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Compressed Hydrogen Cylinder Research and Testing In Accordance With FMVSS 304

DISCLAIMER

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16. Abstract

The Fire Technology Department of Southwest Research Institute (SwRI) performed a series of tests on compressed hydrogen cylinders in accordance with the Federal Motor Vehicle Safety Standard (FMVSS) 304, *Compressed natural gas fuel container integrity*. The main objectives concerned evaluation of the standard's validity for hydrogen cylinder testing and recommendations for improvements. Testing also referenced the International Organization for Standardization's Draft International Standard (ISO/DIS) 15869, *Gaseous Hydrogen and Hydrogen Blends – Land Vehicle Fuel Tanks*.

All six cylinders subjected to the bonfire test successfully released their contents less than 3 minutes after exposure had begun. This implies that the cylinder designs are reasonably safe from a fire safety standpoint. However, it is the author's opinion that the bonfire test outlined in the current test procedure is not sufficient to assess a cylinder's ability to withstand a fire exposure. The test evaluates only whether the test setup can engulf a pressure relief device in flame. It is recommended that a new formal test method be developed that better addresses indicated safety issues. Better testing methods may show a need for a level of fire-resistant thermal insulation material.

The 10,000-psig Type 4 cylinder appeared to suffer physical damage when tested according to the standard cycling procedure. It is not known whether this result is a statistical anomaly, or whether this would be typical of this cylinder design. In either case, a 10,000-psig hydrogen cylinder failing in actual service could have devastating results.

Overall results of the burst pressure tests suggest that the cycling tests did not cause a significant negative impact on the strength of the cylinders. Each of the three cylinder designs still met the minimum burst pressure requirements of FMVSS 304 and NGV 2 (2.25 times service pressure) following exposure to the pressure cycling tests. Furthermore, the 10,000-psig Type 4 cylinder that appeared to suffer physical damage during pressure cycling tests failed at a higher pressure than the new cylinder. However, the new 10,000-psig Type 4 cylinder did not meet the requirements of ISO/DIS 15869, which outlines a slightly higher requirement of 2.35 times service pressure.

Both cylinders that had been exposed to a 4-min fire exposure did fail at a lower pressure than their pressure-cycled counterparts. The Type 3 (aluminum lined) cylinder burst at approximately 70 psig less than the cycled cylinder, and the Type 4 (plastic-lined) cylinder had degraded such that it could no longer be pressurized in excess of 5500 psig with water. This result suggests that there is a much larger safety margin for metallic-lined cylinders as compared to plastic-lined cylinders under fire exposure conditions. For this reason, SwRI recommends a level of thermal insulation be specified for use to help protect Type 4 cylinders. A revised test standard should include validation of this requirement.

Due to the generation of holes in the penetration tests, cylinders could not be pursuantly subjected to a hydrostatic burst test in order to determine the safety margin with this method. A recommendation for determining a sufficient safety margin for this test in the future is to increase the caliber of the penetrating bullet until a burst failure occurs.

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ABSTRACT

The Southwest Research Institute (SwRI) Fire Technology Department performed a series of tests on compressed hydrogen cylinders in accordance with the Federal Motor Vehicle Safety Standard (FMVSS) 304, *Compressed natural gas fuel container integrity*. The main objectives concerned evaluation of the standard's validity for hydrogen cylinder testing and recommendations for improvements. Testing also referenced the International Organization for Standardization's Draft International Standard (ISO/DIS) 15869, *Gaseous Hydrogen and Hydrogen Blends – Land Vehicle Fuel Tanks.*

The following table briefly identifies each cylinder, the tests performed, and the results.

Overall Test Results Matrix.

Cylinder	Test Performed	Results
5,000-psig Type 3	10% Service Pressure Bonfire	Pressure Relief Device (PRD) Activation at 141 s
5,000-psig Type 3	25% Service Pressure Bonfire	PRD Activation at 87 s
5,000-psig Type 3	100% Service Pressure Bonfire	PRD Activation at 68 s
5,000-psig Type 4	25% Service Pressure Bonfire	PRD Activation at 121 s
5,000-psig Type 4	100% Service Pressure Bonfire	PRD Activation at 131 s
10,000-psig Type 4	25% Service Pressure Bonfire	PRD Activation at 164 s
5,000-psig Type 3	Pressure Cycling Test Pursuant Hydrostatic Burst Test	Cycling Test Successful – No Noted Cylinder Damage Hydrostatic Burst Pressure – 19,970 psig
5,000-psig Type 4	Pressure Cycling Test Pursuant Hydrostatic Burst Test	Cycling Test Successful – No Noted Cylinder Damage Hydrostatic Burst Pressure – 13,010 psig
10,000-psig Type 4	Pressure Cycling Test Pursuant Hydrostatic Burst Test	Cycling Test Halted Due to Damage Observed Hydrostatic Burst Pressure –24,620 psig
10,000-psig Type 4	Virgin Cylinder Burst Test	Hydrostatic Burst Pressure – 23,150 psig. Meets FMVSS 304 (22,500); Fails ISO 15869 (23,500)
5,000-psig Type 3	Simulated Bonfire Exposure Pursuant Hydrostatic Burst Test	Hydrostatic Burst Pressure – 19,000 Via Burst Approximate 5% Decrease in Strength
10,000-psig Type 4	Simulated Bonfire Exposure Pursuant Hydrostatic Burst Test	Hydrostatic Burst Pressure – 5,500 Via Leakage Approximate 76% Decrease in Strength
5,000-psig Type 3	100% Service Pressure 0.308-Caliber Penetration	Penetration Through Front Only. Cylinder Did Not Burst.
5,000-psig Type 4	100% Service Pressure 0.308-Caliber Penetration	Penetration Through Front and Out of Dome. Cylinder Did Not Burst.
10,000-psig Type 4	100% Service Pressure 0.308-Caliber Penetration	Penetration Through Front Only. Cylinder Did Not Burst.

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1.0 INTRODUCTION

In the current decade, a large number of factors have contributed to the increased demand for alternative fuels and renewable energy sources research. Hydrogen has been identified as a major candidate for many applications that may range from generating mechanical energy through hydrogen combustion to using hydrogen as an energy carrier in fuel cell applications. Regardless of the manner in which it is used, storage of a significant quantity of hydrogen will be necessary. Compressed hydrogen storage in high-pressure cylinders is an attractive means, because it generally involves well-understood and simple technologies.

Continuous pressure on cost and weight reduction force commercial high-pressure cylinder manufacturers to meet design and safety specifications by very narrow margins. Furthermore, the presence of these manufacturers on the committees involved in the development and modification of safety standards for the equipment that they produce raises questions about the validity and intent of the standards.

Because hydrogen-fueled vehicles are not in the mainstream, there is insufficient statistical field data to provide an accurate assessment of their overall safety. The public knowledge of hydrogen fuel safety is often limited to a poor analysis of the *Hindenburg* explosion, claiming that hydrogen was not a significant factor, or Internet videos involving severely skewed test methods to push the hydrogen agenda.

Two standards in development to evaluate the safety of high-pressure hydrogen cylinders include CSA America Inc.'s HGV2, *Basic Requirements for Hydrogen Gas Vehicle (HGV) Fuel Containers,* and International Organization for Standardization's Draft International Standard (ISO/DIS) 15869, *Gaseous Hydrogen and Hydrogen Blends – Land Vehicle Fuel Tanks*. These two standards, both in draft form, include several prototype tests where it is proposed that new hydrogen cylinder designs be tested. Test methods include drop tests, burst pressure tests, pressure cycling tests, bonfire tests, and penetration tests. The majority of the tests outlined in these standards are based on tests developed for compressed natural gas cylinders: CSA America Inc.'s NGV2, *Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers*, ISO 11439, *Gas Cylinders – High Pressure Cylinders for the On-Board Storage of Natural Gas as a Fuel for Automotive Vehicles*, and FMVSS 304, *Compressed natural gas fuel container integrity*.

SAE J2579, *Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles* (published January 2008), was in the very early stages of development at the initiation of this project. The document outlines design and performance-based requirements for production of hydrogen storage and handling systems, including test protocols (for use in type approval or self-certification) to qualify designs. SAE J2579 was not referenced in this program. The document is currently being revised.

With the intention of taking a proactive approach towards assessing and improving the safety of high-pressure hydrogen cylinders, the National Highway Traffic Safety Administration and Southwest

Research Institute undertook a limited research program. The main objectives of this program were as follows:

1. Review existing standards and practices for hydrogen fuel container testing and select specific tests that would assess a variety of hazards.
2. Acquire a range of commercially available hydrogen cylinder designs that would represent the variety of current technologies available.
3. Perform selected tests on the sample of hydrogen cylinder designs.
4. Assess the validity of current standards and practices and identify weaknesses in the standards with respect to their ability to sufficiently evaluate safety.
5. Provide recommendations to NHTSA for acceptance of a currently available standard or development of a new safety standard for compressed hydrogen cylinder safety.

2.0 TEST SPECIMEN

As the program was initiated, several manufacturers of compressed hydrogen cylinders were contacted and inquired as to their willingness to participate in the program. The goals of the program were clearly stated, and it was emphasized that the program was intended to improve the safety of compressed hydrogen cylinders. Unfortunately, some manufacturers declined to participate and refused to sell cylinders for use in this program.

However, SwRI was able to acquire three commercially available cylinder types for this research program. The three types were intended to represent the variety of cylinders currently available. The following table outlines the details of the cylinders procured.

Table 1. Cylinder Designs.

Manufacturer	Cylinder Type	Quantity	Working Pressure	Nominal Dimensions	Relief Valve Manufacturer
Structural Composites, Inc. (SCI)	Type 3 (Alum. Liner)	6	5,000 psig	16 in. Diameter 38 in. Length	Teleflex GFI (Provided by SCI)
Lincoln Composites	Type 4	4	5,000 psig	16 in. Diameter 33 in. Length	Quantum Technologies (Procured Separately)
Lincoln Composites	Type 4	5	10,000 psig	20 in. Diameter 36 in. Length	Circle Seal (Procured Separately)

For reference, a Type 3 cylinder has a metal liner reinforced with resin-impregnated continuous filament that is "full-wrapped," and a Type 4 cylinder has a nonmetallic liner with a resin-impregnated continuous filament that is "full-wrapped." All cylinders were new and were verified to be in pristine condition before the tests.

Hydrogen was supplied from a 1,400-standard-cubic-meter-capacity trailer pressurized to 12 MPa. The hydrogen had a purity of 99.99 percent or greater.

3.0 TEST PROCEDURES

The tests procedures were discussed and selected between NHTSA and SwRI. Three tests were taken directly from FMVSS 304: *Bonfire Test*, *Pressure Cycling Test*, and *Hydrostatic Burst Test*. The fourth test was taken directly from ISO/DIS 15869: *Penetration Test*.

3.1 Bonfire Tests

Test setup and procedures for the bonfire test followed the FMVSS 304 protocol. Tests were performed on cylinders at 100 percent, 25 percent, or 10 percent of their service pressure. SwRI provided a custom-built test bench that supported and provided the fire exposure for the cylinders. The test bench consisted of a rectangular bottom pan and a hollow top frame that flanged together. A 1-in.-thick layer of ceramic fiber was sandwiched between the pan and frame. Propane was flowed into the bottom of the pan and up through the layer of ceramic fiber, which distributed it evenly across the test bench. The bench resulted in an even fire source that closely simulates a liquid fuel spill, approximately 24 in. wide and 65 in. long. The following figure is an exploded view of the test bench.

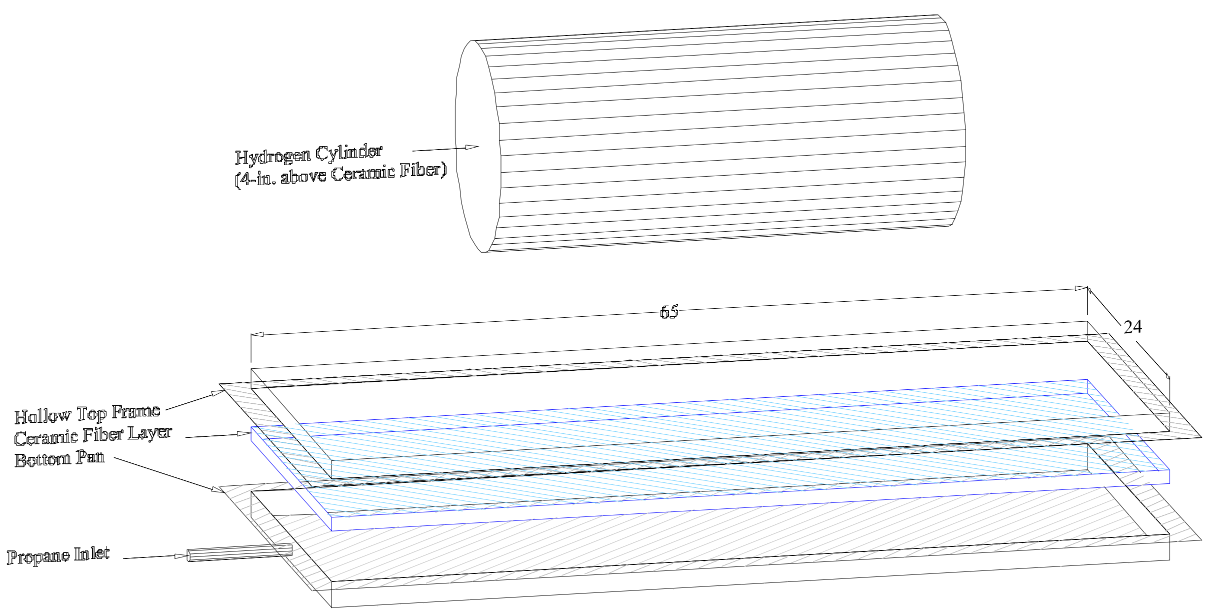


Figure 1. Exploded View of Test Bench Assembly.

Two chains supported the cylinder approximately 4 in. above the fire source. The test setup was instrumented with 11 thermocouples. Three thermocouples measured the flame temperatures 1 in. below the cylinder surface. Three thermocouples measured the lower cylinder surface temperature just above the flame temperature thermocouples. Three thermocouples measured the surface temperature at the front, rear, and zenith of the cylinder's longitudinal center. One thermocouple measured the temperature on each the pressure relief device and opposite end fitting. The following figure outlines the thermocouple (TC) layout for the bonfire tests.

