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William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Evaluation of VERDAGENT® Against the FAA Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems

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16. Abstract

Suitable alternatives to Halon 1301 are being sought throughout the aviation industry as a result of a worldwide agreement to ban the production and use of Halon 1301 due to the detrimental effects to the atmosphere. Fire extinguishing agents proposed for use in transport category airplane cargo compartments must demonstrate effective firefighting performance against the types of fires likely to occur in airplane cargo compartments. The Federal Aviation Administration (FAA) developed a minimum performance standard (MPS) evaluation method to compare the efficacy of any proposed agent against the known performance of Halon 1301. In this study the FAA Technical Center (FAATC) Fire Safety Branch evaluated VERDAGENT®, a potential fire suppression agent, in the FAATC Full Scale Fire Test Facility. Tests were performed according to procedures outlined in the MPS. VERDAGENT® is a blend of two components – carbon dioxide and 2-bromo-3,3,3-trifluoroprop-1-ene (i.e., 2-BTP, commonly called Halotron BrX). The MPS was originally designed considering single component agents similar to Halon 1301. Evaluation of a multicomponent agent required supplementary tests to investigate component separation and uniformity of dispersion throughout the cargo compartment. An additional challenge fire test, not within the scope of the MPS, was also performed. This fire load consisted of lithium-ion batteries and a combination of ordinary combustible materials and flammable liquids. VERDAGENT® demonstrated successful performance in the MPS. Component separation was not observed, and the agent was found to disperse uniformly in the cargo compartment. The agent also performed effectively against the additional challenge fire test. The results summarize that VERDAGENT® met the requirements of the MPS for aircraft cargo compartment Halon replacement fire suppression systems.

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Acronyms

Acronym	Definition
2-BTP	2-bromo-3,3,3-trifluoroprop-1-ene
AC	Advisory Circular
CFR	Code of Federal Regulations
CO_2	Carbon dioxide
EASA	European Union Aviation Safety Agency
ETOPS	Extended-range Twin-engine Operational Performance Standards
FAA	Federal Aviation Administration
FirEx	Fire Extinguisher
GWP	Global Warming Potential
HBr	Hydrogen Bromide
HF	Hydrogen Fluoride
IATA	International Air Transport Association
MIC	Minimum Inerting Concentration
MPS	Minimum Performance Standard
NDIR	Non-Dispersive Infra-Red
NiCr	Nichrome
ODP	Ozone Depleting Potential
ppmv	Parts Per Million Volume
TC	Type Certificate
THC	Total Hydrocarbon Concentration
ULD	Unit load device
v/v	Volume of agent per volume of test compartment

Executive summary

Halon 1301, a firefighting agent currently used in aircraft cargo compartments, was one of several substances banned as part of the Montreal Protocol Act which prohibits the use of ozone depleting substances. The end date for essential-use exemption of Halon, as set by European Union Aviation Safety Agency (EASA), on a new Type Certificate (TC) airplane was 2018 and for current production aircraft it was 2040. VERDAGENT® (formerly known as Blend D), a Halon replacement agent was tested at the William J. Hughes Technical Center as per the current published version of the Minimum Performance Standard (MPS) for Aircraft Cargo Compartments in collaboration with Meggitt Safety Systems Inc., the manufacturer of the agent. Since VERDAGENT® is a multi-component agent, Halotron BrX (2-bromo-3,3,3-trifluoroprop-1-ene also known as 2-BTP) and carbon dioxide, as opposed to Halon 1301 a single component agent; there were concerns of a homogenous distribution of the agent, blend-separation, and its effectiveness as a Halon replacement agent.

The uniform distribution of the agent was observed through concentration tests, tests that discharged agent into an empty test compartment in test-like conditions to measure the concentration distribution at various locations and ensure the agent is neither stratifying nor is the blend of gases separating. The tests demonstrated the capability of VERDAGENT® in both the high-rate discharge (knockdown operation with concentration necessary to knock flames of a fire down) and low-rate discharge (sustaining operation with concentration necessary to keep the fire suppressed) fire suppression systems to distribute the agent throughout the compartment uniformly. The tests also established that there was no blend separation during the duration of the MPS tests.

The effectiveness of the Halon replacement agent was tested by subjecting the agent to a series of fire scenarios in the MPS. The fire scenarios in the MPS are surface burning fire scenario, bulk load fire scenario, containerized fire scenario and aerosol can explosion simulation. VERDAGENT® was subjected to the standard and passed the standard by achieving lower peak temperatures and time-temperature integrals than the values achieved when testing Halon 1301 to the same scenarios. The agent also passed by performing as well as Halon 1301 in the aerosol can explosion simulation scenario.

An additional challenge fire scenario was performed at the request of the certification office. The test comprised of a mixed fire load to represent a fire likely to occur in a cargo compartment. The test was conducted to only look at VERDAGENT® performance without a comparison to its performance against Halon 1301.

1 Introduction

A Halon replacement agent was tested at the William J. Hughes Technical Center as per the current version of the Minimum Performance Standard (MPS) for Aircraft Cargo Compartments (Reinhardt, 2012). The Halon replacement agent tested was VERDAGENT®, formerly known as Blend D or Meggitt Blend D, as supplied by Meggitt Safety Systems Inc., the manufacturer of the agent.

1.1 Background

Under the provisions of Title 14 Code of Federal Regulations (CFR) 25.857, a Class C cargo compartment is classified as one that has a smoke detector that provides a warning to the pilot, an approved built-in fire extinguishing or suppression system controlled from the flight deck, a means to exclude hazardous quantities of smoke, flames, or extinguishing agent from entering any occupied areas, and has a means to control ventilation and drafts within the compartment so the agent stays within the compartment (FAA, Title 14 CFR 25.857, 2016).

Title 14 CFR 25.851 provides the guidelines for built-in fire extinguishers provided on an airplane. The system must be installed such that no extinguishing agent likely to enter personnel compartments will be hazardous to the occupants, no discharge of the agent can cause structural damage, and the capacity of the built-in system must be adequate for any fire likely to occur in the compartment where used while taking the compartment volume, ventilation rate and Extended-range Twin-engine Operational Performance Standards (ETOPS) rating into consideration (FAA, Title 14 CFR 25.851, 2016).

In 1987, the Montreal Protocol was finalized to protect the ozone layer by phasing out the production and consumption of ozone depleting substances. Halon 1301, a fire suppression agent, widely used in aircraft fire suppression applications was affected by the Montreal Protocol. The International Halon Replacement Working Group (IHRWG) was established to determine replacement options that could perform better than or as well as Halon 1301. A report was prepared on the "Chemical options to Halons for Aircraft use" in 2002 and later updated in 2012 (Speitel L. , DOT/FAA/AR-11/31, 2012) which iterates the importance of several criteria needed to identify the proper agent to be used in each fire suppression application. It also provides a list of possible replacement agents that were available in 2012.

The advisory circular (AC) AC 25.851-1 provides guidance concerning compliance with the airworthiness standards for transport category airplanes pertaining to Class C cargo compartments that incorporate built-in fire extinguishing/suppression systems. Section 9 of the

AC provides the guidelines for the evaluation of the alternative gaseous extinguishing or suppression systems and alternative agents. Section 9.4.1 mentions that potential alternative agents will need to meet the MPS requirements as developed by the FAA Technical Center as part of the International Halon Replacement Program (FAA, AC No: 25.851-1, 2016).

1.2 Objective

The Fire Safety Branch is part of the International Aircraft Systems Fire Protection Forum through which potential Halon replacement agents can be identified and recommended to be submitted to the MPS process. As part of this program one such agent, VERDAGENT®, was identified and this report elaborates on the required testing the agent had to accomplish in order to be certified as an acceptable Halon replacement agent for cargo compartments in aircraft. VERDAGENT® was tested as per the latest version of the MPS as described in the body of this document and an additional challenge fire test that comprised of lithium-ion cells, and a combination of Class A and Class B fires as described in "Appendix A: Challenge Fire Scenario."

1.3 Agent Description

VERDAGENT® is the tradename for the agent Blend D. The agent is a blend of Halotron BrX, known within the industry as 2-BTP (2-bromo-3,3,3-trifluoroprop-1-ene) and carbon dioxide (CO_2). The agent is then super-pressurized with nitrogen which is used to propel the agent into the compartment. VERDAGENT® is designed to be a total flooding agent for engine or auxiliary power units (APU) and cargo compartment applications. A total flooding agent is part of a system that is designed to discharge a predetermined concentration of agent into an enclosed space for the purpose of fire suppression.

The Pre-MPS tests showed that VERDAGENT® was able to completely suppress aerosol can explosion events at concentrations above 10% v/v (volume of agent per volume of test compartment) which establishes the minimum inerting concentration (MIC) of the agent. Based on this outcome, and providing additional margin, a design concentration of 11.5% for knockdown (concentration necessary to knock visible flames of a fire down) and 11.0% for sustaining (concentration necessary to keep the fire suppressed) was selected at the onset of the MPS test campaign (Dadia, 2022). Three of the four test scenarios were conducted at these concentrations. The aerosol can simulation scenario was conducted at a concentration of 11.5%v/v. As a result, the recommended design concentration was increased to 12.0% v/v for knockdown, and 11.5% v/v for sustaining.

1.3.1 Environmental Overview

It is well known that Halon 1301 is a potent chemical for destroying ozone, with an ozone depletion potential (ODP) of 15.9 and a global warming potential (GWP) of around 7140 (Fahey, 2011). In contrast, VERDAGENT® has an ODP of 0.0014 and a GWP of 0.63 mainly due to the carbon dioxide used in the extinguisher.

1.3.2 Toxicology Overview

VERDAGENT® is designed for normally unoccupied spaces due to the constituents of the blend, namely carbon dioxide (CO_2) and Halotron BrX (chemically known as 2-BTP).

Carbon dioxide is toxic in many ways. Carbon dioxide acts as a simple asphyxiant at high concentrations by displacing and diluting the oxygen in the air below levels necessary to support life. At much lower concentrations it is a respiratory stimulant which results in the increased uptake of other gases. CO_2 is itself toxic: concentrations of 20% have been shown to cause unconsciousness in humans within 2 minutes (Speitel, 1995). Toxicological testing has shown that acute exposure to 2-BTP, may cause cardiac sensitization The no observable adverse effect level (NOAEL) and the lowest observable adverse effect levels (LOAEL) for 2-BTP are 0.5%v/v and 1.0% v/v respectively (Huntingdon, 2013).

2 Test Setup

The testing of the Halon replacement agent was performed as per the minimum performance standard (Reinhardt, 2012).

Full scale testing was conducted in the aft lower cargo compartment of a repurposed DC-10 as shown in Figure 1. The DC-10 cargo compartment was used to develop the minimum performance standard for the Halon replacement agents in cargo compartments (Reinhardt, Blake, & Marker, 2000). The cargo compartment has an internal volume of 2000 $ft^3 \pm 100$ ft^3 and is designed to have a leakage rate of 50 cfm ± 5 cfm.

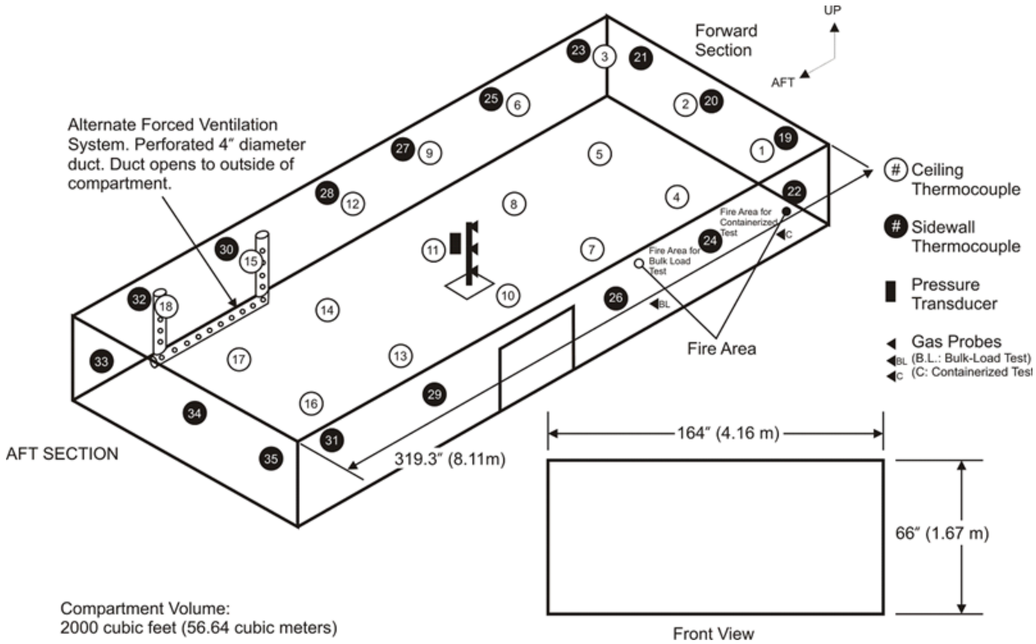

Figure 1. DC-10 Cargo Compartment

2.1 Instrumentation

The cargo compartment was instrumented with K-type thermocouples at the ceiling and along the sidewalls. The ceiling thermocouples (white circles) were placed as shown in Figure 1 and the tip of the thermocouple was placed 1 inch below the ceiling. The sidewall thermocouples (black circles) were placed as shown in Figure 1 and the tip of the thermocouple was placed 18 inches below the ceiling.

The compartment was also instrumented with a Kistler 4080AT005-FL1 pressure sensor (black rectangle in Figure 1. The sensor is a piezoresistive pressure and temperature transmitter that was used for the aerosol can simulator scenario. The data from the sensor was collected at 4800 Hz using a Measurement Computing Data Translation DT8824 data acquisition device.

The compartment was also instrumented with four gas probes that supply gas samples to analyzers that can measure the volumetric concentration of carbon monoxide, carbon dioxide, oxygen, and 2-BTP. The analyzer probes were repositioned based on the needs of the concentration tests, and each fire scenario. The locations of the gas analyzer probes are shown as black triangles in Figure 1. The Rosemount 880A continuous gas analyzer was used to determine the volumetric concentration of the gases carbon monoxide (CO), CO_2, Oxygen (O_2), and 2-BTP within the compartment. This analyzer uses a NDIR (non-dispersive infrared) technique to measure the volumetric concentrations of carbon monoxide, carbon dioxide, and 2-BTP. The analyzer uses dedicated infrared wavelength regions for each of these gases. Oxygen has a dedicated paramagnetic cell within the analyzer to determine its volumetric concentration. The gas samples are conditioned to remove particulates and soot during fire tests to maintain the integrity of the analyzer before they are processed by the analyzers. The samples that travelled from the probes to the analyzer required a transit time of approximately 50 seconds.

A Measurement Computing DT8874 MEASURpoint data acquisition system was used to collect all of the temperature and gas analysis data. The data was collected at a sampling rate of 1 Hz (once every second).

The DC-10 cargo compartment was instrumented with a Halonyzer IV gas analyzer that measured the volumetric concentration of the agent during the concentration tests. The Halonyzer IV measures the concentration of the blended agent as a whole whereas the Rosemount 880A analyzers measure the individual components of the blended agent. The agent was measured using both analyzers to validate the Halonyzer IV measurements. The Halonyzer is commonly used to measure agent concentration during aircraft certification tests. The Meggitt Halonyzer IV is a Statham-derivative analyzer that was developed for measuring Halon 1301 concentrations and is currently used for certification of Halon 1301 systems. The Halonyzer creates a vacuum to pull a gas through a sample cell. The concentration is measured in real time through the changes in viscosity of the gas flow through an orifice. A calibration curve can be developed by passing known concentrations of a gas or gas blend through the instrument and across the orifice. This calibration curve can then be applied for measuring unknown gas samples. The traditional Halonyzer has 12 channels allowing the concentrations of the sample gas from 12 different locations to be measured in real-time. The unit used for the Cargo MPS tests was the Halonyzer IV, which has 24 measurement channels. As the instrument cannot determine the components of a blend in the case of VERDAGENT®, work has been completed successfully to validate the measurement using independent techniques for analyzing 2-BTP and CO_2 (Dadia, 2022).

Figure 2 shows the locations of the probes. Twenty-three probes were distributed within the cargo compartment and one probe was located in the cabin above the cargo compartment. The probes in the compartment were installed in trees of three probes at each location, except for the tree at the aft location which had two probes. Each tree of probes featured one probe located 2 inches below the ceiling, a second probe located at mid-height, and a third probe located 2 inches above the floor. The tree with two probes (22 and 23) featured probes at the ceiling and floor levels. Probes 1through 6, 16 through 18, 22, and23 were located along the compartment centerline, with the rest of the probes located at other regions of interest.

The Rosemount analyzer sample probes for the concentration tests were distributed as shown in Figure 2. Four probes were placed in a tree with the topmost probe placed 2 inches below the ceiling, the next placed 20 inches below the ceiling, the next placed 38 inches below the ceiling and the last placed 56 inches below the ceiling. The sum of the measured values of 2-BTP and CO_2 provide the calculated concentration of VERDAGENT® and multiplying the measured value of CO_2 by the inverse of its mixing ratio provides the predicted value of the concentration of VERDAGENT®.

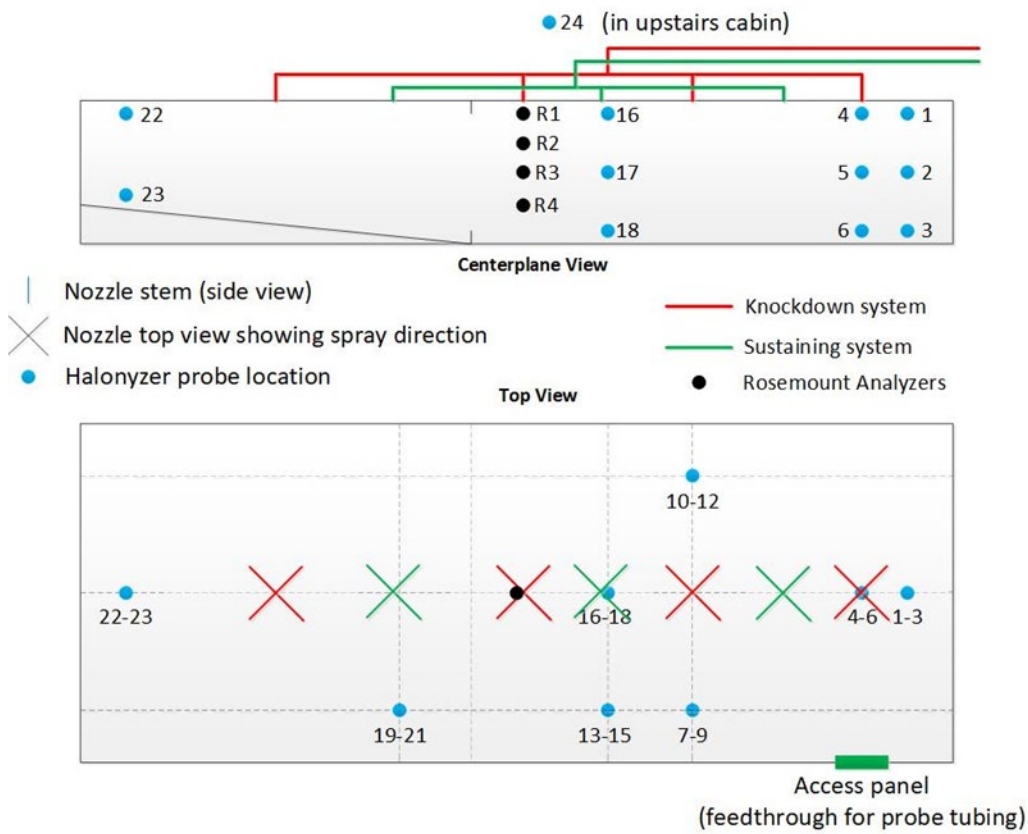

Figure 2. Halonyzer IV Probes Layout

2.2 Agent Distribution System

The agent distribution system, as shown in Figure 3 and Figure 4, consisted of a demonstrator used to house the agent and the activation control, and the discharge plumbing, which included the nozzles.

The Meggitt MPS demonstrator is a structure built from extruded aluminum struts used to support the agent containers and associated components. The agent was contained in Meggitt Fire Extinguisher (FirEx) bottles. For tests where multiple bottles were needed for knockdown or sustaining, several bottles were assembled in a manifold to create a single outlet. Actuated ball valves were provided for each sub-system to activate the agent discharge. These valves feature a solenoid valve that can be triggered remotely to provide shop air pressure to a pneumatic actuator. The pneumatic actuator provides a rapid opening and closing of the ball valve to initiate or stop the agent discharge. The actuated valves were designed to “fail closed” so that they remain closed unless triggered, thereby preventing unintended agent discharge. For the sustaining sub-system, a flow metering device was installed downstream of the pneumatic-solenoid valve. The flow metering device consists of a pressure regulator and a passive mass-flow control which provides a constant agent mass flow rate during the sustaining phase.

The demonstrator was designed to allow for ease of installation and removal of the FirEx bottles between tests to refill agent. Each bottle is provided with an additional ball valve to isolate it from the system prior to removal. Once the filled bottles are reinstalled, the ball valves are opened to allow agent discharge to be controlled by the actuated valves.

The discharge configuration used for the MPS tests featured separate plumbing for each of the knockdown and sustaining sub-systems. The knockdown (high rate) discharge plumbing consisted of main and branch lines, that transition to smaller lines and terminating in four nozzles. The sustaining (low rate) discharge plumbing consisted of main and branch lines, terminating in three nozzles. All nozzles were installed in representative nozzle-pans and the nozzles were oriented so that the orifice directions issued at an angle of 45° relative to the cargo compartment centerline.

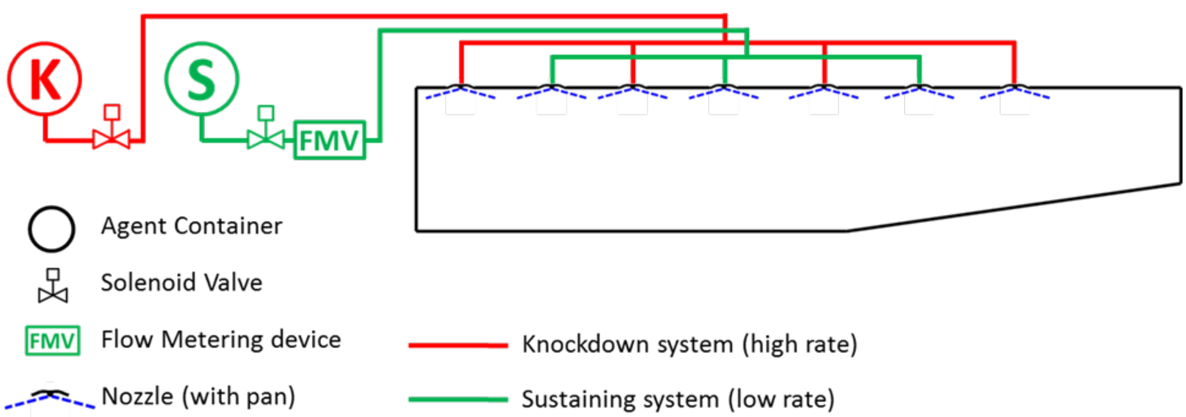

Figure 3. Agent Distribution System Design

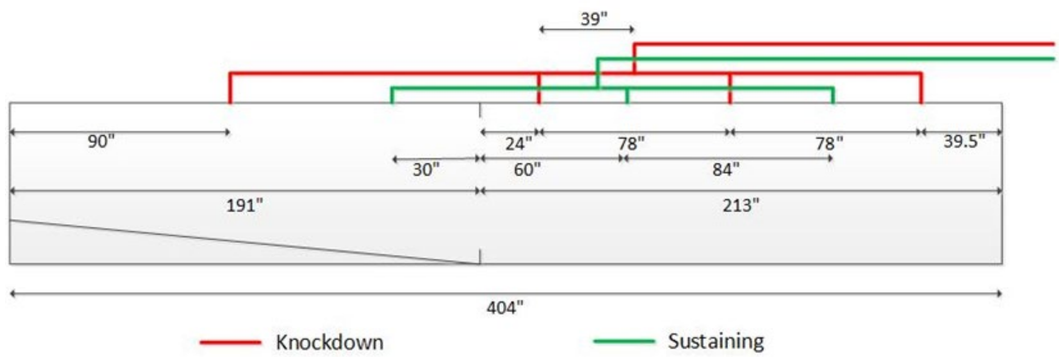

Figure 4. Agent Distribution System Layout

2.3 Fire Load

The MPS subjects any Halon replacement agent to four different fire scenarios: surface burning fire scenario, bulk-load fire scenario, containerized fire scenario, and an aerosol can explosion simulation scenario. Each fire scenario represents a fire likely to occur in the cargo compartment where built-in fire suppression systems are used (Reinhardt, 2012; FAA, Title 14 CFR 25.851, 2016).

2.3.1 Surface Burning Fire Scenario

The surface burning fire scenario is designed to represent the hazard posed by a flammable fluid (Class B fire hazard) leak or spill during transport. This scenario is based on a flammable fluid that could spill or leak and accumulate in a small area that could then ignite upon exposure to an ignition source. The fire load for this scenario was comprised of a ½ gallon of Jet-A fuel and 13 ounces of gasoline. This flammable mixture is placed in a 2-foot by 2-foot square steel pan with a 4-inch lip in an otherwise empty compartment. The pan was filled with 2.5 gallons of water as a base to keep the pan from warping from the heat generated by the fire. Jet-A was poured on top of the water and then the gasoline was added to aid in the ignition of the jet fuel. The top of the pan was placed 12 inches below the ceiling and in between two discharge nozzles as shown in Figure 5. The flammable liquids were ignited using a set of igniters, mounted to the pan, whose tip was placed just above the surface of the fuel.

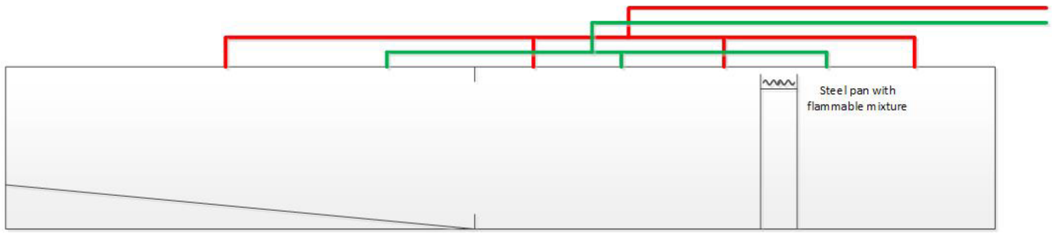

Figure 5. Surface Burning Fire Steel Pan Placement

2.3.2 Bulk Load Fire Scenario

The bulk load fire scenario is designed to represent the hazard posed by the bulk transport of packages that are made of Class-A materials such as wood, paper, fabric, and light plastics. The fire load for this scenario was comprised of 178 single-wall corrugated cardboard boxes filled with 2.5 lbs of loosely packed shredded office paper. Each cardboard box had a nominal dimension of 18 in x 18 in x 18 in. The 178 cardboard boxes represented 30% of the volume of the cargo compartment. The flaps of the boxes were tucked under each other and the boxes were stacked in two layers across the floor of the compartment. The boxes were stacked in a way that there weren't any significant air gaps between them. One of the boxes was replaced with an ignition box to initiate the fire in the compartment. Figure 6 displays the location of the ignition box within the cargo compartment.

Acid gas measurements were made for two of the five bulk load fire tests. The system was setup as shown in Figure 7 and as described in Speitel & Safranova (2021). Sample tubes and blank sample tubes were positioned at the sampling point, without upstream tubing or valves. This avoids high sample losses from absorption of the acid gas analytes on moist surfaces.

The combustion gas is drawn through a timed sequence of sample tubes to obtain a stepped concentration history of the gases of interest. For each sample the gas flows through its sample tube to a cooling line, high-capacity HEPA filter, sample solenoid valve, flowmeter, needle valve and vacuum pump. Five collection tubes (three sample tubes and two non-sampling tubes) were placed 36" above the floor mounted on the outside wall across the ignition box. The flow rate was set at 80ml/minute. The sample duration for each tube is 10 minutes.

