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FULL-SCALE TESTING OF WATER MIST FIRE SUPPRESSION SYSTEMS FOR SMALL MACHINERY SPACES AND SPACES WITH COMBUSTIBLE BOUNDARIES

VOLUME I

FINAL REPORT
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16. Abstract (MAXIMUM 200 WORDS)

This report provides an evaluation of the firefighting capabilities of the state-of-the-art water mist fire suppression systems in smaller (~ 100 m^3) machinery space applications. The primary objective of this investigation was to evaluate the applicability of the International Maritime Organization's (IMO) test protocol and design requirements to smaller machinery spaces and to machinery spaces with combustible boundaries. The following water mist systems were included in this evaluation: Chemetron CFS, Fike Micromist, Grinnell AquaMist, Fogtec Fire Protection Systems, and the U.S. Navy's water mist system.

The five water mist systems were each capable of extinguishing a majority (at least nine out of fifteen) of the test fires included in this evaluation. Variations in system capabilities were observed primarily during the tests conducted with forced ventilation. Machinery spaces with combustible boundaries were shown not to pose a significant challenge to the water mist systems. The results of these tests suggest that the current IMO design requirements can be reduced for smaller machinery spaces. The amount of reduction needs to be determined on a case-by-case basis. An approach for defining the protection requirements (i.e., duration of protection) for these smaller machinery spaces is also described in this report.

The report and Appendix A (Instrumentation and Camera Details) are contained in Volume I. Volume II consists of Appendix B (Test Data) and Appendix C (Combustible Boundary Test Data). Appendices B and C are available in paper copy only from the Research and Development Center.

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EXECUTIVE SUMMARY

The firefighting capabilities of the state-of-the-art water mist fire suppression systems were evaluated in smaller (~100 m^3) machinery space applications. The primary objective of this investigation was to evaluate the applicability of the International Maritime Organization's (IMO) test protocol and design requirements to smaller machinery spaces and to machinery spaces with combustible boundaries.

In December 1994, the IMO Maritime Safety Committee approved guidelines for alternative arrangements for halon fire extinguishing systems (MSC Circular 668) [1]. Annex B of the guidelines provides an interim test method for evaluating equivalent water-based fire extinguishing systems for Category A machinery spaces and cargo pump rooms. Since the development of these guidelines, numerous research programs [2, 3, 4] have demonstrated that a properly designed and tested water mist fire suppression system can provide effective protection of Category A machinery spaces. These tests have suggested that smaller spaces should be easier to protect due to water mist's dependence on oxygen depletion to extinguish obstructed fires. The concern for these smaller spaces is whether any of the strict design requirements for larger spaces (i.e., duration of protection) can be reduced to achieve a lighter, less costly system.

Machinery spaces regulated under Sub-chapter T and K of Title 46 of the Code of Federal Regulations and IMO's High Speed Craft (HSC) code may be constructed with combustible boundaries. Therefore, combustible boundaries needed to be evaluated in assessing the extinguishment capabilities of water mist fire suppression systems in smaller machinery spaces. The goal of this effort was to determine appropriate protection requirements for smaller spaces and spaces with combustible boundaries. This work was performed under a research and development project for the Life Saving and Fire Safety Standards Division (G-MSE-4) of Coast Guard Headquarters.

The fire suppression capabilities of five commercially available water mist systems (Chemetron, Fike, Grinnell, Fogtec, and the U.S. Navy's water mist system) were evaluated in a

machinery space with nominal dimensions of 5 m x 7 m x 3 m using three ventilation conditions (closed compartment, a naturally ventilated compartment with a 1.7 m^2 vent opening, and a compartment with forced ventilation 25 m^3/min). The five water mist systems were each capable of extinguishing 9 out of 15 of the test fires included in this evaluation. Degradation in the performance of each system's capabilities was observed primarily during the tests conducted with forced ventilation.

A steady state extinguishment model developed during a previous investigation was used to analyze and explain the results of these tests. The model was used to predict the critical fire size for the three ventilation conditions included in this evaluation. The critical fire size is defined as the smallest fire that will reduce the oxygen concentration in the space due to consumption of the oxygen by the fire and a dilution of the oxygen with water vapor to the Limiting Oxygen Index (LOI) of the fuel. These critical fire size predictions helped explain which fires could not be extinguished.

The model was capable of accurately predicting the steady state compartment temperatures and extinguishment times for the spray fire scenarios but had difficulty predicting the results of the pan fire scenarios. Throughout this test series, the pan fires were more difficult to extinguish than spray fires of a given size. This is believed to be the result of a reduction in burning rate caused by the lower oxygen concentrations in the space. If a reduced burning rate (50 percent of the estimated ambient value) is used in the model, the predictions become similar to those measured during the tests.

Three of the water mist systems were tested against three different boundary materials to evaluate performance of water mist technologies against combustible boundaries. The initiating spray fire used during these tests (250 kW) was one of the more difficult fires to extinguish during the system capabilities evaluation. However, this initiating fire was sufficient to ignite a significant amount of the combustible boundary material. The combustion of the boundary material increased the fire size (higher heat release rate) making them easier to extinguish. Consequently, all of the combustible boundary fires were extinguished during this evaluation. In only one test did fire burn through the combustible material. This test with its unexplainable variance was viewed as an anomaly in the data, and is believed not to alter the conclusion. In general, combustible boundaries do not pose a significant challenge to water mist systems.

The final objective of this investigation was to determine if the current system design requirements (primarily duration of protection) can be reduced for water mist systems applied to smaller machinery spaces. This would result in a lighter, less costly system. The results of these tests suggest that the current IMO design requirements can be reduced for smaller machinery spaces. The amount of reduction needs to be based on the size/volume of the protected area, as well as on the ventilation conditions in the space. An approach for determining these requirements is also described.

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Table of Contents

Table of Contents (Continued)

List of Illustrations

List of Tables

1.0 INTRODUCTION

In December 1994, the International Maritime Organization's (IMO) Maritime Safety Committee approved guidelines for alternative arrangements for Halon fire extinguishing systems (MSC Circular 668) [1]. Annex B of the guidelines provides an interim test method for evaluating equivalent water-based fire extinguishing systems for Category A machinery spaces and cargo pump rooms. Since the development of these guidelines, numerous research programs [2, 3, 4] have demonstrated that a properly designed and tested water mist fire suppression systems can provide effective protection of Category A machinery spaces. These tests also suggest that smaller spaces should be easier to protect due to water mist's dependence on oxygen depletion to extinguish obstructed fires. The concern for these smaller spaces is whether any of the strict design requirements for larger spaces (i.e., duration of protection) can be reduced to achieve a lighter, less costly system.

These smaller machinery spaces are regulated internationally under IMO's International Convention for the Safety of Life at Sea (SOLAS) [5] and The International Code of Safety for High Speed Craft (HSC) [6]. Domestically, these smaller machinery spaces are typically regulated under Sub-chapter T or K of Title 46 of the Code of Federal Regulations [7]. Machinery spaces regulated under Sub-chapter T, K and the HSC may be constructed with combustible boundaries. Therefore, combustible boundaries needed to be evaluated in assessing the extinguishment capabilities of water mist fire suppression systems in smaller machinery spaces.

The goal of this effort was to determine appropriate protection requirements for smaller spaces and spaces with combustible boundaries. This work was performed under a research and development project for the Life Saving and Fire Safety Division (G-MSE-4) of Coast Guard Headquarters.

2.0 OBJECTIVES

The overall objective of this evaluation was to further develop an understanding of the capabilities and limitations of water mist fire suppression systems as applied to the range of machinery space applications. More specifically, our objective was to further develop the understanding of how to extrapolate the results of the IMO test protocol to smaller machinery spaces having a range of ventilation conditions, and to spaces with combustible boundaries.

3.0 TECHNICAL APPROACH

3.1 System Capabilities

The fire suppression capabilities of the state-of-the-art in water mist technologies were identified for small machinery spaces (~100 m^3) using a wide range of fire sizes and ventilation conditions. The information collected during these tests aided in the further development of an extinguishment model developed and validated during previous phases of this investigation [3, 8]. The model was originally developed to provide scaling information applicable to designing and approving systems for machinery spaces having a wide range of volumes and ventilation conditions.

Five commercially available total flooding water mist systems were evaluated during this investigation. The systems were evaluated against a series of obstructed spray and pan fires. The fires were produced using heptane as the fuel and consisted of three spray fires (0.25, 0.5, and 1.0 MW), and two pan fires (0.25 and 0.41 m^2). The obstructed fires were located under a one-meter horizontal obstruction adjacent to the port engine mock-up. Three ventilation conditions were also included in this evaluation (closed compartment, natural ventilation through a 1.7 m^2 vent opening, and forced ventilation (15 air changes per hour).

3.2 Combustible Boundary Effects

The effect that combustible boundaries have on the firefighting capabilities of the system(s) was evaluated using two fire scenarios and three combustible materials. The first scenario consisted of a 0.25 MW heptane spray fire located in the corner of the space with the adjacent bulkheads and the overhead directly above produced of combustible material. The second scenario consisted of a 0.25 MW heptane spray fire directly impinging on a combustible overhead. The tests were conducted using natural ventilation through a 1.7 m^2 vent opening. In both cases, a test performance goal was set that the water mist system was required to extinguish the fire prior to burning through the combustible boundary. An assessment of the boundary damage was also conducted. A free-burn[1] test was conducted on each fire scenario to serve as a baseline comparison.

4.0 TEST COMPARTMENT

The tests were conducted in a simulated machinery space aboard the test vessel, STATE OF MAINE, at the U.S. Coast Guard Fire and Safety Test Detachment located at Little Sand Island in Mobile, AL. The simulated machinery space was located on the fourth deck of the Number 6 cargo hold. The machinery space had a compartment volume of approximately 100 m^3 with nominal dimensions of 5 m x 7 m x 3 m as shown in Figure 1. The space contained two engine mock-ups each measuring 1.0 m x 3.0 m x 1.5 m. The space was equipped with one standard door (0.85 m x 2.0 m) used for natural ventilation located on the forward bulkhead on the port side of the compartment.

The space was also equipped with a forced ventilation system designed to provide approximately 15[2] air changes per hour. The ventilation system consisted of a Dayton Model 7H/70 blower regulated using a supply damper to provide air into the space at a rate of 25 m^3/min. The blower had a maximum capacity of 170 m^3/min. The supply entered through the aft

[1] A free-burn test is a test run without any extinguishment system actuated. It is conducted to document the thermal and gas species' conditions in the space if no suppression is attempted. It is used for comparison purposes.
[2] This air change rate represents the higher end of ventilation commonly found on commercial vessels. It is also the standard air exchange rate found on Coast Guard cutters. It was chosen as a likely worst case scenario.

bulkhead at a height of 1.2 m above the deck. The exhaust exited the space through the standard door and through leaks in the spaces.

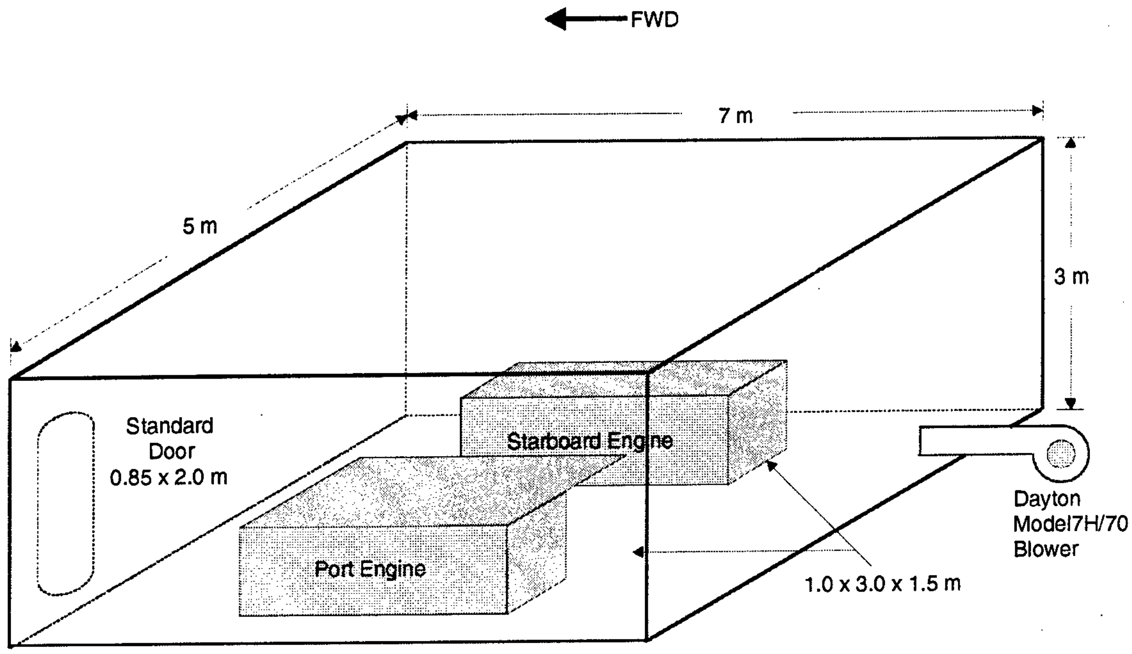


Figure 1. Test Compartment

5.0 WATER MIST SYSTEMS

5.1 Water Mist Systems/Nozzles

Five commercially available water mist systems were included in this evaluation. These systems consisted of Chemetron - CFS, Fike - Micromist, Grinnell - AquaMist, Fogtec Fire Protection, and the U.S. Navy's Water Mist system. The candidate systems cover the range of single-fluid technologies including high, medium, and low-pressure systems. The individual nozzles are designed to flow 5.0 to 12.5 Lpm and operate at pressures ranging from 5.5 to 100 bar. All of these systems have previously demonstrated adequate capabilities against Class B fires in previous testing [2, 3, 8]. A brief description of each system is given in the following sections.

5.1.1 Chemetron - CFS

The CFS system is a low-pressure, single-fluid system which has a working pressure of 12 bar. The system was developed and tested for gas turbine enclosures in a wide range of experimental programs conducted overseas. The system was recently approved by Factory Mutual (FM) for gas turbines enclosures up to 260 m^3. The nozzles are available with nominal K-factors ranging from 1.3 to 2.9 Lpm/bar$^{1/2}$ and are typically installed with a 1.5 to 2.0-m nozzle spacing. During these tests, nozzles' with a 1.3 Lpm/bar$^{1/2}$ K-factor were evaluated using 1.5-m nozzle spacing.

5.1.2 Fike – Micromist

The Micromist system is an intermediate-pressure single-fluid system which has an operating pressure of 21 bar. The system was also recently approved by Factory Mutual (FM) for gas turbines enclosures up to 260 m^3. The nozzles have a K-factor of 1.75 Lpm/bar$^{1/2}$ and are typically installed with up to 2.4-m nozzle spacing. For this evaluation, the nozzle manufacturer chose to have them evaluated using the 2.5-m nozzle spacing verses the 1.5-m spacing. The discharge from the Micromist system is typically cycled[3] for gas turbine applications. Cycling the discharge reduces the water requirements and may increase the firefighting capabilities of the system. In order to conduct a direct comparison to the other water mist systems, the Micromist system was evaluated with a continuous discharge during this evaluation.

5.1.3 Grinnell - AquaMist

The AquaMist system (AM-4 nozzles) is a single-fluid, intermediate-pressure system which has a working pressure of 13 bar. The system is UL listed for flammable liquid storerooms up to 1,600 m^3. The listing is performance specific and only applies to applications with limited ventilation. The AM-4 nozzles have a K-factor of 3.5 Lpm/bar$^{1/2}$ and are typically installed with up to a 4.0-m nozzle spacing. For this evaluation, the nozzle manufacturer chose to have them evaluated using the 2.5-m nozzle spacing.

5.1.4 Fogtec Fire Protection

The Fogtec system is a high-pressure single-fluid system, which has an operating pressure of 100 bar. The system has been evaluated for machinery spaces of various sizes (volumes) by numerous overseas authorities and testing laboratories. The nozzles have K-factors ranging from 0.23 - 0.35 Lpm/bar$^{1/2}$ and are typically installed with a 2.5-m nozzle spacing. During these tests, the manufacturer supplied nozzles with a 0.35 Lpm/bar$^{1/2}$ K-factor and they were evaluated using the 2.5-m nozzle spacing.

