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The Evaluation of Water Mist With and Without Nitrogen as an Aircraft Cargo Compartment Fire Suppression System

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16. Abstract

This report documents the full-scale evaluation tests of a water mist system, with and without nitrogen that would be available from an onboard inert gas generation system (OBIGGS) against a series of standardized aircraft cargo fires. These evaluation tests followed the testing protocols specified in the Minimum Performance Standard for Aircraft Cargo Compartment Gaseous Fire Suppression Systems modified with a draft new protocol for an exploding aerosol can fire scenario that would be applicable to nongaseous systems. The developmental work was performed in conjunction with the International Aircraft Systems Fire Protection Working Group. The results showed that a hybrid water mist and nitrogen system met the minimum performance standard, with lower cargo compartment temperatures than either plain water mist or halon, and with less weight of water consumed than halon.

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LIST OF ABBREVIATIONS

CFM	Cubic Foot per Minute
dc	Direct Current
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
IHRWG	International Halon Replacement Working Group
IASFPWG	International Aircraft Systems Fire Protection Working Group
MPS	Minimum Performance Standard
OBIGGS	Onboard Inert Gas Generator System
Vac	Alternating Current Voltage
WMS	Water Mist System

EXECUTIVE SUMMARY

This final report documents the full-scale test evaluation of a water mist system with and without nitrogen, that would be available from an onboard inert gas generation system (OBIGGS), against a series of standardized aircraft cargo fires. The International Aircraft Systems Fire Protection Working Group (IASFPWG) requested this testing program to evaluate identified Halon 1301 replacement agents for aircraft cargo compartment fire suppression systems, namely water mist and nitrogen. The systems were challenged against the fire threats specified in the Minimum Performance Standards (MPS) for Aircraft Cargo Compartments Gaseous Fire Suppression Systems, DOT/FAA/AR-00/28, modified with a draft new test protocol for an exploding aerosol can fire, in order to evaluate nongaseous agents.

The MPS specifies four cargo fire test scenarios: bulk-load fires, containerized fires, flammable liquid fires (surface burning), and aerosol can explosions. Each fire test scenario is repeated five times. The bulk-load and containerized fire tests, which are basically deep-seated fires, use shredded paper loosely packed inside cardboard boxes to simulate a Class A fire load. In the bulk-load fire scenario, the boxes are placed directly onto the cargo compartment floor, while the boxes used in the containerized fire scenario were stacked inside an LD-3 container. In the surface burning test (Class B fires) 0.5 gallon (1.89 liters) of Jet A fuel was placed in a 2′ x 2′ steel pan. The aerosol can explosion scenario employed a simulator that released a flammable/explosive mixture of propane, alcohol, and water into an arc from a sparking electrode.

The fire test results showed that the water mist system (WMS) passed three out of the four MPS tests, meeting the acceptance criteria defined for bulk-load fires, containerized fires, and surface burning tests. The MPS requires the following average peak temperatures and average temperature-time areas:

- ≤ 582º and 10452ºF-minute for the bulk-load tests
- ≤ 612º and 14102ºF-minute for the containerized tests
- ≤ 1125º and 2964ºF-minute for the surface burn tests

The water mist system attained an average peak temperature of 535ºF and an average temperature-time area of 5900ºF-minute in the bulk-load fires, 487º and 9106ºF-minute in the containerized fires, and 742º and 1307ºF-minute in the surface burn tests. However, the water mist system did not pass the draft new aerosol can simulation explosion criteria. The oxygen depletion (as low as 15%) created by water steam (dilution) and fire (consumption) was not sufficient to prevent the hydrocarbon explosion. In order to inert the compartment against ignition of the aerosol can hydrocarbon mixture, the required oxygen volumetric concentration was below 12%. With an average ceiling peak temperature of 976ºF, this water mist system failed the temperature requirement (it should be below the bulk-load temperature requirement).

The average quantity of water consumed by the water mist system during these tests ranged between 61 pounds (surface burn test) and 273 pounds (containerized test); Halon 1301 is effective against these threats with 80 pounds of agent.

The same water mist system, combined with nitrogen was able to meet all of the MPS acceptance criteria with very competitive water and nitrogen consumption rates. With the water mist and nitrogen system, the cargo compartment temperatures were much cooler than with the plain water mist system or even with halon during the period of performance. The results showed that the average compartment peak temperatures and the average temperature-time area were 387º and 4744ºF-minute for the bulk-load fire, 313º and 5518ºF-minute for the containerized fire, 438º and 1054ºF-minute for the surface burn test, and 533º and 3810ºF-minute for the aerosol can simulation explosion test. Since this hybrid system was designed via a close-loop system to reduce the oxygen volumetric concentration to less than 12%, the hydrocarbon gases released during the aerosol can explosion test did not explode. The water mist and nitrogen were discharged independently from one another, which resulted in a low-weight penalty. Both agents were activated during the initial knock down of the fire, but after 5 minutes the water was turned off and reactivated if the ceiling or sidewall temperature exceeded 212ºF and deactivated if the temperature dropped below 212ºF. Similarly, the nitrogen discharge was cycled, based on the oxygen volumetric concentration. The water consumption ranged between 22 pounds (surface burn test) and 73 pounds (aerosol can explosion test). The nitrogen consumption ranged between 111 ft^3 (surface burn test) and 2930 ft^3 (aerosol can explosion test). It was also noted that the burn damage to the boxes inside the compartment was significantly less than with halon.

A new exploding aerosol can test protocol was used for these nongaseous systems, e.g., water mist. This protocol basically combined the bulk-load test protocol with the previous aerosol can explosion test protocol in order to determine the simulator activation time. Previously, the simulator activation time depended only on the volumetric concentration of the agent. The new protocol considers the fire suppression capabilities of a nongaseous system, which dictates the activation time of the aerosol can simulator.

1. INTRODUCTION.

In September 2000, the Halon Options Task Group, working under the International Aircraft Systems Fire Protection Working Group (IASFPWG), submitted their report entitled "Options for Aircraft Cargo Compartment Fire Protection" to the IASFPWG Chairman. This report was a review of six available fire extinguishing/suppression systems options for potential use in aircraft engines and cargo compartments. After reviewing proposals and resolving public concerns, the team recommended, by consensus, the following two systems for Federal Aviation Administration (FAA) tests: a water mist and inert gas system and pentafluoroethane (HFC-125) [1].

The FAA Technical Center Fire Safety Section, as part of their Halon Replacement Program, adopted the recommendations and evaluated the fire suppression performance of these alternative agents. The testing program used the fire test protocols specified in the "Minimum Performance Standards (MPS) for Aircraft Cargo Compartment Gaseous Fire Suppression Systems" [2] in order to assess the capabilities and limitations of these systems.

Previously, in the early 1990s, FAA investigated the performance of water spray systems installed in the passenger cabin to provide protection against a postcrash fuel fire. Results showed that an optimized system was capable of providing a significant increase in survival time, in all transport aircraft sizes, during a postcrash fire [3]. Due to its effectiveness against postcrash cabin fires, the FAA explores the application of water sprays and mists in other areas of the aircraft. A major area investigated was the cargo bay, precipitated by two main events—the ban on the production of Halon 1301 and the Class D to C cargo compartment conversion. This interest in determining the fire protection performance of water mist systems (WMS) in the cargo bay led to the evaluation of four design concepts. These designs included high-pressure, low-pressure, single-fluid, and dual-fluid systems. Initial test results indicated that water mist systems were effective in suppressing flaming and deep-seated fires, but more work needed to be done to reduce water consumption and optimize system and control logic design in order to fully meet the MPS fire test acceptance criteria, especially regarding the exploding aerosol can scenario [4].

This follow-on test program expanded the earlier work on cargo water mist systems by fully subjecting the system to the MPS fire threats and determining the parameters and resources needed to meet the acceptance criteria. Availability of gaseous nitrogen from an onboard inert gas generator system (OBIGGS) was examined in conjunction with the water mist system. During the tests, a nitrogen bank simulated the OBIGGS whose primary function would be for the inerting of fuel tanks. Unlike the dual-fluid flow water mist systems, the nitrogen did not propel the water mist through the nozzles. The bank had its own plumbing and was activated independently from the water mist system primarily to inert the cargo compartment after initial fire knock-down by the water mist discharge.

The MPS provides an objective means of comparing a system's fire protection performance with that of halon, which maintains the current level of safety. However, the current standard does not address nongaseous systems, like water mist or solid propellant gas generators. It specifies that "the aerosol can simulator should be activated when the agent concentration 2 feet (60.9 cm) above the compartment floor is at the minimum volumetric design concentration ±0.1%." This standard does not apply because the design of nongaseous systems may not be based on minimum volumetric design concentrations or cannot be measured. Therefore, a new, performance-based approach was used to test the water mist/nitrogen systems.

1.1 OBJECTIVES.

The primary objective of the test program was to determine the fire protection performance of a water mist system and a hybrid water mist nitrogen system when subjected to the fire threats described in the Minimum Performance Standard (MPS) for Aircraft Cargo Compartment Gaseous Fire Suppression Systems. The intent of the program was to design and develop a system that was capable of meeting the MPS acceptance criteria. The systems were not optimized for weight, space, reliability, etc.

The secondary objective was to develop a new exploding aerosol can test protocol for nongaseous agents.

2. TEST SETUP AND INSTRUMENTATION.

2.1 TEST ARTICLE.

The fire tests were conducted inside a Class C cargo compartment of a wide-body aircraft, with a volume of 2000 ±100 cubic feet (see figure 1). The compartment was configured to have a leakage rate of 50 ±5 cubic feet per minute. The original cargo liners were replaced with mild steel sheeting in order to preserve the article for multiple testing; the ceiling was 0.0625-inch-thick sheeting, while the sidewalls were 0.050-inch-thick sheeting. The compartment was equipped with multiple sensors to record temperature, combustion, extinguishing agent gas concentrations, and pressure. The aft section of the test article contained a small video camera compartment with a high-temperature glass window. A second camera, also inside a heat-resistant box, was mounted inside the test bay near the burn area. Lighting was provided by a series of high-wattage lights mounted on the floor and sidewalls of the aircraft compartment.

The cargo compartment ventilation was supplied from the passenger cabin floor grills. The cabin was forced-ventilated by two 10-inch-diameter perforated ducts connected to a large fan. The ducts were installed between the cabin ceiling and the overhead storage bins and ran the length of the fuselage. An outflow valve was installed on the aft underside of the fuselage to provide the main outflow for cabin air.

2.2 INSTRUMENTATION.

The instrumentation requirements were taken from the MPS and consisted of thermocouples, gas analyzers, and a pressure transducer (see table 1). The sensor outputs were connected to an analog-to-digital converter and recorded on a personal computer.

2.2.1 Temperature Measurement.

A total of 40 thermocouples were installed along the ceiling and sidewalls of the compartment and at the fire load (see figure 1). These thermocouples (Part No. 0129) were type K chromel/alumel 20 gauge made by Thermo Electric. The ceiling thermocouples were evenly spaced along the compartment ceiling with a maximum of 5 feet between adjacent thermocouples. One of the ceiling thermocouples was installed directly above the initial ignition location for all fire scenarios. The beads of the ceiling thermocouples, in the fire area, were 1 inch below the compartment ceiling. One of the three sidewall thermocouples, thermocouple number 24, was placed 1 foot below the ceiling and centered on the fire ignition location. The sidewall thermocouple was installed on the starboard side of the compartment nearest the ignition location. Five thermocouples monitored the temperature inside and above the ignition box and the surfaces of the three simulated aerosol cans (galvanized steel pipes).

2.2.2 Oxygen Concentration Measurement.

During the execution of the tests, oxygen volumetric concentrations were measured inside the cargo compartment. The compartment had four gas collection probes, spaced vertically at different levels from the floor; 16, 32.5, and 49 inches, and one that was located near the fire. The vertically separated probes were installed in the centerline of the aircraft as shown in figure 1. The placement of probe number 4 varied because it depended on the type of fire scenario conducted. During the bulk-load and exploding aerosol can test this fourth probe was located approximately 6 inches to the side of the ignition box and 9 inches above the floor. When the containerized test was conducted, probe number 4 was placed inside the LD-3 container, approximately 6 inches from the ignition box and 9 inches above the LD-3 floor. During the surface burn, it was placed 12 inches away from the pan and 12 inches below the ceiling. These probes were connected to the analyzer by means of a 0.5-inch copper tubing network containing particle filters, ice bath, water filters, and pumps. The oxygen volumetric concentration was measured by means of four Rosemount Analytical Model OM11EA analyzers. These analyzers used the polarographic oxygen analysis technique to measure the oxygen concentration.

2.2.3 Weight Measurement.

The weight of the water was measured with a scale model Weight-Tronix Model WI-120. This scale had a maximum capacity of 2000 pounds and a resolution of 0.2 pound. The readings were collected manually every minute via a camera.

2.2.4 Pressure Measurement.

A pressure transducer, Omega model PX951-50S5V, was installed as shown in figure 1 to monitor the overpressure during the aerosol can explosion test. This piezoresistive transducer had a pressure range from 0 to 50 psig (0 to 1379 KPa) with a frequency response of 3000 Hz.

The nitrogen bank cylinder and output pressures were collected by reading the regulator gauges (Matheson Model 3020) via a video camera every minute.

2.2.5 Data Collection.

The data collection system used was a Keithley model DAS Scan Metrabyte connected to a Gateway model E-5200 personal computer. Each data channel was programmed to record every 5 seconds. The pressure data was collected using a data acquisition system from EME, DAS-48S, connected to a Micron Transport XKE Pentium II/266 MHz laptop. The high-speed acquisition system sampled at a rate of 10,000 samples per second.

2.2.6 Water Mist Solenoid Controller.

The activation and control of the WMS was accomplished by the integration of a Gateway Solo laptop with a data acquisition system (Computer Boards, Inc. PCM-DAS16S/12) and a solid-state relay rack (Computer Boards, Inc. SSR-RACK24). The HP VEE computer software was used to program the data acquisition and control the operation of the relay rack. The compartment temperatures were monitored with the data acquisition, while the relay rack controlled the activation of the WMS solenoid valves. The control logic sequence was written to initially open the WMS solenoid valves for 5 minutes. Later, the valves closed if the compartment temperature dropped below 212ºF, and opened if the temperature exceeded 212ºF. All of the solenoid valves opened if the environment exceeded 350ºF.

2.3 FIRE LOADS.

The MPS required that the suppression system be subjected to four different fire scenarios: bulk-load fire, containerized fire, surface burning, and aerosol can explosion. Each of these fire scenarios had different fire loads simulating potential fire threats in a cargo compartment.

2.3.1 Bulk-Load Fire.

The fire load for this scenario was 178 single-wall corrugated cardboard boxes, each with nominal dimensions of 18 x 18 x 18 inches. The weight per unit area of the cardboard was 0.11 lbs/ft^2. These boxes were filled with 2.5 pounds of shredded office paper, loosely packed without compacting. The weight of each filled box was 4.5 ±0.4 lbs. The flaps of the boxes were tucked under each other. The boxes were stacked in two layers inside the cargo compartment without any significant air gaps between them. Ten 1-inch-diameter ventilation holes were placed in the side of the initially ignited box to ensure that the fire did not self-extinguish (figure 2).

2.3.2 Containerized Fire.

The same type of filled cardboard boxes and the same igniter used in the bulk-load fire scenario (section 2.3.1) was used in this scenario. Only 33 boxes were stacked inside an LD-3 container as shown in figure 3. The boxes were touching each other with no significant air gaps between them. The LD-3 container was constructed of an aluminum top and inboard side, a Lexan™. (polycarbonate) front, and steel remaining side. Two ventilation slots were cut on the LD-3 container. The first slot was cut on the center of the Lexan™ sheet and the second one was cut in the center of the sloping sidewall at the bottom of the LD-3 container. The slots were 12 by 3 inches ±1/4 inch. The igniter was placed in a box on the bottom row, near the corner formed by the sloping side of the container and the Lexan™ front face. Ten, 1-inch-diameter ventilation holes were placed in the sides of the box. Two additional, empty LD-3 containers were also placed adjacent to the loaded LD-3 container, as shown in figure 3.

2.3.3 Surface Burning.

For this scenario, the fire load was comprised of 0.5 gallon of Jet A fuel and 13 ounces of gasoline inside a square pan. The pan was constructed of 1/8-inch-thick steel and measured 2 feet by 2 feet by 4 inches high. The gasoline facilitated ignition of the jet fuel. In addition, 2.5 gallons of water was placed in the bottom of the pan to keep the pan cooler and minimize warping. The fuel will burn vigorously for approximately 4 minutes, if not suppressed. The pan was positioned 12 inches below the compartment ceiling and at the maximum horizontal distance from any discharge nozzles (figure 4) to provide a difficult location for water mist to extinguish the fire.

2.3.4 Aerosol Can Explosion.

This scenario addresses the overpressure, bursting, and flaming of an aerosol can subjected to a cargo compartment fire. Since the aerosol can explosion standard for gaseous agents was not applicable to the evaluation of a water mist system, a new test protocol was employed. It combined the bulk-load and the aerosol can explosion fire test scenarios in order to determine the activation time of the aerosol can simulator (see figure 5). The simulator was developed to better control the product/propellant mix, explosion time (activation), and improve reliability.

The bulk-load cardboard boxes were identical to those previously described (section 2.3.1), except fewer boxes were used. In addition to the cardboard boxes, the cargo compartment was loaded with 3 simulated aerosol cans (galvanized steel pipes). As shown in figure 5, 58 boxes were stacked in two layers, occupying 9.8% of the cargo compartment. The boxes were stacked tight to avoid any significant air gaps between boxes. Each galvanized steel pipe, with a surface thermocouple centered on the pipe, was placed in a box adjacent to the box above the ignition box (figure 5). The pipes were 8.25" long, schedule 80, and had an inner diameter of 1.50". The fire in the ignition box was initiated by applying 115 Vac to a 7 foot (2.1 m) length of nichrome wire wrapped around four paper towels folded in half. The resistance of the nichrome igniter coil was approximately 7 ohms. The igniter was placed inside a box (off center) on the bottom outside row of the stacked boxes. A second igniter is used as a backup in case the first one fails. Ten, 1-inch-diameter ventilation holes were placed in the side of the box to ensure adequate air for burning.

The aerosol can explosion simulator was placed close to the centerline of the cargo compartment, 5 feet forward of the box containing the igniter. The water mist did not directly impinge on the simulator. The simulator basically consisted of a cylindrical pressure vessel for the storage of the flammable base product and propellant, a quick-operating ball valve, and a pneumatic actuator to activate the ball valve. The contents were discharged horizontally as a vapor cloud. Details of the aerosol can simulator are found in reference 5.

The flammable contents of the simulator consisted of a base product/propellant mix that weighed 16 ounces. The mix consisted of 20% liquid propane (3.2 ounces), 60% ethanol (denatured alcohol, 9.6 ounces), and 20% water (3.2 ounces). These percentages were based on the concentrations found in an actual 16-ounce hair spray aerosol can.

2.4 IGNITION SOURCE.

Two types of ignition sources were used during the execution of these tests, resistance heat and electrical arc.

2.4.1 Resistance.

A 115 Vac was applied to a 7 foot length of nichrome wire to ignite the cardboard box in bulk-load, containerized, and aerosol can explosion fire tests. The wire was wrapped around four paper towels folded in half. The resistance of the nichrome igniter coil was approximately 7 ohms. The igniter was placed in the center of the ignited box.

2.4.2 Arc.

A set of direct current (dc) arc igniters were used to ignite the fuel in the surface burning tests and the propellant/base product mixture in the aerosol tests. The igniters were connected to a transformer capable of providing 10,000 volts and 23 mA output. The interchangeable ignition transformer was manufactured by Franceformer™, model number 37.9 (LAHV). The igniters were placed 36 inches from the point of discharge for the aerosol can simulator test. The igniters were placed about 0.25 inch above the surface of the fuel for the surface-burning scenario. The gap in between the two electrodes was 0.25 inch.

2.5 EXTINGUISHING SYSTEM.

The fire-extinguishing system tested was a hybrid water mist/nitrogen system. A water hand line and fixed carbon dioxide was available for backup.

The WMS was composed of a 120-gallon water tank, an Environmental Engineering Concepts (EEC) (MicroCool® pump Enviromist® Fog Systems nozzles, and the water mist solenoid controller as described in section 2.2.6. The EEC system was a balanced high-pressure, Class I system. The high-pressure pump, MicroCool®, operated at a maximum pressure of 1150 psi with the number of zones and nozzles installed onboard the aircraft. The Enviromist® Fog Systems' single-fluid nozzles produced a water droplet size between 70 and 100 microns. Additional relays were added to the system to open and close the water lines (zones). The WMS had four zones (atomizing lines) and each zone had eight nozzles. The atomizing lines were 3/8" stainless steel tubing. The horizontal distance between zones was 30" and between nozzles was 16". The nozzles were pointed vertically downward, 1-inch below the ceiling (see figure 6).

A nitrogen bank was also installed in the cargo compartment to roughly simulate the output of an OBIGGS producing nitrogen enriched air. Although the bank cylinders were filled with 99.98% nitrogen, it was understood that the desired oxygen concentration (10%) in the cargo compartment was reached sooner, due to the higher concentration of nitrogen in the cylinders. However, the test indicated the potential benefits of having a system like the OBIGGS onboard an aircraft. It was used in combination with the WMS described above during the second test series. The bank was composed of 16 size T regulated cylinders, a plumbing network, and a pneumatic actuator connected to a switch that was manually operated to maintain the compartment oxygen concentration at 10%. The output pressure of the cylinders was regulated to 500 psig to attain an initial flow rate of 89.3 CFM. The plumbing lines varied in size because of the different parts connected to them; for example, the cylinders regulators required a 1/2-inch-diameter line, the main manifold was 1.5 inches, and the nozzle diameters were 5/8 inch.

A carbon dioxide system was available in case the tested agent was ineffective. There were two nozzles installed on the sidewalls of the compartment protecting the area.

A 1.5-inch hand line (fire fighter hose), connected to the house water supply, was also available as an additional backup. It was mainly used at the end of each test to completely extinguish any smoldering combustibles and clean the area.

3. TEST PROCEDURES.

3.1 BULK-LOAD FIRE SUPPRESSION TESTS.

This test scenario consisted of 178 cardboard boxes in the cargo compartment as specified in section 2.3.1 (see figure 2). The boxes occupied 30% of the cargo compartment. The data acquisition, video recorders, WMS control system, and the aircraft ventilation system were activated prior to ignition, as was the case in each test scenario. The suppression system was activated 1 minute after any of the ceiling or sidewall thermocouples reached 200°F. This test scenario was replicated five times for each system and had a test duration of 30 minutes.

3.2 CONTAINERIZED FIRE SUPPRESSION TESTS.

This fire scenario consisted of three LD-3 containers required in the cargo compartment as described in section 2.3.2 (see figure 3). Thirty-three cardboard boxes were loaded inside the ignited container. An igniter placed in one of the boxes in the lower row provided the ignition source.

The nichrome wire igniter started the fire; 1 minute after the cargo compartment temperature reached 200°F the suppression system was activated. This test scenario was replicated five times for each system and each test had a duration time of 30 minutes after the initial discharge of water and nitrogen (when used).