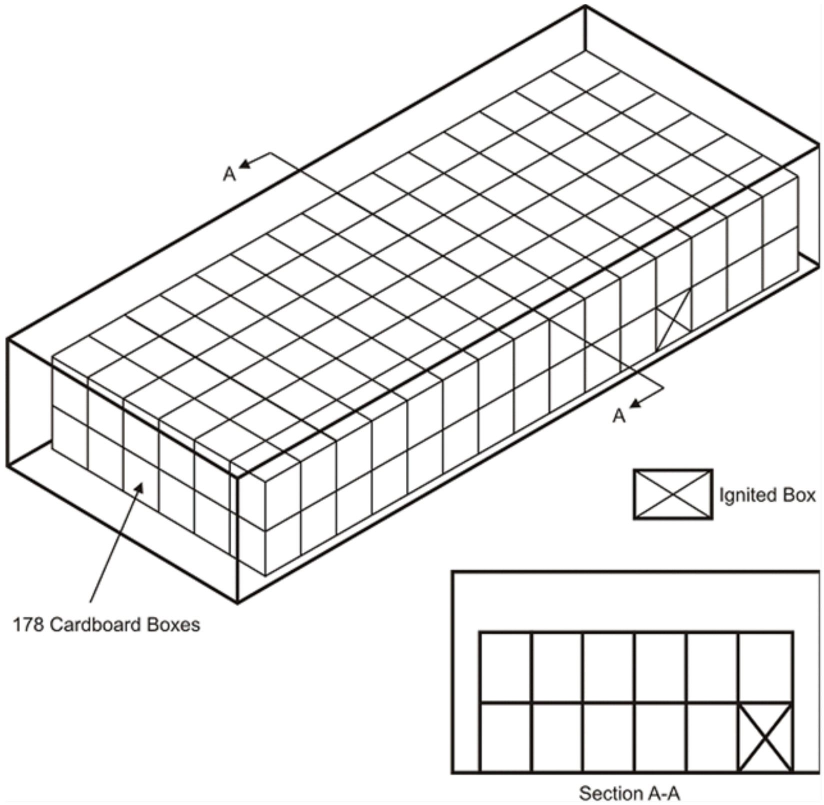

Figure 6. Bulk Load Fire Scenario Setup

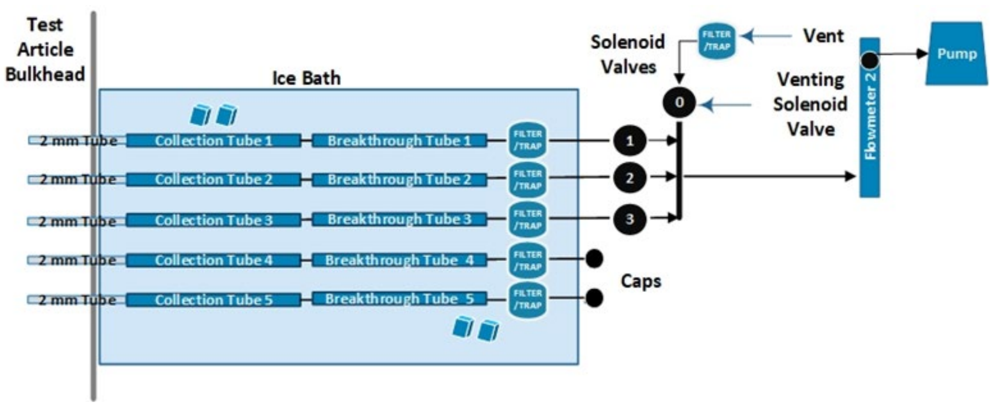

Figure 7. Acid Gas Collection System

2.3.3 Containerized Fire Scenario

The containerized fire scenario is designed to represent the hazard posed by a fire within a unit load device (ULD) inside a below-floor cargo compartment. In this scenario, an LD3 container, a specific type of ULD, is loaded with 33 cardboard boxes made as described earlier in Section 2.3.2. The LD3 container, as shown in Figure 8, has one of the 33 cardboard boxes replaced with an ignition box. The ignition box is placed in the middle column on the bottom row along the sloped wall. The location of the ignition box is shown in Figure 9. Two more LD3 containers are placed adjacent to the container filled with boxes as shown in Figure 9.

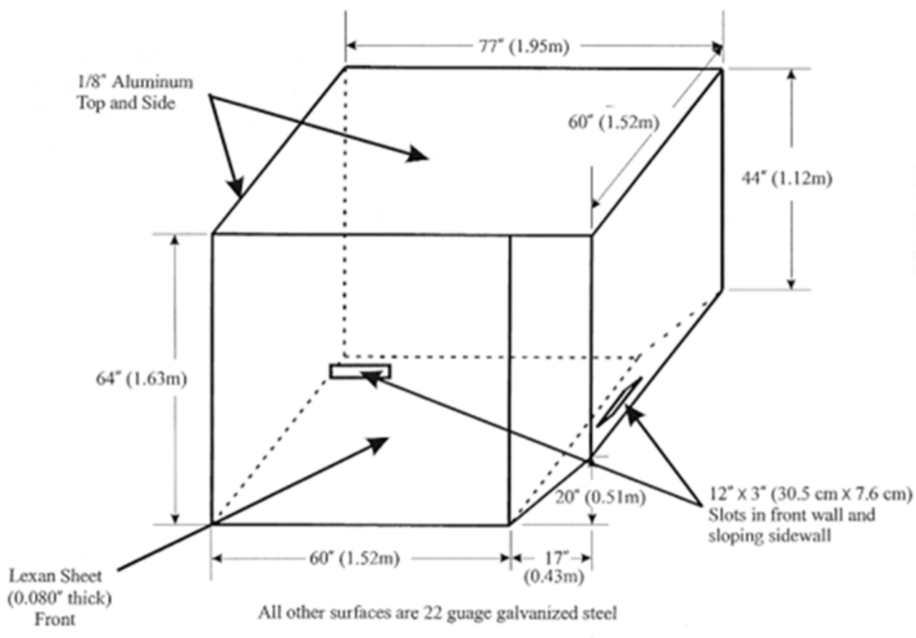

Figure 8. LD3 Container

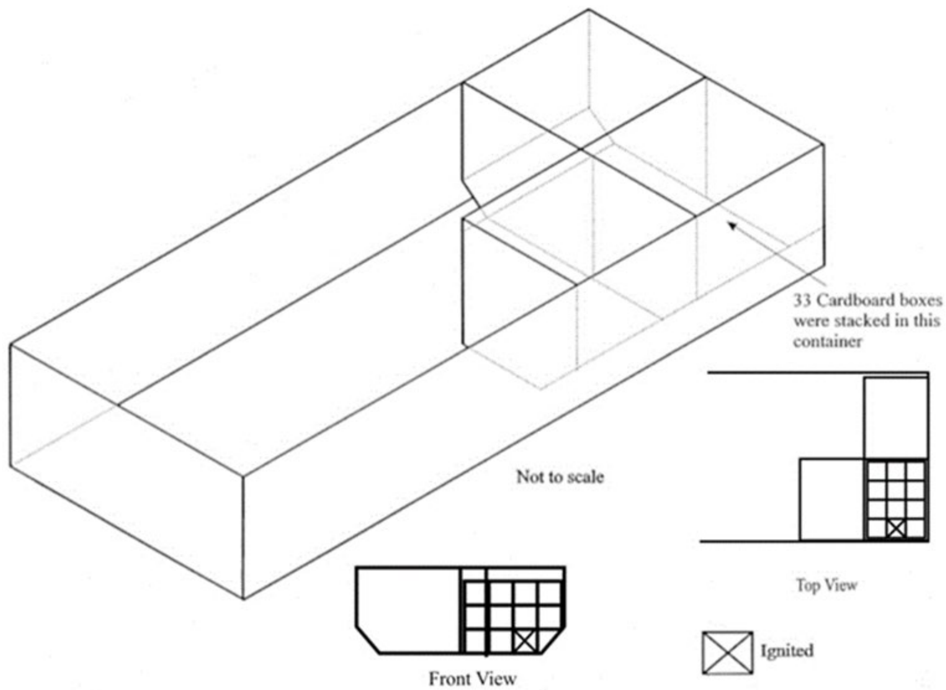

Figure 9. Containerized Fire Scenario Setup

2.3.4 Aerosol Can Explosion Simulation Scenario

The fire load in this scenario was an aerosol can simulator that is designed to represent the hazard of an aerosol can involved in a cargo compartment fire. The aerosol can explosion simulation test scenario is based on a cargo compartment fire progressing towards an aerosol can packed within a piece of luggage. The fire in the compartment increases the temperature of the aerosol can, resulting in an increase of pressure inside the can until the contents are quickly released. Hence, it is assumed that the cargo compartment smoke detector would have detected the presence of a fire and the suppression system would have been activated by the time the aerosol can reached its critical temperature. The aerosol can simulator was filled with a mixture of 3.2 ounces of liquid propane, 3.2 ounces of water, and 9.6 ounces of ethanol and then pressurized to 240 psig. The total weight of the mix is 16 ounces which simulates a typical 16-ounce hairspray aerosol can. A heat tape was used to heat the simulator surface, pressurizing the contents inside. The simulator pressure was maintained by a ball valve that is opened using a pneumatic rotary actuator. Triggering the actuator releases the pressurized contents in a conical spray over the electrodes. The simulator is placed along the centerline of the otherwise empty compartment with the sparking electrodes placed 36 inches in front of the opening of the simulator as shown in Figure 10. Triggering of the actuator occurs when the minimum inerting concentration is reached at the gas probe measuring 18 inches to the side of the spark ignitors. A separate sample tube was run to the analyzers only for this test to reduce the travel time to 28 seconds to improve the accuracy of the time at which the actuator was triggered.

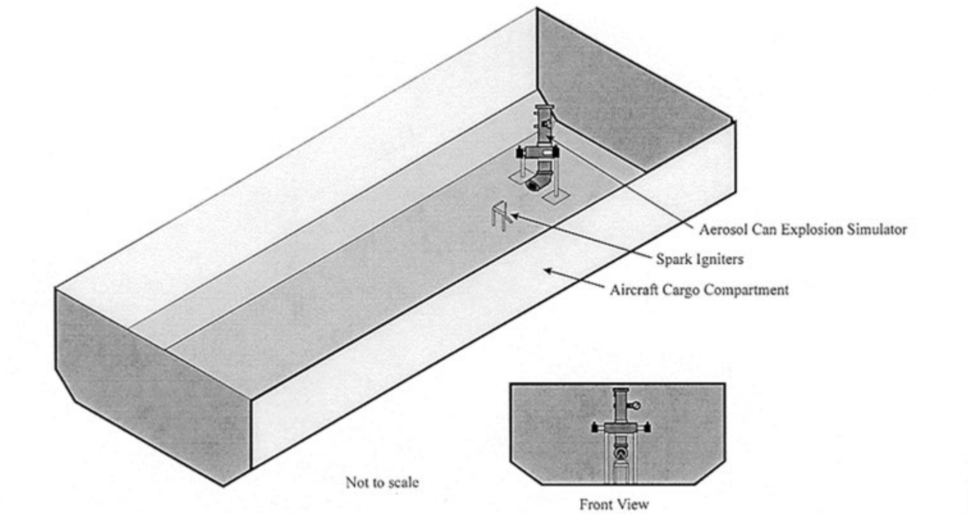

Figure 10. Aerosol Can Explosion Simulator Test Setup

2.4 Ignition System

2.4.1 Ignition Box

The ignition box was used in the bulk load fire scenario and the containerized fire scenario as the mechanism to initiate the fire within the compartment. The ignition box, as shown in Figure 10, was a single walled corrugated cardboard box sized at 18 in x 18in x 18in. The box was filled with 2.5 lbs of loosely packed shredded office paper. A 7-foot-long Nichrome (NiCr) wire was wrapped around four folded paper towels and was connected to an 115VAC electrical source to provide the resistance heat to create the ignition source. This mechanism was placed in the middle of the shredded paper. One face of the cardboard box featured ten 1-inch diameter holes to provide ventilation to the recently ignited fire. The pattern of ventilation holes is shown in Figure 11.

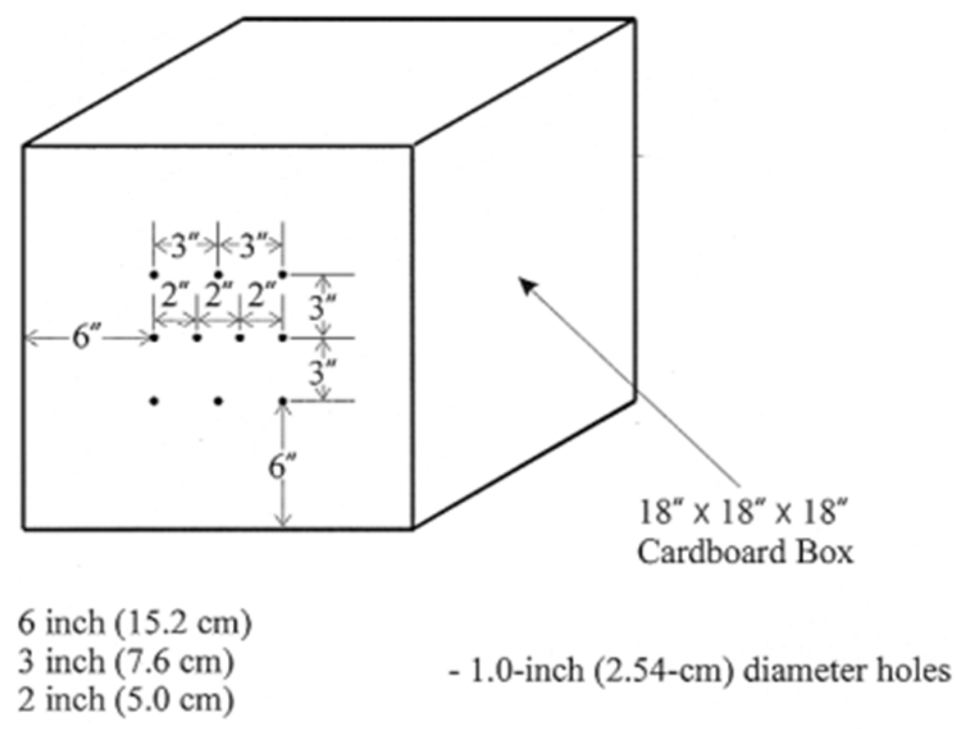

Figure 11. Ignition Box

2.4.2 Electrical Arc

The ignition method used in the surface burning fire scenario and the aerosol can explosion simulation scenario employed a set of DC arc igniters. The igniters are connected to an Allanson transformer, model 421-BT636, which provides 10,000V over 23mA between the tips of the two igniters to create an electrical arc. The igniters used were Westwood 2M5 electrodes and the tips were placed a ¼ inch apart. The arc provides a steady ignition source for the duration of the aerosol simulator discharge as well as until the surface burning fire is initiated.

3 Test Procedures

The series of testing was initiated with concentration tests to determine the adequacy of the agent delivery system and to alleviate concerns of agent stratification and separation. The concentrations tests were followed by the MPS tests. All of the tests were initiated with the cargo door closed and ventilation system turned on. The ventilation system turns on a motor that produces a 50 ± 5 cfm leakage rate for the duration of the tests (Reinhardt, 2012).

3.1 Concentration Tests

The concentration tests were performed in an empty cargo compartment. The data acquisition system recorded the temperatures, gas concentrations inside the compartment, and gas concentration in the cabin above the compartment. The agent was then discharged into the compartment and monitored. The agent discharge sequence was initiated by activating the knockdown sub-system. Upon emptying the knockdown sub-system, the sustaining sub-system was activated which discharged the agent at a steady rate into the compartment. The compartment was monitored for agent concentration using the Halonyzer as well as the Rosemount 880A analyzers for the individual components of the agent. Three tests were conducted for a duration of 30 minutes each to observe the consistency of the agent delivery system.

3.2 Surface Burning Fire Scenario

This test was initiated with the pan placed between two nozzles and in the middle of the compartment so that the agent wasn't directly sprayed onto the pan. The pan was filled with the fuel mixture and the compartment was then closed and the ventilation system was turned on. The data acquisition recorded and provided a live display of the temperatures and gas concentrations within the compartment. The spark igniters were activated which ignited the fuel vapors to commence the surface burning fire scenario.

Ceiling temperatures were monitored to determine the exact time at which any of the ceiling thermocouples reached 200°F, the trigger point. This time was noted and the agent was discharged into the compartment exactly one minute after the trigger point was achieved. Only the knockdown system was discharged for this test scenario due to the short test time. The temperatures within the compartment were monitored for 5 minutes after the agent discharge and then the test was terminated. The data acquisition system continued collecting data for an additional minute to account for the delay in gas concentration measurements due to the line lengths of the gas sampling system. The test was conducted 5 times for a duration of 5 minutes each as prescribed by the MPS.

3.3 Bulk Load Fire Scenario

This test was initiated with the 178 cardboard boxes loaded in the compartment and the ignition system readied as described in the Fire Scenarios section of Reinhardt (2012). The compartment was closed and the ventilation system was turned on. The data acquisition was used to record data and provide a live display of the temperatures and gas concentrations within the compartment. The ignition box was activated to commence the bulk load fire scenario.

Ceiling temperatures were monitored to determine the exact time at which any of the ceiling thermocouples reached 200°F, the trigger point. This time was noted and the agent was discharged into the compartment exactly one minute after the trigger point was achieved. The temperatures within the compartment were monitored until the test was terminated. The data acquisition system was collecting data for a subsequent minute to account for the delay in gas concentration measurement due to the line lengths of the gas sampling system. The test was conducted five times, four of the tests were 30 minutes in duration and one test lasted 180 minutes, as prescribed by the MPS. Acid gas concentrations were measured for two of the five bulk load tests (Test#3 and Test #4). The acid gas measurements were collected in three 10-minute samples that provided the average concentration of the acid gases over each sample time. Once the suppression agent was activated the solenoid valve switched to each collection tube sequentially for a 10-minute period. The acid gas collection tube wash solutions were analyzed using i fluoride ion selective electrodes and Ion Chromatography (IC) to determine the concentrations histories of Hydrogen Fluoride (HF) and Hydrogen Bromide (HBr) (Speitel, 1995).

3.4 Containerized Fire Scenario

This test was performed with one LD3 container filled with 33 cardboard boxes and the ignition box readied. Two additional empty LD3 containers were placed in the compartment next to the loaded LD3 container. The compartment was closed and the ventilation system was turned on. The data acquisition was turned on to record and provide a live display of the temperatures and gas concentrations within the compartment. The ignition box was activated to commence the containerized fire scenario.

The ceiling temperatures were monitored to determine the exact time at which any of the ceiling thermocouples reached 200°F, the trigger point. This time was noted and the agent was discharged into the compartment exactly one minute after the trigger point was achieved. The temperatures within the compartment were monitored until the test was terminated. The data acquisition system collected data for a subsequent minute to account for the delay in gas concentration measurement due to the line lengths of the gas sampling system. The test was conducted five times, four of the tests were 30 minutes in duration and one lasted 180 minutes, as prescribed by the MPS.

3.5 Aerosol Can Explosion Simulation Scenario

This testing was performed by conducting baseline tests within the cargo compartment followed by the MPS required tests.

3.5.1 Baseline Testing

The purpose of the baseline testing was to ensure that the pressure rise caused by the simulator being discharged into the compartment was measured. The averaged value of the highest-pressure rise observed over three baseline tests will be considered as the maximum allowable pressure during the MPS testing of the aerosol can explosion simulation scenario.

The baseline tests were initiated by placing the filled aerosol can simulator in the empty compartment. The compartment was closed and the ventilation system was turned on. The data acquisition was turned on to record and provide a live display of the temperatures and gas concentrations within the compartment. The simulator was pressurized to 240 psi using a heat tape which typically took about eight to nine minutes. The knockdown bottle of the agent was then discharged into the compartment. As the concentration of the agent measured by the spark ignitors reached the minimum inerting concentration, the readied aerosol can simulator at 240 psi was discharged without activating the spark ignitors. The high-speed data acquisition system was started 5 seconds prior to the discharge of the simulator and turned off 5 seconds after the event. This was repeated three times to obtain an average baseline pressure measurement within the compartment from the simulator operating in an environment similar to the MPS tests.

3.5.2 Aerosol Can Explosion Testing

The aerosol can explosion testing was initiated similarly to the baseline testing except that the spark ignitors are active when the simulator is discharged. The spark ignitors are activated approximately 10 seconds prior to the simulator discharge. The high-speed data acquisition system was started 5 seconds prior to the discharge of the simulator and turned off 5 seconds after the event. This test was repeated five times as prescribed by the MPS. The test data acquisition was turned off a minute after the high-speed data acquisition was turned off to account for the delay in gas concentration measurement due to the line lengths of the gas sampling system.

4 Results and Analysis

4.1 Concentration Tests

The results of the concentration tests are discussed and analyzed in this section. Figure 12, Figure 13, and Figure 14, show the concentration of VERDAGENT® as calculated from measured values of 2-BTP and CO_2 by the Rosemount analyzers at three different heights in the center of the compartment. The measurements of VERDAGENT® as represented by the Rosemount analyzers are values that are calculated from measured values of carbon dioxide and 2-BTP. For the figures showing concentration measurement plots, Verdagent#1 is the concentration calculated by the gases measured in the R1 location, Verdagent #2 is the concentration calculated by the gases measured in the R2 location, and Verdagent#4 is the concentration calculated by the gases measured in the R4 location as shown in Figure 4 The agent concentration measurement for the R1 location appears to have a noisier signal than the rest of the locations since the probe is placed close to the agent discharge nozzles and the small pressure difference locally creates this effect.

The concentration tests were performed to ensure that there was a homogenous mixture throughout the compartment. As described earlier in Section 1.3, the design concentration for knockdown was 11.5% by volume and the sustaining design concentration was 11% by volume. The results show that the concentrations as calculated by the Rosemount analyzers reached 11.5% during the knockdown phase and maintained a concentration above 11% during the sustaining phase at the ceiling probe. The other two probes beneath the ceiling probe show a higher concentration due to the agent settling over time since VERDAGENT® is denser than air. Fire tests conducted at the technical center show the importance of maintaining the MIC at the ceiling due to the convective stirring caused by the heat of the suppressed fire. If the agent concentration drops below the MIC, most likely at the ceiling, re-ignition could occur. Hence, these tests show that the system was able to maintain the MIC at the ceiling for the required duration of the test. As stated in Section 7.3 of AC 25.851-1 that "compliance requires the use of point-concentration data from each sensor and that the sensors closest to the cargo compartment ceiling be at least at the highest level that cargo and baggage can be loaded as specified by the manufacturer and certified by the FAA" (FAA, AC No: 25.851-1, 2016).

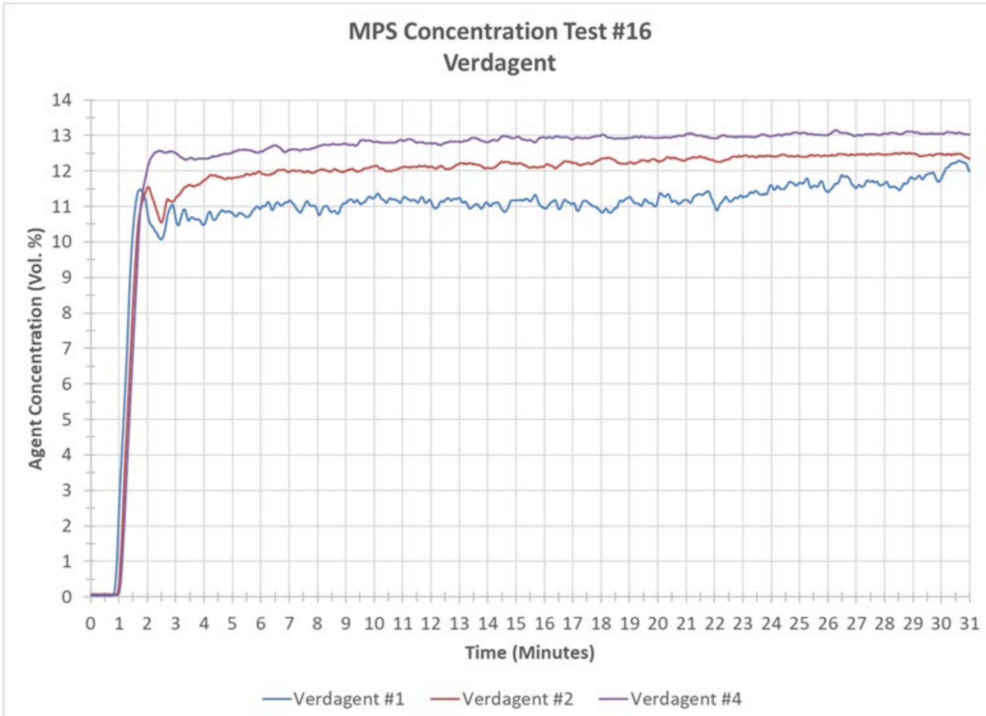

Figure 12. MPS Concentration Test# 16: Rosemount Analyzer Measurement

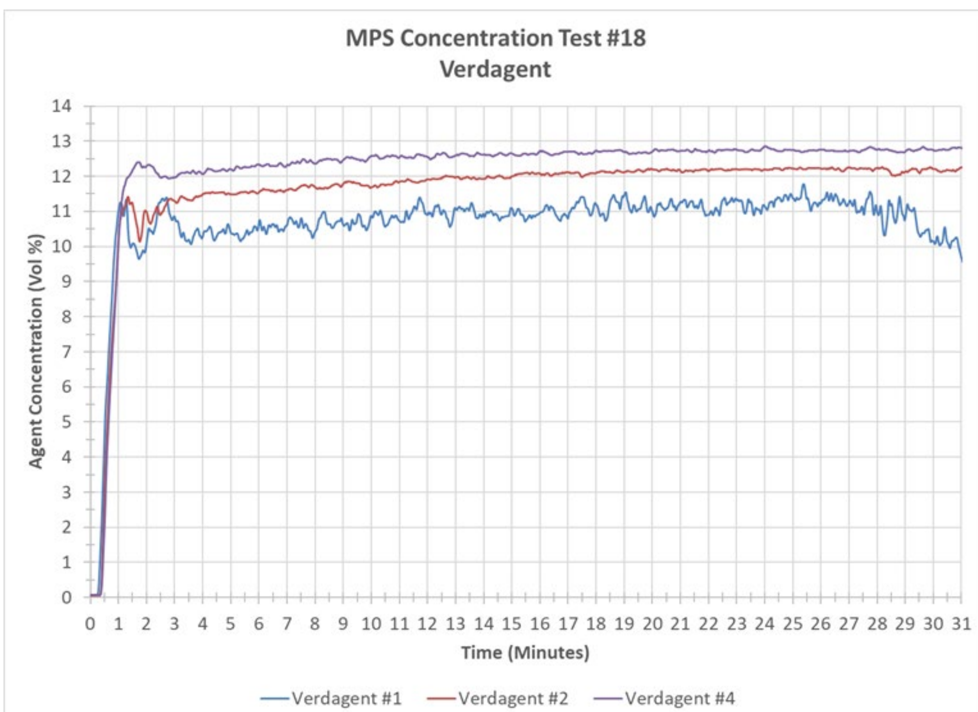

Figure 13. MPS Concentration Test #18: Rosemount Analyzer Measurement

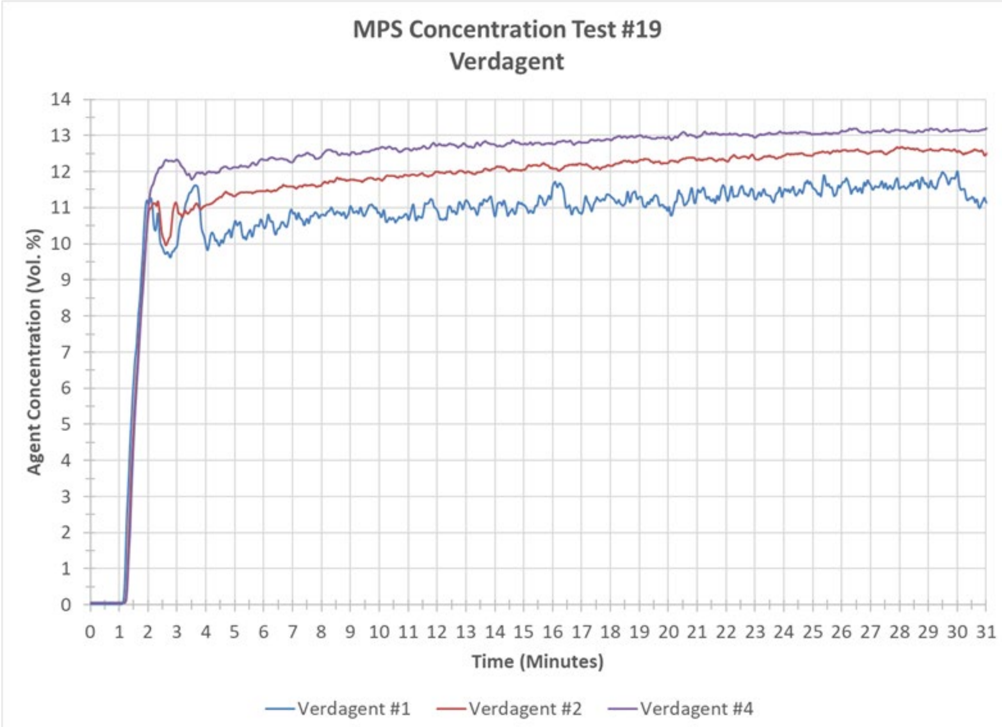

Figure 14. MPS Concentration Test #19: Rosemount Analyzer Measurement

Figure 15, Figure 16, and Figure 17 show the concentration of VERDAGENT® as measured with the Halonyzer IV. The concentration values measured at the ceiling are an average from the concentrations measured at probe locations 1, 4, 7, 10, 13, 16, 19, and 22 as shown in Figure 2. The concentration values measured at mid-height are an average from the concentrations measured at probe locations 2, 5, 8, 11, 14, 17, and 20 as shown Figure 2. The concentration values measured at the floor are an average from the concentrations measure at probe locations 3, 6, 9, 12, 15, 18, 21, and 23 as shown in Figure 2. The results show that the concentrations as measured by the Halonyzer reach above 11.5% during the knockdown phase and maintained a concentration above 11% during the sustaining phase.

