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Evaluating a Heptafluoropropane System with a Water Spray Cooling System for Compartments with Low Flash Point Liquids

Halon Replacement Agent Testing Compartment I

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14. ABSTRACT

As part of Halon 1301 replacement research, the Navy Technology Center for Safety and Survivability at the Naval Research Laboratory (NRL) has been investigating the use of HFP (heptafluoropropane, HFC-227ea, C_3F_7H) as a substitute in US Navy ship compartments. HFP has been shown to readily extinguish fires in a small-sized flammable liquid storage room. In the presence of fire HFP degrades into the extremely hazardous acid gas hydrogen fluoride (HF) in quantities signficantly greater than those generated from Halon 1301 extinguished fires. The presence of HF in the room's atmosphere greatly hinders recovery. To counter the HF threat, we evaluated fire suppression via HFP with the NRL-invented Water Spray Cooling System (WSCS) in a 28 m^3 (1,000 ft^3) simulated shipboard flammable liquid storage room. The objective of this test series was to quantify the benefit of using WSCS in conjunction with an HFP system. The resulting combined fire suppression system readily suppressed a fire while greatly reducing HF concentrations and cooling the compartment. The quantified benefits of WSCS were reduced temperatures, improved reignition protection, and reduced HF levels (by 75%), all allowing for enhanced safe compartment re-entry and recovery.

15. SUBJECT TERMS

Halon replacement; Halon substitute; Water spray cooling system; WSCS; Flammable liquid store room; FLSR; Fire protection; Shipboard fires; Heptafluoropropane; HFC-227ea; HF reduction; Compartment re-entry

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CONTENTS

NOMENCLATURE

AD	Application Duration
AR	Application Rate
CAA	Continuous Acid Analyzer
CBD	Chesapeake Bay Detachment
ERPC	Experiment Running Personal Computer
FID	Flame Ionization Detector
FLSR	Flammable Liquid Storeroom
FTIR	Fourier Transform Infrared Spectroscopy or Spectrometer
GC	Gas Chromatograph(y)
HF	Hydrogen Fluoride
HFP	Heptafluoropropane, C_3F_7H (HFC-227ea)
IDLH	Immediately Dangerous to Life and Health Concentration
IR	Infrared
LCAC	Landing Craft Air Cushion
IT	Initiation Time
n-Heptane	normal heptane (n-C_7H_{16})
NRL	Naval Research Laboratory
MCR	Mobile Control Room
TCD	Thermo Conductivity Detector
WSCS	Water Spray Cooling System

EVALUATING A HEPTAFLUOROPROPANE SYSTEM WITH A WATER SPRAY COOLING SYSTEM FOR COMPARTMENTS WITH LOW FLASH POINT LIQUIDS

HALON REPLACEMENT AGENT TESTING COMPARTMENT I

1.0 INTRODUCTION

The Naval Research Laboratory (NRL) has conducted extensive intermediate[1] and full scale[2] Halon 1301 replacement tests. For the protection of shipboard Flammable Liquid Storage Rooms (FLSRs), testing has included using 1,1,1,2,3,3,3-heptafluoropropane (HFP, C_3F_7H, HFC-227ea) by itself and together with the NRL-invented Water Spray Cooling System (WSCS)[3,4,5]. Although HFP by itself has been proven effective in extinguishing low flash point liquid fuel fire scenarios, the amount of hydrogen fluoride (HF) produced during an HFP suppression is a safety concern. Furthermore, HFP produces very limited compartment cooling, as do all gaseous agents. High compartment temperatures can result in increased fuel evaporation and reignition/reflash potential upon re-entry. The WSCS has been found to be beneficial in reducing HF production when initiated prior to agent discharge[6]. The WSCS also "scrubs" HF from compartment air and lowers compartment temperatures.

This effort identifies the usage parameters for protecting shipboard compartments containing low flash point liquids using HFP in conjunction with the WSCS. Initial testing using water mist technology has proven the potential for hazardous energetic reflashes[7]. To avoid energetic reflashes and facilitate potential system implementation, low-pressure WSCS using pressures available in shipboard fire mains will be used instead of high-pressure water mist.

The tests are being conducted at NRL's Chesapeake Bay Detachment Facility (CBD). The program is designed to provide implementation guidance for increasingly larger compartments containing low flash point liquids. Initial tests were conducted in a 28 m^3 (1,000 ft^3) volume test compartment similar in size to many smaller shipboard compartments. The results of the initial testing, as reported herein, served as a learning process for designing and executing further tests conducted in a 126 m^3 (4,460 ft^3) sub-compartment constructed within a 297 m^3 (10,500 ft^3) test compartment. Testing in the 297 m^3 (10,500 ft^3) compartment is in progress.

This document includes the findings and results of the HFP testing in conjunction with the WSCS system for test compartments up to 28 m^3 (1,000 ft^3) in volume.

2.0 OBJECTIVE

The primary objective of the overall program is to quantify the benefits of using the WSCS together with HFP for the extinguishment of low flash point liquids. Methanol was one of the flammable liquids tested because it is the most challenging shipboard flammable liquid to extinguish with HFP.

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The objective of the work presented here was to evaluate the use of the WSCS to improve the performance of HFP in terms of compartment cooling and HF time weighted exposure (loading) in compartments up to 28 m^3 (1,000 ft^3) in volume. The WSCS variables evaluated included nozzle type, water application rate, water application duration, and water initiation time relative to HFP discharge. Results include nozzle selection and guidance on the WSCS initiation time and application duration. This report discusses the findings of this testing and provides preliminary recommendations for implementation of WSCS/HFP systems.

3.0 CONCEPTUAL SYSTEM IMPLEMENTATION

The WSCS system was designed to provide good nozzle coverage, minimize the weight added to the ship, and provide simple installation requirements. The WSCS system was designed to operate off the ship's fire main at a pressure of 10 bar (150 psi), thus eliminating the need for a pump. The system can be initiated via manual activation or may be interlocked with the HFP discharge and ventilation systems. The WSCS system may remain on until it is manually secured or may be secured automatically by a timer. To reduce dewatering, the WSCS system should operate at the lowest effective water application rate, making compartment re-entry easier and faster.

4.0 TEST PARAMETERS

4.1 Test Compartment 1

Tests were conducted in a 3.0 m x 3.0 m x 3.0 m (10 ft x 10 ft x 10 ft) steel compartment (designated compartment 1) designed to simulate a small shipboard flammable liquid storeroom. The total enclosed volume was approximately 28 m^3 (1,000 ft^3). It was equipped with a watertight door in the aft bulkhead. See Figure 1 for an exterior view of the compartment.