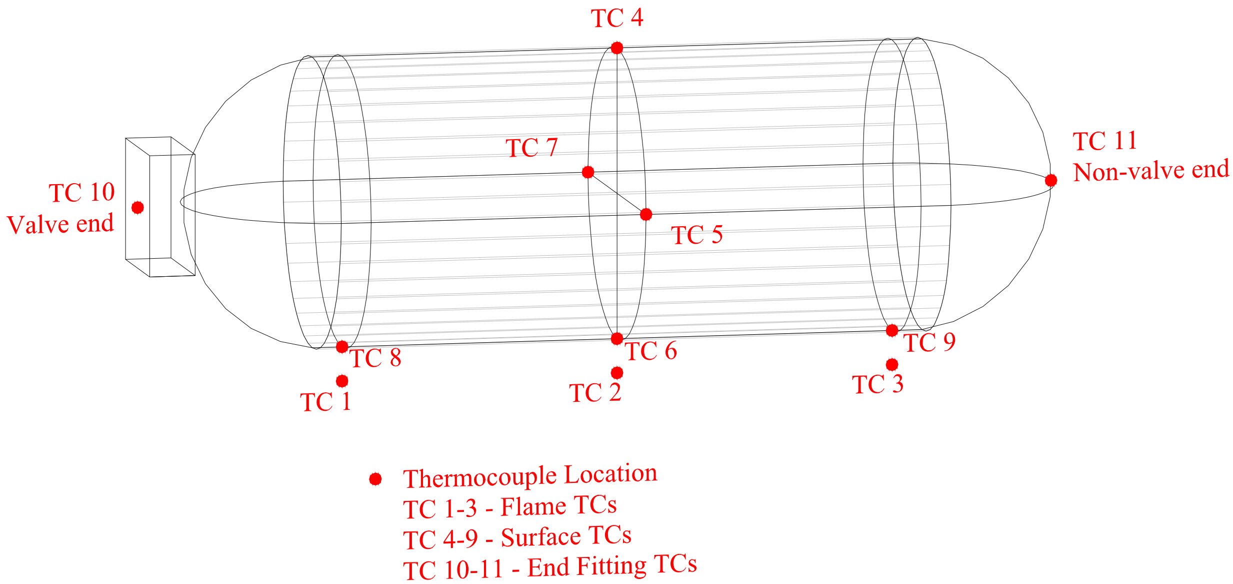


Figure 2. Thermocouple Layout.

Temperature of the bonfire source was controlled to exceed 800 °F via propane flow rate with a mass flow controller. Pressure on the interior of the cylinder was measured with a pressure transducer located in the cylinder fill line. Once the propane began to flow, combustion was initiated remotely with pyrotechnic igniters. The cylinder pressure and temperatures were logged at 1-second intervals through the duration of the test. Each test was concluded once the cylinder had relieved its contents.

3.2 Pressure Cycling Tests

Test setup and procedures for the pressure cycling test followed the FMVSS 304 protocol. In the pressure cycling test, each cylinder is connected to a pressure control system and hydrostatically cycled at a rate of no more than 10 cycles per minute in the following manner:

1. Up to 100 percent of service pressure and down to 10 percent of service pressure for 13,000 cycles; and
2. Up to 125 percent of service pressure and down to 10 percent of service pressure for 5,000 cycles.

The medium used for pressurization when cycling up to 5,000 psig was CIRRO 32 R&O Hydraulic Oil. The medium used for pressurization when cycling above 5,000 psig was water.

3.3 Hydrostatic Burst Test

Test setup and procedures for the hydrostatic burst test followed the FMVSS 304 protocol. Each cylinder was hydrostatically pressurized to the service pressure ratio outlined in FMVSS 304 (2.25) times its service pressure at a rate of not more than 200 psig per second. It should be noted that NGV2 and ISO/DIS 15869 specify testing to service pressure ratios of 2.25 and 2.35 (respectively) for carbon fiber cylinders. Each cylinder was pressurized until failure occurred.

3.4 Penetration Test

Test setup and procedures for the penetration test followed the ISO/DIS 15869 protocol. Each cylinder was supported on the test bench and pressurized to its service pressure. A 0.308-caliber (7.62-mm) diameter rifle barrel was supported on a rigid test bench and aimed such that it would penetrate the sidewall of the cylinder at a 45° angle to its longitudinal axis. The following picture shows the general setup for the penetration test.

The trigger mechanism of the rifle barrel is initiated remotely by a lanyard. An armor-piercing bullet is required to penetrate through at least one side of the cylinder. The cylinder must not burst catastrophically following penetration.

Figure 3. Penetration Test General Setup (Prior to Securing Cylinder to Test Stand).

4.0 FACILITY

Setup and testing for the bonfire and penetration tests were performed at SwRI's Fire Technology Department's remote facility, located in Sabinal, Texas. The Fire Technology Department's remote facility consists of a large open field with access to power and water. Tests are viewed and controlled from a mobile armored control unit that contains a data acquisition system, monitors for video, and a control system for operating the tests. Testing was performed outdoors at ambient conditions.

Setup and testing for the pressure cycling and hydrostatic burst tests was performed at SwRI's main campus, located in San Antonio, Texas. Pressure cycling tests were performed in the Vehicle Systems Research Laboratory, and hydrostatic burst tests were performed in the High-Pressure Laboratory.

5.0 INSTRUMENTATION

Temperature measurements were made with 1.6-mm ($^1/_{16}$-in.) diameter Inconel-sheathed grounded-junction Type K thermocouples. This type of thermocouple has an accuracy of approximately ± 2.2 °C and a 90 percent response time of 1½ s in air. The pressure transducer used to measure the hydrogen inlet pressure during filling and throughout each test was a 60,000-psig (420-MPa) model with an accuracy of ± 0.5 percent full-scale and a 90-percent response time of 5 ms.

Mass flow of propane was controlled with a 0–80-slpm thermal-conductivity mass flow controller. The flow controller was calibrated specifically for propane, had an accuracy of ± 1 percent of full-scale, and a response time of 800 ms.

Data was logged on a dedicated PC-based data acquisition system. Pressure and thermocouples were logged and saved at a rate of 1 Hz. This data acquisition card has an accuracy of 0.02 percent for voltage signals and ± 0.5 °C for thermocouple signals.

6.0 DOCUMENTATION

Digital photographs were taken of the test setup and results. One standard video camera was used to capture digital video of the bonfire and penetration tests. A high-speed video camera was used in the penetration tests in order to view the penetration.

7.0 RESULTS

Graphical depiction of the bonfire test data can be found in Appendix A, and graphical depiction of the pressure cycling test data can be found in Appendix B. Selected photographic documentation is provided in Appendix C.

7.1 Bonfire Tests

A total of six bonfire tests were performed. The 5,000-psig Type 3 cylinder was the only cylinder provided with a valve/pressure relief device assembly directly from the manufacturer. This setup was tested three times under different fill levels (10%, 25%, and 100% service pressure). The additional low-pressure (10%) test was performed to ensure successful activation of the pressure relief device under lower pressures just high enough to cause significant bodily harm. For the tests performed at 25 percent and 100 percent of service pressure, the cylinders' pressure relief valves actuated between 1 and 1.5 min of bonfire exposure. For the test performed at 10 percent of service pressure, the cylinder's pressure relief valve actuated at almost 2.5 min. In all tests, the contents of the cylinders were relieved without bursting of the cylinder.

Two bonfire tests were performed on the 5,000-psig Type 4 cylinders at 25 percent and 100 percent service pressure, respectively. The cylinders' pressure relief valves actuated at just over 2 min for both the 25 percent and 100 percent service pressure levels. In both tests, the contents of the cylinders were relieved without bursting of the cylinders.

One bonfire test was performed on the 10,000-psig Type 4 cylinder at the 25 percent service pressure. The cylinder's pressure relief valve actuated at 2 min 44 s of exposure, relieving all of its contents without bursting of the cylinder. The following table outlines the individual bonfire tests.

Table 2. Bonfire Test Data.

Cylinder	Fill Level	Valve Actuation
5,000-psig Type 3	10%	141 s
5,000-psig Type 3	25%	87 s
5,000-psig Type 3	100%	68 s
5,000-psig Type 4	25%	121 s
5,000-psig Type 4	100%	131 s
10,000-psig Type 4	25%	164 s

7.2 Pressure Cycling Tests

A total of three pressure cycling tests were performed, including one of each cylinder design. The following table outlines the test parameters and results for the cycling tests.

Table 3. Pressure Cycling Test Data.

Cylinder	Cycling Level	Cycles Completed	Observations
5,000-psig Type 3	Phase I 100% Service Pressure	13,000	Cylinder in Good Condition. Phase II Followed.
5,000-psig Type 3	Phase II 125% Service Pressure	5,000	Cylinder in Good Condition. Pressure Cycling Test Passed.
5,000-psig Type 4	Phase I 100% Service Pressure	13,000	Cylinder in Good Condition. Phase II Followed.
5,000-psig Type 4	Phase II 125% Service Pressure	5,000	Cylinder in Good Condition. Pressure Cycling Test Passed.
10,000-psig Type 4	Phase I 100% Service Pressure	13,000	Cylinder in Poor Condition. Damage Noted Near Valve Fitting.
10,000-psig Type 4	Phase II 125% Service Pressure	Not Performed	Apparent Cylinder Damage Result is Failure

The following figure depicts the condition of the 10,000-psig Type 4 cylinder following the first 13,000 cycles to its service pressure.

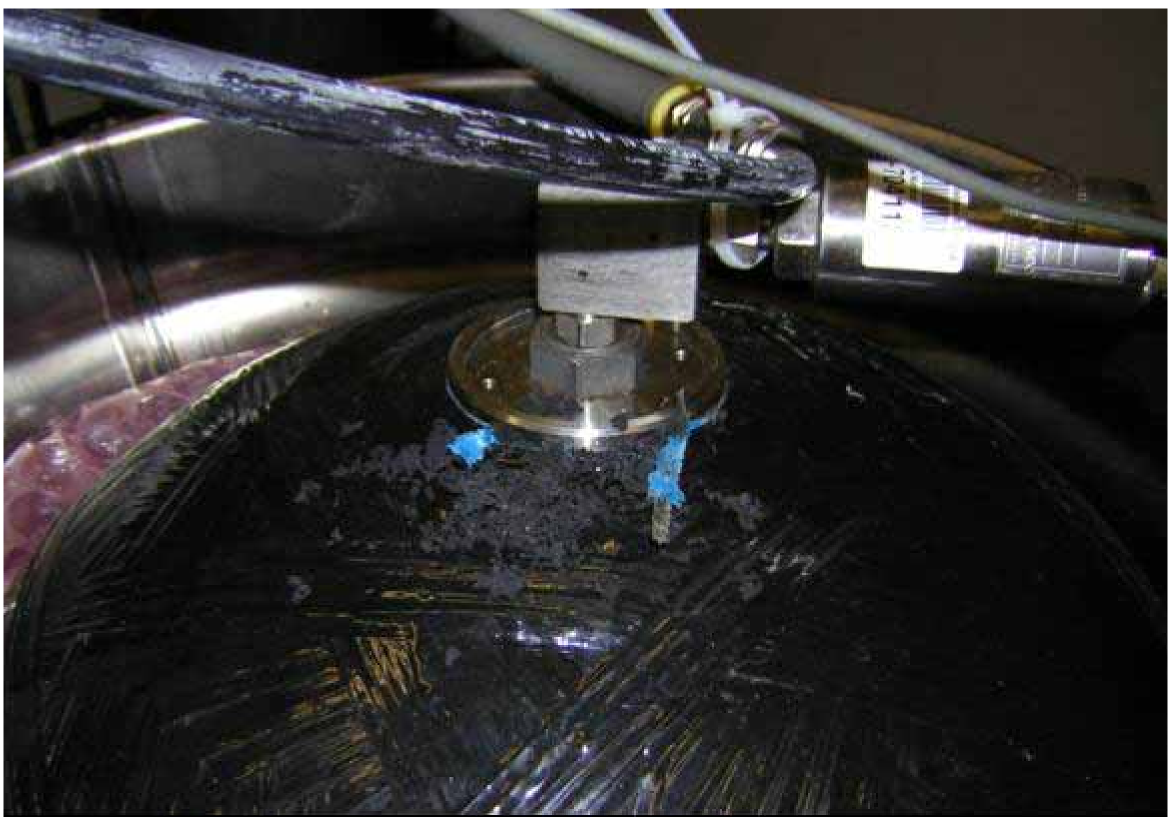


Figure 4. Condition of 10,000-psig Type 4 Cylinder Following Initial 13,000 Cycles.

7.3 Burst Pressure Tests

A total of six burst pressure tests were performed. Each of the three cylinders that had undergone cyclic pressure testing was hydrostatically burst tested in order to determine if they would still meet the minimum requirements. The 10,000-psig Type 4 is the only cylinder that had a burst pressure test performed on a virgin cylinder that did not undergo any other testing. Another two cylinders were exposed to a bonfire exposure prior to being burst-pressure-tested to determine if they would still meet the minimum requirements. Each cylinder was exposed to the bonfire for a period of 4 min, assuming that under less ideal fire conditions, pressure relief device actuation would occur at a time somewhat later than measured in the bonfire tests (longest time 2.7 min).

The following table outlines the results from each of the burst tests, and the figure depicts the condition of the cylinders following each test.

Table 4. Burst Pressure Test Results.

Cylinder Design	Minimum Design Burst Pressure	Cylinder Condition	Failure Pressure	Failure Mode
10,000-psig Type 4	22,500 psig	New	23,150 psig	Catastrophic Burst
10,000-psig Type 4	22,500 psig	Cycled	24,620 psig	Catastrophic Burst
10,000-psig Type 4	22,500 psig	4-min Fire Exposure	5,500 psig	Excessive Leakage Bursting Not Possible
5,000-psig Type 4	11,250 psig	Cycled	13,010 psig	Catastrophic Burst
5,000-psig Type 3	11,250 psig	Cycled	19,970 psig	Catastrophic Burst
5,000-psig Type 3	11,250 psig	4-min Fire Exposure	19,000 psig	Catastrophic Burst

Figure 5. Cylinders Following Burst Pressure Tests.
Shown Left to Right, Top to Bottom in Order of Results Table.

7.4 Penetration Tests

A total of three penetration tests were performed, one of each cylinder design. In both the 5,000-psig Type 3 cylinder and 10,000-psig Type 4 cylinder penetrations, the bullet entered the side of the cylinder at the required 45° angle, but did not exit through the other side. In the 5,000-psig Type 4 cylinder penetration, the bullet entered the side of the cylinder at the required 45° angle and exited the opposite side of the cylinder near the end dome. The force resulting from the exit hole was sufficient to knock over the test stand. Upon impact with the ground, the hydrogen jet exiting the cylinder ignited, producing a large hydrogen flame. The following picture sequences were compiled from the high-speed video.