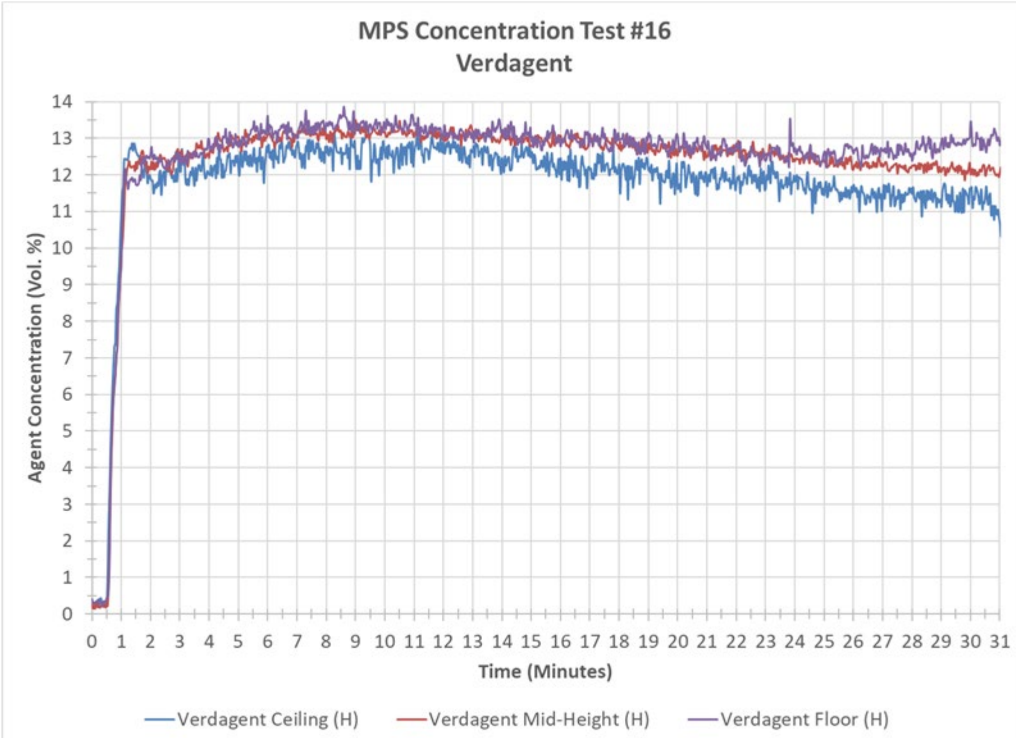

Figure 15. MPS Concentration Test #16: Halonyzer Measurement

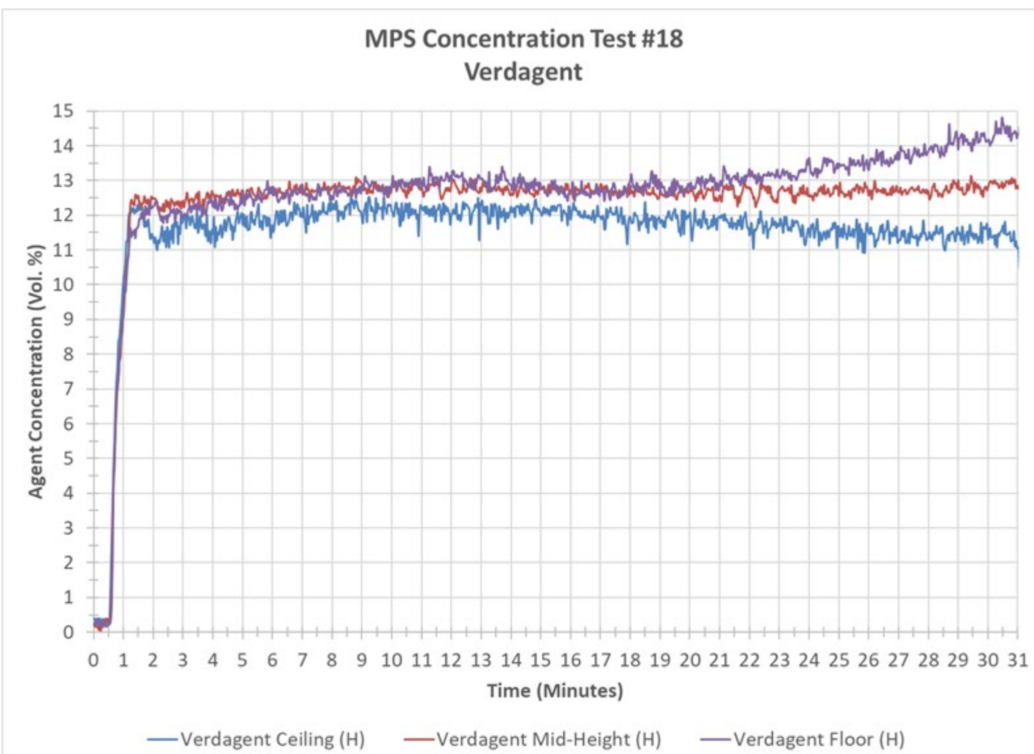

Figure 16. MPS Concentration Test #18: Halonyzer Measurement

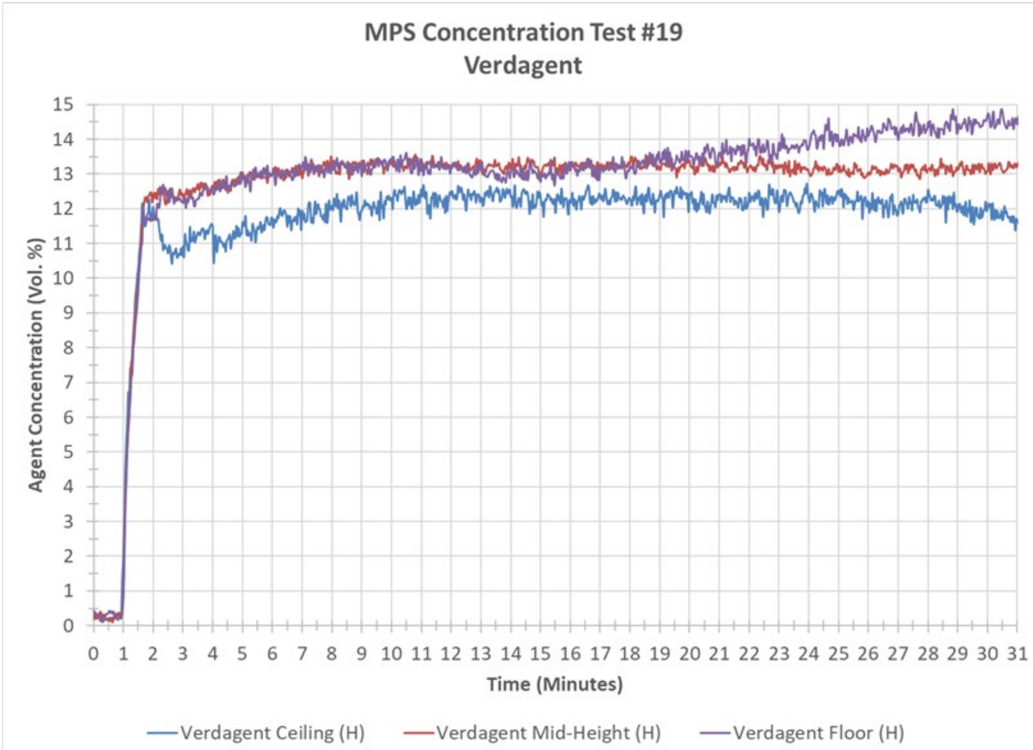

Figure 17. MPS Concentration Test #19: Halonyzer Measurement

Figure 18, Figure 19, and Figure 20 show the average concentration of VERDAGENT® as measured by the Rosemount gas analyzer and Halonyzer. They also show the concentration of the fire suppression agent that is predicted by using the measured CO_2 concentration values and the expected volume fraction of CO_2 in VERDAGENT®.

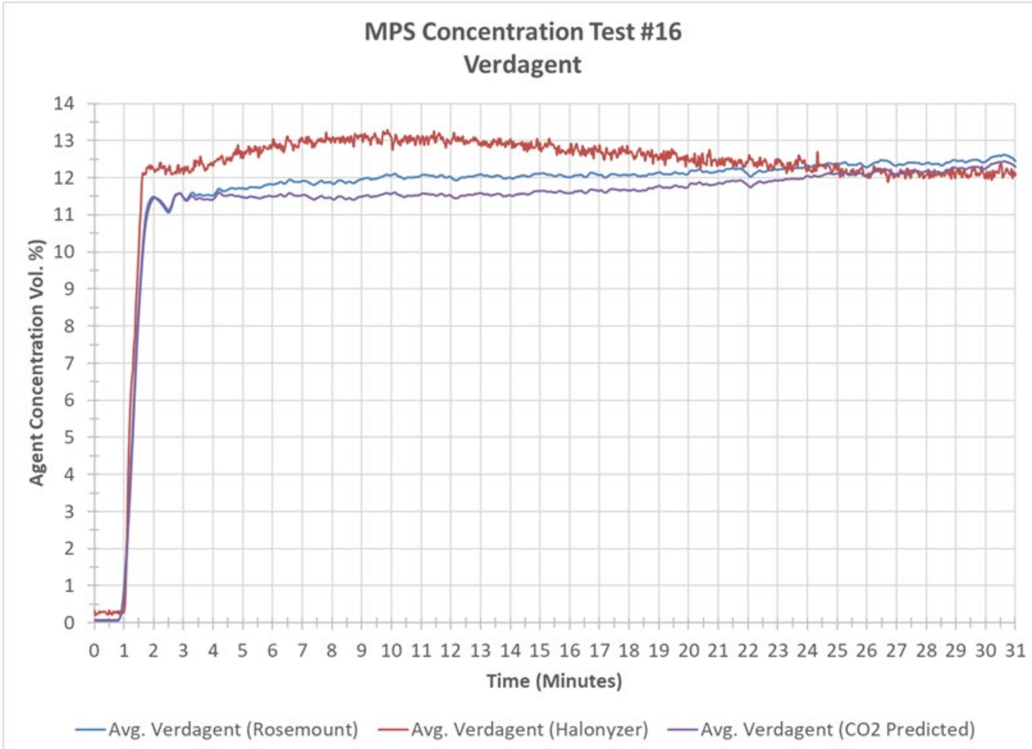

Figure 18. MPS Concentration Test #16: Average Agent Concentration

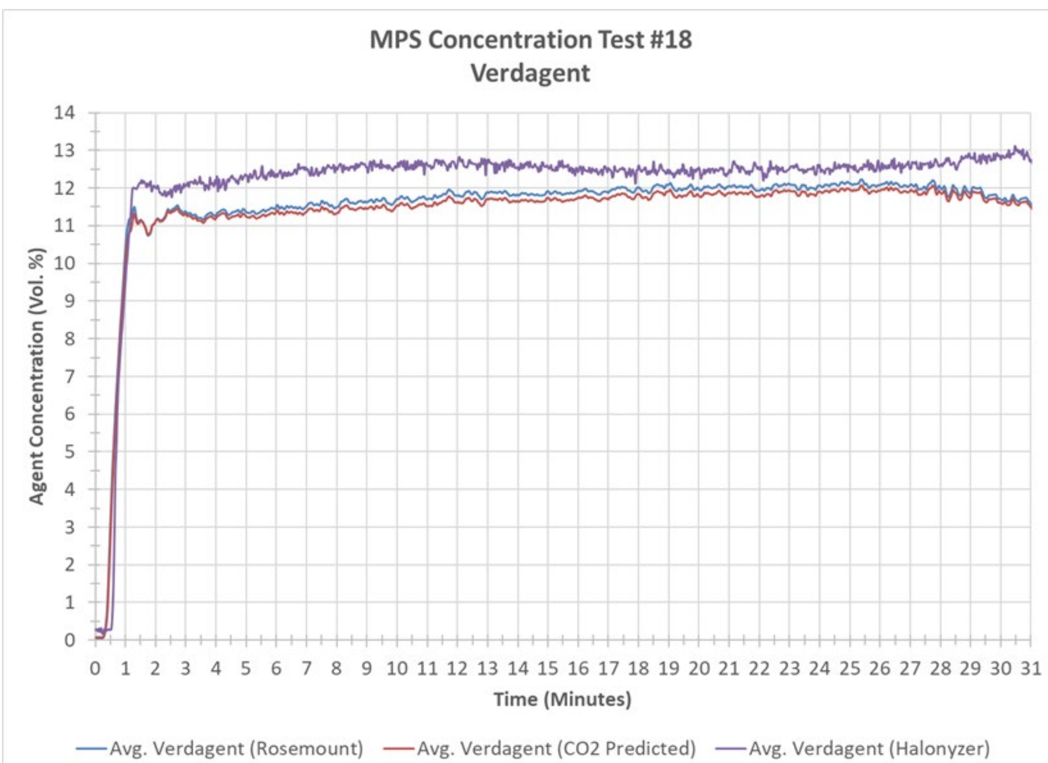

Figure 19. MPS Concentration Test #18: Average Agent Concentration

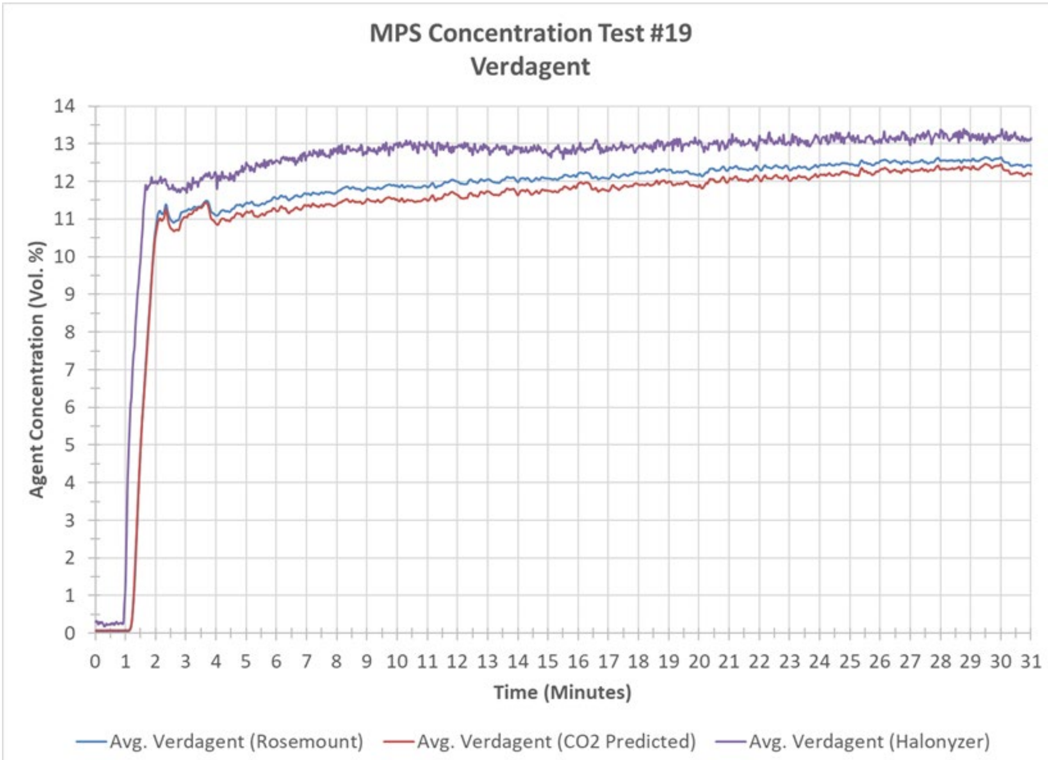

Figure 20. MPS Concentration Test #19: Average Agent Concentration

Figure 21, Figure 22, and Figure 23 show the ratio of 2-BTP to VERDAGENT® present in the compartment during the concentration tests at different heights. The ratio is calculated from gas concentration values of CO_2 and 2-BTP measured by the Rosemount analyzers. This analysis shows that the agent does not separate after being discharged into the compartment. If there was blend separation, the results would show a lower ratio at the ceiling and a higher ratio at the lower locations. The results show that the fire suppression distribution system maintains the ratio around 0.21±0.02 for most of the test and hence proves that there is no blend separation and the presence of a homogenous mixture. The initial rise in the ratio is attributed to the agent being injected rapidly into the compartment during the knockdown phase. Once the sustaining phase activates streaming agent into the compartment, the environment within the compartment is more stable and stability of the ratio supports this observation.

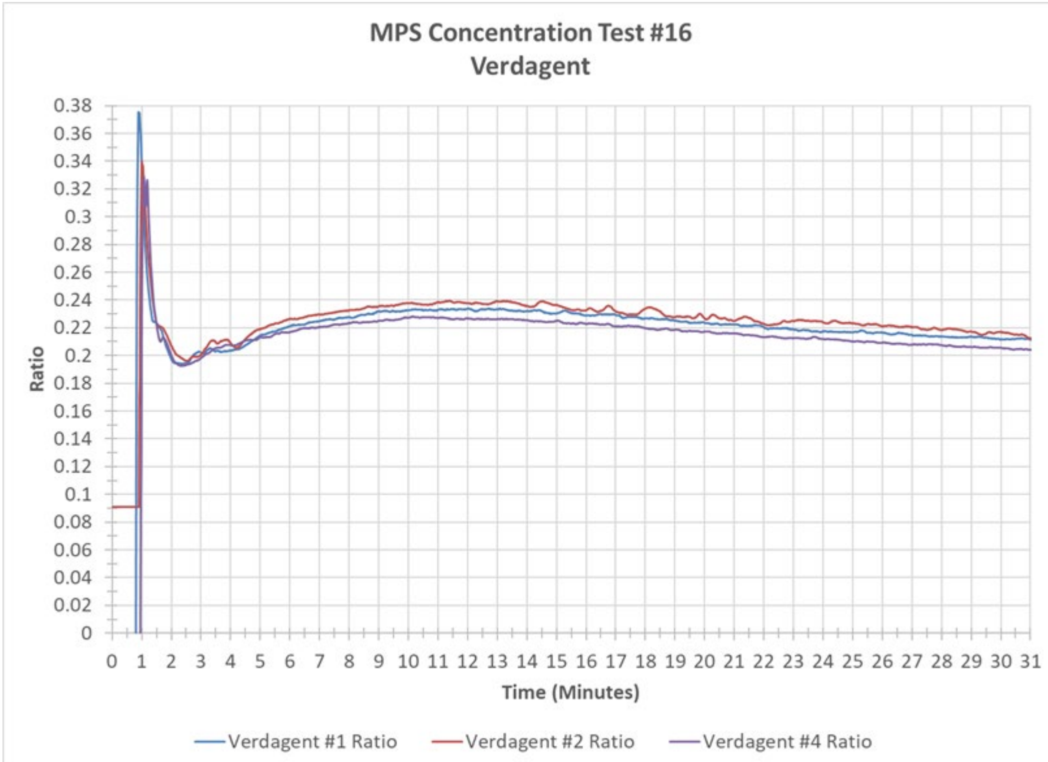

Figure 21. MPS Concentration Test #16: Ratio

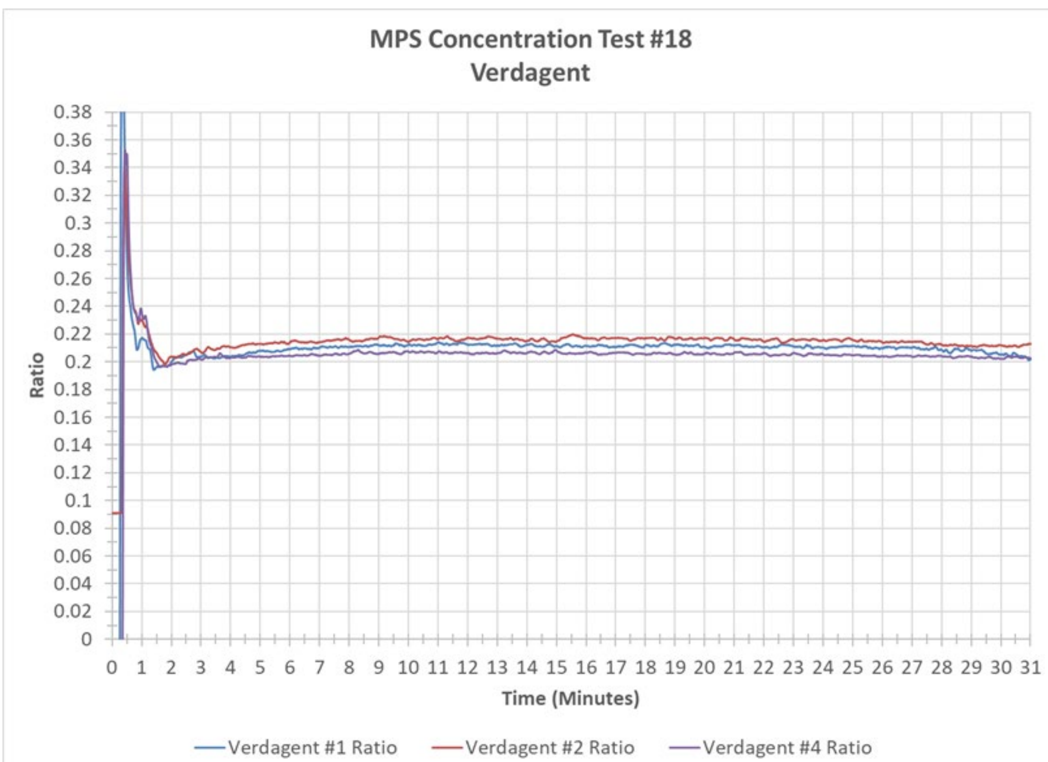

Figure 22. MPS Concentration Test #18: Ratio

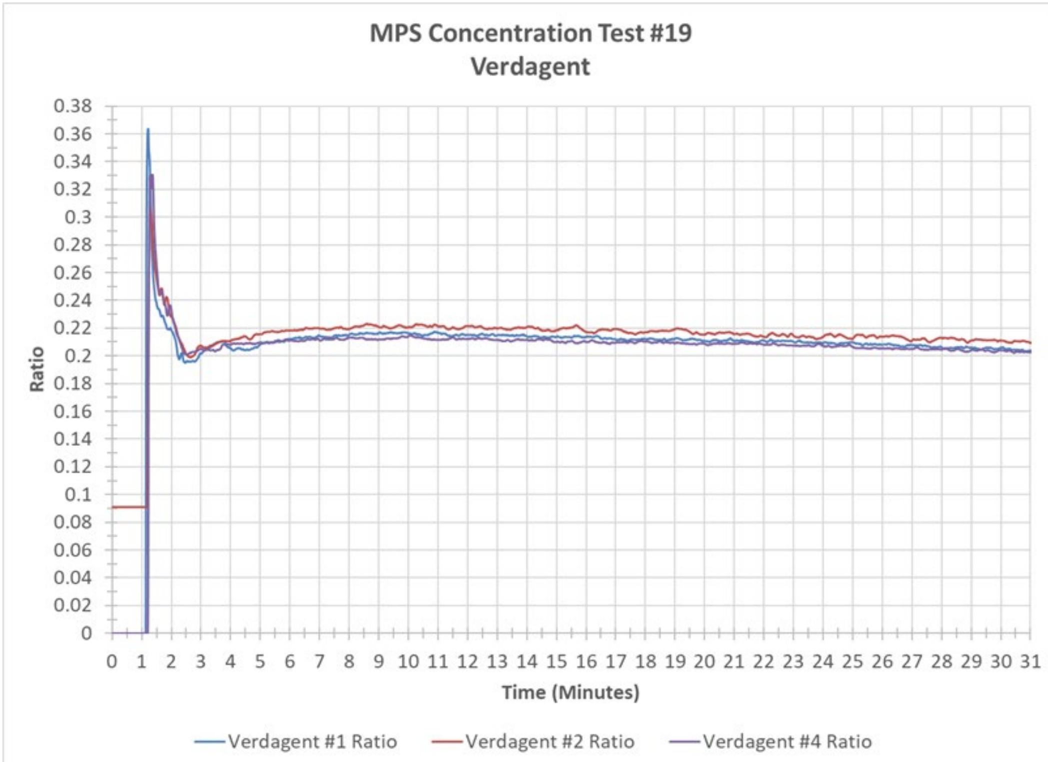

Figure 23. MPS Concentration Test #19: Ratio

The measurements obtained from the Halonyzer and the Rosemount analyzers indicate that the agent distribution system is capable of providing a uniform mixture of VERDAGENT® in the compartment. There was no indication of agent stratification or separation based on the gas concentration measurements from the concentration tests.

4.2 Surface Burning Fire Tests

The results from the surface burning fire tests are summarized in this section and compared to the acceptance criteria described in the MPS (Reinhardt, 2012). As per the MPS, the acceptance criteria for this fire scenario states that the average of the five test peak temperatures shall not exceed 570°F starting 2 minutes after the suppression system is initially activated until the end of the test. In addition, the average of the five test areas under the time-temperature curve shall not exceed 1190°F-Min. The time-temperature area is computed for the 3-minute time interval from two to five minutes after the activation of the fire suppression system. The time-temperature area is calculated by multiplying the temperature at a specific time by the time increment and then adding up all the areas calculated or integrating the temperature versus time curve.

Table 1 summarizes the peak temperatures observed and the time-temperature integral calculated from each of the tests. The test results show that VERDAGENT® was able to pass the surface burning fire scenario with an average peak temperature of 433°F and the average time-temperature integral of 971°F-Min.

Table 1. Surface Burning Fire Test Results

Date	**Test #**	**Peak Temperature (°F)**	**Time-Temperature Integral (°F-Min)**	**Video Reference #**
1/28/2019	Test 1	424	937	TST 683.13
3/5/2109	Test 4	451	1008	TST 683.13
3/6/2019	Test 5	423	958	TST 683.13
3/6/2019	Test 6	442	982	TST 683.13
3/7/2019	Test 7	426	973	TST 683.13
	Average	433	971	
	Acceptance Criteria	570	1190	

The temperature results from each of the tests are shown in Figure 24, Figure 25, Figure 26, Figure 27, and Figure 28. Each figure displays the temperature data from the thermocouple that reached the peak temperature with a solid black line, an average temperature of the surrounding four thermocouples with a solid green line, and the oxygen concentration measured at station 1 by a blue dashed line. The figures also depict the time at which ignition occurred, the trigger temperature of 200°F was reached, the agent activation, 2-minute mark of the test (which denotes the start of the evaluation period), and the 5-minute mark of the test (which denotes the end of the evaluation period as well as the end of test) with a vertical solid red line. The average temperature of the surrounding ceiling thermocouples is displayed to observe the fire spread within the compartment.

The temperature results show a quick rise in temperature when the fire is lit and a sharp decline in temperature as the fire suppression agent is activated. As the temperature starts to rise, the oxygen concentration begins decreasing which indicates the presence of a fire. As the fire suppression agent is activated and the temperatures start decreasing, the oxygen concentration increases above 12%. Twelve percent oxygen concentration in an enclosed environment is generally regarded as the minimum amount of oxygen needed for ignition (Summer, 2004). Hence, the steady presence of a higher level of oxygen concentration means the fire is extinguished in this scenario.

To obtain a copy of the videos for the testing accomplished at the W.J. Hughes Technical Center, contact 9-act-troubledesk@faa.gov with a reference to this report and the video reference number associated with each fire scenario.

