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ANALYSIS OF INDUCED CATASTROPHIC FAILURE OF A 5000 PSIG TYPE IV HYDROGEN CYLINDER

FINAL REPORT
Consisting of 28 Pages
SwRI® Project No. 01.06939.01.001
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Prepared for:

Motor Vehicle Fire Research Institute
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ABSTRACT

Southwest Research Institute's® Department of Fire Technology, located in San Antonio, Texas, examined the effects of catastrophic failure of a 5,000-psig Type-IV hydrogen cylinder on May 21, 2004. The analysis was performed in general accordance with Federal Motor Vehicle Safety Standard (FMVSS) No. 304, *Compressed natural gas fuel container integrity*[1] and the Draft International Standard ISO 15869-1, *Gaseous hydrogen and hydrogen blends – Land vehicule fuel tanks – Part 1: General requirements*.[2] Because it was the intent of the test to examine catastrophic failure, the test procedures were modified and the pressure relief device was removed so that controlled venting of the hydrogen from the cylinder during the test was prevented.

The cylinder was a 5,000-psig (34.5-MPa), 33-in. (84-cm) long, 16-in. (41-cm) diameter (outer dimensions) Type-IV cylinder with an inner volume of approximately 4,420 in^3 (72.4 L). Each end of the cylinder consisted of a dome and an aluminum end fitting with female SAE threads for connection to instrumentation and hydrogen filling equipment. The cylinder was filled to 4,980 psig (34.3 MPa) with 3.62 lb (1.64 kg) of hydrogen.

Instrumentation included internal cylinder temperature and pressure, cylinder surface temperature, flame temperatures, and blast wave pressures at four locations.

The cylinder was placed over a propane bonfire source of 580 scfh (270 slpm) of propane (21,000 Btu/min or 370 kW of exposure). The cylinder was exposed to the fire for 6 min 27 sec when it lost its integrity and failed catastrophically. The internal temperature at this time had risen from its initial temperature of 81°F to 103°F (27°C to 39°C) and the internal pressure had risen to 5,180 psig (35.7 MPa).

An estimated 11,800 Btu (12.4 MJ) in mechanical energy was released when the tank burst, and up to 187,000 Btu (197 MJ) in chemical energy was released when the hydrogen combusted. The cylinder failed through the bottom, destroying the burn shield and launching it 270 ft (82 m) east of the test location. The remainder of the polyethylene liner was expelled through the bottom of the cylinder as it arced through the air. The following blast wave pressures were recorded with the transducers:

Blast Pressures and Associated Times.*

	North - 166 in. (420 cm)	West - 76 in. (190 cm)	West - 166 in. (420 cm)	West - 256 in. (650 cm)
Pressure - psig (kPa)	9 (62)	43 (300)	12 (83)	6 (41)
Time (s)	0.0245	0.0200	0.0243	0.0296

***Distances of pressure gauges are from the center of the cylinder. Times are relative.**

INTRODUCTION

The objective of this program was to induce the catastrophic failure of a 5,000-psig (34.5-MPa) Type-IV hydrogen cylinder and conduct a failure analysis of the event. The main measurements were intended to determine the mechanical and chemical energy released from the event.

The intent was not to evaluate the specific tank for its ability to resist failure but rather to evaluate the extent and magnitude of the failure. Safety measures typically required on compressed gas cylinders (pressure relief devices) were not utilized, as inducing failure of the cylinder was the object of the test.

TEST PROCEDURES

Standard Test Procedures for Compressed Gas Cylinders

Procedures referenced include the Federal Motor Vehicle Safety Standard (FMVSS) No. 304, *Compressed natural gas fuel container integrity*[1] [*] and the Draft International Standard ISO 15869-1, *Gaseous hydrogen and hydrogen blends – Land vehicule fuel tanks – Part 1: General requirements*.[2] These standards outline similar bonfire test procedures.

Both procedures expose a compressed hydrogen cylinder at its working pressure to a 65-in. (165-cm) long bonfire. The fuel for the fire is not specified in either standard. Southwest Research Institute® (SwRI®) typically uses natural gas or propane for control and environmental reasons. FMVSS 304 requires two of three thermocouple measurements below the tank (directly in the flames) to average in excess of 800°F (427°C) for the duration of the test. ISO 15869-1 requires one of three shielded thermocouple measurements of the cylinder surface exposed to the fire to be in excess of 1094°F (590°C) for the duration of the test. Both of these objectives were met in this investigation.

Tests are performed with the tank manufacturers' specified fire protection system in place (pressure relief device, e.g.). All tank valves, fittings, and pressure relief devices are protected from direct flame impingement during the test. FMVSS 304 requires a cylinder to either not rupture during a 20-min bonfire test, or to safely vent its contents through a pressure relief device. ISO 15869-1 requires a hydrogen cylinder to vent its contents prior to rupture (no specified maximum duration).

Customization of Test Procedure

The objective of this test was to determine the effects of a catastrophic failure, not to determine the ability to prevent failure. Therefore, the procedure was customized to ensure this objective would be met. The length of the bonfire was lowered from 65 in. to 33 in. (84 cm) in order to concentrate the bonfire on the cylinder. This was done to lower the probability that any fittings would fail prior to

[*] Superscripted numbers correspond to references listed at the end of the test of this report.

cylinder rupture. Additionally, there was no pressure relief device located on the cylinder. This was to allow the cylinder contents to reach pressures in excess of the relief device limits without venting its contents.

TEST SPECIMEN

SwRI acquired a single 5,000-psig (34.5-MPa) Type-IV hydrogen cylinder for this program. The 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 inner volume of the tank was approximately 4,420 in.^{3} (72.4 L). The cylinder 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 with female SAE threads.

The threads were used for connection to instrumentation and gas handling equipment for this program. One end was fitted with a bushing machined in-house for connection to a high-pressure thermocouple assembly. The opposite end was fitted with a commercially available three-port gas manifold. The manifold was provided with a ball valve and two port plugs. The manifolds are typically provided with a pressure relief device, but no pressure relief device was desired for this scope of work. One of the ports was used for connection to a pressure transducer, and the remaining port was left plugged.

All fittings and instrumentation installed on the cylinder were rated for a minimum of 5000 psig. The empty cylinder with all fittings attached weighed 73.2 lb (33.2 kg).

FACILITY

Initial instrumentation preparation and verification was performed at SwRI's main campus in San Antonio, Texas. This included assembly of the cylinder's instrumentation and fittings as well as evacuating and filling of the cylinder. The induced failure was conducted at SwRI's remote fire testing facility, located in Sabinal, Texas. The remote facility consists of a 15-acre test field, a steel test pad, an instrumentation trailer, and a remote-monitoring building.

Bonfire Source

A 250-gal (950 L) propane tank equipped with vaporizers was located on the outside of the remote-monitoring building. Liquid propane flowed from the tank, to the vaporizers, through a rotameter, and to a buried pipe supplying the burner. The supply pipe ran underground from the propane supply system, stubbed out of the ground next to the steel test pad, and was connected to the burner system via flexible hose.

Propane was combusted out of a line burner intended to simulate a fuel-spill scenario. The line burner was approximately 12 in. (30 cm) wide and 65 in. (165 cm) long. It was constructed from three 2-in. (5-cm) diameter pipes, with holes drilled on 6-in. (15-cm) centers at its zenith and two horizontal quadrants. The line burner was fed on both ends in order to achieve an even distribution of fuel. For this program, holes outside of the 33-in. (84-cm) cylinder area were plugged with high-temperature tape in order to concentrate the bonfire on the cylinder.

