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WATER MIST PROTECTION REQUIREMENTS FOR VERY LARGE MACHINERY SPACES

FINAL REPORT
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16. Abstract (MAXIMUM 200 WORDS)

This report provides an evaluation of the fire fighting capabilities of water mist fire suppression systems in large (~3000 m^3) machinery spaces. The primary objective of this investigation was to evaluate the applicability of the International Maritime Organization test protocol to larger, Class 3 machinery spaces (>3000 m^3).

Four generic water mist systems produced using off-the-shelf industrial spray nozzles were included in this evaluation. The capabilities of both total protection and zoned total protection systems were identified during this investigation. The zoned systems demonstrated the same extinguishment capabilities as the total protection systems. The systems were evaluated against a series of heptane spray and pan fires ranging in size from 2.5 – 10.0 MW. The fires were located under a 1.0 m horizontal obstruction plate adjacent to a bulkhead similar to the fires conducted in MSC Circular 668.

The capabilities observed for the water mist systems (both zoned and total flooding) in the 3000 m^3 machinery space followed the same trends found throughout literature on water mist. The steady-state extinguishment model developed during previous phases with this investigation showed reasonably good agreement with the results of these tests. The strengths and weaknesses of the IMO test protocol were also identified. The conservative nature of the protocol (due to the high ventilation rates and smaller fire sizes (i.e., 1.0 MW)) will limit the use of water mist in larger machinery spaces. Based on this analysis, it was concluded that it is highly unlikely that any system discharging only water will ever successfully complete the protocol for volumes greater than 2000 m^3.

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EXECUTIVE SUMMARY

In December 1994, the International Maritime Organization (IMO) approved guidelines for alternative arrangements for halon fire extinguishing systems. Since the development of these guidelines, numerous research programs have demonstrated that, if properly designed and tested, water mist fire suppression systems can provide effective protection of Category A machinery spaces with volumes up to 500 m^3. The conclusions developed during these previous investigations also suggest that water mist systems may be inappropriate for larger machinery spaces due to the need for some degree of oxygen depletion to aid in the extinguishment of obstructed fires. To validate these conclusions, a series of full-scale fire suppression tests were conducted to evaluate the capabilities and limitations of water mist systems in large machinery spaces (~3000 m^3).

Four generic water mist systems, produced using off-the-shelf industrial spray nozzles, were included in this evaluation. The capabilities of both total protection and zoned total protection systems were identified during this investigation. Surprisingly, the zoned systems demonstrated the same extinguishment capabilities as the total protection systems. The systems were evaluated against a series of heptane spray and pan fires ranging in size from 2.5 – 10.0 MW. The fires were located under a 1.0 m horizontal obstruction plate adjacent to a bulkhead similar to the fires required by MSC Circular 668, "Interim Test Method for Fire Testing Equivalent Water-Based Fire-Extinguishing Systems for Machinery Spaces of Category A and Cargo Pump-Rooms (IMO, 1996b)." The fires were conducted at two elevations in both ventilated (the doors to the space were left open) and unventilated (closed compartment) machinery spaces.

The capabilities observed for the water mist systems (both zoned and total flooding) in the 3000 m^3 machinery space followed the same trends found throughout literature on water mist. Small fires must be extinguished by direct flame interaction with the mist, while the obstructed fires are extinguished primarily by oxygen depletion (indirect effects). Fires that are extinguished by direct flame interaction are typically extinguished in less than one minute and are relatively unaffected by compartment volume or ventilation conditions. Fires that require some degree of oxygen depletion to aid in extinguishment (obstructed fires) have longer

extinguishment times which have been shown to be a function of fire size to compartment volume ratio (assuming a constant ventilation condition). The extinguishment times for these fires approach infinity as the size of the fire is reduced to the critical value. This critical value/size is primarily a function of the ventilation conditions in the space. These obstructed fires serve as the limiting case.

The steady-state extinguishment model developed during previous phases with this investigation was further validated using the results of these tests. The model assumes that obstructed fires are extinguished through a reduction in oxygen concentration resulting from both the consumption of oxygen by the fire and dilution of the oxygen with water vapor. The predictions made by the model showed reasonably good agreement with the results of these tests. Variations between predicted and measured results were attributed to the lack of a well-mixed environment in the space during extinguishment, which is one of the primary assumptions used by the model.

The strengths and weaknesses of the IMO test protocol were also identified. As currently written, the protocol ensures that water mist systems are designed with the proper nozzle spacing and spray characteristics to have a high probability of extinguishing a wide range of fire sizes in machinery spaces with varying degrees of ventilation. The protocol also ensures that the discharge rate is adequate to provide the required thermal management needed to minimize the damage for the longer extinguishment times that are characteristic of water mist systems for smaller obstructed fires. The conservative nature of the protocol (due to the high ventilation rates and smaller fire sizes (i.e., 1.0 MW)) will limit the use of water mist in larger machinery spaces. Based on this analysis, it was concluded that it is highly unlikely that any system discharging only water will ever successfully complete the protocol for volumes greater than 2000 m^3.

Recommendations were made for improving the IMO test protocol which should broaden the range of machinery space volumes in which water mist systems can be installed. These recommendations include selecting a more representative ventilation condition during testing and scaling the size of the test fires as a function of the volume of the machinery space.

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LIST OF ACRONYMS, ABBREVIATIONS, AND/OR SYMBOLS

AHJ	Authority Having Jurisdiction
FMRC	Factory Mutual Research Corporation
G-MSE-4	Life Saving and Fire Safety Division of Coast Guard Headquarters
HPS	High Pressure System
IMO	International Maritime Organization
IPS	Intermediate Pressure System
LFHPS	Low Flow High Pressure System
LOI	Limiting Oxygen Index
LPS	Low Pressure System
MSC	Maritime Safety Committee

1.0 INTRODUCTION

In December 1994, the International Maritime Organization (IMO) approved guidelines for alternative arrangements for halon fire extinguishing systems (IMO, 1994 and 1996b). 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 of various sizes. Category A machinery spaces contain either internal combustion machinery used for propulsion or power generation or oil-fired boilers and fuel units (SOLAS, 1996). Since the development of these guidelines, numerous research programs (Back et al., 1996, 1997a, 1997b, 1998, 1999a, 1999b, and 1999c) have demonstrated that, if properly designed and tested, water mist fire suppression systems can provide effective protection of Category A machinery spaces with volumes up to 500 m^3. The conclusions developed during these previous investigations also suggest that water mist systems may be inappropriate for larger machinery spaces due to the need for some degree of oxygen depletion to aid in the extinguishment of obstructed fires.