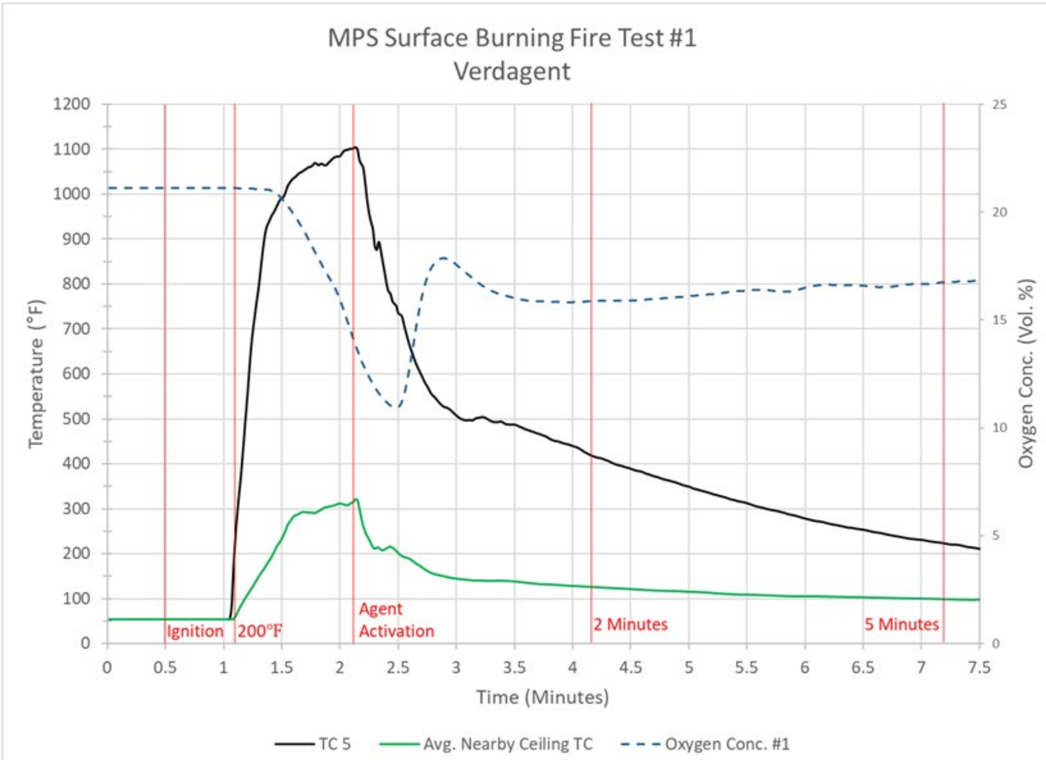

Figure 24. Results from Surface Burning Fire Test #1

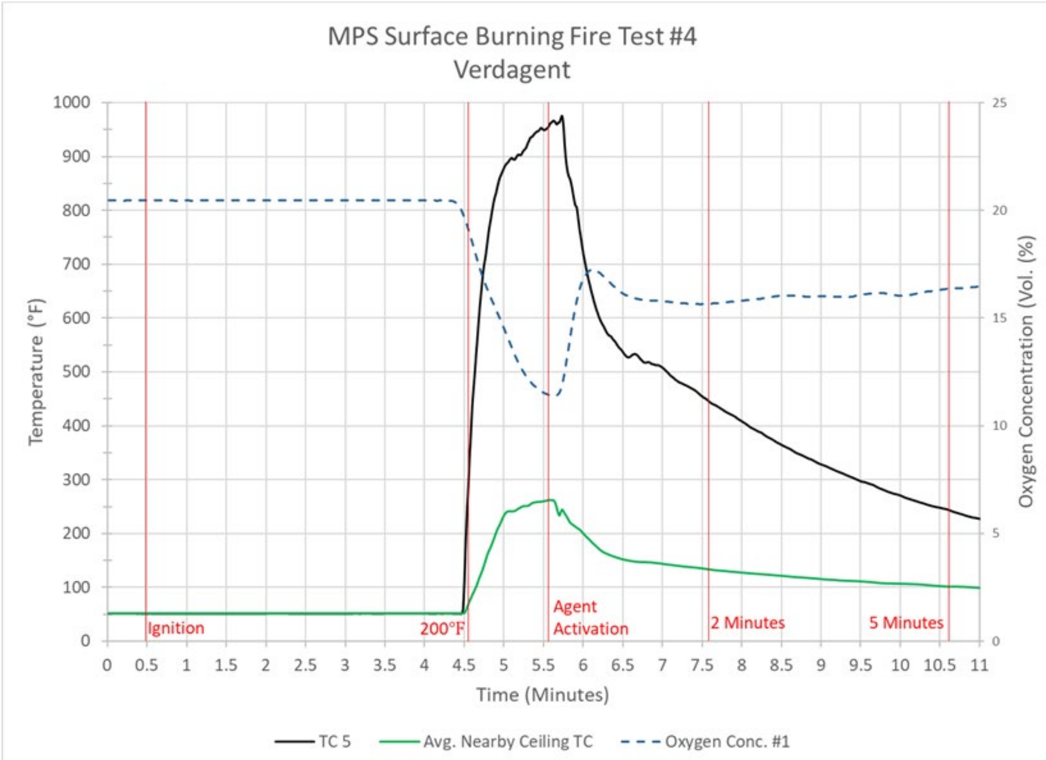

Figure 25. Results from Surface Burning Fire Test #4

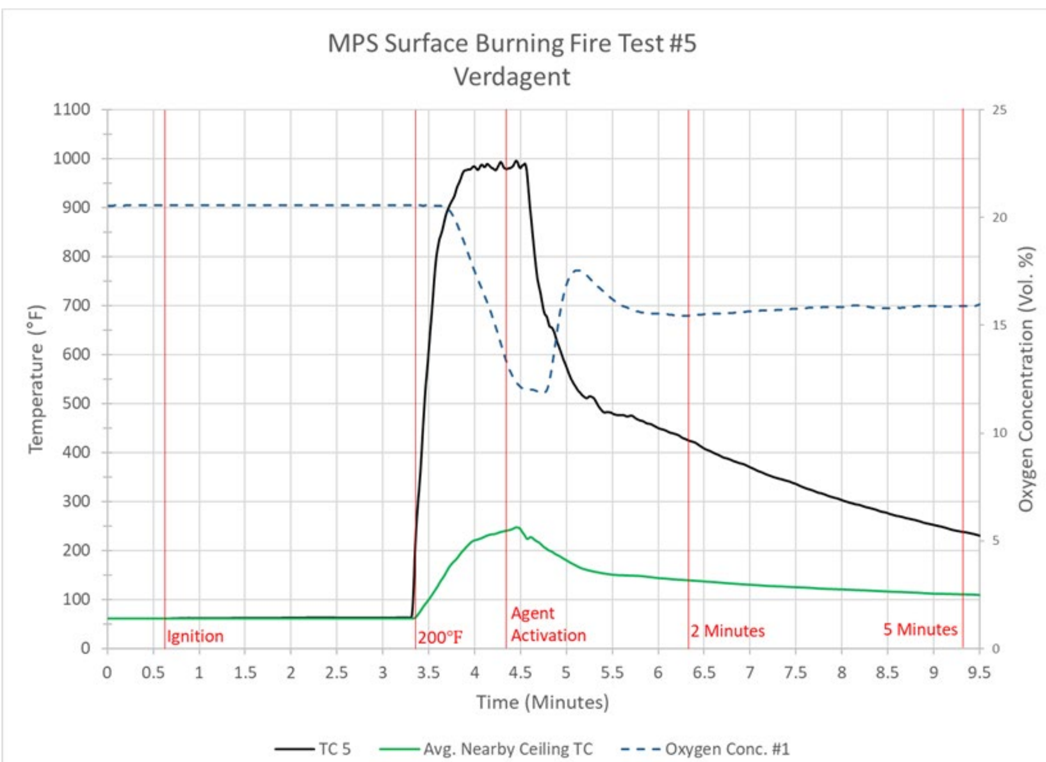

Figure 26. Results from Surface Burning Fire Test #5

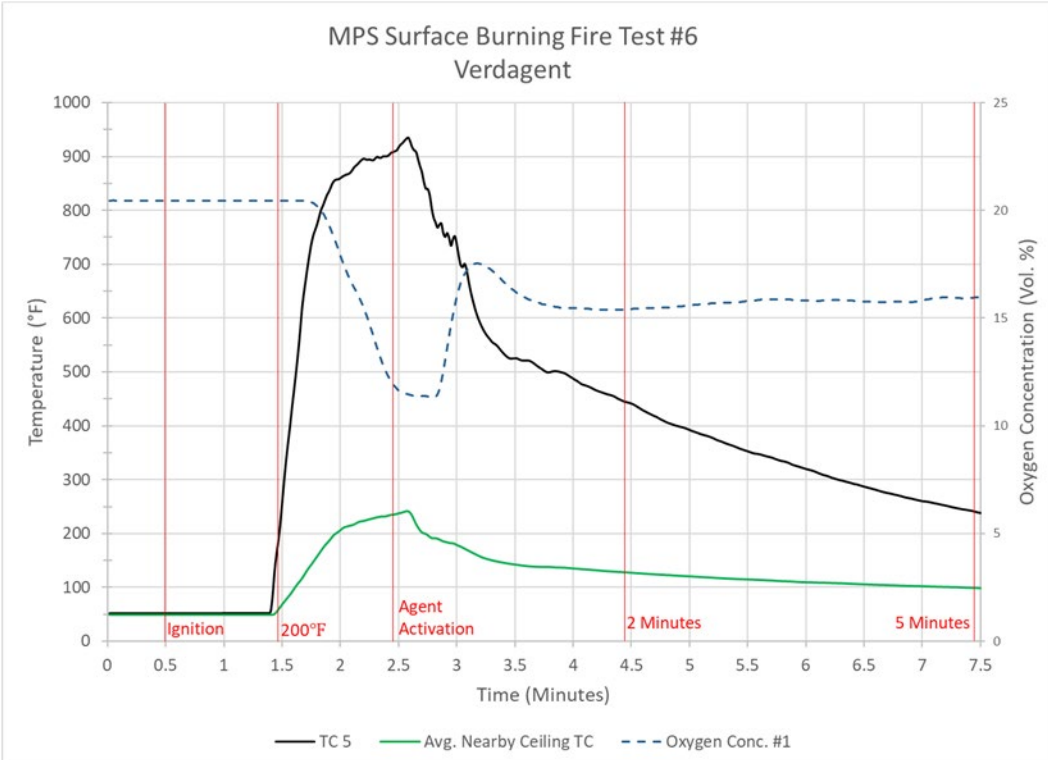

Figure 27. Results from Surface Burning Fire Test #6

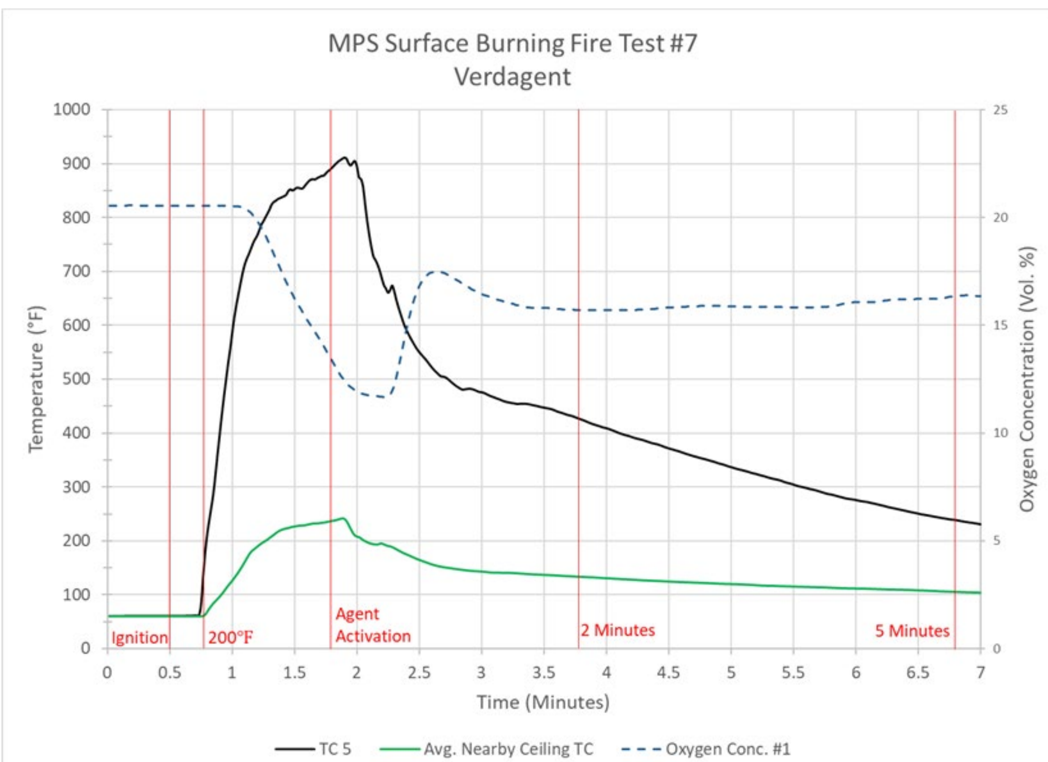

Figure 28. Results from Surface Burning Fire Test #7

4.3 Bulk Load Fire Tests

The results from the bulk load fire tests are summarized in this section. The results were compared to the acceptance criteria as set by the MPS (Reinhardt, 2012). As per the MPS, the acceptance criteria for this fire scenario is that the average of the five test peak temperatures shall not exceed 710°F, starting 2 minutes after the suppression is initially activated until the end of the test. In addition, the average of the five test areas under the time-temperature curve shall not exceed 9850°F-Min. The time-temperature area is computed for the 28-minute time interval between 2 to 30 minutes after the activation of the fire suppression system. The time-temperature area is calculated by multiplying the temperature at a specific time by the time increment and then adding up all the areas calculated or integrating the temperature versus time curve. An additional acceptance criteria for the long duration test was to ensure that the temperatures at the end of the test are stable or decreasing.

Table 2 summarizes the peak temperatures observed and the time-temperature integral calculated from each of the tests. The test results show that the fire suppression agent was able to pass the bulk load fire scenario by limiting the average peak temperatures to 289°F and the average time-temperature integral to 5649°F-Min.

Table 2. Bulk Load Fire Test Results

Date	**Test #**	**Peak Temperature (°F)**	**Time-Temp Integral (°F-Min)**	**Video Reference #**
1/30/2019	Test 1	286	5583	TST 683.11
6/13/2019	Test 2	334	5603	TST 683.11
7/9/2019	Test 3	259	5584	TST 683.11
7/11/2019	Test 4	292	6163	TST 683.11
7/15/2019	Test 5	274	5314	TST 683.11
	Average	289	5649	TST 683.11
	Acceptance Criteria	710	9850	

The temperature results from each of the tests are shown in Figure 29, Figure 30, Figure 31, Figure 32, Figure 33, and Figure 34. Each figure displays the temperature data from the thermocouple that reached the peak temperature with a solid black line and an average temperature of the surrounding four thermocouples with a solid green line. The figures also depict the time at which ignition was initiated, the trigger temperature of 200°F was reached, the agent activation, 2-minute mark of the test (which denotes the start of the evaluation period), and the 30-minute mark of the test (which denotes the end of the evaluation period as well as the end of test) with a vertical solid red line. The long duration test also depicts the 180-minute mark of the test which denotes the end of that particular test.

The test results from MPS Bulk Load Fire Test #1, as shown in Figure 29 display the oxygen concentration measurement until minute 17 of the test. The rest of the gas data during the testing was lost. The oxygen concentration measurement is displayed to show a representative environment present inside the test cell and it wasn't part of an acceptance criteria of the test. Hence, the loss of gas data for this one particular test doesn't alter its status as an acceptable test. The test results from MPS Bulk Load Fire Test #2, as shown in Figure 30displays a dip in the oxygen concentration between the second and fourth minute of the test. This dip was due to a filter bank being clogged and the issue was resolved by switching to an alternate filter bank to resume the correct measurement of the oxygen concentration.

The results show a quick rise in temperature when the fire spreads across the fire load and a sharp decline in temperature as the fire suppression agent is activated. As the temperature starts to rise, the oxygen concentration begins decreasing which indicates the presence of a fire. As the fire suppression agent is activated and the temperatures start decreasing, the oxygen concentration slowly decreases and steadies around 10%. This indicates the presence of a deep-seated fire that continues to consume the slowly entraining oxygen at a slow rate. This also shows that the fire suppression agent is successfully suppressing the fire.

To obtain a copy of the videos for the testing accomplished at the W.J. Hughes Technical Center, contact 9-act-troubledesk@faa.gov with a reference to this report and the video reference number associated with each fire scenario.

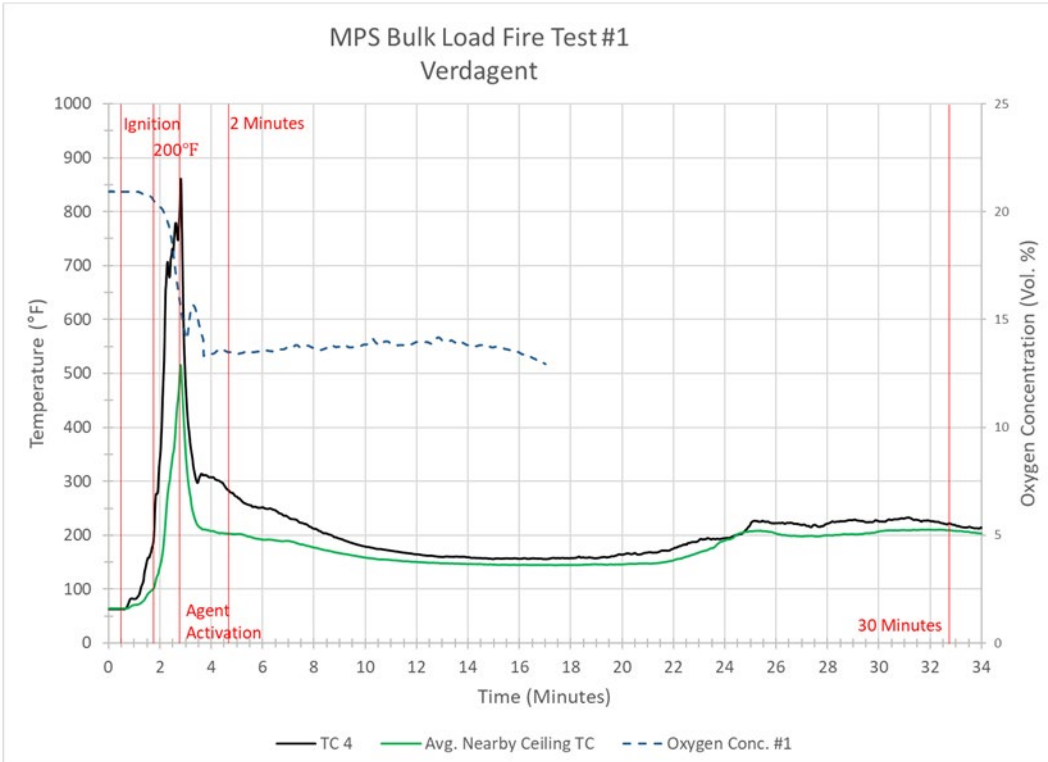

Figure 29. Results from Bulk Load Fire Test #1

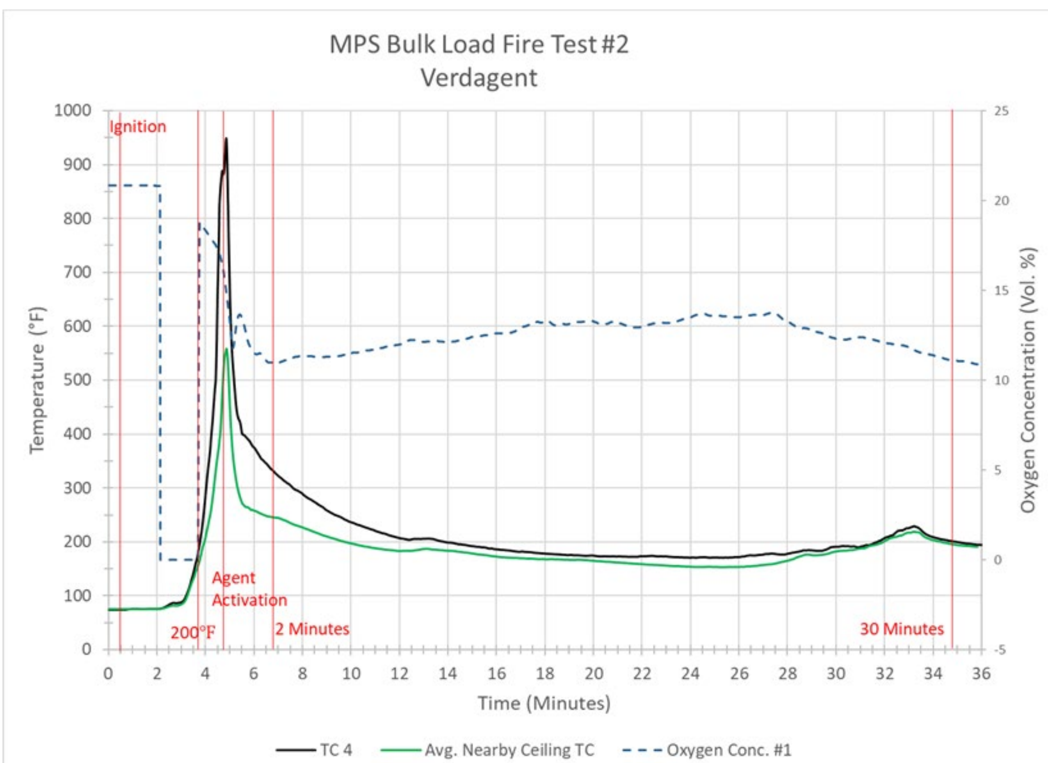

Figure 30. Results from Bulk Load Fire Test #2

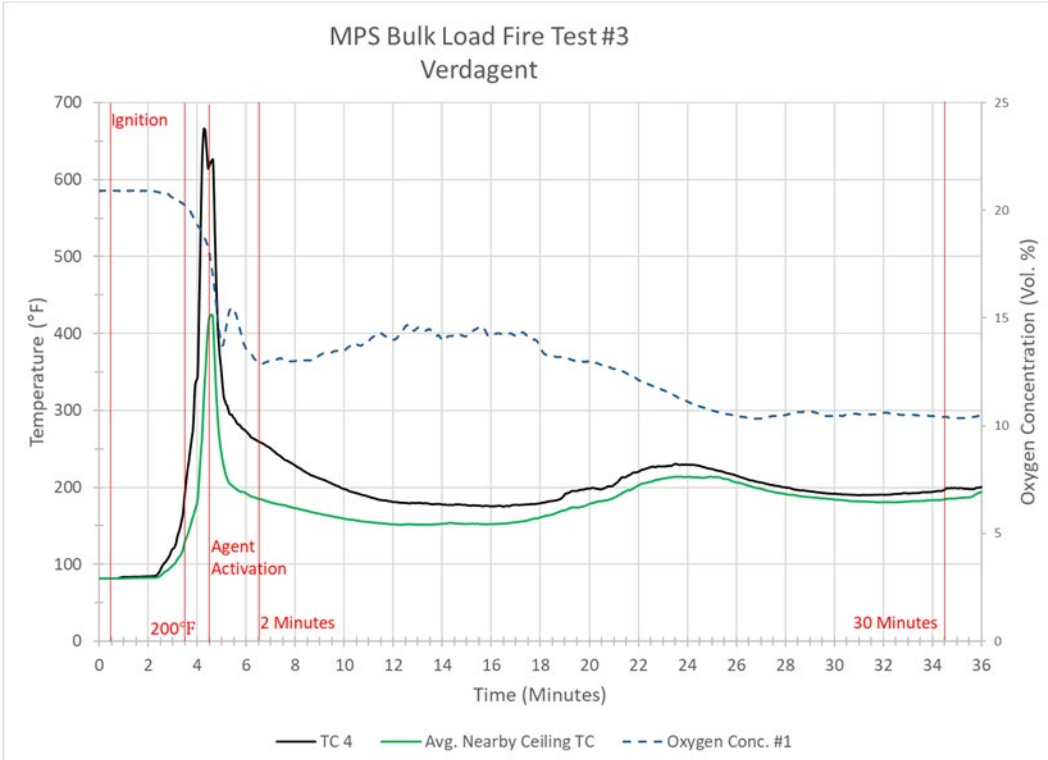

Figure 31. Results from Bulk Load Fire Test #3

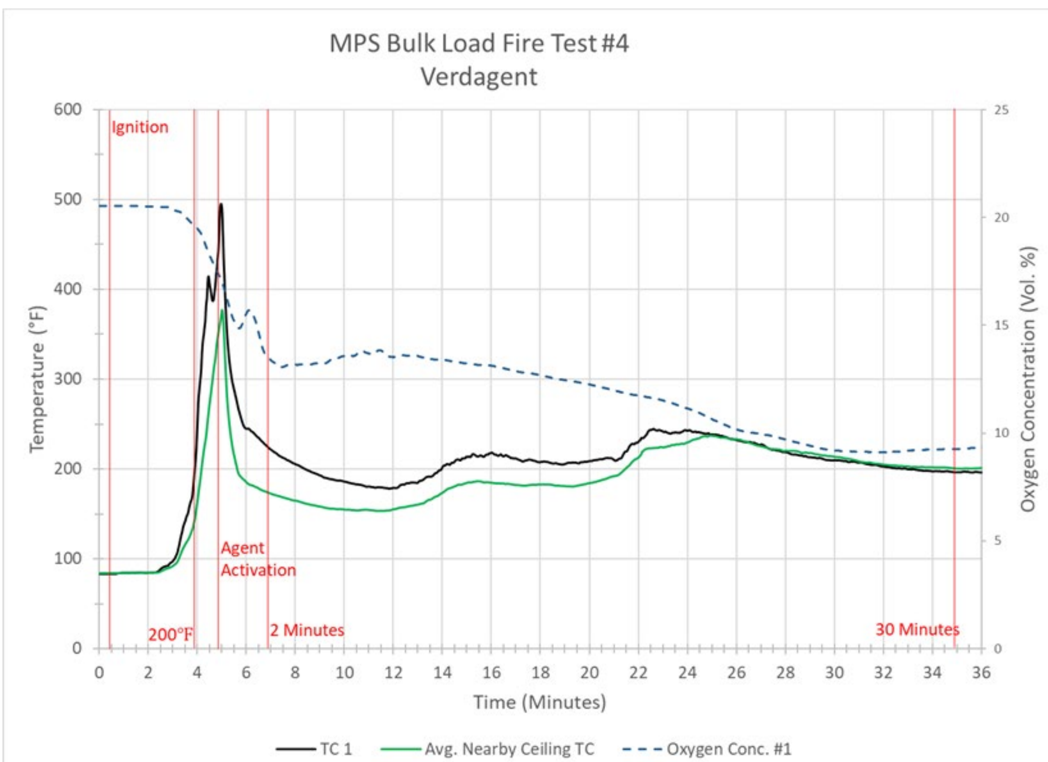

Figure 32. Results from Bulk Load Fire Test #4

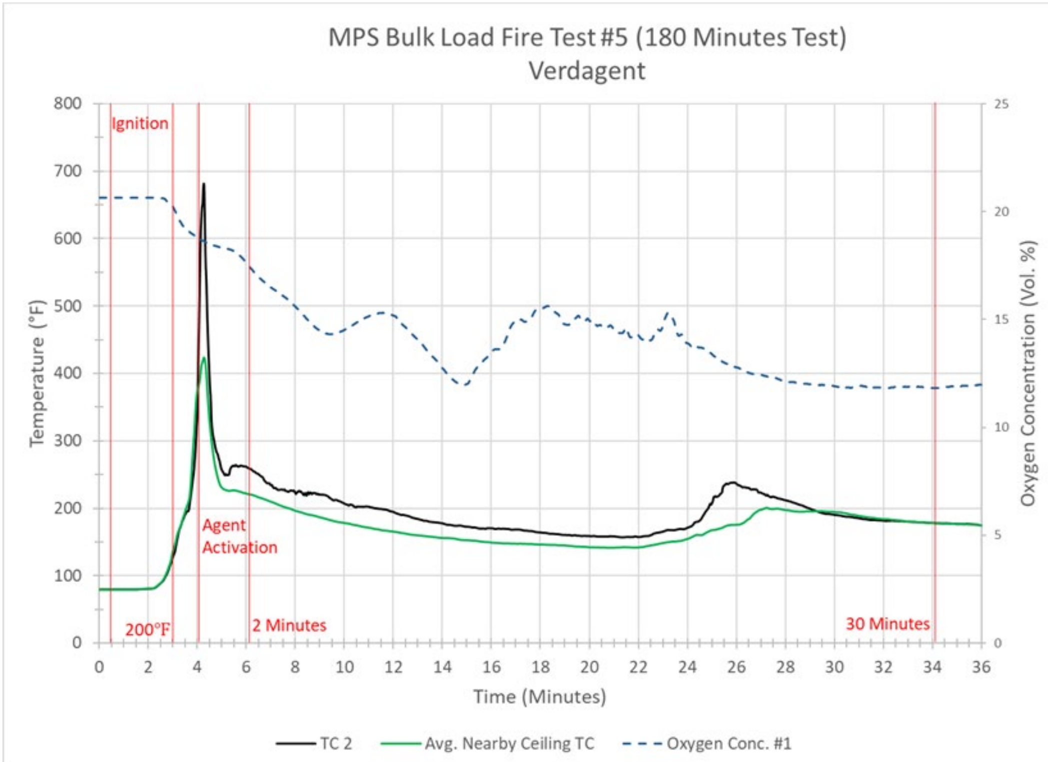

Figure 33. Results from Bulk Load Fire Test #5 (180 Minutes)

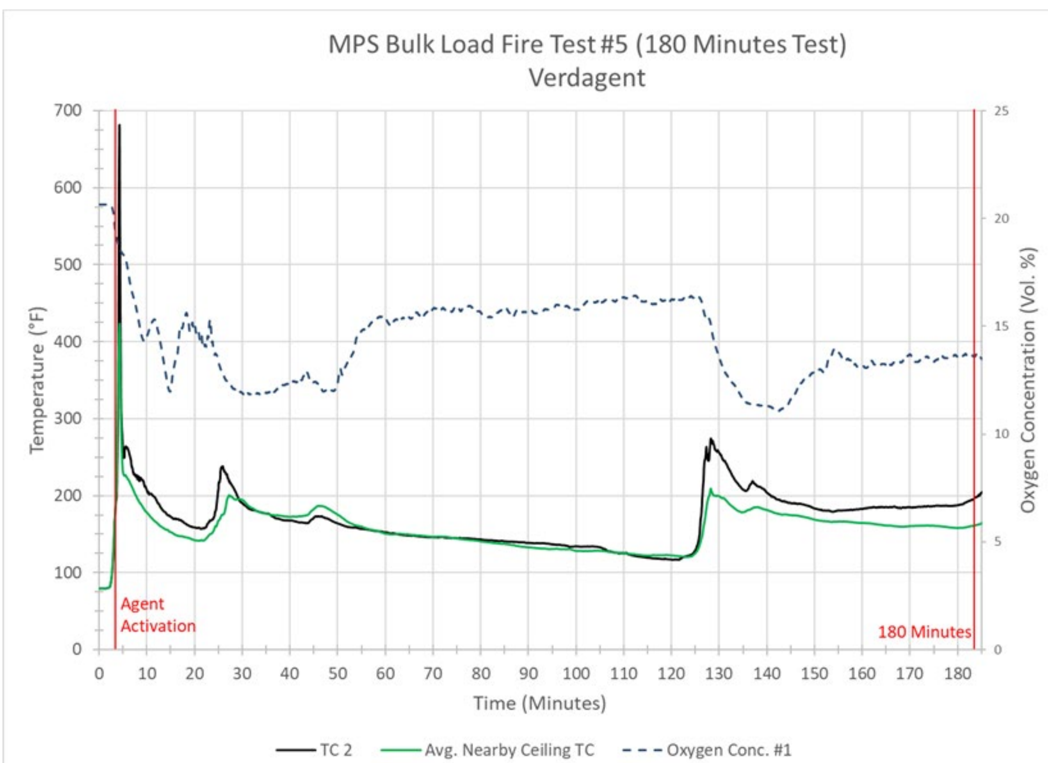

Figure 34. Results from Bulk Load Fire Test #5 (180 Minutes Test)

4.3.1 Acid Gas Test Results

The acid gases, HF and HBr, were measured during two of the bulk load fire tests. The test results displayed an increasing concentration of HF and HBr as the test progressed. The bulk load fire scenario represents a deep-seated fire that is extremely hard to extinguish since a gaseous agent cannot penetrate into the boxes or luggage within the compartment. The suppression agent acts to suppress the fire by maintaining an inert environment and interrupting the chemical chain reactions of a fire when it is not able to get to the source of the fire, whereas in the surface burning fire when the agent is able to interact with the source of the fire it is capable of extinguishing the fire. Note, the fire suppression system is not required to completely extinguish the fire, rather suppress the fire into a low energy state. While in this low energy state, the fire continues to react with oxygen at a slower rate, smoldering and making incomplete combustion reactions that results in the formation of acid gases. The concentration of acid gases is measured to gain a general understanding of the types and amounts of toxic gases created when suppressing a deep-seated fire with VERDAGENT®. These measurements are not a part of the MPS and therefore have no pass/fail criteria to compare to.