The line burner was protected from wind with a 32 x 90 x 8-in. deep (81 x 230 x 20-cm) pan. The bottom of the pan had 1-in. (2.5-cm) holes on approximately 6-in. (15-cm) centers to allow the induction of combustion air. A spark-plug igniter was located just above the line burner. Power was provided to the igniter from a high-voltage ignition transformer located underneath the pan.

Two chains were welded to the top of the pan across its width, approximately 24 in. (61 cm) apart. These chains were used to support the cylinder during the test. The chains were protected from the bonfire with 1-in. (2.5-cm) thick glass-wool insulation.

INSTRUMENTATION

The hydrogen cylinder was instrumented with an internal thermocouple and pressure transducer to monitor its conditions during the test. The thermocouple was a $^{1}/_{16}$-in. (1.5-mm) inconel-sheathed Type-K thermocouple. The pressure transducer had a range of 0-20,000-psig (138-MPa).

Blast-wave pressures were measured with four blast-pressure pencil probes. The two probes nearest the cylinder had a range of 0-500 psig (3.4 MPa), and the two probes farther from the cylinder had a range of 0-50 psig (340 kPa). One of the 0-500 psig probes was located perpendicular to the axis of the cylinder, approximately 76 in. (190 cm) from the center of the tank. The two 50 psig probes were located in a straight line with this probe, perpendicular to the cylinder, spaced 90 in. (230 cm) apart, placing them 166 in. (420 cm) and 256 in. (650 cm) from the center of the cylinder, respectively. The remaining 500-psig probe was located just off the axis of the cylinder, approximately 166 in. (420 mm) from the center of the cylinder, placing it equidistant from the cylinder with the second perpendicular probe.

Three $^{1}/_{8}$-in. (3.2-mm) diameter inconel-sheathed Type-K thermocouples were set 1 in. (25 mm) below the tank exterior in order to measure the flame exposure temperatures. Three 22-gauge exposed-bead Type-K thermocouples were placed on the side surface of the cylinder, on the top surface of the cylinder, and in the air, approximately 8 in. (20 cm) from the surface of the cylinder.

Thermocouple and signal wires were run underground from the steel test pad to the instrumentation trailer, located approximately 100 ft (30 m) from the test pad, where they were connected to the data acquisition system. The instrumentation trailer was protected with an 8-ft (2.5-m) tall wall of railroad ties. A weather station consisting of wind speed and wind direction sensors was set up at the instrumentation trailer in order to document the conditions during the test.

Data was logged on a high-speed data acquisition system. Slow speed data, which included the thermocouples, cylinder pressure, and weather conditions, were logged and saved at a rate of 2Hz throughout the entire exposure. The high-speed blast-wave pressure transducers were logged at a rate of 10 kHz throughout the test. The acquisition system was set up such that 3 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 in the remote-monitoring building.

Documentation

A wireless video camera was placed atop the railroad ties in front of the instrumentation trailer to monitor the event. The video signal was captured and recorded at the remote-monitoring building at fifteen frames per second.

A high-speed infrared camera was used to capture the heat emitted from the hydrogen combustion at 200 frames per second. The mid-wave infrared camera is sensitive from 3 – 5.2 microns and uses a MCT (mercury cadmium telluride) based focal plane array sensor cooled with a closed-cycle Stirling cooler. The video was captured using the PC-based analysis and reporting software.

A high-speed video camera was used to capture the cylinder as it failed. This camera was set to capture 1000 frames per second. Both high-speed cameras were set up such that they continuously recorded video to a buffer. A manual trigger by the operator saved video for a period before the trigger (in the buffer) and after the trigger.

The following diagram provides a general depiction of the test setup:

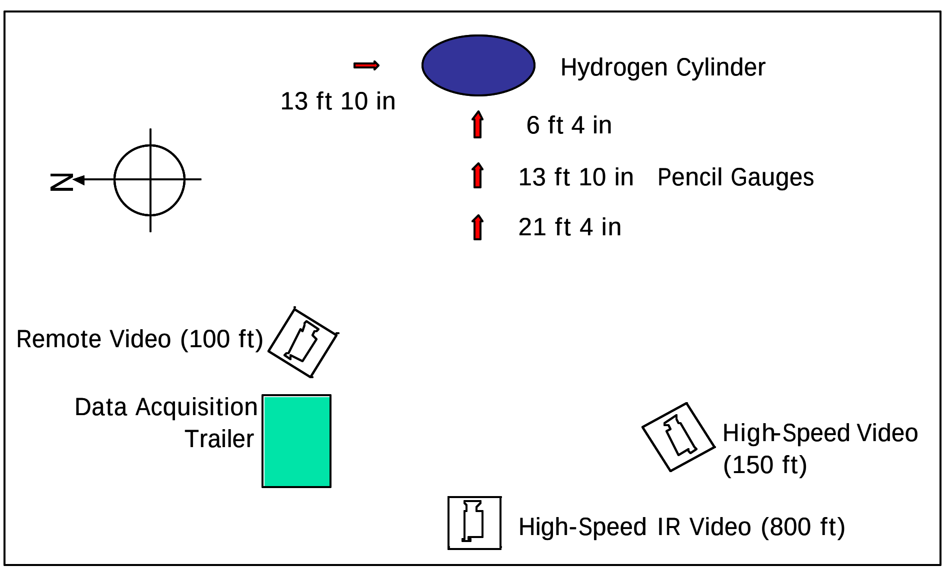


Figure 1. General Test Setup. Note - Not to scale.

EXPERIMENTAL PROCEDURE

The hydrogen cylinder was filled to 5,000 psig (34.5 MPa) from laboratory hydrogen cylinders two days prior to the test. The cylinder was then allowed to cool overnight and topped off to 5,000 psig the following day. Once the cylinder was full, the ball valve opening was capped to prevent the accidental release of hydrogen. The cylinder was then transported to the test site.

All instrumentation was connected and verified prior to the test. The propane burner was ignited and adjusted to achieve a fully-engulfing fire source. The propane was then cut off, and the burner and pan were allowed to cool. Once sufficiently cool, the tank was placed on the support chains.

All cameras were set up and focused on the cylinder, and video and data acquisition were initiated. The spark igniter was energized, and the area was cleared. The internal cylinder temperature and pressure at the beginning of the test were 81°F (27°C) and 4,980 psig (34.3 MPa), respectively. This temperature and pressure corresponds to a 3.62 lb (1.64 kg) mass of hydrogen in the tank, as calculated by the Redlich/Kwong correlation.[3] Wind speed averaged 8 mph from the south, ambient temperature was approximately 77°F (25°C), and relative humidity was 95%. Propane flow was initiated and ignition was verified. Propane flow began at approximately 415 scfh (195 slpm), and was quickly increased to approximately 580 scfh (270 slpm) for the duration of the test. This corresponds to approximately 21,000 Btu/min (370 kW), assuming a 95% combustion efficiency.

Composite material on the surface of the tank ignited approximately 45 sec into the test, as evidenced by the appearance of black soot. The internal cylinder temperature and pressure slowly increased during the exposure. The cylinder was exposed to the fire for 6 min 27 sec when it lost its integrity and failed catastrophically. The internal temperature and pressure at this time had risen to 103°F (39°C) and 5,180 psig (35.7 MPa), respectively. The temperature and pressure rise correlated within 0.1% of expected values from the Redlich/Kwong correlation.