5.1.5 U.S. Navy's Water Mist System

The Navy's water mist system is a high-pressure single-fluid system that was developed by the Navy for the machinery spaces on the Amphibious Transport Dock Ship's LPD-17. The system is designed to operate at a pressure of 70 bar. The nozzles have a K-factor of 1.35 Lpm/bar$^{1/2}$ and are typically installed with 3.0-m nozzle spacing. For this evaluation, the nozzles were evaluated using the available 2.5-m nozzle spacing.

5.2 Pipe Network

The water mist system pipe network was similar (in nozzle spacing and continuous loop design to minimize pressure differences between nozzles) to the one tested in the larger machinery spaces [3, 8]. The system consisted of an overhead nozzle grid containing either 6 or 15 nozzles uniformly spaced with a nominal 1.5-m or 2.5-m nozzle spacing (Figure 2). The two nozzle spacing configurations were chosen by the Coast Guard and the nozzle manufacturers selected from the two. The system was constructed of 25 mm, stainless steel tubing with a 2.1-mm wall thickness and connected together with stainless steel compression fittings. Stainless steel tubing and fittings were required to prevent rust and/or corrosion from developing inside the

[3] Cycling of water mist systems as used here refers to operating the nozzle with a discharging period followed by a non-discharging period and then repeating that pattern. Each period (discharging and non-discharging) can be a separate duration.

pipe network between tests[4]. This system design has a working pressure of 200 bar and a burst pressure of 800 bar.

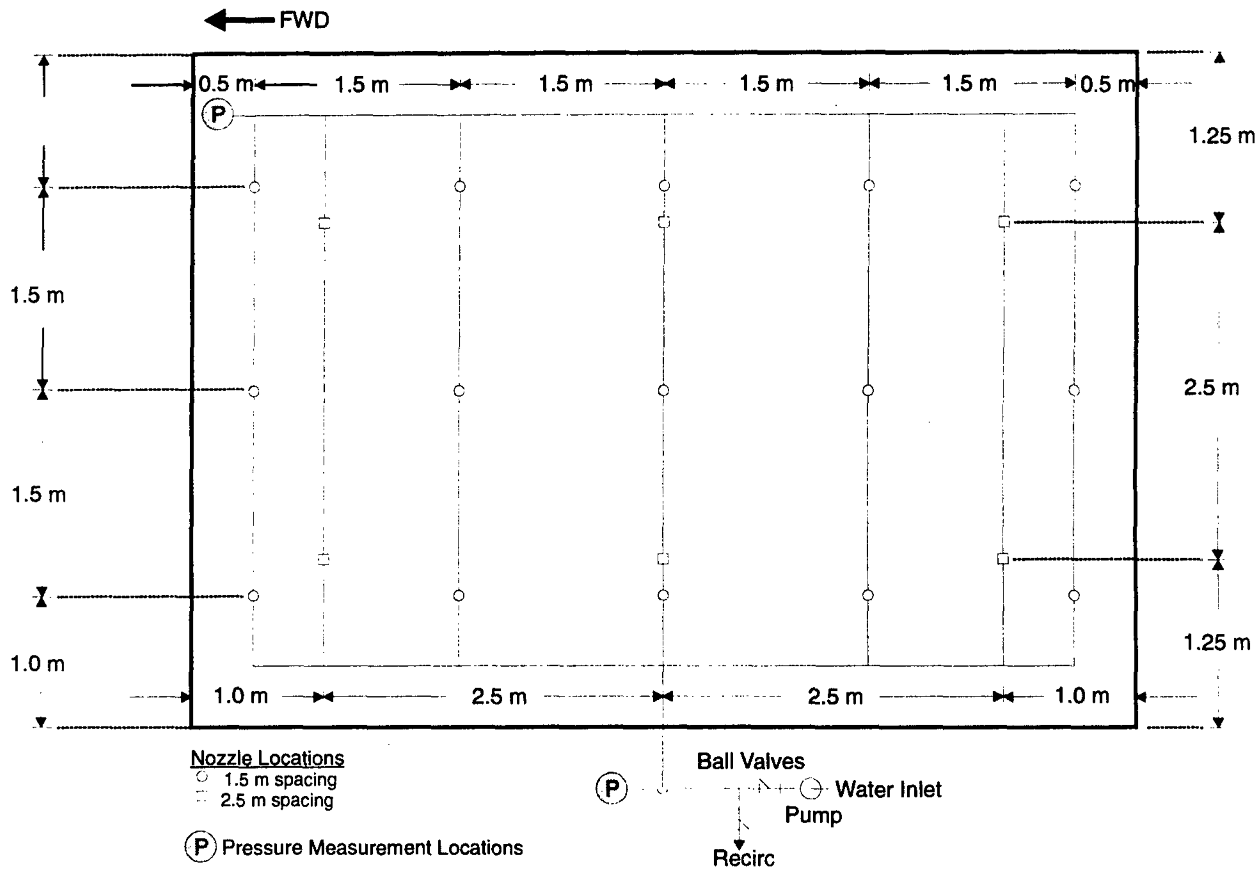


Figure 2. Water Mist System Pipe Network

5.3 Pump System

A high-pressure pump system manufactured by Cliant Pump, Inc. was used to provide water to the various water mist systems (Figure 3). The pump system had a capacity of 170 Lpm at 110 bar. The pump was equipped with an integral pressure regulating unloader valve, this allowed flexibility in setting the pressure of the system for the higher operating pressures and a manually controlled bypass line for setting the pressure in the lower pressure ranges. The net

[4] The system was allowed to drain after each test. The system could sit in this condition as long as over a weekend between tests.

result was a pump system that could provide a maximum flow rate of 170 Lpm over the range of pressures from 5-110 bar.

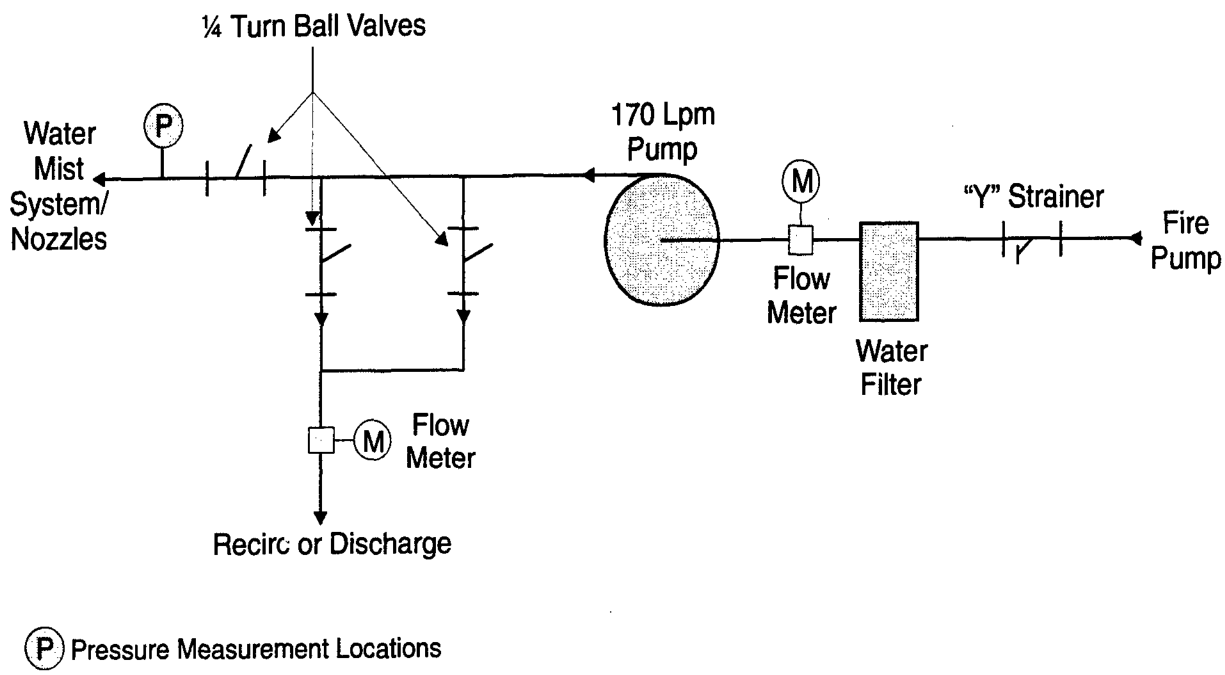


Figure 3. Pumping System

6.0 FIRE SCENARIOS

6.1 Fuel Spray and Pan Fire Scenarios

Three fuel spray fires (nominally 0.25, 0.5, and 1.0 MW) and two pan fires (0.25 and 0.41 m^2) were included in this evaluation. All fires were produced using heptane as the fuel. The fires were located under a one-meter horizontal obstruction plate located inboard of the port engine. The locations of these fires are shown in Figure 4.

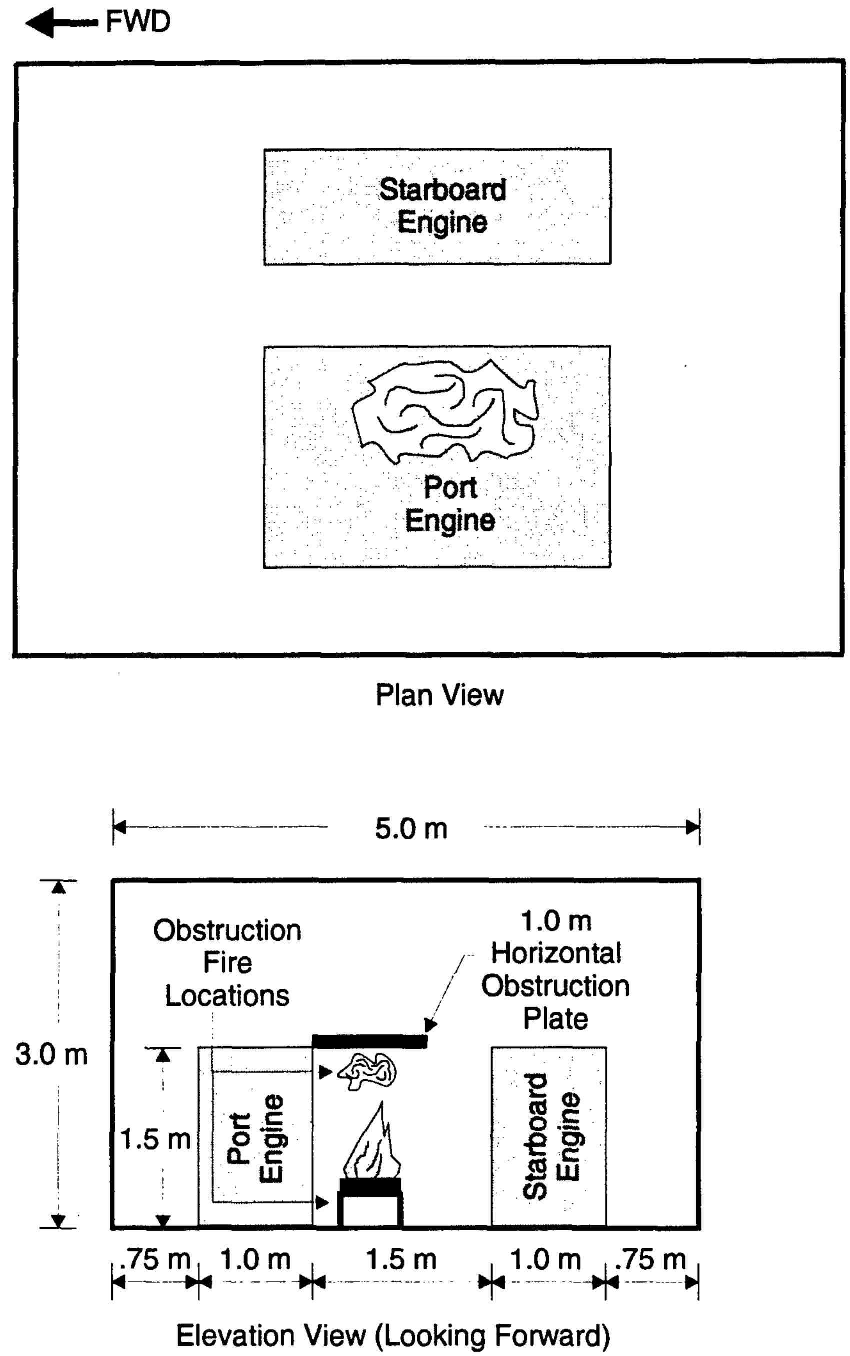


Figure 4. Fire Locations

The spray fires were produced using the pressurized fuel system shown in Figure 5. The fuel sprays were produced used P-series nozzles manufactured by Bete Fog Nozzle, Inc. The following nozzles were included in this evaluation (P28, P40, and P54). The fires produced by these nozzles are shown in Table 1. The actual heat release rates of these fires were estimated based on the fuel nozzle pressure measured during these tests.

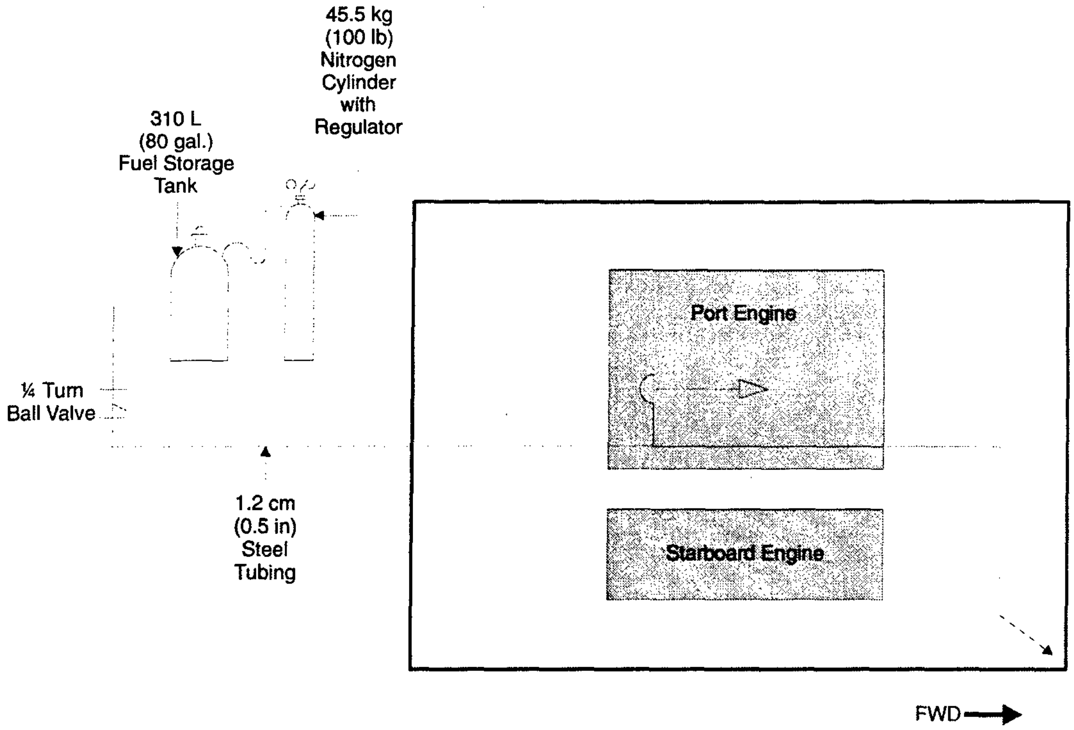


Figure 5. Pressurized Fuel System

Table 1. Spray Fire Sizes

Nozzle Model	Pressure (bar)	Heat Release Rates (MW)
P28	3.5	0.29
P40	3.5	0.59
P54	3.5	1.13

The fuel pans were constructed of 3.2-mm steel plate with welded seams and 15.0-cm sides. In all pan fire tests, the pans contained a 2.5-cm water substrate and 5.0-cm of fuel (heptane). Two pan sizes were included in this evaluation ((square pans) - 0.5 and 0.64 m). The theoretical heat release rates [9] of these fires are shown in Table 2. The actual heat release rates of these fires were estimated based on the fuel regression rate (based on fuel column height) as determined by a pressure transducer installed in the bottom of each pan.