Figure 35 demonstrates the rising concentration of HF from 36 ppmv to 368 ppmv in the third test and from 18 ppmv to 329 ppmv in the fourth test over 30 minutes. Figure 36 demonstrates the rising concentrations of HBr from 0 ppmv to 23 ppmv in the third test and from 0 ppmv to 9 ppmv in the fourth test.

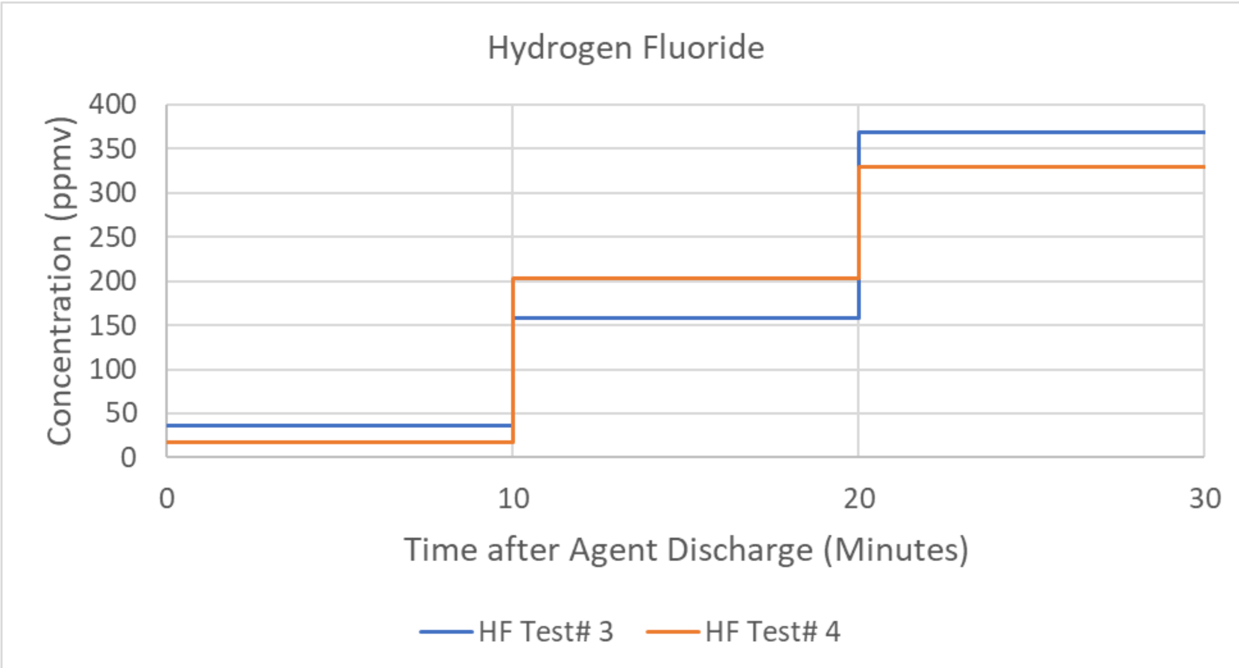

Figure 35. Hydrogen Fluoride Measurements for Bulk Load Fire Tests

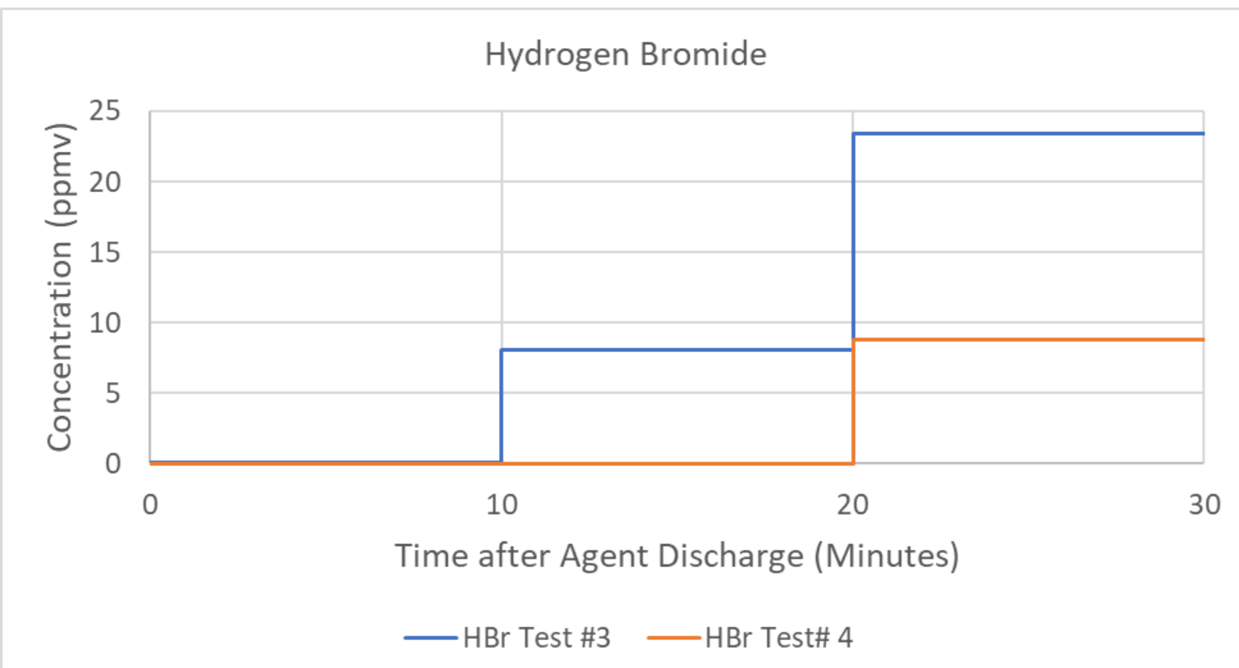

Figure 36. Hydrogen Bromide Measurements for Bulk Load Fire Tests

4.4 Containerized Fire Test Results

The results from the containerized fire tests are summarized in this section. The results were compared to the acceptance criteria as set by the MPS (Reinhardt, 2012). As per the MPS, the acceptance criteria for this fire scenario is that the average of the five test peak temperatures shall not exceed 650°F, starting 2 minutes after the suppression system is initially activated until the end of the test. In addition, the average of the five test areas under the time-temperature curve shall not exceed 14520°F-Min. The time-temperature area is computed for the 28-minute time interval starting from 2 to 30 minutes after the activation of the fire suppression system. The time-temperature area is calculated by multiplying the temperature at a specific time by the time increment and then adding up all the areas calculated or integrating the temperature versus time curve. An additional acceptance criteria for the long duration test was to ensure that the temperatures at the end of the test are stable or decreasing.

Table 3 summarizes the peak temperatures observed and the time-temperature integral calculated from each of the tests. The test results show that VERDAGENT® was able to pass the containerized fire scenario by limiting the average peak temperatures to 378°F and the average time-temperature integral to 9296°F-Min.

Table 3. Containerized Fire Test Results

Date	**Test #**	**Peak Temperature (°F)**	**Time-Temp Integral (°F-Min)**	**Video Reference #**
3/13/2019	Test 3	382	9475	TST 683.10
3/14/2019	Test 4	362	8879	TST 683.10
3/18/2019	Test 5	324	8710	TST 683.10
3/19/2019	Test 6	450	10934	TST 683.10
8/20/2019	Test 7	374	8479	TST 683.10
	Average	378	9296	
	Acceptance Criteria	650	14520	

The temperature results from each of the tests are shown in Figure 37, Figure 38, Figure 39, Figure 40, Figure 41, and Figure 42 Each figure displays the temperature data from the thermocouple that reached the peak temperature with a solid black line and an average temperature of the surrounding four thermocouples with a solid green line. The figures also depict the time at which ignition was initiated, the trigger temperature of 200°F was reached, the agent activation, 2-minute mark of the test (which denotes the start of the evaluation period), and the 30-minute mark of the test (which denotes the end of the evaluation period as well as the end of test) with a vertical solid red line. The long duration test also depicts the 180-minute mark of the test which denotes the end of that particular test.

The temperature results show a quick rise in temperature when the fire spreads across the fire load and a sharp decline in temperature as the fire suppression agent is activated. As the temperature starts to rise, the oxygen concentration begins decreasing which indicates the presence of a fire. As the fire suppression agent is activated and the temperatures start decreasing, the oxygen concentration decreases and steadies around 10%. This indicates the presence of a deep-seated fire that continues to entrain oxygen and burn at a slow rate. The decrease in oxygen also shows that the fire suppression agent is able to suppress the fire and conversely, in the agent's absence, the fire has the capability to uncontrollably consume the remainder of the fuel within the cargo compartment.

An additional insight from the containerized fire scenario is the continuous slow rise in the ceiling temperature after the fire suppression agent is activated. This is due to the continuous slow burn that draws the agent into the container at a slow rate. The agent maintains a suppressed environment and prevents the fire from spreading to adjacent containers, but is unable to suppress the fire as effectively as observed in the bulk load fire scenario. This phenomenon is not unique to VERDAGENT®, as any fire suppression agent will experience the same behavior.

To obtain a copy of the videos for the testing accomplished at the W.J. Hughes Technical Center, contact 9-act-troubledesk@faa.gov with a reference to this report and the video reference number associated with each fire scenario.

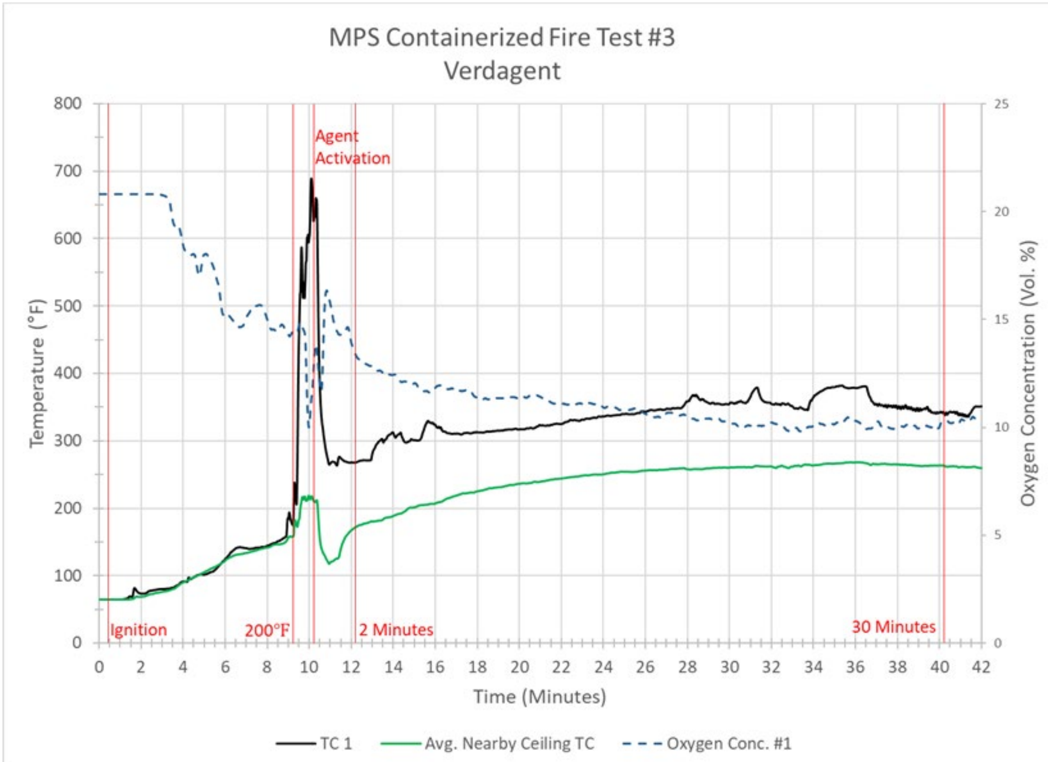

Figure 37. Results from Containerized Fire Test #3

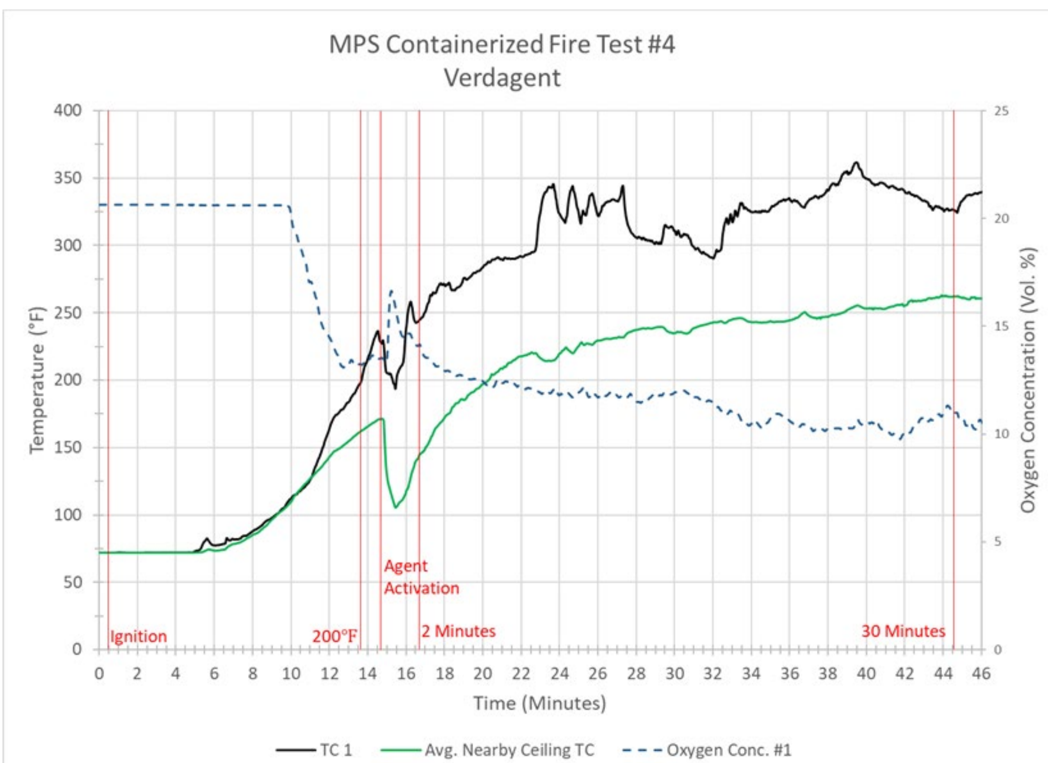

Figure 38. Results from Containerized Fire Test #4

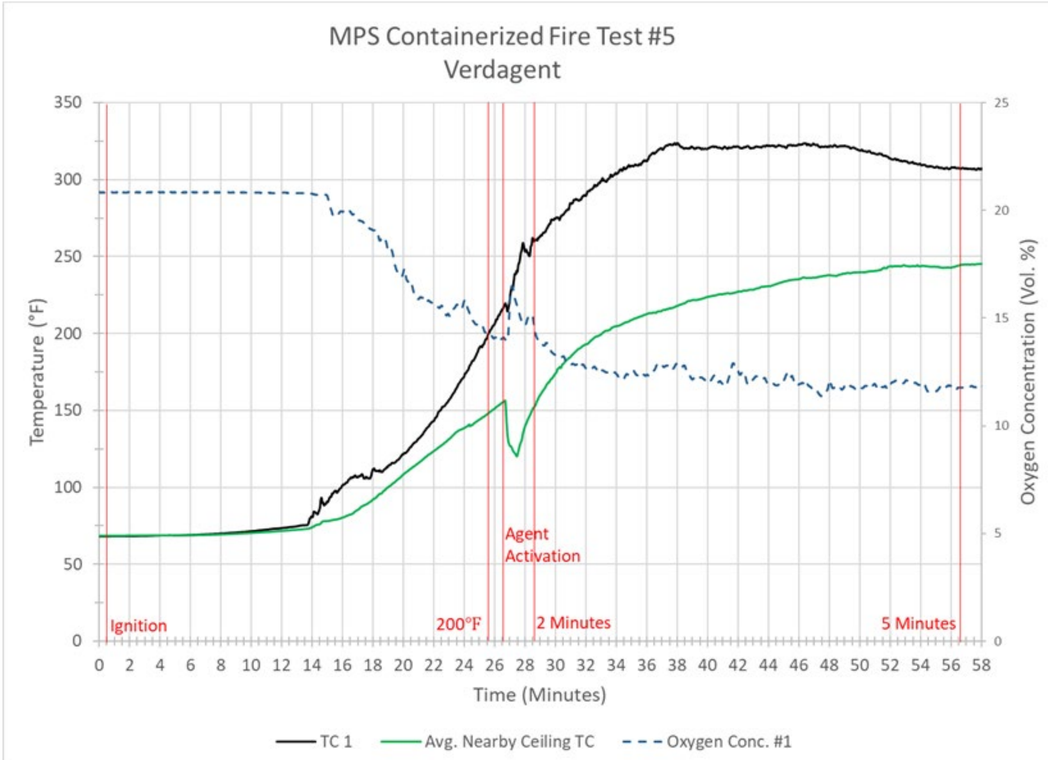

Figure 39. Results from Containerized Fire Test #5

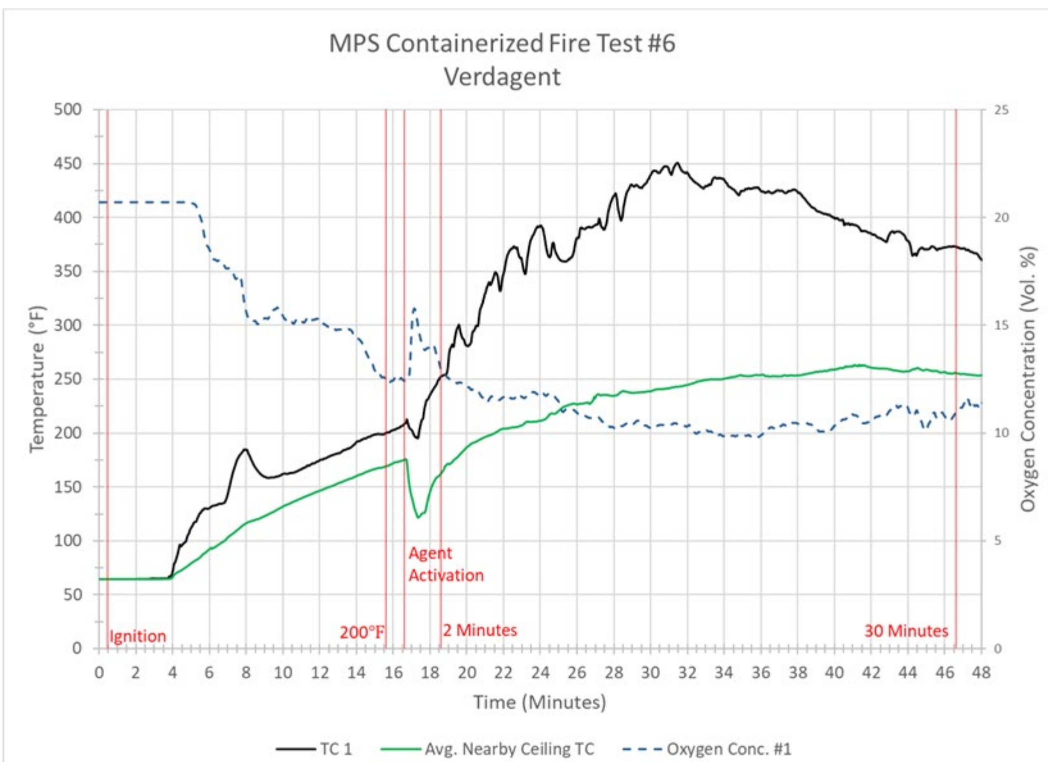

Figure 40. Results from Containerized Fire Test #6

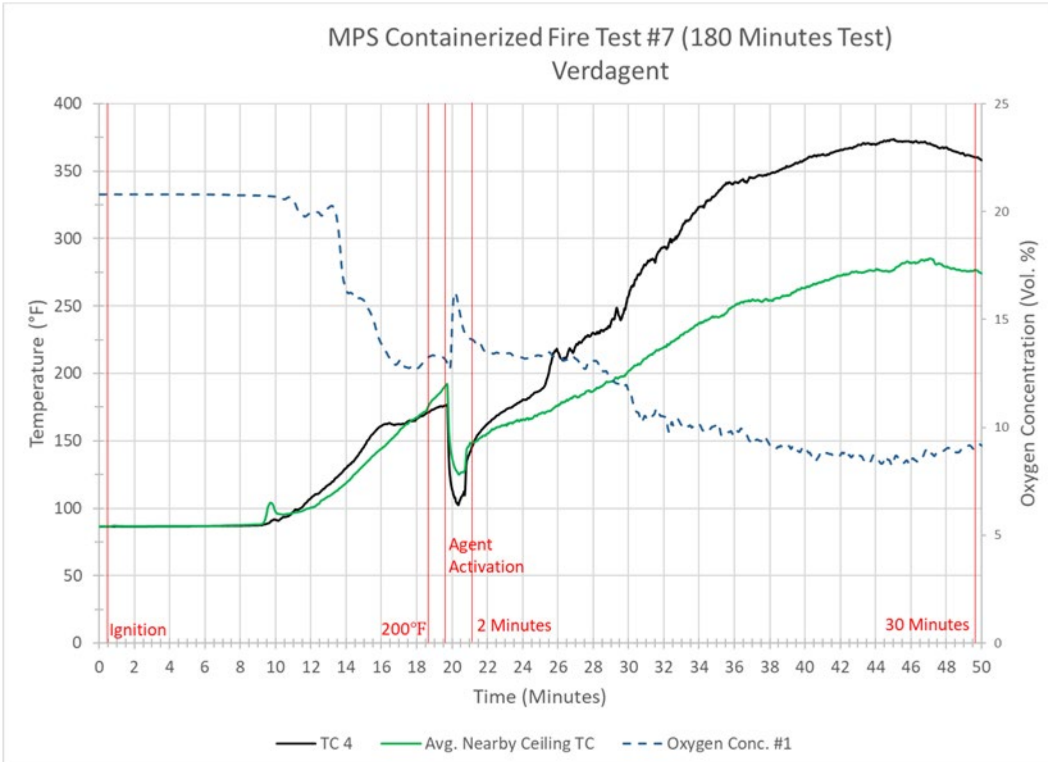

Figure 41. Results from Containerized Fire Test #7 (180 Minutes Test)

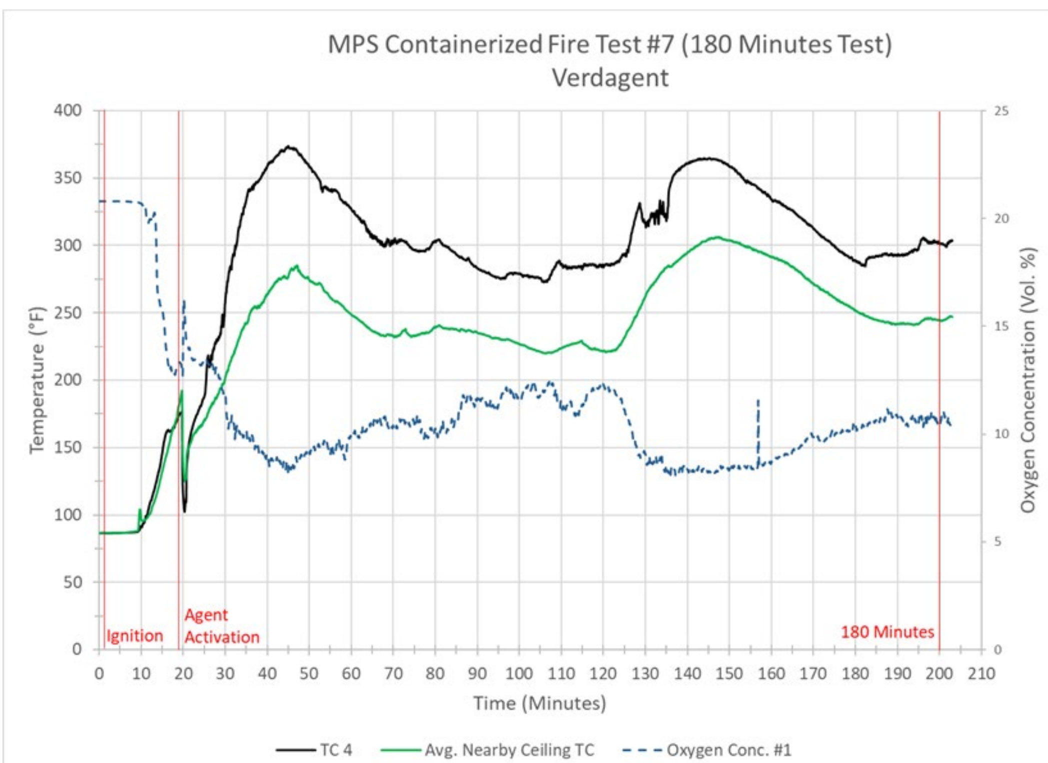

Figure 42. Results from Containerized Fire Test #7 (180 Minutes Test)

4.5 Aerosol Can Explosion Simulation Test Results

4.5.1 Baseline Tests

The results from the baseline tests are summarized in this section. The baseline testing was conducted with the minimum inerting concentration of the fire suppression agent of 11.5%, which was the design concentration during the metering phase.

The results from the baseline testing established an acceptance criteria of 0.031 psi. This value was determined by adding the standard deviation of the peak pressure from the three tests to the average peak pressure of the three tests, as shown in Table 4. The peak pressure values are obtained from the 25-point moving average to reduce the noise in the data.

Table 4. Pressure Rise from Baseline Tests

Tests	**Pressure Rise (psi)**
Baseline Test #1	0.015
Baseline Test #2	0.025
Baseline Test #4	0.03
Average	0.023
Acceptance Criteria	0.031

Figure 43, Figure 45, and Figure 47show the concentration of the agent within the compartment and Figure 44, Figure 46, and Figure 48 show the pressure pulse generated when the simulator was activated in an empty compartment without an ignition source.