Graphical depiction of the test data is provided in Appendix A. Photographic documentation of the test is provided in Appendix B. Calibration data for the test instrumentation is provided in Appendix C.

RESULTS

The cylinder failed through the bottom, destroying the burn shield and launching the 30.9-lb (14.0-kg) main portion 270 ft (82 m) east of the test location. The main portion included the aluminum end fitting to which the manifold and ball valve were still attached. The opposite aluminum end fitting was not attached, nor was it located.

The remainder of the polyethylene liner was expelled through the bottom of the cylinder as it arced through the air. Three main pieces of the liner were found: a 3.6-lb (1.6-kg) split cylinder approximately 74 ft (22 m) east of the test location, and two 4.3-lb (2.0-kg) domes approximately 157 and 163 ft (48 and 50 m) northeast of the test location; it is assumed that the domes' location north of the cylinder's eastward trajectory is due to wind.

Several small pieces of polyethylene liner were found, mostly north of the test site, up to approximately 170 ft (52 m) from the test location. Clumps and shreds of carbon fiber were found scattered around the test site, again mostly to the north. SwRI gathered all significant polyethylene and carbon fiber remains that could be found; a total of 4.6 lb (2.1 kg) was recovered.

The visible fireball from the hydrogen released as recorded by the high-speed video camera was initially a hemispherical shape, 25 ft (7.6 m) in diameter. It then rose up into the air as it transformed into a shrinking sphere. The visible fireball lasted approximately 2 sec. The fireball observed with the high-speed infrared camera was also approximately 25 ft (7.6 m) in diameter. However, the fireball was observed for a longer duration (approximately 4.5 sec).

The chemical energy released from the hydrogen combustion was estimated using the high-speed infrared camera. The radiance was provided as pixilated data, separated into frames, in units of heat flux per steradian (solid angle). The data was processed by SwRI to obtain the average radiance for each frame. The heat release rate was obtained over the 35 x 25 ft view area (at the cylinder's distance) by estimating a spherical geometry of 4π steradians and dividing by the radiative fraction of 10% (the percent of hydrogen combustion emitted as radiation). The heat release rate was integrated over time, resulting in 10,200 Btu (10.8 MJ) of energy. Theoretical heat released from 3.62 lb (1.64 kg) of hydrogen combusting is 187,000 Btu (197 MJ). The low measured heat release (approximately 5% of theoretical) is most likely due to the fact that the peak IR emission from hydrogen flames (2.7 microns) is outside of the IR camera's 3-5.2 micron range. The adiabatic flame temperature of hydrogen is approximately 3850°F (2120°C).

The mechanical energy released is equivalent to the work on the surrounding environment by the expanding gasses:

$$E = \int P dV$$

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[3], 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,

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).

Solving this integral results in a mechanical energy release of approximately 11,800 Btu (12.4 MJ).

The highest point that the cylinder reached was not captured by video. The initial angle of the cylinder, estimated from the high-speed video as 65° from horizontal, and the final position of the cylinder were used in kinematics equations to estimate the apex of its flight as 145 ft (44 m), and the time of flight as 6 sec. Accuracy of these estimations are expected to be low due to the estimations made from video, and the assumption that the cylinder left the ground with an initial velocity (no continuing acceleration force other than gravity).

Table 1 outlines the maximum 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[4] outlines the ideal blast pressures of TNT and estimates the effects of various overpressures.

Table 1. Blast Pressures and Associated Times.

	North - 166 in. (420 cm)	West - 76 in. (190 cm)	West - 166 in. (420 cm)	West - 256 in. (650 cm)
Pressure - psig (kPa)	9 (62)	43 (300)	12 (83)	6 (41)
Time (s)	0.0245	0.0200	0.0243	0.0296

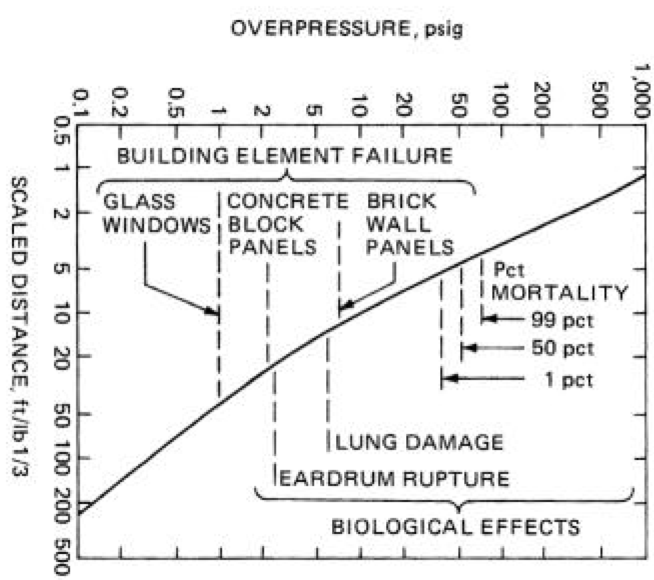


Figure 2. Ideal Blast Wave Overpressure vs. Scaled Distances.[4]

The time at which the blast wave reached the north and west pressure transducers located at approximately the same distance was virtually identical. However, the pressure obtained at the west transducer was significantly more (33%) than the north transducer. This is consistent with the trajectory of the cylinder as the higher pressures were obtained in the opposite direction of the trajectory. The velocity of the blast wave can be estimated by dividing the distance between the three in-line pressure transducers by the time at which they reached their peak reading. This results in a velocity of 1750 ± 50 ft/sec (533 m/s) between the first and second west pressure transducers, and a velocity of 1400 ± 50 ft/sec (427 m/s) between the second and third pressure transducers. These velocities are approximately 50% to 25% (respectively) faster than the speed of sound in air, which is approximately 1140 ft/sec (347 m/s) at the ambient test temperature. There was no second peak corresponding to the combustion of hydrogen as a second event. It is therefore assumed that hydrogen combustion was able to occur as rapidly as the hydrogen mixed with air.

CONCLUSIONS

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. Failure of hydrogen cylinders must therefore be prevented.

Previous tests have shown that Type II cylinders constructed with a steel liner (and hoop-wrapped with composite) have been known to split across the cylinder upon failure. Once the composite has lost its integrity in a given location, and the pressure has increased sufficiently, the steel splits around the cylinder, where the composite material shows the least strength. Type IV cylinders utilize polyethylene liners, which unlike steel liners, are not designed to provide integrity. Therefore, once the composite has lost its integrity due to the fire in a given location, a catastrophic rupture occurs.

Also, unlike metal-lined cylinders, a polyethylene liner provides thermal insulation for the contents of the cylinder. Therefore, when exposed to fire, the temperature and pressure inside a Type IV cylinder will not climb as quickly as a Type I, II, or III cylinder.

In this experiment, the pressure inside the cylinder did not rise sufficiently so that a pressure-activated pressure relief device would have activated to prevent rupture. The temperature inside the cylinder also did not climb sufficiently to activate a thermally-activated pressure relief device if it had been present. Thermally-activated pressure relief devices must, therefore, be exposed to a sufficient external heat source to guarantee activation. In the most extreme case, a pressure relief device would prove ineffective when a cylinder is exposed to a point source of heat or flame. The incorporation of one or multiple layers of thermal insulation with a debris shield might prevent catastrophic failure of a compressed hydrogen cylinder exposed to a flame source as observed in this test.