The goal of this effort was to determine if water mist fire suppression systems can provide adequate protection for larger machinery spaces (3000 m^3 and above). This work was conducted under a research and development project for the Life Saving and Fire Safety Division (G-MSE-4) of the United States Coast Guard.

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 larger machinery spaces having a range of ventilation conditions.

3.0 TECHNICAL APPROACH

The IMO segregates Category A machinery spaces into three classes: Class 1 – less than 500 m³ net volume, Class 2 – greater than 500 m³ but less than 3000 m³, and Class 3 – greater than 3000 m³ net volume. Class 1 spaces are typically auxiliary engine rooms or main machinery spaces on small vessels. Class 2 spaces are typically main machinery spaces on medium size ships such as passenger ferries. Class 3 are main machinery spaces on large ships such as oil tankers, container ships and cruise liners. Based on this information, A machinery space with a minimum volume of 3000 m³ was required for this investigation.

The #2 Cargo Hold on the U.S. Coast Guard's test vessel met this requirement. The #2 Hold spans three decks vertically and is just over 3000 m³ in volume. Only slight modifications were required to prepare the space for testing. As originally constructed, the openings between the three decks consisted of a 5.5 m x 10.0 m cargo hatch which was equivalent to only 15 percent of the deck area. Additional openings in the decks were required to allow the mist and vitiated gases to flow freely throughout the compartment. Additional openings were added aft in the compartment to increase the opening size to 25 percent of the deck area. A larger opening area was originally desired but the results of these tests showed that in a majority of the tests, the gases in the compartment became fairly well-mixed even with an opening area of only 25 percent.

The gaseous halon alternatives are designed and tested with the intent that the machinery space is secured (i.e., doors closed and ventilation systems shut down) prior to discharge. The IMO test protocol for water mist requires that the systems be evaluated in well-ventilated compartments. This has been a point of controversy for years. As a result of these issues/requirements, it was decided to conduct tests in both an open/ventilated and closed compartment.

For Class 1 and 2 machinery spaces, the IMO tests are to be conducted in a well-ventilated compartment (i.e., containing a 2 m x 2 m vent opening). For Class 3 spaces, the tests are to be conducted basically without an enclosure (i.e., no walls or ceiling in the middle of a large test hall without any restrictions in air supply for the test fires). For this test series, the

ventilation conditions were dictated primarily by the geometry of the space. The ventilation scheme consisted of opening two standard shipboard doors high in the space (adjacent to the forward bulkhead) and one standard door low in the space (aft stair tower). The resulting ventilation conditions were significantly greater than those required for Class 1 and 2 machinery spaces but still allowed some degree of oxygen depletion. A more detailed description and analysis of these ventilation conditions is found in the modeling section of this report (Section 10.3).

The mechanisms of extinguishment associated with water mist can be broken down into two basic groups: direct and indirect flame interaction. Direct flame interaction occurs when an adequate amount of mist reaches the fire to extinguish the fire primarily by the flame cooling effects of the mist/water droplets. Fires that are extinguished by direct effects are typically unobstructed and are unaffected by the volume of the compartment and the ventilation conditions in the space. Indirect effects include global oxygen depletion and become the primary mechanism of extinguishment when only a limited amount of mist reaches the fire (i.e., obstructed fires). The ability of mist to diffuse into all areas in the space, such as a gaseous agent, is significantly limited in the range of drop sizes produced by current commercially available hardware. These obstructed fires that require some degree of oxygen depletion to aid in extinguishment serve as the limiting case.

The obstructed spray fires in the IMO test protocol have been shown to be extinguished primarily by indirect effects (Back et al., 1998, 1999a, and 1999b). These obstructed fires have been selected to serve as the basis for this evaluation.

The selected fires consisted of three spray fires (2.5, 5.0 and 10.0 MW) and one pan fire (2.0 m^2 (estimated HRR 7.5 MW at ambient conditions (Babrauskas, 1988))). The fires were located under a 1.0 m horizontal obstruction extending from a vertical bulkhead similar to the obstructed fires in the MSC Circular 668. The obstructions were constructed of sheet steel and angle iron. The fire sizes were selected based on the extinguishment time relations developed previously (Back et al., 2000). Based on this relation, it appeared that most systems would be capable of extinguishing the 5.0 MW and 10.0 MW spray fires, but should have trouble

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extinguishing the 2.5 MW spray fire and the 2.0 m^2 pan fire in under 15 minutes (the required IMO extinguishment time).

In selecting the water mist systems, it was originally intended to allow a limited number of commercially available water mist system manufacturers to participate in this test series. Due to an overwhelming response of manufacturers that wished to participate, the commercial systems were abandoned for generic systems produced using off-the-shelf industrial spray nozzles. Time constraints would not allow all of the commercial systems to be fully evaluated. There was also the slight concern that the limited open areas in the compartment decks would skew the results and give an inaccurate depiction of the capabilities/limitation of a given system.

The four generic water mist systems selected for this evaluation were produced using off-the-shelf industrial spray nozzles manufactured by either Bete Fog Nozzle Inc. or Spraying Systems Co. The systems covered the range of single fluid technologies including low, intermediate and high pressure systems. All four of these systems have demonstrated adequate capabilities against Class B hazards during a previous U.S. Coast Guard investigation (Back et al., 1999a).

Two water mist system design approaches were also included in this evaluation: a total protection system and a zoned system. The total protection system was designed to uniformly discharge mist throughout the space as tested in the previous investigations (Back et al., 1998, 1999a, and 1999b) and required by MSC 668 (IMO, 1994). The zoned system was designed to discharge mist only in the area around the fire. Previous studies (Back et al., 1999a) have shown that zoned systems that entrain the vitiated gasses in the upper layer and produce localized areas of oxygen depletion around the fire have greater extinguishment capabilities than standard total protection systems. The evaluation of the zoned system was supported by the lack of data on zoned systems as well as the potential for reducing the cost and impact of the system on the ship.