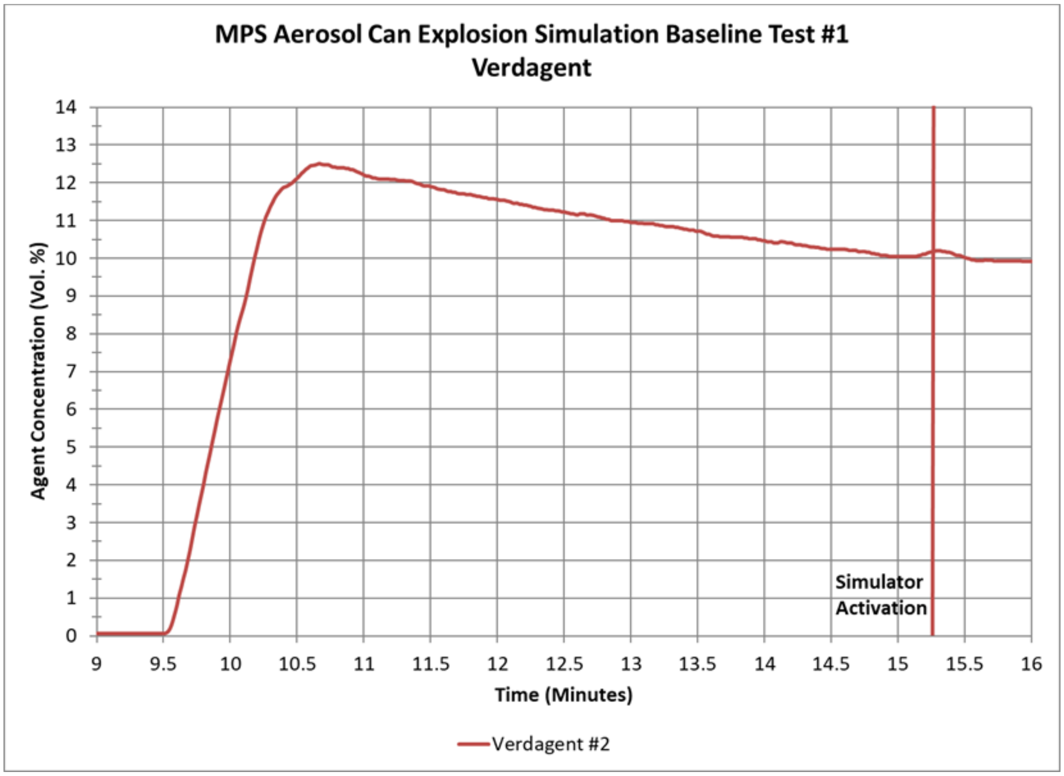

Figure 43. MPS Aerosol Can Explosion Simulation Baseline Test #1: Agent Concentration

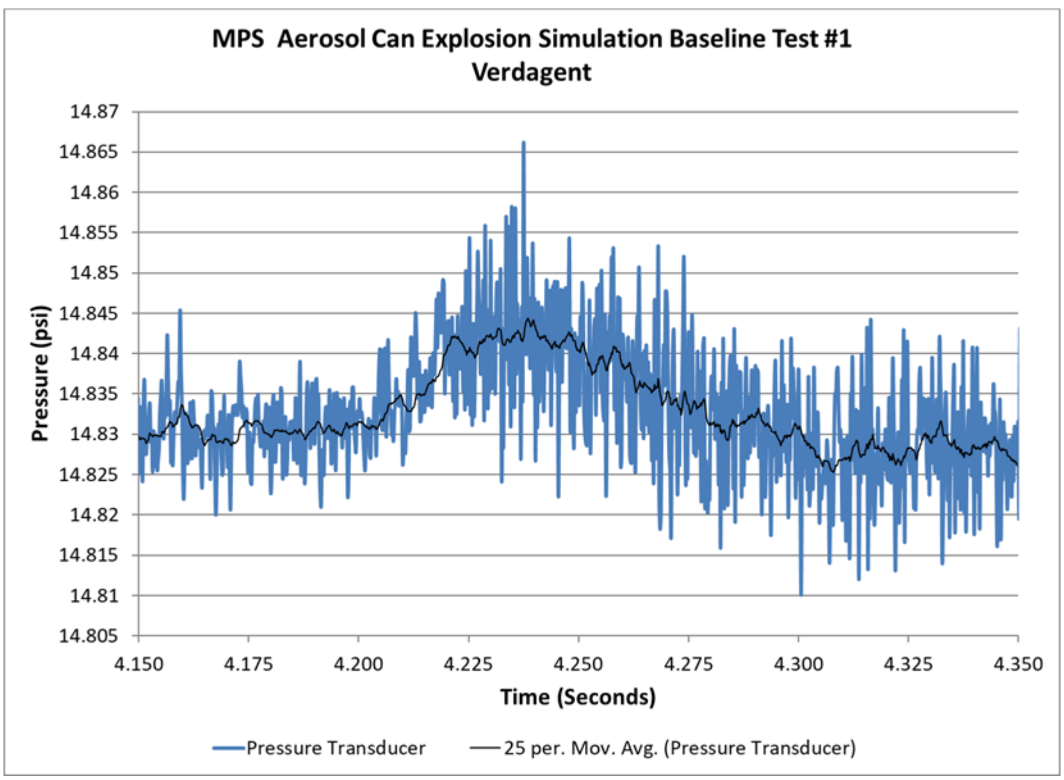

Figure 44. MPS Aerosol Can Explosion Simulation Baseline Test #1: Pressure Measurement

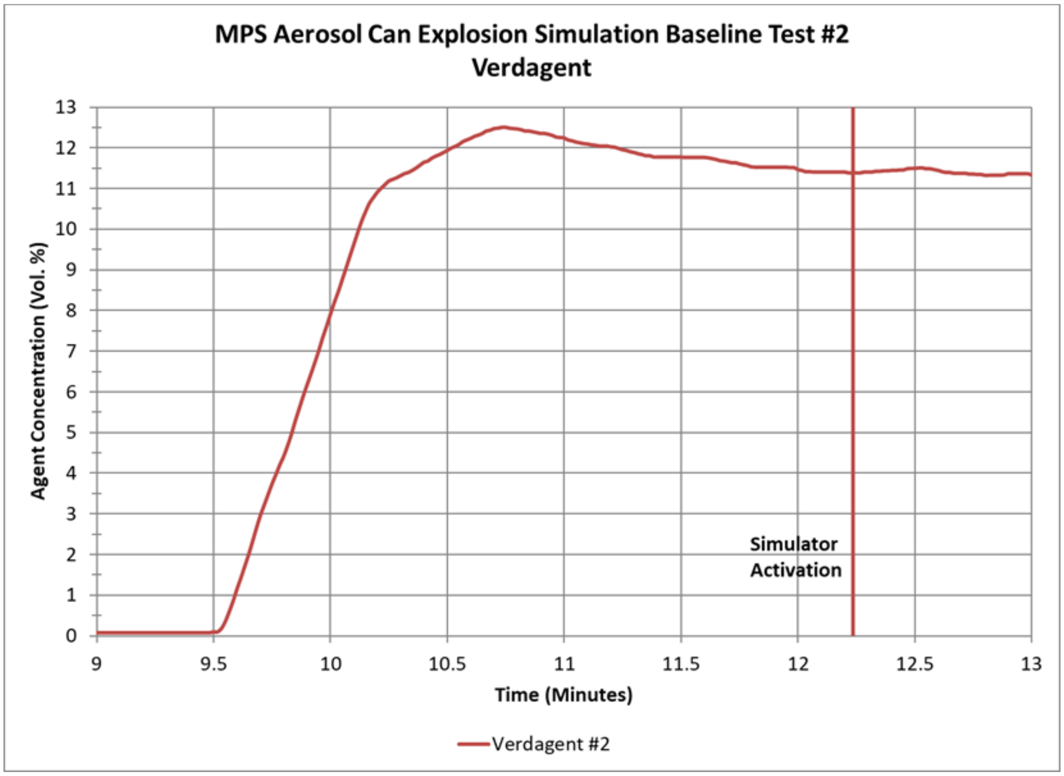

Figure 45. MPS Aerosol Can Explosion Simulation Baseline Test #2: Agent Concentration

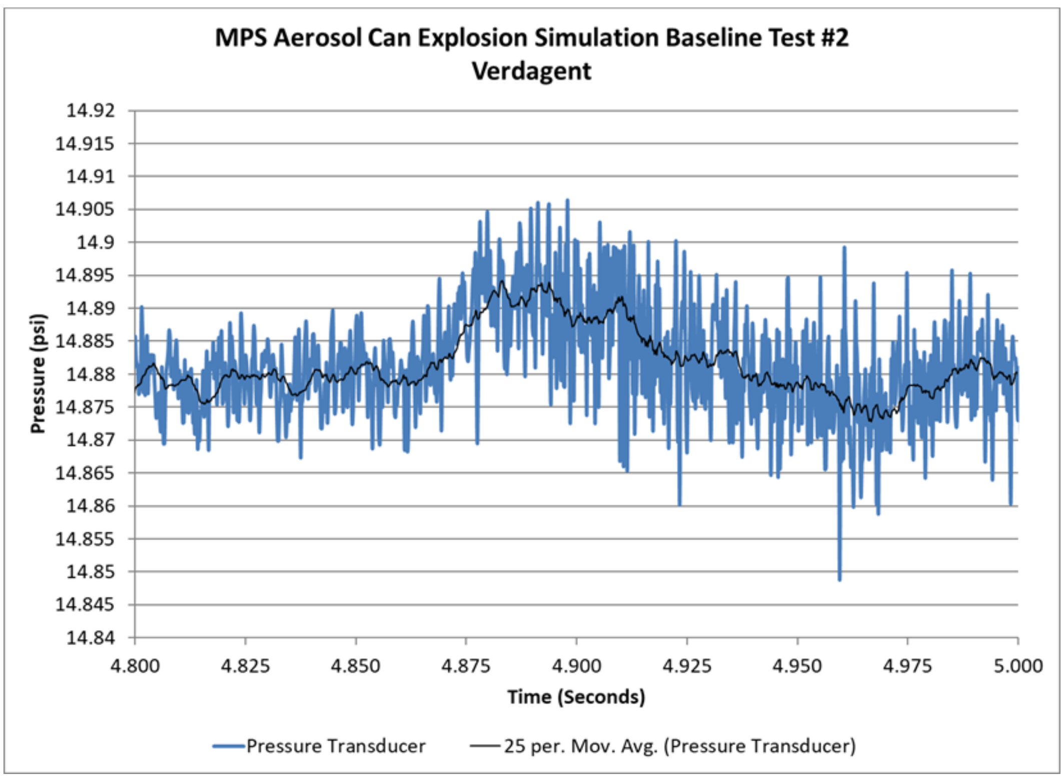

Figure 46. MPS Aerosol Can Explosion Simulation Baseline Test #2: Pressure Measurement

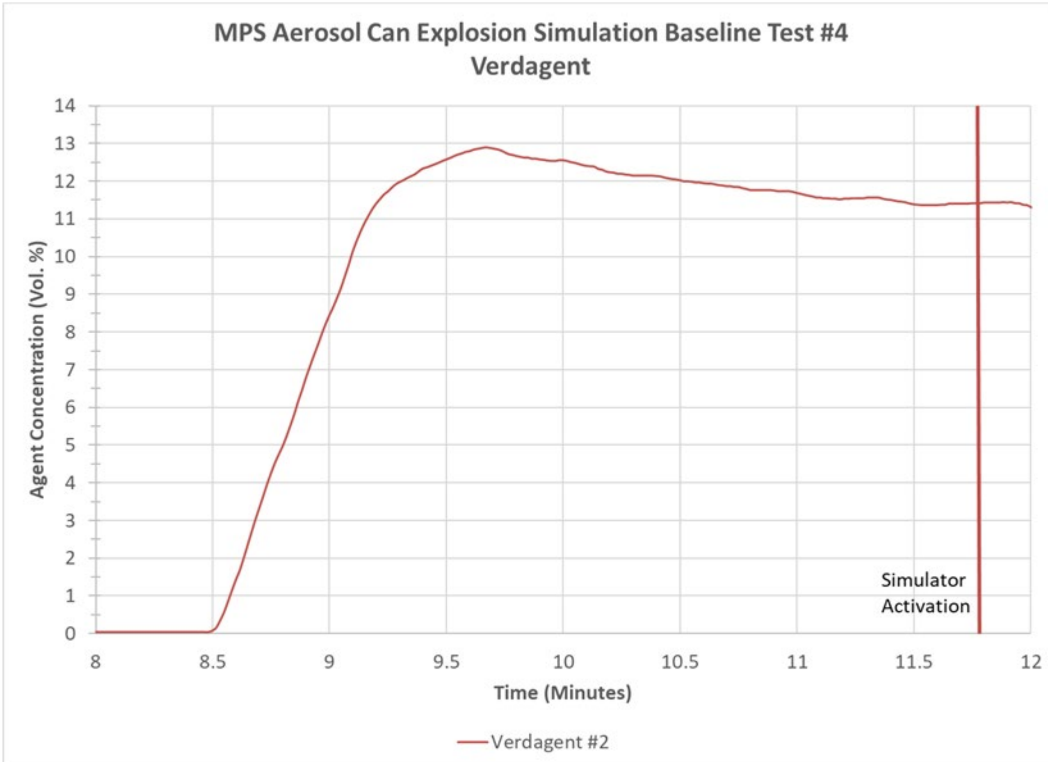

Figure 47. MPS Aerosol Can Explosion Simulation Baseline Test #4: Agent Concentration

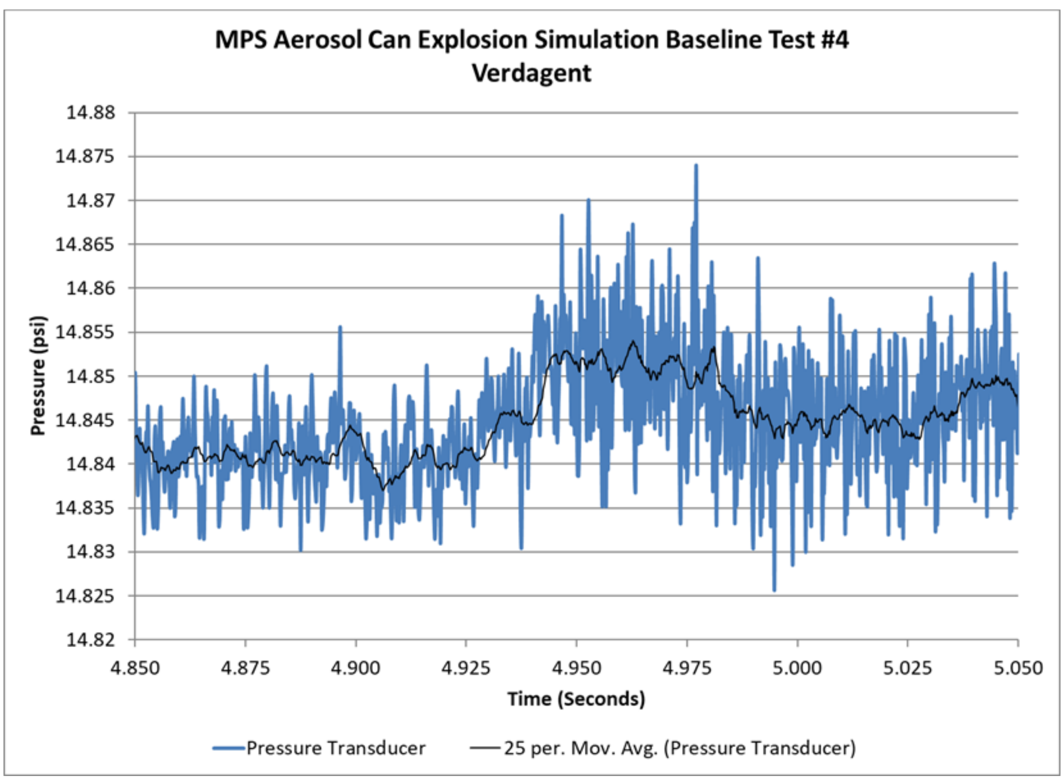

Figure 48. MPS Aerosol Can Explosion Simulation Baseline Test #4: Pressure Measurement

4.5.2 Aerosol Can Explosion Simulation Test

The results from the MPS aerosol can explosion simulation tests are shown in this section. The acceptance criteria for this scenario was updated since the MPS as defined in Reinhardt (2012) didn't provide enough information regarding the amount of allowable pressure. Hence, a new acceptance criteria was proposed and accepted via an International Aircraft System Fire Protection Forum Task Group. The new acceptance criteria for this test is that there should be no evidence of an explosion or unacceptable reaction. Evidence of an explosion is to be understood as there shall be no pressure rise more than the measurement of the baseline simulator pressure release into the compartment. The criteria of an unacceptable reaction is based on the observed performance with Halon 1301 (Video Reference# TST 683.05).

Table 5 summarizes the results of each of the aerosol can explosion simulation tests. The test results show that the fire suppression agent successfully subdued the explosive reaction in the presence of an ignition source. Video recordings were reviewed to ensure that there was not an unacceptable reaction that occurred near the ignition source.

Table 5. Aerosol Can Explosion Simulation Test Results

Date	**Tests**	**Pressure Rise (psi)**	**Pass/Fail**	**Video Reference #**
6/10/2019	Test 3 (V2)	0.019	Pass	TST 683.12
6/10/2019	Test 4 (V2)	0.016	Pass	TST 683.12
6/11/2019	Test 5 (V2)	0.013	Pass	TST 683.12
6/11/2019	Test 6 (V2)	0.018	Pass	TST 683.12
6/12/2019	Test 7 (V2)	0.016	Pass	TST 683.12
	Acceptance Criteria	0.031		

Figure 49, Figure 51, Figure 53, and Figure 55show the concentration of the agent within the compartment and Figure 50, Figure 52, Figure 54, Figure 56, and Figure 58show the pressure pulse generated when the simulator was activated over the ignition source.

To obtain a copy of the videos for the testing accomplished at the W.J. Hughes Technical Center, contact 9-act-troubledesk@faa.gov with a reference to this report and the video reference number associated with each fire scenario.