References

[1] Federal Register, Vol. 65, No. 210. Part 571.304: *Standard No. 304, Compressed natural gas fuel container integrity*. October 30, 2000. pp. 64626-64627.

[2] International Organization for Standardization. Draft International Standard ISO/DIS 15869-1: *Gaseous hydrogen and hydrogen blends – Land vehicule fuel tanks – Part 1: General requirements*. 2004. pp. 14 – 15.

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

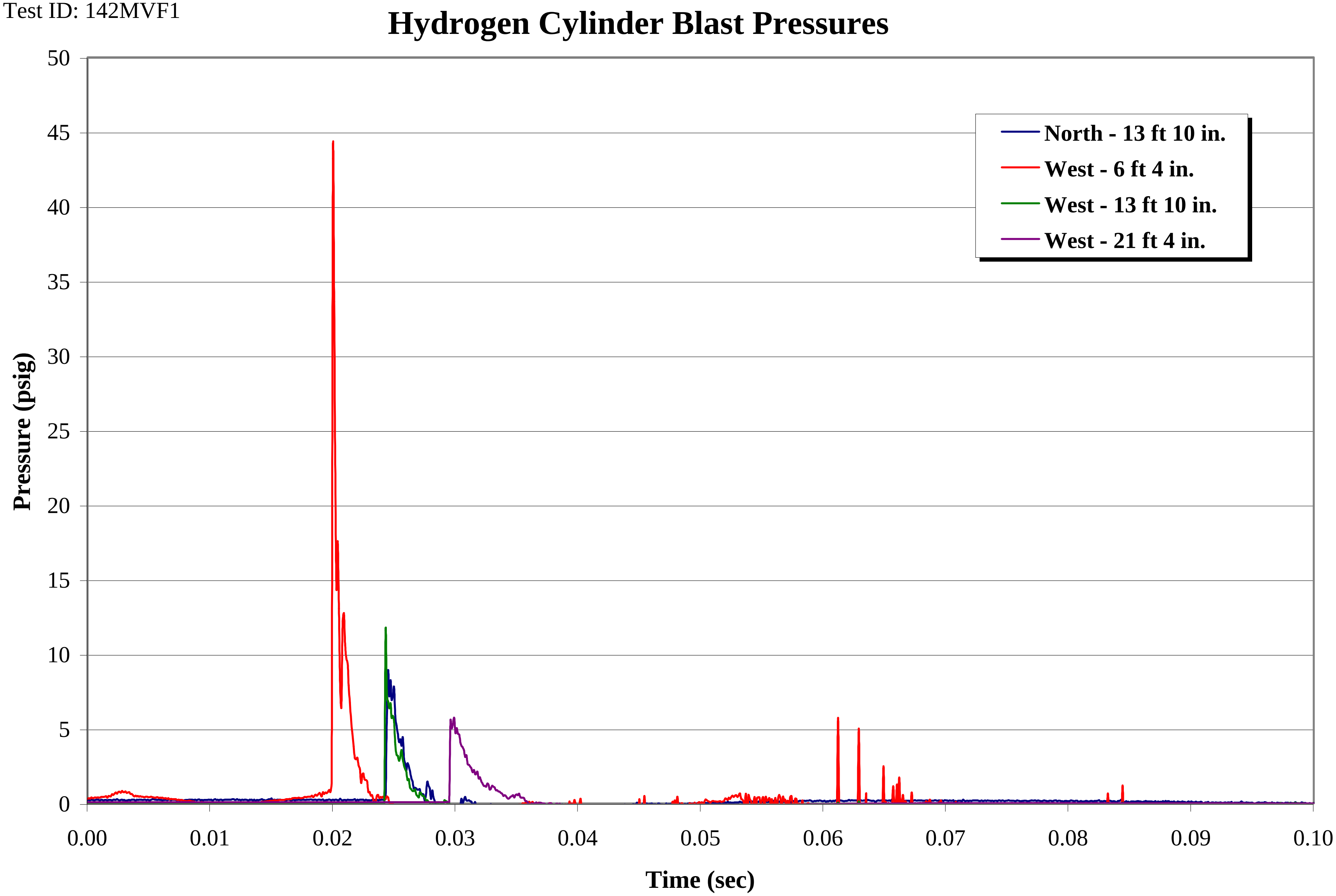
[4] Society of Fire Protection Engineers. *The SFPE Handbook of Fire Protection Engineering*, 2nd ed. National Fire Protection Association, 1995. pp. 3-326 – 3-327.

APPENDIX A

GRAPHICAL DATA

(CONSISTING OF 5 PAGES)

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.001
Test Date: May 21, 2004
Test ID: 142MVF1



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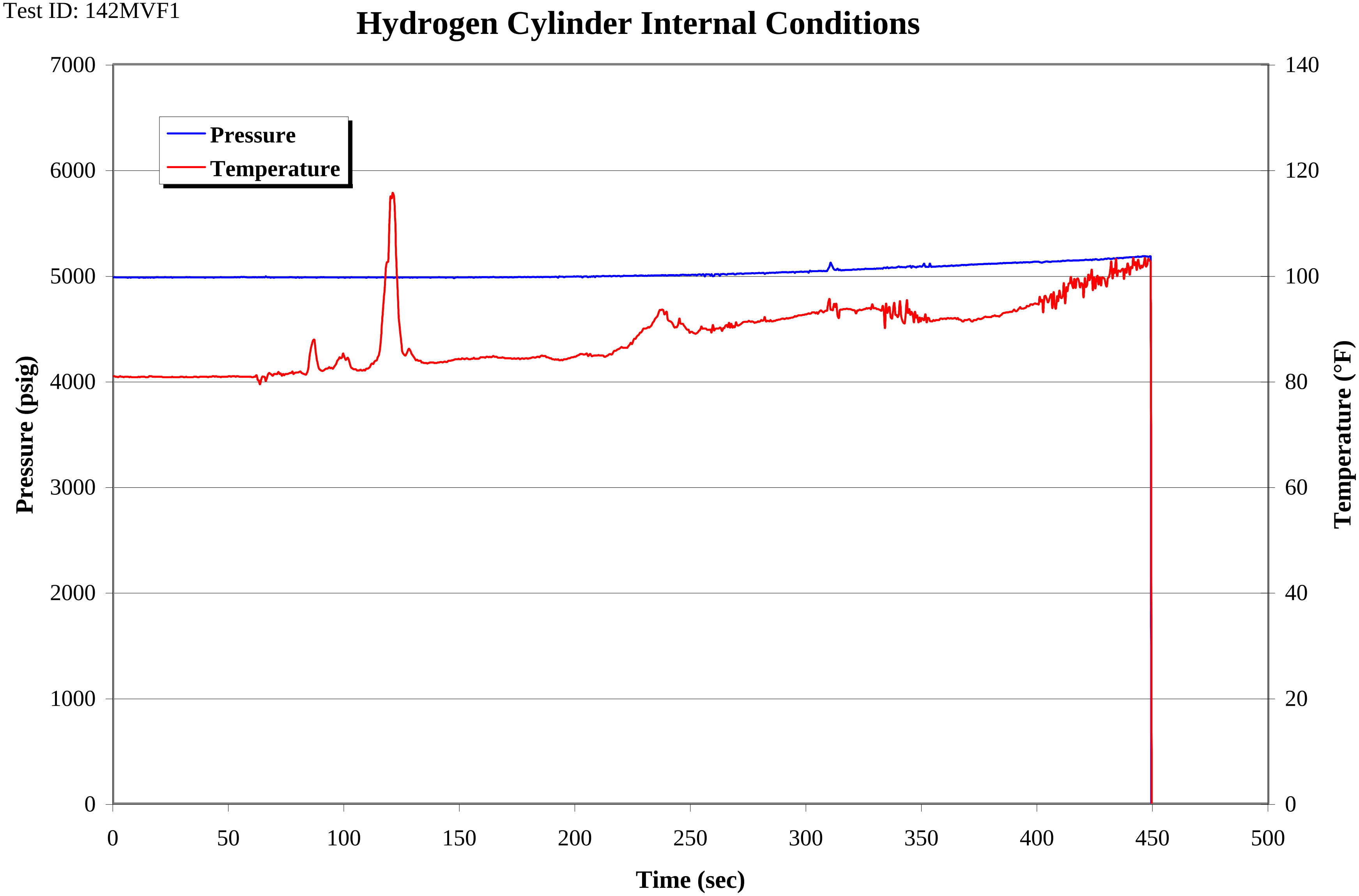
SwRI Project No. 01.06939.01.001
Test Date: May 21, 2004
Test ID: 142MVF1