3.3 SURFACE-BURNING FIRE SUPPRESSION TESTS.

A 4-ft^2 pan, containing 1/2 gallon of Jet A Fuel, was placed inside the cargo compartment as described in section 2.3.3 (see figure 4). As in the other test scenarios, the system was discharged 1 minute after any of the ceiling or sidewall thermocouples reached 200°F. After discharge of the agent the test was run for 5 minutes and repeated five times for each system.

3.4 AEROSOL CANS EXPLOSION TESTS.

These tests were conducted in the DC-10 cargo compartment after taking some precautions. The aircraft was protected against explosion damage by using the loading door as a "blowout panel." In the case of the WMS, the door was left opened, but a plastic sheet covered the entrance to maintain the enclosure and contain the water spray. When nitrogen was used, the doors were closed, but instead of latching the doors, safety wire was used to secure the door in place. The cargo compartment was filled with 58 boxes as described in section 2.3.4, and the aerosol can simulator was placed in front of the boxes (see figure 5). The simulator discharge port and the spark igniter were mounted 2 feet above the cargo compartment floor. The spark igniter was 36 inches away from the discharge port. Before the test, the pressure vessel was heated to raise the pressure of the contents to 210 psig (sometimes the pressure would go higher due to the heat of the burning boxes). After initiating the cargo compartment leakage ventilation, video recorders, WMS control system, and the data acquisition system, the fire was initiated in one of the boxes, as indicated in section 2.3.4. The suppression system was activated 1 minute after any of the ceiling or sidewall thermocouples reached 200°F. The aerosol can simulator was then activated, to release its flammable/explosive mixture, 2.5 minutes after any of the thermocouples attached to the pipes inside the boxes reached 400°F or 29 minutes after discharging the agent (if the pipe temperature did not reach 400°F). The simulator activation time, 2.5 minutes, and aerosol can temperature, 400°F was based on prior testing. Generally, it was found that the aerosol cans would fail in 2-3 minutes when exposed to temperatures ranging from 400° to 1200°F. The average of the exploding times (2.5 minutes) and a conservative temperature (400°) were selected for this test procedure. High-speed data collection, at a rate of 10,000 samples per second, was started just before releasing the explosive mixture. This test scenario was replicated five times for each system and had a test duration time of 30 minutes.

4. RESULTS.

The MPS test results for the WMS with and without nitrogen are described in the next subsections. Tables 2 and 3 summarize the test results in terms of peak temperature and temperature-time area, criteria established for halon replacement agents in cargo compartment [2]. Time boundaries were established for the determination of the peak temperatures and the calculation of the area under the temperature-time curve in order to provide the necessary time for the agent to react and combat the fire. The time boundary for the recorded maximum temperature was 1 minute 30 seconds after a cargo compartment thermocouple reached 200°F and ended 29 minutes 30 seconds later. The time boundary for the area under the temperature-time curve was 1 minute after a cargo compartment thermocouple reached 200°F and ended 30 minutes later. The maximum values are tabulated in tables 2 and 3. Also, sensors that experience significant activity were plotted as well. The plots were organized first by system and second by test scenario; for example, figures 8 through 12 show temperature and gas data that was collected when the plain water mist system was evaluated during the bulk-load tests.

4.1 PLAIN WATER MIST SYSTEM.

4.1.1 Bulk-Load Fire Tests.

Results from bulk-load fire tests 1 through 5 are shown in table 2 and the temperature-time/volumetric concentration plots are shown in figures 8 through 12. The cargo compartment temperatures were found to be much cooler than when Halon 1301 was used. This is attributed to the heat extraction capacity of the water, oxygen displacement, and the attenuation of radiant heat. The average peak temperature for these tests was 535°F, which met the MPS acceptance criteria of 582°F. The large standard deviation, 185°F, shows the need for replicate tests. The plots show that the open flames were quickly extinguished, but the boxes continued to smolder throughout the duration of the tests. The water mist system suppressed the smoldering fire by being programmed to inject water mist if the temperature in the compartment exceeded 212°F. The average area under the temperature-time curve was 5900°F-min, with a standard deviation of 350°F-min. The temperature-time area easily met the MPS acceptance criteria of 10,452°F-min. Also, the temperature-time area did not exhibit the extreme variability shown by the peak temperature. Oxygen consumption by the fire and dilution effects by the water mist accounted for the reduction of the oxygen volumetric concentration in the cargo compartment. Concentrations were recorded as low as 12% (tests 1 and 4) but the average hovered around 15%. Oxygen concentrations above 15% support flaming combustion. The average weight of water used to control these bulk-load fires was 148 pounds (18 gallons of water). Figure 13 shows the water consumption during these tests. When compared with the amount of Halon 1301 required to suppress the same fire, this particular system requires 1.85 times more agent.

4.1.2 Containerized Fire Tests.

Tests 6 through 10 were containerized fires controlled with water mist. The temperature-time/volumetric concentration charts are presented in figures 14 through 20. It was difficult for the water mist to reach and attack the fire located inside the container. As expected, the mist did not extinguish but effectively suppressed these deep-seated fires. During the initial discharge of the WMS, two zones (near the fire) continuously discharged for 5 minutes, which created a misty blanket around the container that dissipated the convective and conductive heat. After the initial 5 minutes, the system injected water, as needed, to maintain the cargo compartment below 212°F. Table 2 shows that the average peak temperature for this fire scenario was 487°F, which is below the MPS 612°F. Even though the average peak temperature was lower than for the bulk-load tests, the overall cargo environment was hotter, as shown by the temperature-time areas. The calculated area was 9106°F-min, 1.54 times the bulk-load value, and met the required MPS criteria, (14102°F-min). The oxygen levels inside the container dropped significantly, as low as 1% (test 8), due to the fire growth in the small container volume; although the fire consumed significant oxygen, it continued to smolder throughout the test. The oxygen concentration increased as the flames were knock down and fresh air flowed through the vent holes. The oxygen concentrations outside the container were higher, comparable to the bulk-load values. On average these tests consumed 273 pounds of water, the most water of any fire scenario, because of the inaccessibility of the fire (see figure 21). This quantity of water was 3.4 times the amount of Halon 1301 (80 pounds) that would be used to suppress the fire.

During tests 11 and 12, a single additional water mist nozzle was placed at the ceiling of the LD-3 container to determine its effectiveness and resource conservation characteristics when used in conjunction with the original WMS. Results showed that the average ceiling temperature was 453°F and the average area under the temperature-time curve was 7016°F-minute. These numbers were better than with the WMS alone. Moreover, the significant benefit was in the reduction of water used to achieve these results. The amount of water used was reduced from 273 pounds (32.9 gallons) to 140 pounds (17 gallons), or a 49% reduction, but was still heavier than the needed amount of Halon 1301.

4.1.3 Surface Burn Test.

The WMS extinguishing performance against a Jet A fuel pan fire, simulating a burning surface, was evaluated during tests 13 through 17. The plots shown in figures 22 through 26 show that the fires were completely extinguished, and all within 1 minute. The average peak temperature was 742°F, which is much cooler than the MPS criteria (<1125°F). The average area was 1307°F-minute, also significantly less than the MPS value (<2964°F-minute). It was noted, that the flames flared up for several seconds during the initial discharge of water mist; after that, the fire was extinguished. Since the oxygen level only dropped a few percentage points below its original concentration (21%) a test was conducted to examine if the extinguishing agent was not effective (test 15). During test 15 the water was turned off before the flames were extinguished and, therefore, the fire was reignited. During test 15, 67 pounds of water was used, less than the 74 pound average measured during tests 13-17. Figure 27 shows the water consumption history during these surface burning tests. By comparison, only 38.6 pounds of Halon 1301 was required to extinguish the Jet A fuel pan fire.

4.1.4 Aerosol Can Simulator Explosion Test.

Tests 18 through 22 were conducted with the new test protocol but with a shorter test duration. During these tests, the protocol was still under review. The tests were terminated after the activation of the simulator. The purpose of the test was to determine the inerting capabilities of the WMS, via oxygen dilution, under the described test conditions. However, the WMS was ineffective since the hydrocarbon mixture of the simulator exploded when exposed to the electric arc. Because of the pressure relief caused by the large blowout panel used, the pressure pulse of the explosion recorded on the transducer was not significant; but visual evidence (video recorder) showed that the explosion occurred because of the separation of the plastic cover on the door and deflagration. As seen in table 2, three out of the five tests showed evidence of explosion. Moreover, the calculated average peak temperature in the cargo compartment was 976°F, which exceeded the MPS acceptance criteria value (<582°F). A possible reason for this higher temperature could be that the bottom of the blowout panel (plastic sheet) was not attached to the aircraft due to its complex shape, which may have allowed fresh air into the fire. In some instances, as in tests 18 through 20, the fire reignited after the two zones that were activated continuously for 5 minutes were turned off to initiate the cycling process (refer to figures 28 through 32). The average maximum temperature-time area was not calculated because these tests were not conducted for 30 minutes. The oxygen level dropped to about 16% on all the tests due to the open flames. The average amount of water used during this scenario was 61 pounds or 7.3 gallons of water which was lower than in the bulk-load case because of the shorter test duration. The water consumption history can be seen in figure 33.

4.2 WATER MIST SYSTEM COMBINED WITH NITROGEN.

4.2.1 Bulk-Load Fire Tests.

The results of bulk-load tests 23 through 27 are presented in table 3 and the temperature-time/volumetric concentration plots are shown in figures 34 through 38. The nitrogen system significantly enhanced the suppression performance of the WMS in this scenario. The cargo compartment temperatures remained below 212°F after the initial knock down of the flames. The average peak temperature for these tests was calculated to be 387°F and the average area under temperature-time curves was calculated to be 4744°F-minute. These values easily met the MPS acceptance criteria. The plots show that the open flames were quickly extinguished and that the ceiling and sidewall temperatures were "flat lined" after that, even though the boxes continued to smolder throughout the duration of the tests. The oxygen consumed by the fire and the dilution effects of the water mist and nitrogen system reduced the oxygen volumetric concentration in the cargo compartment to an average of 10% within about 12.5 minutes. Afterward, the flow of nitrogen was adjusted to maintain the oxygen concentration at 10%. It was noted that the water mist system was off most of the time after the initial 5 minutes discharge due to the introduction of nitrogen. The reduced water discharge resulted in an average water weight of 67.2 pounds (8 gallons). A significant weight savings of 54.6% when compared to the WMS without nitrogen. Figure 39 shows that the water discharge essentially stopped after 5 minutes. Based on agent used, the water and nitrogen system offers fire protection at a competitive weight compared to Halon 1301 (80 pounds). On average a total of 2325 ft^3 (7.7 size T cylinders pressurized at 2500 psig) of nitrogen was used to suppress this fire. The amount of undamaged boxes ranged between 86% and 96%.

4.2.2 Containerized Fire Tests.

The results of containerized fire tests 28 through 33 are presented in table 3 and plotted in figures 40 through 45. Test 28 was a 90-minute test, while the other followed the MPS required 30-minute test duration. Again, as in the case of the bulk-load test, the addition of nitrogen significantly enhanced the fire protection performance of the WMS in terms of cooler cargo compartment temperatures and less resource consumption. During the 90-minute test, the cargo compartment temperatures remained below 200°F after the initial knock down of the flames. A high-peak temperature of 700.4°F was recorded 30 seconds after discharging the system. This high temperature was encountered due to the late activation of the WMS but dropped very quickly once the system was activated. The 30-minute temperature-time area for the 90-minute test was calculated to be 5295°F-minute, well below the acceptance criteria value. The results for tests 29 through 33 show that the temperatures, after initial flames knock down, were maintained below 212°F. The average peak cargo compartment temperature was 313°F (not using the 90-minute test) and the average area was 5518°F-minutes, for the fire tests, once again passing the MPS. Even though the fire was located inside the LD-3 container, the nitrogen penetrated into the LD-3 container and smothered the open flames; this combined with the "mist blanket," effectively suppressed these deep-seated fires. After the 5-minute deluge of mist, the system rarely injected water as needed to maintain the cargo compartment environment below 212°F (see figure 56). The nitrogen system was manually activated to maintain the oxygen concentration at 10%. As in the bulk-load case, the use of nitrogen reduced the WMS activation;

but it was more active than in the bulk-load tests. The average temperature in the cargo compartment was relatively low and similar to the bulk-load test. The oxygen levels inside and outside of the LD-3 container dropped to about 10%. The oxygen depletion in the LD-3 container was not as significant, as the WMS without nitrogen due to the efficient control of the fire. The average amount of nitrogen used to control the fires was 2321 ft^3. These tests consumed 68.2 pounds (8.2 gallons) of water (see figure 46), which is comparable to the amount used during the bulk-load test, but less than halon and significantly less than the WMS without nitrogen. The amount of undamaged boxes ranged between 33% and 70%.

4.2.3 Surface Burn Tests.

Table 3 contains the results of the fire protection performance of the WMS combined with nitrogen during the surface burn tests (tests 34 through 38). Figures 47 through 51 show the peak temperature and oxygen concentration history. This combined system completely extinguished the flammable liquid fires within 1 minute. The average ceiling peak temperature was 438°F, and the average area was 1054°F-minute, easily meeting the MPS values (<1125° and <2964°F-minute). The oxygen level only decreased slightly from its original concentration (21%). On average the fire was extinguished with 22 pounds of water (2.7 gallons) and 111.2 ft^3 of nitrogen (<1 size T cylinder pressurized at 2500 psig). Figure 52 shows the water consumption history of this system during surface burning tests. Once again, the water conservation was better than with Halon 1301 (38.6 pounds) during the extinguishment.

4.2.4 Aerosol Can Simulator Explosion Test.

The new aerosol can explosion test protocol was used for tests 39 through 43 (see data in table 3 and figures 53 to 57). After starting the fire in the cargo compartment, the sufrace temperature of the galvanized steel pipes (simulated aerosol cans) was monitored to determine the simulator activation time. Because the system controlled the fire effectively, in three out of the five tests the pipe temperatures did not reach 400°F thus, in these tests the simulator was activated 29 minutes after the water mist and nitrogen were discharged. (The protocol calls for a simulator activation time at 29 minutes after discharging the WMS, if the galvanized steel pipe's temperature does not reach 400°F.) Actually, the pipe temperature did not exceed 200°F during tests 39, 40, and 43. In tests 41 and 42 the simulator was activated much earlier since the pipes reached 400°F. In all tests, when the simulator was activated, the oxygen volumetric concentration was 10%, which prevented the explosion of the hydrocarbon mixture when exposed to the electric arc. Also, the cargo compartment temperatures were maintained well below 200°F (as shown in figures 53 through 57). The calculated average peak temperature was 533°F, which met the MPS acceptance criteria value (<582). The average maximum temperature-time area was 3810°F-minute, which is almost a third of the MPS value. The average water usage during this scenario was 73 pounds (8.8 gallons). The water consumption history during this test is shown in figure 58. The amount of nitrogen used was 2930 ft^3. Again, less water was used than halon.

5. SUMMARY OF FINDINGS.

The fire suppression performance of a water mist system (WMS) and a water mist system with nitrogen system (simulated OBIGGS) were characterized for four MPS fire scenarios: bulk-load fire (Class A fire), containerized fire (Class A fire), surface burn (Class B fire), and aerosol can explosion. It was determined that:

- Both systems (with and without nitrogen) met the MPS bulk-load fire, containerized fire and surface burn fire test acceptance criteria because they were capable of extinguishing open flames and suppressing deep-seated fires.
- The plain water mist system failed the draft MPS exploding aerosol can fire test acceptance criteria because the hydrocarbon gases exploded and the ceiling temperatures exceeded the specified criteria.
- The oxygen dilution provided by plain water mist system was less than required to prevent the explosion of the hydrocarbon gases.
- The water mist and nitrogen system passed the draft MPS exploding aerosol can fire test acceptance criteria.
- The depletion of oxygen (10%) during the water and nitrogen system tests prevented the explosion of hydrocarbon gases released by the aerosol can simulator.
- The use of nitrogen in the water and nitrogen system reduced the consumption of water by more than 50% compared to the plain water mist system in the majority of the tests.
- The draft test protocol for the aerosol can simulator explosion test was developed to evaluate nongaseous agents/systems.

6. REFERENCES.

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2. Reinhardt, J., D. Blake, and T. Marker, "Development of a Minimum Performance Standard for Aircraft Cargo Compartment Gaseous Fire Suppression Systems," DOT/FAA/AR-00/28, September 2000.
3. Hill, R., T. Marker, and C. Sarkos, "Water Spray Development and Evaluation for Enhanced Postcrash Fire Survivability and In-Flight Protection in Cargo Compartments," AGARD Symposium on Aircraft Fire Safety, 1996.
4. Marker, T., and J. Reinhardt, "Water Spray as a Fire Suppression Agent for Aircraft Cargo Compartment Fires," DOT/FAA/AR-TN01/1, June 2001.
5. Marker, T., "Initial Development of an Exploding Aerosol Can Simulator," DOT/FAA/AR-TN97/103, April 1998.