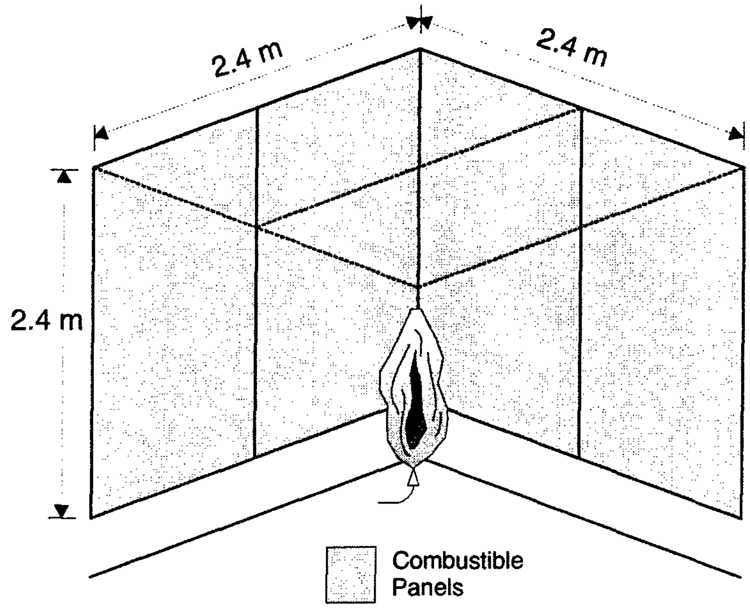
Table 2. Pan Fire Sizes

Size (m^2)	Side Length (m)	Heat Release Rates (MW)
0.41	0.64	1.00
0.25	0.50	0.51

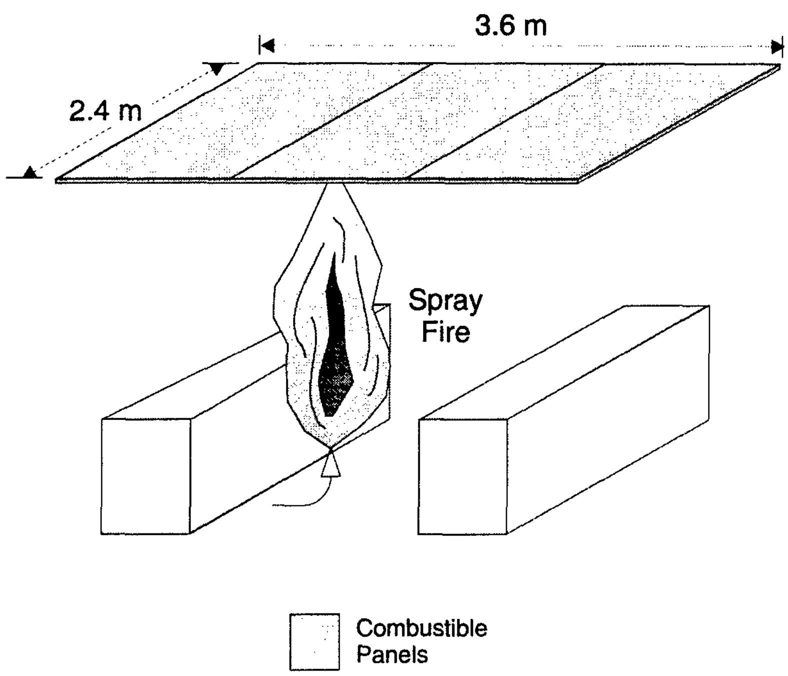
6.2 Combustible Boundary Fire Scenarios

The effect that combustible boundaries have on the fire fighting capabilities of the system(s) was evaluated using two fire tests (corner and overhead tests).

The first test consisted of a 0.25 MW heptane spray fire located in the Forward Starboard corner of the space surrounded by combustible bulkheads and a combustible overhead as shown in Figure 6A. The second test consisted of the 0.25 MW heptane spray fire (unobstructed) directly impinging on a combustible overhead as shown in Figure 6B. The ventilation conditions in the space were selected based on the results of the system performance evaluation [Section 9.2] portion of the test series. It was found that a nozzle performance threshold occurred with naturally ventilated 1.7 m^2 vent opening. This ventilation condition was the highest rate that still resulted in extinguishment. Based on those findings, these tests were run naturally ventilated through the 1.7 m^2 vent opening. The water mist system was required, by the performance criteria set forth in the test plan, to extinguish the fire prior to burning through the combustible boundary. If the panel sustained burning throughout the test and/or the fire burned through the panel, the test was viewed as a failure.



6A Corner Scenario



6B Overhead Scenario

Figure 6. Combustible Boundary Fire Scenarios

The effect that combustible boundaries have on the fire fighting capabilities of the system was evaluated for three water mist systems (covering the range of suppression capabilities as identified during the system performance evaluation). A free burn test was conducted for each fire scenario/material combination.

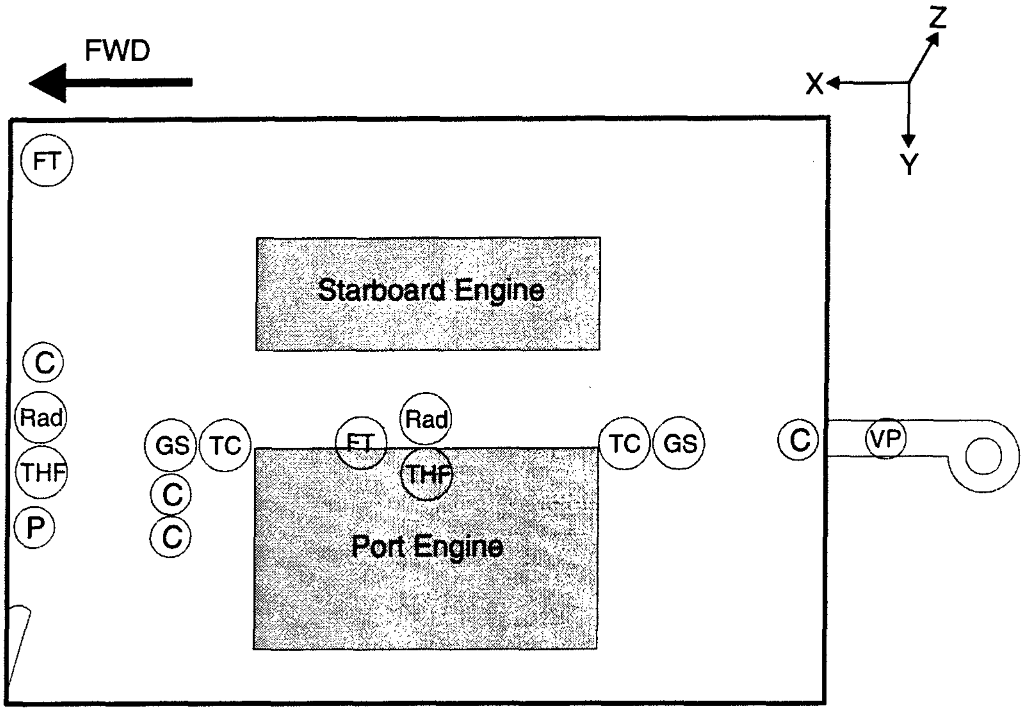
6.2.1 Combustible Boundary Construction

The combustible boundaries were produced using three constructions: (1) nominal half-inch marine grade plywood and (2) nominal half-inch marine grade plywood coated on the exposed side with a 6 mm layer of chopped fiberglass or (3) nominal half inch marine grade plywood coated on the exposed side with a 6 mm layer of woven fiberglass. Both composites used a non-fire retardant (non-FR) vinyl ester resin. These materials and their burning characteristics were chosen to represent a worst case scenario that might be found in a marine application.

7.0 INSTRUMENTATION

7.1 Machinery Space Instrumentation

The machinery space was instrumented to measure both the thermal conditions in the space as well as the range of typical fire gas concentrations. Instruments were installed to measure air temperatures, fire/flame temperature (to note extinguishment time), radiant and total heat flux, compartment pressure, and oxygen (O_2), carbon dioxide (CO_2), and carbon monoxide (CO) gas concentrations as shown in Figure 7. Measurements were sampled at a rate of one scan per second. A complete list of the instruments and their location is found in Appendix A. A more detailed description of the instrumentation scheme is listed as follows.



GS Gas Sampling CO, CO_2, O_2 (1.0, 2.5 m)

TC Thermocouple Trees (0.5, 1.0, 1.5, 2.0, 2.5 m)

FT Fire Thermocouples (1.5 m)

Rad Radiometers (1.5, 3.0 m)

THF Calorimeters (1.5, 3.0 m)

P Pressure Measurements (1.5 m)

C Video Cameras (1.5 m)

T Combustible Panel Thermocouples

VP Velocity Probe (1.2 m)

Figure 7. Instrumentation

7.1.1 Temperature Measurements

Two thermocouple trees were used to measure the gas temperatures in the compartment. Each tree consisted of five thermocouples positioned 0.5, 1.0, 1.5, 2.0, and 2.5 m above the deck. The trees were located at the centerline of the space one m from the forward and aft bulkheads. Inconel sheathed type K thermocouples (3.2-mm diameter) were used in both applications.

7.1.2 Gas Concentration Measurements

Carbon monoxide, carbon dioxide, and oxygen concentrations were sampled at two locations and two elevations in the compartment. These concentrations were measured at the center line of the space 1.5 m from both the forward and aft bulkheads adjacent to the thermocouple trees. These measurements were made 1.0 and 2.5 m above the deck. The carbon monoxide gas analyzer had a full-scale range of 0-5 percent. The carbon dioxide gas analyzer had a full-scale range of 0-15 percent. The oxygen gas analyzer had a full-scale range of 0-25 percent.

7.1.3 Heat Flux Measurements

Both the radiant and total heat flux were measured at two locations in the compartment. One pair of transducers (radiant and total heat flux) was installed at the centerline on the forward bulkhead 1.5-m above the deck. A second pair was installed in the overhead directly above the fire location (center of the space). Schmidt Boelter transducers manufactured by Medtherm Co. with a full-scale range of 0-50 kW/m^2 were used for this application. The radiometers were equipped with 150° sapphire windows.

7.1.4 Compartment Pressure Measurements

The compartment pressure was measured at the centerline of the port bulkhead 1.0-m above the deck. A Setra Model 280E pressure transducer with a range of ± 1.24 kPa was used for this application.

7.1.5 Forced Ventilation Measurements

A bi-directional probe was used to measure the air velocity in the supply duct during the forced ventilation tests. The probe was located in the center of the supply duct half way between the test compartment and the supply blower.

7.2 Water Mist System Instrumentation

The water mist system was instrumented to provide the system operating pressures and total water flow rate of the system. The locations of these instruments are shown in Figures 2 and 3.

7.2.1 Pressure Measurements

System pressures were measured at two locations: at the pump discharge and at the most remote nozzle location. Setra Model 280E pressure transducers were used for this application. These transducers had a full-scale range of 0-210 bar.

7.2.2 Water Flow Rate Measurements

The flow rate of the water mist system was measured using two paddle wheel type flow meters. The flow meters were installed just upstream of the pump inlet and in the bypass line. The flow meter in the supply line had a full-scale range of 0-227 Lpm. The flow meter in the bypass line had a full-scale range of 0-158 Lpm.

7.3 Fire Instrumentation

The fires' conditions were instrumented to identify the extinguishment times and estimate the heat release rates of the fires. A more detailed description of these instruments is listed as follows.

7.3.1 Fire Temperature Measurements

A thermocouple was located in the flame/plume of each fire to determine the extinguishment time. Inconel sheathed type K thermocouples (3.2-mm diameter) were used for this application.

7.3.2 Fire Oxygen Concentration

A separate oxygen concentration probe at the fire's entrainment zone was not required due to the close proximity to the compartment's sampling probes. The oxygen at the fire location was estimated based on the oxygen concentration measured using the gas sampling trees.

7.3.3 Heat Release Rate Measurements and Estimations

7.3.3.1 Spray Fires

Nozzle pressure was used to calculate the fuel flow rates in each spray fire test. The energy release rates of the spray fires were calculated using the fuel flow rate and heat of combustion of the fuel. This assumes that all of the fuel is consumed as well as a 100 percent combustion efficiency. The fuel nozzle pressure transducers had a full-scale range of 0-1723 kPa.

7.3.3.2 Pan Fires

The fuel regression rate was used to estimate the heat release rates of the pan fires. The fuel regression rate was measured using a pressure transducer installed in the bottom of each pan. These pressure transducers had a full-scale range of 0-3735 Pa.

7.4 Video Equipment

Four video cameras were used during each test. Two video cameras, one standard and one infrared (IR), were movable and located inside the compartment. The other two cameras were located outside the compartment, viewing through ports at the area around the engine mock-ups. These cameras were located on the forward and aft bulkheads, 1 m above the deck. A microphone was installed in the center of the space to provide the audio for the four video cameras.

8.0 TEST OVERVIEW

8.1 Test Sequence

The fire extinguishment capabilities of the five water mist systems were determined using the test matrix shown in Table 3. The tests evaluated the systems' fire fighting capabilities against a series of obstructed fuel spray and pan fires for three ventilation conditions (closed compartment, natural ventilation through a 1.7 m^2 vent opening, and forced ventilation (15 air changes per hour)). For a given ventilation condition, the tests were conducted in an order of increased difficulty (decreasing size). Previous testing [2, 3, 4, and 8] found that smaller fires, for a given compartment size and ventilation condition, are more difficult for a water mist system to extinguish. This is related to the fire's consumption of oxygen, air entrainment rate, and heat release rate. If a system failed to extinguish a fire in the sequence, the remaining tests in that sequence were assumed to be failures and were not conducted.

Table 3. System Capabilities Test Matrix

Fire Size	Fire Type	Fire Location	Vent Condition
1.00 MW	Heptane Spray	Obstructed	Closed Compartment
0.50 MW	Heptane Spray	Obstructed	Closed Compartment
0.25 MW	Heptane Spray	Obstructed	Closed Compartment
0.41 m^2	Heptane Pan	Obstructed	Closed Compartment
0.25 m^2	Heptane Pan	Obstructed	Closed Compartment
1.00 MW	Heptane Spray	Obstructed	1.7 m^2 Natural
0.50 MW	Heptane Spray	Obstructed	1.7 m^2 Natural
0.25 MW	Heptane Spray	Obstructed	1.7 m^2 Natural
0.41 m^2	Heptane Pan	Obstructed	1.7 m^2 Natural
0.25 m^2	Heptane Pan	Obstructed	1.7 m^2 Natural
1.00 MW	Heptane Spray	Obstructed	Forced Ventilation
0.50 MW	Heptane Spray	Obstructed	Forced Ventilation
0.25 MW	Heptane Spray	Obstructed	Forced Ventilation
0.41 m^2	Heptane Pan	Obstructed	Forced Ventilation
0.25 m^2	Heptane Pan	Obstructed	Forced Ventilation

It was intended to evaluate two of the water mist systems covering the range of suppressing capabilities against six combustible boundary fire extinguishing tests. The six tests consisted of two fire scenarios (corner and overhead) and three combustible materials (half-inch marine grade plywood, plywood covered with chopped, or woven fiberglass with vinyl ester resin). A matrix of these tests is shown in Table 4. The system's performance would be based on time to extinguishment and limiting damage to the combustible panels. Due to similarities between the material burning characteristics (percentage of exposed surfaces that became involved in the fire) and similarities between the different water mist system's fire suppression performance (rapid extinguishment times), only limited numbers of these tests were conducted.

Table 4. Combustible Boundary Test Matrix

Fire Scenario	Combustible Material	Ventilation Condition
Overhead	Plywood	1.7 m^2 Natural
Overhead	Chopped Fiberglass	1.7 m^2 Natural
Overhead	Woven Fiberglass	1.7 m^2 Natural
Corner	Plywood	1.7 m^2 Natural
Corner	Chopped Fiberglass	1.7 m^2 Natural
Corner	Woven Fiberglass	1.7 m^2 Natural

8.2 Procedures

The tests were initiated from the control room located on the second deck level forward of the test compartment. Prior to the start of the test, the pans were fueled (where pan fires were defined for the test's scenario), and the compartment ventilation condition set. The video and data acquisition systems were activated, marking the beginning of the test. One minute after the start of the data acquisition system, the fires were ignited, and the compartment was cleared of test personnel. The fires were allowed to preburn for one minute prior to mist system activation. The test continued until the fires were extinguished or until 10 minutes after the start of mist system discharge, at which point the test was secured. On completion of the test, the space was ventilated to cool the compartment and to remove the remaining products of combustion.

After each combustible boundary test was conducted, the condition of each panel was documented and photographed.