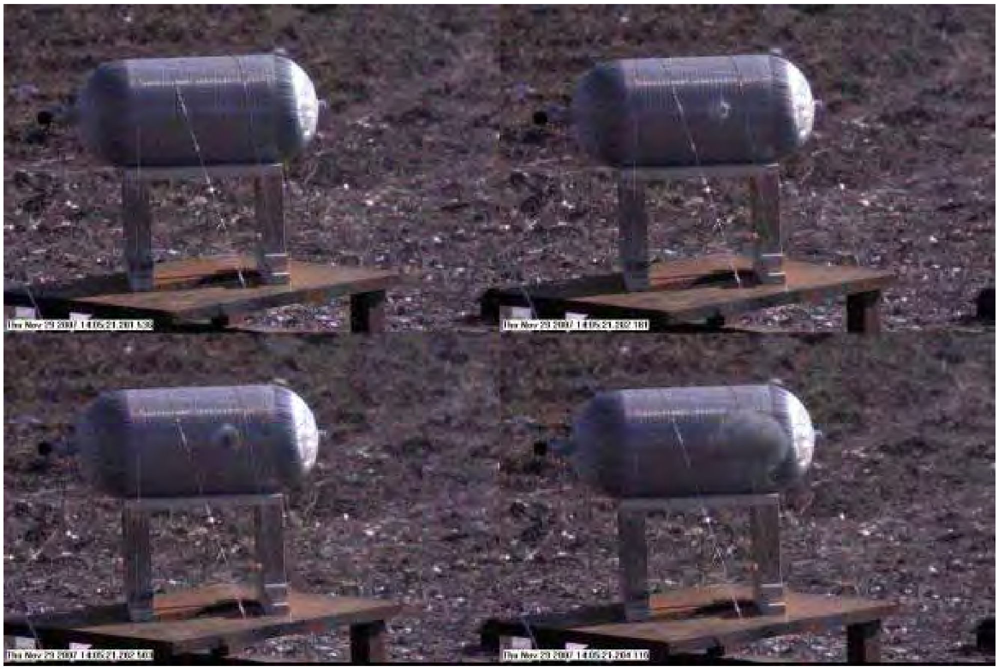


Figure 6. High-Speed Video Frames of 5,000-psig Type 3 Cylinder Penetration Test.

Figure 7. High-Speed Video Frames of 5,000-psig Type 4 Cylinder Penetration Test.

Figure 8. High-Speed Video Frames of 10,000-psig Type 4 Cylinder Penetration Test.

All three-cylinder designs relieved their entire contents without bursting as required by the standard test method.

8.0 CONCLUSIONS

All six cylinders subjected to the bonfire test successfully released their contents less than 3 min after exposure had begun. This implies that the cylinder designs are reasonably safe from a fire safety standpoint. However, it is the author's opinion that the bonfire test outlined in the current test procedure is not sufficient to assess a cylinder's ability to withstand a fire exposure. The test evaluates only whether the test setup can engulf a pressure relief device in flame. Although the procedure specifies for the pressure relief device to be shielded against direct flame impingement from below, in a fully engulfing fire scenario, radiative effects from above will provide enough heat for activation. The bonfire test standards, as written, do not provide a safety measure of the following:

- How long can a cylinder withstand a small fire/heating scenario that does not directly heat the pressure relief device?
- How long can a cylinder withstand a larger-sized fire/heating scenario should a pressure relief device be faulty or bypassed by a user?
- Will the mounting scenario in a vehicle shield the pressure relief device, preventing its heating to a sufficient temperature?

It is recommended that a new formal test method be developed that addresses these issues. Better testing methods may show a need for a level of fire-resistant thermal insulation material.

Although the cylinders had presumably undergone prototype testing with passing results for pressure cycling tests, the 10,000-psig Type 4 cylinder appeared to suffer physical damage when tested according to the standard cycling procedure. It is not known whether this result is a statistical anomaly, or whether this would be typical of this cylinder design. In either case, a 10,000-psig hydrogen cylinder failing in actual service could have devastating results.

Overall results of the burst pressure tests suggest that the cycling tests did not cause a significant negative impact on the strength of the cylinders. Each of the three cylinder designs still met the minimum burst pressure requirements of FMVSS 304 and NGV 2 (2.25 times service pressure) following exposure to the pressure cycling tests. Furthermore, the 10,000-psig Type 4 cylinder that appeared to suffer physical damage during pressure cycling tests failed at a higher pressure than the new cylinder. However, the new 10,000-psig Type 4 cylinder did not meet the requirements of ISO/DIS 15869, which outlines a slightly higher requirement of 2.35 times service pressure.

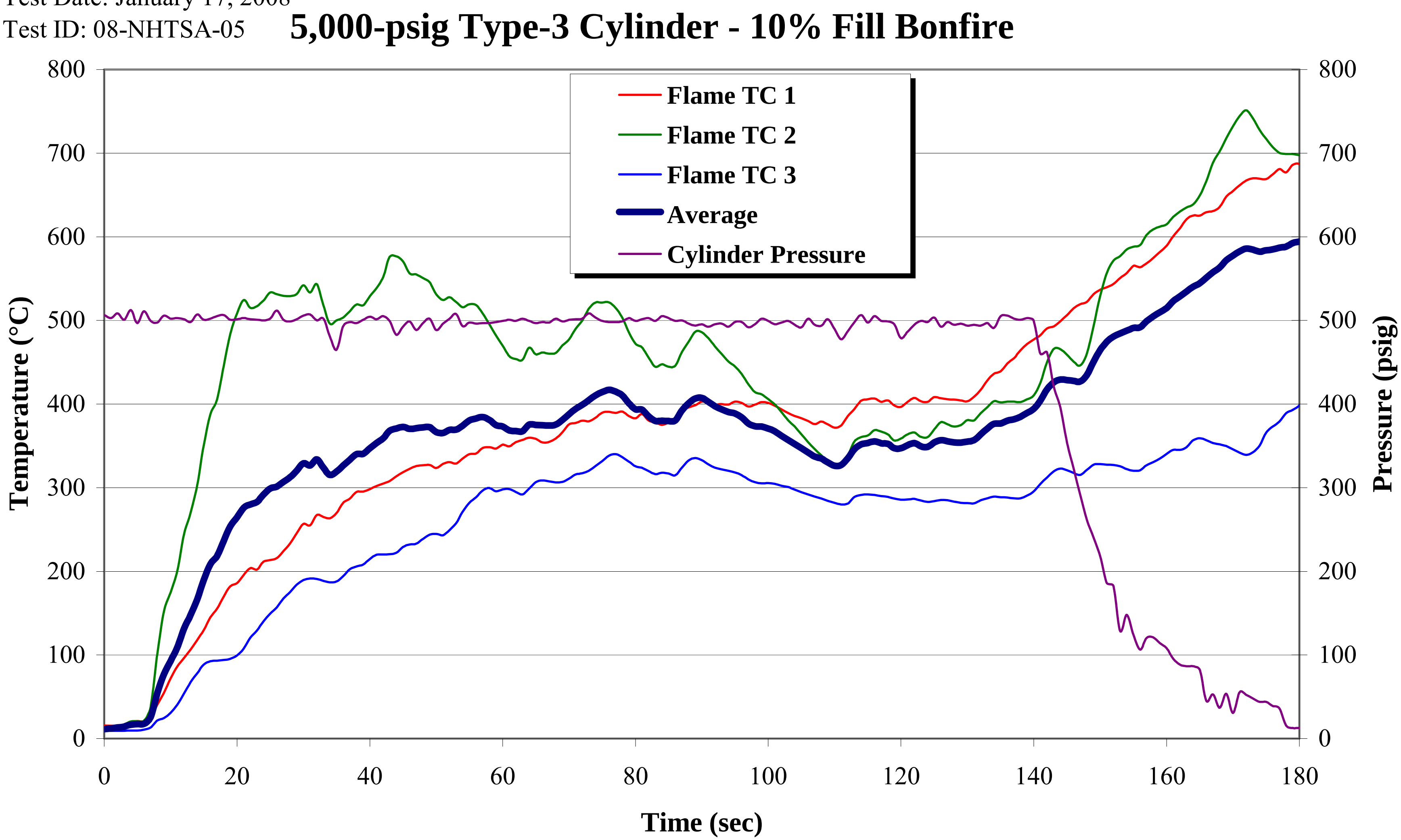
Both cylinders that had been exposed to a 4-min fire exposure did fail at a lower pressure than their pressure-cycled counterparts. The Type 3 (aluminum lined) cylinder burst at approximately 70 psig less than the cycled cylinder; this difference is rather insignificant considering that it still met the minimum burst requirements. However, the Type 4 (plastic-lined) cylinder had degraded such that it could no longer be pressurized in excess of 5500 psig with water. This result suggests that there is a much larger safety margin for metallic-lined cylinders as compared to plastic-lined cylinders under fire exposure conditions. For this reason, SwRI recommends a level of thermal insulation be specified for use to help protect Type 4 cylinders. A revised test standard should include validation of this requirement.

Due to the generation of holes in the penetration tests, cylinders could not be pursuantly subjected to a hydrostatic burst test in order to determine the safety margin with this method. A recommendation for determining a sufficient safety margin for this test in the future is to increase the caliber of the penetrating bullet until a burst failure occurs.

APPENDIX A

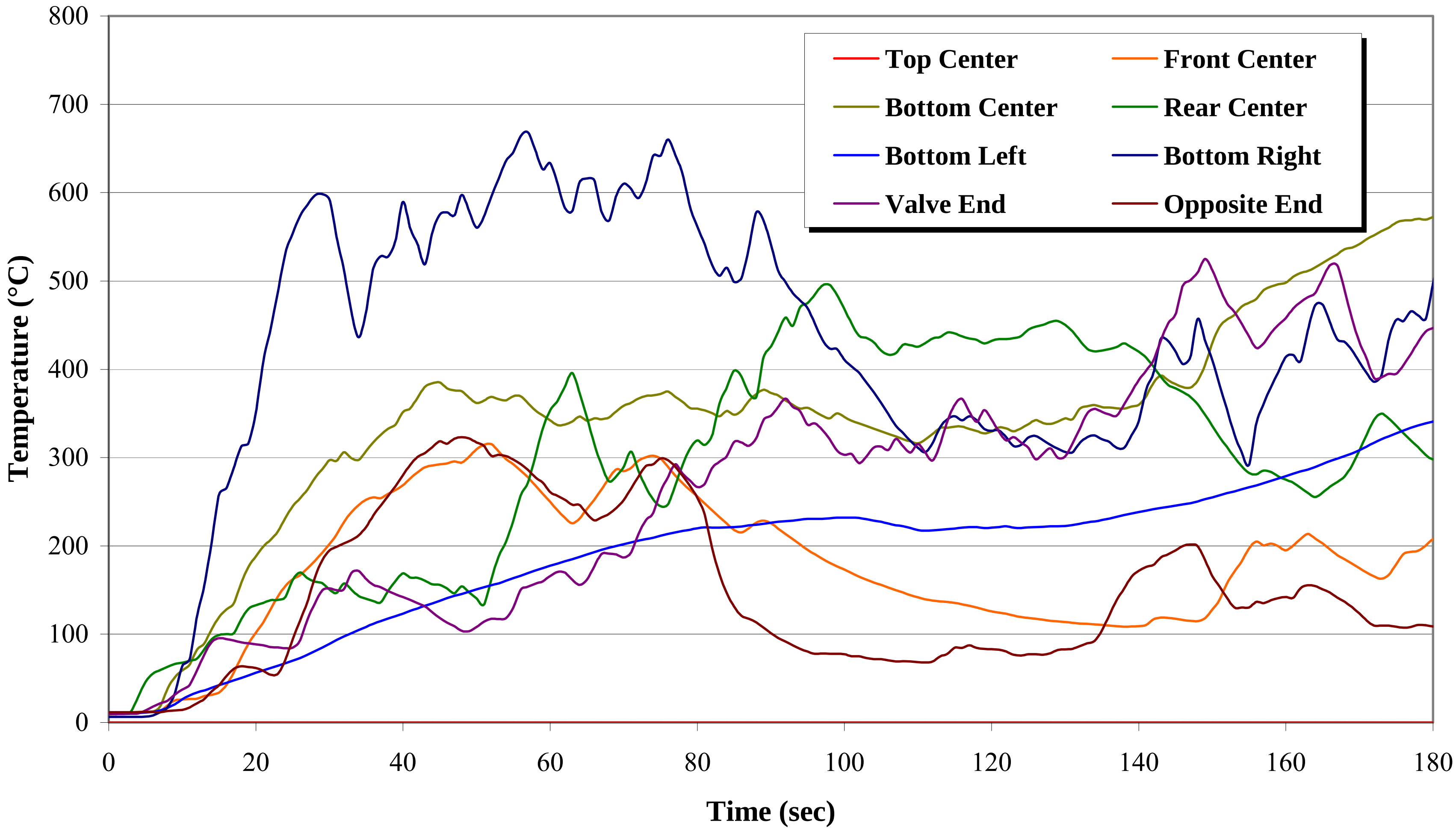
BONFIRE TESTS – GRAPHICAL DATA

NHTSA
SwRI Project No. 01.12575.01.001
Test Date: January 17, 2008
Test ID: 08-NHTSA-05