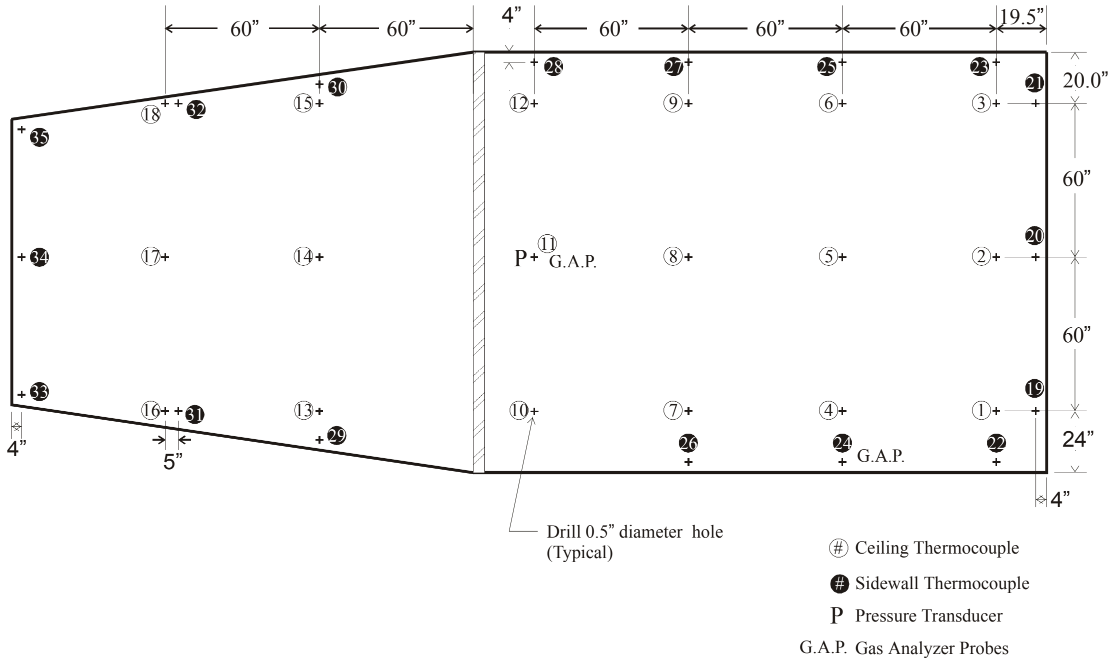

FIGURE 1. CARGO COMPARTMENT INSTRUMENTATION LAYOUT

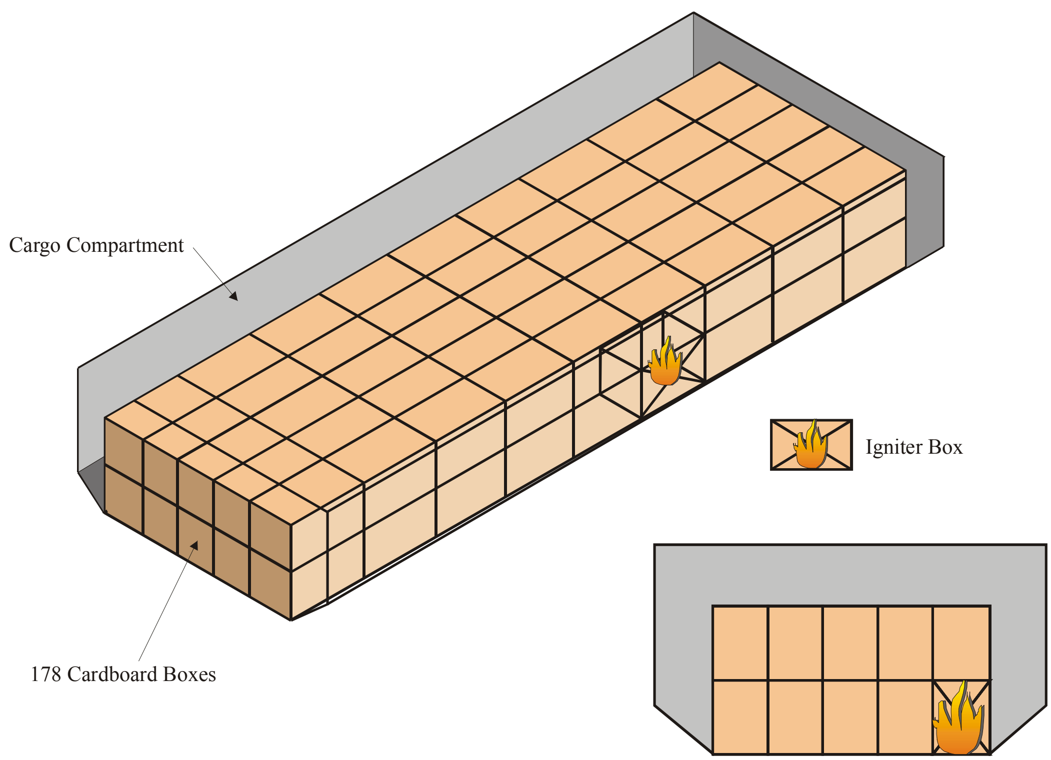

FIGURE 2. MPS BULK-LOAD FIRE TEST SETUP

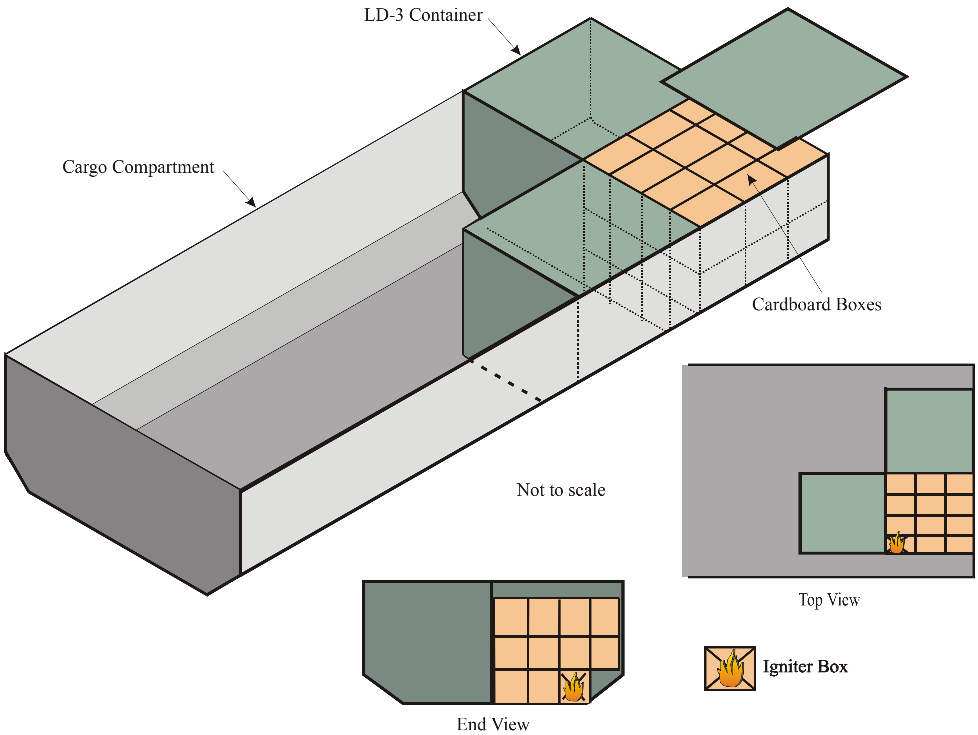

FIGURE 3. MPS CONTAINERIZED FIRE TEST SETUP

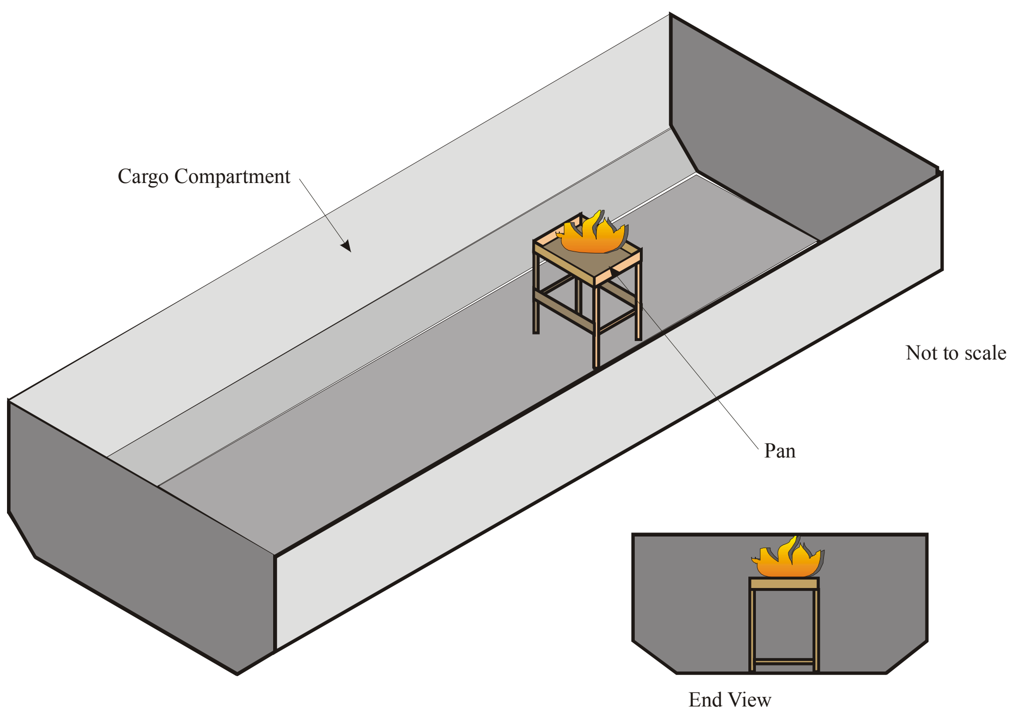

FIGURE 4. MPS SURFACE BURN FIRE TEST SETUP

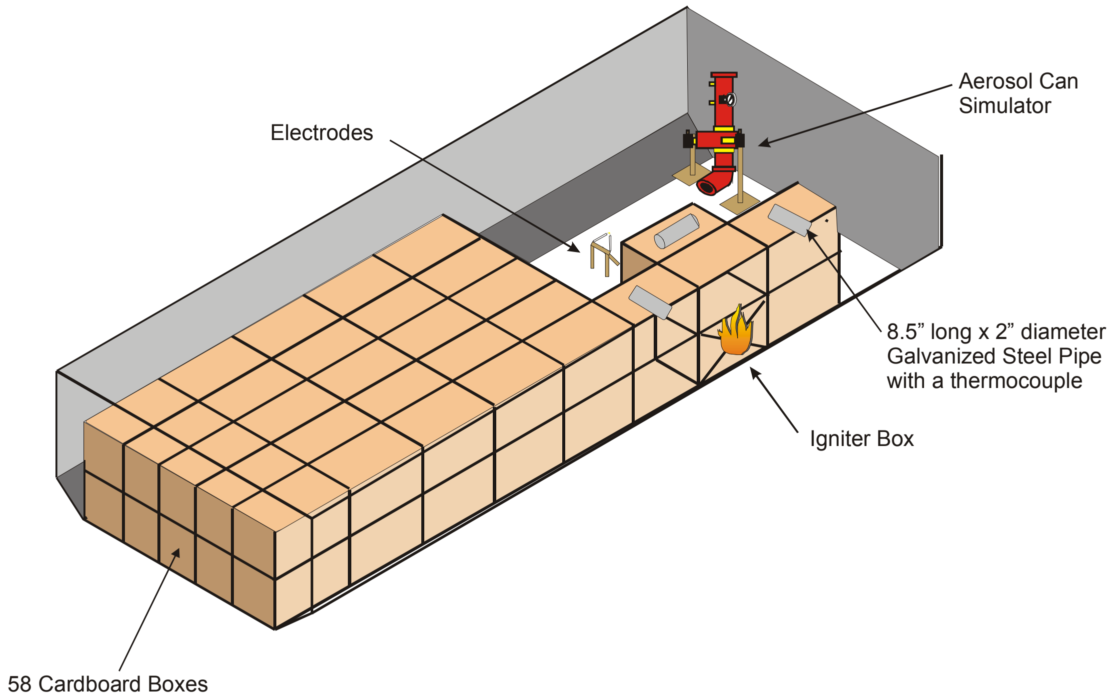

FIGURE 5. AEROSOL CAN SIMULATOR EXPLOSION TEST SETUP

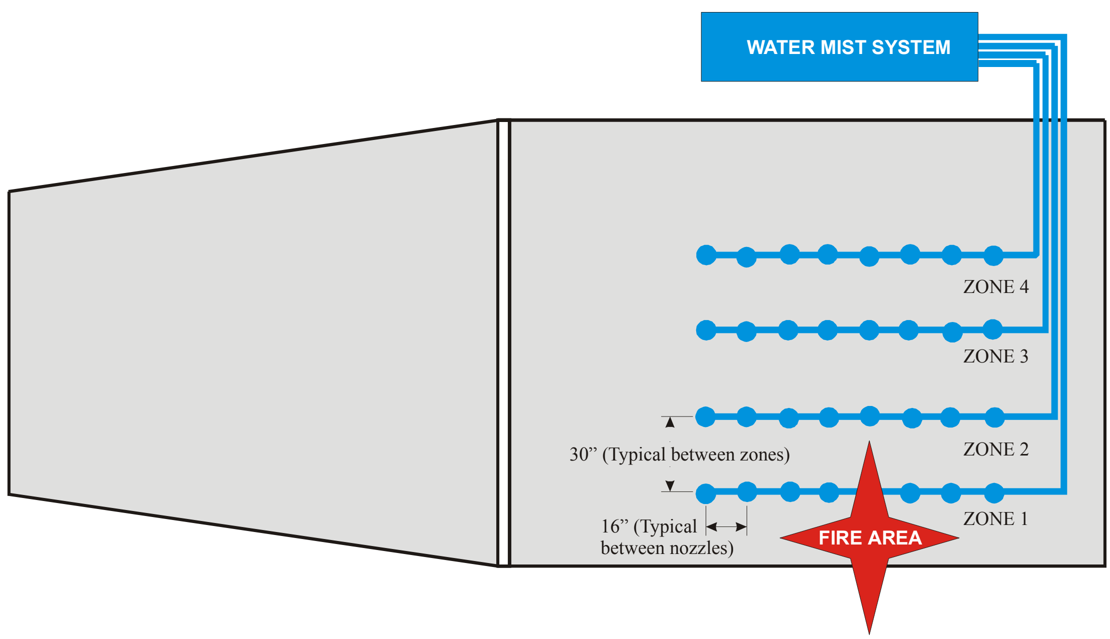

FIGURE 6. WATER MIST SYSTEM ILLUSTRATION

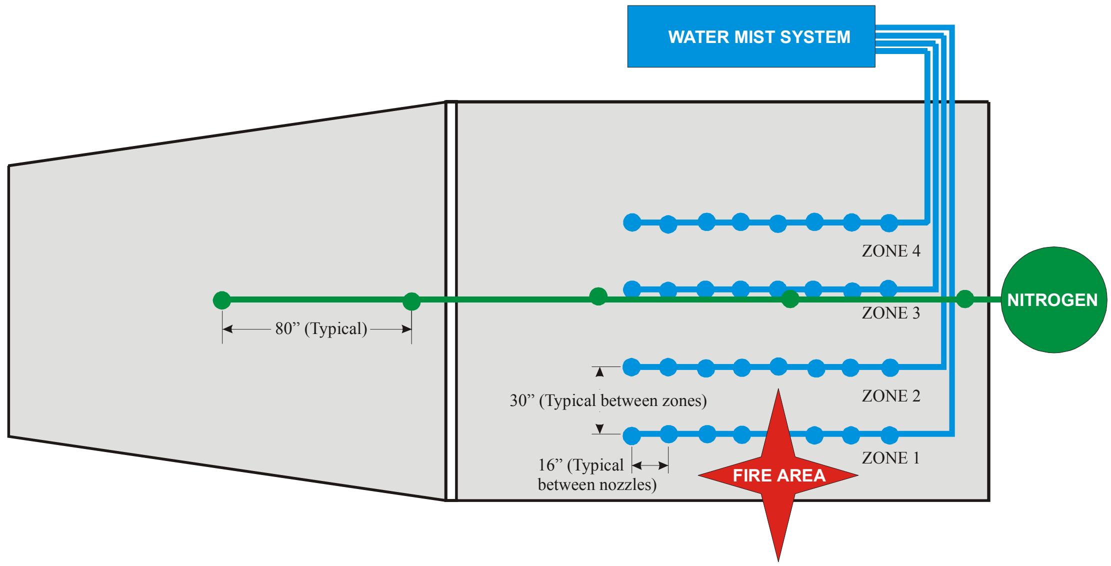

FIGURE 7. WATER MIST AND NITROGEN SYSTEMS ILLUSTRATION

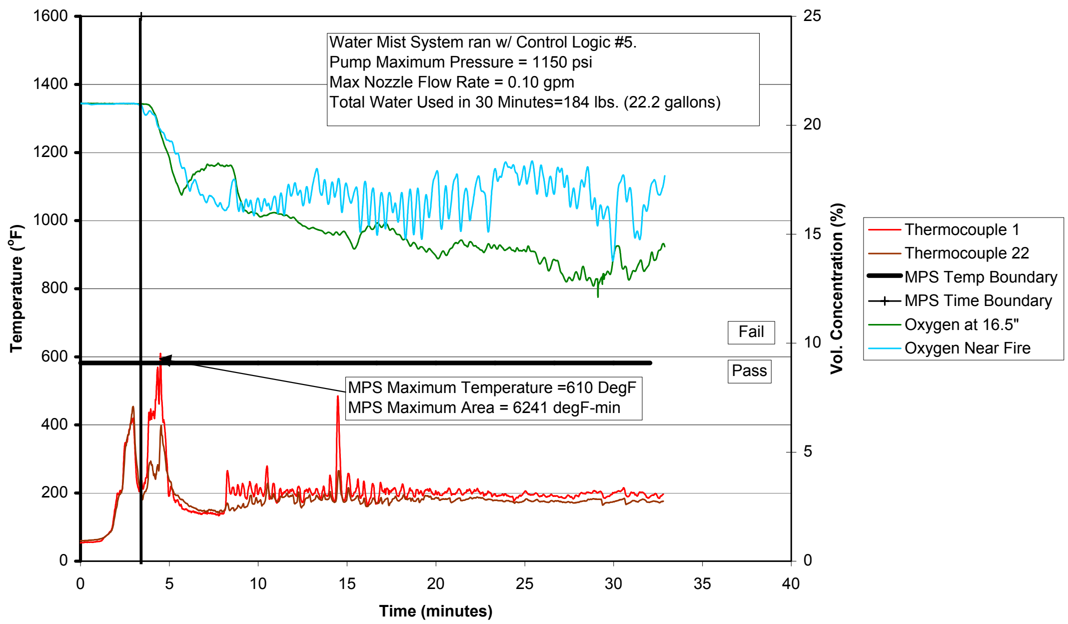

FIGURE 8. BULK-LOAD TEST 1 (030201T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

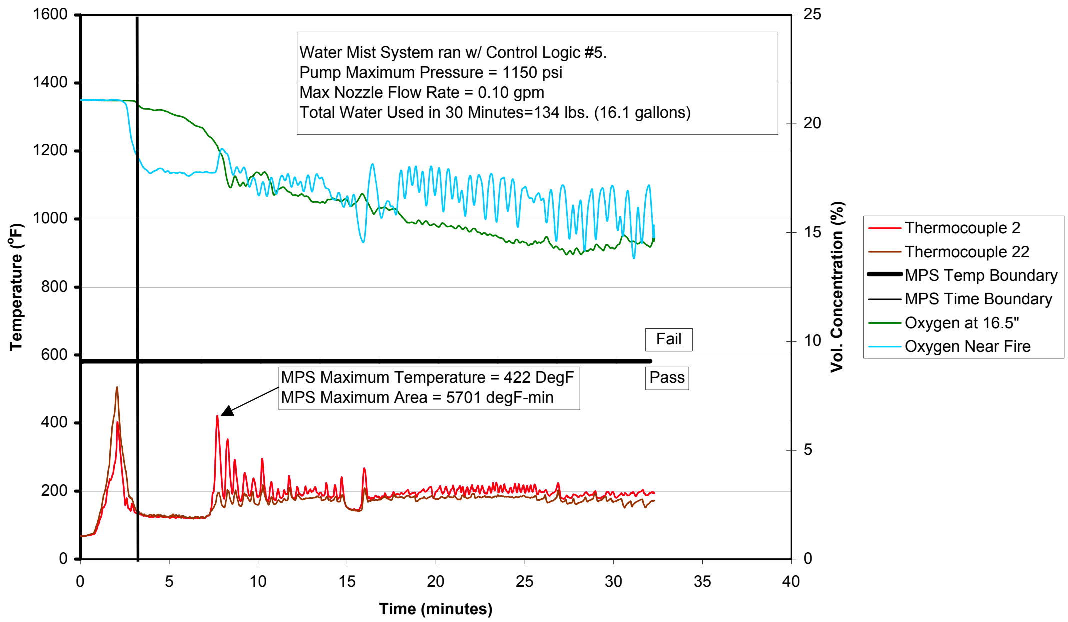

FIGURE 9. BULK-LOAD TEST 2 (030601T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

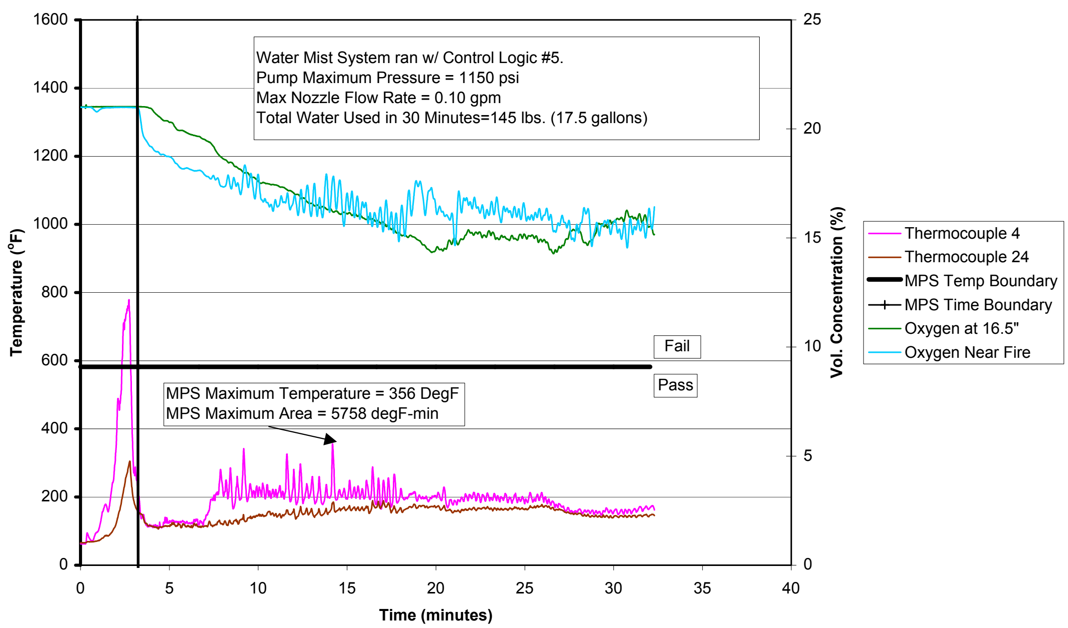

FIGURE 10. BULK-LOAD TEST 3 (030701T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

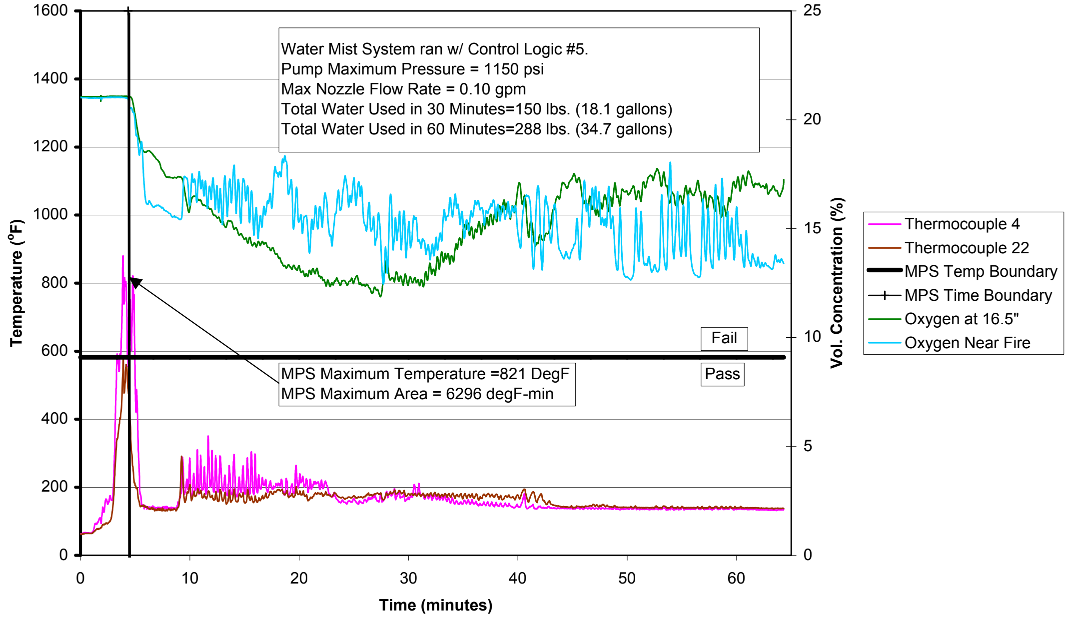

FIGURE 11. BULK-LOAD TEST 4 (030801T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

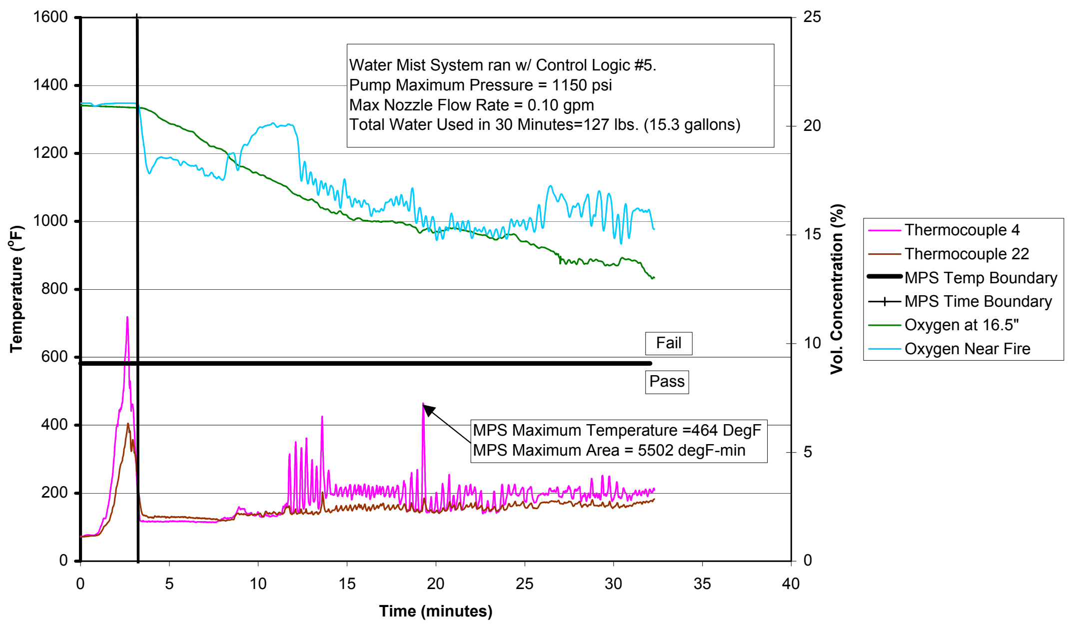

FIGURE 12. BULK-LOAD TEST 5 (031301T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