The extinguishment model developed and validated during three previous phases of this investigation (Back et al., 1998, 1999a, and 1999b) was again used to analyze the results of these tests. The model was originally developed to provide scaling information applicable to

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designing and approving systems for machinery spaces having a wide range of volumes and ventilation conditions. The predictions made by the model have been in agreement with actual test data for machinery spaces with volumes up to 500 m^3, but to this point had not yet been compared to test data for larger spaces. The model was also used to demonstrate the capabilities of water mist as a function of compartment volume and to evaluate the applicability of the IMO test protocol to larger machinery spaces.

4.0   TEST COMPARTMENT

The tests were conducted in the #2 Cargo Hold 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 volume of the space was approximately 3000 m^3 with nominal dimensions of 22.0 m x 16.5 m x 8.25 m as shown in Figure 1. The space is trapezoidal in shape with the length of the forward bulkhead approximately 5.5 m shorter than the aft bulkhead. A plan view of the space is shown in Figure 2. The space was bounded horizontally by Frames 46 and 71 and vertically by the fourth and the main decks. The mist and vitiated gases traveled vertically in the space through openings in the second and third decks. The ship was originally equipped with a 5.5 m x 10.0 m hatch forward in the compartment. This hatch was only 15 percent of the deck area. This value was increased to 25 percent of the deck area ($\sim$ 90 m^2) through additional openings cut into the decks in the aft portion of the compartment.

The space was naturally ventilated during many of the tests using the stair towers located in the compartment (Figure 3). Air was drawn naturally into the space through a standard shipboard door (0.76 m x 2.0 m) located in the aft stair well on the fourth deck. The exhaust gases exited the space through two standard shipboard doors located in the forward stair towers on the main deck. This opening configuration produced an estimated ventilation factor ($A\sqrt{H}$) that was much greater than that used during the 500 m^3 machinery space tests. Tests were also conducted with all of the doors in the compartment closed during the test.

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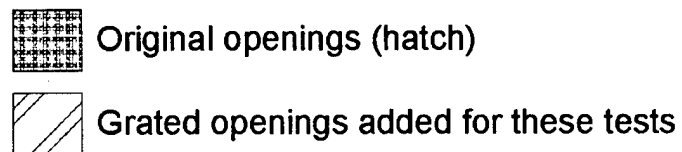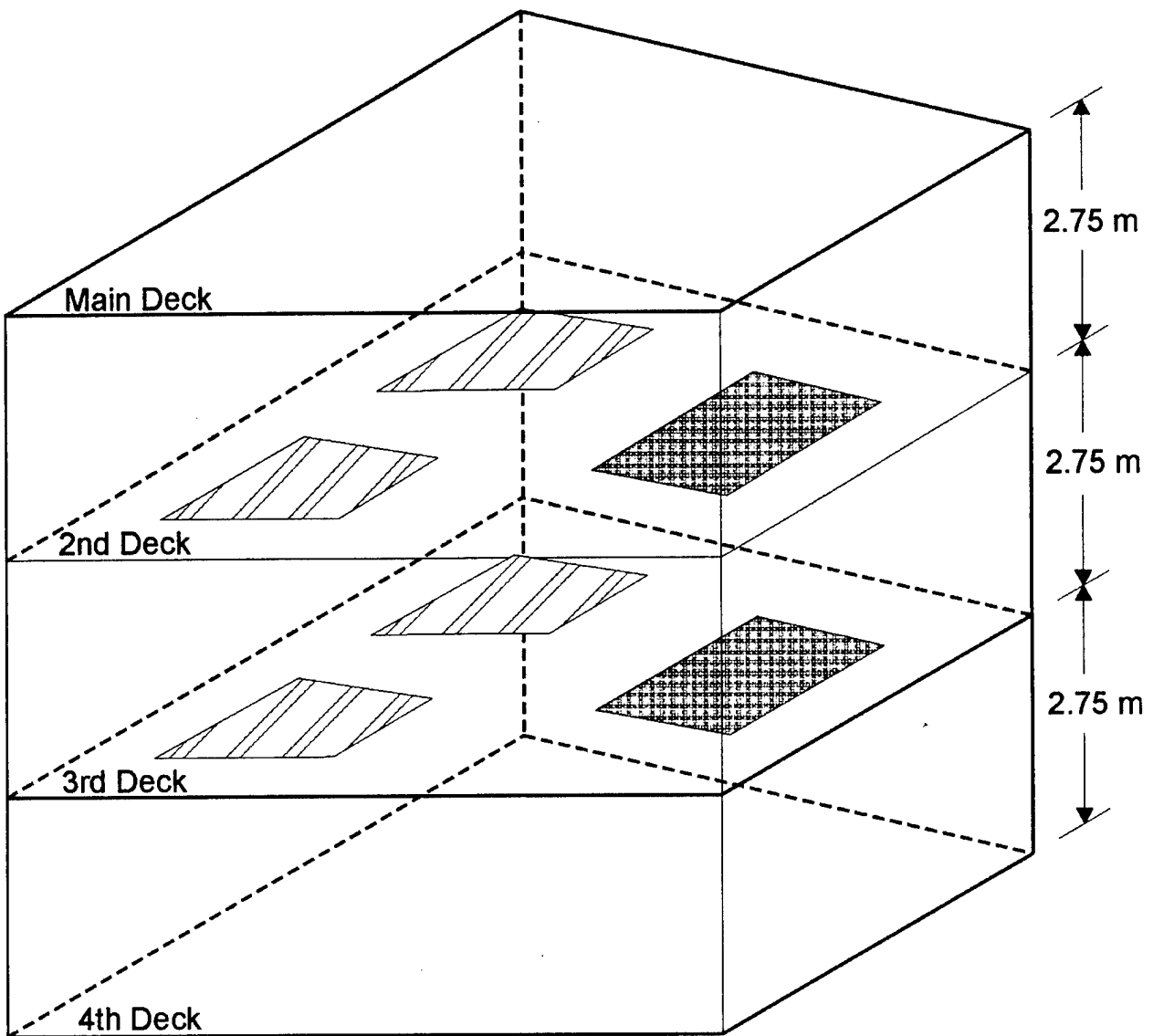
Figure 1. Test compartment – isometric view.
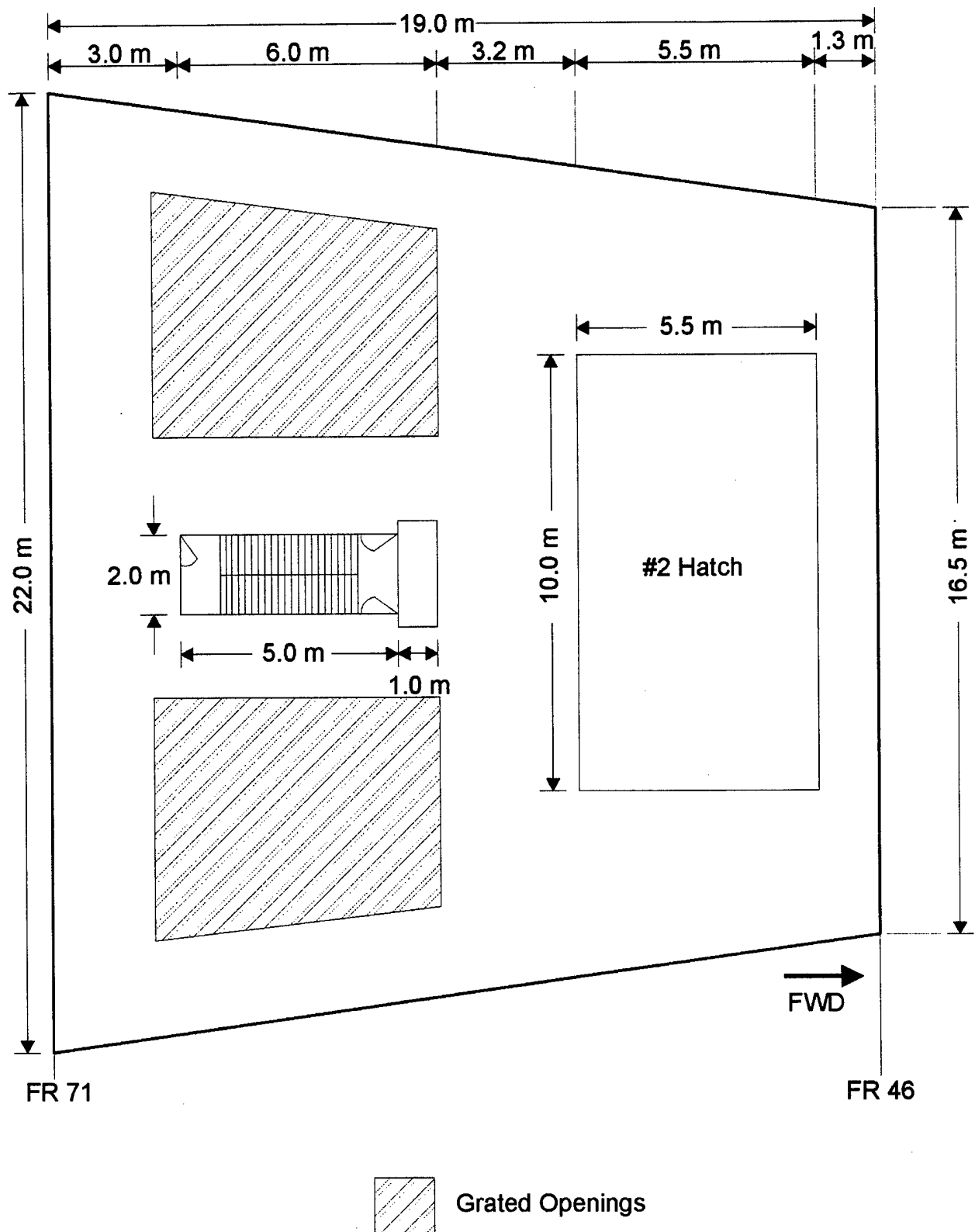
Figure 2. Test compartment – plan view.

