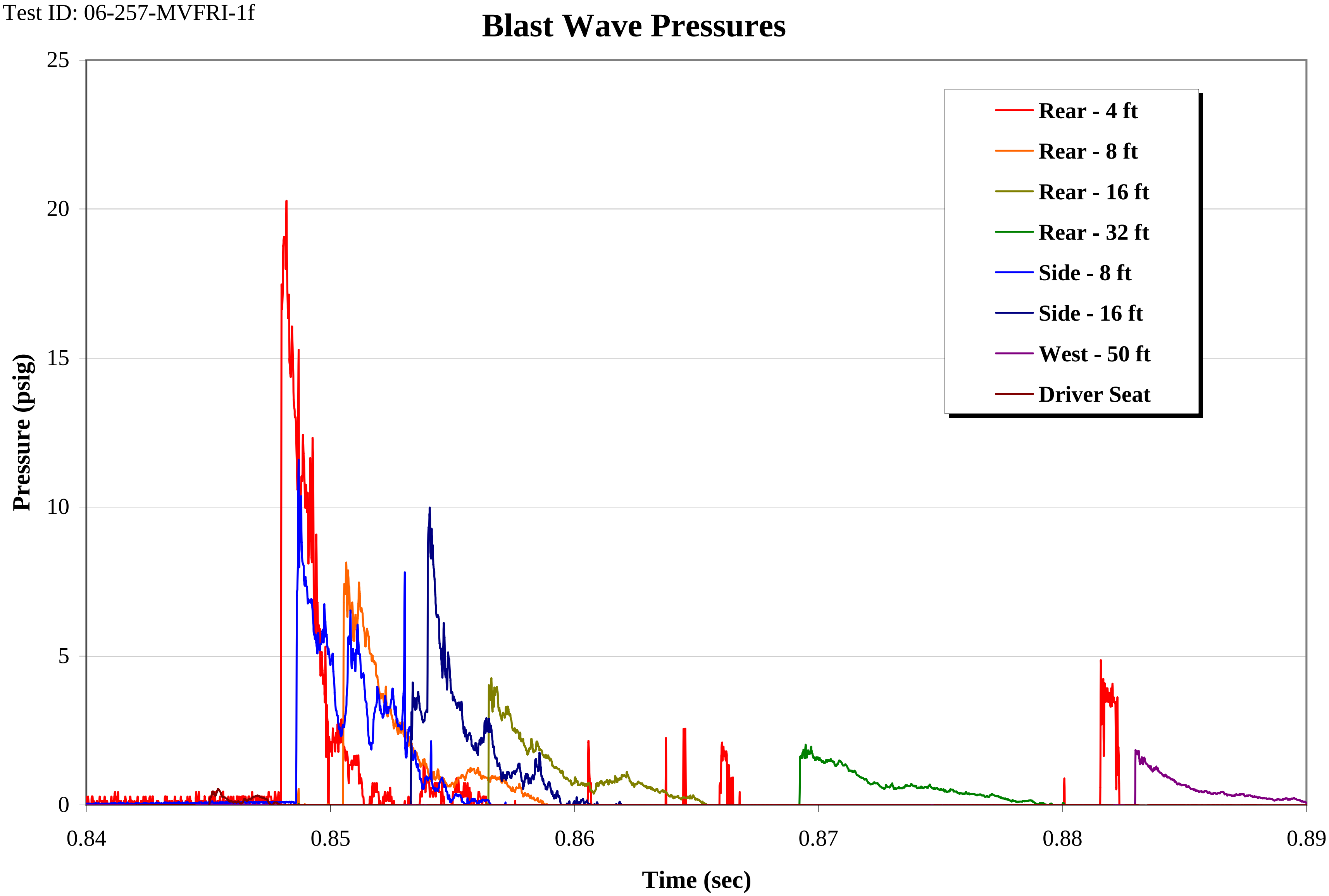

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.005
Test Date: September 14, 2006
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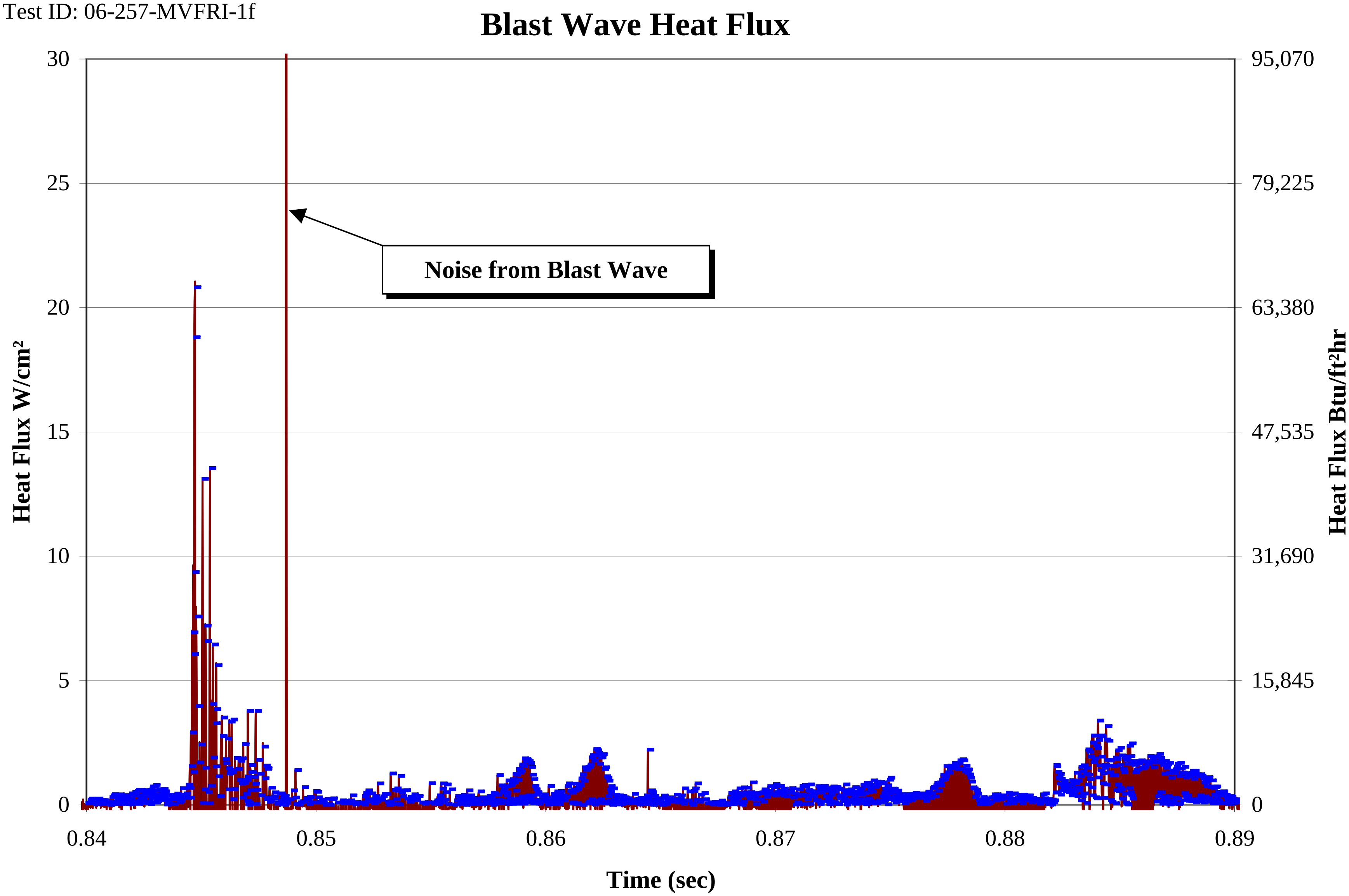

APPENDIX B

PHOTOGRAPHIC DOCUMENTATION

(CONSISTING OF 7 PAGES)

Figure B-1. Overall Test Setup.

Figure B-2. Cylinder Mounted Under Vehicle, Bonfire Pan in Place.

Figure B-3. Beginning of Exposure.

Figure B-4. Approximately 2 Min of Exposure.


Figure B-5. Increasing Involvement of Automobile, Approximately 5 Min of Exposure.


Figure B-6. Full Engulfment of Vehicle, Approximately 10 Min of Exposure.


Figure B-7. Explosion of Cylinder, After Approximately 12 Min of Exposure.


Figure B-8. Smoke Following Explosion, Parts Returning to Ground.

Figure B-9. Remains of Vehicle Following Explosion.

Figure B-10. Remains of Cylinder.

Figure B-11. Overall View of Test Site Following Explosion.

Figure B-12. Large Piece of Sheet Metal Found 112 ft From Test Site.

Figure B-13. Portion of Cylinder Found 35 ft From Test Site.

Figure B-14. Vehicle Rim Found 337 ft From Test Site.