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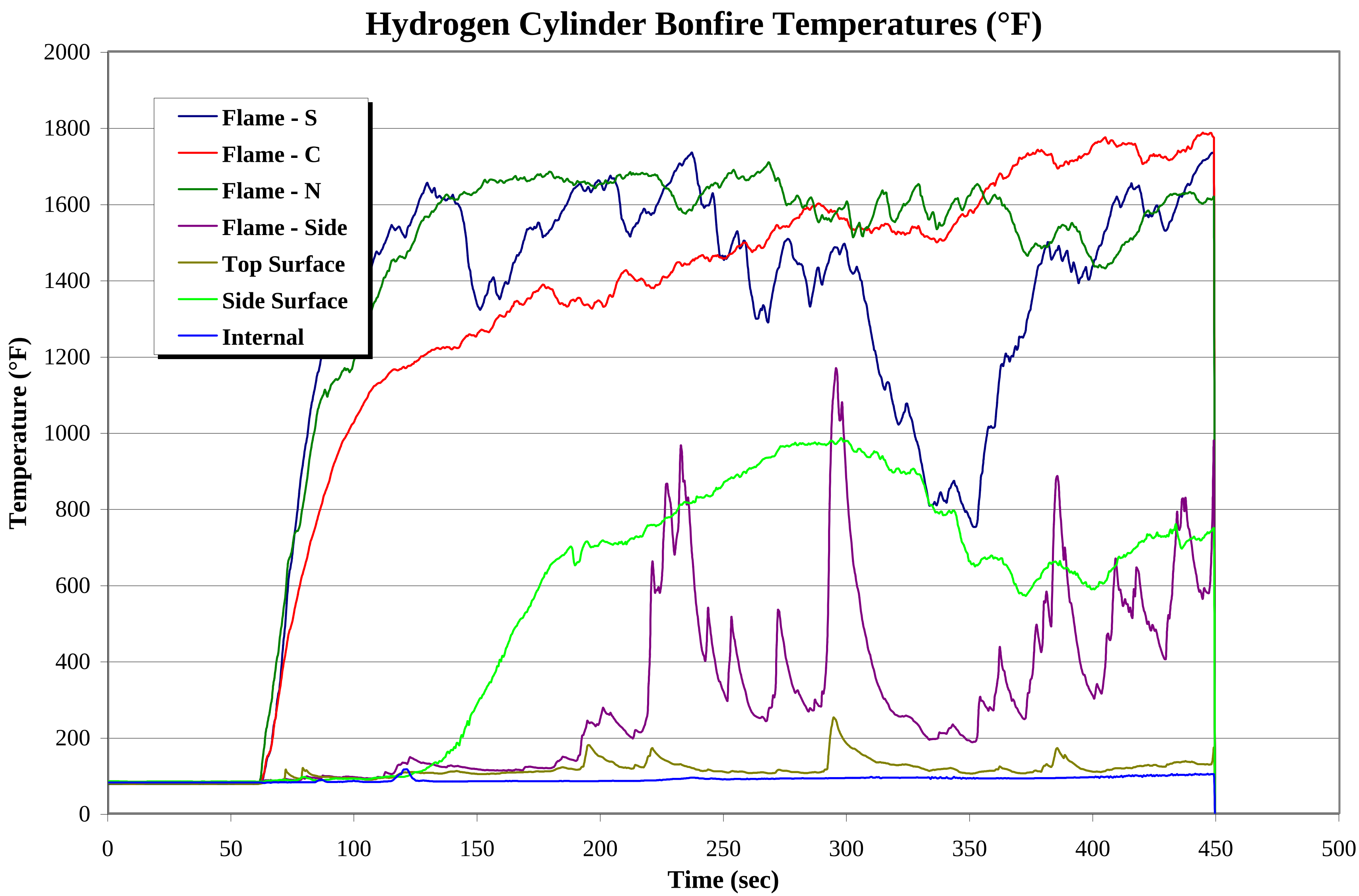

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SwRI Project No. 01.06939.01.001
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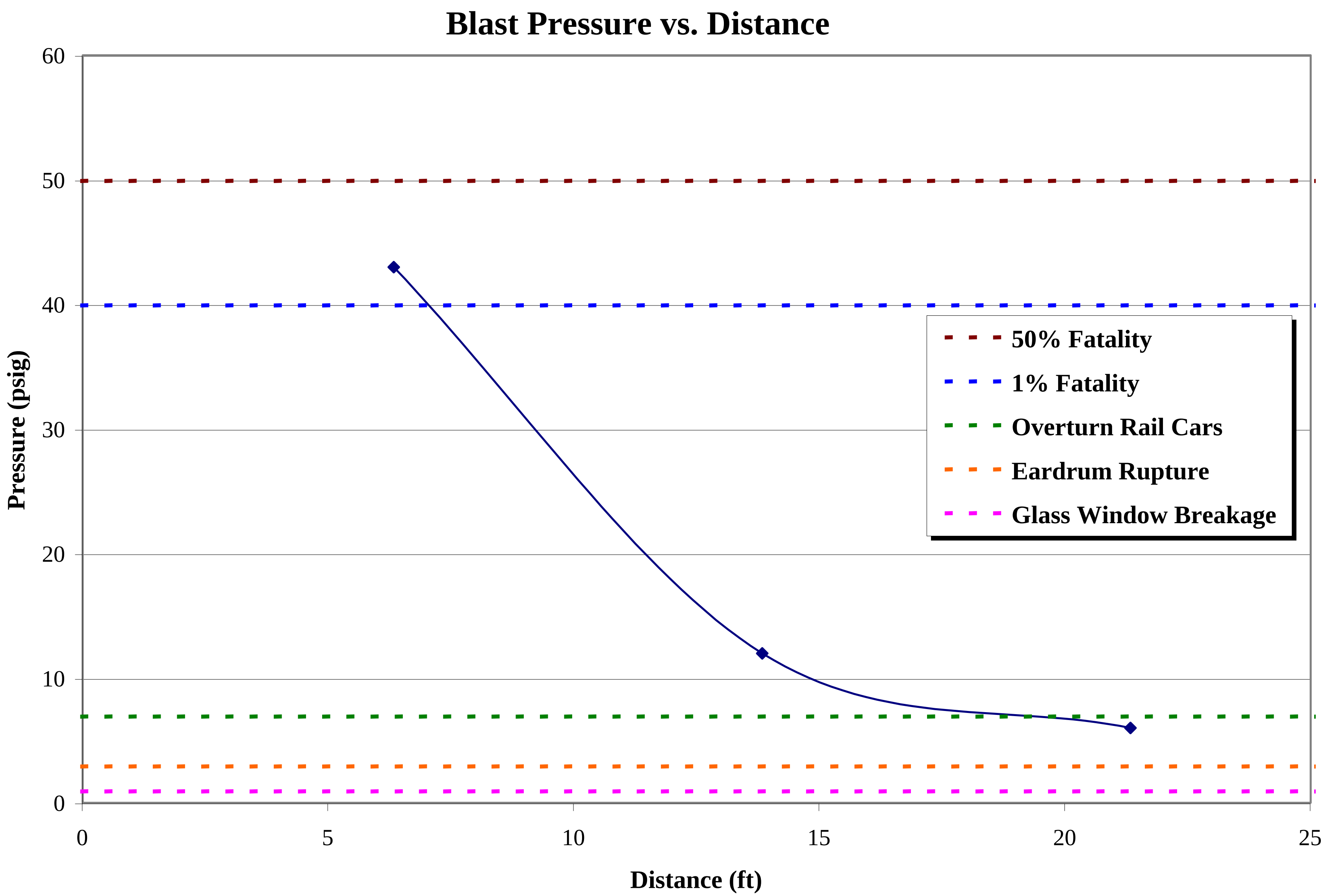
Test ID: 142MVF1