Legend (with grated openings hatch pattern): Grated Openings

Dimensions shown:
- Top: 19.0 m total, with segments 3.0 m, 6.0 m, 3.2 m, 5.5 m, 1.3 m
- Left side: 22.0 m
- Right side: 16.5 m
- #2 Hatch: 5.5 m wide, 10.0 m tall
- Center item: 2.0 m tall, 5.0 m wide, 1.0 m
- FR 71 (bottom left), FR 46 (bottom right)
- FWD (arrow pointing right)

Main Deck

2nd Deck

3rd Deck

4th Deck
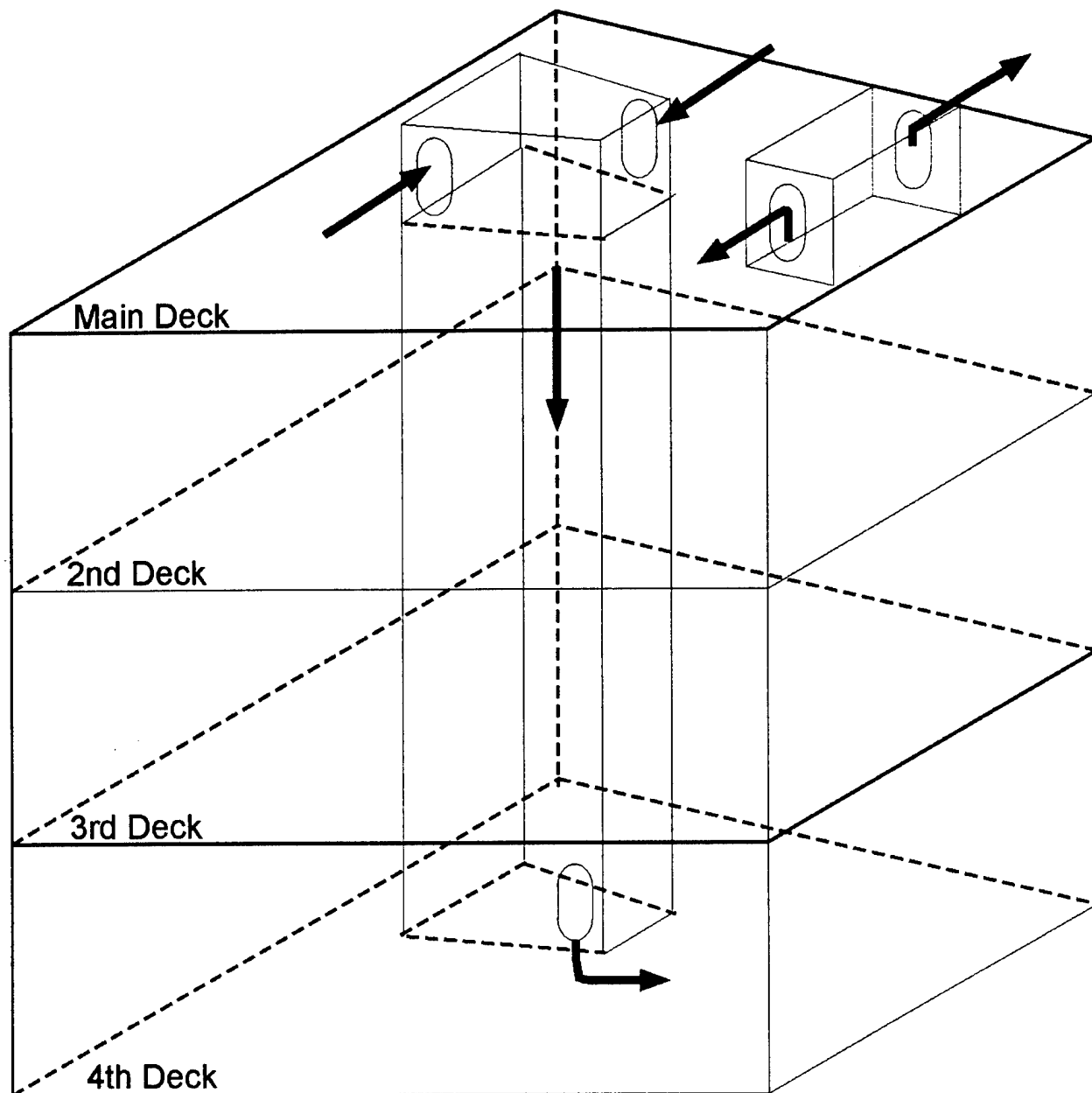
→ Flow Pattern

⬭ 0.76 m x 2.0 m Typ.

Figure 3. Compartment ventilation.

5.0   WATER MIST SYSTEMS

5.1   Design Approaches

Two design approaches were included in this evaluation: total protection and zoned total protection. The first approach consisted of a total protection water mist system designed to discharge mist uniformly throughout the compartment. This system consisted of uniformly spaced nozzles located at the overhead of each deck level. The nozzles were installed with a nominal 3.0 m nozzle spacing producing a six by six nozzle grid as shown in Figure 4. The total protection systems included in this evaluation produced flow rates per unit volume ranging from $0.15 - 0.50$ Lpm/m^3.

The second approach consisted of a zoned system designed to discharge the mist in the area around the fire location. This approach consisted of a single level of uniformly spaced nozzles installed directly below the hatch cover on the main deck. The nozzles were installed with a nominal 1.5 m nozzle spacing producing a five by six nozzle grid as shown in Figure 5. The zoned systems included in this evaluation produced flow rates per unit volume ranging from $0.15 - 0.50$ Lpm/m^3. The volume (450 m^3) used in this calculation is the volume between the fourth and main decks directly below the hatch cover (10.0 m x 5.5 m x 8.25 m).

5.2   Pipe Networks

Both systems were constructed primarily of 2.5 cm, stainless steel tubing with a 2.1 mm wall thickness and connected together with stainless steel compression fittings. Stainless steel tubing and fittings were used to prevent rust and/or corrosion from developing inside the pipe network. This system design has a working pressure of 200 bar and a burst pressure of 800 bar.

The total protection system consisted of three levels of nozzles located at the overhead of each of the three decks (second, third, and fourth). Each grid consisted of 36 nozzles (6 x 6) installed with a nominal 3.0 m spacing as shown in Figure 4.

3.0 m

0.3 m

3.0 m
Typ.

1.0 m

1.0 m 1.0 m

3.0 m

3.0 m

5.0 cm
Supply

2.5 cm
Typ.