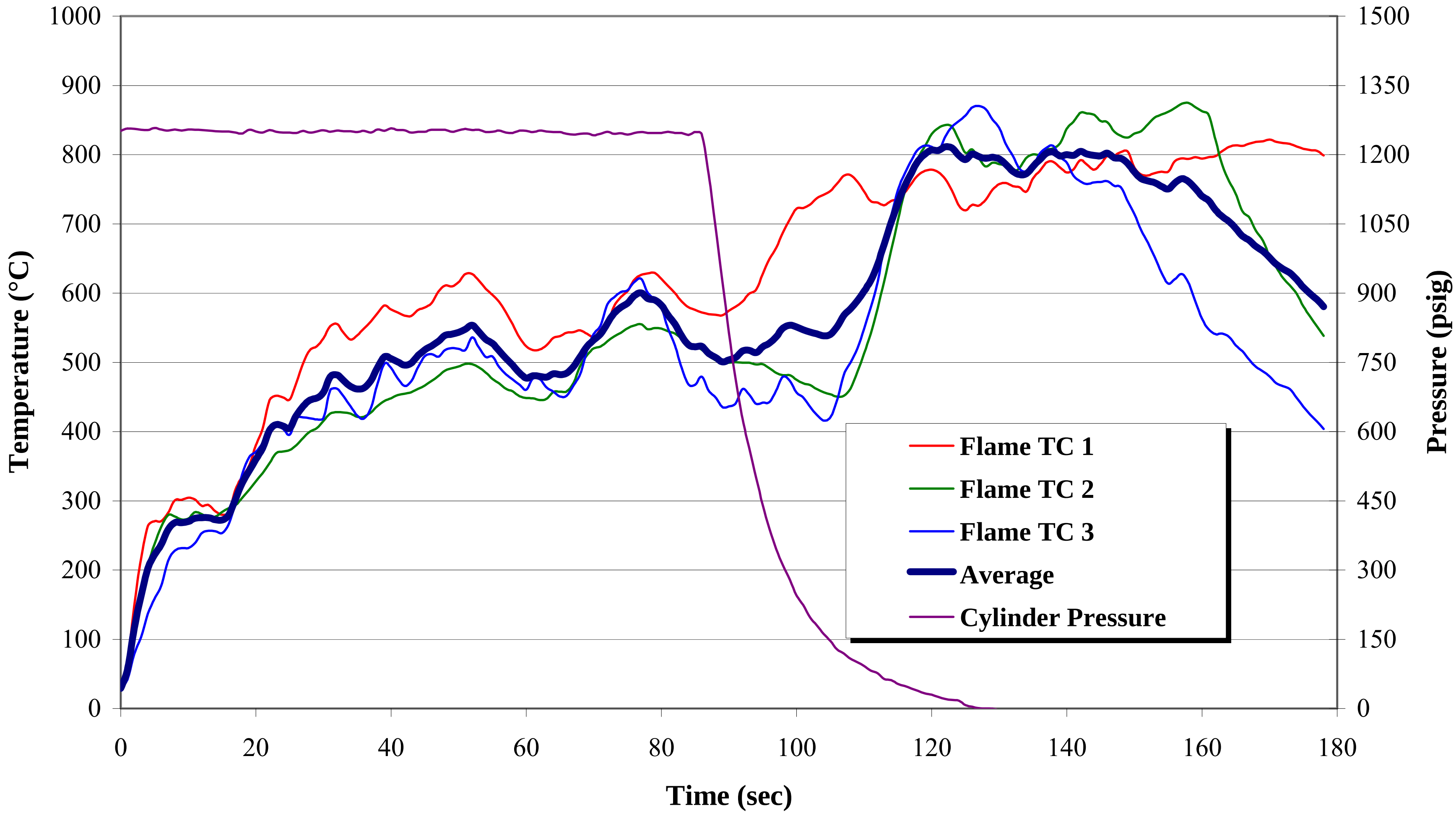
NHTSA
SwRI Project No. 01.12575.01.001
Test Date: January 17, 2008
Test ID: 08-NHTSA-05

5,000-psig Type-3 Cylinder - 10% Fill Bonfire



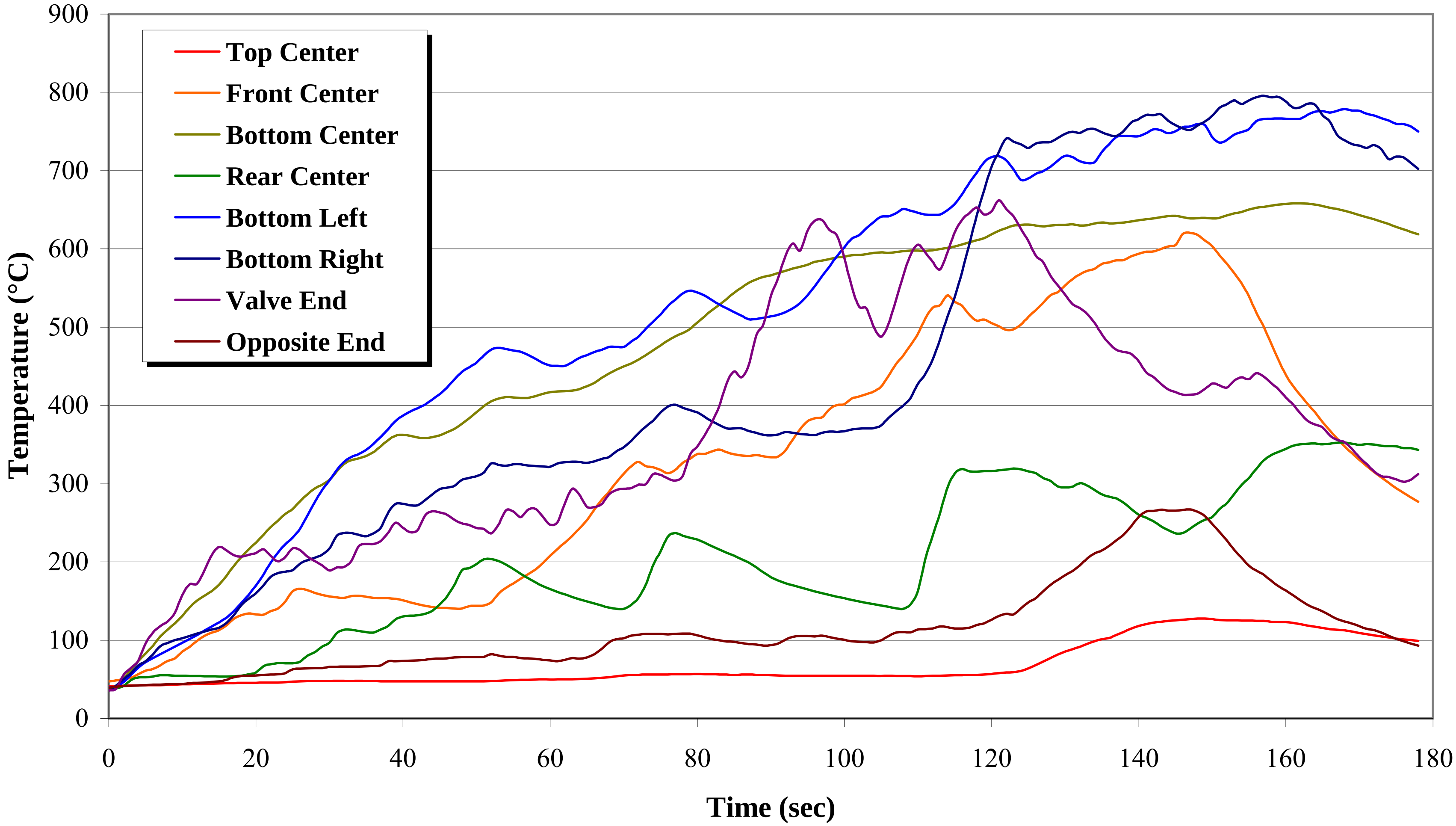
NHTSA
SwRI Project No. 01.12575.01.001
Test Date: December 5, 2007
Test ID: 07-NHTSA-01

5,000-psig Type-3 Cylinder - 25% Fill Bonfire

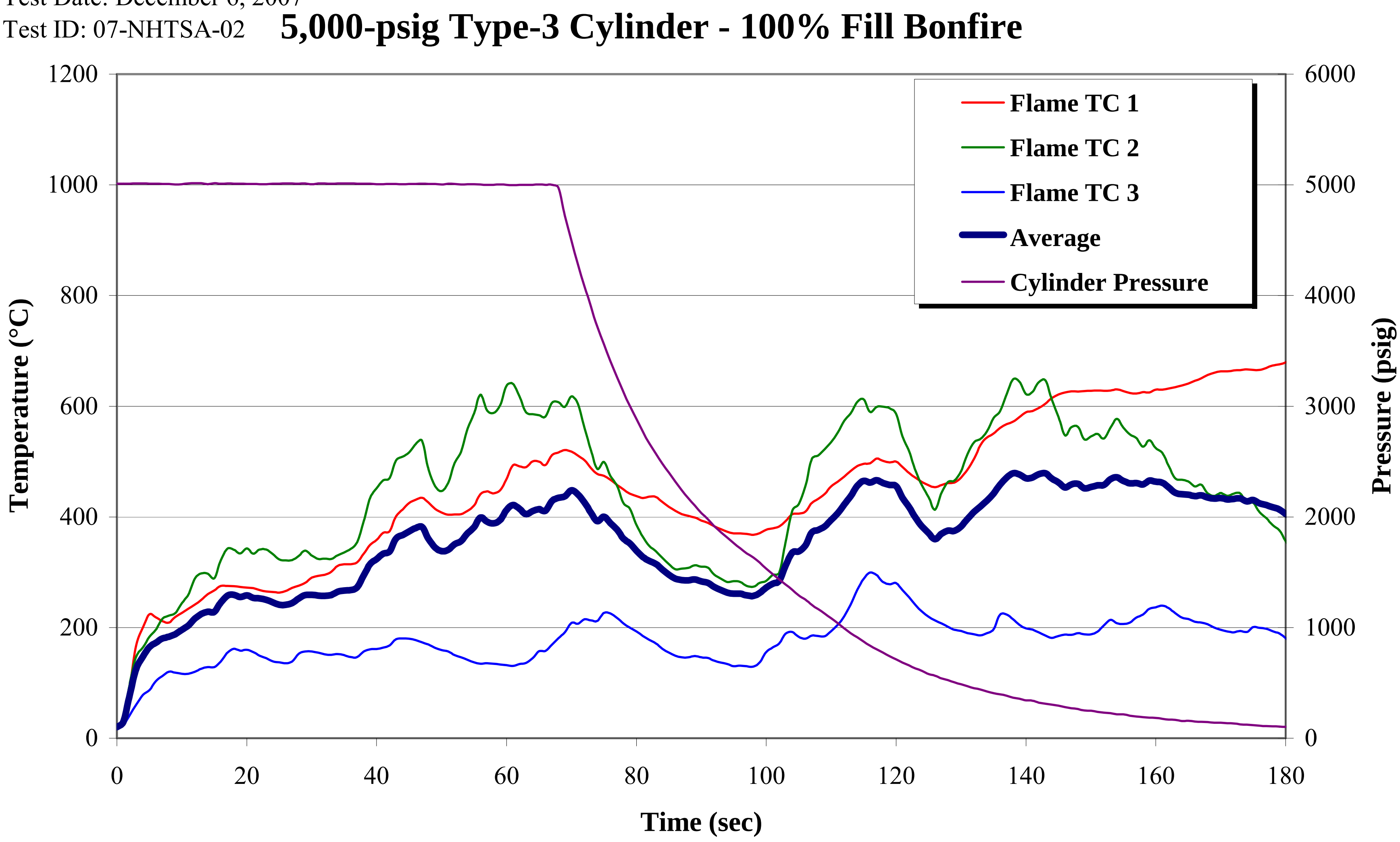


NHTSA
SwRI Project No. 01.12575.01.001
Test Date: December 5, 2007
Test ID: 07-NHTSA-01

5,000-psig Type-3 Cylinder - 25% Fill Bonfire



NHTSA
SwRI Project No. 01.12575.01.001
Test Date: December 6, 2007
Test ID: 07-NHTSA-02



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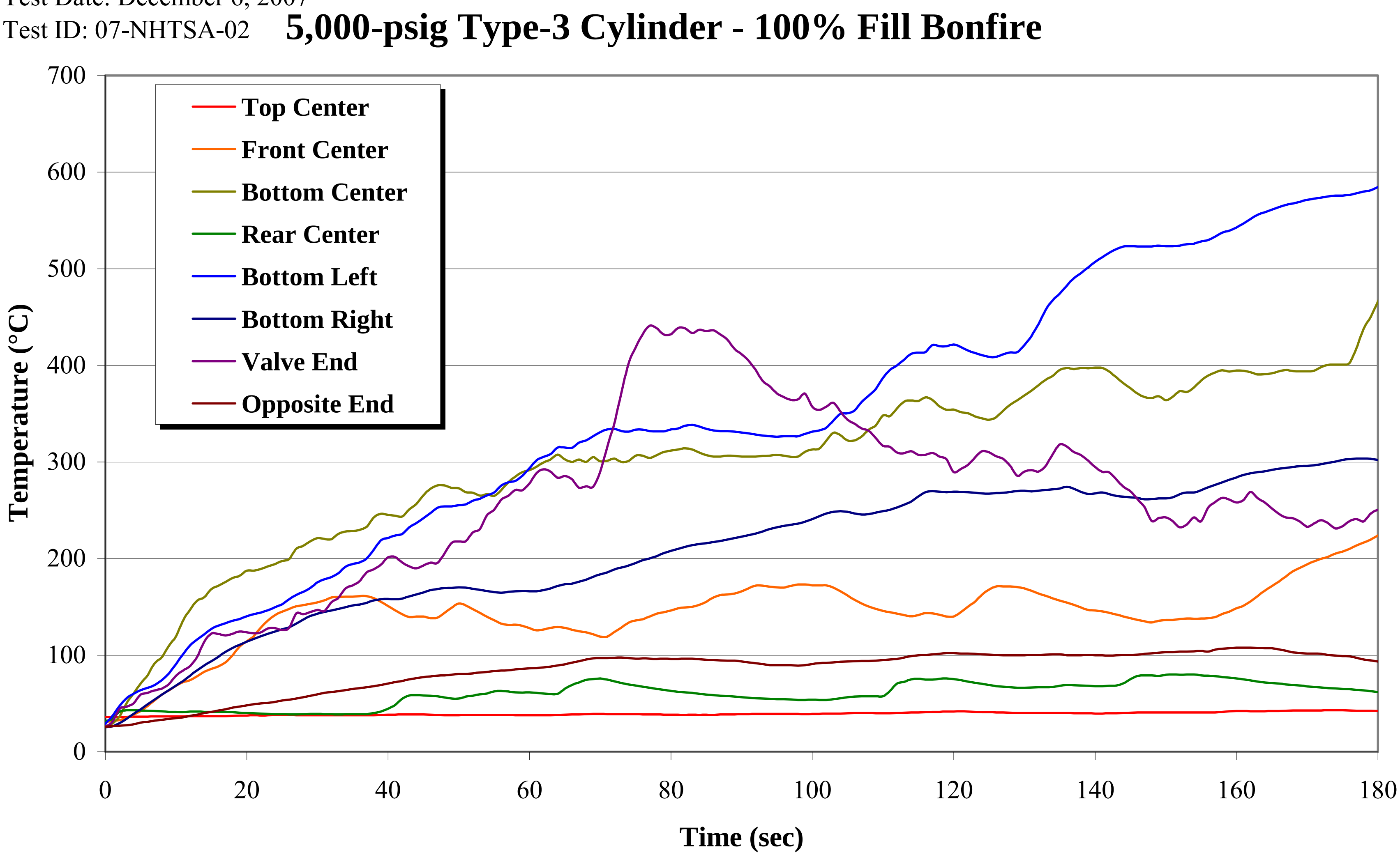
Test ID: 07-NHTSA-02