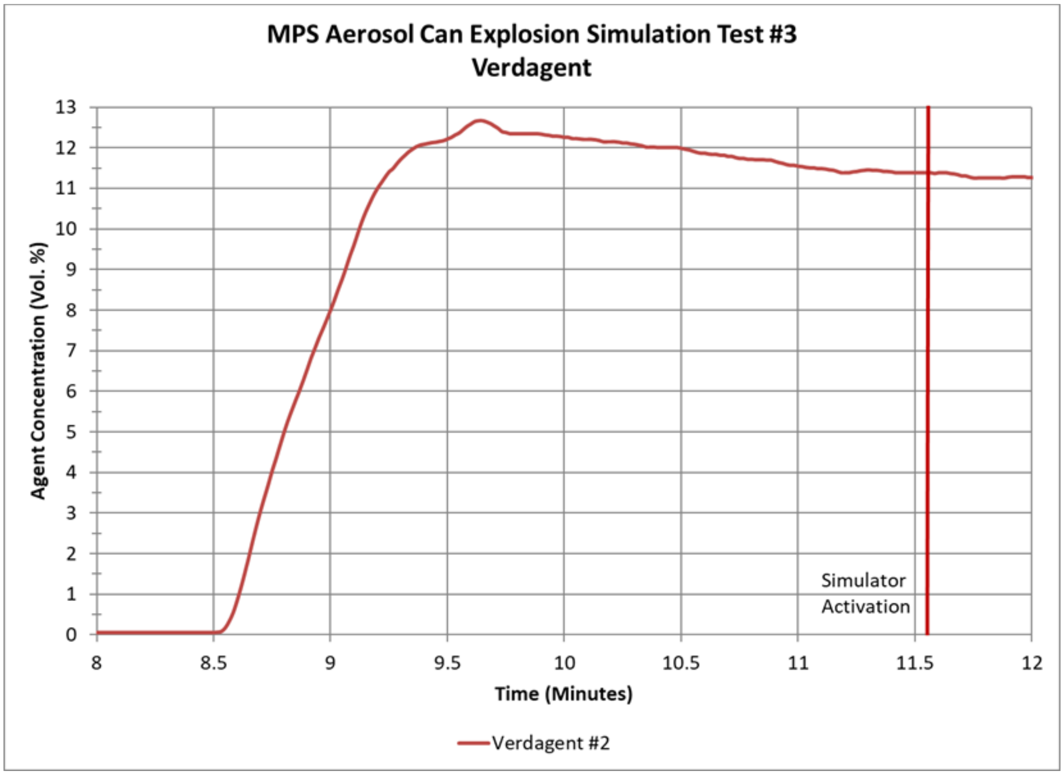

Figure 49. MPS Aerosol Can Explosion Simulation Test #3: Agent Concentration

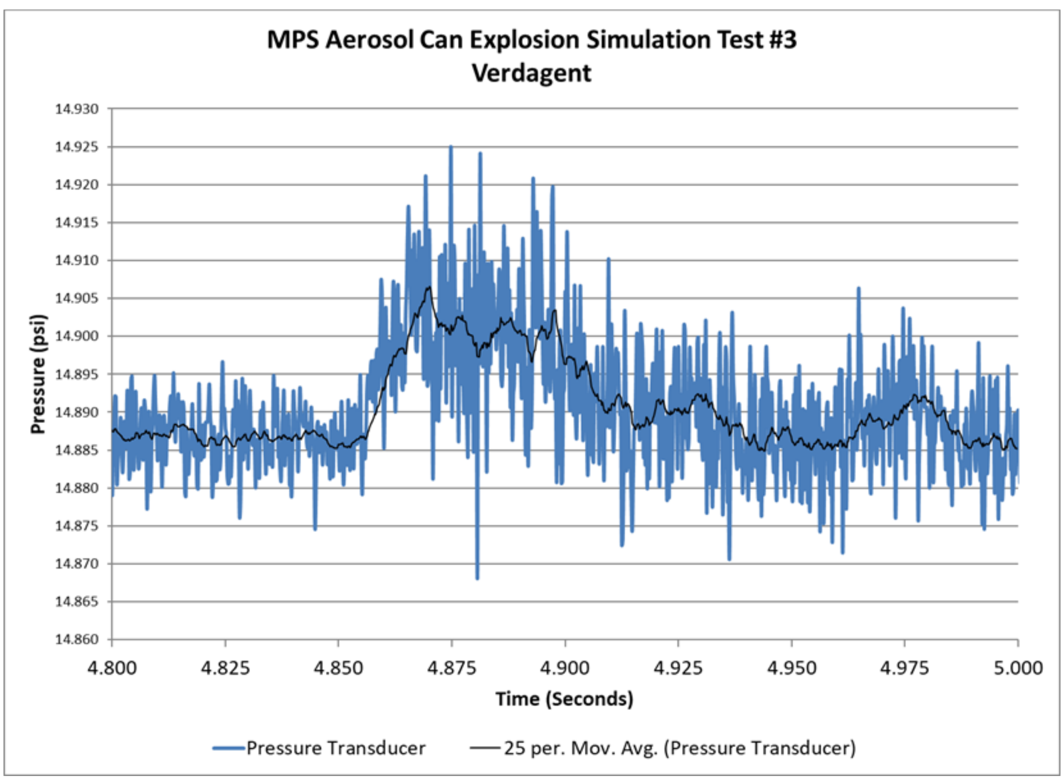

Figure 50. MPS Aerosol Can Explosion Simulation Test #3: Pressure Measurement

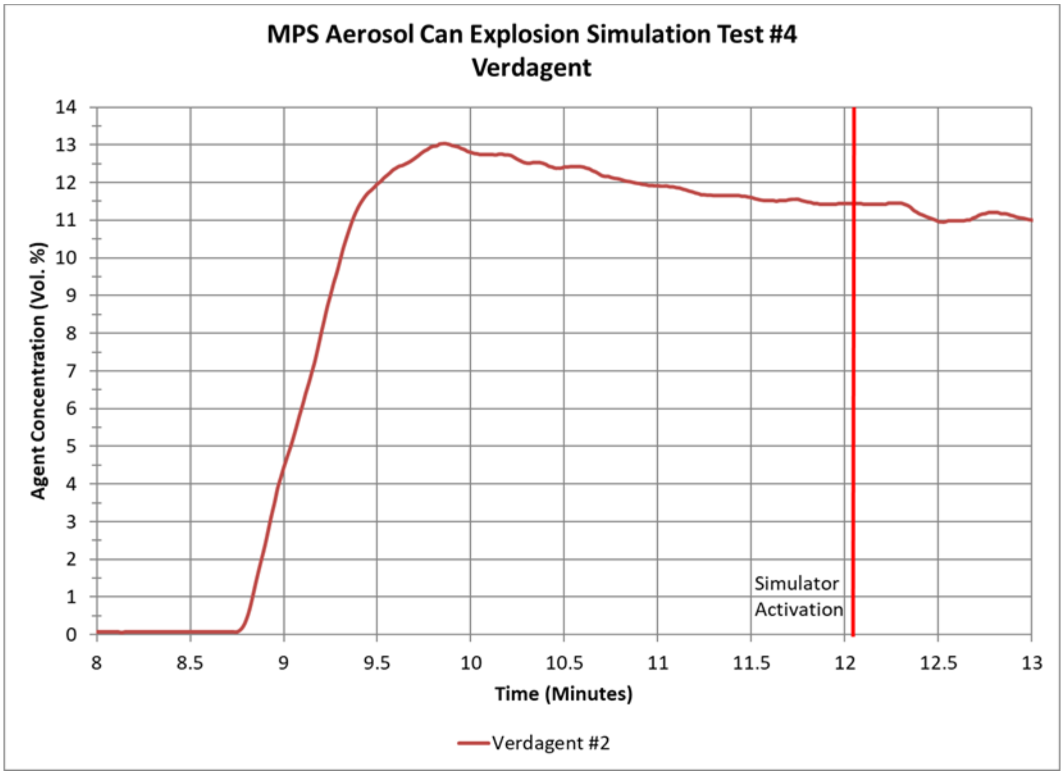

Figure 51. MPS Aerosol Can Explosion Simulation Test #4: Agent Concentration

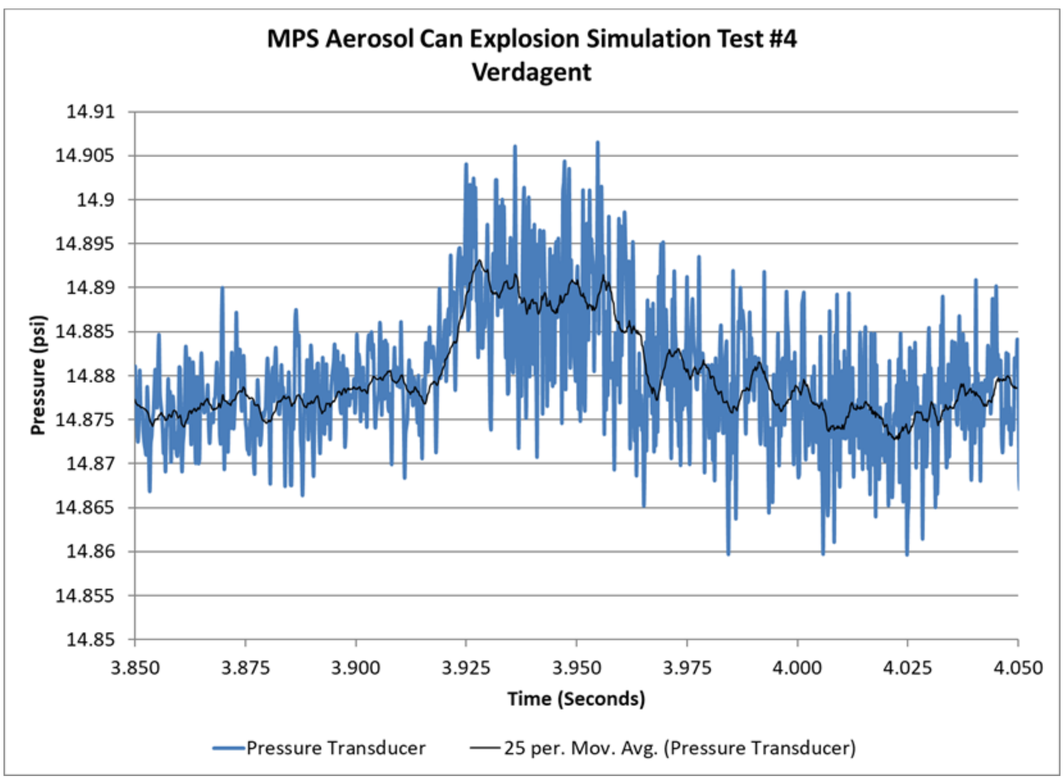

Figure 52. MPS Aerosol Can Explosion Simulation Test #4: Pressure Measurement

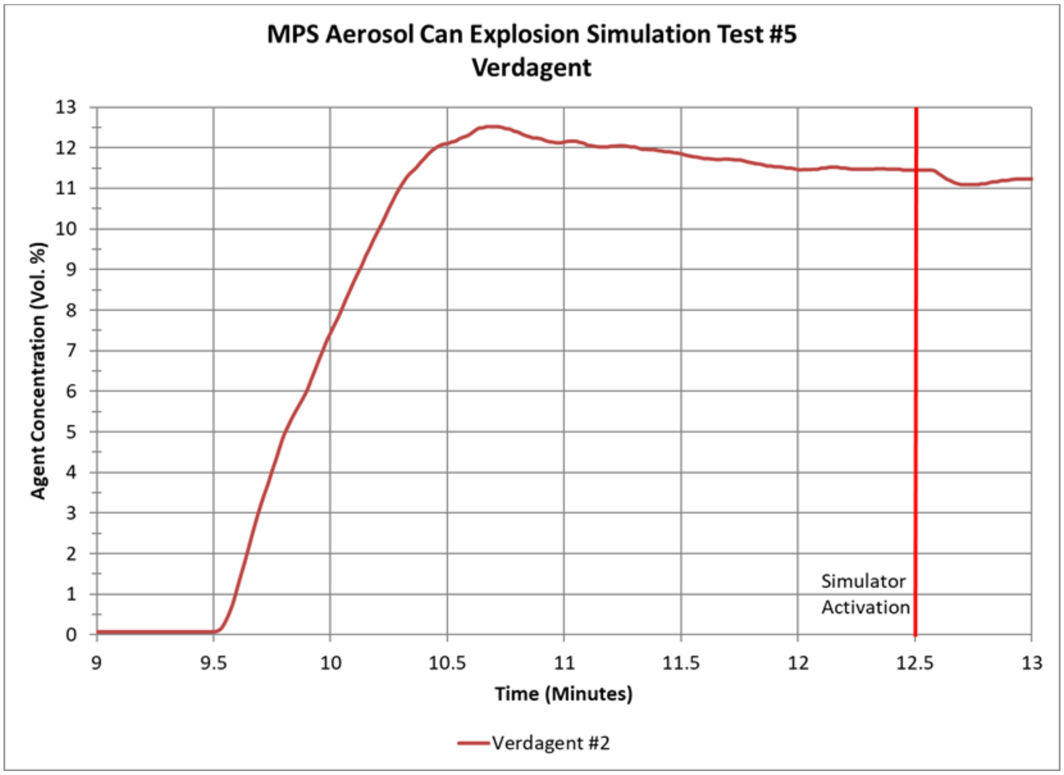

Figure 53. MPS Aerosol Can Explosion Simulation Test #5: Agent Concentration

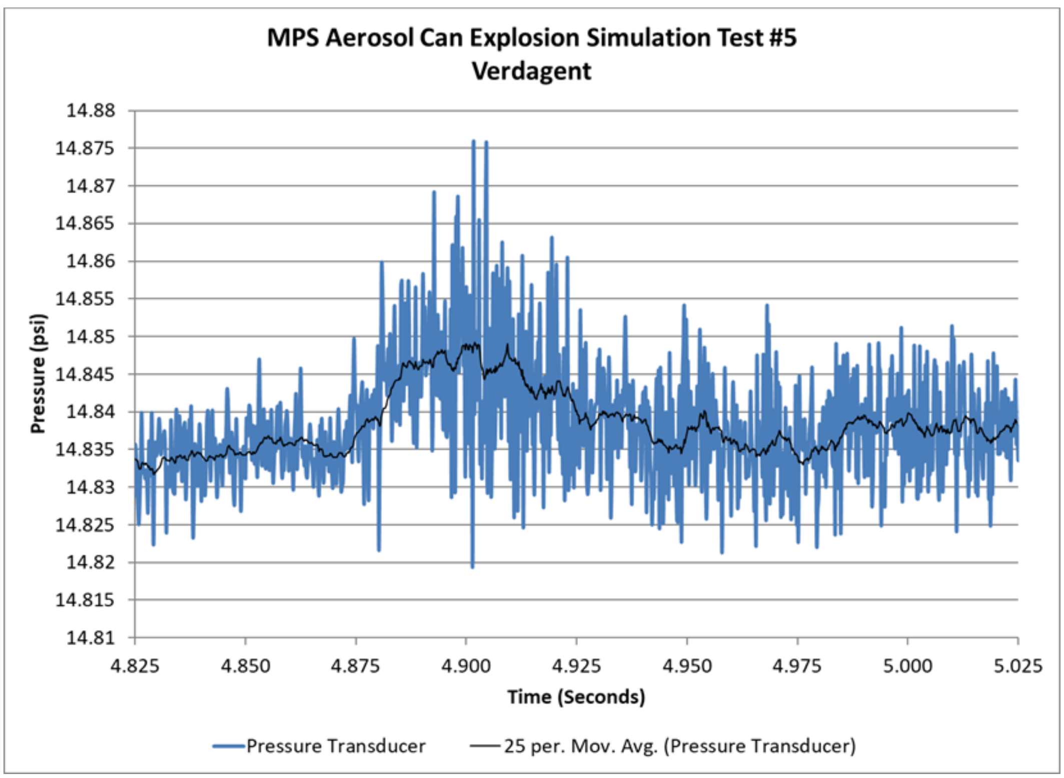

Figure 54. MPS Aerosol Can Explosion Simulation Test #5: Pressure Measurement

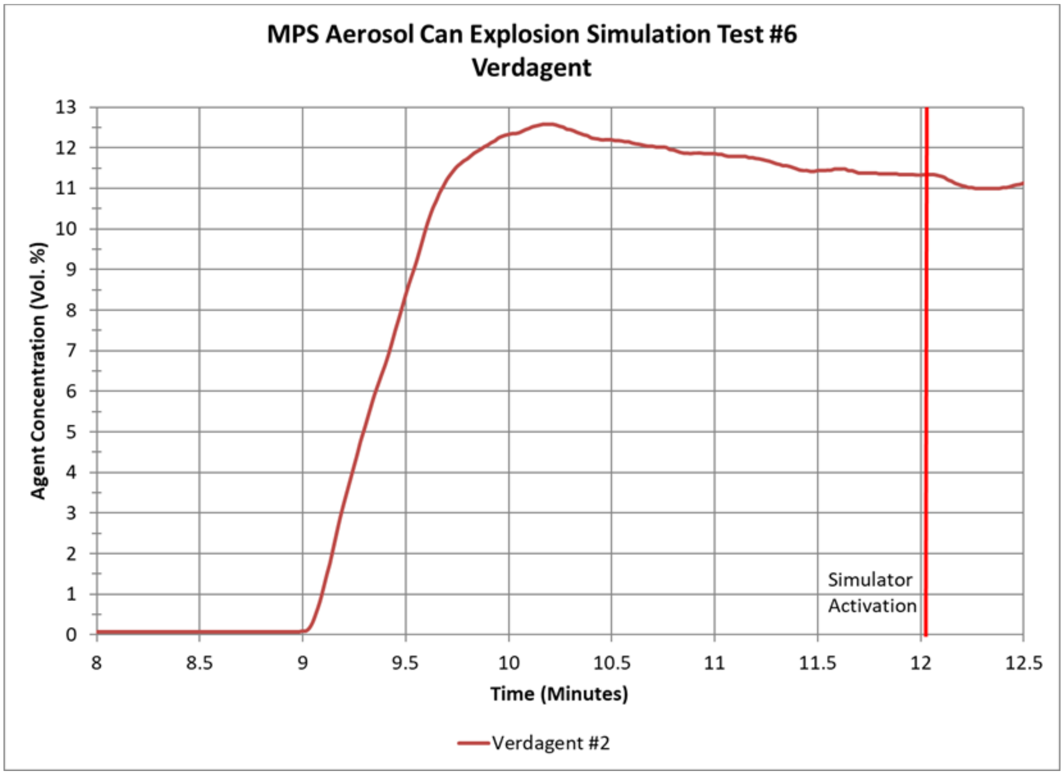

Figure 55. MPS Aerosol Can Explosion Simulation Test #6: Agent Concentration

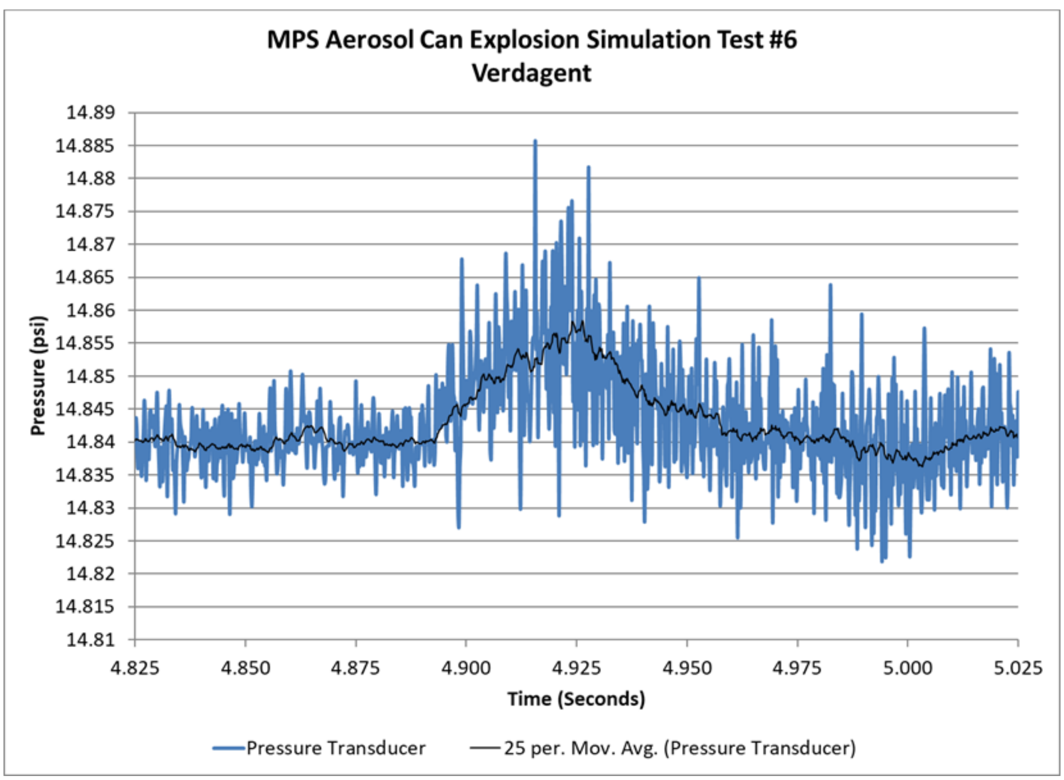

Figure 56. MPS Aerosol Can Explosion Simulation Test #6: Pressure Measurement

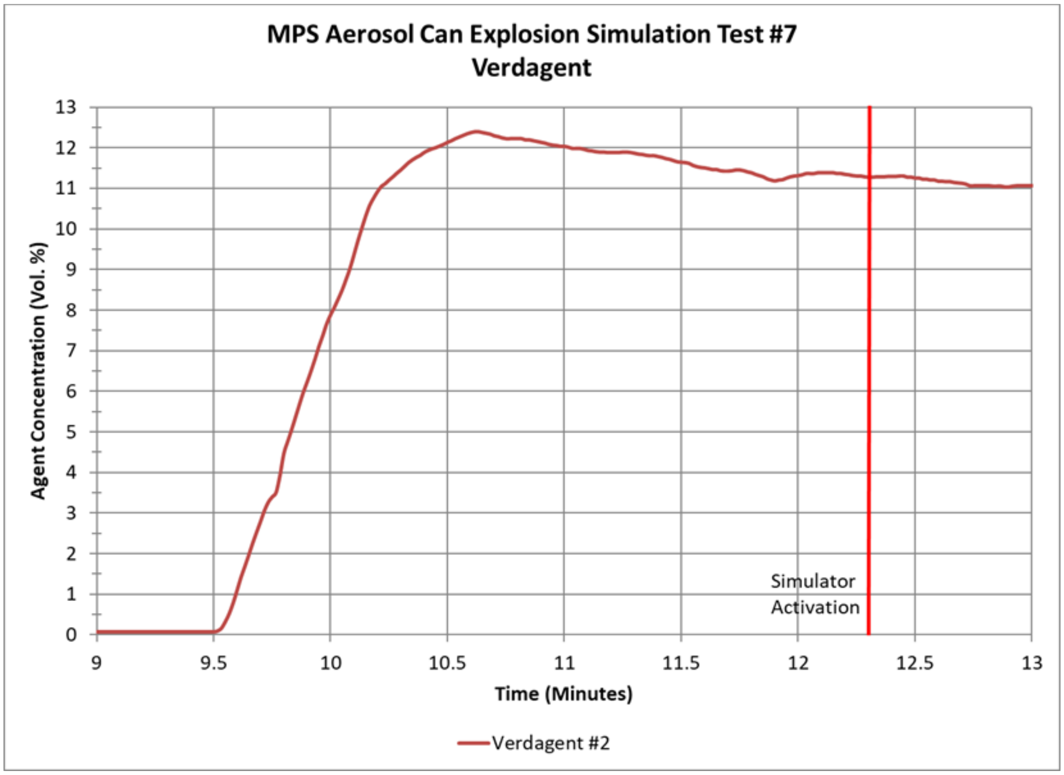

Figure 57. MPS Aerosol Can Explosion Simulation Test #7: Agent Concentration

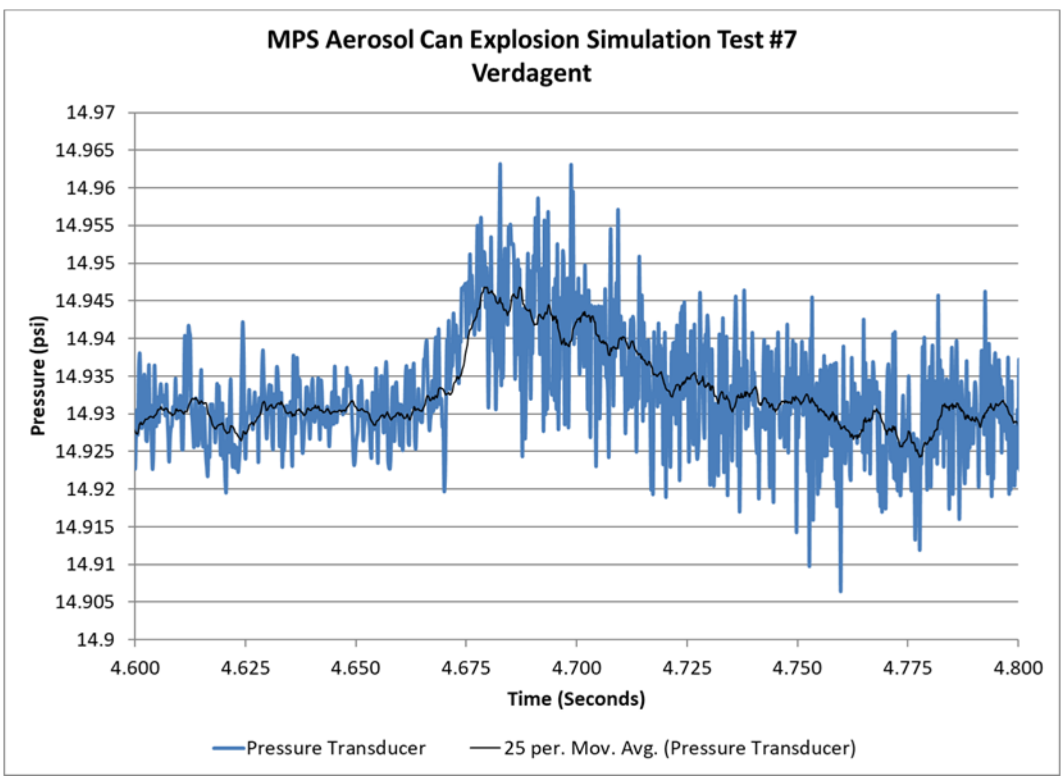

Figure 58. MPS Aerosol Can Explosion Simulation Test #7: Pressure Measurement

5 Conclusions

VERDAGENT®, a Halon replacement agent was tested at the William J. Hughes Technical Center as per the latest version of the Minimum Performance Standard (MPS) for Aircraft Cargo Compartments in collaboration with Meggitt Safety Systems Inc. The homogeneity of the agent was observed through concentration tests and the effectiveness of the agent as a Halon replacement fire suppressant was evaluated by subjecting the agent to fire scenarios in the MPS.

The concentration tests demonstrated the capability of the fire suppression delivery system to distribute the agent throughout the compartment in a homogenous manner. The tests also established that there was no blend separation during the duration tested. VERDAGENT® was subjected to the MPS and passed by achieving lower peak temperatures and time-temperature integrals when comparing the same fire scenarios with Halon 1301 as a fire suppressant. For the surface burning fire scenario, VERDAGENT® limited the average peak temperature to 433°F and the time-temperature integral to 971°F-min where the acceptance criteria was 570°F and 1190°F-min respectively. For the bulk load fire scenario, VERDAGENT® limited the average peak temperature to 289°F and the time-temperature integral to 5649°F-min where the acceptance criteria was 710°F and 9850°F-min respectively. For the containerized fire scenario, VERDAGENT® limited the average peak temperature to 378°F and the time-temperature integral to 9296°F-min where the acceptance criteria was 650°F and 14520°F-min respectively. For the aerosol can explosion simulation, VERDAGENT® also had no pressure rise above the baseline recorded pressure. By meeting and exceeding the aforementioned acceptance criteria of the MPS, VERDAGENT® is a viable alternative to Halon 1301 as a fire suppression agent in a cargo compartment fire suppression system.

6 References

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A Challenge Fire Scenario

Figures

A.1 Background

An additional test was conducted at the behest of FAA sponsors involved in the certification process of airplanes. In order to observe the effectiveness of VERDAGENT® against fires likely to occur in a cargo compartment, a new fire load comprised of Class-A materials (cardboard box and shredded paper), Class-B materials (flammable liquids), and lithium batteries was devised. The intention of this test setup was to replicate small quantities of batteries that could be transported in cargo compartments within equipment or luggage checked in by passengers among other commonly found materials.

The test was conducted only to observe the temperatures and gas concentrations attained during a fire in the cargo compartment. There wasn't an established acceptance criteria against which the results could be compared. The test was conducted in the same test compartment as the minimum performance standard (MPS) described in the body of this report.

A.2 Test Setup

The fire load for this test scenario was 17 cardboard boxes filled with 2.5lb of shredded paper, 1 gallon of ethanol packed according to International Air Transport Association (IATA) standards, 500 ml of ethanol in a balloon, and three packages of 50 lithium-ion cells packed in a cardboard box set on a pallet and wrapped with a generic plastic wrap as shown in Figure A-1.

Figure A-1 Challenge Fire Test Setup

The cardboard boxes filled with shredded paper were made as per the MPS specifications. The IATA package consisted of a one-gallon jug that was filled with a gallon of 99% anhydrous denatured ethanol as shown in Figure A-2. A small balloon was filled with 500 ml of 99% anhydrous denatured ethanol and a 7-foot-long Nichrome wire was wrapped around it as a mechanism to ignite the flammable liquid as shown in Figure A-3. The balloon was then placed on top of the shredded paper in Box 5 as shown in Figure A-4. Three packages of 50 lithium-ion cells that were at a 50% state of charge (SOC) were packed into a box made out of single walled corrugated cardboard as shown in Figure A-5. The lithium-ion cell was a typical 18650 cell that was rated at 2600mAh cell, with a nominal voltage of 3.7V. The cell was made with a lithium cobalt oxide (LCO) chemistry. A polyimide insulated flexible film heater was adhered on a corner cell. The film heater was rated to produce 10W/in^2 on a 2” x 2” surface with an adhesive backing on one side of the heater.

The packages containing the lithium-ion cells were placed on top of the shredded paper in a cardboard box as shown in Figure A-6. There were 3 such boxes: Box 2, Box 4, and Box 6, as shown in Figure A-7.

Figure A-2 Gallon of Ethanol Packaged


Figure A-3 500mL of Ethanol in a Balloon with Nichrome Wire Wrapped Around

Figure A-4 Balloon Filled with 500mL of Ethanol Placed on Top of Shredded Paper

Figure A-5 Package of 50 Lithium-ion Cells

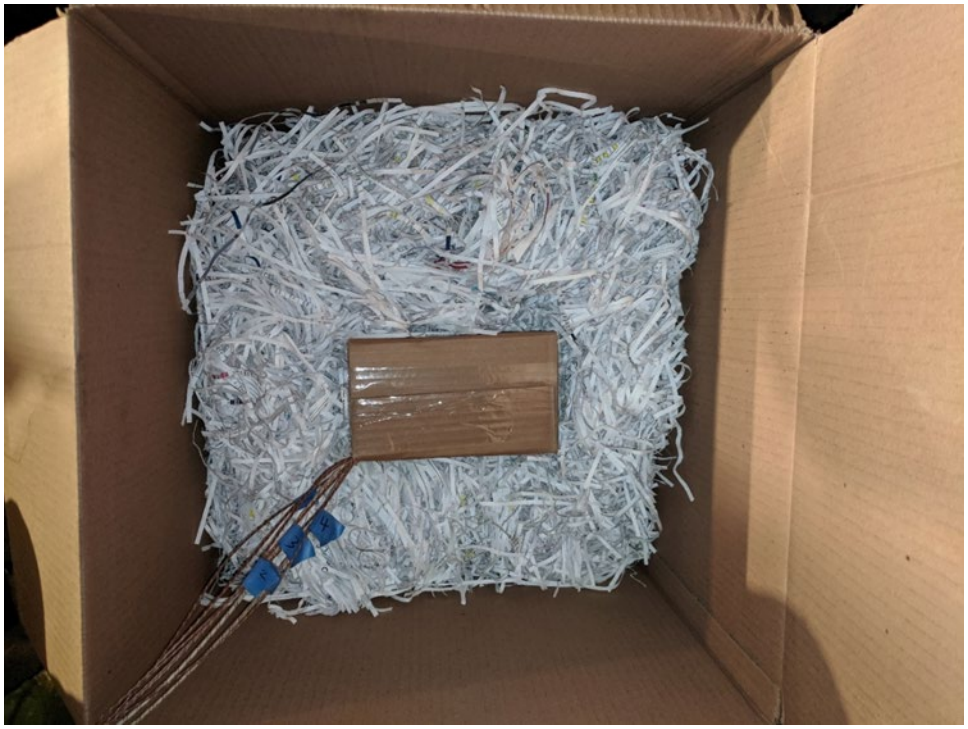

Figure A-6 Lithium-ion Cells Package Placed on Top of Shredded Paper

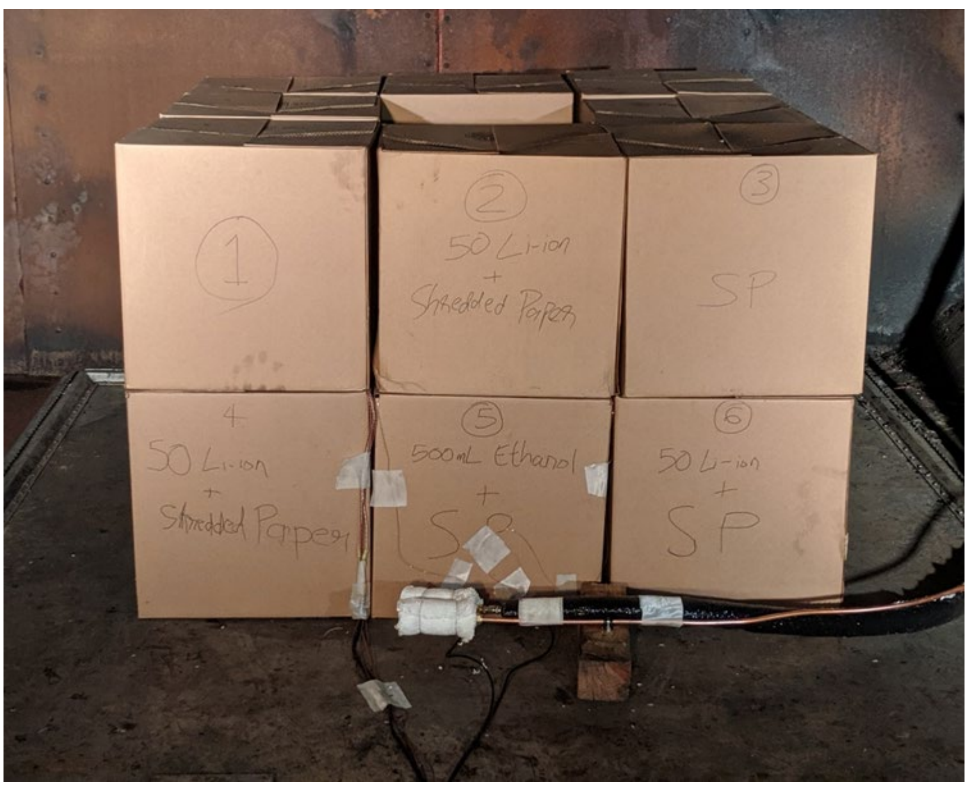

Figure A-7 Challenge Fire Test Setup without Rain Wrap

A.3 Test Instrumentation

In addition to the instrumentation mentioned in Section 2.1, thermocouples were attached to the lithium-ion cell that was induced into thermal runway and four cells adjacent to it as shown in Figure A-5.

Box 2, Box 4, Box 5, and Box 6 were instrumented with a thermocouple that was placed 1” below the top surface of the box by passing the wire through the opening caused by the folds in the box. Box 8 was affixed with a thermocouple on top of the box as shown in Figure A-2.

Total hydrocarbon concentrations were measured using a Signal Instruments 3000 HM THC Analyzer. The gas concentration probes for the gas measurements were placed in front on Box 5 approximately 6” above the ground as shown in Figure A-7.

A.4 Test Procedure

The test was initiated by powering the film heater to thermally initiate one of the lithium-ion cells into thermal runaway at a rate of 5-10°F/min in Box 4. The thermocouples were monitored to observe for three cells to undergo thermal runaway including the initial cell. Once, the third cell goes into runaway, the balloon filled with ethanol is ignited by powering the NiCr wire wrapped around it if the ceiling temperatures hasn’t already reached 200°F. This initiates a pool fire that ignites the paper and cardboard boxes surrounding it and induces the secondary source of fire.

The ceiling temperatures were monitored to determine the exact time at which any of the ceiling thermocouples reached 200°F, the trigger point. The trigger point was noted and exactly one minute after the trigger point was reached, the agent was discharged into the compartment. The temperatures within the compartment were monitored until the test was terminated. The data acquisition system collected data for several minutes after the test to account for the delay in gas concentration measurement due to the line lengths of the gas sampling system.

A.5 Test Results

Results from the challenge fire scenario are summarized here. The initiation of the first cell into thermal runaway led to the propagation of thermal runaway to the adjacent cells as can be seen in Figure A-8. Videos from the test show that the thermal runaway initiation caused the adjacent shredded paper to ignite. The fire propagated and the fire grew large enough to trigger the ceiling temperature requirement without having to ignite the ethanol filled balloon. The test procedure was followed after the ceiling trigger temperature was reached. The test results show that the agent limited the peak temperature to 278°F and the time-temperature integral to 4665°F-min. The test video reference # for this test is TST 683.15.

To obtain a copy of the videos for the testing accomplished at the W.J. Hughes Technical Center, contact 9-act-troubledesk@faa.gov with a reference to this report and the video reference number associated to with each fire scenario.

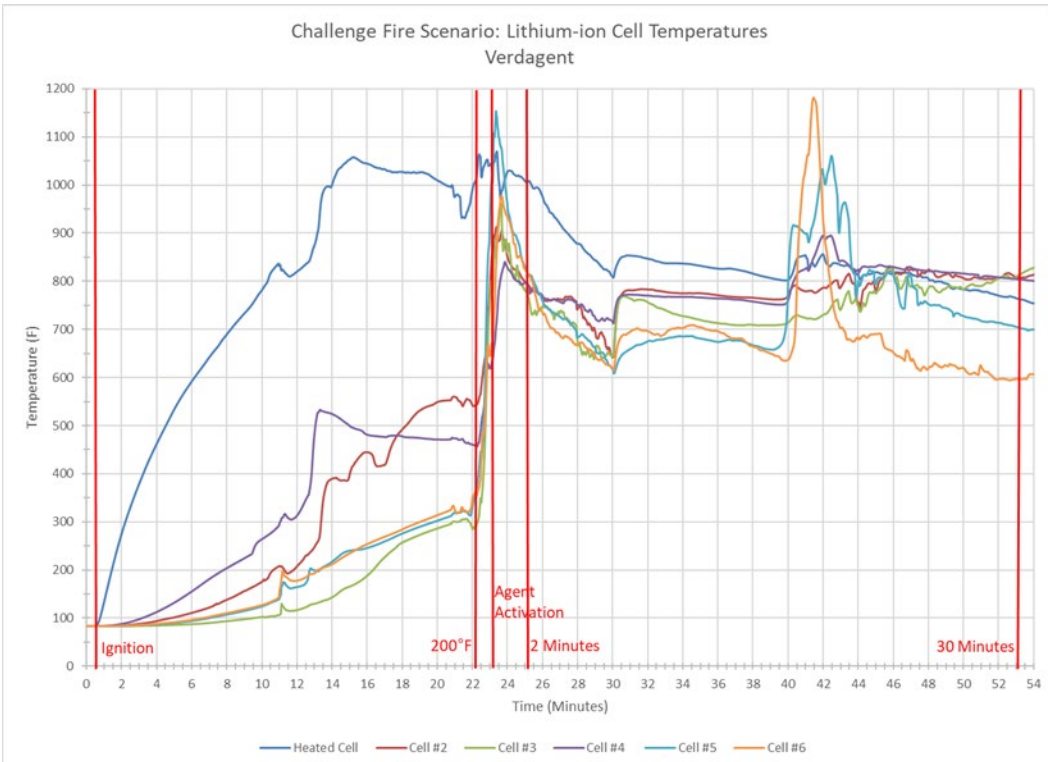

Figure A-8 Lithium-ion Cell Temperatures

The temperature results from the test are shown in Figure A-9. The figure displays the temperature data from the thermocouple that reached the peak temperature with a solid black line, an average temperature of the surrounding four thermocouples with a solid green line, and the oxygen concentration measured at station 1 by a blue dashed line. The figure also depicts the time at which the trigger temperature of 200°F was reached, the agent activation, 2-minute mark of the test (which denotes the start of the evaluation period), and the 5-minute mark of the test (which denotes the end of the evaluation period as well as the end of test) with a vertical solid red line.