4.0 m

3.0 m

3.0 m

FWD
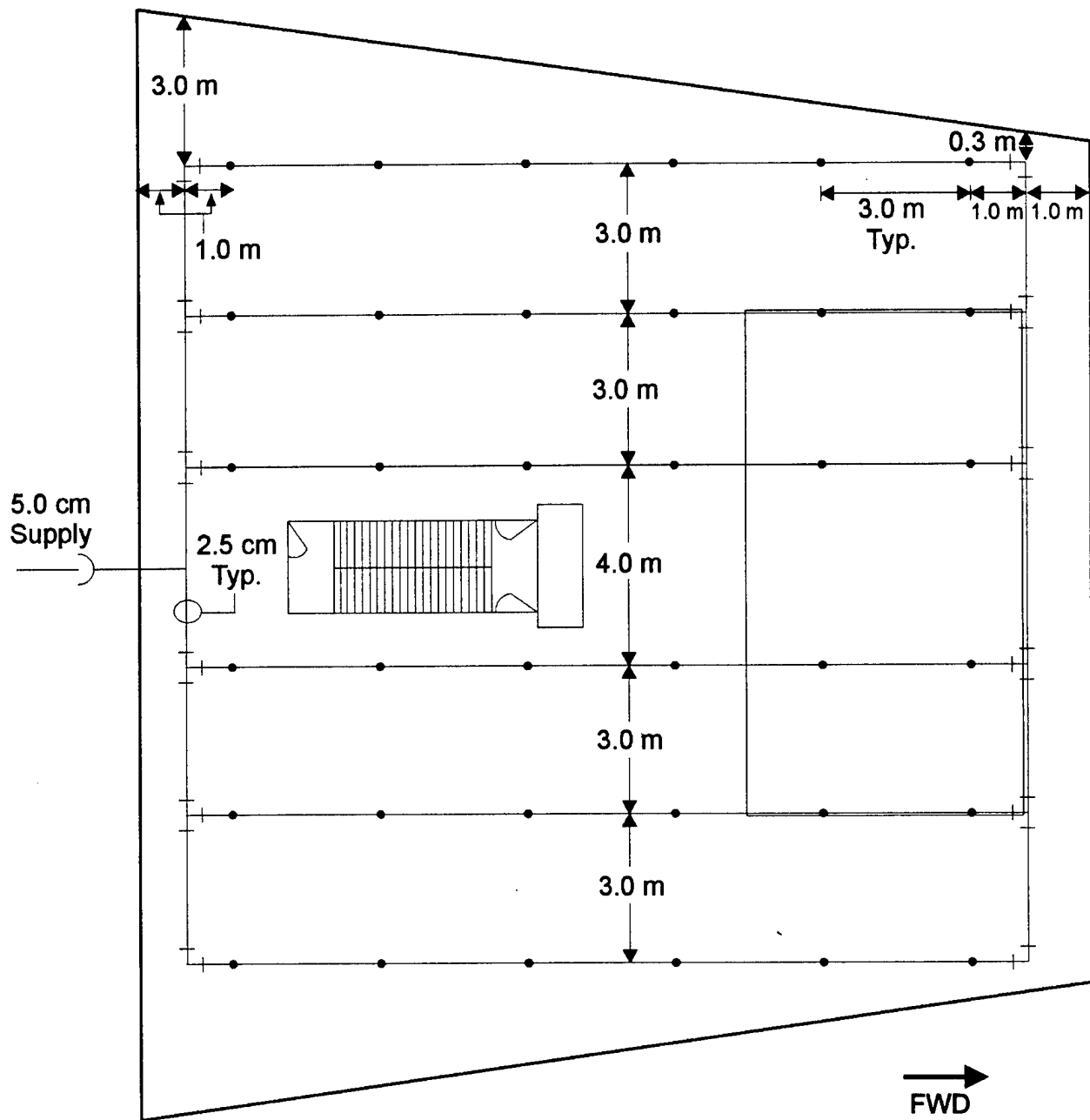
- Nozzle Locations

(P) Pressure Transducer

Figure 4. Nozzle locations – total protection system.

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Figure 5. Nozzle locations – zoned system.

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The zoned system consisted of one level of nozzles installed at the overhead of the second deck as shown in Figure 5. The nozzle grid consisted of 30 nozzles (5 x 6) installed with a nominal 1.5 m spacing directly below the hatch cover on the main deck.

5.3 Water Mist Systems/Nozzles

Four generic water mist systems were included in this evaluation. The systems were produced using off-the-shelf industrial spray nozzles manufactured by Bete Fog Nozzle Inc. and Spraying Systems Co. The candidate systems included two high pressure (normal and low flow), an intermediate pressure, and a low pressure single fluid system. All four of these systems have demonstrated adequate capabilities against Class B hazards during a previous U.S. Coast Guard investigation (Back et al., 1999a). A brief description of each system is given in the following sections.

5.3.1 Generic Low Pressure System (LPS)

LPS is a low pressure single fluid system produced using Spraying Systems, Co. ¼ GG10 nozzles. The system was evaluated with a nozzle pressure of 5 bar. The ¼ GG10 has a nominal K-factor of 4.3 Lpm/bar$^{1/2}$ producing a flow rate of 9.5 Lpm per nozzle. The ¼ GG10 at 5 bar produces a Class 2-3 spray as defined by NFPA (NFPA 750, 1996).

5.3.2 Generic Intermediate Pressure System (IPS)

IPS is an intermediate pressure single fluid system produced using model TF6 nozzles manufactured by Bete Fog Nozzle Inc. The system was evaluated with a nozzle pressure of 21 bar. The TF6 has a nominal K-factor of 3.1 Lpm/bar$^{1/2}$ producing a flow rate of 14.2 Lpm per nozzle. The TF6 at 21 bar produces a Class 2 spray as defined by NFPA (NFPA 750, 1996).

5.3.3 Generic High Pressure System (HPS)

HPS is a high pressure single fluid system produced using Spraying Systems, Co. ¼ LN26 nozzles. The system was evaluated with a nozzle pressure of 70 bar. The ¼ LN26 has a nominal K-factor of 1.0 Lpm/bar$^{1/2}$ producing a flow rate of 8.5 Lpm per. At 70 bar, the nozzle produces a Class 1-2 spray as defined by NFPA (NFPA 750, 1996).

5.3.4 Generic Low Flow High Pressure System (LFHPS)

LFHPS is a low flow high pressure single fluid system produced using Spraying Systems Co. ¼ LN12 nozzles. The system was evaluated with a nozzle pressure of 70 bar. The ¼ LN12 has a nominal K-factor of 0.5 $Lpm/bar^{1/2}$ producing a flow rate of 4.2 Lpm per nozzle. At 70 bar, the nozzle produces a Class 1 spray as defined by NFPA (NFPA 750, 1996).

5.4 Pump System

A Gardner Denver Model PAH-310HP Triplex Mud Pump was used to provide water to the various water mist systems included in this evaluation (Figure 6). The pump system had a capacity of 1350 Lpm at 90 bar. The pump system was connected to a manifold that was equipped with a manually controlled bypass line to allow flexibility in setting the operating pressures for the various systems. The manifold was constructed of nominal two-inch pipe fittings and valves. This configuration produced a system that can provide the maximum flow rate (1350 Lpm) over the range of pressures from 0-90 bar. The Gardner Denver pump was supplied with water (Mobile Bay water) using the permanently installed fire pump on the ship via a nominal 63 mm fire hose connected between the fire pump and the mud pump.

6.0 FIRE SCENARIOS

Three fuel spray fires (2.5, 5.0, and 10.0 MW) and one pan fire (2.0 m^2) were included in this evaluation. All fires were produced using heptane as the fuel. Heptane is a pure distillate fuel with a nominal flashpoint of –4 °C and a heat of combustion (ΔH_c) of 44.6 MJ/kg (Babrauskas, 1988). The fires were located under a 1.0 m horizontal obstruction extending from a vertical bulkhead similar to the obstructed fires in MSC Circular 668. The fires were conducted on the second and fourth decks as shown in Figure 7. The obstruction plates were installed approximately 1.5 m above the decks. The fuel spray nozzles were installed 0.5 m below the obstruction plate spraying horizontally (Figure 7). The pan fires were located on the decks directly below the center of the plates.

Figure 6. Pumping system.

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Fuel Nozzle

Fuel Pan

1.0 m
Typ.

Ⓕ

2.0 m
Typ.