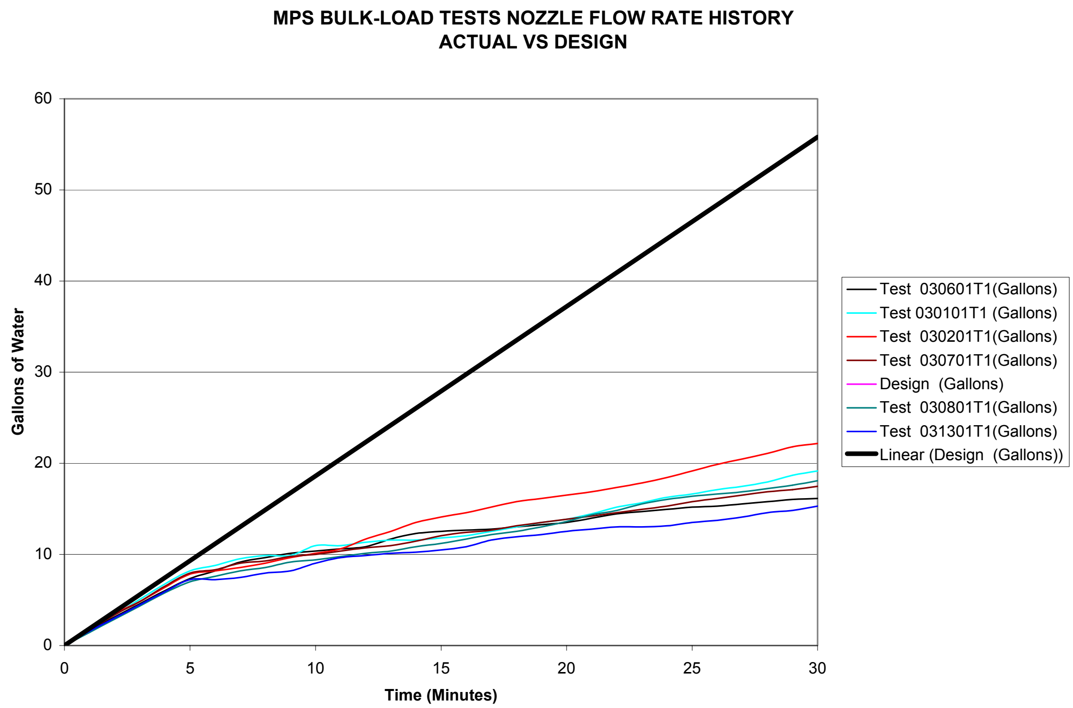

FIGURE 13. WATER MIST SYSTEM WATER FLOW HISTORY DURING THE MPS BULK-LOAD TESTS

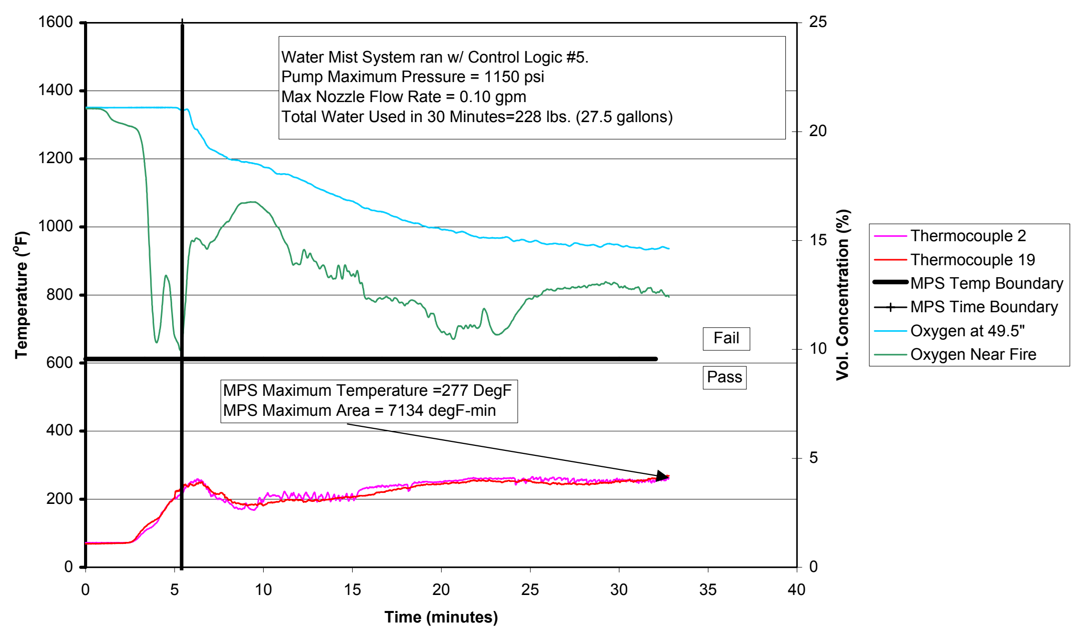

FIGURE 14. CONTAINERIZED TEST 6 (032001T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

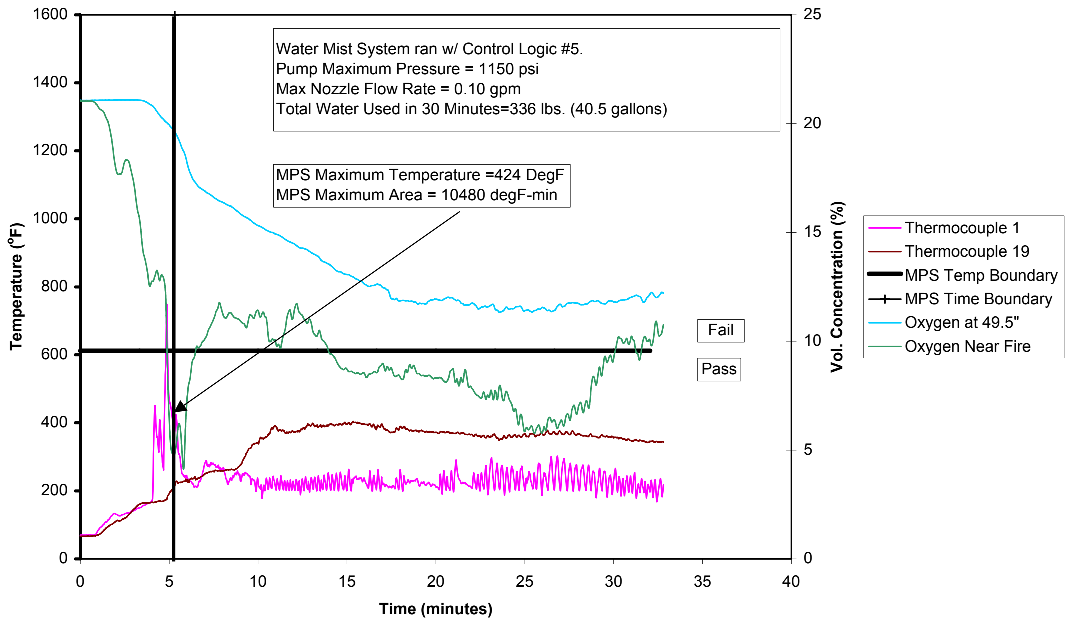

FIGURE 15. CONTAINERIZED TEST 7 (032101T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

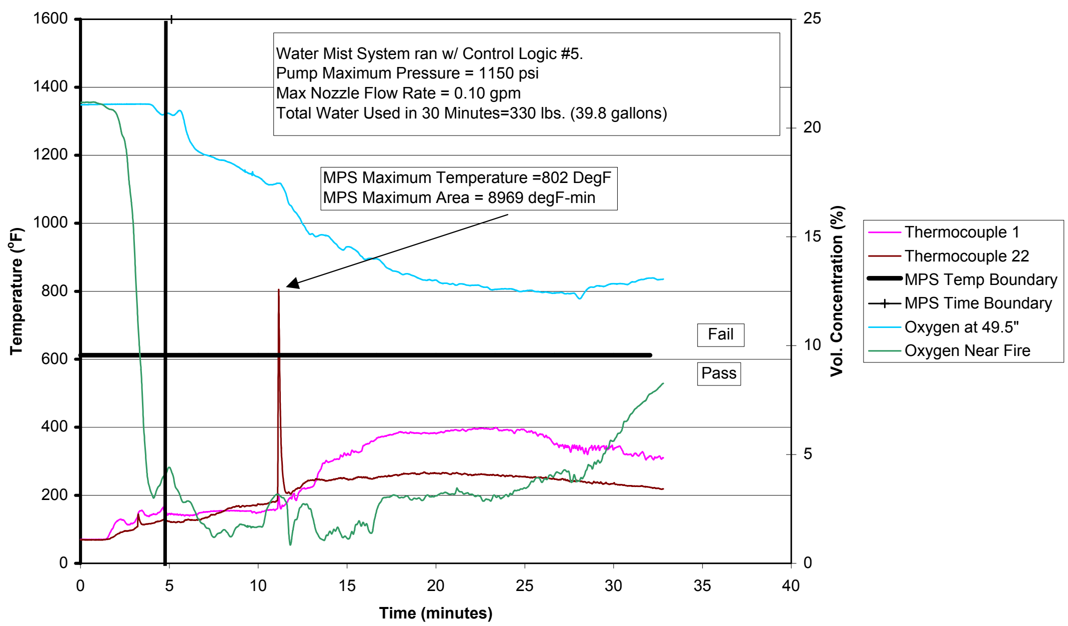

FIGURE 16. CONTAINERIZED TEST 8 (032601T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

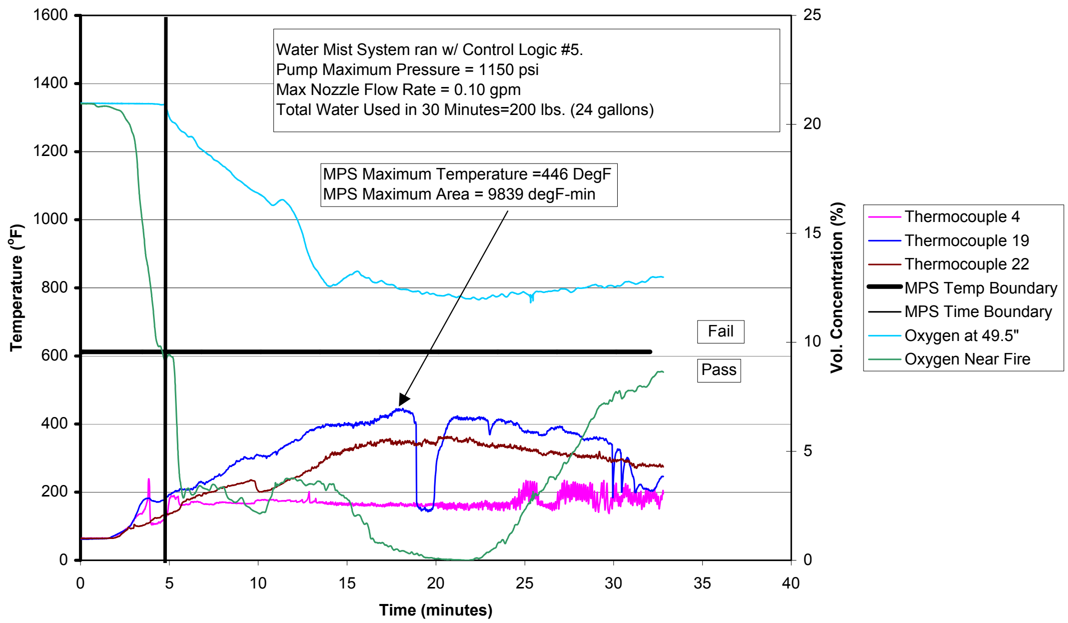

FIGURE 17. CONTAINERIZED TEST 9 (032701T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

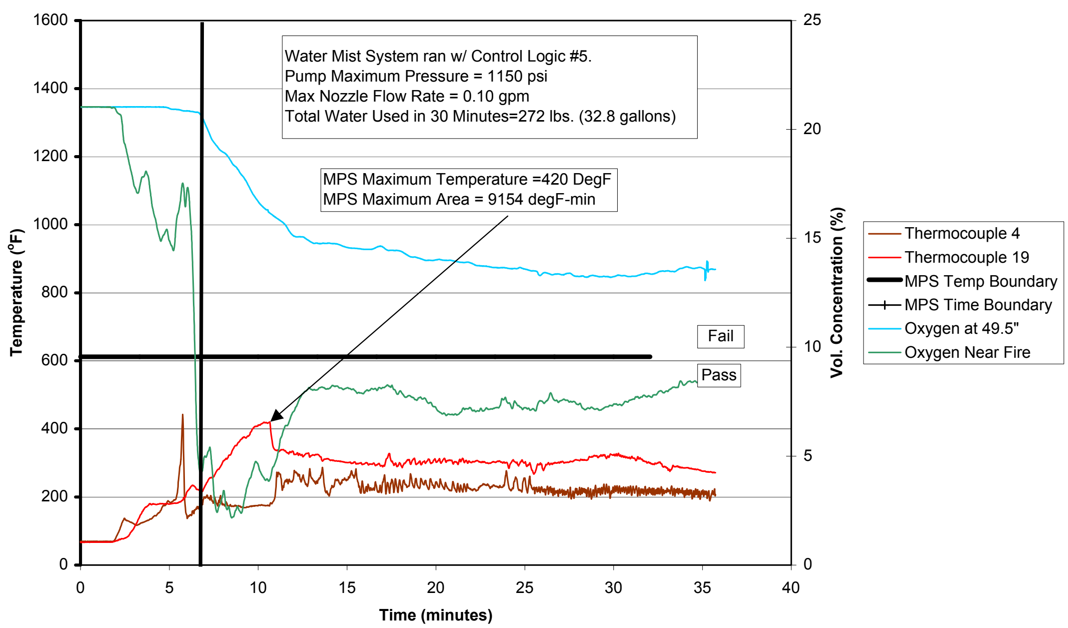

FIGURE 18. CONTAINERIZED TEST 10 (041101T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

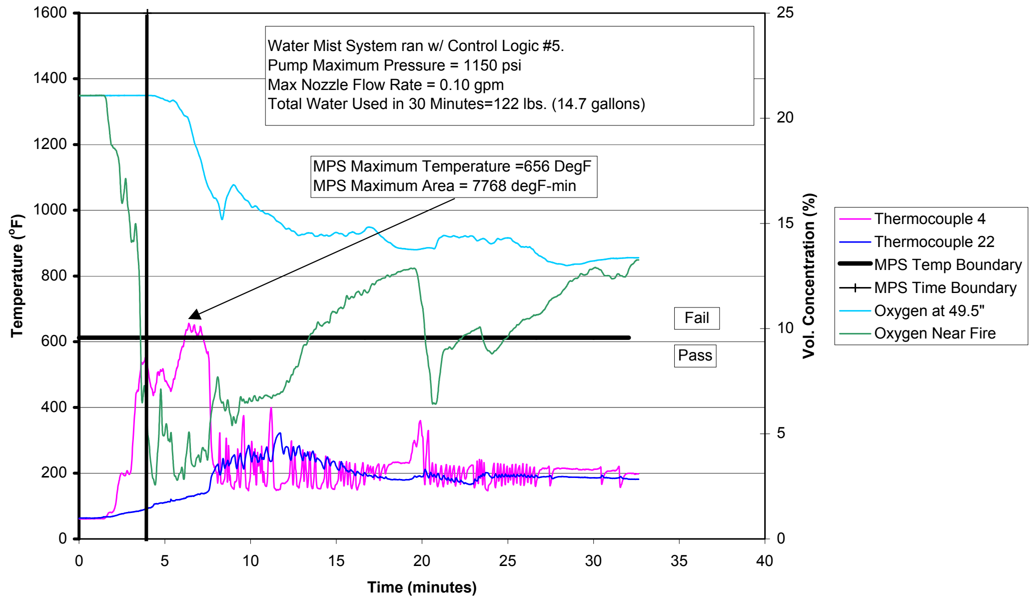

FIGURE 19. CONTAINERIZED TEST 11 (041001T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

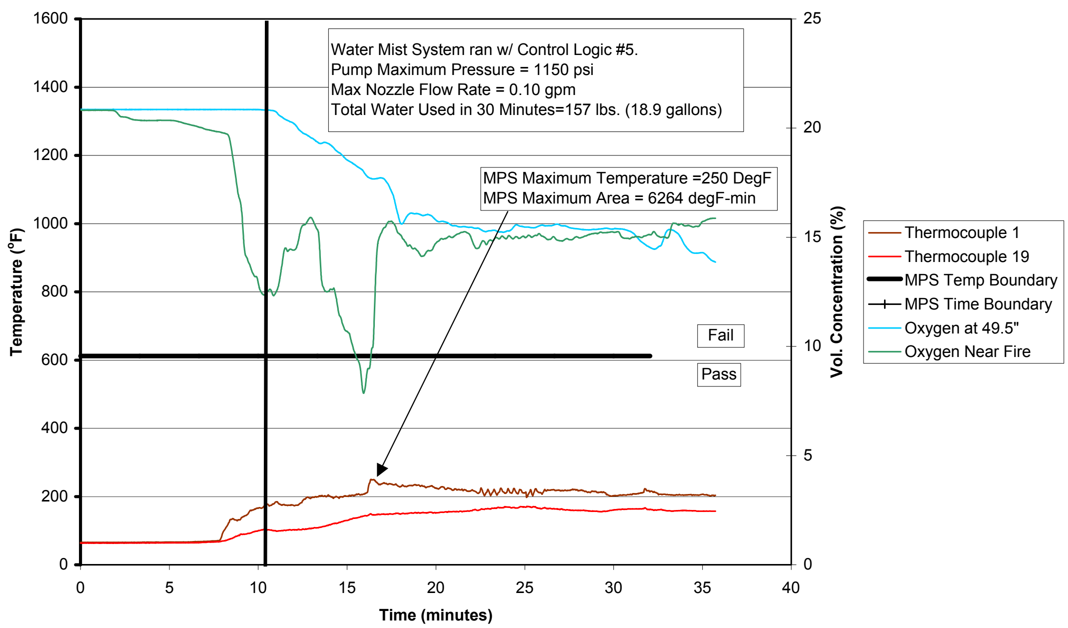

FIGURE 20. CONTAINERIZED TEST 12 (041301T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

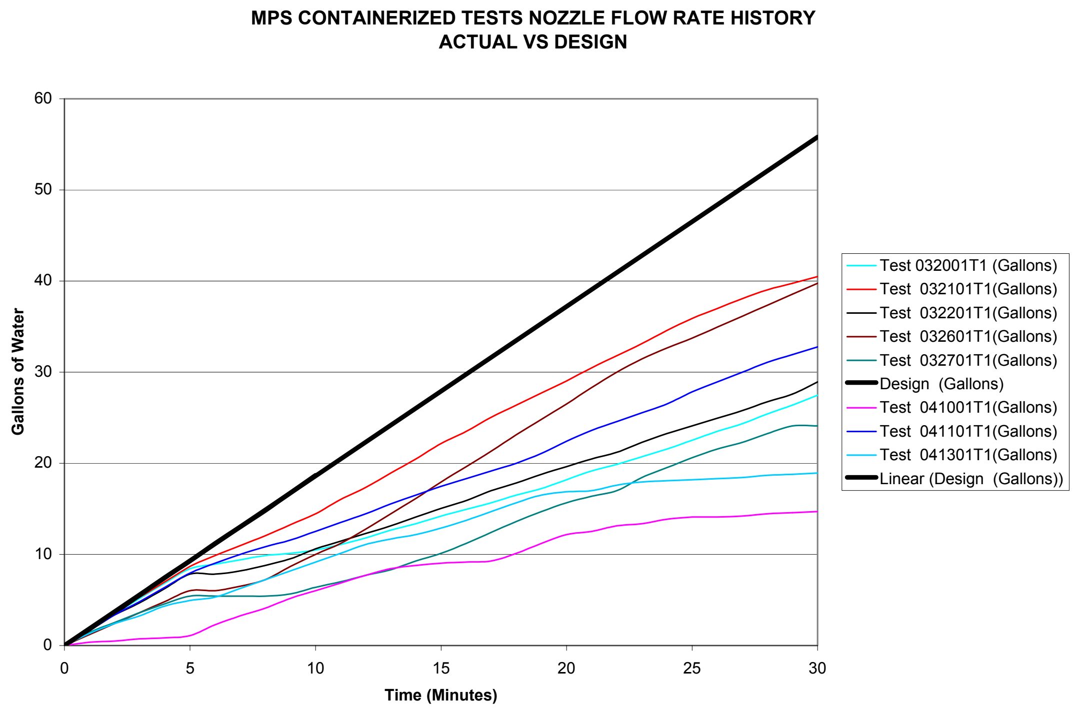

FIGURE 21. WATER MIST SYSTEM WATER FLOW HISTORY DURING THE MPS CONTAINERIZED TESTS

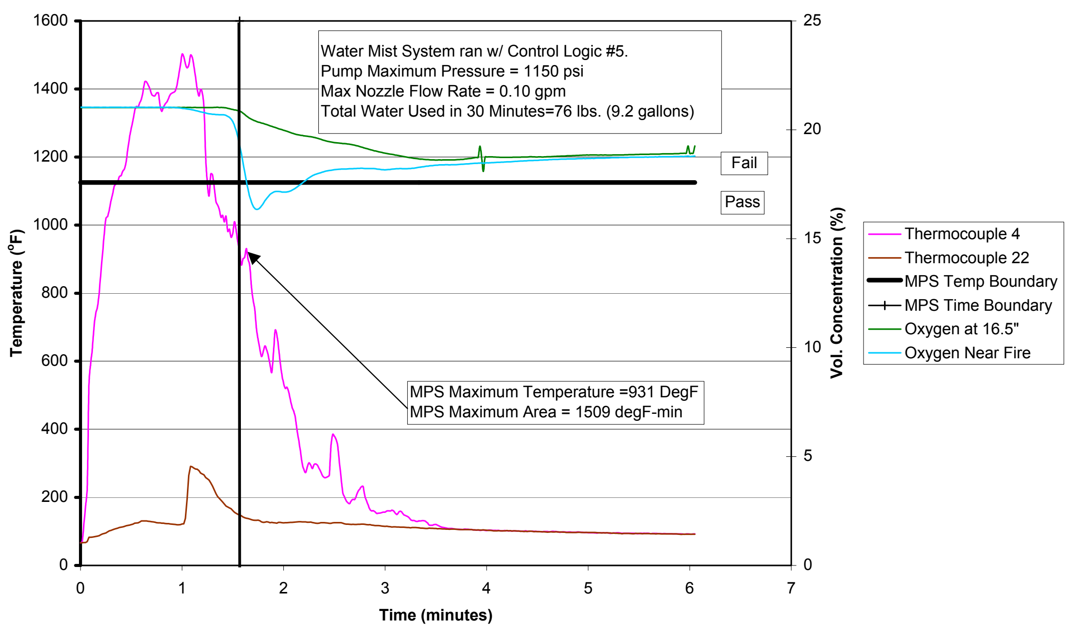

FIGURE 22. SURFACE BURN TEST 13 (031401T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

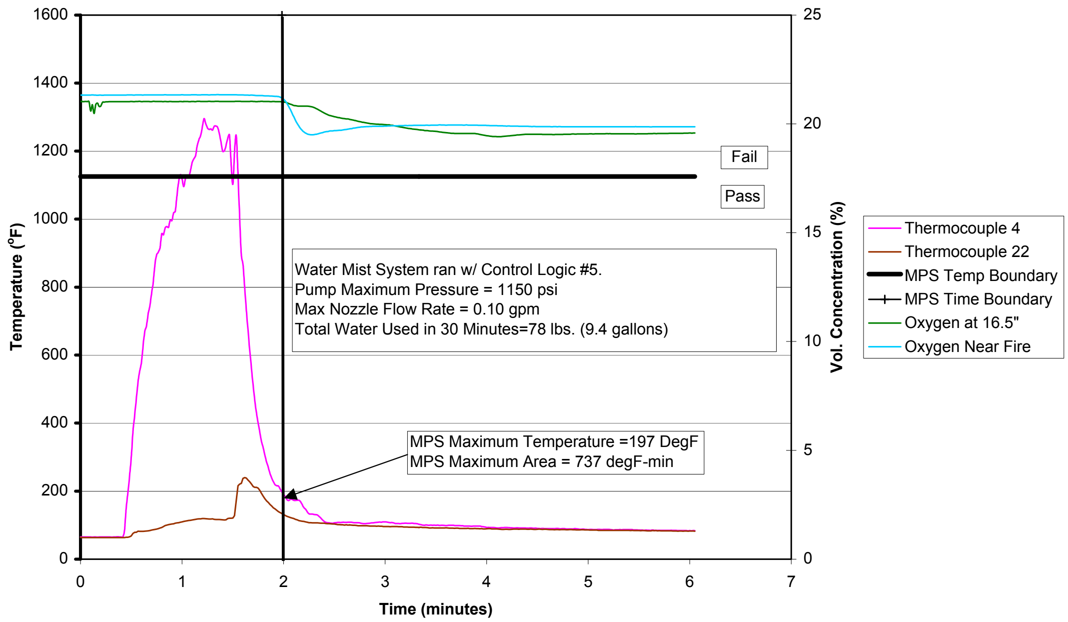

FIGURE 23. SURFACE BURN TEST 14 (031401T2) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