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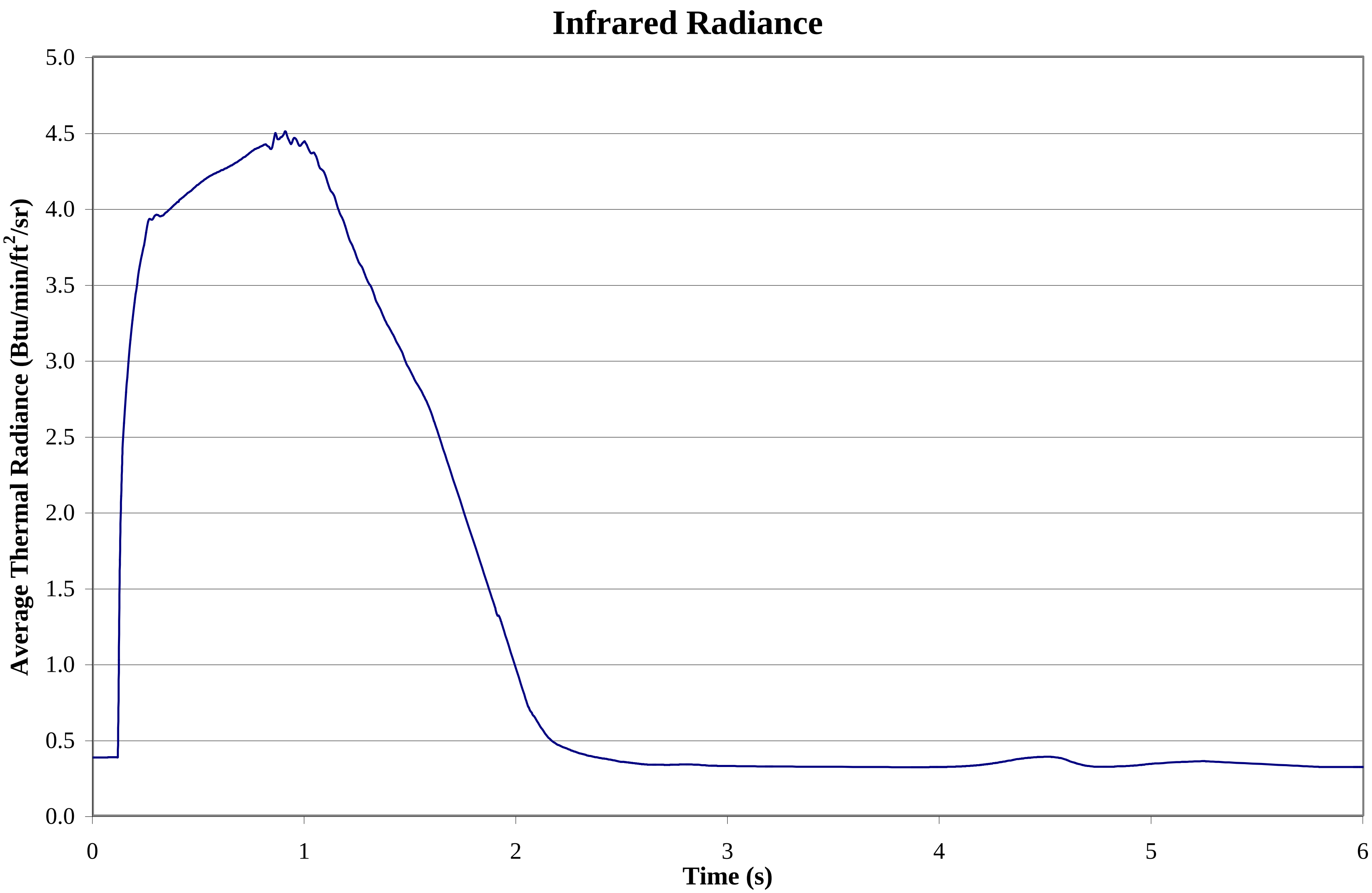
SwRI Project No. 01.06939.01.001
Test Date: May 21, 2004
Test ID: 142MVF1



APPENDIX B

PHOTOGRAPHIC DOCUMENTATION

(CONSISTING OF 4 PAGES)

Figure B-1. Type-IV Hydrogen Cylinder Located on Bonfire Source.

Figure B-2. View of Blast-Wave Pressure Transducers on West Side of Cylinder.

Figure B-3. Camera Setup.

Figure B-4. Cylinder Under Bonfire. Note soot from combustion of cylinder materials.

Figure B-5. Test Site After Cylinder Failure.

Figure B-6. Remains of Bonfire Source and Shield.

Figure B-7. Main Portion of Cylinder Remains.

Figure B-8. Main Cylinder and Dome of Polyethylene Liner.

APPENDIX C

CALIBRATION CERTIFICATES

(CONSISTING OF 5 PAGES)

CALIBRATION CERTIFICATE

Model: 137A22
Serial #: 5545
Description: Pressure Sensor
Type: ICP

Sensitivity*: **9.700 mV/PSI** 9700 mV/kPSI
1407 mV/MPa

#1

Linearity*: 0.2% FS
Uncertainty:** +/- 0.78 %

Date: 4/29/04
By: Eric Kachermeyer, Cal. Tech
Station: 907 Dyn. Med. Press. #1 (Test Procedure AT601-11)