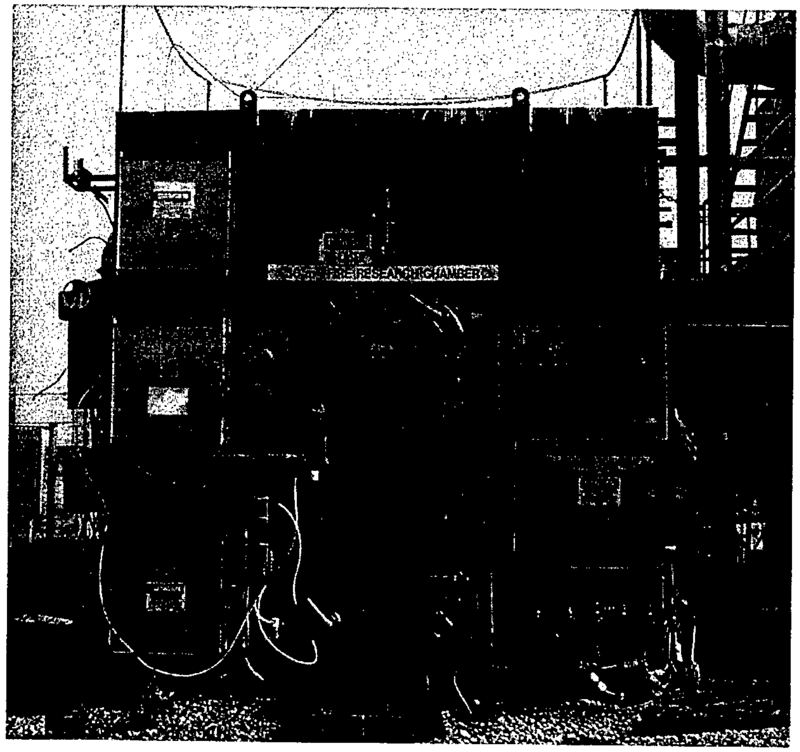


Figure 1.
Exterior View of the Test Compartment, Aft Bulkhead

4.2 Test Compartment Shelving and Mockups

The compartment was fitted with storage racks along the port and forward bulkheads (See Figures 2 and 3). The storage racks were composed of removable shelving sections that were approximately 66 cm (26 inches) in depth. Perforated shelves were positioned at heights of 61 cm (24 inches), 122 cm (48 inches), 183 cm (72 inches) and 244 cm (96 inches) above the deck. Mock-ups consisting of 19 L (5 gallon) buckets were placed on the deck and shelving to challenge the suppression system by obstructing the agent distribution. With the compartment fully loaded with mock-ups, the adjusted compartment floodable volume became 19.8 m^3 (707 ft^3). With limited mock-ups, the compartment floodable volume became approximately 25.6 m^3 (905 ft^3). While full mock-ups provided the maximum agent obstruction, testing was performed with limited mock-ups in order to provide sufficient obstruction while minimizing the increase of agent concentration.

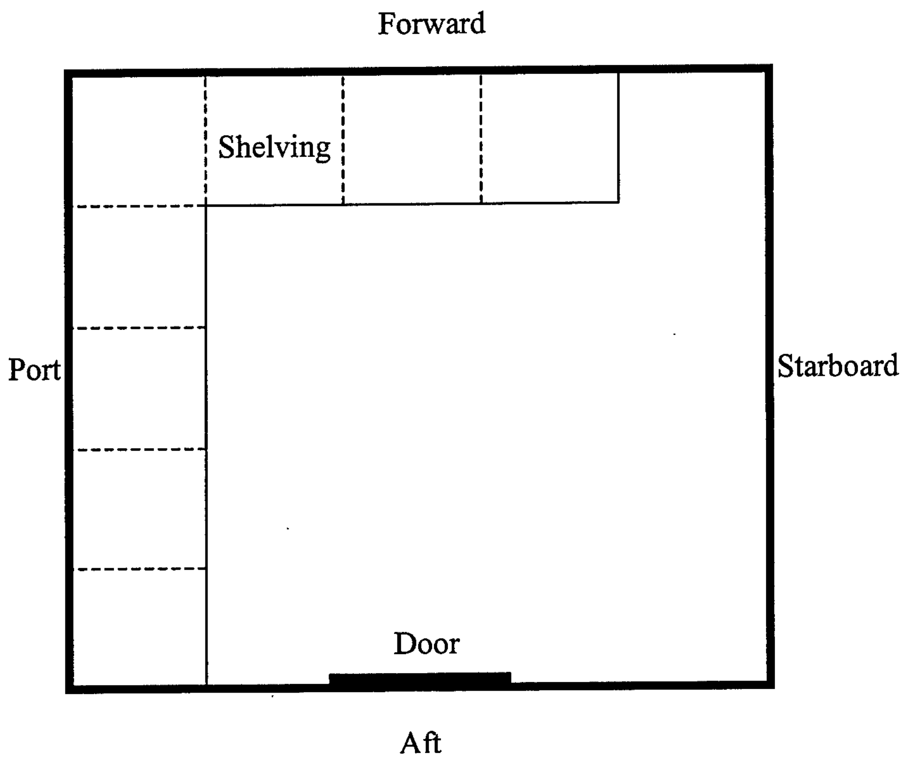


Figure 2.

Plan View of the Interior of the Test Compartment

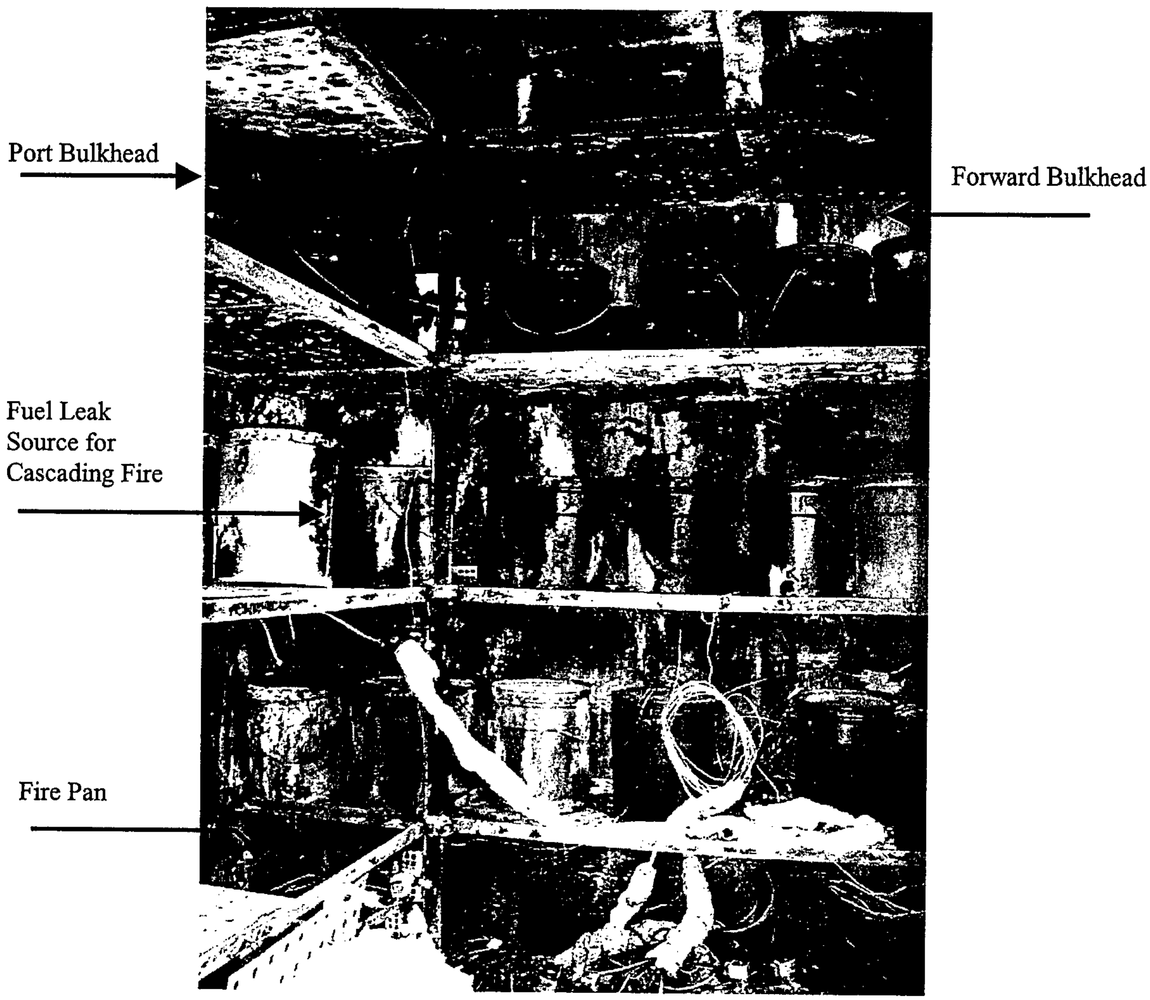


Figure 3.
Interior View of the Test Compartment

4.3 HFP Discharge System

The HFP discharge system consisted of a single overhead nozzle positioned in the center of the compartment. An agent design concentration of 10.6% HFP based on the compartment's total floodable volume of 28 m^3 (1000 ft^3) was used for these tests. Refer to the "Test Plan for Evaluating HFP Gaseous Agent System with a Water Spray Cooling System in Compartments with Low Flash Point Liquids" [8] for more details and for drawings of the discharge system.