9.0 RESULTS AND DISCUSSION

9.1 General

Seventy-nine full-scale fire suppression tests were conducted during this evaluation. These tests consisted of sixty-nine system capabilities tests and ten combustible boundary tests. The specifics of these tests and test results will be discussed in subsequent sections of this report. This section will address the general trends observed during these tests.

The trends observed during these tests follow those found in the literature [2, 3, 4, and 8]. With respect to extinguishment times, the larger the fire the shorter the extinguishment time for a given fire type (i.e., spray or pan fire) and ventilation condition. This trend is shown in Figure 8. In this figure, the extinguishment times of the three spray fires were plotted versus fire size for the tests conducted using the U.S. Navy's water mist system and a naturally vented compartment (1.7 m^2 vent). This extinguishment time/fire size relation is attributed to the oxygen depletion (consumption) and steam generation (heat absorption) created by the larger fires. These trends were observed for each of the five systems included in this evaluation independent of the ventilation condition in the space.

The ventilation condition also produced trends in the extinguishment time data. The higher the vent flow rate, the longer the extinguishment time for a given fire size. In Figure 9, the extinguishment times of the spray fires for the U.S. Navy's water mist system were plotted versus fire size for the three ventilation conditions. As shown in this figure, the forced ventilation produced the longest extinguishment times, followed by the natural vent, and then the closed compartment. The forced ventilation condition prevented many fires from being extinguished that were extinguished in the naturally ventilated and closed compartment. These same trends were observed for each of the five systems. A more detailed analysis of the effect of ventilation on extinguishment time will be discussed in the modeling evaluation.

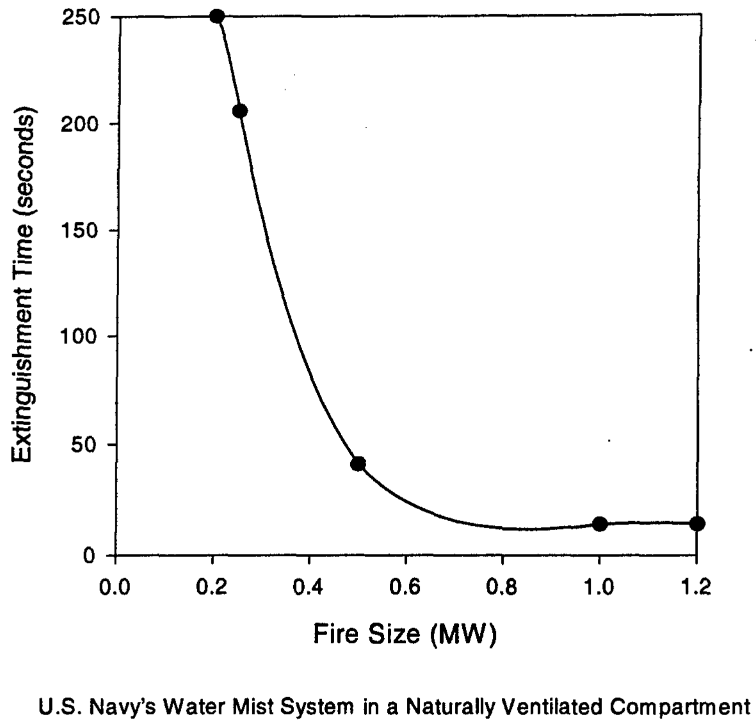


Figure 8. Extinguishment Time as a Function of Fire Size

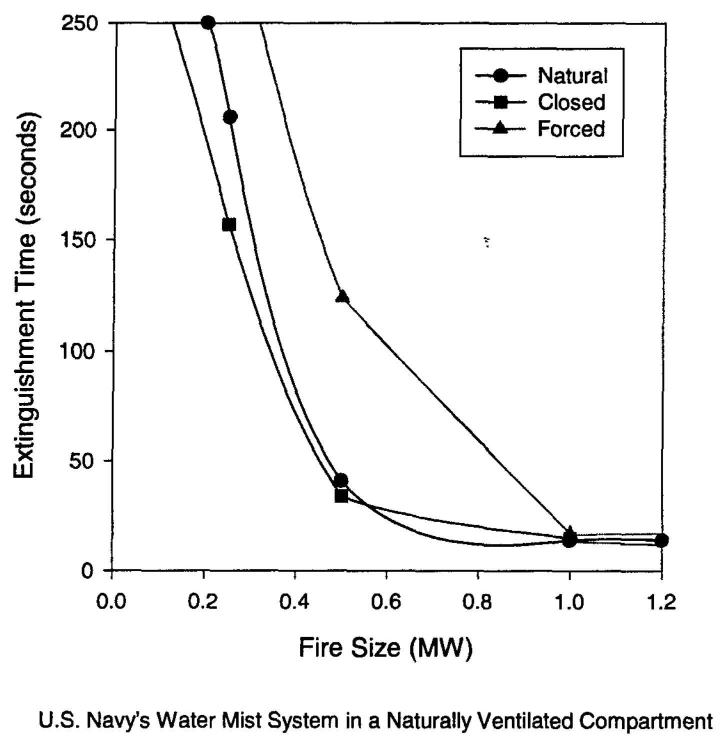


Figure 9. Extinguishment Time as a Function of Ventilation Condition

For a given fire size and ventilation condition, pan fires were more difficult to extinguish than spray fires. There are at least three potential variables that combine to make a pan fire more difficult to extinguish. First, the spray fires may produce better mixing in the space as a result of the turbulence created by the fuel spray. This increased turbulence may also aid in the entrainment of mist into the flame. Second, the pan fires to some extent are self-regulating with respect to oxygen concentration. As the oxygen concentration in the compartment is reduced, the heat release of the fire is reduced. This variation in fire size alters the oxygen concentration depletion rate in the space, resulting in a longer time to reduce the oxygen concentration below Limiting Oxygen Index (LOI). Third, the spray fires are less stable (due to turbulence) than pan fires and consequently are much easier to extinguish. The high sides of the pans may also shield the fires from horizontal dispersion of mist.

9.2 System Performance Evaluation

The extinguishment times recorded during the system performance evaluation are listed in Table 5. In general, the five systems produced similar results. Each of the five systems was capable of extinguishing the ventilation-limited fires. Systems' performance degraded as the ventilation conditions for the test compartment was increased. The extinguishment times for these systems also varied as a function of system type or operating pressure. The two high-pressure systems typically produced faster extinguishment times than the low-pressure or intermediate-pressure systems. Of the two high–pressure systems, the higher flow system generally had better performance with natural or forced ventilation conditions. A discussion of the capabilities of each system is given in the following sections.

Throughout the literature [2, 3, 4, and 8], systems that produce the smallest droplet sizes with adequate spray momentum to distribute the mist throughout the compartment have exhibited superior fire suppression capabilities. These spray characteristics are typically inherent to high-pressure systems. Although these optimum spray characteristics have yet to be quantified, the superior capabilities of the systems that approach these characteristics are indisputable. The performance of the five systems included in this evaluation will be cast in terms of deviations from these desired spray characteristics.

Table 5. System Capabilities Test Results

System		Navy	Grinnell	Fogtec	Chemetron	Fike
Number of Nozzles		6	6	6	15	6
Operating Pressure (bar)		70	13	100	12	21
Flow Rate (Lpm)		68	75	22	70	48
Fire Scenario	Ventilation	Extinguishment Times (sec)				
1.0 MW Spray	Closed	15	26	21	27	21
1.0 MW Spray	Natural	15	40	32	43	35
1.0 MW Spray	Forced	17	55	76	357	133
0.5 MW Spray	Closed	34	70	39	53	56
0.5 MW Spray	Natural	41	117	67	158	140
0.5 MW Spray	Forced	124	No	No	No	No
0.25 MW Spray	Closed	157	360	169	314	277
0.25 MW Spray	Natural	206	No	290	525	566
0.25 MW Spray	Forced	No	No	No	No	No
0.41 m^2 Pan	Closed	121	143	84	180	193
0.41 m^2 Pan	Natural	162	276	200	165	401
0.41 m^2 Pan	Forced	217	No	No	No	No
0.25 m^2 Pan	Closed	244	436	245	404	294
0.25 m^2 Pan	Natural	No	No	No	No	No
0.25 m^2 Pan	Forced	No	No	No	No	No

9.2.1 Chemetron – CFS

The CFS system is a low-pressure, single-fluid system which has an operating pressure of 12 bar. For this evaluation, the system consisted of 15 nozzles installed with a 1.5-m nozzle spacing. The nozzles have a K-factor of 1.3 Lpm/bar$^{1/2}$ producing a total system flow rate of 70 Lpm.

As shown in Table 5, the CFS system was capable of extinguishing a majority of the test fires (10 of 15). The capabilities of the CFS system were comparable to the other systems with respect to which fires were extinguished, but as with the other low- and intermediate-pressure systems, the extinguishment times were slightly longer than the average. For example, the CFS system required 158 seconds to extinguish the 0.5 MW heptane spray fire with natural ventilation as compared to an average extinguishment time for the five systems of 105 seconds. This trend was consistent for a majority of the other fire scenarios as well. The limits of the CFS system were identified during the tests conducted with forced ventilation. The CFS system was only capable of extinguishing one of the five fires (1.0 MW heptane spray) conducted with the forced ventilation system operating. This fire required almost six minutes to extinguish as compared to two minutes or less for the other four systems included in this evaluation.

The longer extinguishment times and difficulty extinguishing the well-ventilated fires are attributed to a lack of spray momentum produced by the system's nozzles. A spray with enough momentum can interact with the fire's and room's ventilation flows sufficiently to aid in the fire's extinguishment. The CFS system produces small droplets by impinging two water streams upon one another. The collision of the two streams limits the velocity/momentum of the spray. Recent tests conducted at Factory Mutual (FM) suggest that the capabilities of the system can be significantly enhanced by increasing the operating pressure of the system. During these FM tests, the system operating pressure was almost twice that used during this evaluation.

9.2.2 Fike – Micromist

The Micromist system is an intermediate-pressure single-fluid system which has an operating pressure of 21 bar. For this evaluation, the system consisted of six nozzles installed with a 2.5-m nozzle spacing. The nozzles have a K-factor of 1.75 $Lpm/bar^{1/2}$ producing a total system flow rate of 48 Lpm. The capabilities of the system identified during these tests may not be representative of a commercially installed system in which the discharge is cycled. Cycling of the mist systems was beyond the scope of this test series.

As shown in Table 5, the Micromist system was capable of extinguishing a majority of the test fires (10 of 15). The capabilities of the Micromist system were comparable to the other systems with respect to which fires were extinguished, but as with the other low- and intermediate-pressure systems the extinguishment times were slightly longer than average. For example, the Micromist system required 140 seconds to extinguish the 0.5 MW heptane spray fire with natural ventilation as compared to an average extinguishment time for the five systems of 105 seconds. This trend was consistent for a majority of the other fire scenarios as well. The limits of the system were again identified during the tests conducted with forced ventilation. The Micromist system was only capable of extinguishing one of the five fires (1.0 MW heptane spray) conducted with the forced ventilation system operating. This fire required just over two minutes to extinguish.

The longer extinguishment times and difficulty extinguishing the well-ventilated fires are attributed to the spray characteristics of the system. The Micromist system produces small drops by impinging a water spray on a deflector plate. The water stream is oriented such that the water just barely impacts the deflector plate, keeping much of the initial momentum of the spray intact. This technique produces only a limited number of fine/small droplets (less than 50 microns) which tend to reduce the capability of the system against small-obstructed fires.

9.2.3 Grinnell – AquaMist

The AquaMist system is a single-fluid, intermediate-pressure system which has an operating pressure of 13 bar. Up to this point in the investigation, the mist systems consisted of uniformly spaced nozzles installed vertically. Grinnell requested permission to deviate from this practice to evaluate a system design developed for machinery spaces on small British ships. The design consisted of six AM-4 nozzles installed and oriented to create mist/air flow patterns around the equipment (i.e., engine mock-ups) in the space. The nozzle locations and orientations are shown in Figure 10. The six AM-4 nozzles used in this design produced a total water flow rate of 75 Lpm.

As shown in Table 5, the AquaMist system was capable of extinguishing a majority of the test fires (9 of 15). The capabilities of the AquaMist system were comparable to the other systems with respect to which fires were extinguished, but as with the other low- and intermediate-pressure systems, the AquaMist system produced slightly longer extinguishment times. For example, the AquaMist system required 117 seconds to extinguish the 0.5 MW heptane spray fire with natural ventilation as compared to an average extinguishment time for the five systems of 105 seconds. This trend was consistent for a majority of the other fire scenarios as well. The limits of the systems were again identified during the tests conducted with forced ventilation. The AquaMist system was only capable of extinguishing one of the five fires (1.0 MW heptane spray) conducted with the forced ventilation system operating. However, this fire was extinguished in less than one minute. The AquaMist system was also the only system that could not extinguish the 0.25 MW heptane spray fire with natural ventilation (1.7 m^2 vent).

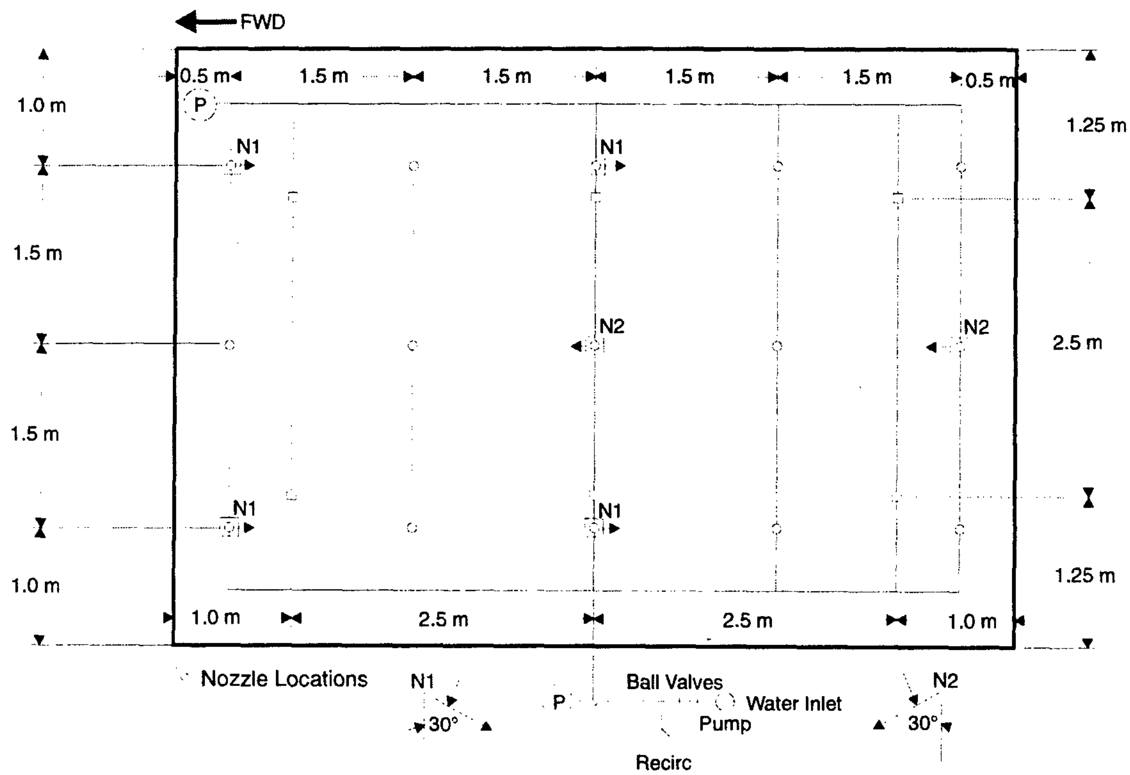


Figure 10. Grinnell - AquaMist System Design

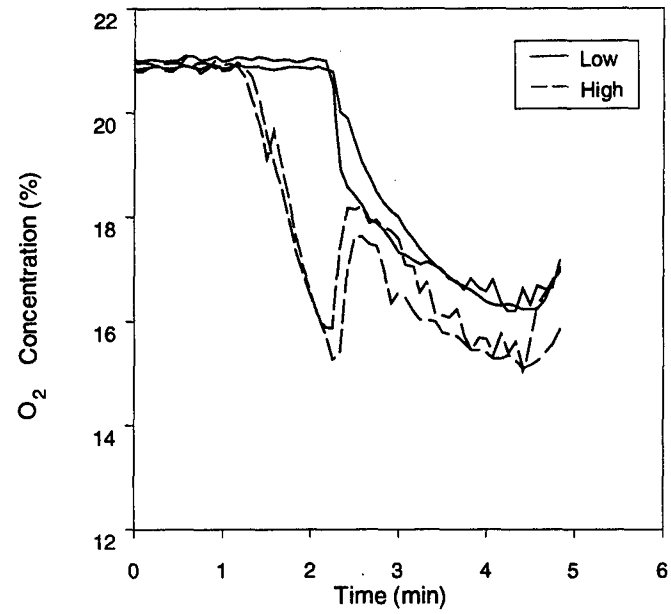
The longer extinguishment times and difficulty extinguishing the well-ventilated fires are again attributed to the spray characteristics of the system. The AquaMist system produces small drops by impinging a water spray on a deflector plate. The impact of the water stream on the deflector plate typically produces sprays with limited velocity/momentum. This technique also produces only a limited number of fine/small droplets (less than 50 microns) which tend to reduce the capability of the system against small obstructed fires.