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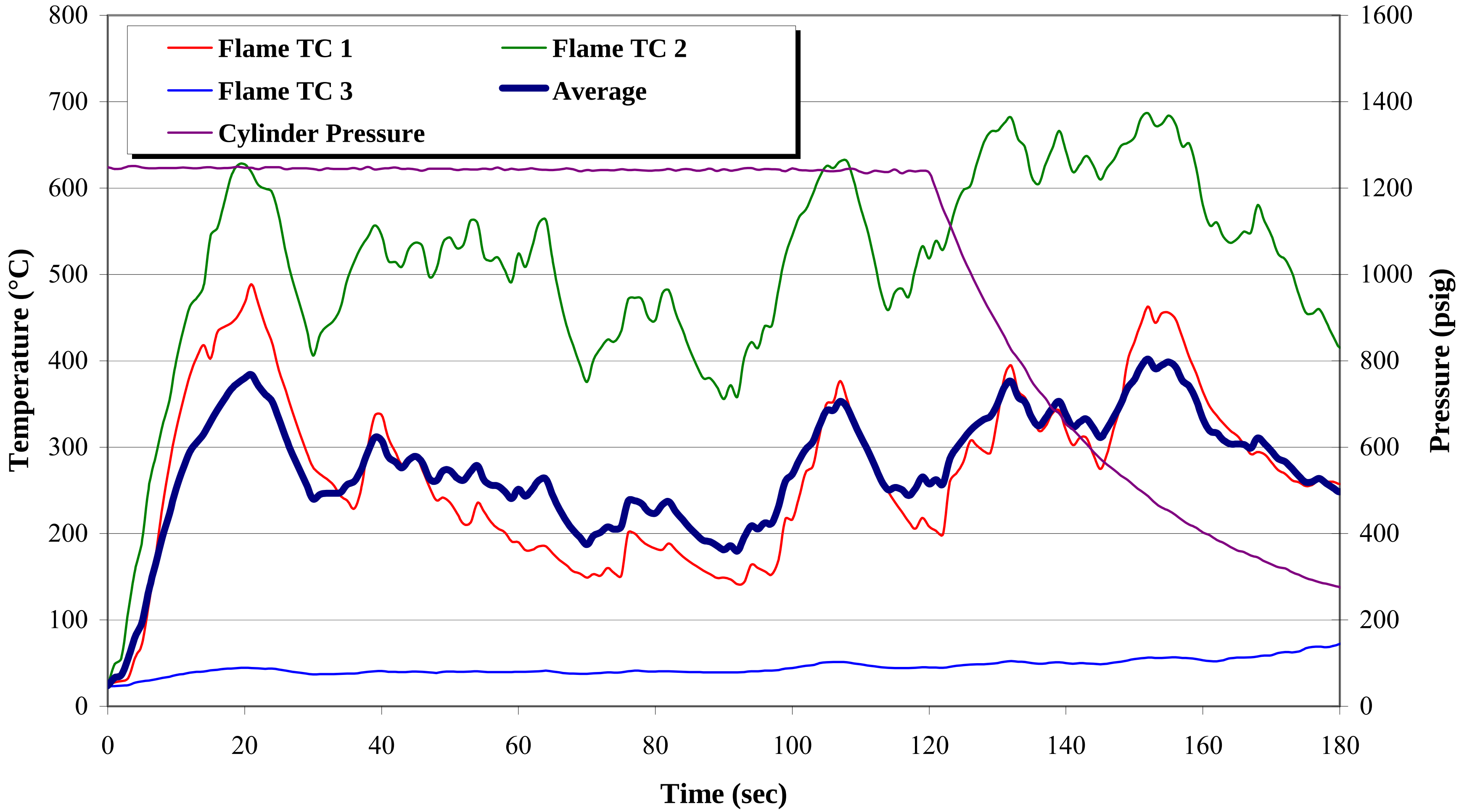
Test Date: December 6, 2007
Test ID: 07-NHTSA-03

5,000-psig Type-4 Cylinder - 25% Fill Bonfire



NHTSA
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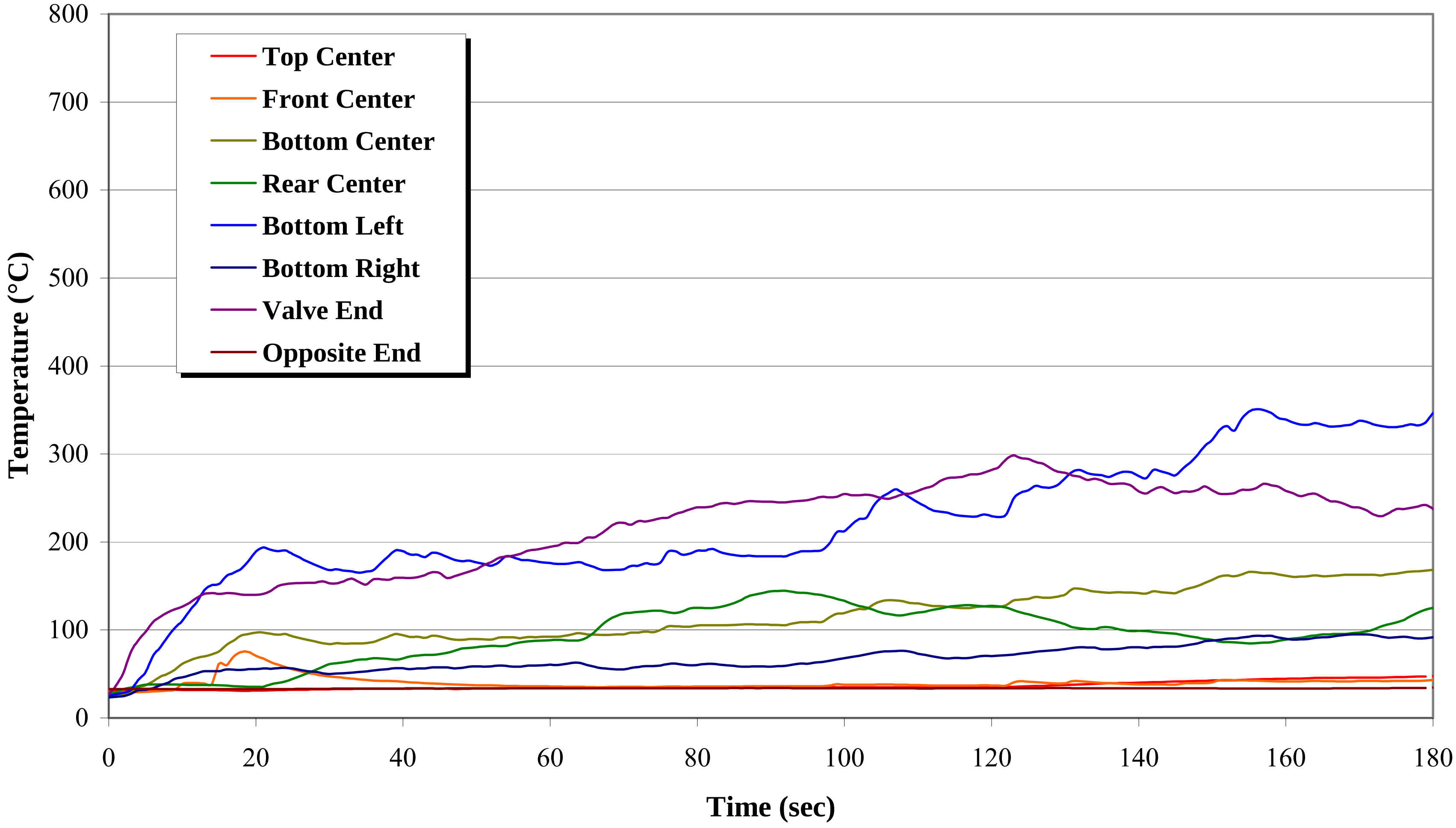
Test Date: December 6, 2007
Test ID: 07-NHTSA-03

5,000-psig Type-4 Cylinder - 25% Fill Bonfire



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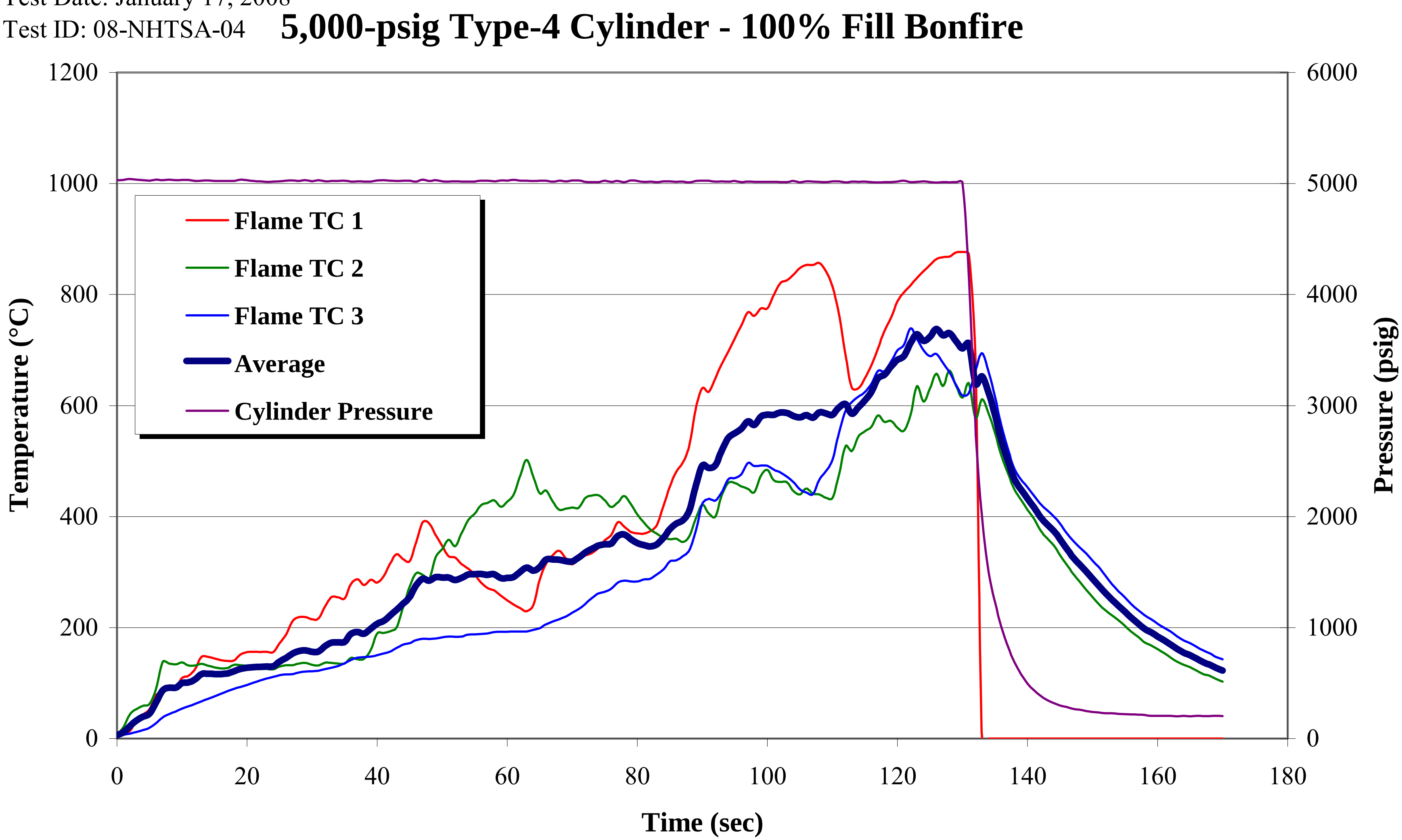
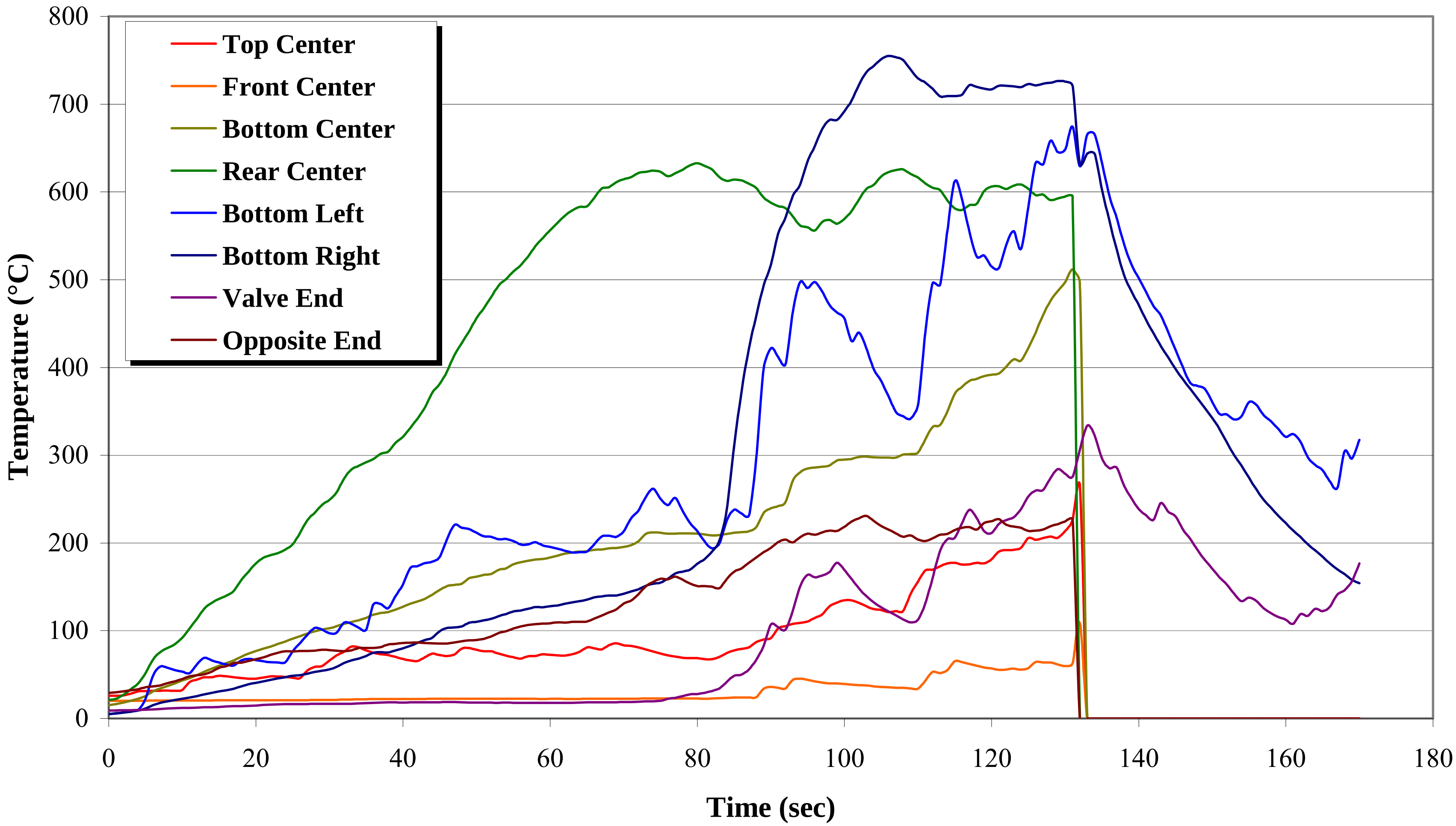
Test Date: January 17, 2008
Test ID: 08-NHTSA-04