4.4 Water Spray Cooling System (WSCS)

The WSCS was first evaluated aboard the *ex*-USS *Shadwell*[6]. Limited testing of the WSCS in conjunction with HFP was also conducted in Compartment 1 at CBD in 1996[9]. These test series have shown that the WSCS reduces compartment temperatures and weakens the fire through energy abstraction and dilution from steam generation. This aids in limiting the production of HF. When HF is produced, the water supplied by the WSCS also lowers HF levels and ultimately reduces the time for compartment re-entry[5]. Future testing in larger compartments will further investigate how the WSCS facilitates suppression, re-ignition protection, and compartment re-entry in conjunction with the HFP system.

A single WSCS nozzle was used in the compartment due to its 3.0 m x 3.0 m (10 ft x 10 ft) floor dimensions. Ten different nozzles with a range of flow rates and droplet size distributions were evaluated (refer to Table 1). In expected shipboard use, water will be supplied to the WSCS from the ship's fire main, operating at 10 bar. Because of this, the WSCS system was designed to operate at the same water pressure to allow shipboard implementation without the use of an additional pump. At the CBD fire research test bed there was no fire main available. Therefore, a 5HP electric pump was used to boost the hydrant pressure to 10 bar (150 psi). The application flow rates depended on the nozzle types that were pre-selected. The WSCS mains were composed of 2.5 cm (1 inch) tubing. All exterior tubing was stainless steel while all interior tubing was brass. The Experiment Running Personal Computer (ERPC) controlled activation of the WSCS.

4.5 Fuels and Fire Scenarios

Each test was conducted with either methanol or n-heptane fueled fires. Methanol, usually present aboard ships for use in Landing Craft Air Cushion (LCAC) operations, was selected as a test fuel because of the high HFP concentration required to extinguish methanol fires. n-Heptane was chosen because it is representative of other flammable liquids found in shipboard FLSRs. Each fuel has different burning characteristics and extinguishment requirements.

Two fires in the shelving burned simultaneously during each test. A pan fire was located approximately 38 cm (15 inches) above the deck in the forward port corner of the compartment. The fuel for a three dimensional cascading fire was introduced 1.6 meters (63 inches) above the deck in the forward port corner of the compartment above the pan fire. The fuel dripped downward through the perforated shelving onto and around the 19 L (5 gallon) containers. The combined fire sizes ranged from 175 to 400 kW. The cascading fire was more dynamic and more obstructed than the pan fire, presenting more of a challenge for the HFP and WSCS system to suppress. The cascading fire accounted for a larger portion of the total heat release rate. Preburn duration was defined as the time between fire initiation and HFP discharge and was based upon response scenarios expected in the Fleet. Several preburn durations ranging from thirty seconds to two minutes were evaluated.

5.0 INSTRUMENTATION

The discussion below includes only the instrumentation that was used to collect the data presented in this report. For complete instrumentation information, refer to the "Test Plan for Evaluating HFP Gaseous Agent System with a Water Spray Cooling System in Compartments with Low Flash Point Liquids"[8]. See Appendix A for the locations of the instrumentation in the test compartment. All instrumentation heights are measured from the deck.

5.1 Temperature Measurements

Two vertical thermocouple trees were used to measure air temperature in the test compartment. Each tree consisted of 7 Type-K thermocouples starting at 38 cm (15 inches) above deck with one thermocouple every 38 cm (15 inches). Additional thermocouples were used to monitor fire, telltale, and grab sample location temperatures. Methanol and n-heptane telltales were placed throughout the compartment to help determine agent distribution characteristics. All thermocouples for compartment, fire/telltale, and grab sample monitoring were connected to the ERPC.

5.2 Gaseous Grab Samples

Gaseous grab samples were taken at the pan and cascading fires and at three other locations within the test compartment. Evacuated 1.7 L (100 in^3) bottles with valves and solenoids were used. The pan and cascading grab bottles were manually activated from the Mobile Control Room (MCR) at fire out or reignition. The samples were analyzed via gas chromatography (GC) for oxygen/argon, carbon monoxide, carbon dioxide, nitrogen, and HFP. An SRI Instruments® GC, configured with a Thermal Conductivity Detector (TCD) and a Flame Ionization Detector (FID), was used to analyze the grab samples.

5.3 Continuous Gas Sampling (O_2 and HFP)

Four sampling lines were used for continuous sampling of oxygen and HFP in the test compartment. Gas samples were collected and transported to the analyzers located in the MCR. The gas transport time from the compartment to the MCR was measured. In the MCR, infrared (IR) analyzers quantified HFP, carbon dioxide and carbon monoxide, and paramagnetic oxygen balances determined O_2 concentration in the sample gas.

5.4 Hydrogen Fluoride (HF) Sampling

Continuous acid analyzers (CAAs) measured airborne HF (gas and aerosol) concentrations. The response time was about 20 seconds. The monitor sampled air through a minimal surface continuous impinger where HF was extracted into an aqueous phase, transported to a flow-through ion selective electrode, and quantified. The concentration of HF in the compartment air was then calculated using air and liquid flow rates. All CAA monitors were positioned outside of the test compartment. The sampling tubes penetrated the bulkhead and ventilation ductwork to reach the sampling locations inside the compartment and exhaust stack.

The Fourier Transform Infrared Spectrometer (FTIR) was a MIDAC Model I2001-F with Axiom Analytic optical conduit and was used to measure *in situ* HFP and HF gaseous concentrations. The FTIR had its own self-contained protective enclosure so that it could be utilized at various locations within the test compartment. The enclosure was constantly purged with N_2 and was cooled by water flowing through a heat exchanger. The FTIR had its own data collection computer located in the MCR and synchronized with the ERPC. [Note: Carbonyl Fluoride (COF_2) generated in the compartment is quickly converted to HF by water and is measured as HF by the CAAs. The FTIR measures COF_2 directly and it is included for comparison in the HF concentrations reported. Both HF and COF_2 have similar toxicities.]

5.5 Video Recording

Four video cameras, two visible and two infrared, were used inside the compartment to monitor the fire activity and fire extinguishment times. One pair of visible and infrared cameras were positioned to observe pan fire activity and one pair was positioned to observe cascading fire activity. An additional video camera was used to view the overall test site. Videocassette recorders with time stamp generators located inside the MCR recorded the output from all five video cameras.

6.0 TEST VARIABLES AND PROCEDURES

6.1 Test Variables

Several WSCS variables were evaluated, including the WSCS nozzle type, application rate, initiation time, and application duration.

6.1.1 WSCS Nozzle Type and Application Rate

The WSCS system simulated a shipboard system with a pump maintaining a supply pressure of approximately 10 bar. Given the constant supply pressure, the WSCS application rate was a function of nozzle type and orifice size. As shown in Table 1, ten different nozzles, with application rates ranging from 6.4 to 44.3 Lpm (1.7 to 11.7 gpm), were evaluated. One WSCS nozzle was positioned in the center of the compartment.

Table 1.

WSCS Nozzle Types, Application Rates, and Droplet Sizes at 10 bar (150 psi)

Manufacturer	Nozzle Type	Manufacturer Listed Application Rates (Lpm/gpm)	Manufacturer Listed DV10 (microns)	Manufacturer Listed DV50 (microns)	Manufacturer Listed DV90 (microns)
Spraying Systems Co.®	1/8G-5.6W[1]	6.4 / 1.7	n/a	n/a	n/a
	1/4G-12W[1]	14.0 / 3.7	n/a	n/a	n/a
	3/8G-17W[1]	18.2 / 4.8	n/a	n/a	n/a
Bete® Fog Nozzle	TF6FC[2]	10.6 / 2.8	44	88	156
	TF8FC[2]	18.9 / 5.0	57	111	196
	TF10FCN[1]	26.8 / 7.1	78	151	269
	TF10FC[2]	29.5 / 7.8	68	132	234
	TF12FC[2]	44.3 / 11.7	n/a	n/a	n/a
GEM (ex-Grinnell) AquaMist®	AM4[1]	10.6 / 2.8	n/a	n/a	n/a
	AM10[1]	10.6 / 2.8	210	340	480

[1] 90° Spray Angle
[2] 120° Spray Angle
n/a = Not Available

6.1.2 WSCS Initiation Time

The WSCS initiation time was also evaluated. Initiation time was defined as the time between initiation of the WSCS and discharge of the HFP. From previous testing, enhanced fire suppression effectiveness and reduced HF production was achieved when the WSCS was initiated prior to agent discharge[6]. The WSCS initiation times ranged from 15 seconds to one minute before HFP discharge to evaluate its effect on HF generation. During some tests, the WSCS was initiated a second time (after reignition and during venting) to help develop compartment re-entry doctrine for future larger compartment testing.