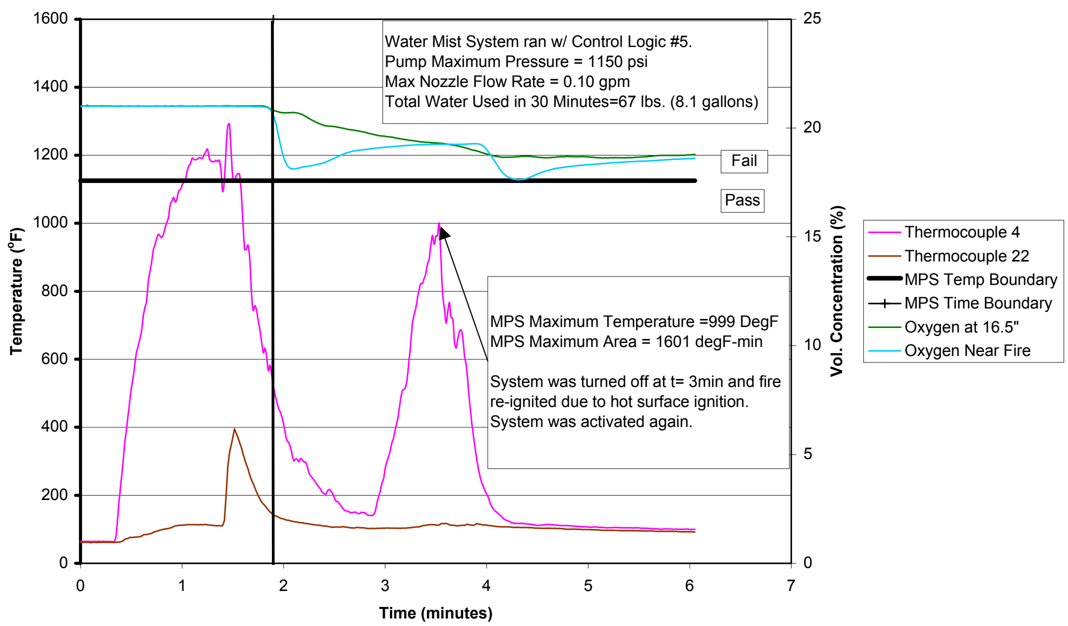

FIGURE 24. SURFACE BURN TEST 15 (031401T3) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

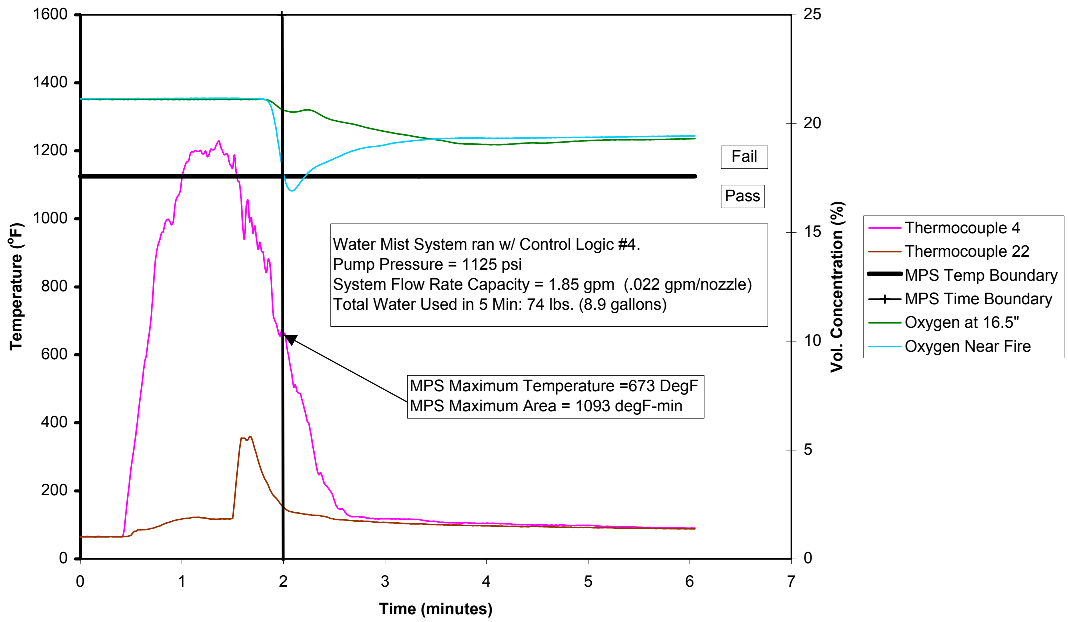

FIGURE 25. SURFACE BURN TEST 16 (031501T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

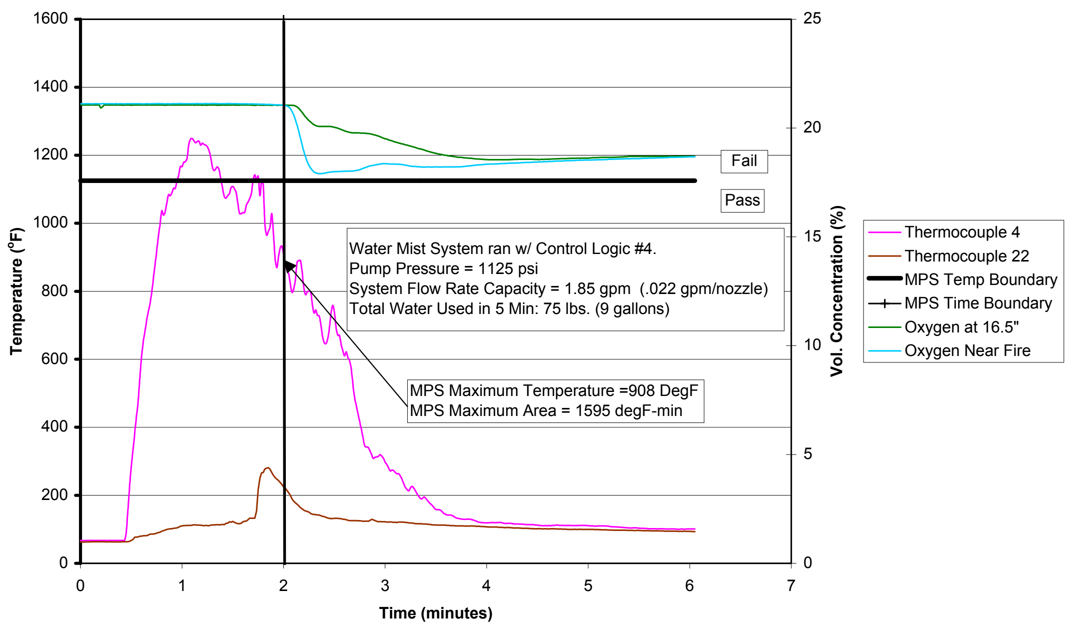

FIGURE 26. SURFACE BURN TEST 17 (031501T2) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

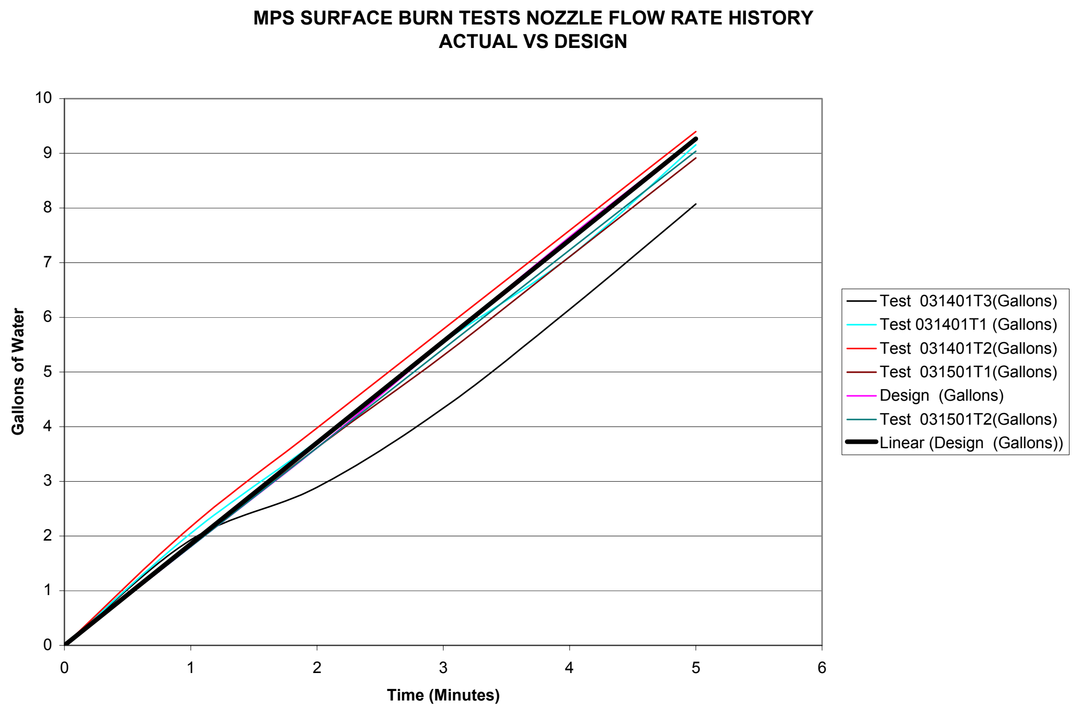

FIGURE 27. WATER MIST SYSTEM WATER FLOW HISTORY DURING THE MPS SURFACE BURN TESTS

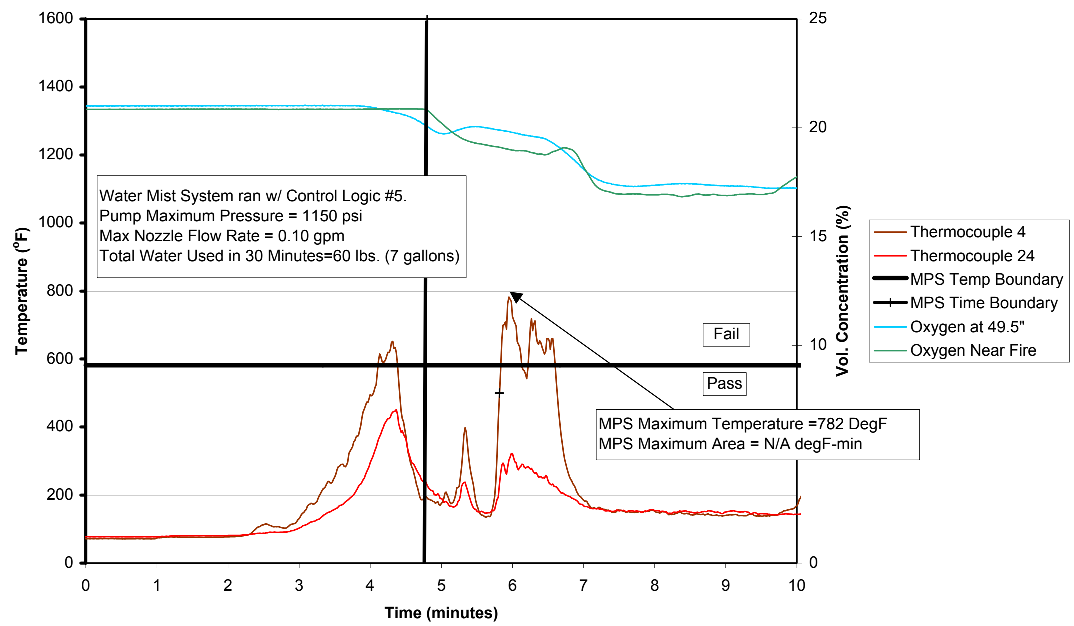

FIGURE 28. AEROSOL CAN EXPLOSION TEST 18 (061501T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

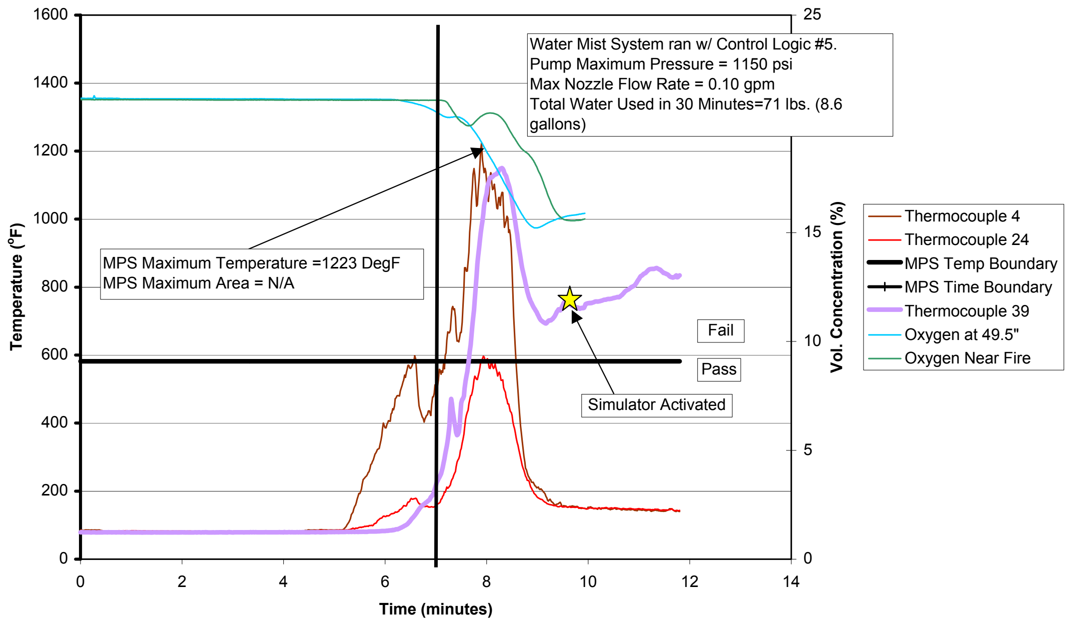

FIGURE 29. AEROSOL CAN EXPLOSION TEST 19 (061801T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

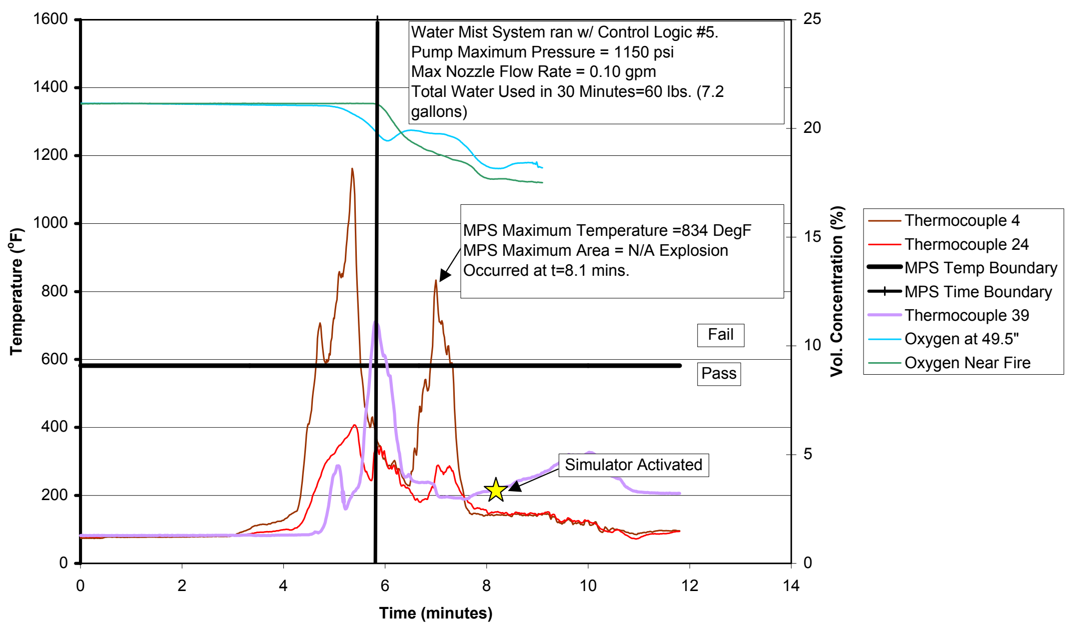

FIGURE 30. AEROSOL CAN EXPLOSION TEST 20 (061901T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

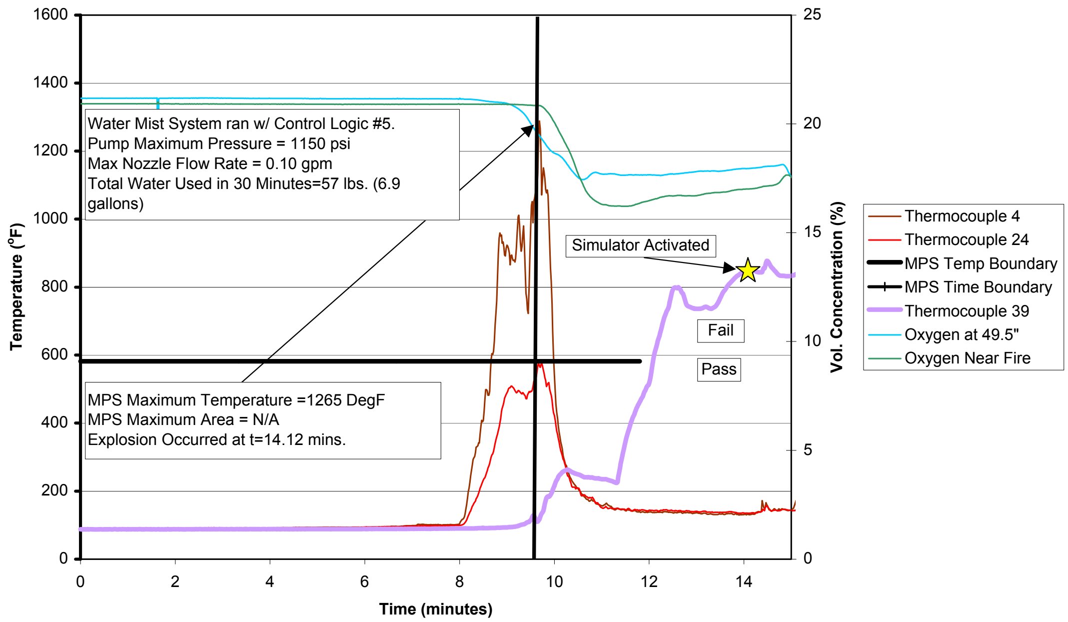

FIGURE 31. AEROSOL CAN EXPLOSION TEST 21 (062101T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

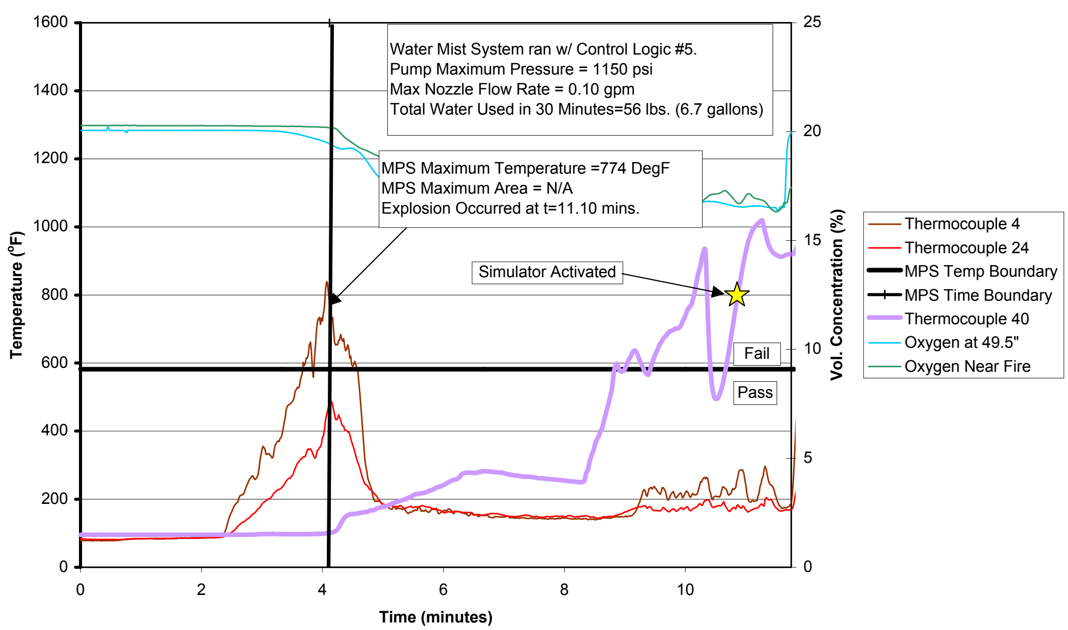

FIGURE 32. AEROSOL CAN EXPLOSION TEST 22 (062201T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

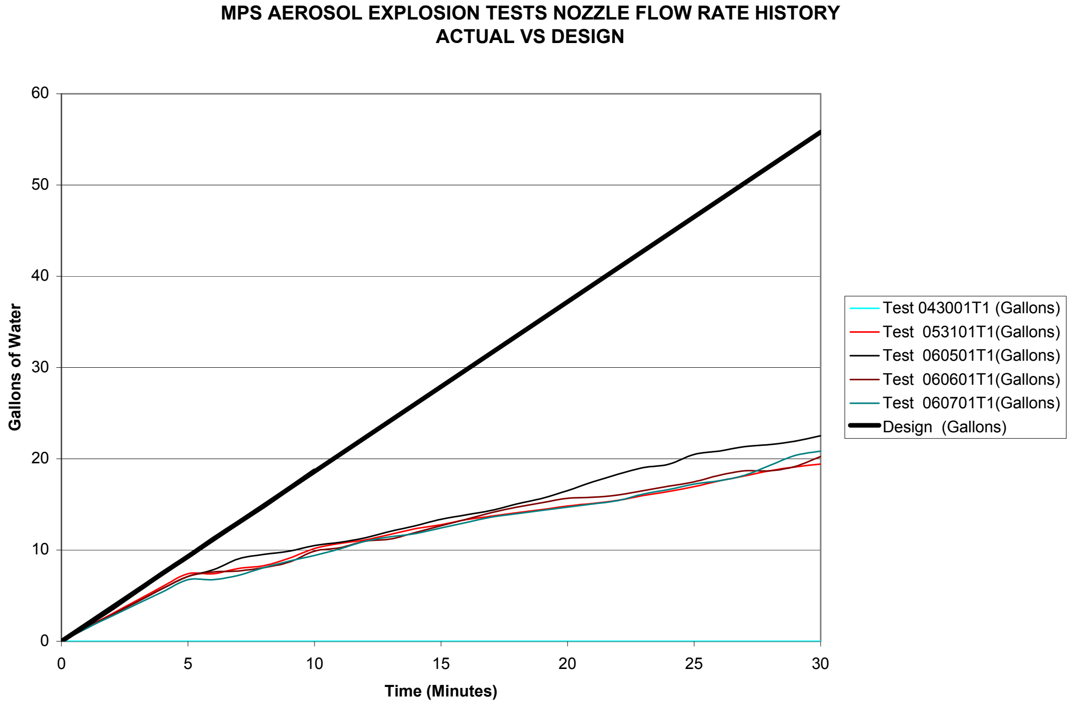

FIGURE 33. WATER MIST SYSTEM WATER FLOW HISTORY DURING THE MPS AEROSOL CAN EXPLOSION TESTS

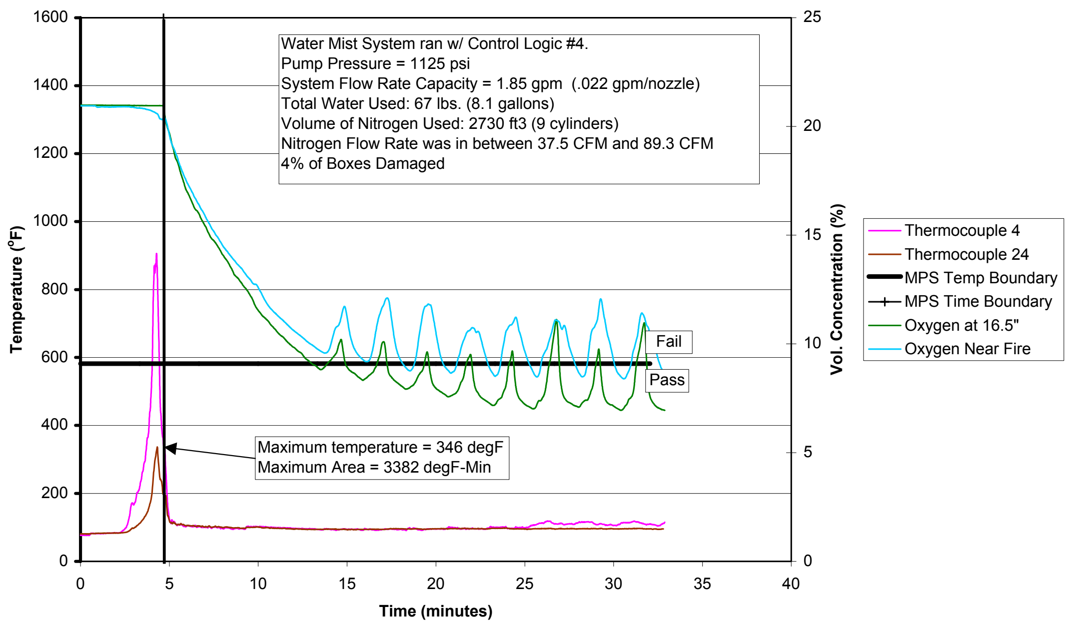

FIGURE 34. BULK-LOAD TEST 23 (070601T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