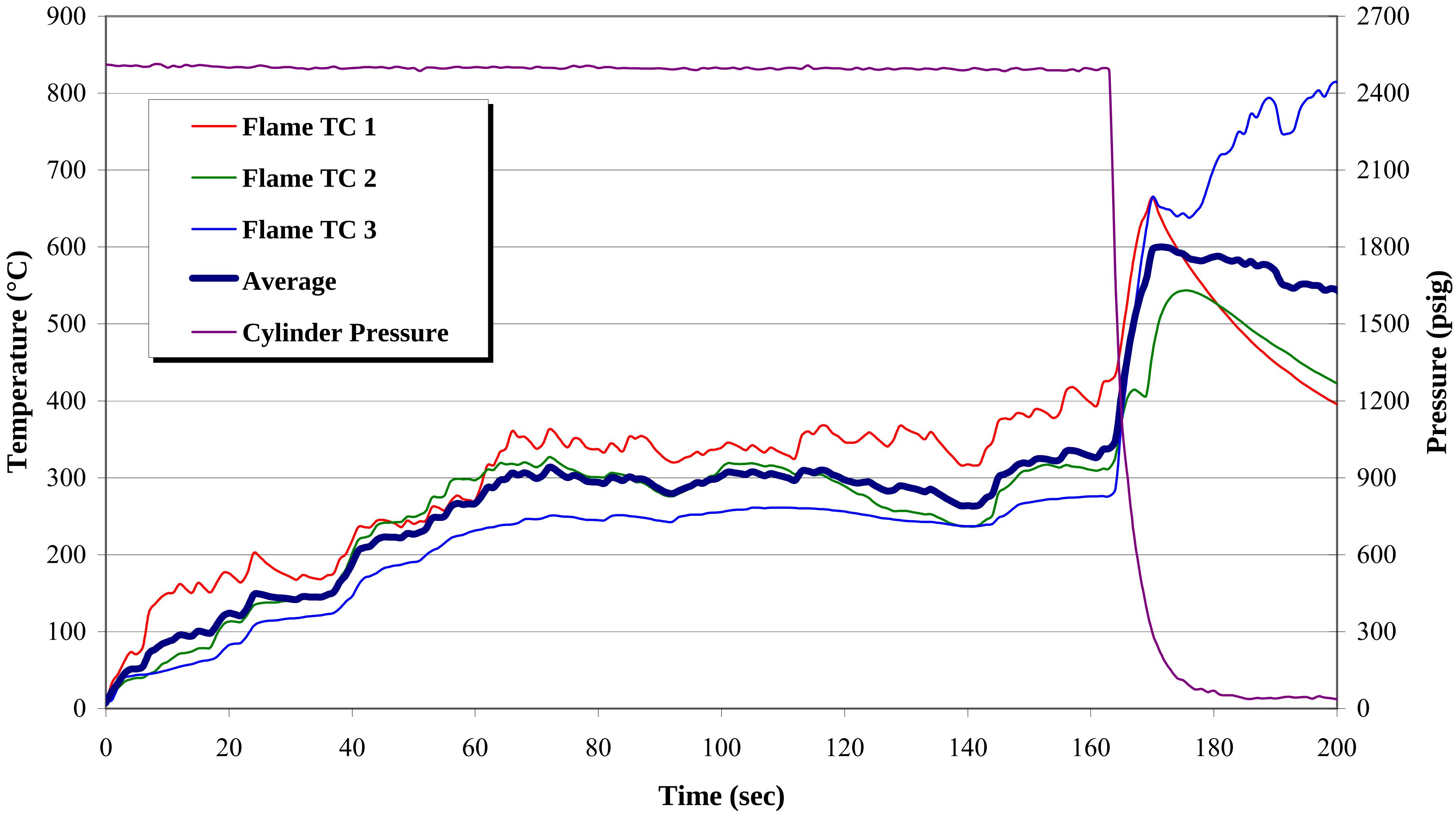


NHTSA
SwRI Project No. 01.12575.01.001
Test Date: January 17, 2008
Test ID: 08-NHTSA-04

5,000-psig Type-4 Cylinder - 100% Fill Bonfire

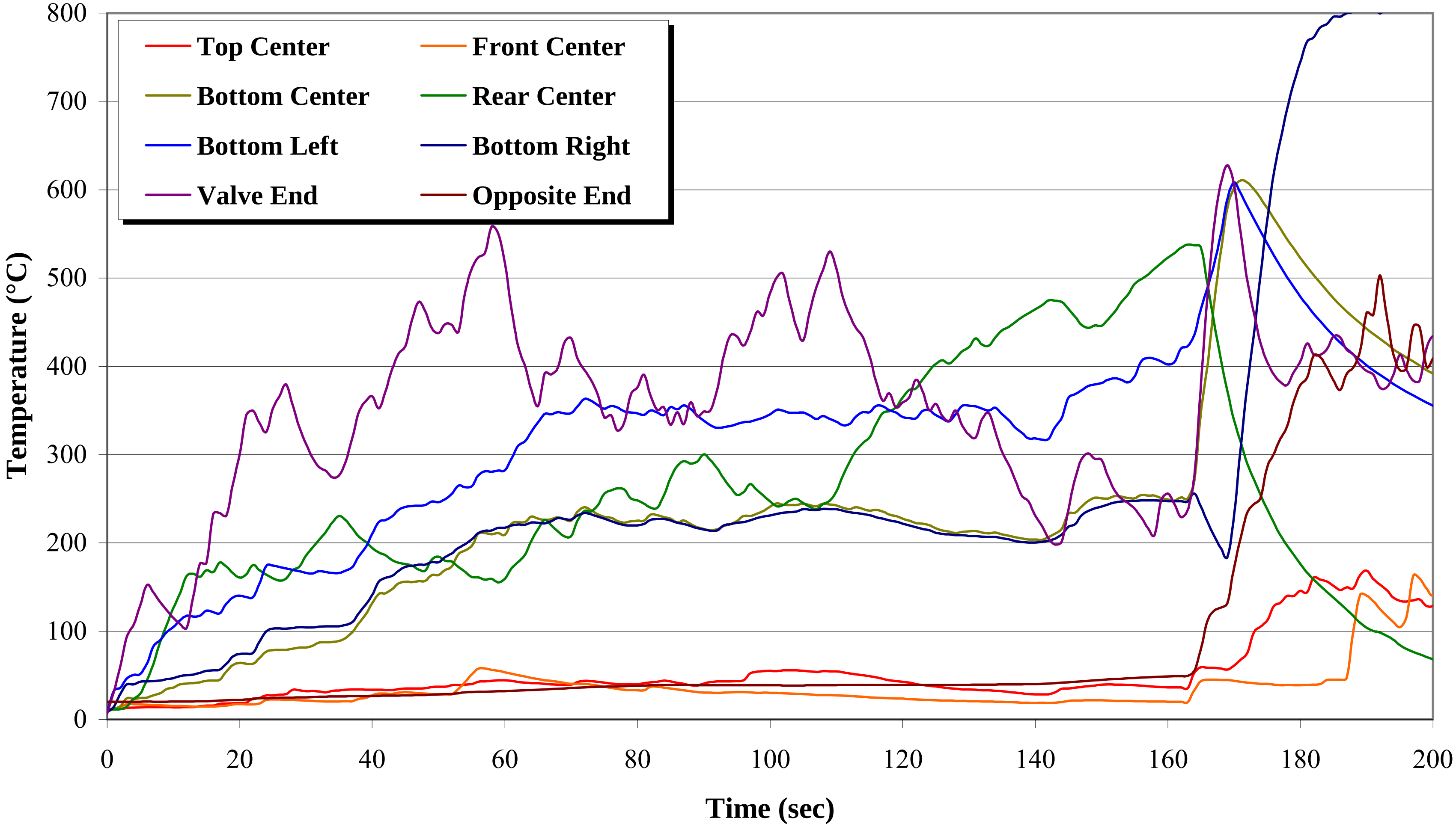


NHTSA
SwRI Project No. 01.12575.01.001
Test Date: January 17, 2008
Test ID: 08-NHTSA-06 **10,000-psig Type-4 Cylinder - 25% Fill Bonfire**



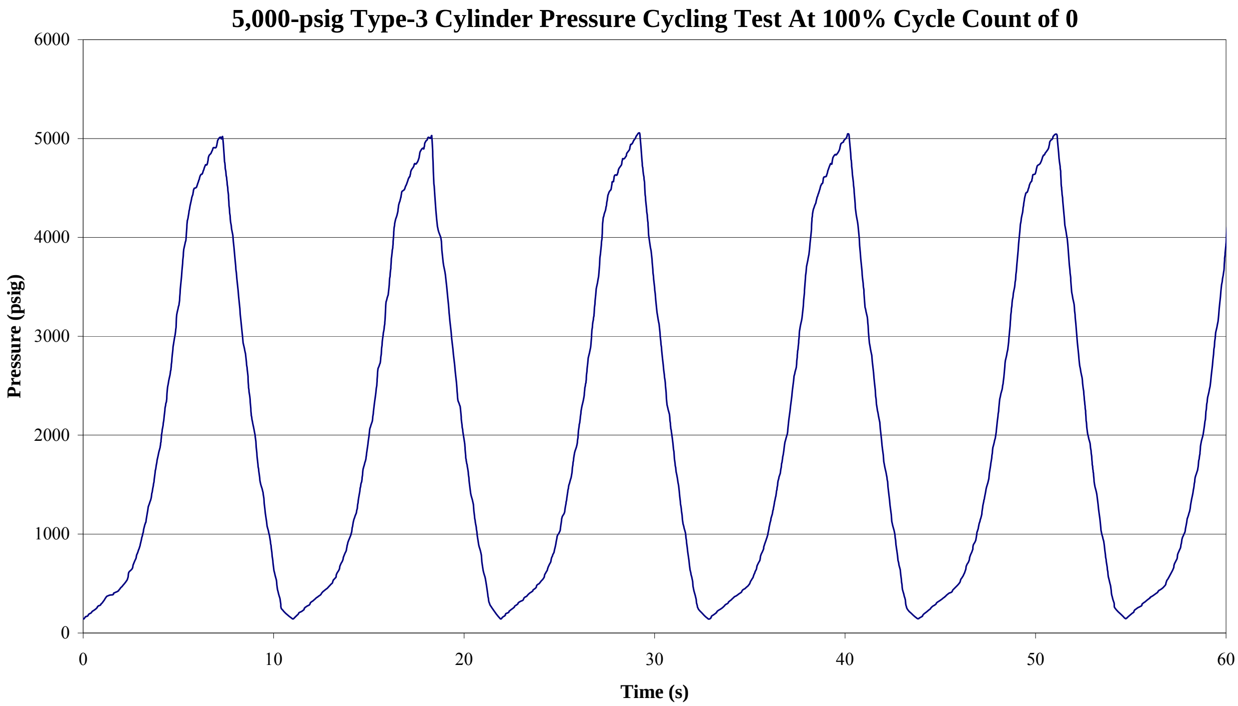
NHTSA
SwRI Project No. 01.12575.01.001
Test Date: January 17, 2008
Test ID: 08-NHTSA-06