9.2.4 Fogtec Fire Protection Systems

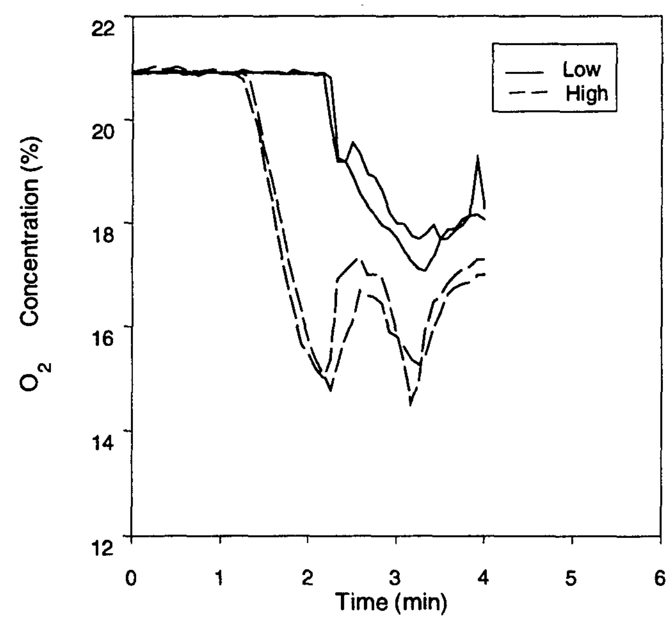
The Fogtec is a high-pressure single-fluid system which has an operating pressure of 100 bar. For this evaluation, the system consisted of six nozzles installed with a 2.5-m nozzle spacing. The nozzles have a K-factor of 0.35 $Lpm/bar^{1/2}$ producing a total system flow rate of 22 Lpm. This flow rate was a factor of two to three times less than the other systems evaluated.

As shown in Table 5, the Fogtec system was capable of extinguishing a majority of the test fires (10 of 15). The capabilities of the Fogtec system were comparable to the other systems with respect to which fires were extinguished, and the extinguishment times were typically equal to or better than a majority of the other systems. For example, the Fogtec system required 67 seconds to extinguish the 0.5 MW heptane spray fire with natural ventilation as compared to an average extinguishment time for the five systems of 105 seconds. This trend was consistent for a majority of the other fire scenarios as well. The limits of the Fogtec system were again identified during the tests conducted with forced ventilation. The Fogtec system, as with the previous three systems (CFS, Micromist, and AquaMist) was only capable of extinguishing one of the five fires (1.0 MW heptane spray) conducted with the forced ventilation system operating. However, this fire was extinguished in only 76 seconds.

The difficulty extinguishing the well-ventilated fires is attributed to a lack of spray momentum and/or the lower system flow rate of the two high-pressure systems. Higher system flow rates typically have higher momentum sprays from the nozzles that result in better mixing due to the increased turbulence in the space. The low flow rate combined with the very small drop sizes produced by the system (Class 1 spray as defined by NFPA 750 [10]), resulted in poor mixing of the mist and vitiated gases throughout the space. The small droplets and lack of spray momentum allowed the supply air from the forced ventilation system to push the mist away from the fire and out of the compartment. A comparison of the mixing provided by the Fogtec system and the Micromist system is shown in Figure 11. As shown by the separation in the high and



Fike - Micromist 0.5 MW Heptane Spray - Natural



Fogtech - Micromist 0.5 MW Heptane Spray - Natural

Figure 11. Mixing Comparison

low oxygen concentrations measured for the Fogtec system after activation (at the 2 minute mark). This clear separation does not exist after system activation for the Micromist system. The Fogtec system was not capable of uniformly mixing the mist and vitiated gases (as seen by the convergence of the high and low oxygen concentration measurements) in the compartment.

9.2.5 U.S. Navy's Water Mist System

The Navy's water mist system is a high-pressure single-fluid system that has an operating pressure of 70 bar. For this evaluation, the system consisted of six nozzles installed with a 2.5-m nozzle spacing. The nozzles have a K-factor of 1.35 Lpm/bar$^{1/2}$ producing a total system flow rate of 68 Lpm.

As shown in Table 5, the Navy's water mist system produced the best firefighting capabilities of the five systems included in this evaluation (12 of 15). The system produced the fastest extinguishment times and was also capable of extinguishing two fires (0.5 MW heptane spray and the 0.41 m^2 heptane pan, both with forced ventilation) that were not extinguished by the other systems.

The superior performance of the Navy's system is attributed to the combination of drop size distribution and spray momentum. The Navy nozzle produces a borderline Class-1/Class-2 spray as defined by NFPA 750 [10], with adequate momentum to distribute the mist and vitiated gases throughout the space. The smaller droplet sizes allow the system to absorb heat and create water vapor (steam) effectively reducing the oxygen concentration in the space. The spray momentum creates a homogeneous mixture by effectively mixing the mist, water vapor, and vitiated gases uniformly throughout the space.

9.2.6 System Performance Summary

The five commercially available water mist systems were each capable of extinguishing a majority of the test fires included in this evaluation. The extinguishment times for these systems ranged from 15 seconds to no extinguishment depending on the fire size, fire type, and ventilation condition. The extinguishment times for the high-pressure systems were typically faster than the low- and intermediate-pressure systems. Variations in the system capabilities were observed primarily during the tests conducted with forced ventilation. Less than 30 percent of the fires were extinguished when the forced ventilation system was operating.

The U.S. Navy's water mist system demonstrated superior capabilities throughout this test series. The system typically produced the fastest extinguishment times and was capable of extinguishing two fires (0.5 MW spray and 0.41 m^2 pan, both with forced ventilation) that were not extinguished by the other systems.

9.3 Modeling Predictions

The steady state extinguishment model developed during a previous investigation [3] was used to analyze the results of these tests. The model assumes that water mist systems extinguish obstructed fires through a reduction in oxygen resulting from both consumption of oxygen by the fire and dilution of the oxygen with water vapor. The model assumes that the water mist systems produce a well mixed/saturated environment.

The model is based on conservation of energy and mass and requires the following input parameters: fire size, compartment geometry, vent area, and water mist system flow rate. From these conditions, the model can predict the steady state compartment temperature and steady state oxygen concentrations in the space. The steady state oxygen concentrations can be used to determine the smallest fire (critical fire size) that will adequately reduce the oxygen concentration in the space below the Limiting Oxygen Index (LOI) of typical fuels and result in extinguishment.

The steady state temperatures measured during these tests are listed in Table 6. The steady state temperatures ranged from 49–77°C, depending on the fire size, ventilation condition, and water mist system flow rate. In general, for a fixed fire size (i.e., 0.5 MW), the range of ventilation conditions resulted in a variation in temperature of ten degrees Celsius.

Table 6. Steady State Compartment Temperatures

Fire Scenario	Ventilation	Navy	Grinnell	Fogtec	Chemetron	Fike
		Steady State Temperatures (°C)				
1.0 MW Spray	Closed	N/A	76	N/A	71	N/A
1.0 MW Spray	Natural	N/A	72	N/A	66	N/A
1.0 MW Spray	Forced	N/A	76	N/A	71	N/A
0.5 MW Spray	Closed	53	69	N/A	69	77
0.5 MW Spray	Natural	55	64	N/A	66	75
0.5 MW Spray	Forced	55	66	N/A	67	76
0.25 MW Spray	Closed	49	62	64	64	61
0.25 MW Spray	Natural	48	59	62	61	59
0.25 MW Spray	Forced	53	–	–	–	–
0.41 m^2 Pan	Closed	59	63	67	61	69
0.41 m^2 Pan	Natural	58	60	62	59	64
0.41 m^2 Pan	Forced	58	62	70	63	67
0.25 m^2 Pan	Closed	59	56	63	56	61
0.25 m^2 Pan	Natural	57	56	62	55	59
0.25 m^2 Pan	Forced	–	–	–	–	–

N/A = Steady conditions were never achieved
– = Test not conducted

The model was used to accurately predict the steady state compartment temperatures for the tests conducted with the spray fires during this evaluation. Figure 12 shows a comparison of the predicted temperatures for the range of water flow rates discharged by the five systems and the temperatures measured during the spray fire tests. As shown in Figure 12, the temperatures predicted by the model are typically slightly lower (~ 2-3°C) than those measured during these tests. The slightly higher temperatures measured during these tests and the variations in temperatures for a given fire size are attributed to the compartment boundary temperatures prior to the test. The timing of the tests did not allow the boundaries to cool back to ambient between tests which would result in higher than expected temperatures.

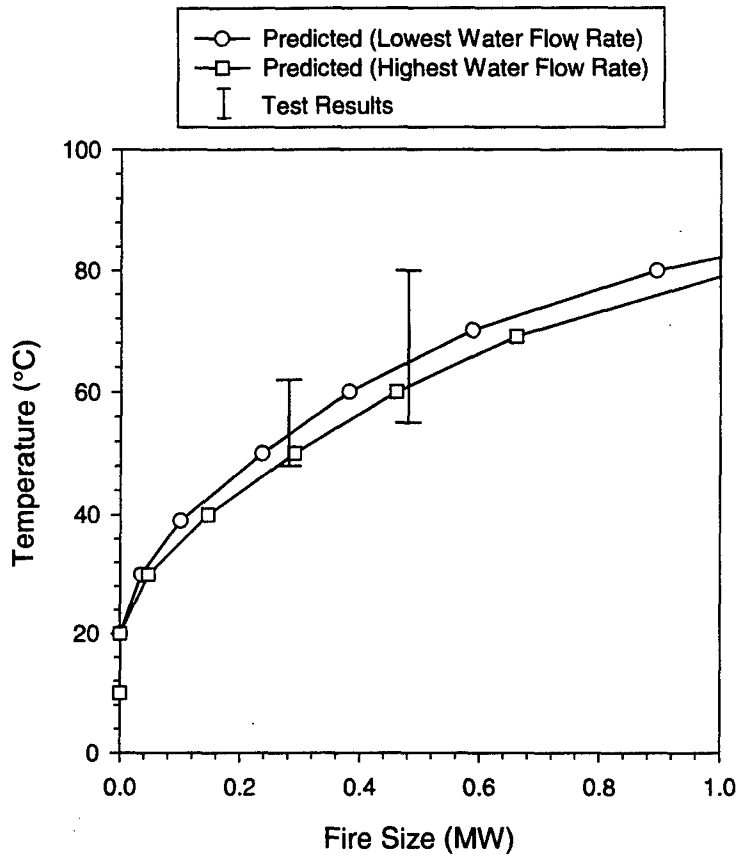


Figure 12. Steady State Temperature Comparison

The minimum oxygen concentrations measured in the compartment during these tests are shown in Table 7. The measurements are made on samples taken from the test compartment and mechanically dried to remove all water vapor prior to measurement. This is required by the analyzer for accurate measurement. The minimum oxygen concentrations typically ranged from 13-18 percent by volume (dry). The measured dry concentrations were adjusted post-test to include water vapor, assuming that the gases were saturated, and are shown in Table 8. These data suggests that a conservative estimate for the LOI of heptane using the products of combustion and water vapor as the diluent is between 14 and 15 percent by volume. All of the fires conducted during this evaluation with the exception of those conducted with the Navy nozzles were extinguished when the adjusted wet oxygen concentrations approached 14 percent by volume. This compares favorably to the results found in the literature [11] and in the previous two phases of this investigation [3 and 8].

Table 7. Minimum Oxygen Concentrations (Measured Dry)

Fire Scenario	Ventilation	Navy	Grinnell	Fogtec	Chemetron	Fike
		Oxygen Concentrations (%) Dry				
1.0 MW Spray	Closed	12.7	14.6	12.4	14.7	12.6
1.0 MW Spray	Natural	14.6	16.8	16.2	15.5	16.5
1.0 MW Spray	Forced	14.8	16.5	14.1	16.2	15.3
0.5 MW Spray	Closed	16.8	14.8	15.7	15.4	15.2
0.5 MW Spray	Natural	17.3	15.4	16.0	15.0	15.0
0.5 MW Spray	Forced	16.9	15.2	15.2	16.3	15.4
0.25 MW Spray	Closed	16.5	14.5	16.2	14.0	14.8
0.25 MW Spray	Natural	17.9	15.2	16.6	15.1	17.5
0.25 MW Spray	Forced	17.7	–	–	–	–
0.41 m^2 Pan	Closed	16.0	16.0	16.7	15.2	15.0
0.41 m^2 Pan	Natural	17.2	16.0	16.3	16.0	16.5
0.41 m^2 Pan	Forced	17.8	16.6	16.6	17.5	16.8
0.25 m^2 Pan	Closed	16.4	15.4	16.6	15.5	15.6
0.25 m^2 Pan	Natural	16.6	16.8	16.8	16.1	16.9
0.25 m^2 Pan	Forced	–	–	–	–	–

Note: Shaded areas are fires that were not extinguished.

Table 8. Minimum Oxygen Concentrations (Adjusted Wet)

Fire Scenario	Ventilation	Navy	Grinnell	Fogtec	Chemetron	Fike
		Oxygen Concentrations (%) Wet				
1.0 MW Spray	Closed	10.0	12.7	10.0	12.7	10.0
1.0 MW Spray	Natural	10.5	14.6	8.8	13.9	11.9
1.0 MW Spray	Forced	10.5	13.7	11.0	14.0	8.3
0.5 MW Spray	Closed	16.0	12.8	12.3	13.8	12.6
0.5 MW Spray	Natural	16.5	13.8	11.5	12.4	11.7
0.5 MW Spray	Forced	15.9	15.2	15.0	15.5	15.1
0.25 MW Spray	Closed	15.7	13.3	14.5	12.6	13.6
0.25 MW Spray	Natural	17.1	15.0	14.9	13.9	13.5
0.25 MW Spray	Forced	16.6	–	–	–	–
0.41 m^2 Pan	Closed	14.7	14.9	14.8	14.0	13.6
0.41 m^2 Pan	Natural	15.6	14.7	14.6	14.3	14.8
0.41 m^2 Pan	Forced	15.7	15.9	15.0	15.2	15.1
0.25 m^2 Pan	Closed	15.4	14.5	14.6	14.5	14.4
0.25 m^2 Pan	Natural	15.6	15.6	15.1	15.8	15.2
0.25 m^2 Pan	Forced	–	–	–	–	–

Note: Shaded areas are fires that were not extinguished.

The model was used to predict the steady state oxygen concentrations for the tests conducted during this evaluation. These concentrations are shown in Figure 13. A 0.25 m^2 leakage/vent area was used to represent the closed compartment ventilation condition. A comparison between the predicted and measured oxygen concentrations is inappropriate because a majority of these fires were extinguished before steady state conditions were achieved. However, the predicted oxygen concentration can be validated based on the prediction of the critical fire size for a given ventilation condition.