Temp: 73 deg F [23deg C]
Humidity: 24 %

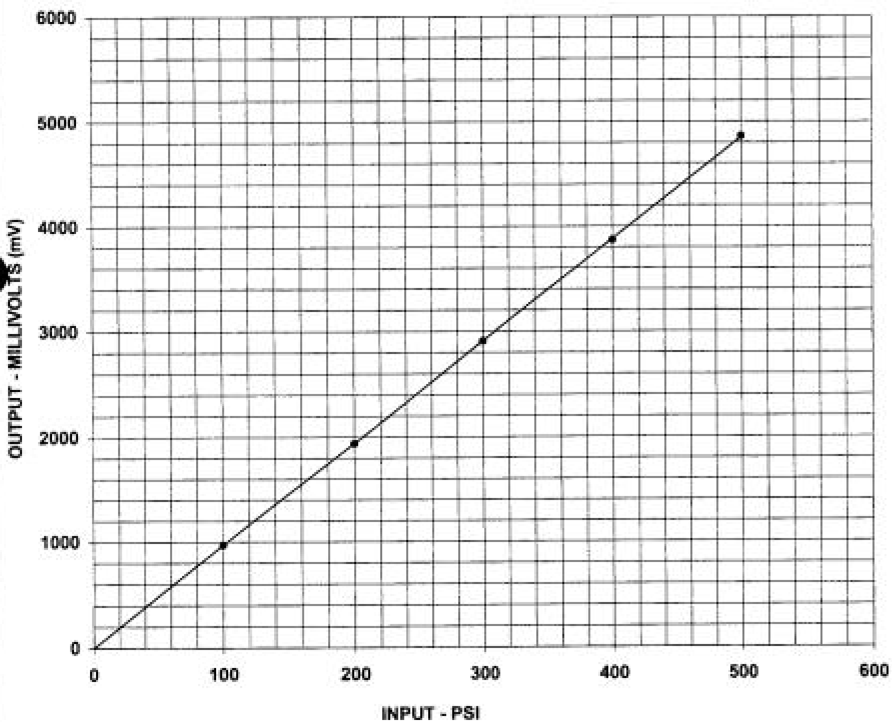
Cert #: 168653

Bias: 10.8 VDC

* Zero based, least-squares straight line.

** Measurement uncertainty represented using a coverage factor of k=2 which provides a level of confidence of approximately 95 %.

Condition of Unit:
As Found: Not applicable
As Left: In tolerance, new unit



TEST DATA

INPUT (PSI)	OUTPUT (mV)
100	970.381
200	1938.443
300	2908.015
400	3869.119
500	4860.262

Notes:
1 STATION #15
2 This certificate may not be reproduced, except in full without the written approval of PCB Piezotronics, Inc.
3 NIST traceability through PCB control # CA334.
4 This certificate may not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.

A2LA ACCREDITED
Cert. No. 1862.01

PCB PIEZOTRONICS

Tel: 716-684-0001 Fax: 716-684-0987 Email: sales@pcb.com
3425 Walden Avenue, Depew NY 14043

ISO 9001 CERTIFIED

Page 1 of 1

CALIBRATION CERTIFICATE

Model:	137A22	**Date:**	4/29/04
Serial #:	5546	**By:**	Eric Kachermeyer, Cal. Tech
Description:	Pressure Sensor	**Station:**	907 Dyn. Med. Press. #1 (Test Procedure AT601-11)
Type:	ICP		

#2

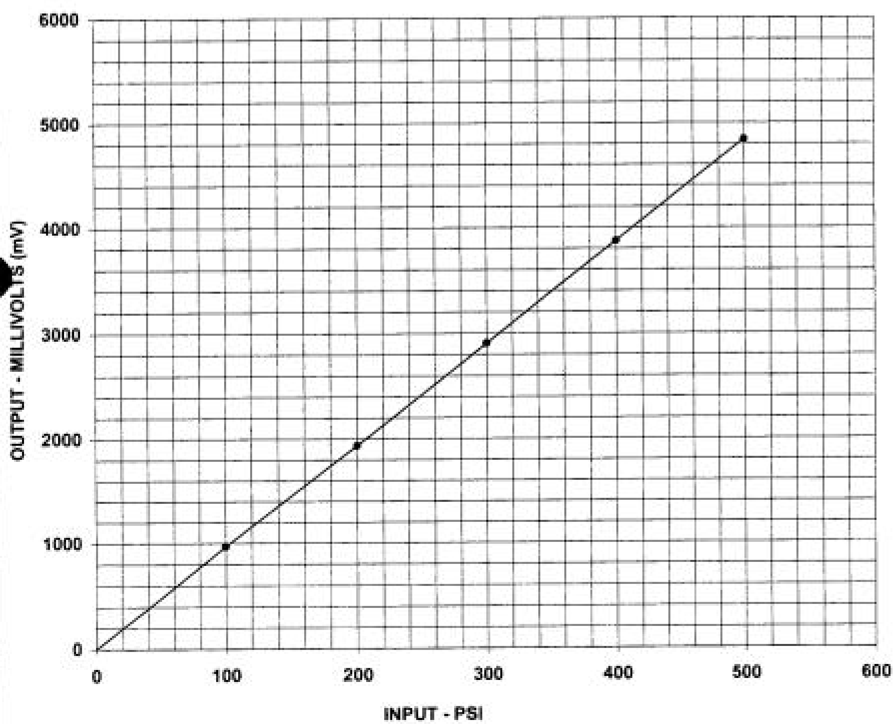
Sensitivity*:	9.681 mV/PSI 1404 mV/MPa	**Temp:** **Humidity:**	73 deg F [23deg C] 24 %
Linearity*:	0.1% FS	**Cert #:**	168655
Uncertainty:**	+/- 0.78 %		

Bias: 10.7 VDC

* Zero based, least-squares straight line.

** Measurement uncertainty represented using a coverage factor of k=2 which provides a level of confidence of approximately 95 %.

Condition of Unit:
As Found: Not applicable
As Left: In tolerance, new unit



TEST DATA

INPUT (PSI)	OUTPUT (mV)
100	970.895
200	1936.436
300	2906.306
400	3871.354
500	4839.118

Notes:
1 STATION #15
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3 NIST traceability through PCB control # CA334.
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Page 1 of 1

CALIBRATION CERTIFICATE

Model: 137A23
Serial #: 5526
Description: Pressure Sensor
Type: ICP   Time Constant: 3.1 sec

Date: 4/14/04
By: Eric Kachermeyer, Cal. Tech
Station: 903 Pulse #1 (Test procedure AT601-6)

Sensitivity*: 93.10 mV/PSI
13.50 mV/kPa

#3

Temp: 73 deg F [23deg C]
Humidity: 24 %

Linearity*: 0.1% FS
Uncertainty**: +/- 0.64 %

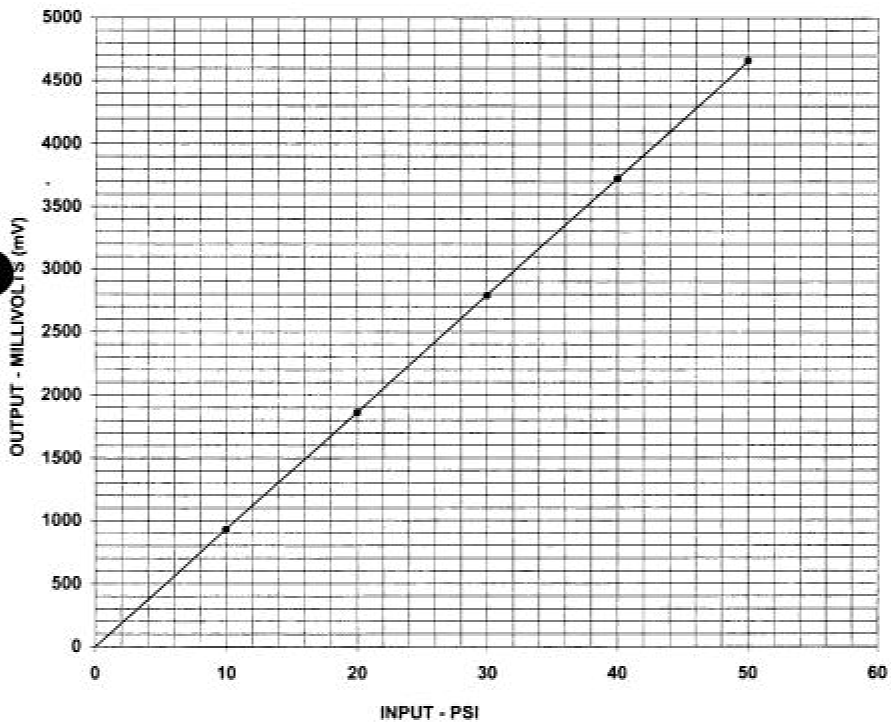
Cert #: 167525

Bias: 12.7 VDC

* Zero based, least-squares straight line.