FWD

Ⓕ - Fire Location

Plan View

Main Deck

2nd Deck

3rd Deck

4th Deck
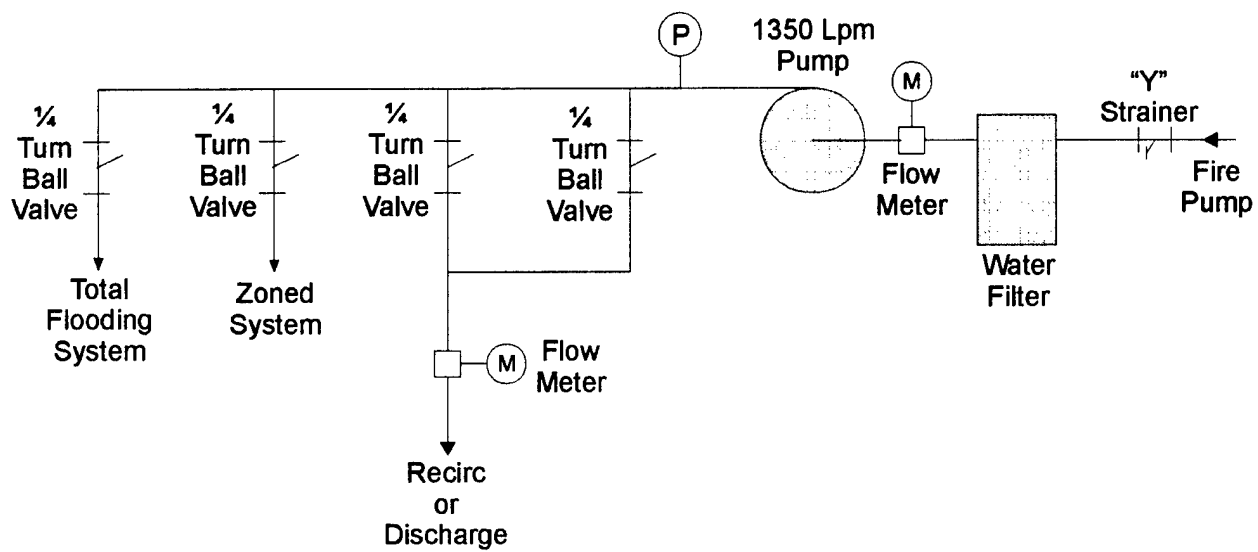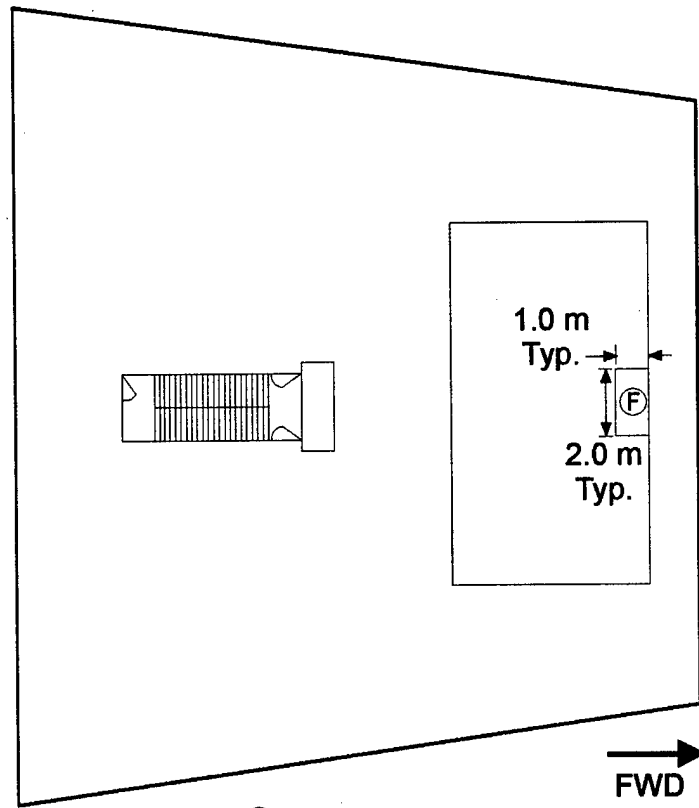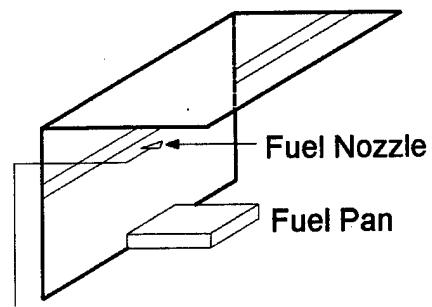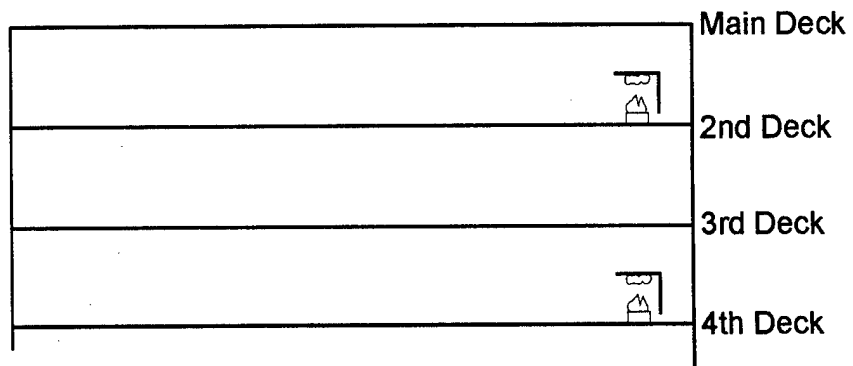
Elevation View

Figure 7. Fire locations.

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6.1   Fuel Spray Fire Scenarios

The spray fires were produced using P series nozzles manufactured by Bete Fog Nozzle Inc. and the pressurized fuel system shown in Figure 8. Two nozzle sizes (P80 and P120) were used during these tests. 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, the published K-factors of the nozzles and the heat of combustion (ΔH_c) of heptane. The spray fires were ignited by placing a small heptane pan fire (spray cup) directly in front of the fuel nozzle.

Table 1. Spray fire sizes.

NOZZLE MODEL	PRESSURE (bar)	VOLUMETRIC FLOW RATE Lpm	MASS FLOW RATE kg/s	HEAT RELEASE RATES (MW)
P80	3.5	4.8	.56	2.5
P120	3.5	10.0	.117	5.2
2 - P120's	3.5	20.0	.233	10.4

6.2   Pan Fire Scenarios

A 2.0 m^2 pan fire was also included in this evaluation. It was originally intended to also include a 1.0 m^2 pan, but the smaller pan proved to be too challenging for the systems included in this investigation. This was based on the candidate systems' inability to extinguish the 2.0 m^2 pan fire. The 2.0 m^2 pan was constructed of 3.2 mm steel plate with welded seams and 15.0 cm sides. During these tests, the pan contained a 2.5 cm water substrate and 7.5 cm of fuel. To produce this fuel depth the pan was fueled with 150 L of heptane. The theoretical heat release rate of this fire is 7.5 MW (Babrauskas, 1988). The actual heat release rate of the fire varied during the test and was estimated based on the fuel regression rate (as determined by a pressure