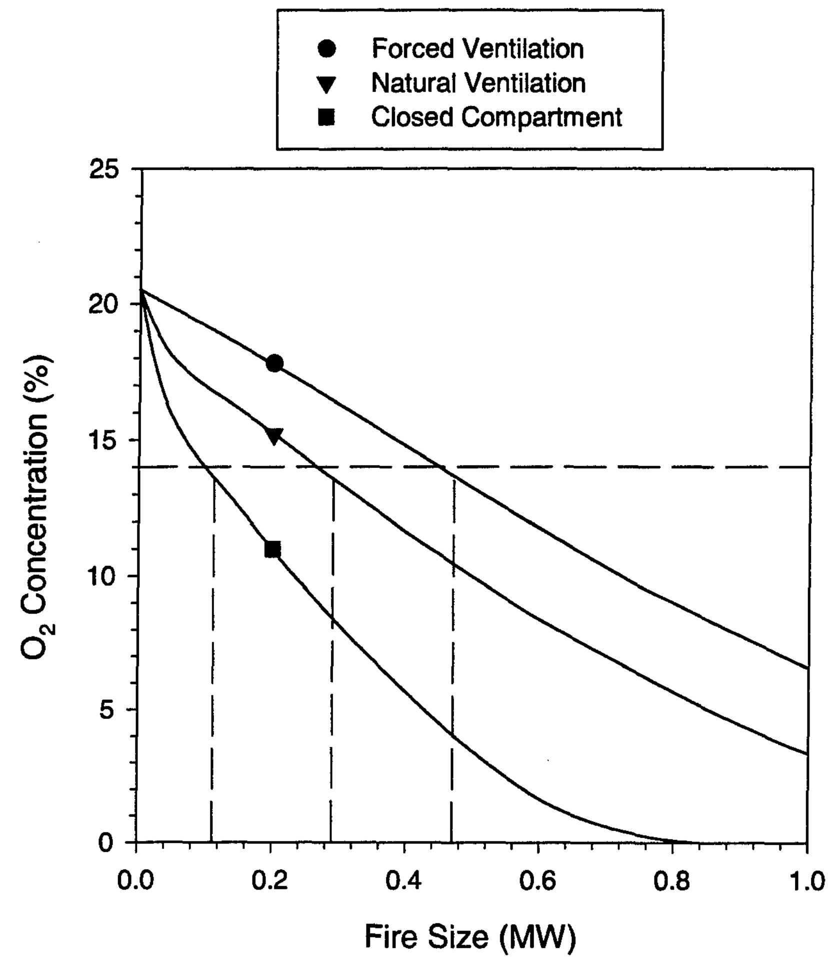


Figure 13. Predicted Steady State Oxygen Concentrations

Assuming the LOI for heptane using a mixture of water vapor and combustion products as the diluent is 14 percent by volume, the critical fire size for the three ventilation conditions evaluated during these tests can be determined from Figure 13. The critical fire size is defined as the smallest fire that will reduce the oxygen concentration in the compartment below the LOI of the fuel. This oxygen concentration prediction is based on both consumption of the oxygen by the fire and the dilution of the oxygen with water vapor. Figure 13 suggests that the critical fire sizes are 100 kW for the closed compartment, 250 kW for the 1.7 m^2 vent opening and 440 kW for the forced ventilation condition (25 m^3/min).

This critical fire size prediction can be used to explain the results of these tests. For example, the critical fire size predictions suggest that all the spray fires should have been extinguished in the closed compartment, the 1.0 MW and 0.5 MW fires should have been extinguished in the naturally ventilated (1.7 m^2) compartment, and only the 1.0 MW spray fire should have been extinguished in compartment with forced ventilation. The critical fire size predictions also suggests that the 0.25 MW spray fire should not be extinguished in the compartment with forced ventilation. These predictions are in agreement with the results of these tests. The only fire scenarios remaining are the 0.5 MW spray fire with forced ventilation and the 0.25 MW spray fire with natural ventilation which appear marginal. This is also in agreement with the results. Four of the five systems were capable of extinguishing the 0.25 MW spray fire under naturally ventilated conditions while only one system was capable of extinguishing the 0.5 MW spray fire with forced ventilation.

The model was also used to provide a rough estimate of the extinguishment times for these fires. The term rough estimate is used since steady state models are not typically appropriate for predicting transient events. This is due to the model's assumption that steady state conditions are achieved instantaneously rather than over time as actually occurs. The extinguishment times predicted by the model for the naturally ventilated compartment are shown as the lines on Figure 14. Also shown on Figure 14 are the range of extinguishment times recorded during these tests.

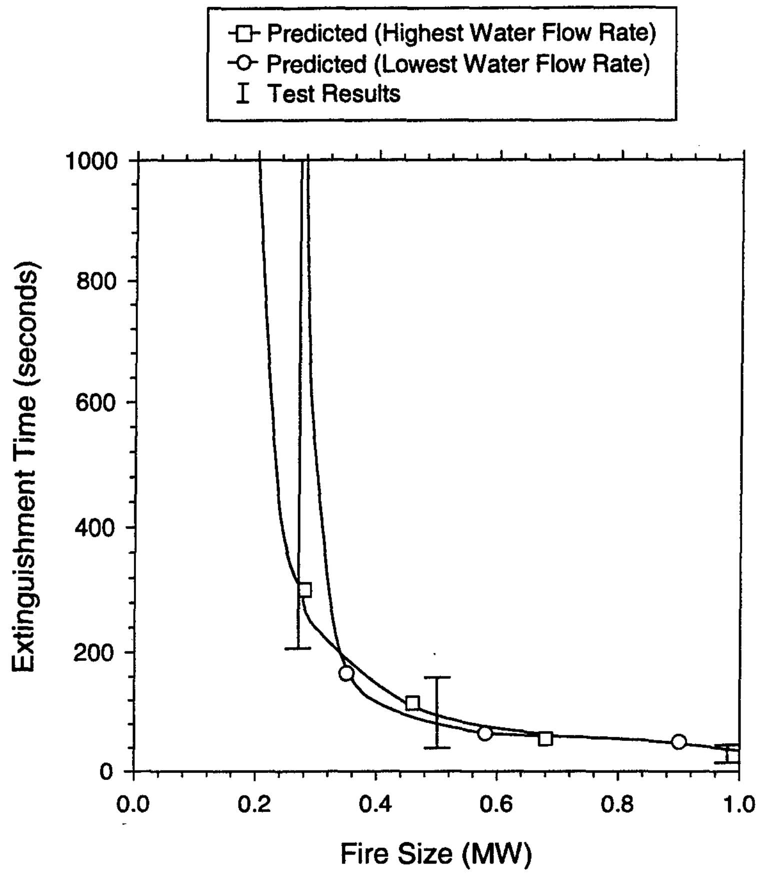


Figure 14. Extinguishment Time Comparison

As shown in this figure, the extinguishment times predicted by the model lie in the range of those measured during this evaluation. It would be inappropriate to analyze this comparison any farther due to the variations (scatter) in the extinguishment times observed for a given fire scenario (fire size and ventilation condition).

The scatter in the data and the variation between the measured and predicted results may be associated with the assumptions made in the model. The two main assumptions are that the space becomes well mixed during mist discharge and the gases in the compartment become saturated with water vapor. The model also assumes that these conditions are reached shortly after system activation. The gas sampling and temperature measurements made in the space during these tests suggests that the time required to produce these conditions may be nozzle dependent. For example, the Fogtec system did not produce well-mixed conditions for three to four minutes after system activation (Figure 11). This was attributed to the lower water flow rates and the limited spray momentum of the system. Consequently, deficiencies in spray characteristics, identified during the system capability discussion, may delay the timing of steady state conditions being achieved. However, this delay does not appear to effect the steady state conditions once achieved.

To this point, the discussion has focused primarily on spray fires with the results of the pan fire tests intentionally omitted. The results of the pan fire tests were significantly different than those observed for the spray fire tests. For a given fire size (assuming ambient conditions) and ventilation condition, the pan fires produced lower compartment temperatures and longer extinguishment times. This was attributed to a reduction in heat release rate of the pan fires resulting from decreasing oxygen concentrations in the space.

Previous studies [12] have shown that the heat release rate of a pan fire may be reduced as much as 50 percent as the oxygen concentration approaches the LOI of the fuel (~ 13-15 percent depending on the diluent). Based on this information, we can assume the actual heat release rate of the pan fires at extinguishment was 50 percent of the expected value. The predictions made by the model also support this assumption (for ambient conditions).

The steady state temperatures predicted by the model are again shown in Figure 15. Also shown in this figure are the temperatures recorded during the pan fire tests. The temperatures are plotted for both the ambient and reduced (50 percent) heat release rates. As shown in Figure 15, the measured and predicted temperatures are similar for the reduced heat release rate values. Again, the slightly higher temperatures measured for the smaller fires may be associated with the compartment boundary temperatures prior to the test.

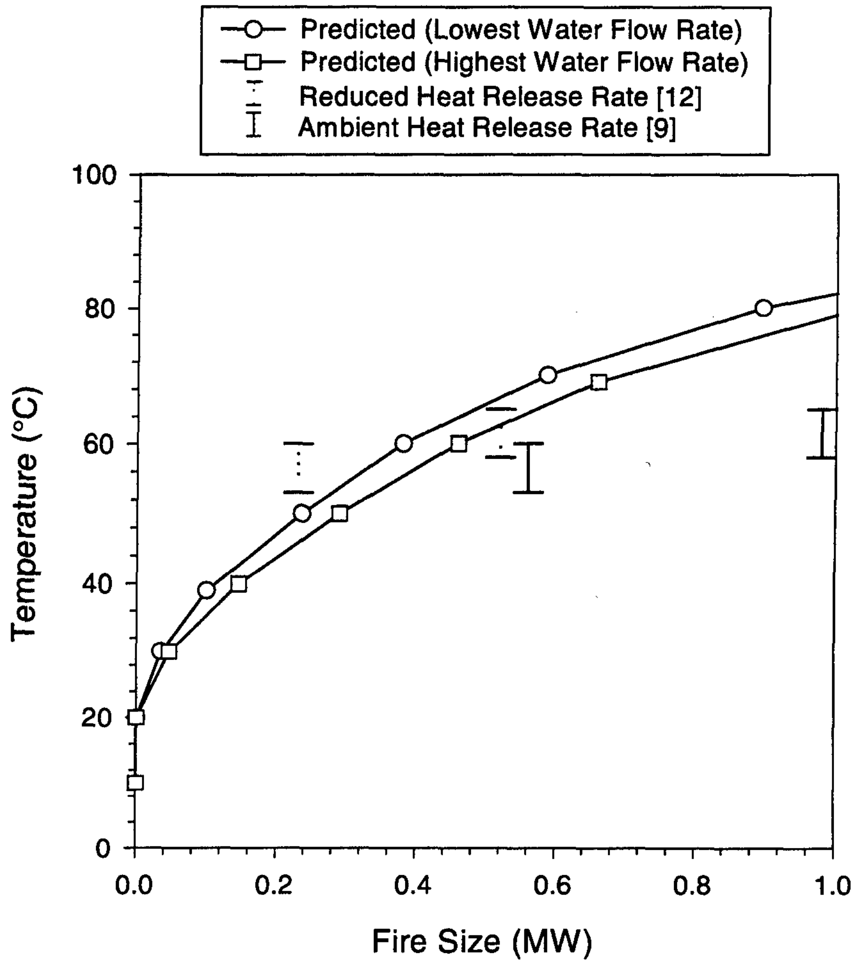


Figure 15. Pan Fire Temperature Comparisons

The fire extinguishment times for the pan fires also follow the same trends. If the heat release rates are reduced by 50 percent, the extinguishment times show better agreement with the model predictions. However, there are still significant variations in the data. This comparison is shown in Figure 16.

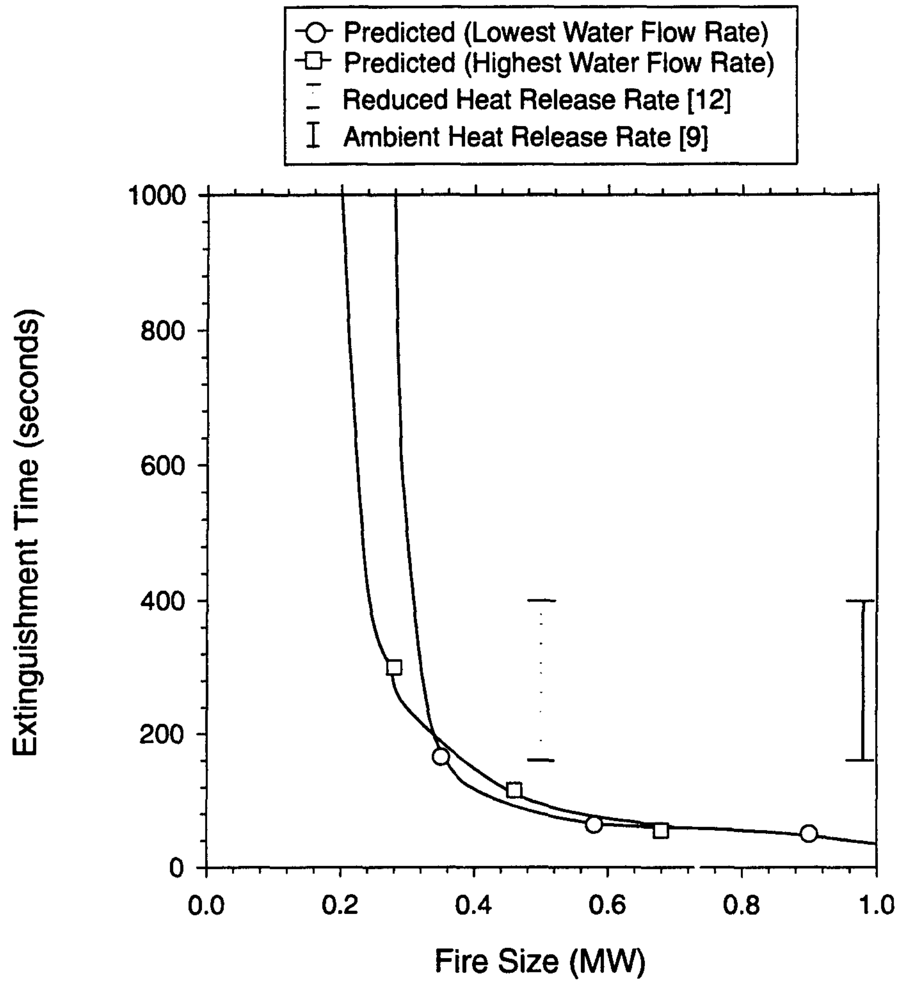


Figure 16. Pan Fire Extinguishment Time Comparison

9.4 Combustible Boundary Evaluation

Ten combustible boundary tests were conducted during this evaluation. These tests consisted of nine corner tests and one test conducted with a combustible overhead.

Three water mist systems (Navy, Fogtec, and Grinnell) were included in this evaluation. The water mist systems were selected based on their suppression capabilities, system specifications, and spray characteristics. The systems cover the range of suppression capabilities, drop size distribution, operating pressure, and water flow rates evaluated in this study. The Navy water mist system was selected for its superior suppression capabilities as identified in the performance evaluation. The Fogtec water mist system was selected for both its suppression capabilities as well as its low water flow rate (22 Lpm). The Grinnell water mist system was selected for its low operating pressure (13 bar) and due to the longer extinguishment times observed during the performance evaluation.

The three systems were installed as tested in the performance evaluation. The performance of each water mist system was judged based on the time to extinguishment, peak compartment temperature, and damage to the combustible boundary. The damage to the combustible boundaries during each test is shown in Appendix C.

9.4.1 Corner Tests

The results of the corner fire tests are shown in Table 9.

Table 9. Corner Fire Test Results

Mist System	Combustible Material	Extinguishment Time (sec)	Peak Temp.[1] (°C)	Minimum Oxygen Level (%) dry	Area of Damage[2] (m^2)	Area of Burn Through (m^2)
Baseline	Plywood	- -	350	5.0	10.9	3.57
Navy	Plywood	116	55	16.2	8.79	- -
Navy	Vinyl Ester	133	47	15.0	8.82	- -
Fogtec	Plywood	117	65	17.1	7.50	- -
Fogtec	Vinyl Ester	145	90	15.8	8.73	- -
Grinnell	Plywood	395	62	14.2	7.90	0.11
Grinnell	Vinyl Ester	136	60	15.5	7.41	- -

1. Peak temperature during the steady state time when the water mist was activated.
2. Damage includes all areas where any physical surface damage (e.g., charring, browning, blistering) was visually evident.