** Measurement uncertainty represented using a coverage factor of k=2 which provides a level of confidence of approximately 95 %.

Condition of Unit:
As Found: Not applicable
As Left: In tolerance, new unit



TEST DATA

INPUT (PSI)	OUTPUT (mV)
10.0	927
20.0	1861
30.0	2789
40.0	3724
50.0	4659

Notes:
1 STATION #15
2 Calibration is traceable to NIST and is accredited to ISO 17025 and ANSI/NCSL Z540-1-1994.
3 NIST traceability through PCB control # CA215.
4 This certificate may not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.

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Page 1 of 1

CALIBRATION CERTIFICATE

Model: 137A23
Serial #: 4897
Description: Pressure Sensor
Type: ICP
Time Constant: 1.9 sec

Date: 4/21/04
By: Chris Schultz, Cal. Tech CS
Station: 903 Pulse #1 (Test procedure AT601-6)

Sensitivity*: 97.45 mV/PSI
14.13 mV/kPa

#4

Temp: 73 deg F [23deg C]
Humidity: 32 %

Linearity*: 0.2% FS
Uncertainty:** +/- 0.64 %

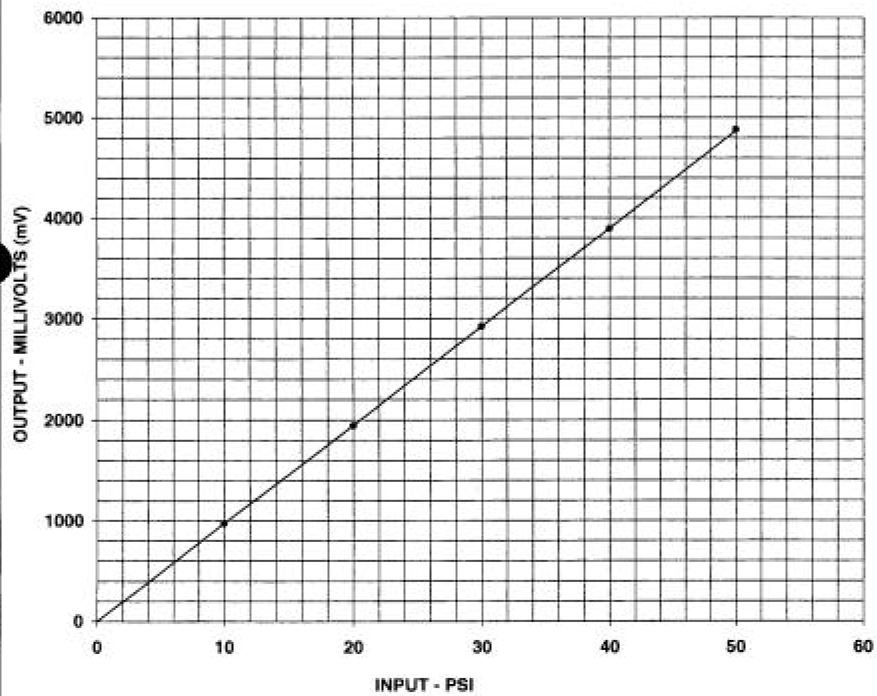
Cert #: 168052

Bias: 12.2 VDC

* Zero based, least-squares straight line.

** Measurement uncertainty represented using a coverage factor of k=2 which provides a level of confidence of approximately 95 %.

Condition of Unit:
As Found: Not applicable
As Left: In tolerance, new unit



TEST DATA

INPUT (PSI)	OUTPUT (mV)
10.0	972
20.0	1944
30.0	2922
40.0	3892
50.0	4881

Notes:

1 STATION# 17
2 Calibration is traceable to NIST and is accredited to ISO 17025 and ANSI/NCSL Z540-1-1994.
3 NIST traceability through PCB control # CA215.
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Page 1 of 1

SOUTHWEST RESEARCH INSTITUTE™

6220 Culebra Road, P.O. Drawer 28510
Institute Quality Systems
Institute Calibration Laboratory
Phone: 210-522-5215 Fax 210-522-3692

ACCREDITED
Certificate #
0972-01

Certificate of Calibration

Submitted By:	DIV01	**Work Order:**	444054636
Address:	B143	**Date Issued:**	Aug 18, 2003
Contact:	ROBERT LOPEZ	**Calibration Date:**	Aug 18, 2003
Manufacturer Model:	YOKOGAWA WE7235	****Calibration Due:**	Aug 18, 2004
Description:	ACCELEROMETER	**Calibration Location:**	Bldg. 64
Serial No:	12C405858	**Environment:**	Temp. 72.0°F Hum. 37 %RH
Asset No:	010306	***As Found:**	IN TOLERANCE
Procedure:	Yokogawa QIS 707235-E, Jan. 2002	***As Left:**	IN TOLERANCE

This certificate documents traceability to the National Institute of Standards and Technology (NIST) and the International System of Units (SI). The Laboratory quality system conforms to ISO/IEC 17025, 1999 and ANSI/NCSL Z540-1-1994 which are equivalent to relevant requirements of the ISO 9000-1994 series of standards. This certificate may not be reproduced, except in full, without the written approval of the Southwest Research Institute Calibration Laboratory. The results of this calibration relate only to the individual instrument described above. This certificate shall not be used to claim product endorsement by the American Association for Laboratory Accreditation (A2LA) or any agency of the U. S. Government

Uncertainty evaluation includes the item under test and is calculated in accordance with the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM). The uncertainty represents an expanded uncertainty using a coverage factor of k=2 to approximate a 95% confidence level. The calibration process provides a Test Uncertainty Ratio (TUR) of less than or equal to 25% (4:1) of the test limit unless otherwise stated in remarks or an attachment

*The client has sole responsibility for determination of in/out of tolerance or compliance/noncompliance. An in/out of tolerance opinion is provided for your convenience based only on the Test Instrument (TI) reading(s) and limits as reported. The reported uncertainty relates only to the results at the time of calibration and does not imply any short or long term stability of the TI.

**Calibration interval is determined by the client and does not assure the instrument will remain within tolerance until this date. Any number of factors may cause the instrument to be out of tolerance before the next calibration date.

Remarks: None

Standards Used

Asset	Manufacturer	Model	Description	Cal Due
006413	FLUKE	5520A/SC1100	MULTI-PRODUCT CALIBRATOR	Jan 17, 04

Approved by: Walt Hill
Metrology Group Leader
m:\a2la1.rpt Rev date 15, August 02

Measurements by: Tom Hannon
Metrology Technician

1 of 1