6.1.3 WSCS Application Duration

Shipboard compartments containing low flash point liquids do not have floor drains. To avoid compartment flooding and facilitate compartment re-entry, the shortest effective WSCS application duration was desired. A range of two to five minutes was evaluated to determine the effects of short and long WSCS application durations.

6.2 Test Procedures

Four different test scenarios were used to evaluate the individual effects of WSCS and HFP:

- Background tests (no WSCS or HFP);
- Preburn tests (WSCS only);
- Baseline suppression tests (HFP only); and
- Suppression tests (WSCS and HFP).

Background, preburn, and baseline suppression tests were conducted prior to the suppression tests with HFP and WSCS. The data from the baseline suppression tests were compared to the data from the tests in which HFP and WSCS were both discharged to quantify the effects of the WSCS on the quantity of HF produced. The events of suppression test WSCS1S2.8 are shown in Table 2. The sequence of events is typical of the suppression tests although the events used and exact times varied.

Table 2.

Test Events for Test WSCS1S2.8 (HFP Discharge at Time = 0)

Test Time (sec)	Test Events and Observations
-300	Test Start
-60	Cascading and Pan Fires initiated (1 minute preburn)
-45	WSCS initiated
-30	Ventilation (supply and exhaust) secured
0	Gaseous agent discharged, hold time initiated
90	WSCS secured
300 600	Reignition attempts during hold time
900	Ventilation (supply and exhaust) initiated Hold time completed
900 960 1020	Reignition attempts during venting
1072	Cascading Fire reignited (observed)
1120	Pan Fire reignited (observed)
1130	WSCS initiated manually after reignition to scrub HF
1790	WSCS secured manually
1800	Test secured

7.0 TEST RESULTS

7.1 Nozzle Selection for Background and Preburn Tests

The purpose of the background and preburn tests was to characterize the effects of the WSCS variables on the compartment temperatures and fire characteristics. The ten nozzle types included as part of this test series were evaluated based on their effect on the temperature inside the compartment and their effect on the flame sheet size and fire extinguishment time (determined visually from video recorded during the tests).

Initial preburn tests showed that the six highest flow rate nozzles (those with flow rates of 14.0 Lpm (3.7 gpm) and greater) did not provide any advantage over the lower flow nozzles in terms of compartment temperatures and fire knock-down (reduction of flame sheet size). In some cases, these higher flow rate nozzles performed worse than the lower flow rate nozzles.

Based on these results and discussions with the US Naval Sea Systems Command, the four low flow nozzles were selected for further evaluation. The lowest flow nozzle (6.4 Lpm (1.7 gpm)) was not effective at reducing the compartment temperatures or the flame sheet size and was eliminated from further testing. The three remaining nozzles, with application rates of 10.6 Lpm (2.8 gpm), significantly reduced the compartment temperatures and the size of the flame sheet.

Due to the need to limit the number of suppression tests conducted, two of the three remaining nozzles (Bete® TF6FC, GEM® AM4, and GEM® AM10) were chosen for further evaluation. Other nozzles may work as well as the ones that were chosen for further evaluation but extensive testing of all the nozzles was not possible. The Bete® TF6FC nozzle was chosen because it was effective at reducing the size of the flame sheets in both 175 kW methanol and 200 kW n-heptane fires. Neither of the GEM® nozzles had an effect on the 175 kW methanol fire. While the AM4 was more effective than the AM10 in reducing the size of the flame sheet in 200 kW n-heptane fire, the AM10 was chosen over the AM4 because it was more effective in reducing the size of the flame sheet in the more challenging 350 kW total methanol fire. Table 3 provides a summary of why each nozzle was selected.

Table 3.
Summary of Nozzles Selected

Nozzle	Spray Angle	Application Rate	Reason for Final Selection
Bete® TF6FC	120°	10.6 Lpm (2.8 gpm)	More effective than the AM4 and AM10 in reducing the size of the 175 kW methanol and 200 kW n-heptane fires
GEM® AM10	90°	10.6 Lpm (2.8 gpm)	More effective than the AM4 nozzle in reducing the size of the 350 kW methanol fire

7.2 Nozzle Selection for Suppression Tests

The Bete® TF6FC and the GEM® AM10, having been chosen for use in the suppression tests, were evaluated based on their effects on the following parameters: the peak HF concentration, the HF time weighted exposure ("loading"), the time to fire out, and the reduction of compartment temperatures. Testing was limited to these two nozzles because of the limited suppression test matrix. Other nozzles that were not evaluated may produce similar results.

The peak HF concentration was defined as the maximum HF concentration measured in the compartment by the CAAs and typically occurred within 15 seconds of agent discharge. The decay of the HF concentration in the compartment over time was evaluated to determine the effects of the water application rate and duration on the HF concentration. The data collected from the CAAs was graphed for each test and the area under the curve between agent discharge (zero seconds) and ventilation initiation (960 seconds) was numerically integrated to estimate the

HF "loading". The HF concentration was also measured by the FTIR. Visible and infrared videos were taken of both the pan and cascading fires, allowing accurate determination of the fire events. The time to fire out was determined by reviewing the videotapes of the tests. The compartment temperatures after agent discharge were also examined to determine the cooling capacity of each nozzle.

7.3 Suppression Test Results

A summary of the suppression tests conducted can be found in Table 4.

7.3.1 Hydrogen Fluoride Reduction

The 175 kW methanol fire with a preburn duration of 1 minute produced the highest HF concentrations in the test compartment in this test series. This cascading/pool fire threat was used for subsequent experiments. To evaluate the effect of the WSCS nozzle type on the peak HF concentration, three baseline suppression tests with HFP only and four suppression tests with WSCS and HFP, two with each nozzle, were conducted. The WSCS with HFP suppressions consisted of a 175 kW methanol fire and a WSCS initiation time of 30 seconds prior to HFP discharge. The average peak HF concentrations for each nozzle are in Table 5. It is difficult to draw conclusions from the data for CAA position 1 because the sampling point was located close to the flame sheet. The turbulence of the moving flame sheet caused large fluctuations at that sampling point, compromising its usefulness. CAA positions 2 and 3, located near the FTIR, suggest that both nozzles diminished the peak HF concentration equally well. The peak HF concentration at CAA position 4, located next to the aft bulkhead door, does not indicate that either nozzle had an effect at that location. The fifth CAA, located in the exhaust stack, only provided HF concentration data during ventilation and is not included here.

To further evaluate the performance of the WSCS with respect to HF concentration, the effects of the WSCS initiation time (IT) and application duration (AD) on HF loading were evaluated. WSCS initiation times ranging from 15 to 60 seconds prior to HFP discharge and WSCS application durations of 90 and 270 seconds after agent discharge were examined. Table 6 contains the HF loading calculated for each CAA location for the 175 kW total methanol fire tests with a one minute preburn.

Table 4.

Summary of Suppression Tests

Test	Fire Size (kW)	WSCS AR (Lpm/gpm)	WSCS IT[1] (sec)	WSCS AD (sec)	Design HFP Concentration at 70°F (% in empty compartment)	Pan Out (sec)[1]	Casc. Out (sec)[1]	Peak HF @ Suppression (ppm)[2]
n-Heptane Tests								
1S1.1	200	18.9 / 5.0	n/a	n/a	10.3	5	6	950 (CAA 1)
1S1.2	450	18.9 / 5.0	n/a	n/a	12.1	5	5	450 (CAA 4)
1S1.3	200	18.9 / 5.0	n/a	n/a	10.0	7	7	1500 (CAA 2)
Methanol Tests								
1S2.1	175	n/a	n/a	n/a	10.7	10	8[3]	2500 (CAA 4)
1S2.1rep	175	n/a	n/a	n/a	10.1	11	20, flashing to 30	6000 (CAA1)
1S2.1rep2	175	n/a	n/a	n/a	10.4	9	12, flashing to 25	3900 (CAA1)
1S2.2	175	10.6 / 2.8	-30	120	10.5	16	14	3500 (CAA1)
1S2.3	175	10.6 / 2.8	-30	120	10.6	10	12	5600 (CAA1)
1S2.7rep[4]	175	10.6 / 2.8	-15	105	10.6	10	12	4300 (CAA1)
1S2.8	175	10.6 / 2.8	-45	135	10.6	10	13	3600 (CAA1)
1S2.9	175	10.6 / 2.8	-60	150	10.7	10	11	4800 (CAA1)
1S2.10	175	10.6 / 2.8	-30	300	10.7	9	13	2600 (CAA4)
1S2.11	175	10.6 / 2.8	-30	300	10.7	9	12	5200 (CAA1)
1S2.4	350	n/a	n/a	n/a	11.4	6	6	540 (CAA1)
1S2.5	350	10.6 / 2.8	-45	120	10.7	7	8	160 (CAA4)

[1] Times in reference to agent discharge at t = 0.
[2] CAA locations can be found in Appendix A.
[3] Rapid cascading fire extinguishment without flashing due to high agent concentration. See Appendix B.
[4] Test 1S2.7 is not included here because it was not a valid test.

n/a = not applicable

Table 5.