The baseline fire test was conducted to identify the conditions that develop in the compartment if the fire grows unabated. The baseline test was conducted using plywood as the combustible material. During the fire, a two-layer system developed, with high temperature combustion products in the upper part of the compartment and lower temperature gases in the lower part of the compartment. Upper layer temperatures peaked at approximately 350°C, while lower layer temperatures remained below 100°C. The oxygen concentrations in the upper-layer were reduced to 5.0 percent, while the concentrations in the lower part of the room remained near ambient levels. The damage to the combustible boundary was extensive, as shown in Figure 17. The fire caused an upside down L-shaped burn pattern on both the forward and starboard side bulkheads. The overhead was fully involved with char present over the entire surface. The fire burned through the combustible material at the top of the corner where the bulkheads join with the overhead. The burn through region started approximately 0.25 m above the deck and extended to the overhead. The most severe damage, an opening through the combustible boundary into the void space (created between the combustible boundary and the compartment's steel bulkhead), occurred at the upper corner of the space.

The Navy water mist system was evaluated against the corner fire scenario using both plywood and vinyl ester combustible boundaries. In tests with the plywood, the water mist system extinguished the fire in 116 seconds. The water mist system produced a well-mixed environment, resulting in relatively uniform temperatures throughout the compartment. The peak temperature measured during discharge was 55°C. Oxygen concentrations in the compartment were also well mixed with a minimum oxygen concentration of 16.2 percent (dry). The damage to the combustible material is shown in Figure 18. Approximately 8.8 m^2 of the combustible boundary was damaged, which is similar for all of the fire suppression tests, regardless of the boundary material. The shape of the char pattern is similar to that found in the baseline tests, but the damage was limited to the surface of the plywood. The char was approximately 0.8 mm deep, and no burn through (char on unexposed side) was evident.

The results were similar between the plywood and vinyl ester tests. The water mist system extinguished the vinyl ester fire in 133 seconds. Temperatures in the compartment were well mixed during discharge and peaked at approximately 47°C. The minimum oxygen concentration was 15 percent (dry) and was well mixed. No burn through (char on unexposed side) was evident.

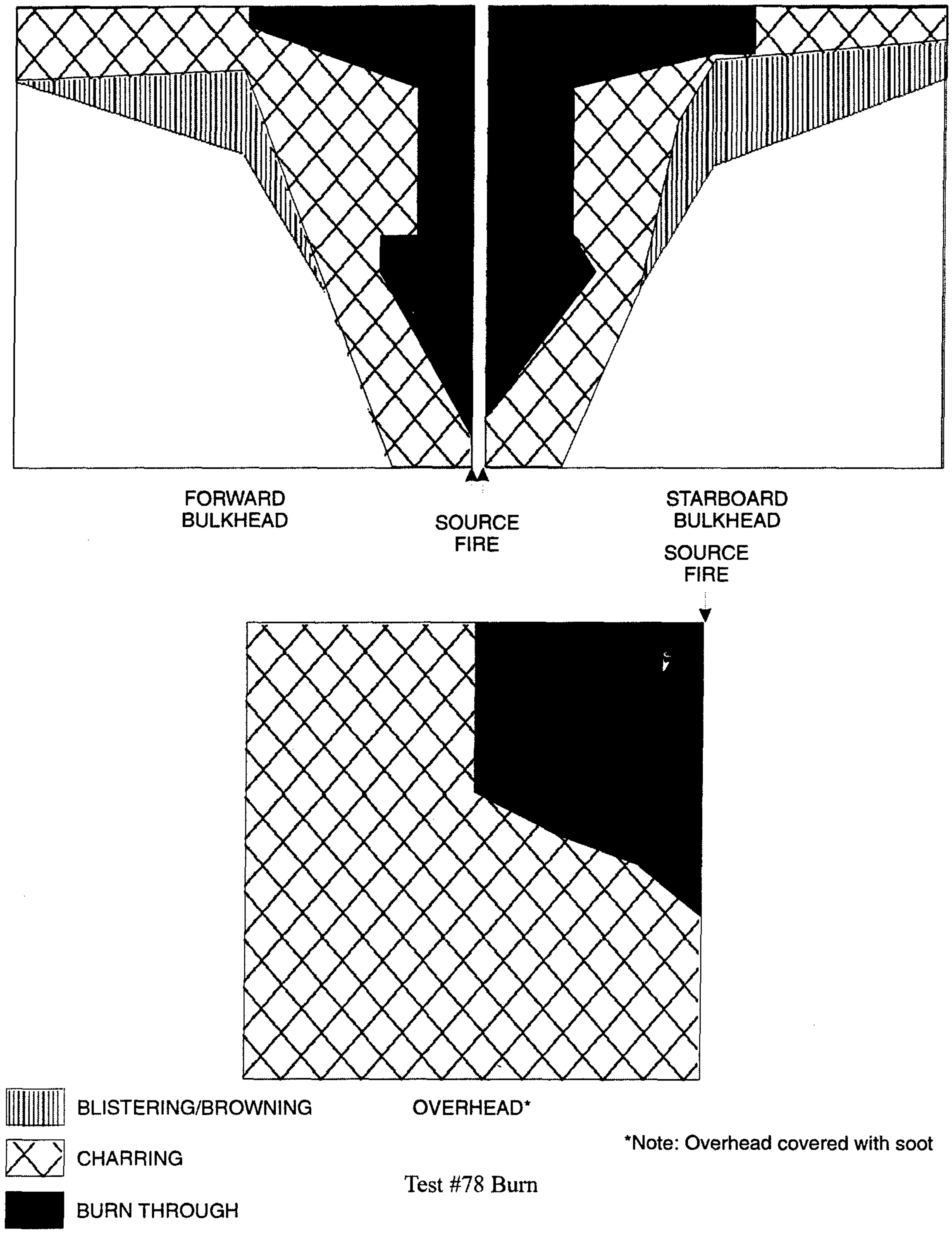


Figure 17. Baseline Fire Test (Combustible Boundary Damage)

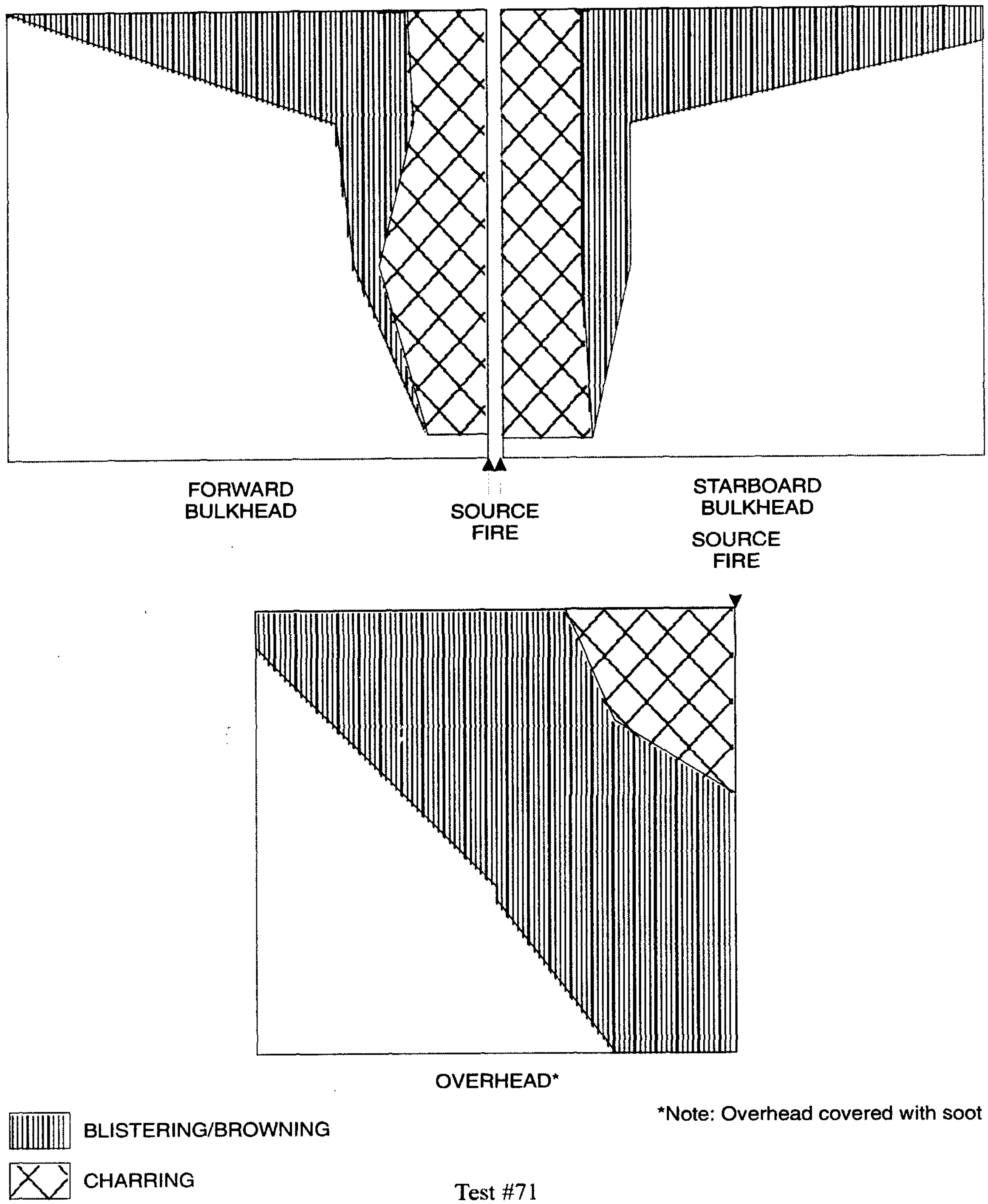


Figure 18. Typical Combustible Boundary Damage

The Fogtec water mist system was also evaluated using both types of combustible boundaries. The plywood fire scenario was extinguished in approximately 117 seconds. The top thermocouple in the compartment was as much as 20°C higher than the thermocouples below it, suggesting the presence of a weak upper layer. The presence of the upper layer was attributed to the low water flow rate (22 Lpm) and spray characteristics (low momentum) of the system's nozzles. The Fogtec system could not produce a well-mixed environment during this test due too the nozzles low spray momentum and flow rate. The peak temperature measured during water mist discharge was approximately 65°C. Oxygen concentrations were measured as low as 17.1 percent (dry). The damage pattern was similar to what was observed in the tests with the Navy water mist system, with the depth of the char being approximately 0.8 mm. No burn through (char) was again evident on the unexposed sides of the plywood.

Test results were similar between the plywood and vinyl ester fire tests. The vinyl ester fire was extinguished in 145 seconds. During the water mist discharge, the temperatures high in the compartment were 20-30°C higher than temperatures measured elsewhere. This again indicates the presence of a weak upper layer. The oxygen concentrations in the compartment were fairly well mixed, with a minimum concentration of 15.8 percent (dry). Damage to the boundary was similar to that in other tests. The depth of the char was approximately 0.8 mm. No burn through was again evident on unexposed sides of the boundary.

The Grinnell AquaMist system was also evaluated using both combustible boundary materials. The plywood fire was extinguished in 395 seconds. This is more than double the times measured in tests with the other two water mist systems. The environment in the compartment was well mixed with all temperatures and oxygen concentrations relatively uniform throughout the space. The peak temperature measured during discharge was 62°C with the oxygen concentrations measured as low as 14.2 percent (dry). The damage pattern on the plywood boundary was similar to the other tests. However, due to the longer extinguishment time, the damage was slightly more extensive than that observed in previous tests. The char depth was on average of approximately 1.6 mm deep, and burn through (char) was evident at the upper corner of the unexposed sides.

The Grinnell AquaMist system performed better in the test conducted with the vinyl ester boundaries. The fire was extinguished in 136 seconds after system activation. During discharge, the compartment temperatures and oxygen concentrations were measured to be relatively uniform throughout the compartment. Temperatures during discharge were measured to be as high as 60°C, while oxygen concentrations were measured as low as 15.5 percent (dry). The damage to the boundary was similar to those observed in tests using the other two water mist systems with the vinyl ester material. The depth of the damaged area was approximately 0.8 mm, and no burn through was evident.

9.4.2 Overhead Tests

The corner fire test results demonstrated that combustible boundaries do not pose a significant additional challenge to water mist systems. This is demonstrated by preventing burn-through and limiting damage to mostly surface damage. Consequently, the overhead evaluation was limited to one test with a combustible plywood overhead using the Grinnell AquaMist system. The Grinnell AquaMist system was selected as a result of its performance as observed during the corner tests.

The Grinnell AquaMist system extinguished the overhead fire in 76 seconds of mist activation. This time is faster than the time required to extinguish the corner fire scenario. As with the previous tests, the compartment temperatures and oxygen concentrations were well mixed throughout the compartment. The temperature was measured to be as high as 42°C, while the oxygen concentrations were measured to be as low as 18.8 percent (dry). The burn pattern on the overhead was relatively symmetric, with significant charring approximately 0.80 m radially from the center of the impinging spray fire. The charring was approximately 8 mm deep, and no burn through was evident.

9.4.3 Combustible Boundary Test Summary

The initiating fire (0.25 MW heptane spray) used in the combustible boundary tests was one of the more difficult fires to extinguish during the performance evaluation. However, this initiating fire was sufficient to ignite a significant amount of the combustible boundary material. The net result was a large fire, which are easier to extinguish than smaller fires. As a result, all of the combustible boundary fire tests were extinguished.

All of the systems passed (i.e., extinguished the fire with no burn through on the boundary) with the exception of the Grinnell AquaMist system with plywood as the combustible material. The AquaMist system produced similar results as the other two systems for vinyl ester corner fire scenario. Results for the other two systems indicate that the vinyl ester was more difficult to extinguish than the plywood, with extinguishment times approximately 17-29 seconds longer. In addition, the AquaMist system extinguished the plywood overhead in 76 seconds, which is less time than any system required to extinguish the corner fire with a plywood boundary. The longer extinguishment time for the AquaMist system in the plywood corner scenario is unexplainable. With the AquaMist system capable of extinguishing fires equally or more challenging than the corner fire test with plywood, the result from the plywood corner test with the Grinnell AquaMist system appears to be an anomaly.

The results of the combustible boundary testing indicate that extinguishment is primarily caused by reducing the oxygen concentration below the LOI, with surface wetting a secondary mechanism. This was demonstrated by the results of the Fogtec water mist system. The Fogtec water mist system had extinguishment times that were comparable to the other two systems but used two to three times less water. This indicates that surface wetting was not as crucial as the reduction in oxygen concentration in the extinguishment of these fires. Drysdale [13] indicates, however that the LOI for charring materials (i.e., wood) may be as low as nine percent. A potential water mist system design for spaces with combustible boundaries that is conservative in its design, would not only produce a well mixed environment but would also provide adequate surface wetting to prevent charring.

9.5 Protection Requirements

The system capabilities observed during this evaluation were in many respects similar but in other respects covered the range of possible scenarios. The capabilities of the five systems were similar for larger fires with limited ventilation but begin to vary as the size of the fires were reduced and/or the ventilation condition in the compartment was increased. These variations in capabilities should be considered by the designers when defining the design parameter requirements for water mist systems applied to machinery spaces of various sizes and ventilation conditions.

The primary design parameter associated with these systems is the duration of protection. Water mist systems are currently required to have a pressurized water source of adequate size to discharge the system for a period of one minute, an adequate amount of fresh/potable water to discharge the system for an additional thirty minutes, and a permanent sea water cross connect. These requirements significantly increase the impact the system has on the ship as well as the cost. The results of these tests suggest that these requirements can be reduced but the degree of reduction requires interpretation.

The approach of selecting a universal requirement for duration of protection that covers the entire spectrum of current system capabilities would over burden the higher performance systems to allow the lower performance systems to be included. If a general set of requirements is the only acceptable approach due to regulatory concerns, the current requirements are adequate. There are however, other approaches to defining these requirements that should be considered.

An alternative approach is to define the design parameters of the system on a case-by-case basis and allow the Authority Having Jurisdiction (AHJ) the final say. This approach in some respects is similar to the approval process used by Factory Mutual (FM) for water mist systems used in gas turbine applications [14]. The issues that need to be addressed when adopting this approach are described in the following paragraphs. Other issues that may need to be considered are the maximum extinguishment time based on an acceptable damage level and/or the availability and timing of manual intervention.