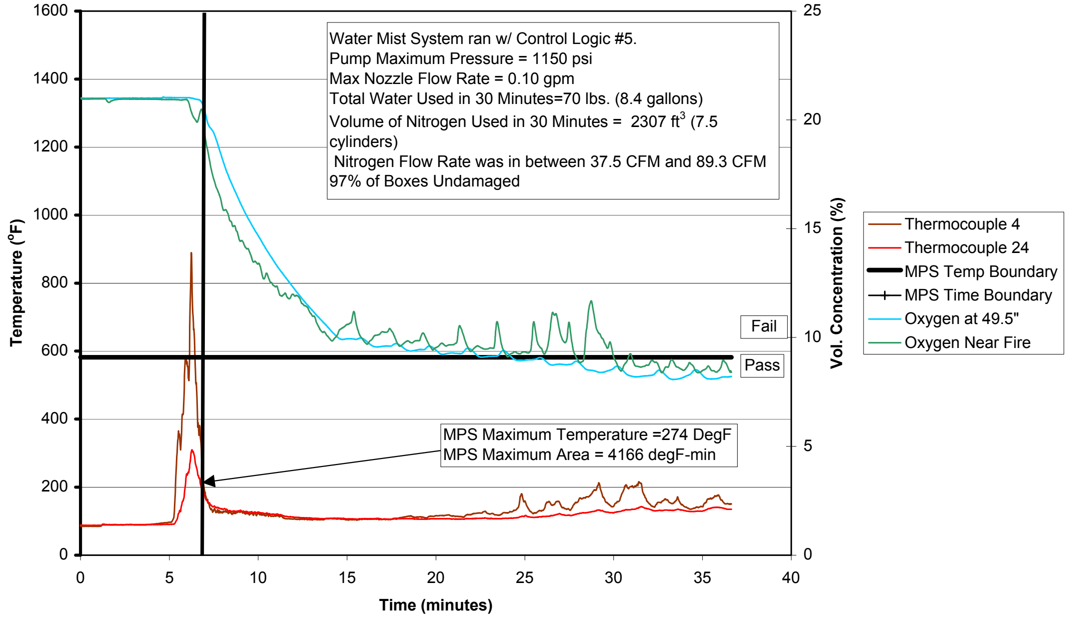

FIGURE 35. BULK-LOAD TEST 24 (072601T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

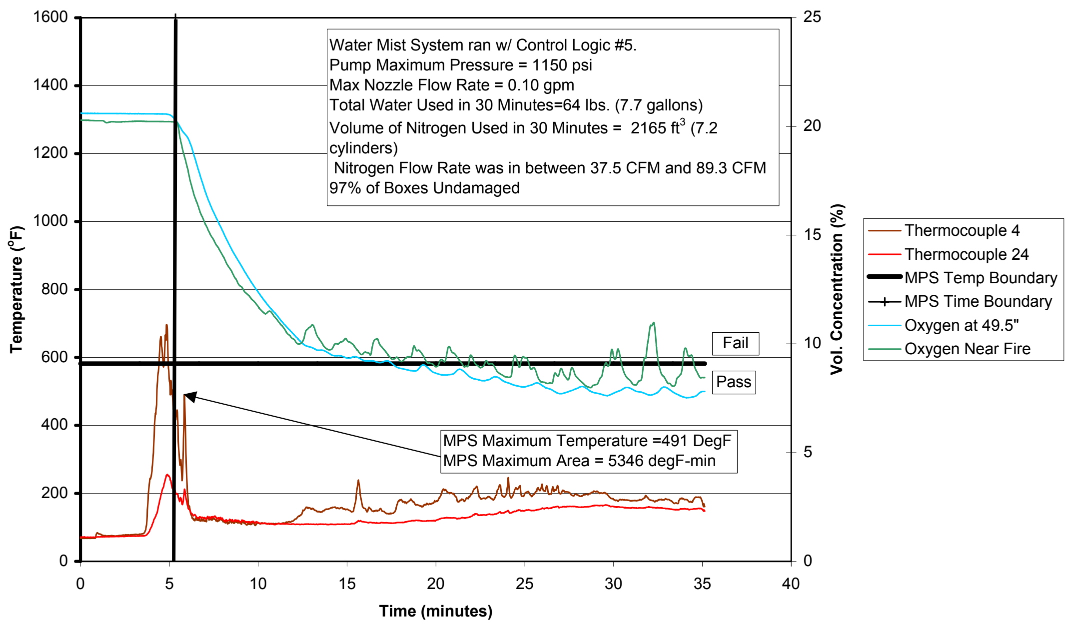

FIGURE 36. BULK-LOAD TEST 25 (072701T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

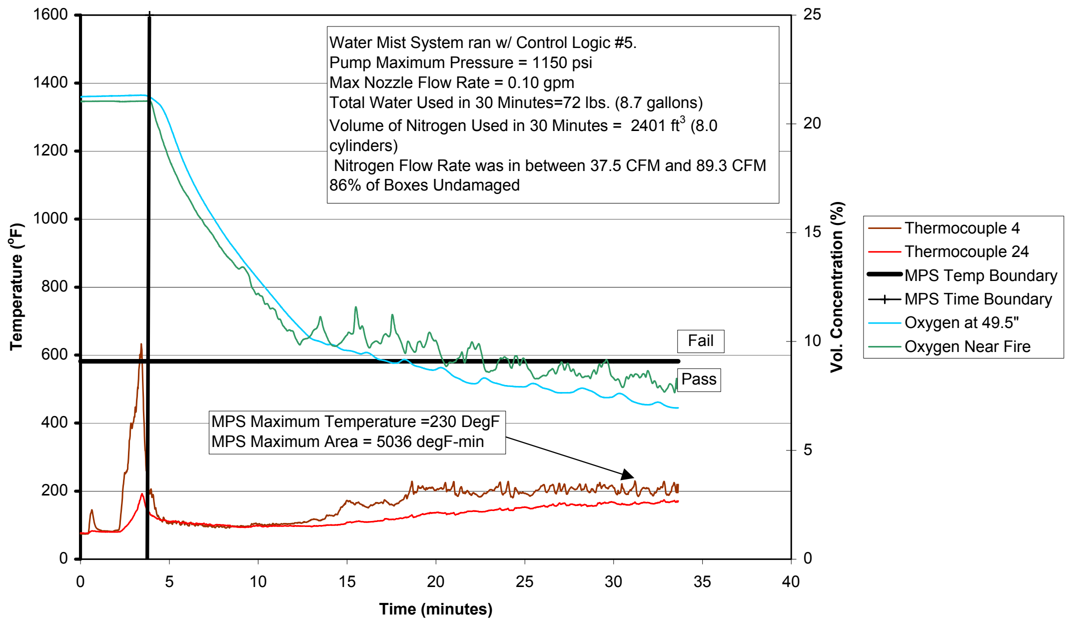

FIGURE 37. BULK-LOAD TEST 26 (073101T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

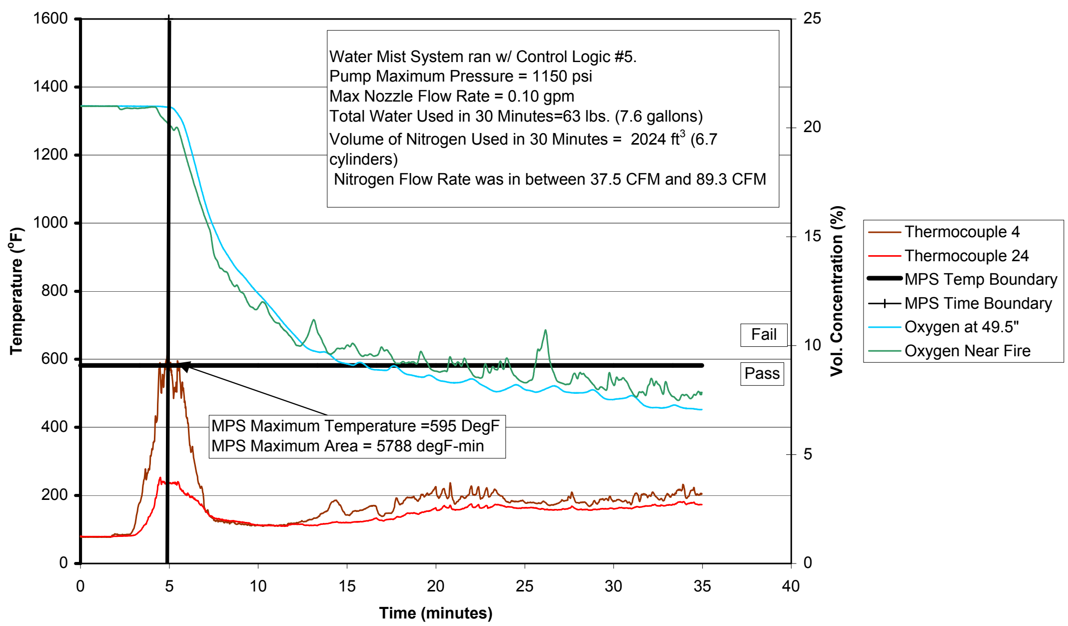

FIGURE 38. BULK-LOAD TEST 27 (080101T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

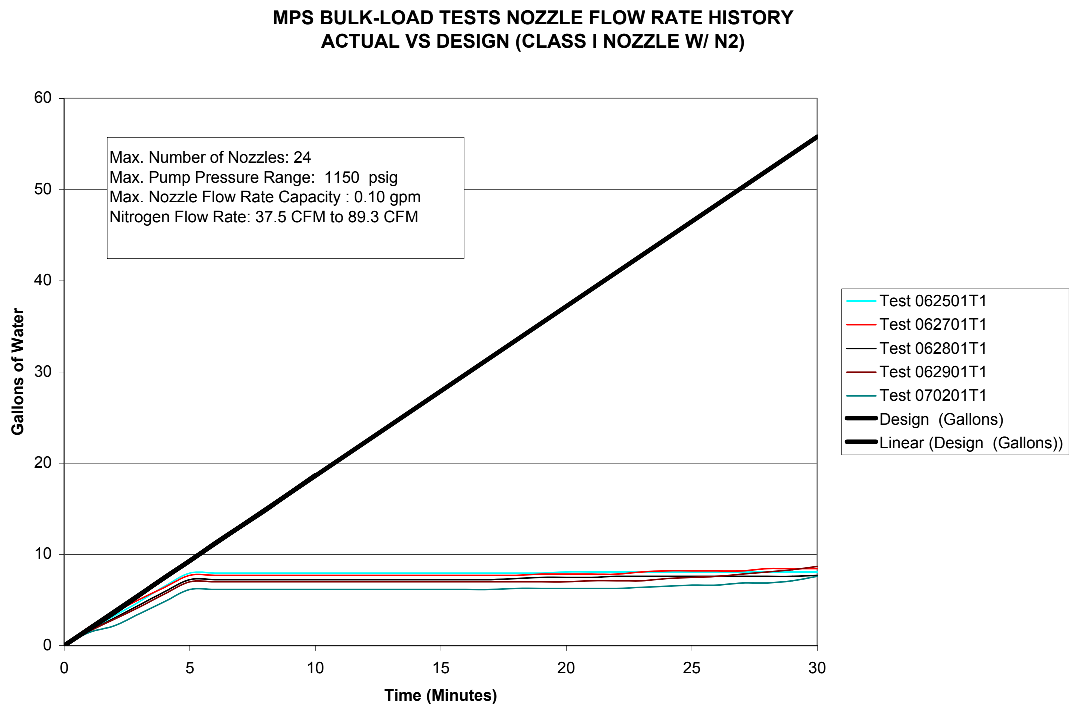

FIGURE 39. WATER MIST/NITROGEN SYSTEM WATER FLOW HISTORY DURING THE MPS BULK-LOAD TESTS

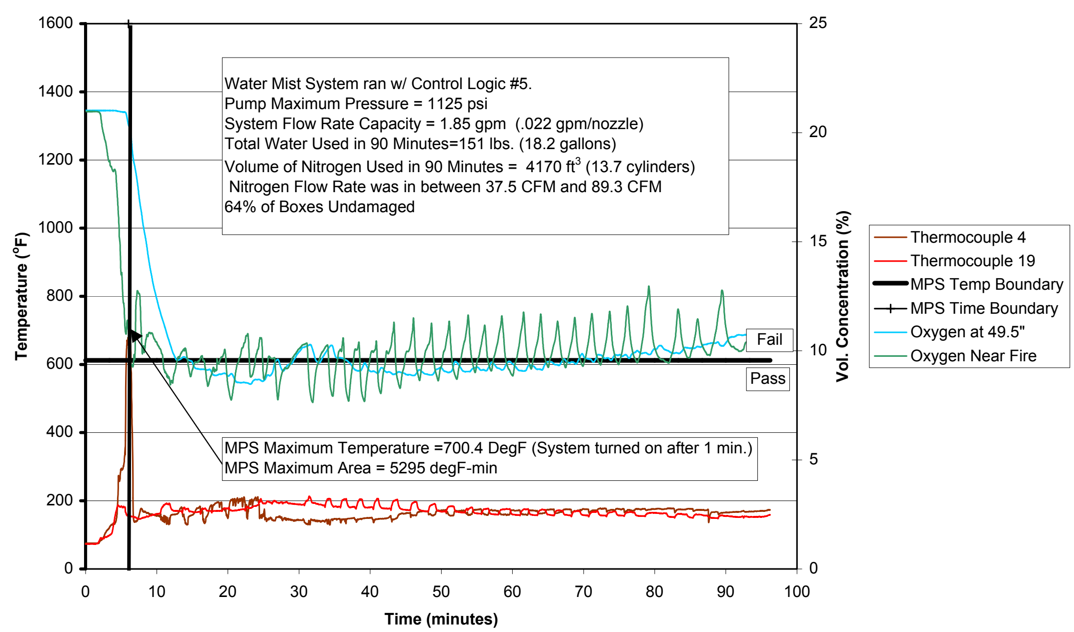

FIGURE 40. CONTAINERIZED TEST 28 (070901T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

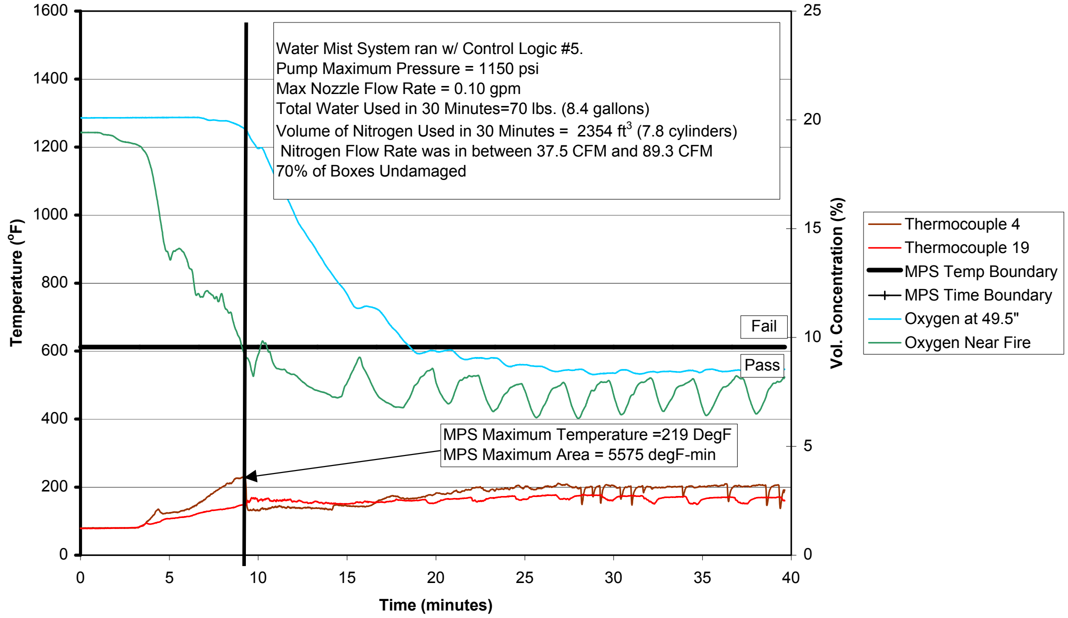

FIGURE 41. CONTAINERIZED TEST 29 (071101T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

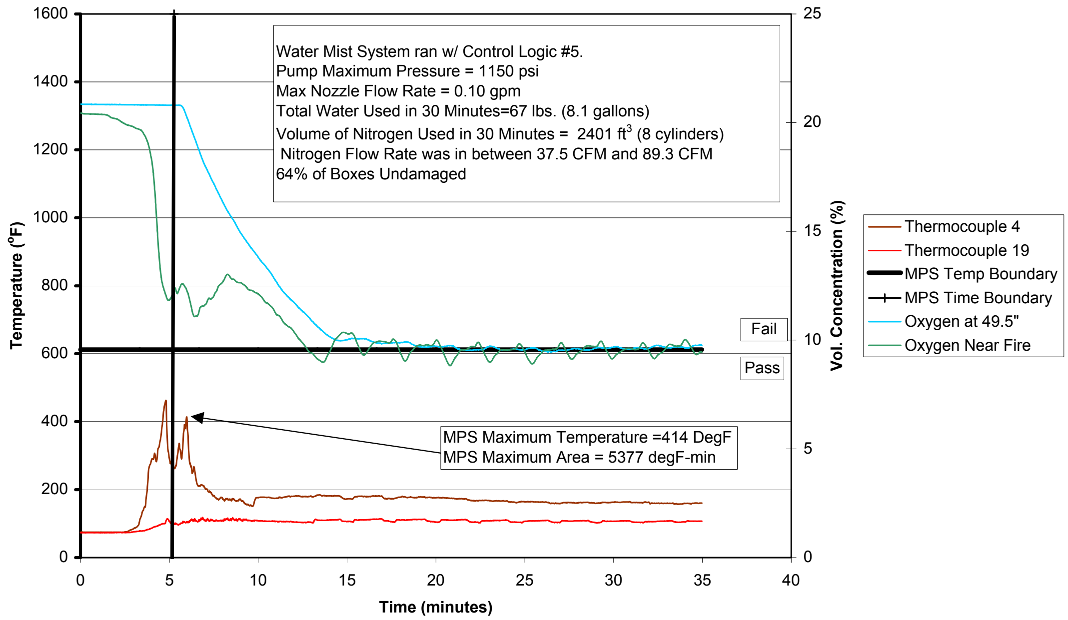

FIGURE 42. CONTAINERIZED TEST 30 (072001T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

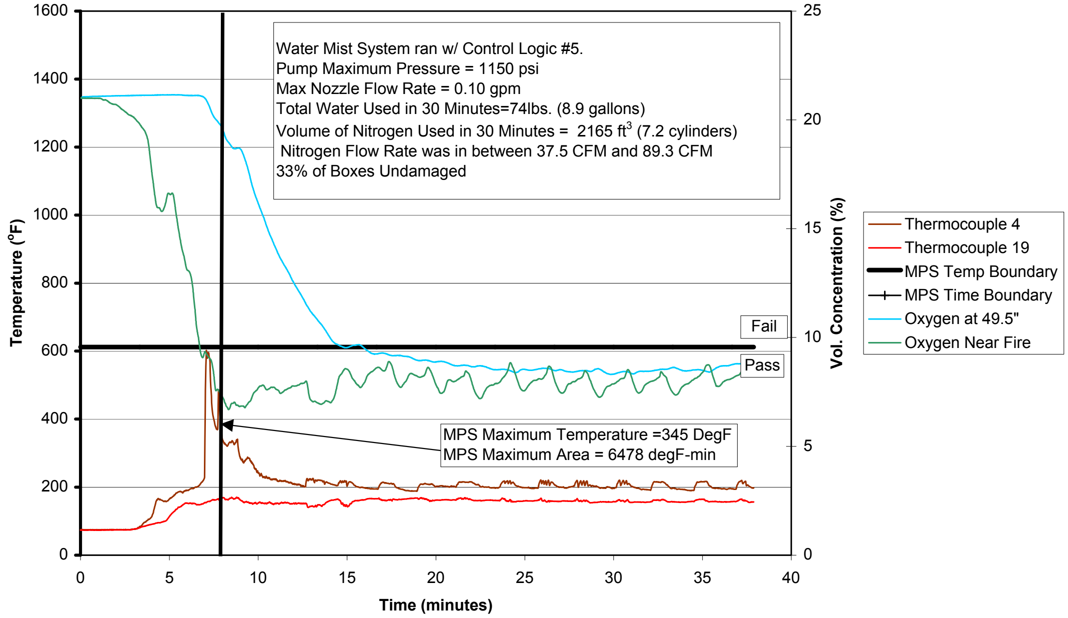

FIGURE 43. CONTAINERIZED TEST 31 (072301T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