Average Peak HF Concentrations in PPM

CAA Position	No WSCS	Bete® TF6FC	GEM® AM10
1	3400 (3)	2800	5400
2	1700	1100	1000 (1)
3	1600	960	970
4	2500	2700	2500

Results are the average of two data points unless otherwise specified in parentheses.

Two factors affecting the fire suppression performance of the WSCS are the compartment temperatures just prior to and during the WSCS discharge and the amount of water reaching the flame sheet. A hotter compartment will vaporize more water resulting in greater oxygen dilution. An obstructed (especially a smaller) fire will be exposed to fewer WSCS drops. Less water at the fire will reduce the effectiveness of the WSCS at inhibiting the fire by energy abstraction.

Table 6.

HF Loading for Different WSCS Initiation Times and Application Durations

Test Name	WSCS Initiation Time WSCS IT (sec)[1]	Water Application Duration After Agent Discharge (sec)	FTIR (ppm-seconds)	CAA 1 (ppm-seconds)	CAA 2 (ppm-seconds)	CAA 3 (ppm-seconds)	CAA 4 (ppm-seconds)
1S2.1	n/a	n/a	300,000	260,000	260,000	240,000	220,000
1S2.1rep	n/a	n/a	390,000	690,000	280,000	310,000	□
1S2.1rep2	n/a	n/a	380,000	550,000	□	□	400,000
1S2.7rep[2]	-15	90	98,000	150,000	73,000	75,000	130,000
1S2.2[2]	-30	90	63,000	210,000	50,000	68,000	100,000
1S2.3[3]	-30	90	130,000	250,000	□	28,000	130,000
1S2.8[2]	-45	90	110,000	130,000	51,000	48,000	83,000
1S2.9[2]	-60	90	□	190,000	68,000	87,000	□
1S2.10[2]	-30	270	96,000	63,000	73,000	48,000	110,000
1S2.11[3]	-30	270	82,000	210,000	54,000	74,000	80,000

[1] Times in reference to agent discharge at t = 0.
[2] Bete® TF6FC nozzle
[3] GEM® AM10 nozzle
□ Data not available.

The data in Table 6 clearly demonstrates that the WSCS reduced the HF loading. The HF loading generally decreased as the initiation time increased from 15 to 45 seconds prior to HFP discharge. An initiation time of 60 seconds prior to HFP discharge reversed this trend. This is most probably due to the fire having time to recover after the initial "knock-down" from the water vapor generated by the WSCS. Since the ventilation was still operating, much of the water vapor diluted air was lost through the exhaust ducts. Subsequent to ventilation shutdown, less additional water vapor was produced because the compartment was cooled by the initial WSCS application. Therefore, the fire was able to recover before the discharge of the HFP. Although initiating the WSCS 45 seconds prior to HFP discharge resulted in the greatest reduction of the HF loading (test WSCS1S2.8), an initiation time of 30 seconds was recommended because implementation would not require any change to the current Fleet Firefighting Doctrine. In the Fleet, the ventilation system is secured 30 seconds prior to HFP discharge for small FLSRs such as those simulated by the test compartment. Recommending a WSCS initiation time of 45 seconds would require changing the time ventilation is secured to 45 seconds prior to agent discharge. Both the 30 and 45 second initiation times reduced the HF loading by about 75% when compared to the HF loading in non-WSCS scenarios in this compartment and fire scenarios. Despite the different nozzle spray angles, there is no statistically meaningful difference between the Bete® and the GEM® nozzles in reducing HF loading. HF loading reduction is fire scenario and sampling location specific.

Initial suppression tests were conducted with a WSCS application duration of 90 seconds after agent discharge. The HF concentration decayed slowly between the time the WSCS was secured and the time ventilation was initiated (hold time - 15 minutes). For tests in which the WSCS was initiated 30 seconds prior to agent discharge (WSCS1S2.2 and WSCS1S2.3), the average HF concentration in the compartment 5 minutes after HFP discharge was 55 ppm. To evaluate if a longer WSCS application duration would decrease the HF concentration during the hold time even further, tests WSCS1S2.10 and WSCS1S2.11 were conducted with a 270 second WSCS application duration after agent discharge. The average HF concentration 5 minutes after HFP discharge in these tests was 30 ppm. The extended WSCS application duration decreased the average HF concentration to 30 ppm, the Immediately Dangerous to Life and Health concentration (IDLH)[10]. The average HF concentration measured 5 minutes after HFP discharge in the tests without the WSCS system was 300 ppm. As a result, an application duration of 270 seconds after agent discharge (5 minutes total) was recommended. See Table 7 for a summary of this data.

Table 7.

Summary of HF Concentrations During Hold Time For Tests With and Without WSCS (60 second preburn)

Test Name	WSCS Initiation Time (sec)	HF Concentration at 5 minutes after HFP discharge (ppm)	HF Concentration at Venting Initiation (ppm)
Without WSCS	n/a	300	70
2 minute WSCS Application	-30	55	45
5 minute WSCS Application	-30	30	30

Figure 4 compares the HF concentration over time as measured by the same CAA for two tests. Test WSCS1S2.1rep2 was a suppression test in which the WSCS system was not used. Test WSCS1S2.11 was a suppression test with WSCS. The WSCS system was initiated 30 seconds prior to HFP discharge and was secured five minutes later at t = 270 s. During both of these tests, ventilation was secured at t = -30 s, HFP was discharged at t = 0 s, and ventilation was initiated at t = 900 s. Reignition of the pan and cascading fires occurred after ventilation was initiated in the test with WSCS. Only the cascading fire reignited in the test without WSCS because the pan hot rod failed during the hold time. As shown in the figure, the HF concentration in the test with WSCS decreased dramatically from the peak value. At five minutes after HFP discharge, the HF concentration at this CAA location was 600 ppm in the test without WSCS whereas it was 45 ppm in the test with WSCS. The HF concentration in the test without WSCS remained above 100 ppm throughout the hold time (0 s - 900 s). This trend was typical of those seen at all CAA locations. These results clearly demonstrate the increased HF reduction provided by a low flow (10.6 Lpm (2.8 gpm)) WSCS system.

Figure 5 compares the CAA data with the HF concentrations measured by the FTIR at the same location during a test without WSCS (WSCS1S2.1rep). The HF concentrations measured by the CAAs are higher because the CAAs measure both aerosol and gaseous HF whereas the FTIR measures only gaseous HF.

7.3.2 Effects on Fire Out Times

The fire out times for the 175 kW methanol fires (with and without WSCS) can be found in Table 8. The average fire out times for the pan and cascading fires with and without WSCS are within about two seconds of each other. During two of the tests without WSCS (WSCS1S2.1rep and WSCS1S2.1rep2), a small amount of fire activity (i.e., flashing) was observed around the cascading hot rod for several seconds after the fire was not observed with. Although the fire out times are similar, the cascading fire flashing was not observed with addition of WSCS, indicating significant compartment surface cooling and reduction of fuel evaporation.

Table 8.