The first step is to define the minimum fire size that the system would be required to extinguish. This assumes that the crew will extinguish the smaller fires using hand held portable extinguishers or fire hoses rather than activate the system. Larger fires are easier to extinguish and do not need to be addressed. The selection of a minimum fire size should be related to the size of the protected space and can be based on the thermal conditions produced by the fire. More simple relations such as heat release rate to compartment volume ratios may also be appropriate. For example, an acceptable heat release rate to compartment volume ratio may be on the order of five kW/m^3. This would correspond to a 0.5 MW fire in our 100-m^3 machinery space.

The next step is to estimate or measure the extinguishment time of the minimum fire size in the space being protected. This can be accomplished through extrapolation of full-scale fire test results or through modeling techniques as described in Section 9.3 when determining this extinguishment time, emphasis should be placed on the ventilation conditions in the space. The ventilation condition is one of the primary variables associated with the extinguishment of obstructed fires using water mist systems. An example of the impact of both natural and forced ventilation on extinguishment time is shown in Figures 19 and 20 respectively. The lines on Figure 19 are the extinguishment time predictions using the model described in Section 9.3 for our 100 m^3 machinery spaces for vent areas from 1-5 m^2. Figure 20 shows the same trends for forced ventilation rates ranging from 10-50 m^3/min. Both figures illustrate the effect of ventilation on the extinguishment capabilities of a system.

The duration of protection and water storage requirements can now be bounded based on the extinguishment time for the minimum fire size. At a minimum, the system should provide a two shot capability or alternately can be referred to as a factor of safety of two. This would require the system to flow water for twice the time required to extinguish the minimum fire size. This is just one approach to defining these requirements. There may be other approaches that include similar considerations. Defining the system requirements on a case-by-case basis may be a viable alternative.

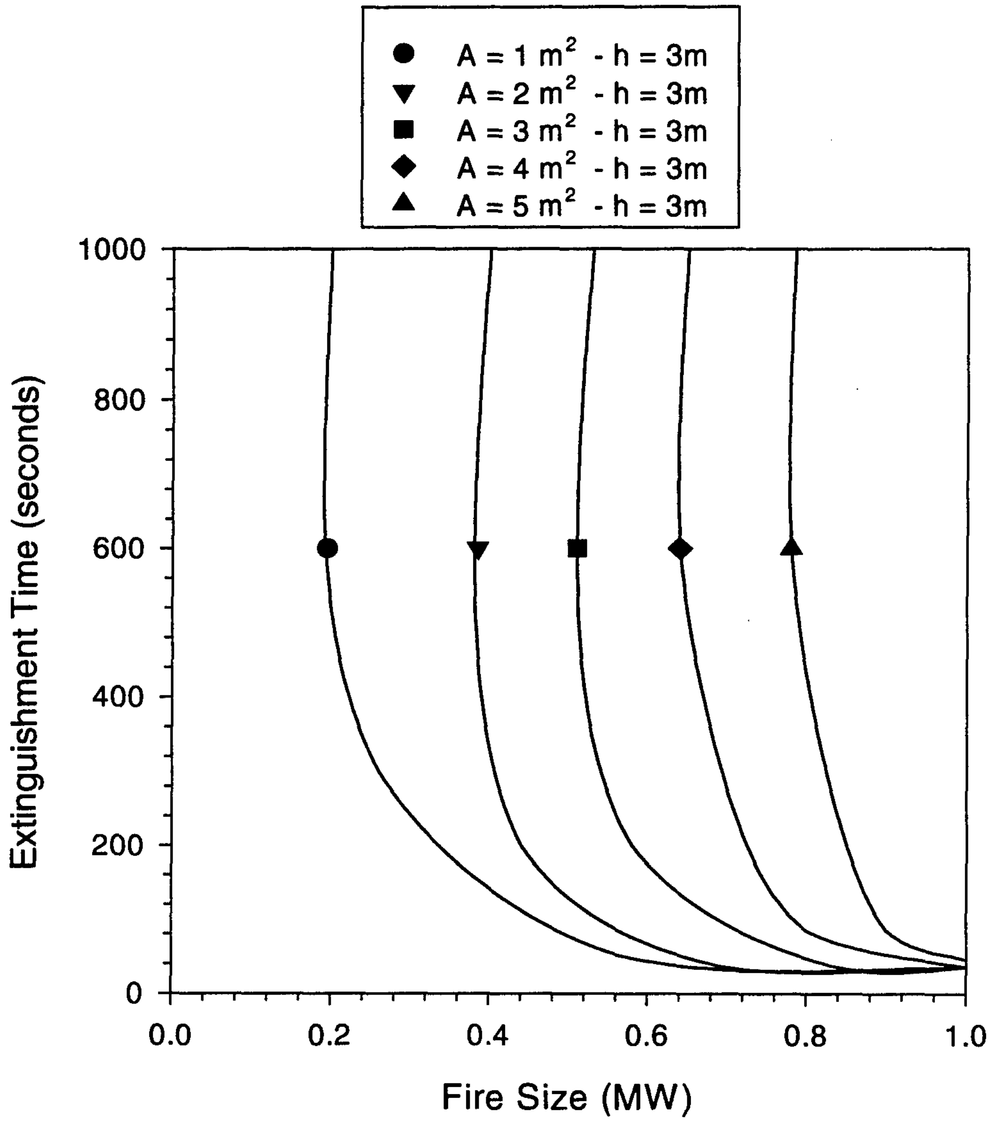


Figure 19. Effects of Natural Ventilation on Extinguishment Time

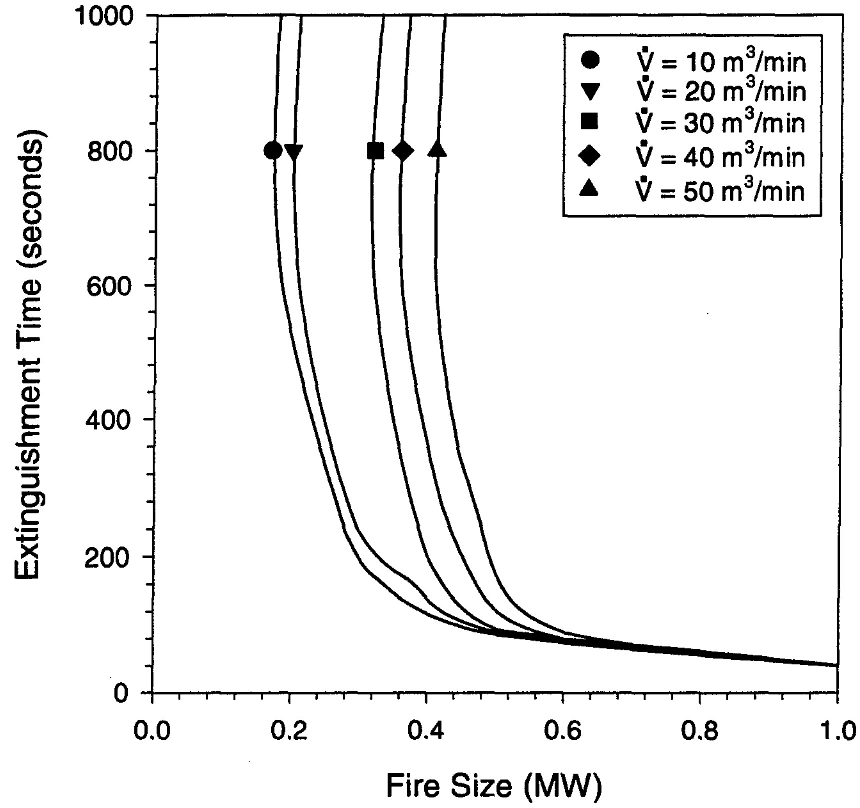


Figure 20. Effects of Forced Ventilation on Extinguishment Time

9.6 Summary

Seventy-nine full-scale fire suppression tests were conducted during this evaluation. These tests consisted of sixty-nine system capabilities tests and ten combustible boundary tests.

The fire suppression capabilities of five commercially available water mist systems (Chemetron, Fike, Grinnell, Fogtec, and the U.S. Navy's water mist system) were evaluated in a 100 m^3 machinery space using three ventilation conditions (closed compartment, a naturally ventilated compartment with a 1.7 m^2 vent opening and a compartment with forced ventilation 25 m^3/min). The five water mist systems were each capable of extinguishing a majority (at least 9 out of 15) of the test fires included in this evaluation. Variations in the system capabilities were observed primarily during the tests conducted with forced ventilation.

The U.S. Navy's water mist system demonstrated superior capabilities throughout this test series. The system typically produced the fastest extinguishment times and was capable of extinguishing two fires (0.5 MW spray and 0.41 m^2 pan, both with forced ventilation) the other four systems could not extinguish.

The steady state extinguishment model developed during a previous investigation [3] was used to analyze and explain the results of these tests. The model was used to predict the critical fire size for the three ventilation conditions included in this evaluation. The critical fire size is defined as the smallest fire that will reduce the oxygen concentration in the space due to consumption of the oxygen by the fire and a dilution of the oxygen with water vapor to the (LOI) of the fuel. These critical fire size predictions helped explain which fires could not be extinguished.

The model was capable of accurately predicting the steady state compartment temperatures and extinguishment times for the spray fire scenarios but had difficulty predicting the results of the pan fire scenarios. Throughout this test series, the pan fires were more difficult to extinguish than spray fires of a given size. This is believed to be the result of a reduction in burning rate caused by the lower oxygen concentrations in the space. If a reduced burning rate (50 percent of the estimated ambient value) is applied to these results, the model predictions become similar to those measured during the tests.

The results of the combustible boundary tests were similar between the three water mist systems and three combustible boundaries. The initiating spray fire used during these tests (250 kW) was one of the more difficult fires to extinguish during the system capabilities evaluation. However, this initiating fire was sufficient to ignite a significant amount of the combustible boundary material. The combustion of the boundary material increased the fire size (high release rate) making them easier to extinguish. As a result, all of the combustible boundary fires were extinguished during this evaluation. In only one test did fire burn through the combustible material. This test was viewed as an anomaly in the data, and should not alter the conclusion. In general, combustible boundaries do not pose a significant challenge to water mist systems.

The final objective of this investigation was to determine if the current system design requirements (primarily duration of protection) can be reduced for water mist systems applied to smaller machinery spaces. This would result in a lighter, less costly system. The results of these tests suggest that the current IMO design requirements can be reduced for smaller machinery spaces. The amount of reduction needs to be based on the size/volume of the protected area as well as on the ventilation conditions in the space. An approach for determining these requirements was also described.

10.0 REFERENCES

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APPENDIX A - INSTRUMENTATION AND CAMERA DETAILS

F.I.R.E.S.

INSTRUMENT LIST & TEST REQUIREMENTS

TEST NAME: WATER MIST/SMALL MACHINERY SPACES			ORIGIN: LOWER AFT STBD CORNER
TEST SERIES: 98WM			TIME FOR EACH TEST: –20 MIN
TOTAL NUMBER OF TESTS: –90			SCAN INTERVAL: 1 SEC
PROJECT NUMBER: 3308.1.98			

CHANNEL						OUTPUT RANGE		
#	SP	RE	ID	INSTRUMENTATION DESCRIPTION	SERIAL NUMBER	ENG. UNIT	LOCATION	REMARKS/NOTES
0			X	Humidity	8292031	0-100% R.H.	Portside, 01 DK	Ambient
1			X	Barometer	123	91-106 kPa	Portside, 01 DK	Ambient
2			X	Wind – Intensity	04401A-1	0-44 m/s	Portside, 02 DK	Ambient
3	X		X	Wind – Direction	04401A-D	0-360E	Portside, 02 DK	Ambient 0E = Bow
4	X		X	TC Reference Junction	TC-1	0-50EC	Portside, 1 DK	
5		41	X	TC	K50FT 1/8 in.	0-800EC	(1.0, 2.5, 0.5)	TC Tree 1
6		41		TC	K50FT 1/8 in.	0-800EC	(1.0, 2.5, 1.0)	TC Tree 1
7		41		TC	K50FT 1/8 in.	0-800EC	(1.0, 2.5, 1.5)	TC Tree 1
8		41		TC	K50FT 1/8 in.	0-800EC	(1.0, 2.5, 2.0)	TC Tree 1
9		41		TC	K50FT 1/8 in.	0-800EC	(1.0, 2.5, 2.5)	TC Tree 1
10		41		TC	K50FT 1/8 in.	0-800EC	(6.0, 2.5, 0.5)	TC Tree 2
11		41		TC	K50FT 1/8 in.	0-800EC	(6.0, 2.5, 1.0)	TC Tree 2
12		41		TC	K50FT 1/8 in.	0-800EC	(6.0, 2.5, 1.5)	TC Tree 2
13		41		TC	K50FT 1/8 in.	0-800EC	(6.0, 2.5, 2.0)	TC Tree 2
14		41		TC	K50FT 1/8 in.	0-800EC	(6.0, 2.5, 2.5)	TC Tree 2
15	X	41		TC	K50FT 1/8 in.	0-800EC	(3.5, 2.5, 2.0)	Fire TC
16	X	41		TC	K50FT 1/8 in.	0-800EC	(6.5, 0.5, 1.0)	Fire TC
17			X	CO Analyzer	41092	0-5%/0-10%	(1.0, 2.5, 1.0)	Gas Tree #1
18			X	CO_2 Analyzer	30606	0-15%/0-25%	(1.0, 2.5, 1.0)	Gas Tree #1
19	X		X	O_2 Analyzer	1001451	0-25%/0-25%	(1.0, 2.5, 1.0)	Gas Tree #1
20				CO Analyzer	41093	0-5%/0-10%	(1.0, 2.5, 2.5)	Gas Tree #1
21				CO_2 Analyzer	31334	0-15%/0-25%	(1.0, 2.5, 2.5)	Gas Tree #1
22	X			O_2 Analyzer	2002910	11-21%/0-25%	(1.0, 2.5, 2.5)	Gas Tree #1
23				CO Analyzer	41094	0-5%/0-10%	(6.0, 2.5, 1.0)	Gas Tree #2

F.I.R.E.S.

INSTRUMENT LIST & TEST REQUIREMENTS

TEST NAME: WATER MIST/SMALL MACHINERY SPACES

TEST SERIES: 98WM

TOTAL NUMBER OF TESTS: ~90

PROJECT NUMBER: 3308.1.98

ORIGIN: LOWER AFT STBD CORNER

TIME FOR EACH TEST: ~20 MIN

SCAN INTERVAL: 1 SEC

CHANNEL						OUTPUT RANGE		
#	SP	RE	ID	INSTRUMENTATION DESCRIPTION	SERIAL NUMBER	ENG. UNIT	LOCATION	REMARKS/NOTES
24				CO_2 Analyzer	31335	0-15%/0-25%	(6.0, 2.5, 1.0)	Gas Tree #2
25	X			O_2 Analyzer	1001638	11-21%/0-25%	(6.0, 2.5, 1.0)	Gas Tree #2
26				CO Analyzer	41347	0-5%/0-10%	(6.0, 2.5, 2.5)	Gas Tree #2
27				CO_2 Analyzer	34056	0-15%/0-25%	(6.0, 2.5, 2.5)	Gas Tree #2
28	X			O_2 Analyzer	1001641	11-21%/0-25%	(6.0, 2.5, 2.5)	Gas Tree #2
29			X	Radiometer	219858	0-50 kW/m^2	(3.5, 2.5, 3.0)	Overhead
30			X	Calorimeter	New	0-50 kW/m^2	(3.5, 2.5, 3.0)	Overhead
31				Radiometer	924853	0-50 kW/m^2	(7.0, 2.5, 1.5)	FWD Blkhd
32				Calorimeter	New	0-50 kW/m^2	(7.0, 2.5, 1.5)	FWD Blkhd
33			X	Pressure Transducer	536826	20,658 kPa	(6.5, 0.5, 2.9)	Exting Syst - Grid
34				Pressure Transducer	536827	20,658 kPa	At Manifold	Exting Syst - Mnfld
35			X	Pressure Transducer	139969	0-1723 kPa	In Fuel Line	LP Fuel Syst
36			X	Pressure Transducer	223787	+/- 1244 Pa	(7.0, 2.5, 1.0)	Comp. Press
37				Velocity Probe	632824		∀ 19 m/s	Vent Flow
38	X		X	Flow Meter	15024	5-227.1 Lpm	Manifold	Water Supply
39	X		X	Flow Meter	258	0-158.8 Lpm	Manifold	By-pass
40				TC Reference Junction	TC 2	0-50EC	In Junction Box	
41			X	Pressure Transducer	780521	0-3735 Pa	(3.5, 2.5, 1.0)	Fuel Pan Regression

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