10,000-psig Type-4 Cylinder - 25% Fill Bonfire



APPENDIX B

PRESSURE CYCLING TESTS – GRAPHICAL DATA



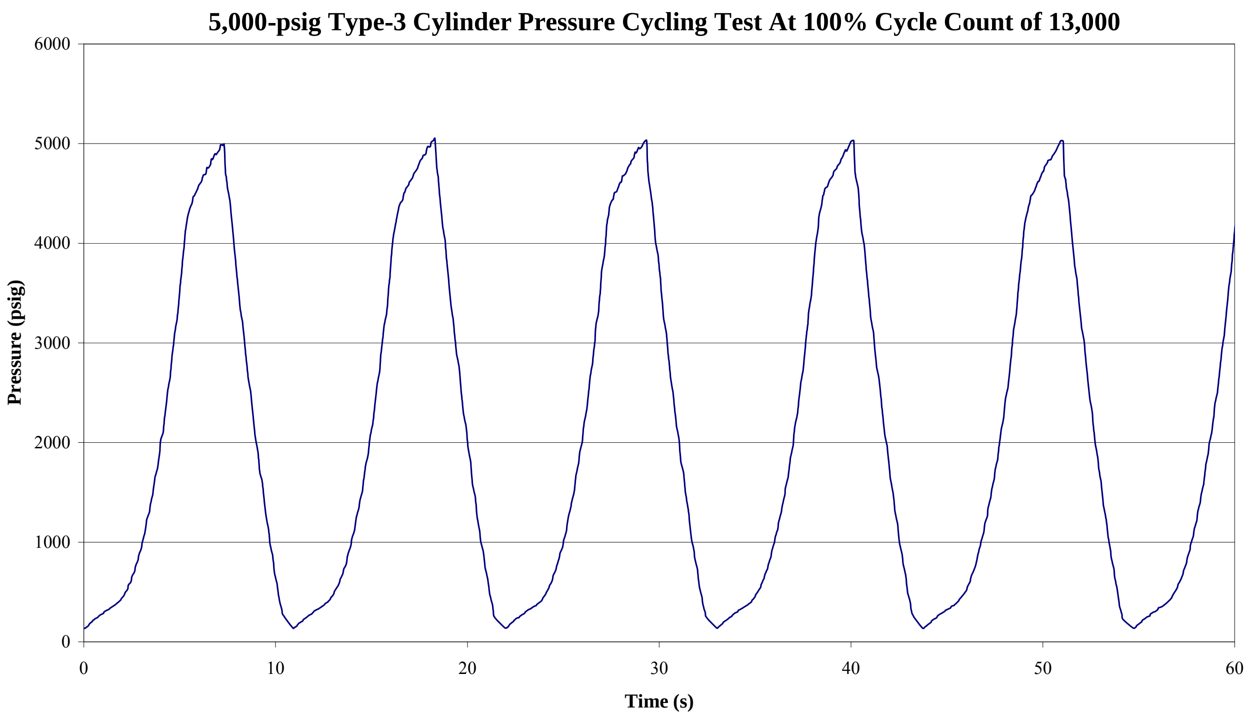
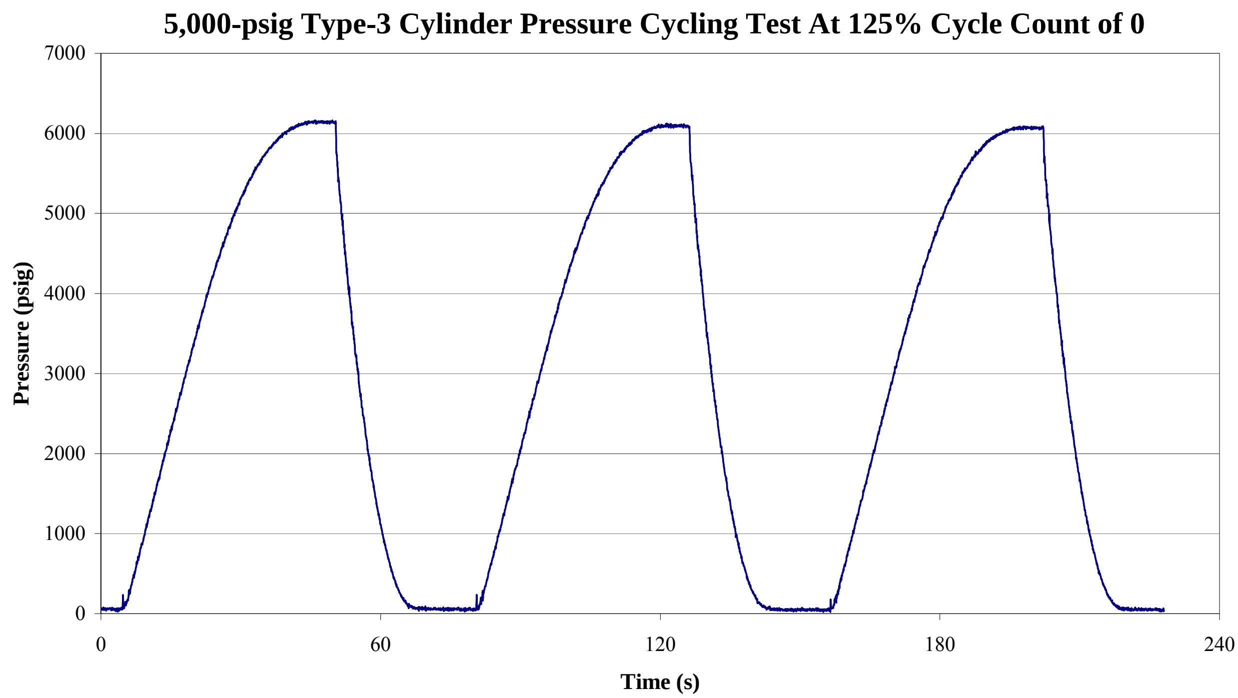


Figure B-1. 5000-psig Type 3 Cylinder Pressure Cycling Test Data (1 of 2).



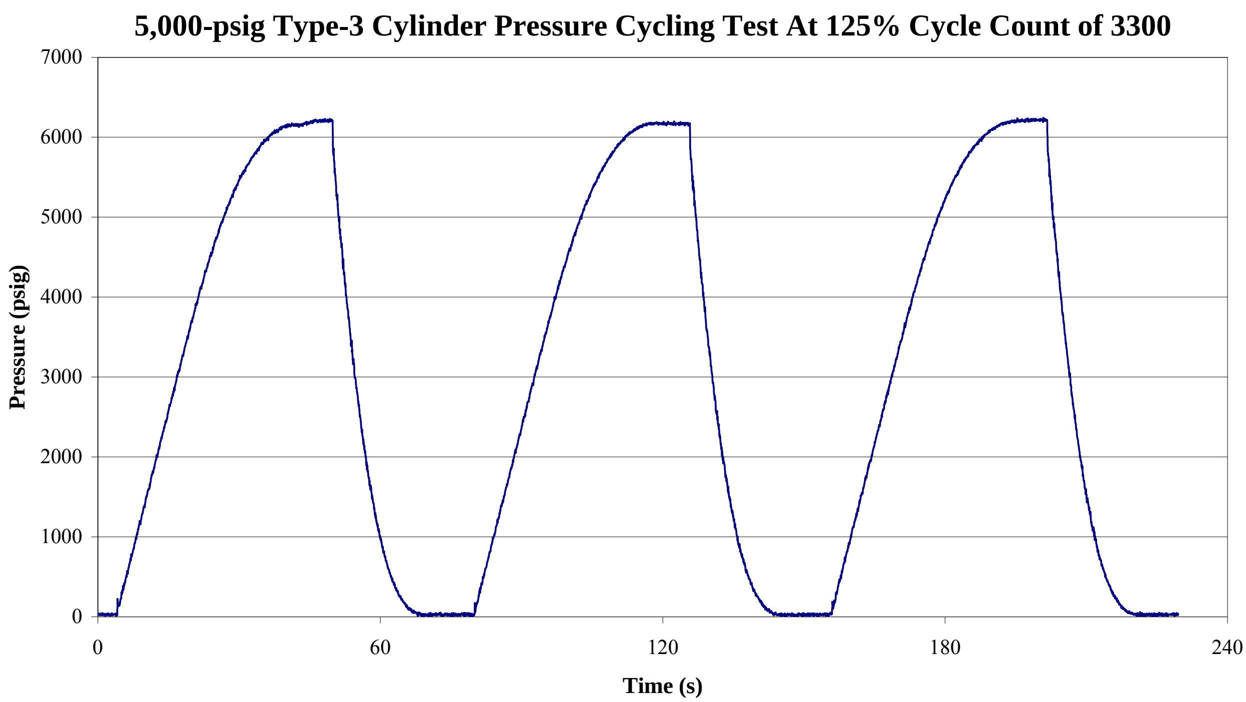
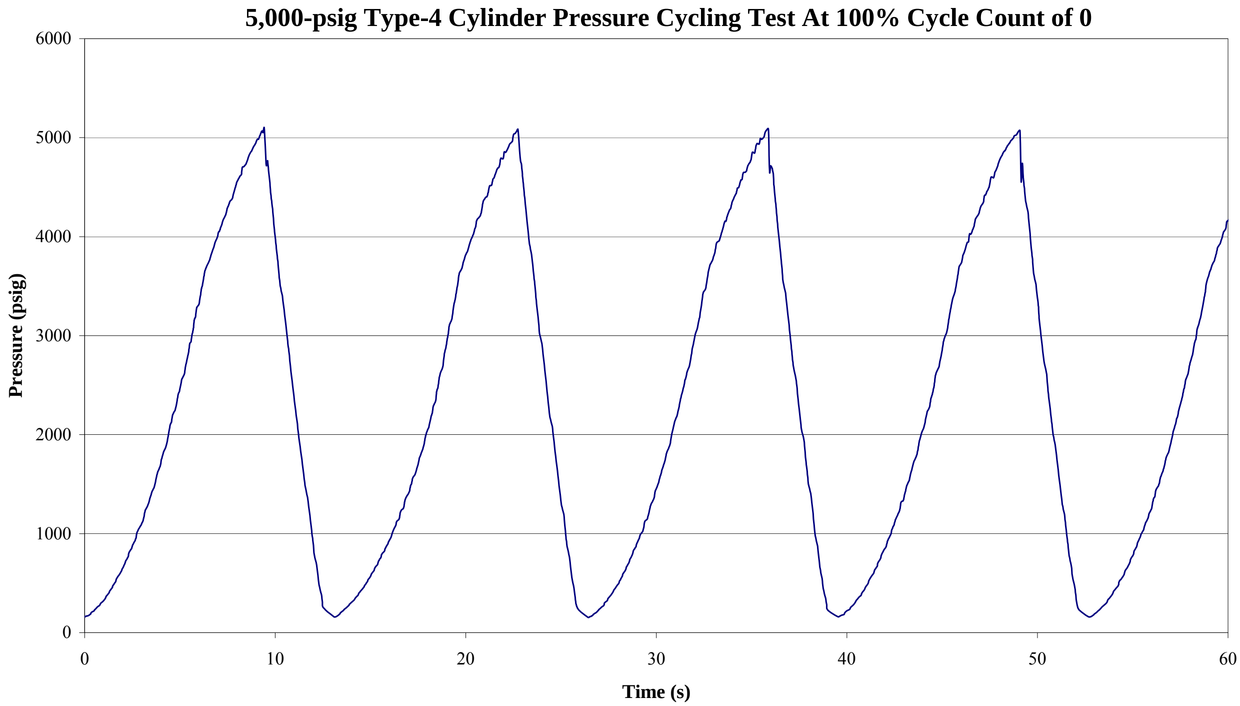


Figure B-2. 5000-psig Type 3 Cylinder Pressure Cycling Test Data (2 of 2).



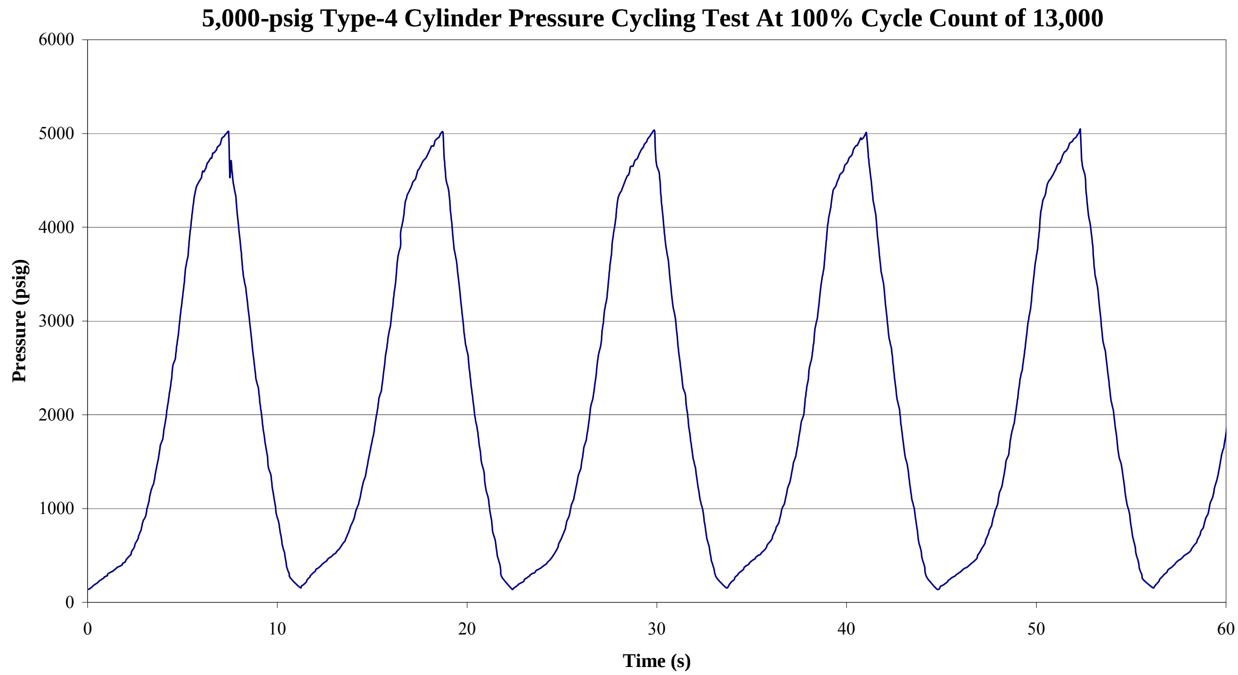
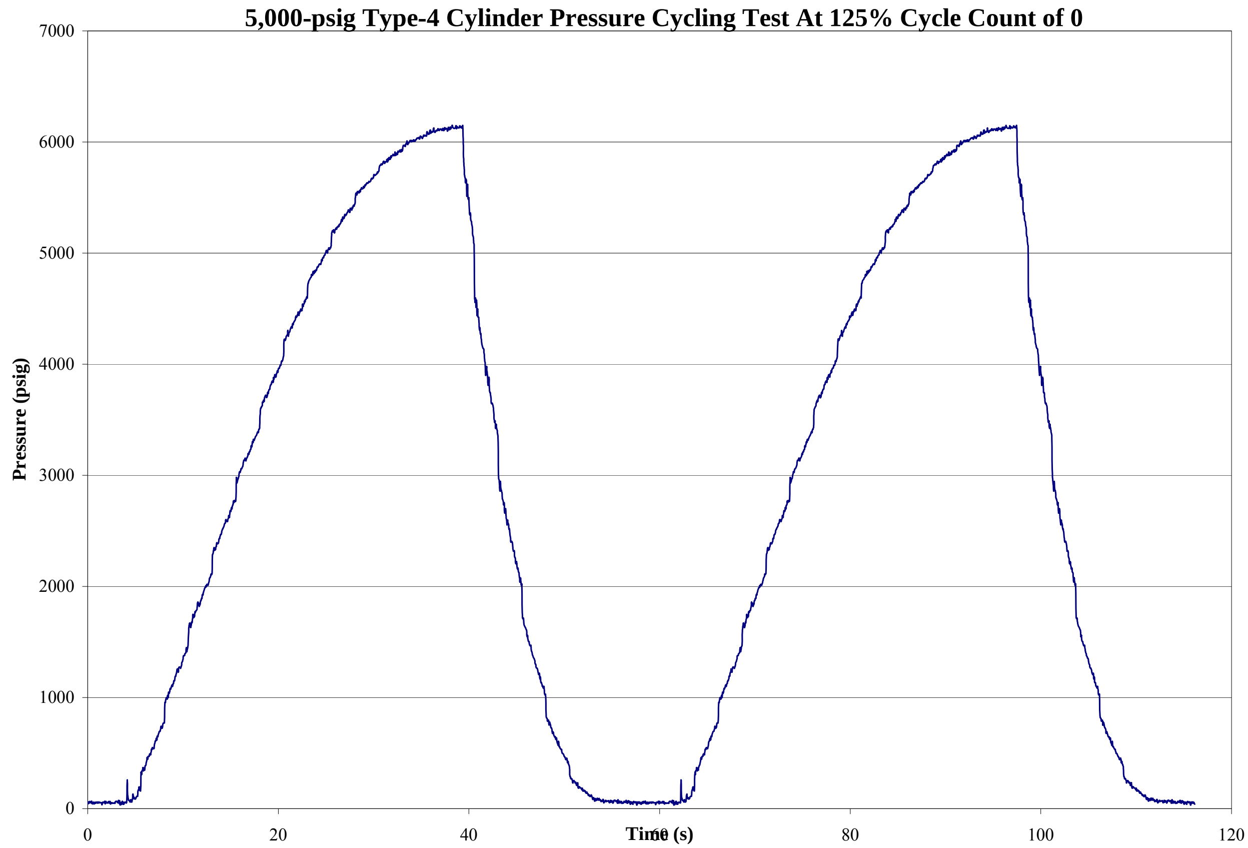


Figure B-3. 5,000-psig Type 4 Cylinder Pressure Cycling Test Data (1 of 2).