Fire Out Times (175 kW Methanol Fires)

Test Name	WSCS Initiation Time[1] (sec)	Pan Fire Out Time (sec)	Cascading Fire Out Time (sec)
WSCS1S2.1	No WSCS	10	8
WSCS1S2.1rep	No WSCS	11	20, flashing to 30
WSCS1S2.1rep2	No WSCS	9	12, flashing to 25
WSCS1S2.2	-30	16	14
WSCS1S2.3	-30	10	12
WSCS1S2.7rep	-15	10	12
WSCS1S2.8	-45	13	13
WSCS1S2.9	-60	11	11
WSCS1S2.10	-30	13	13
WSCS1S2.11	-30	12	12

[1] Times in reference to agent discharge at t = 0.

Figure 4.
Continuous Acid Traces for Tests With and Without WSCS

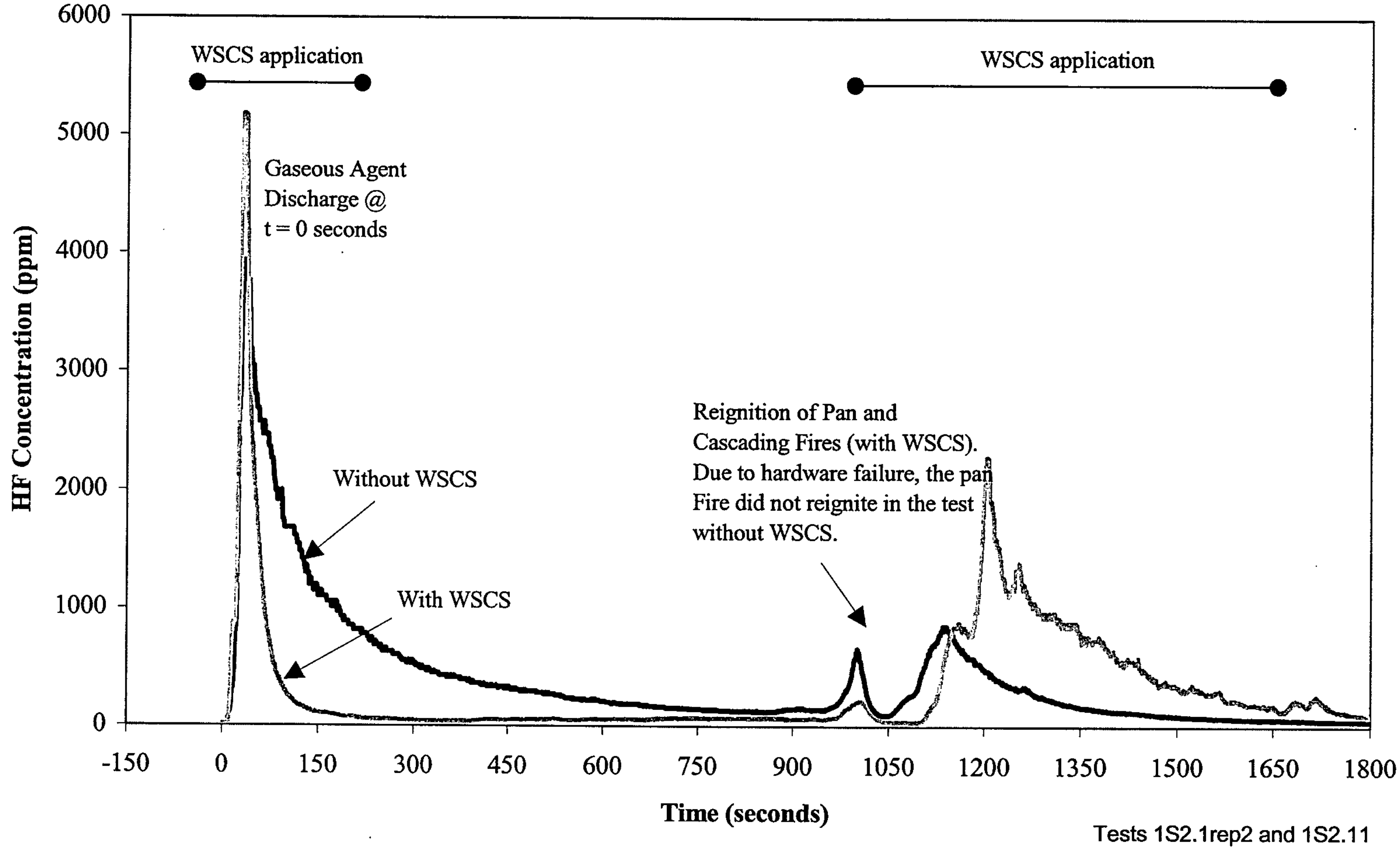
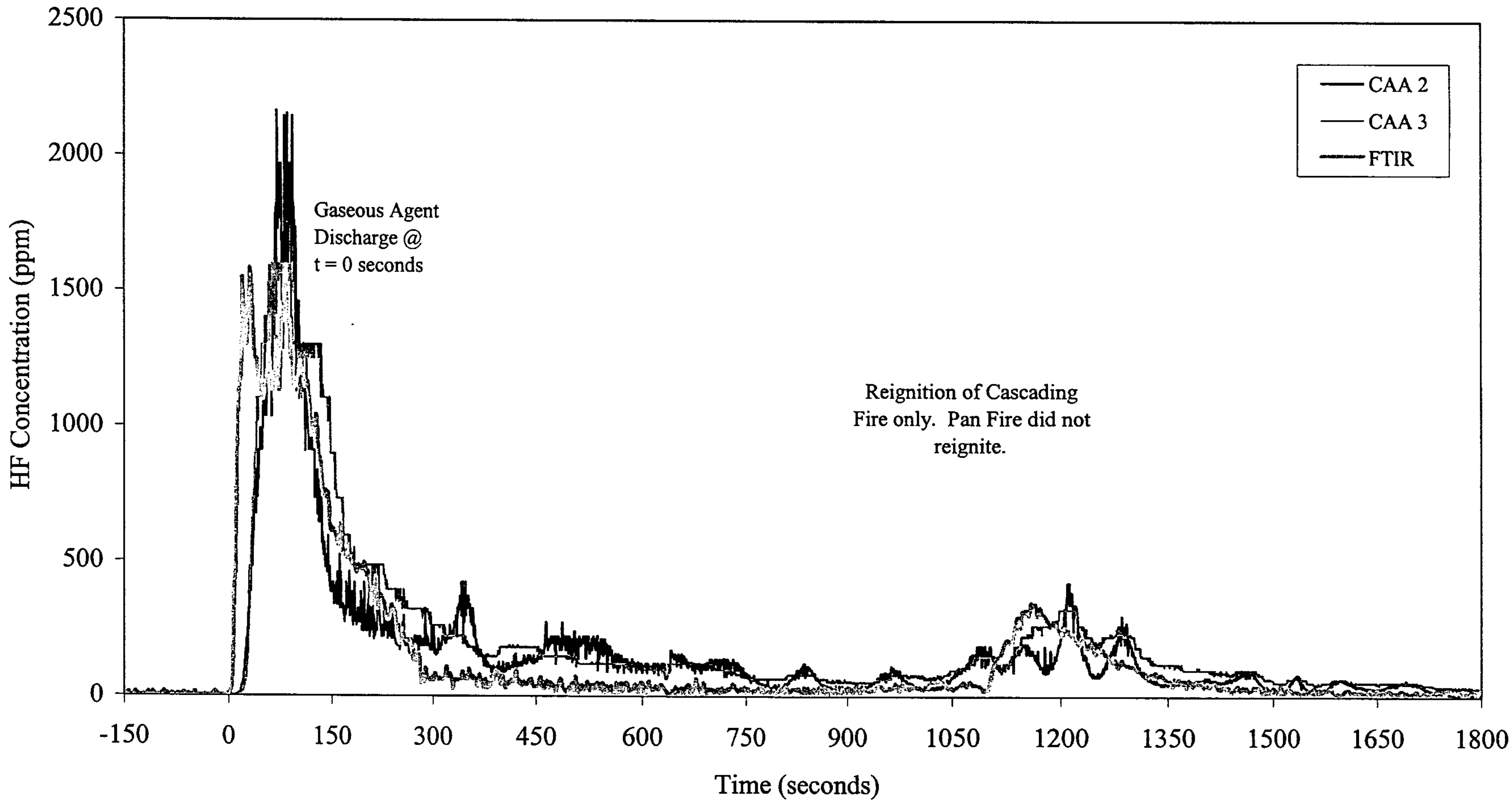


Figure 5.
HF Concentration - CAA (ERPC) and FTIR
WSCS1S2.1rep



7.3.3 Compartment Temperature Reduction

Unlike water, gaseous fire suppression agents do not provide much compartment cooling. Compartment temperatures for the 175 kW methanol tests with HFP and WSCS were approximately 10°C lower after fire extinguishment than those from the tests with HFP only. The temperatures in the 375 kW methanol tests with HFP and WSCS were approximately 20°C lower after fire extinguishment than the temperatures from the tests with HFP only. Both nozzles (the Bete® TF6FC and the GEM® AM10) provided similar cooling effects in the compartment.