The temperature results show a quick rise in temperature when the fire is lit and a sharp decline in temperature as the fire suppression agent is activated. As the temperature starts to rise, the oxygen concentration begins decreasing which indicates the presence of a fire. Figure A-9 also shows the cycling of oxygen concentration around 15% which means that there is a deep-seated fire that has the potential to grow in the absence of a fire suppression agent.

The total hydrocarbon concentration (THC) was measured as a volume percent in terms of propane. The THC rose up to about 3% while the ceiling temperatures were increasing towards the trigger temperature. At the end of the test, the THC measured about 5.5% by increasing at a steady rate throughout the 30 minutes.

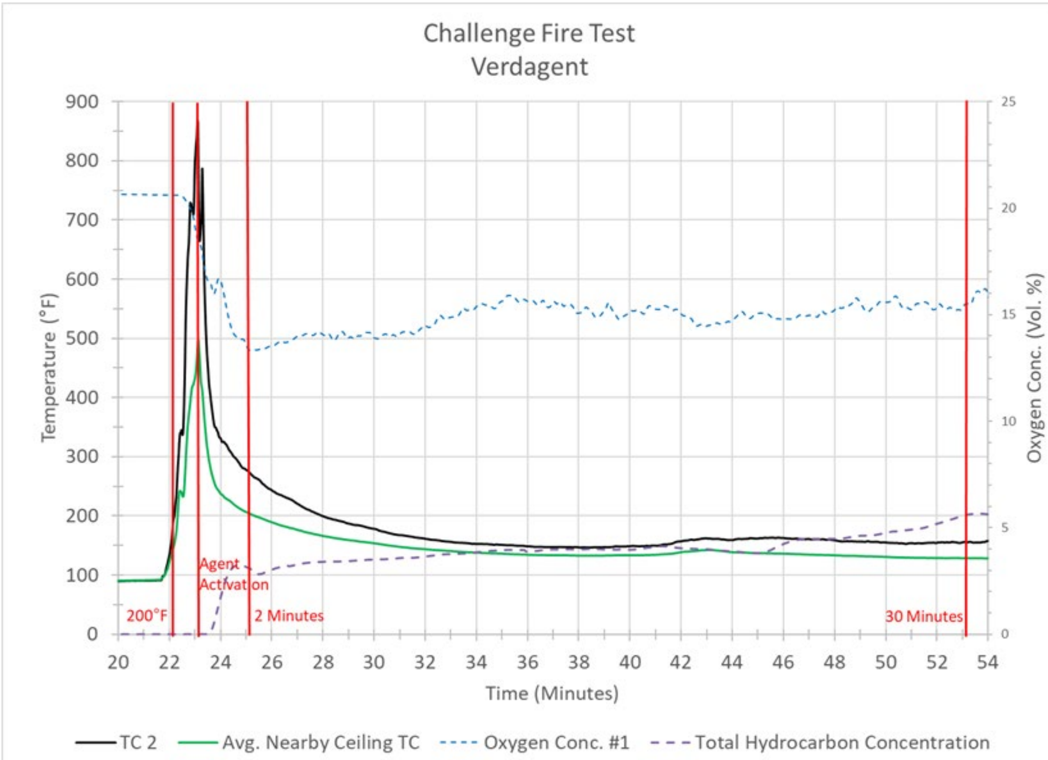

Figure A-9 Results from Challenge Fire Test

A.5 Test Conclusions

VERDAGENT®, a Halon replacement agent was tested at the William J. Hughes Technical Center as per the requirements of the challenge fire scenario, as developed at the time of testing, in collaboration with Meggitt Safety Systems Inc. For the challenge fire scenario, VERDAGENT® limited the average peak temperature to 278°F and the time-temperature integral to 4665°F-min. The test was not compared to an acceptance criteria since one was not developed for this scenario at the time of testing. The testing successfully exhibited the agents' capability to suppress a fire that involved multiple sources of fire.

B Detailed Concentration Test Data

Figures

This appendix displays the individual location measurements for each concentration test using the Halonyzer (Figures B-1 through B-9). The channel number in each chart refers to the locations as described in Figure 2.

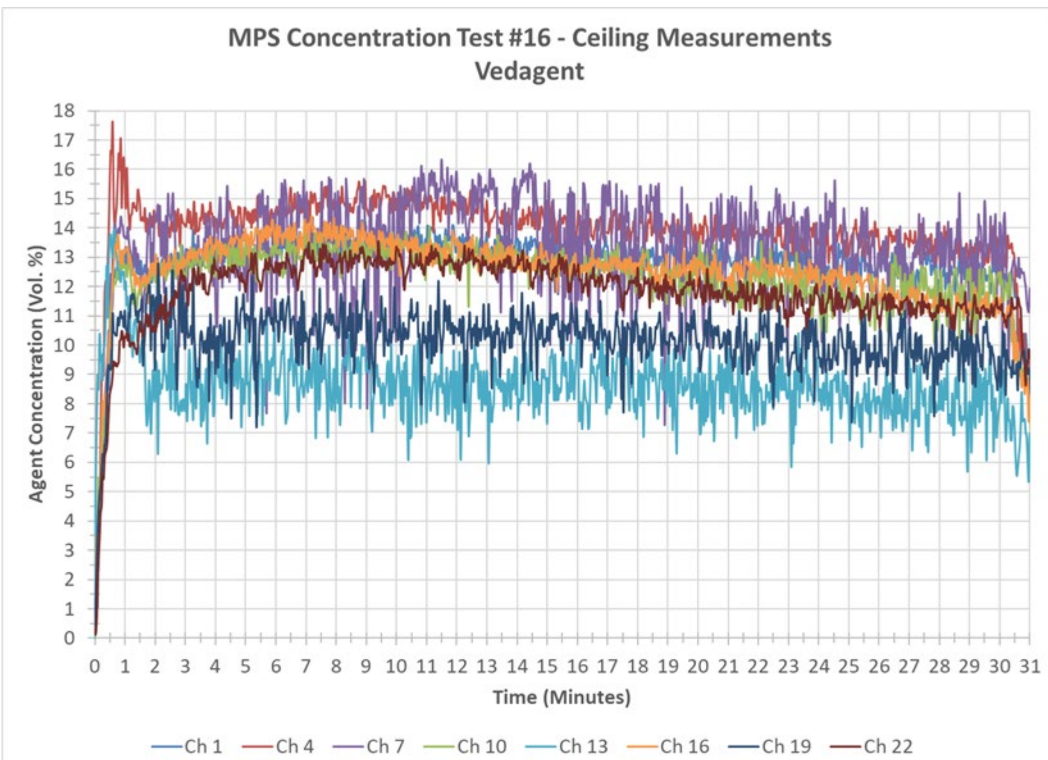

Figure B-1 MPS Concentration Test #16: Ceiling Measurements

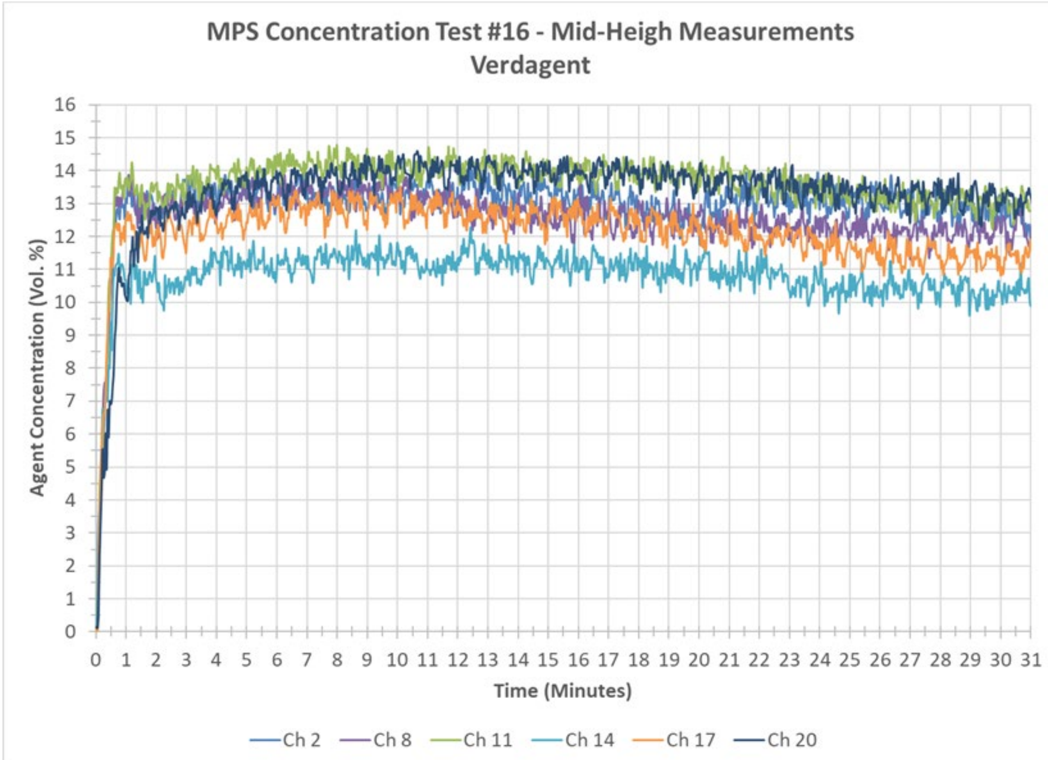

Figure B-2 MPS Concentration Test #16: Mid-Height Measurements

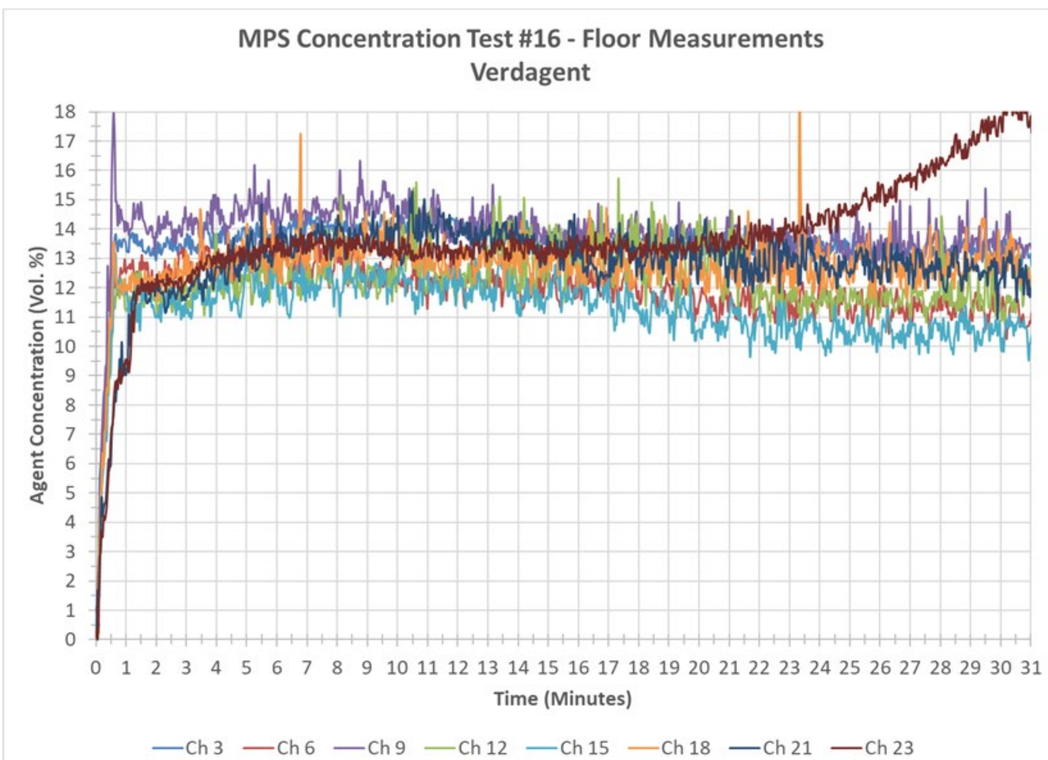

Figure B-3 MPS Concentration Test#16: Floor Measurements

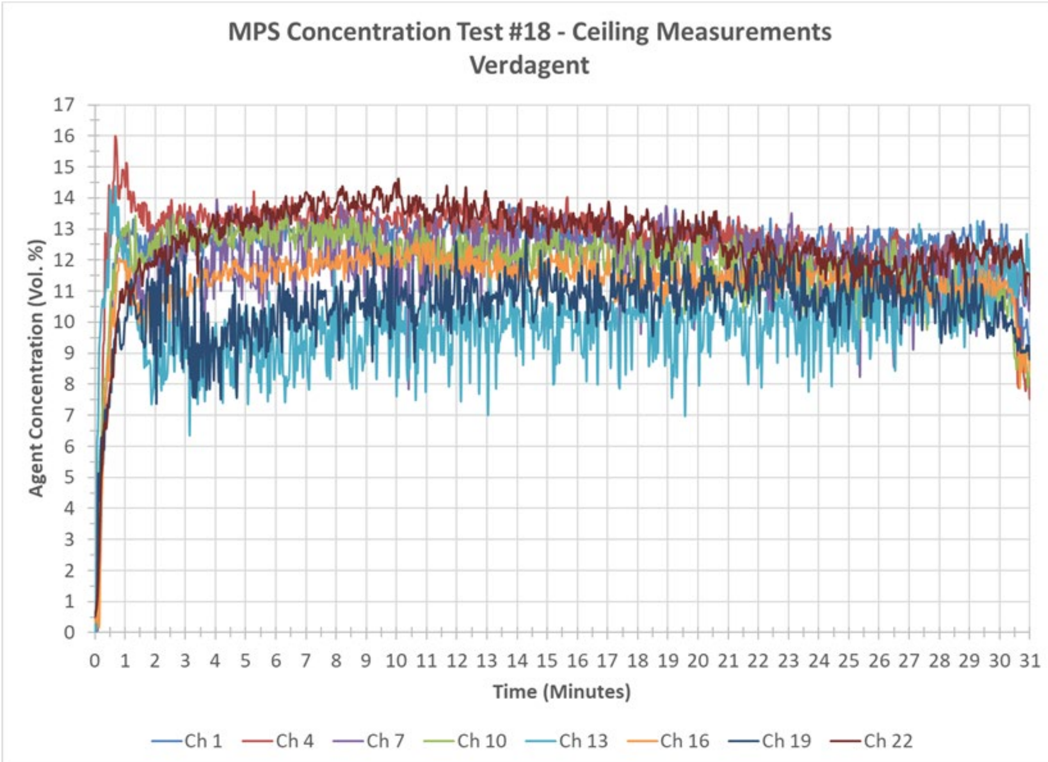

Figure B-4 MPS Concentration Test#18: Ceiling Measurement

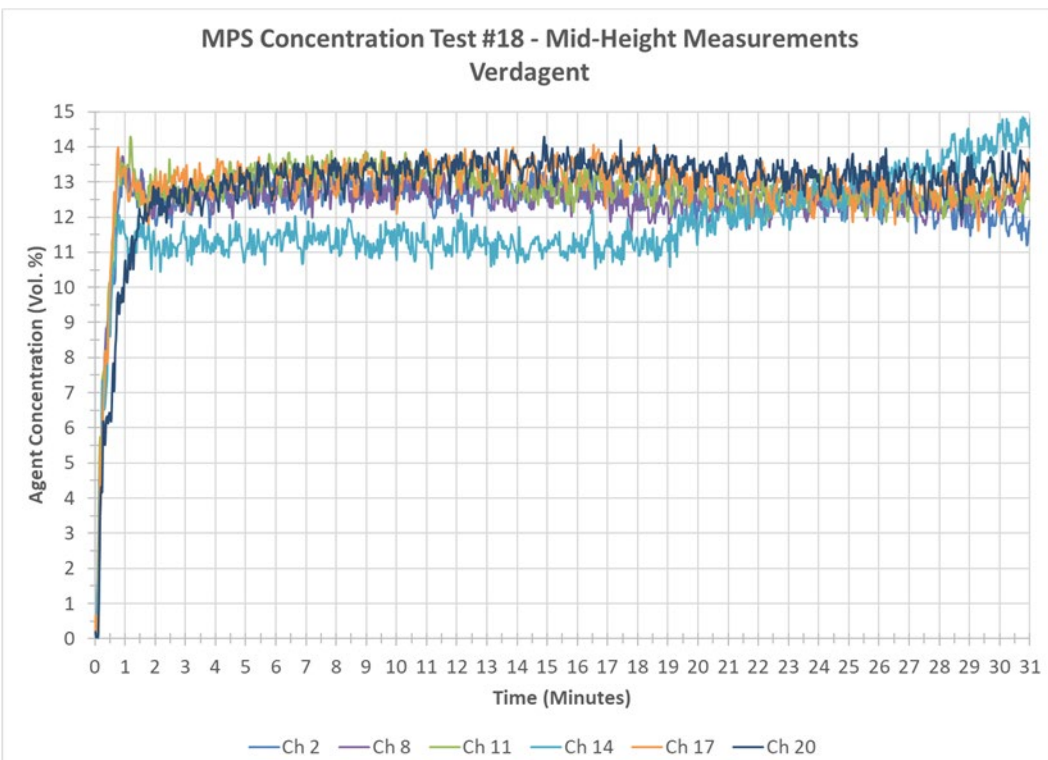

Figure B-5 MPS Test#18: Mid-Height Measurements

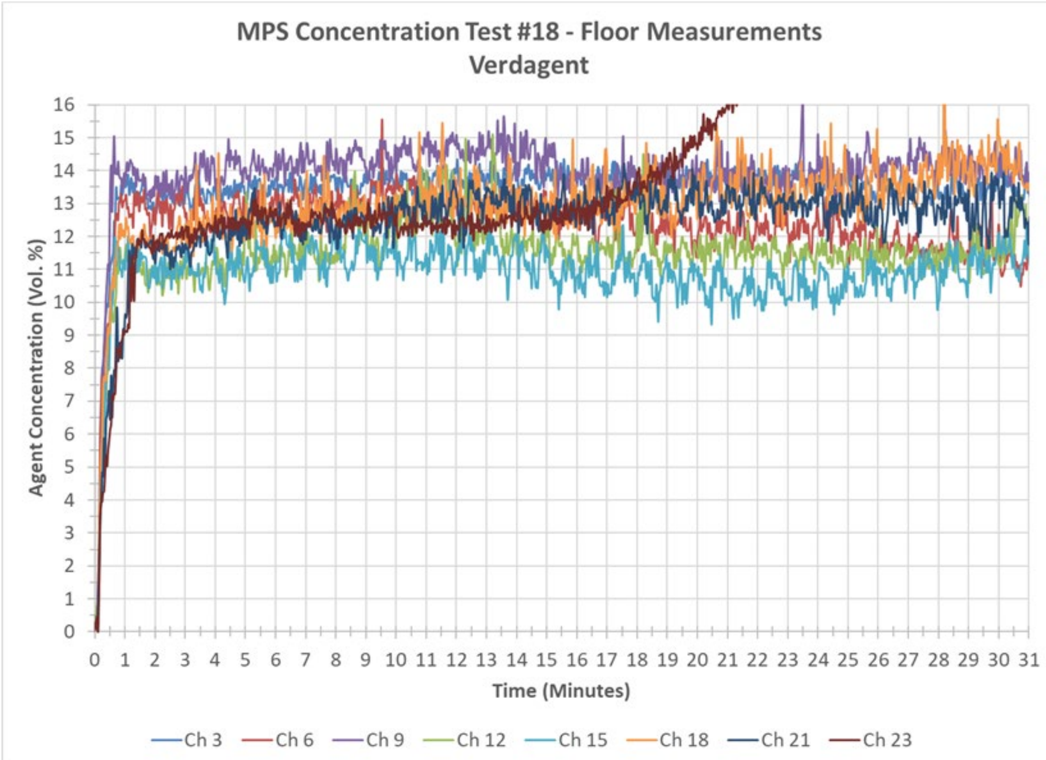

Figure B-6 MPS Concentration Test#18: Floor Measurements

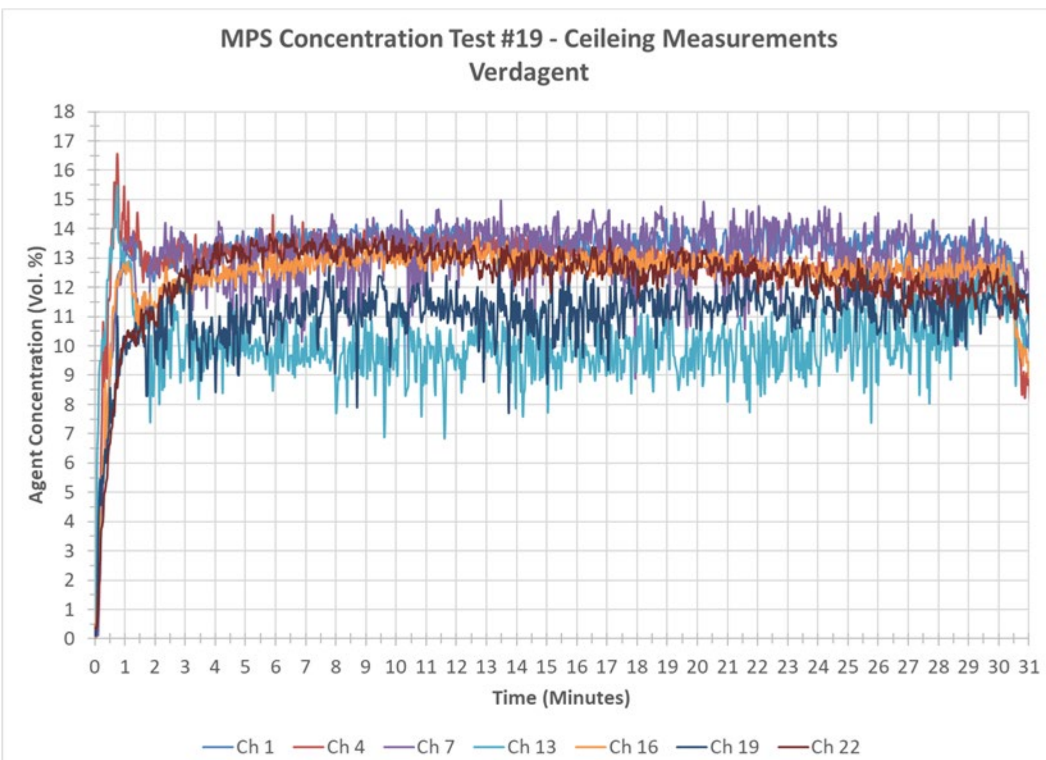

Figure B-7 MPS Concentration Test#19: Ceiling Measurements

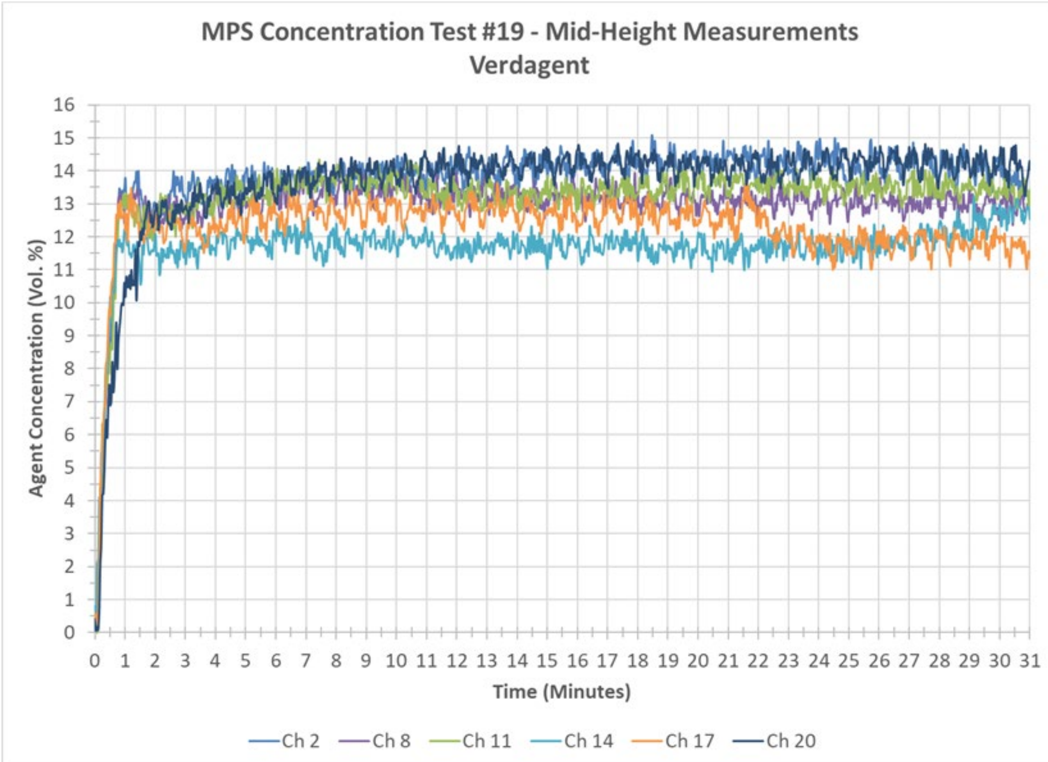

Figure B-8 MPS Concentration Test# 19: Mid-Height Measurements

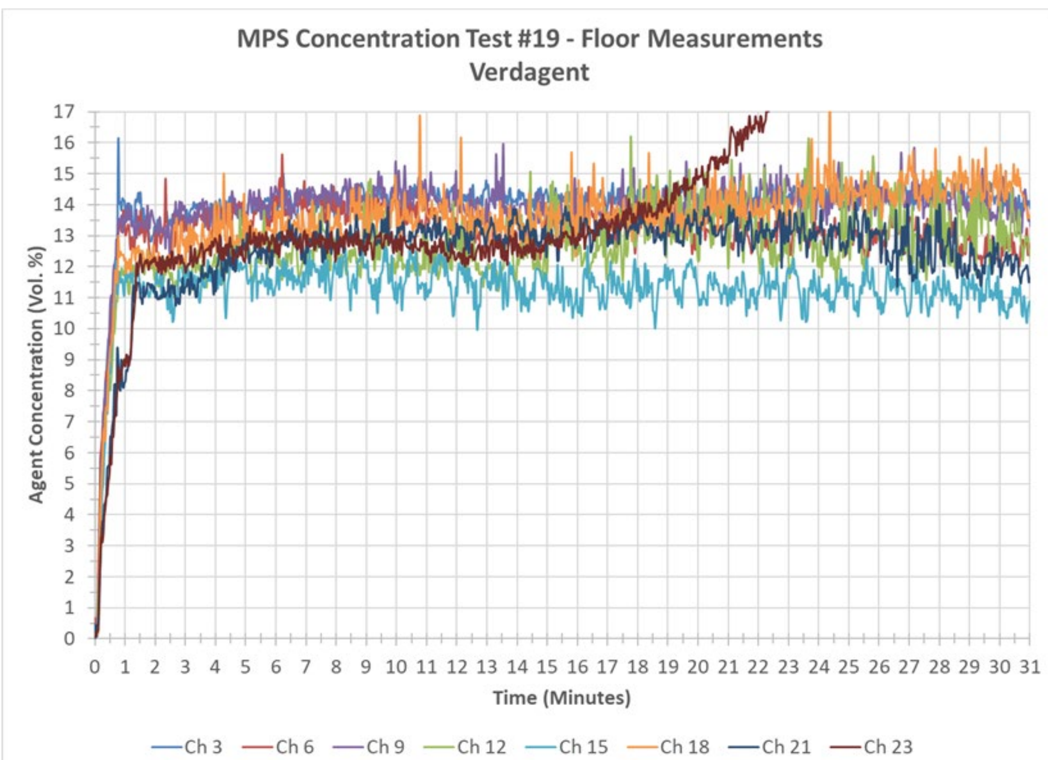

Figure B-9 MPS Concentration Test#19: Floor Measurements