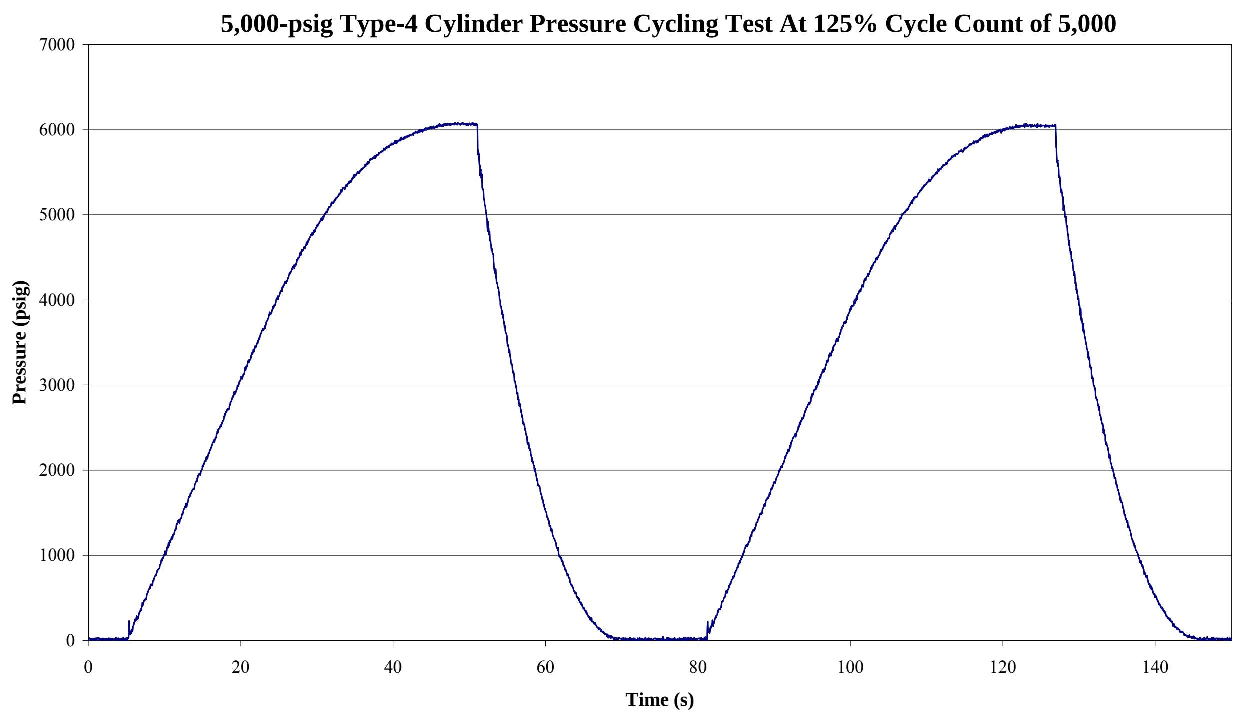
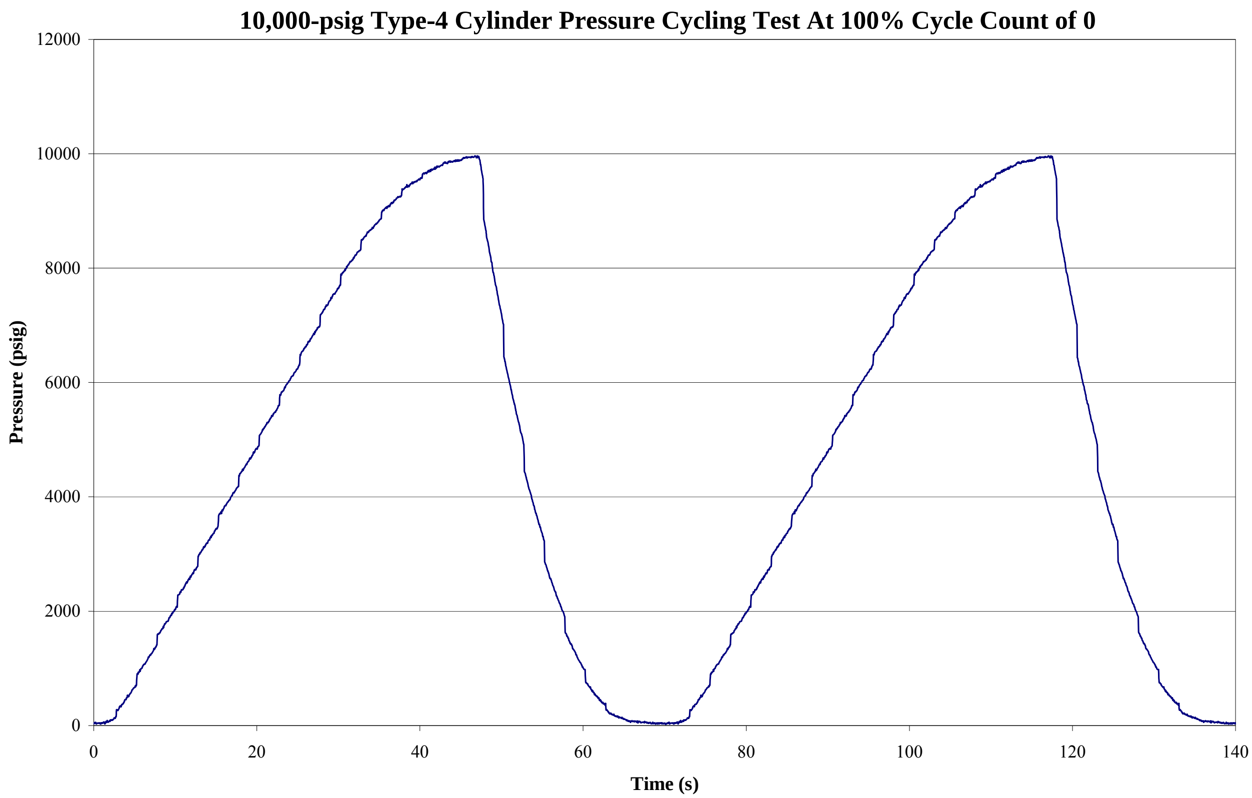


Figure B-4. 5,000-psig Type 4 Cylinder Pressure Cycling Test Data (2 of 2).



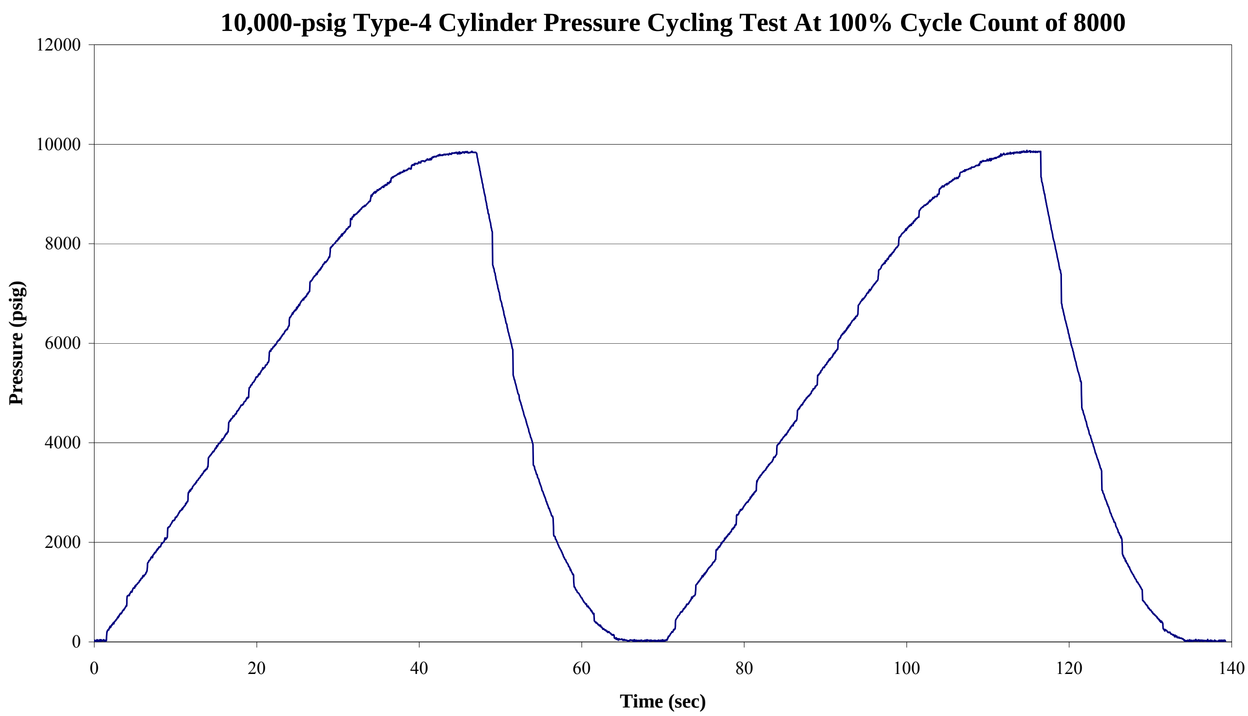


Figure B-5. 10,000-psig Type 4 Cylinder Pressure Cycling Test Data (1 of 1).

APPENDIX C

PHOTOGRAPHIC DOCUMENTATION

Figure C-1. Overall Setup for Cylinder Bonfire Tests – 5,000-psig Type 3 Cylinder Shown.

Figure C-2. View of 5,000-psig Type 3 Cylinder Venting.

Figure C-3. View of 5,000-psig Type 4 Cylinder Venting.

Figure C-4. View of 5,000-psig Type 4 Cylinder Venting.

Figure C-5. View of 10,000-psig Type 4 Cylinder Venting.

Figure C-6. 5,000-psig Type 4 Cylinder Setup for Pressure Cycling Tests.

Figure C-7. 10,000-psig Type 4 Cylinder Setup for Pressure Cycling Tests.

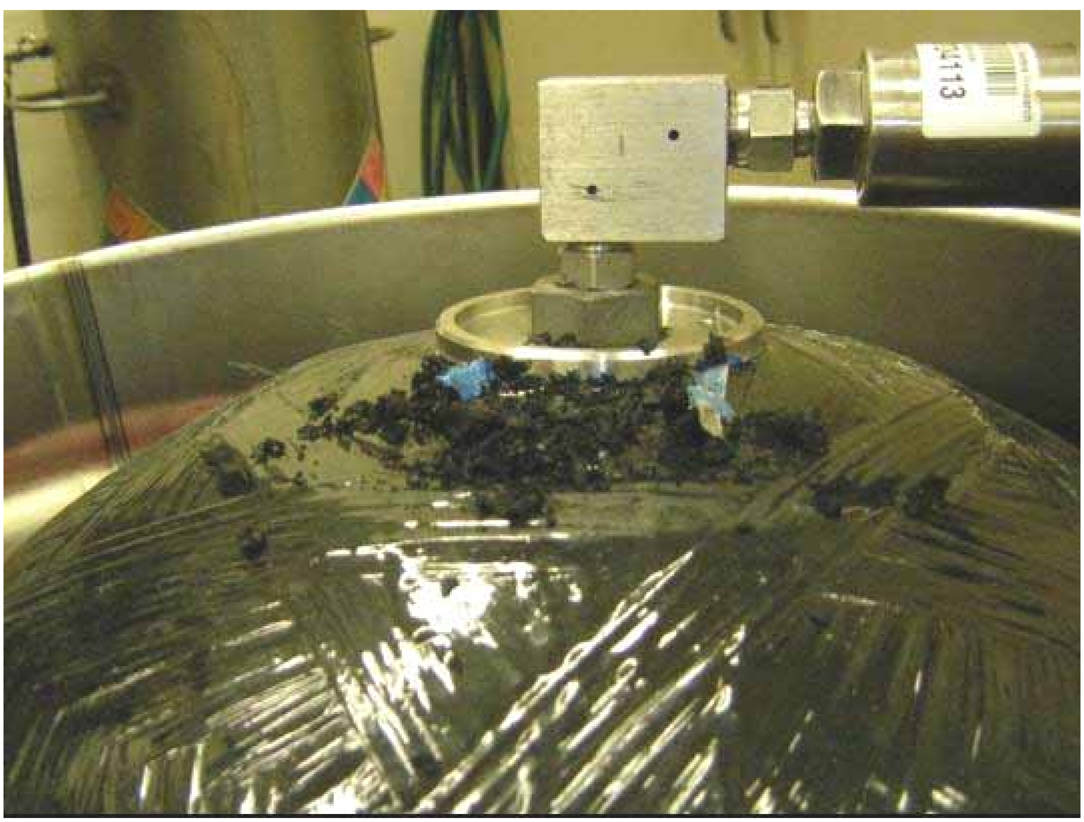


Figure C-8. Damage at Fitting on 10,000-psig Cylinder Following Pressure Cycling Tests.

Figure C-9. General Setup for Burst-Pressure Tests. (5,000-psig Type 4 Cylinder Shown)

Figure C-10. Typical Failure of Catastrophic Failure Following Burst-Pressure Test.

Figure C-11. Gun Bolt and Bullet for Penetration Tests.

Figure C-12. Hole in 5,000-psig Type 3 Cylinder Following Penetration Test.

Figure C-13. Hole in 5,000-psig Type 4 Cylinder Following Penetration Test.

Figure C-14. Hole in 10,000-psig Type 4 Cylinder Following Penetration Test.

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