Tests conducted during this test series consisted of short preburn durations, yielding cooler compartment temperatures than those observed in past test series. Short, realistic preburns were chosen in order to challenge the WSCS and gaseous agent systems via limited oxygen depletion and high HF concentrations. The WSCS would produce more dramatic cooling effects in scenarios with higher compartment temperatures, such as those seen in previous testing conducted aboard the ex-USS *Shadwell*[4].

7.4 Final Nozzle Selection

Both the Bete® TF6FC nozzle and the GEM® AM10 nozzle provided desirable results throughout the test series. Neither nozzle performed significantly better than the other during fire suppression in terms of the reduction of HF, the time to fire out, or the reduction of compartment temperatures. The TF6FC is preferred due to structural failures observed with the AM10 nozzles during evaluation.

8.0 SUMMARY OF FINDINGS

It has been shown that the WSCS system:

- Reduces the average HF peak near the fire from 1700 ppm to 1000 ppm;
- Reduces the HF loading in the compartment by about 75%;
- Reduces the HF concentration 5 minutes after HFP discharge from 300 ppm to 30 ppm;
- Reduces the HF concentration 15 minutes after HFP discharge from 70 ppm to 30 ppm;
- Reduces the compartment temperatures by 10-20°C; and
- Eliminates the flashing at the cascading fire location after fire extinguishment, indicating cooling of hot surfaces.

These findings apply only to protecting compartments with a maximum volume of 28 m^3 (1000 ft^3), a maximum area of 9 m^2 (100 ft^2), and a maximum height of 3 m (10 ft) with a combined HFP and WSCS system having a nominal HFP design concentration of 10.6% at 21°C

(70°F). The WSCS system discharged through a single nozzle with a spray angle of 90°-120° at 10 bar (150 psi).

The higher flow rate nozzles evaluated in this test series did not provide added protection over the 10.6 Lpm nozzles (2.8 gpm). In some cases, the higher flow rate nozzles provided reduced protection. Although other nozzles and application rates may provide adequate protection, only the Bete® TF6FC and GEM® AM10 were examined due to the limited number of suppression tests available. A WSCS initiation time of 30 seconds prior to gaseous agent discharge provided about a 75% reduction in HF loading in this fire scenario. Although longer application durations may provide further reduction of the HF concentration, a 270 second WSCS application duration after gaseous agent discharge is recommended here to limit the quantity of water discharged into the compartment. Shorter application durations (but at least 90 seconds) may be acceptable if water availability is an important consideration.

9.0 IMPLEMENTATION GUIDANCE

The following guidelines are recommended for system implementation. The WSCS system should operate at 10 bar (150 psi) and be supplied by the ship's fire main. The system should be activated at the same time and by the same means as the HFP system. The water should begin discharging 30 seconds prior to HFP discharge, at the same time the ventilation system is secured. The water should discharge for a minimum of 5 minutes at an application rate of 10.6 Lpm (2.8 gpm). The WSCS nozzle spacing was limited to 3 m x 3 m (10 ft x 10 ft) during this testing. Further guidance on nozzle spacing will be mandated from future testing.

In terms of system performance, the WSCS should reduce the HF loading by a minimum of 50%, reduce the size of the flame sheet, provide reignition protection through the cooling of hot surfaces, and reduce the compartment temperatures. Reignition and re-entry issues will be evaluated in future test series.

10.0 CONCLUSIONS

Tests of HFP with WSCS in the 28 m^3 (1000 ft^3) have demonstrated the performance advantages provided by the WSCS over an HFP only system. The HF loading reduction by 75% expedited compartment reentry and reduced HF exposure. The WSCS also lowered compartment temperatures and improved reignition protection. These advantages were achieved with a low-pressure system flowing only 10.6 Lpm (2.8 gpm) for 5 minutes.

The diminished effectiveness of the WSCS noted with higher application rates or longer periods of application prior to gaseous agent discharge provide significant input for optimizing water mist (only) suppression systems.

11.0 FUTURE PLANS

These findings will provide guidance for future evaluation in larger compartments. Additional implementation guidance and considerations for future testing include: the effects of WSCS usage during hold time, the effects of WSCS usage during ventilation, WSCS nozzle spacing, and reignition and re-entry issues.

12.0 ACKNOWLEDGMENTS

A number of US Government employees and contractors have participated in these tests. The contributions of Howard Burchell, Leroy Levenberry, and Jennifer Montgomery were particularly valuable.