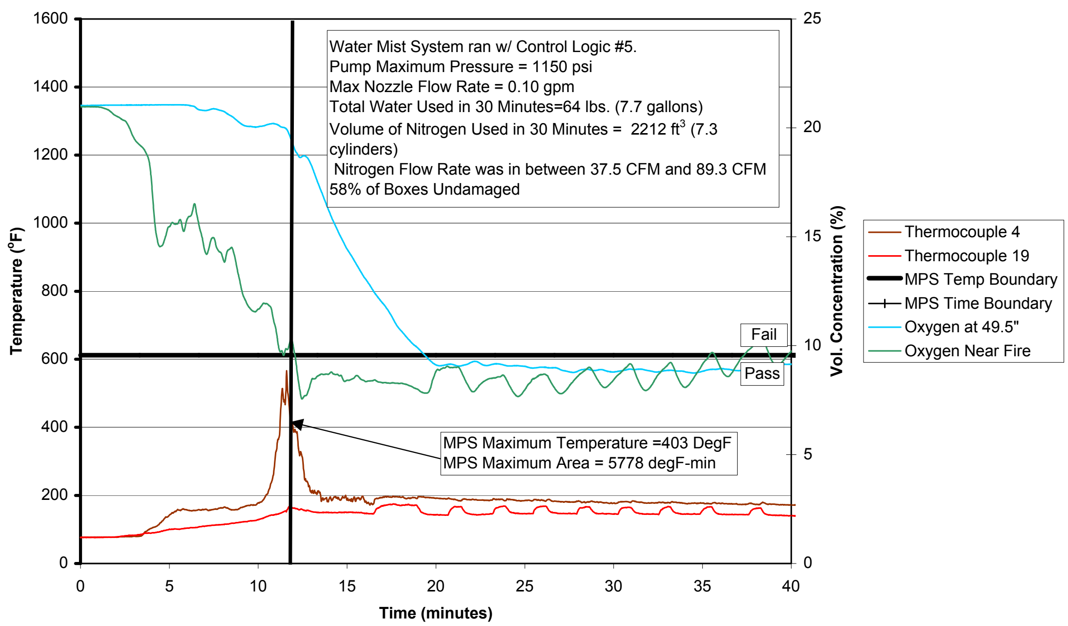

FIGURE 44. CONTAINERIZED TEST 32 (072401T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

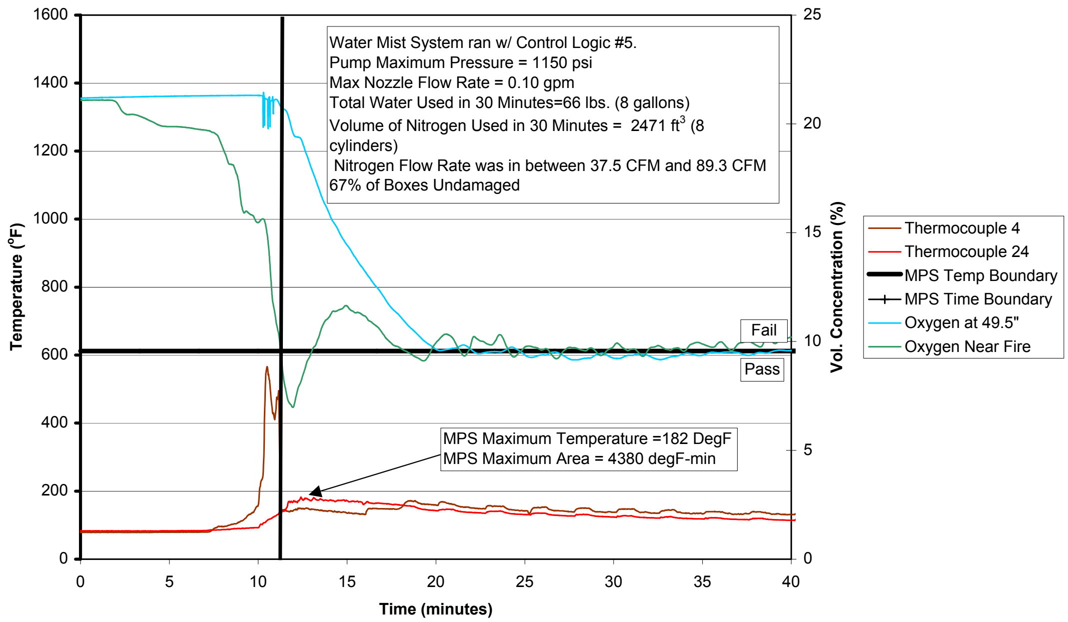

FIGURE 45. CONTAINERIZED TEST 33 (072501T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

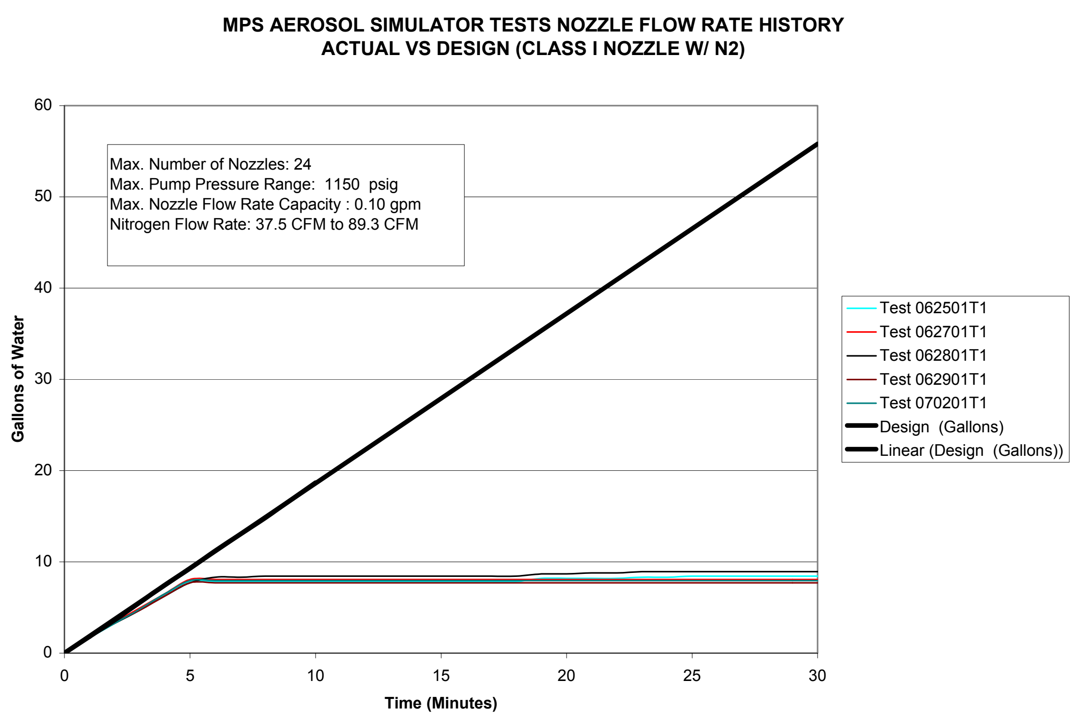

FIGURE 46. WATER MIST/NITROGEN SYSTEM WATER FLOW HISTORY DURING THE MPS CONTAINERIZED TESTS

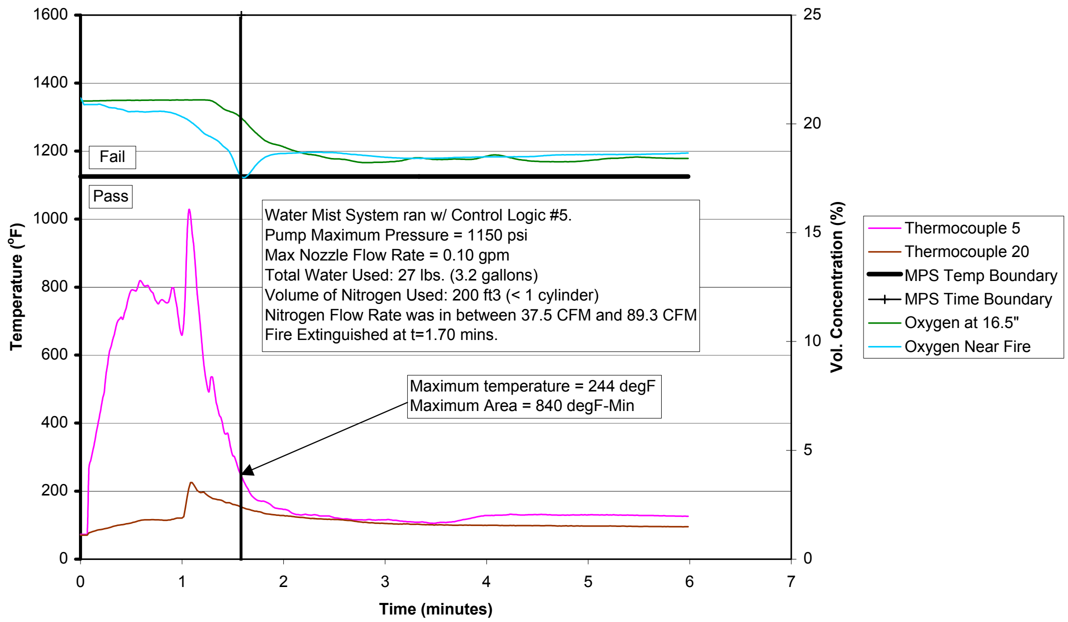

FIGURE 47. SURFACE BURN TEST 34 (070301T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

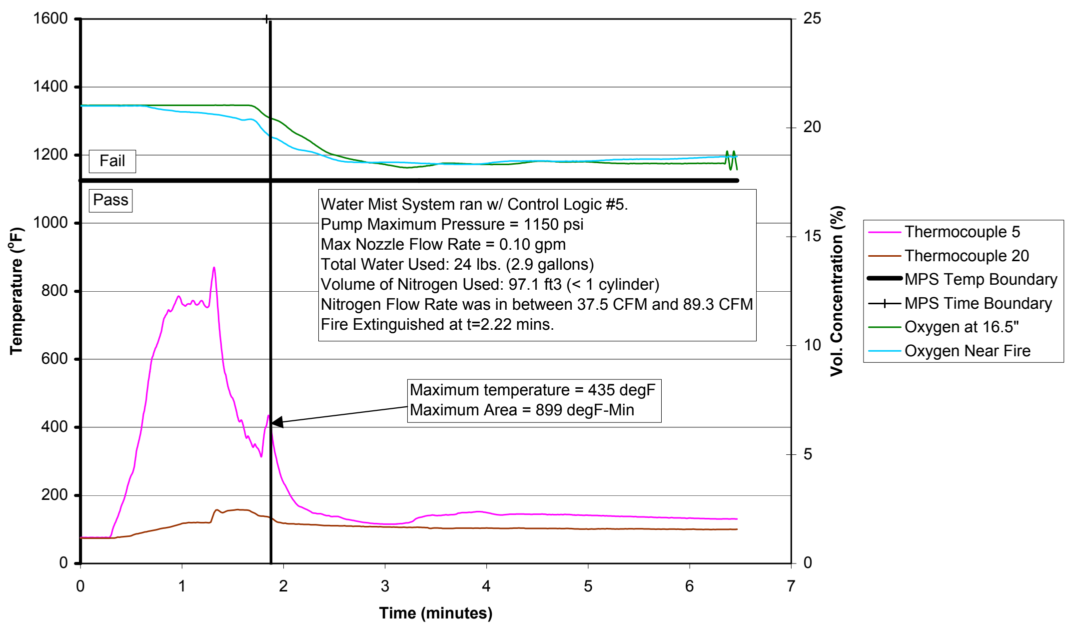

FIGURE 48. SURFACE BURN TEST 35 (070301T2) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

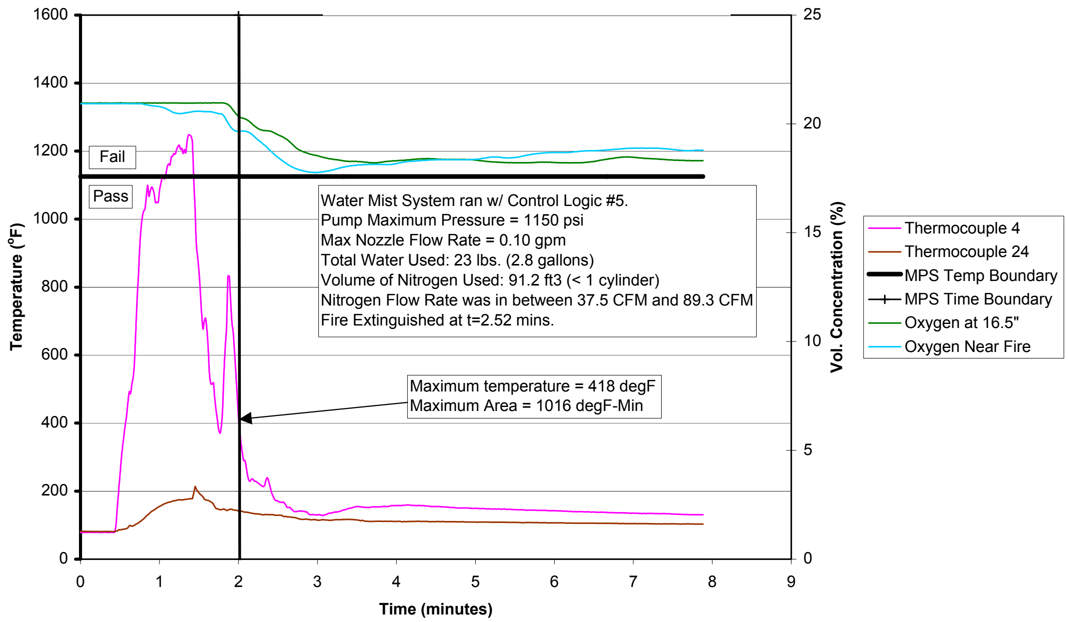

FIGURE 49. SURFACE BURN TEST 36 (070501T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

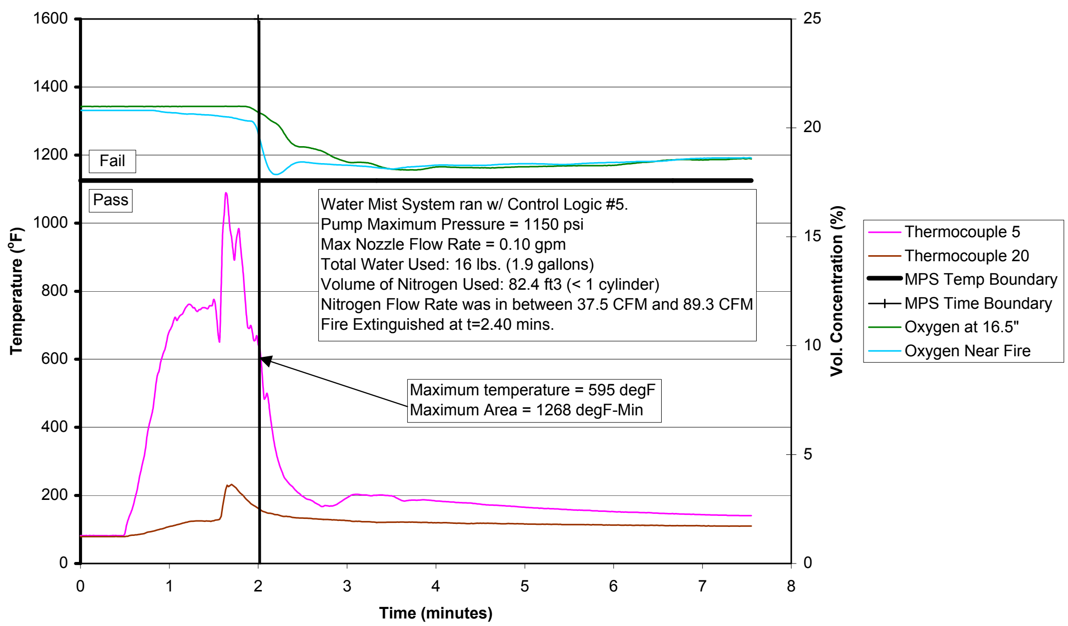

FIGURE 50. SURFACE BURN TEST 37 (070501T2) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

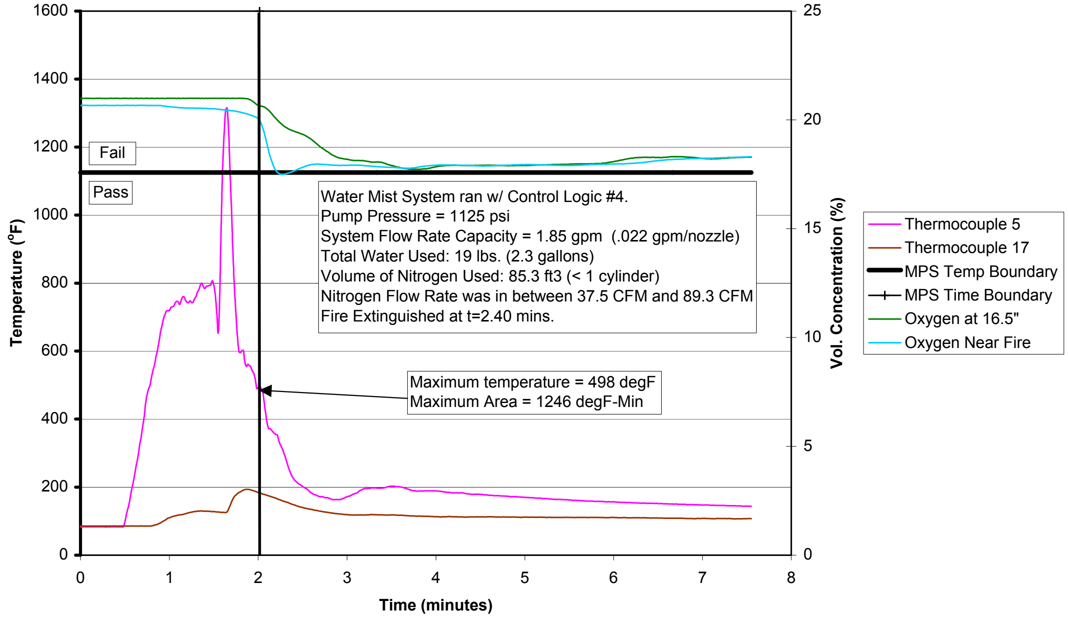

FIGURE 51. SURFACE BURN TEST 38 (070501T3) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

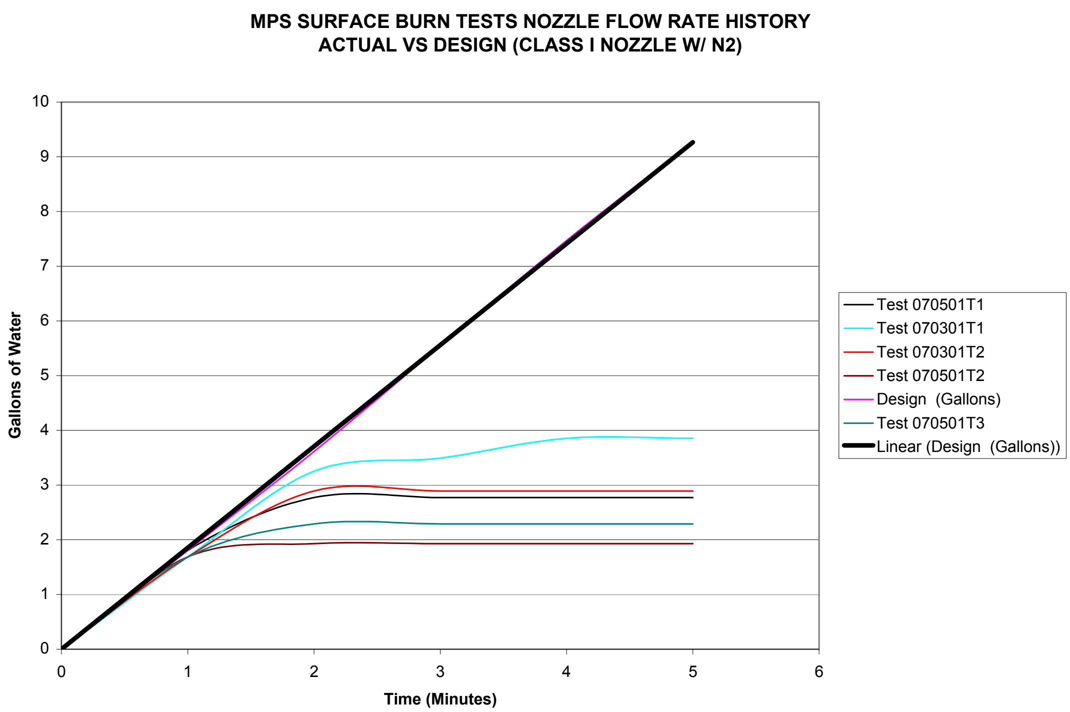

FIGURE 52. WATER MIST/NITROGEN SYSTEM WATER FLOW HISTORY DURING THE MPS SURFACE BURN TESTS

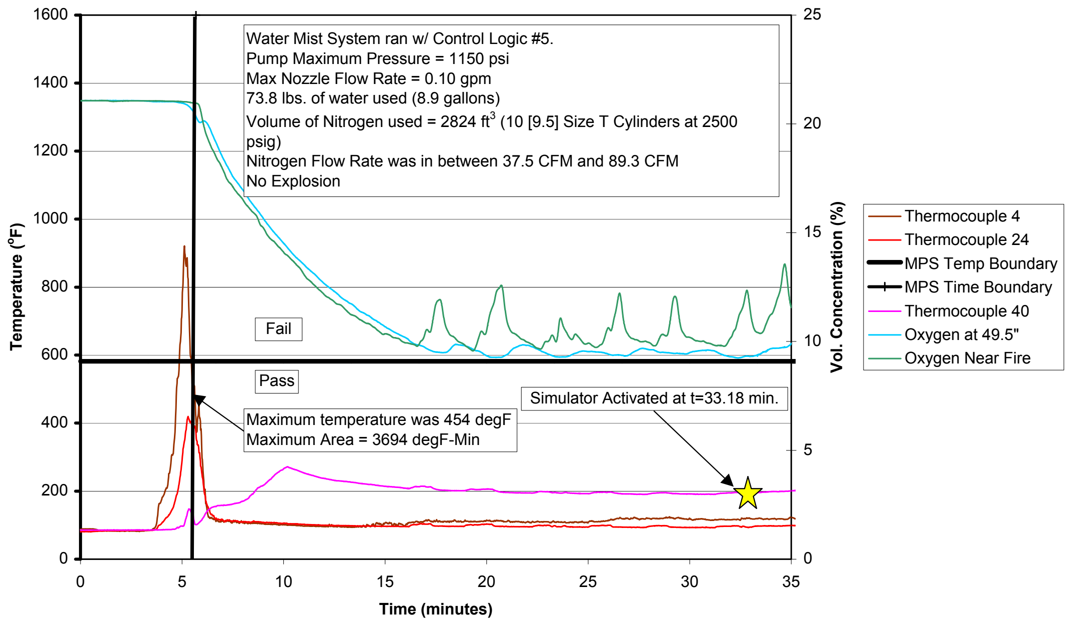

FIGURE 53. AEROSOL CAN EXPLOSION TEST 39 (062501T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