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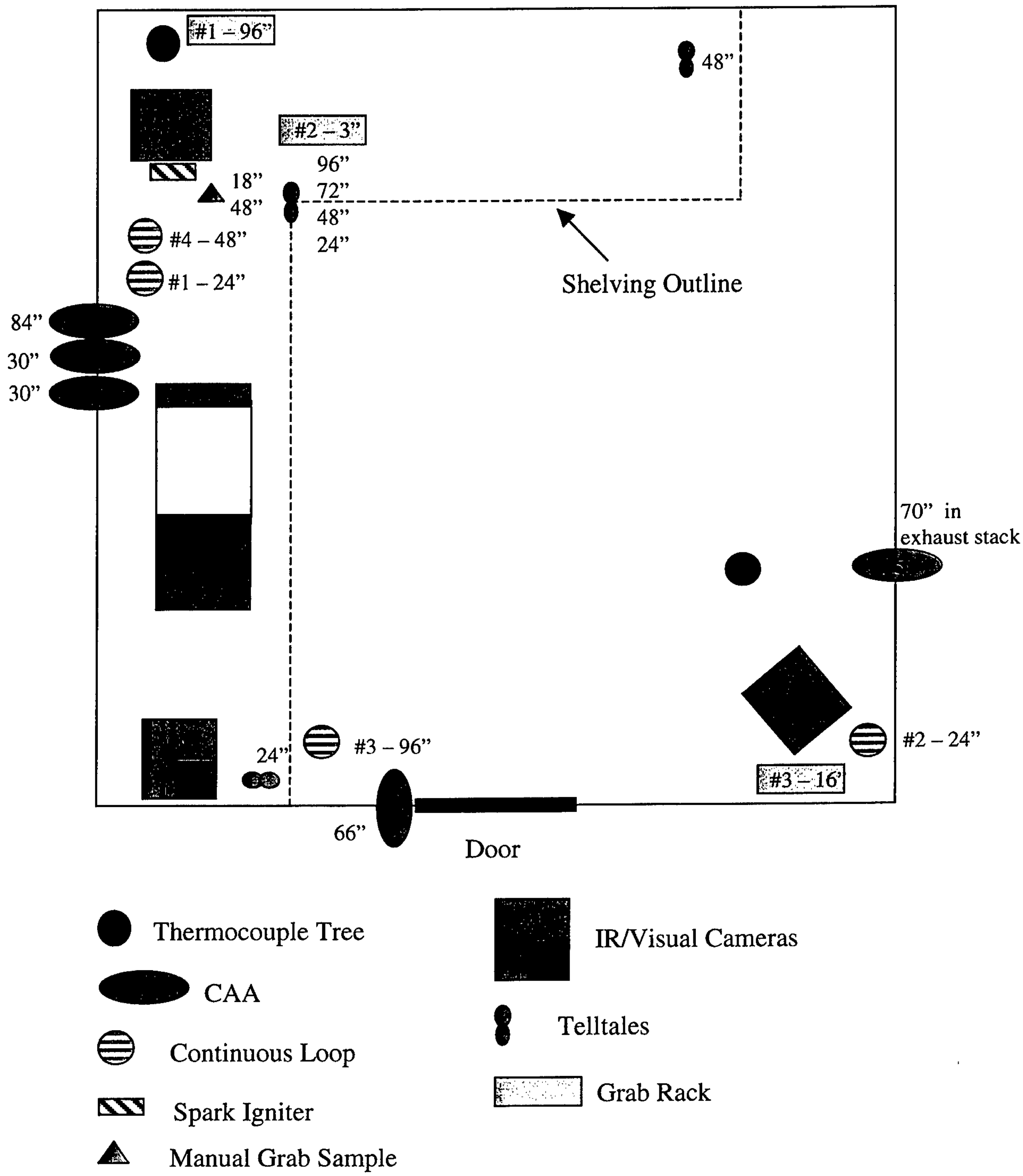
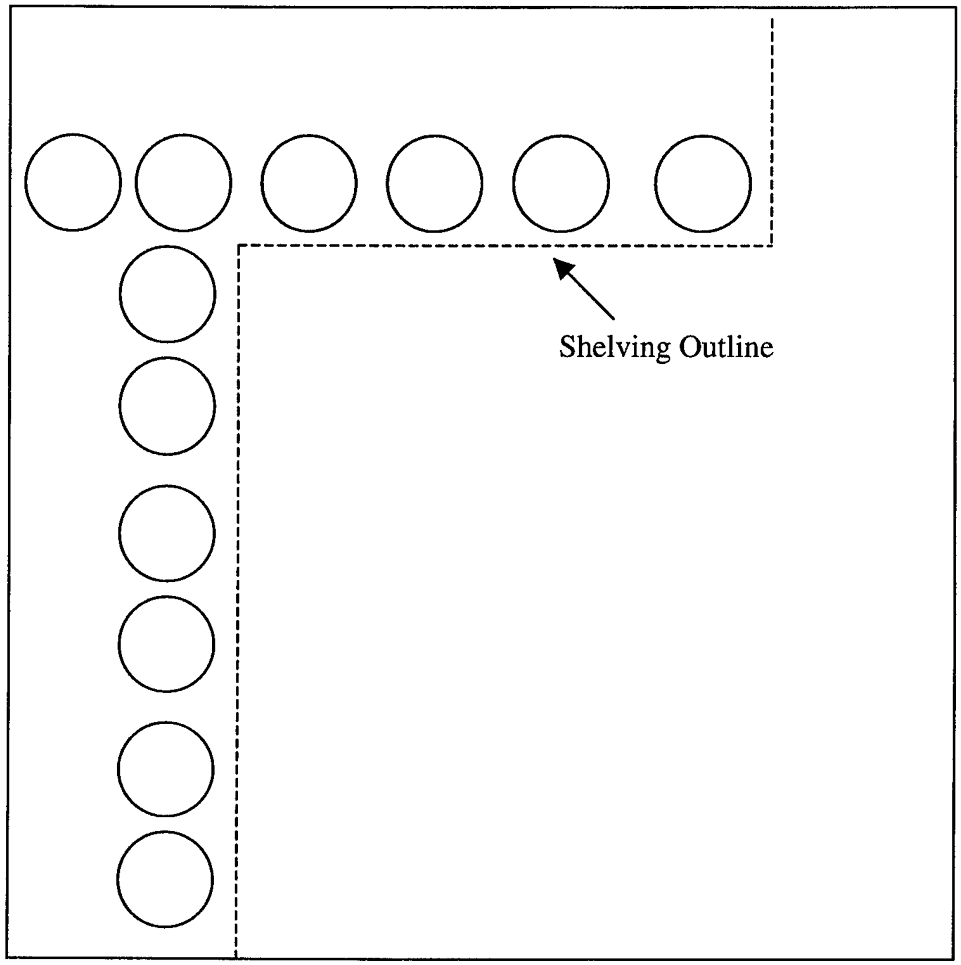
Appendix A
Instrumentation Maps

Compartment 1 Instrumentation Map



Mock-up Arrangement – 72" Shelf
Compartment 1



Shelf Height (from deck)	Total 5-Gallon Buckets
Deck	7
24"	8
48"	10
72"	12
96"	12

Appendix B
Suppression Test Results

Test	Fire Size (kW)	Preburn Duration (seconds)	WSCS Duration (seconds)	Agent Design Concentration at 70F Ltd Mock-ups (%)	Pan Out (sec)	Agent Concentration @ Pan Fire Out (%) (Rack 2 grab bottles)[1]	Casc. Out (sec)	Agent Concentration @ Cascading Fire Out (%) (Rack 1 grab bottles)[1]	Peak HF @ Suppression (ppm)	Minimum HFP Conc. During Hold (after equilibrium)(%)	HF 15 min After Suppression (max/avg)	Agent @ Pan Re-ignition Manual Grab (%)	Pan Re-ignition (sec)	Agent @ Casc Re-ignition Manual Grab (%)	Cascading Re-ignition (sec)	Peak HF @ Re-ignition (ppm)
Heptane Tests																
1S1.1	200	120	150	11.6	5	6.6	6	13.0	950 (CAA 1)	11.8	7/6	8.9	1418	1.4	172	1300 (CAA 4)
1S1.2	450	120	270	13.9	5	8.0	5	18.5	450 (CAA 4)	15.9	16/8	1.7	1412	1.0	184	7500 (CAA 1)
1S1.3	200	60	405	11.5	7	13.8	7	13.0	1500 (CAA 2)	11.0	27/23	0.2	1415	0.0	185	1750 (CAA 1)
Methanol Tests																
1S2.1	175	60	n/a	12.4	10	13.1	8	15.4	2500 (CAA 4)	11.0	58/39	10.8	2	11.8	2	2500 (CAA 1)
1S2.1rep	175	60	n/a	11.6	11	11.6	20, flashes to 30	10.8	6000 (CAA 1)	10.1	120/63	n/a	n/a	4.0	154	950 (CAA 1)
1S2.1rep2	175	60	n/a	12.0	9	12.3	12, small flashes to 25	10.6	3900 (CAA 1)	10.5	137/73	n/a	n/a	3.5	153	820 (CAA 1)
1S2.2	175	60	120	12.1	16	10.1	14	11.8	3500 (CAA 1)	11.2	94/48	1.4	1414	1.1	182	4500 (CAA 3)
1S2.3	175	60	120	12.2	10	11.4	12	10.0	5600 (CAA 1)	10.4	88/44	0.2	1416	8.1	146	1500 (CAA 1)
1S2.7rep	175	60	105	12.2	10	10.9	12	10.1	4300 (CAA 1)	10.7	49/34	1.2	1416	0.8	183	3300 (CAA 3)
1S2.8	175	60	135	12.2	10	10.7	13	9.9	3600 (CAA 1)	10.7	33/18	0.9	1419	2.0	172	2500 (CAA 2)
1S2.9	175	60	150	12.4	10	9.9	11	9.6	4800 (CAA 1)	10.1	51/24	0.6	1459	0.0	186	1100 (CAA 2)
1S2.10	175	60	300	12.1	9	11.0	13	9.1	2600 (CAA 4)	10.1	24/12	0.6	1463	5.5	186	2600 (CAA 2)
1S2.11	175	60	300	12.3	9	11.0	12	9.2	5200 (CAA 1)	10.7	58/40	0.1	1462	5.7	185	2200 (CAA 1)
1S2.4	350	120	n/a	12.7	6	13.2	6	6.7	540 (CAA 1)	11.6	21/9	10.0	1390	10.5	139	6000 (CAA 1)
1S2.5	350	120	120	12.3	7	11.3	8	9.7	160 (CAA 4)	12.0	5/3	1.2	1399	4.3	152	3000 (CAA 1)

All times are with respect to t = 0 at agent discharge.

[1] Samples were taken at 4, 7, 10, & 25 seconds after discharge. Values are from samples taken closest to cascading fire out times.
[2] No sustained re-ignition. Fuel secured at first flashes.

n/a = not applicable

CAA 1 - Port Top
CAA 2 - Port Bottom Low
CAA 3 - Port Bottom Low
CAA 4 - Aft

Shaded cells indicate solenoids that may not have been operating properly. The solenoids were found to be leaky causing HFP values to be lower than the actual conditions in the compartment. It is uncertain when the solenoids began to leak.