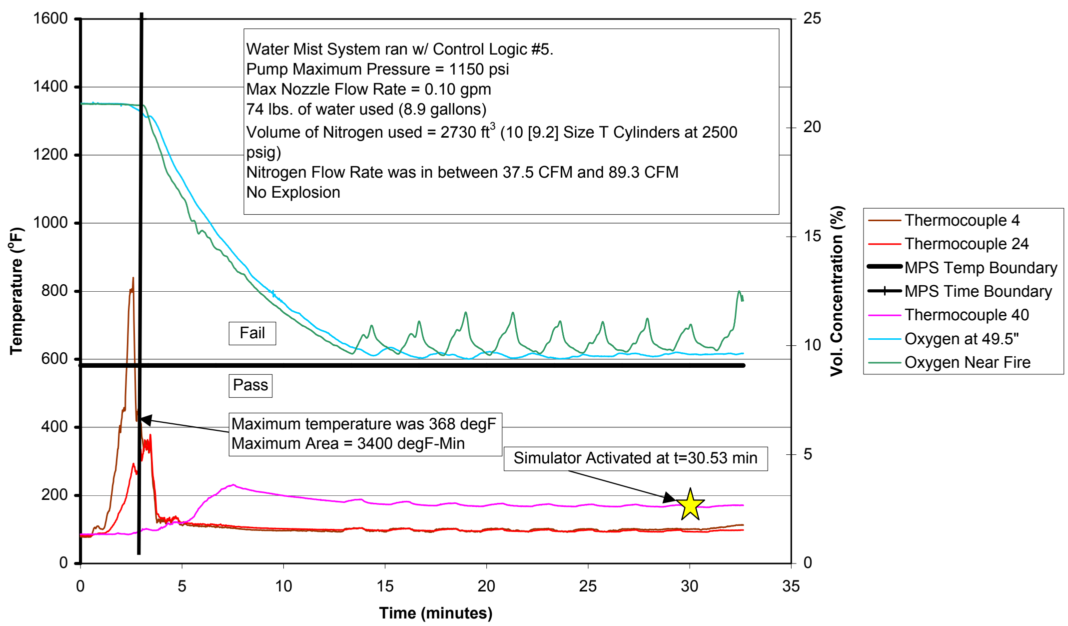

FIGURE 54. AEROSOL CAN EXPLOSION TEST 40 (062701T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

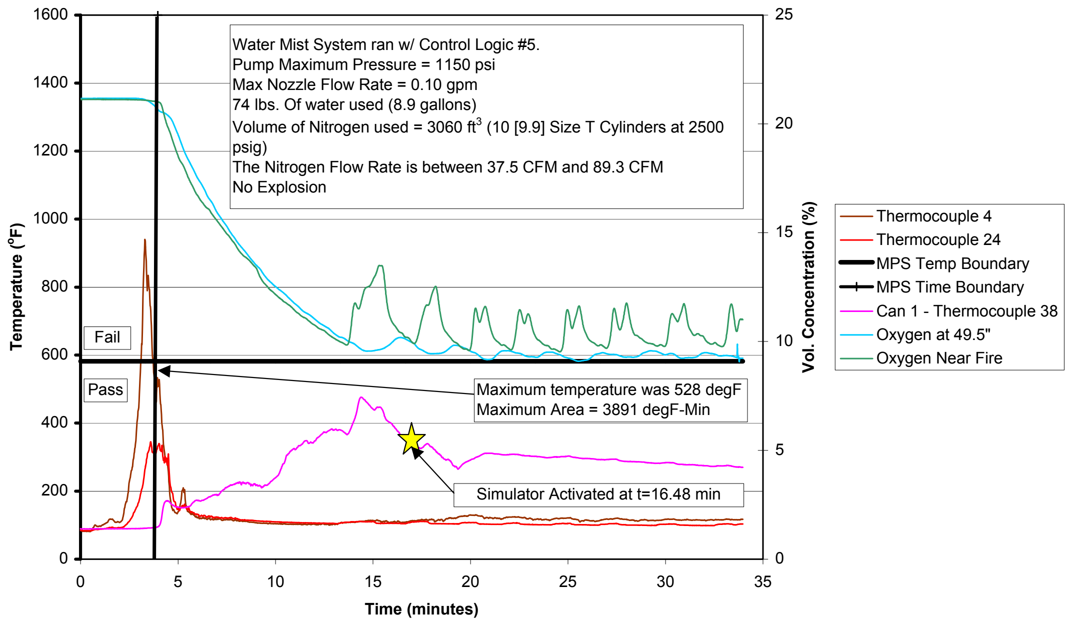

FIGURE 55. AEROSOL CAN EXPLOSION TEST 41 (062801T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

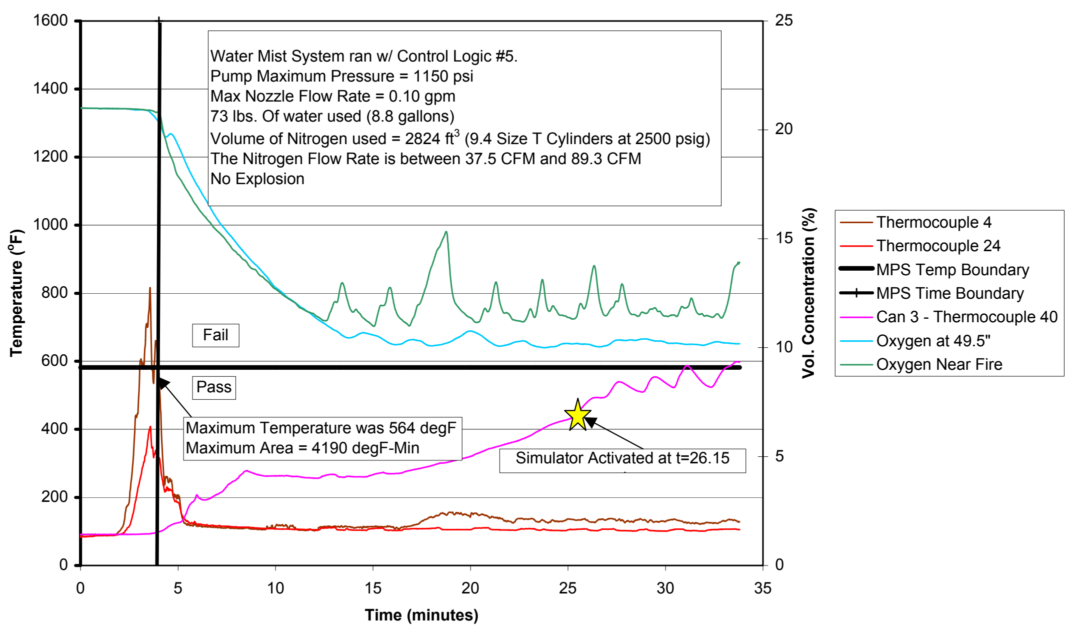

FIGURE 56. AEROSOL CAN EXPLOSION TEST 42 (062901T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

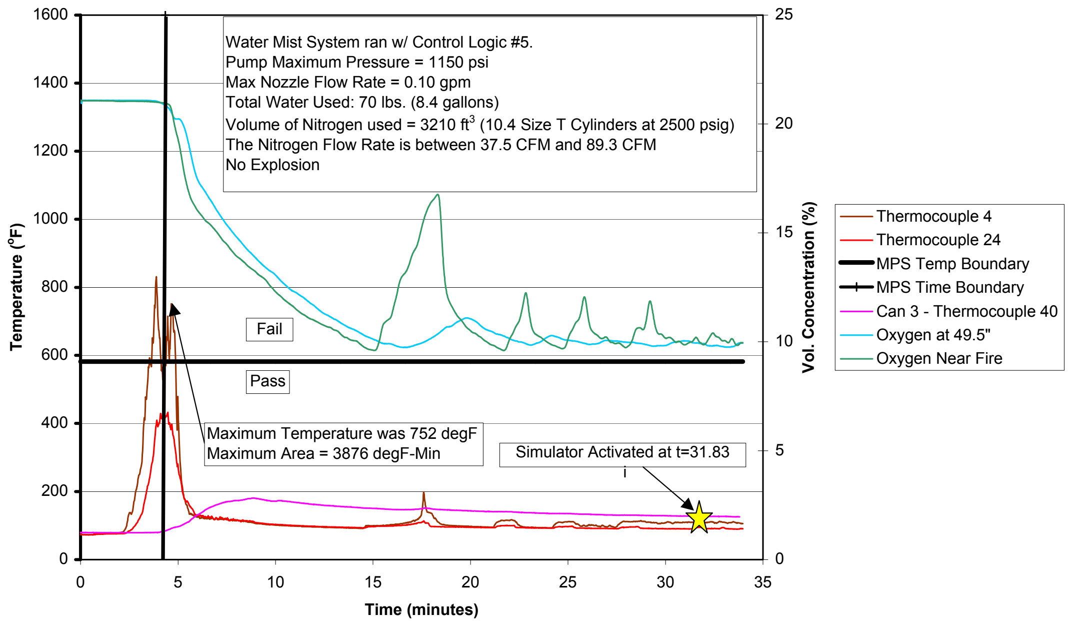

FIGURE 57. AEROSOL CAN EXPLOSION TEST 43 (070201T1) OXYGEN AND MAXIMUM TEMPERATURE HISTORY

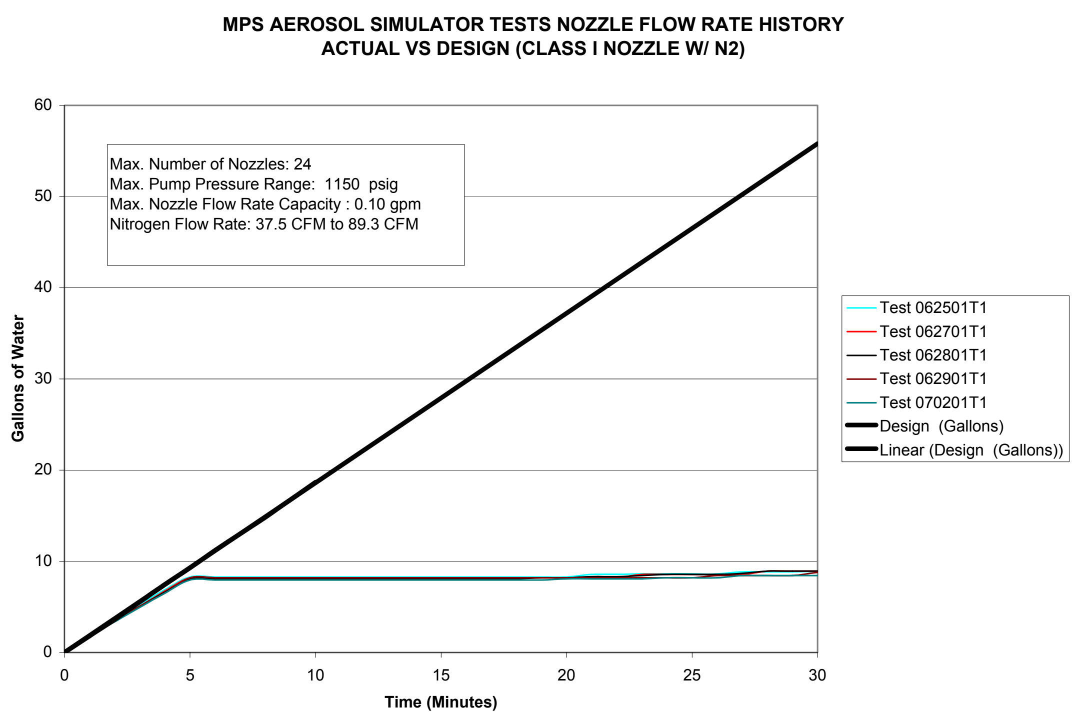

FIGURE 58. WATER MIST/NITROGEN SYSTEM WATER FLOW HISTORY DURING THE MPS AEROSOL CAN EXPLOSION TESTS

TABLE 1. SENSOR INFORMATION

Sensor	Model Number	Location (X, Y, Z)	Channel Number
Thermocouple 1	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (383, 24, 65)	512
Thermocouple 2	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (383, 84, 65)	513
Thermocouple 3	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (383, 144, 65)	514
Thermocouple 4	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (323, 24, 65)	515
Thermocouple 5	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (323, 84, 65)	516
Thermocouple 6	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (323, 144, 65)	517
Thermocouple 7	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (263, 24, 65)	518
Thermocouple 8	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (263, 84, 65)	519
Thermocouple 9	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (263, 144, 65)	520
Thermocouple 10	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (203, 24, 65)	521
Thermocouple 11	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (203, 84, 65)	522
Thermocouple 12	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (203, 144, 65)	523
Thermocouple 13	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (119.5, 24, 65)	524
Thermocouple 14	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (119.5, 84, 65)	525
Thermocouple 15	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (119.5, 144, 65)	526
Thermocouple 16	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (59.5, 24, 65)	527
Thermocouple 17	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (59.5, 84, 65)	528
Thermocouple 18	Thermo Electric Part No. 0129 Type K, 20 Gauge	Ceiling (59.5, 144, 65)	529
Thermocouple 19	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (394.5, 24, 54)	530
Thermocouple 20	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (394.5, 84, 54)	531
Thermocouple 21	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (394.5, 144, 54)	532
Thermocouple 22	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (383, 4, 54)	533

TABLE 1. SENSOR INFORMATION (Continued)

Sensor	Model Number	Location (X, Y, Z)	Channel Number
Thermocouple 23	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (383, 160, 54)	534
Thermocouple 24	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (323, 4, 54)	535
Thermocouple 25	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (323, 160, 54)	536
Thermocouple 26	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (263, 4, 54)	537
Thermocouple 27	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (263, 160, 54)	538
Thermocouple 28	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (203, 160, 54)	539
Thermocouple 29	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (119.5, 11.7, 54)	540
Thermocouple 30	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (119.5, 152.3, 54)	541
Thermocouple 31	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (64.5, 24, 54)	544
Thermocouple 32	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (64.5, 144, 54)	545
Thermocouple 33	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (4, 26.5, 54)	546
Thermocouple 34	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (4, 84, 54)	547
Thermocouple 35	Thermo Electric Part No. 0129 Type K, 20 Gauge	Sidewall (4, 141.5, 54)	548
Thermocouple 36	Thermo Electric Part No. 0129 Type K, 20 Gauge	Inside Ignition Box	549
Thermocouple 37	Thermo Electric Part No. 0129 Type K, 20 Gauge	Above Ignition Box	550
Thermocouple 38	Thermo Electric Part No. 0129 Type K, 20 Gauge	Attached to Aerosol Can 1	551
Thermocouple 39	Thermo Electric Part No. 0129 Type K, 20 Gauge	Attached to Aerosol Can 2	552
Thermocouple 40	Thermo Electric Part No. 0129 Type K, 20 Gauge	Attached to Aerosol Can 3	553
Agent 1	Rosemount 880A	Centerline and 49" from the floor	753
Agent 2	Rosemount 880A	Centerline and 32.5" from the floor	754
Agent 3	Rosemount 880A	Centerline and 16" from the floor	755

TABLE 1. SENSOR INFORMATION (Continued)

Sensor	Model Number	Location (X, Y, Z)	Channel Number
Agent 4	Rosemount 880A	For the bulk-load test the probe was 6" to the right of the ignition box and 9" above the floor. and for the aerosol explosion test, it was placed 24" above the floor and 36" in front of the simulator discharge port.	756
Oxygen 1	Rosemount OM11EA	Centerline and 49" from the floor	741
Oxygen 2	Rosemount OM11EA	Centerline and 32.5" from the floor	744
Oxygen 3	Rosemount OM11EA	Centerline and 16" from the floor	747
Oxygen 4	Rosemount OM11EA	For the bulk-load test, the probe was 6" to the right of the ignition box and 9" above the floor, and for the aerosol explosion test, it was placed 24" above the floor and 36" in front of the simulator discharge port.	750
Pressure	Omega PX951-200S5V	Ceiling and 16 3/8" from bulk head, centerline	1 (High Speed Data Acquisition System)

TABLE 2. WATER MIST SYSTEM TEST RESULTS

Test ID	Test No.	Max Temp. (°F)	Max Area (°F-min)	Pressure (psig)	Water Usage (lbs.)	Comments
Bulk-Load Test						
Test ID	Test No.	Max Temp. (°F)	Max Area (°F-min)	Pressure (psig)	Water Usage (lbs.)	Comments
030201T1	1	610	6241	N/A	184	
030601T1	2	422	5701	N/A	134	
030701T1	3	356	5758	N/A	145	
030801T1	4	821	6296	N/A	150	
031301T1	5	464	5502		127	
	Average:	535	5900	N/A	148	
	Std. Deviation:	185	350		22	
	MPS Acceptance Criteria:	582	10452			
	Performance Rating:	Passed	Passed	N/A	(18 Gallons)	
Containerized Test						
Test ID	Test No.	Max Temp. (°F)	Max Area (°F-min)	Pressure (psig)	Water Usage (lbs.)	Comments
032001T1	6	277	7134	N/A	228	
032101T1	7	424	10480	N/A	336	
032601T1	8	802	8969	N/A	330	
032701T1	9	446	9839	N/A	200	
041101T1	10	420	9154	N/A	272	
	Average:	487	9106	N/A	273.2	
	Std. Deviation:	195	1259		60	
	MPS Acceptance Criteria:	612	14102			
	Performance Rating:	Passed	Passed	N/A	(33 Gallons)	
Tests With 1 Nozzle Inside LD-3 Container						
041001T1	11	656	7768		122 (15 Gallons)	
041301T1	12	250	6264		157 (19 Gallons)	

TABLE 2. WATER MIST SYSTEM TEST RESULTS (Continued)

Surface Burning Test						
Test ID	Test No.	Max Temp. (°F)	Max Area (°F-min)	Pressure (psig)	Water Usage (lbs.)	Comments
031401T1	13	931	1509	N/A	76	
031401T2	14	197	737	N/A	78	
031401T3	15	999	1601	N/A	67	
031501T1	16	673	1093	N/A	74	
031501T2	17	908	1595	N/A	75	
	Average:	742	1307	N/A	74	
	Std. Deviation:	328	381		4	
	MPS Acceptance Criteria:	1125	2964			
	Performance Rating:	Passed	Passed	N/A	(9 Gallons)	

Aerosol Explosion Test (Bulk-Load Version w/Aerosol Can Simulator)						
Test ID	Test No.	Max Temp. (°F)	Max Area (°F-min)	Pressure (psig)	Water Usage (lbs.)	Comments
061501T1	18	782	-	Blow Out Plastic Sheet Used	60	No Explosion Observed. Short test.
061801T1	19	1223	-	Blow Out Plastic Sheet Used	71	No Explosion Observed. Short test
061901T1	20	834	-	Blow Out Plastic Sheet Used	60	Explosion occurred at 8.1 mins. Short test
062101T1	21	1265	-	Blow Out Plastic Sheet Used	57	Explosion occurred at 14.12 mins. Short test.
062201T1	22	774	-	Blow Out Plastic Sheet Used	56	Explosion occurred at 11.10 mins. Short test.
	Average:	976	-	Explosion Occurred	61	
	Std. Deviation:	247	-		6	
	MPS Acceptance Criteria:	582	N/A	No Explosion		
	Performance Rating:	Failed	N/A	Failed	(7.3 Gallons)	

TABLE 3. WATER MIST AND NITROGEN SYSTEM TEST RESULTS

Bulk-Load Test							
Test ID	Test No.	Max Temp. (°F)	Max Area (°F-min)	Pressure (psig)	Water Usage (lbs.)	Nitrogen Usage (ft^3)	Comments
070601T1	23	346	3382	N/A	67	2730	96% of boxes Undamaged (versus 75% with Halon 1301)
072601T1	24	274	4166	N/A	70	2307	96% of boxes Undamaged (versus 75% with Halon 1301)
072701T1	25	491	5346	N/A	64	2165	88% of boxes Undamaged (versus 75% with Halon 1301)
073101T1	26	230	5036	N/A	72	2401	86% of boxes Undamaged (versus 75% with Halon 1301)
080101T1	27	595	5788	N/A	63	2024	
	Average:	387	4744	N/A	67.2	2325	
	Std. Deviation:	153	965		4	268	
	MPS Acceptance Criteria:	582	10452				
	Performance Rating:	Passed	Passed	N/A	(8 Gallons)	7.7 T-Size Cylinders at 2500 psig	

Containerized Test							
Test ID	Test No.	Max Temp. (°F)	Max Area (°F-min)	Pressure (psig)	Water Usage (lbs.)	Nitrogen Usage (ft^3)	Comments
070901T1	28	700.4	5295	N/A	151	4170	90-Minute Test; Water mist system was turned on later than required due to a closed valve. 61% of boxes undamaged.
071101T1	29	219	5575	N/A	70	2354	70% of boxes undamaged
072001T1	30	414	5377	N/A	67	2401	64% of boxes undamaged
072301T1	31	345	6478	N/A	74	2165	33% of boxes undamaged
072401T1	32	403	5778	N/A	64	2212	58% of boxes undamaged
072501T1	33	182	4380	N/A	66	2471	67% of boxes undamaged
	Average:	313	5518	N/A	68.2	2320.6	
	Std. Deviation:	106	630		4	129	
	MPS Acceptance Criteria:	612	14102				
	Performance Rating:	Passed	Passed	N/A	(8.8 Gallons)	9.7 T-Size Cylinders at 2500 psig	

TABLE 3. WATER MIST AND NITROGEN SYSTEM TEST RESULTS (Continued)

Surface Burning Test							
Test Id	Test No.	Max Temp (°F)	Max Area (°F-Min)	Pressure (Psig)	Water Usage (Lbs.)	Nitrogen Usage (Ft^3)	Comments
070301T1	34	244	840	N/A	27	200	Fire Extd. in 37.2 secs.
070301T2	35	435	899	N/A	24	97.1	Fire Extd. in 53.4 secs.
070501T1	36	418	1016	N/A	23	91.2	Fire Extd. in 61.2 secs.
070501T2	37	595	1268	N/A	16	82.4	Fire Extd. in 52.2 secs.
070501T3	38	498	1246	N/A	19	85.3	Fire Extd. in 58.8 secs.
	Average:	438	1054	N/A	22	111.2	52.6
	Std. Deviation:	129	196		4	50	
	MPS Acceptance Criteria:	1125	2964				
	Performance Rating:	Passed	Passed	N/A	(2.7 Gallons)	< 1 T-Size Cylinder at 2500 psig	53 seconds to extinguish fire

Aerosol Explosion Test (Bulk-Load Version W/ Aerosol Can Simulator)							
Test Id	Test No.	Max Temp (°F)	Max Area (°F-Min)	Pressure (Psig)	Water Usage (Lbs.)	Nitrogen Usage (Ft^3)	Comments
062501T1	39	454	3694	0	73.8	2824	30 minutes test. Sim activated at t=33.18 minutes since cans did not heat up to 400 degF. No explosion
062701T1	40	368	3400	0	74	2730	30 minutes test. Sim activated at t=30.53 minutes since cans did not heat up to 400 degF. No explosion
062801T1	41	528	3891	0	74	3060	30 minutes test. Can 1 reached 400 degF. Sim activated at t=16.48 minutes. No explosion
062901T1	42	564	4190	0	73	2824	30 minutes test. Can 3 reached 400 degF. Sim activated at t=26.15 minutes. No explosion
070201T1	43	752	3876	0	70	3210	30 minutes test. Sim activated at t=31.83 minutes since cans did not heat up to 400 degF. No explosion
	Average:	533	3810	0	73	2930	
	Std. Deviation:	144	290	0	2	199	
	MPS Acceptance Criteria:	582	10452	0			
	Performance Rating:	Passed	Passed	Passed	(8.8 Gallons)	9.7 T-Size Cylinders at 2500 psig	No Explosion