45.5 kg
(100 lb)
Liquid
Nitrogen
Cylinder

4-310 L
(80 gal)
Fuel
Storage
Tanks

¼
Turn
Ball
Valve

1.2 cm
(0.5 in)
Steel
Tubing

4-310 L
(80 gal)
Fuel
Storage
Tank

45.5 kg
(100 lb)
Liquid
Nitrogen
Cylinder

¼
Turn
Ball
Valve

1.2 cm
(0.5 in)
Steel
Tubing

Spray Fire

Spray Fire
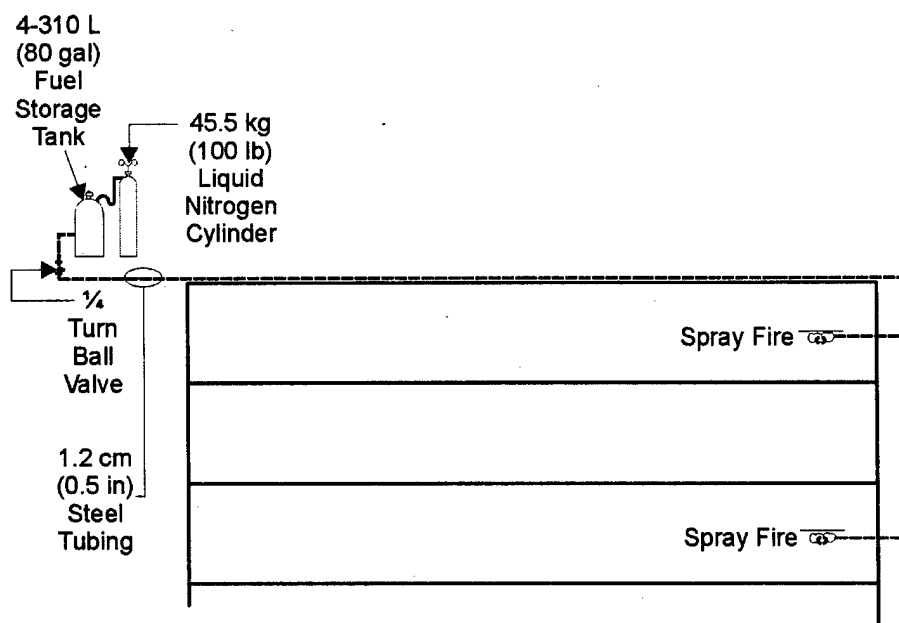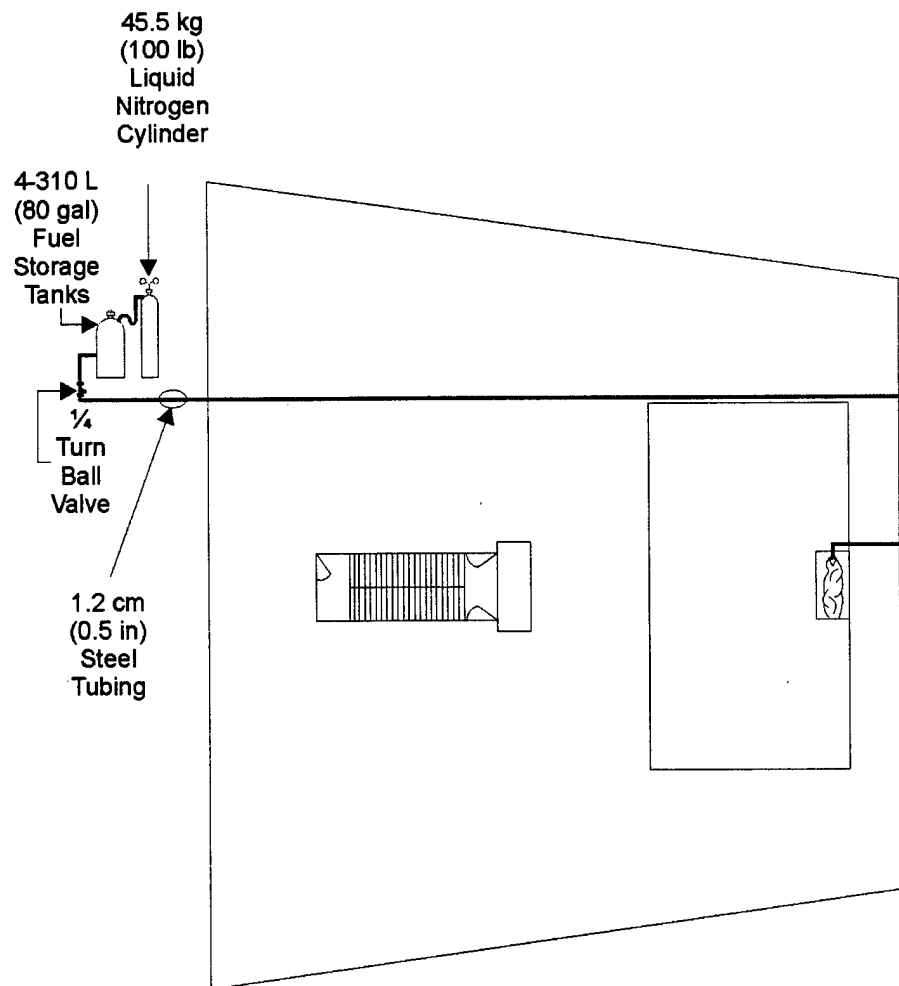
Figure 8. Pressurized fuel system.

transducer installed in the bottom of the pan), the area of the pan, and the heat of combustion of the fuel (ΔH_c).

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 temperature; fire/flame temperature (to note extinguishment time); radiant and total heat flux; compartment pressure; and oxygen, carbon dioxide, and carbon monoxide gas concentrations as shown in Figure 9. Measurements were taken at a rate of one scan per second. A channel listing and the specifics on each instrument are found in Appendix A. The locations are measured from the lower aft port corner of the space. A more detailed description of the instrumentation scheme is included in the following paragraphs.

7.1.1 Temperature Measurements

Two thermocouple trees were used to measure the gas temperatures in the compartment. Each tree consisted of nine thermocouples positioned the following heights above the lower (fourth) deck: 0.5, 1.4, 2.3, 3.2, 4.1, 5.0, 5.9, 6.8, and 7.7 m. The trees were located on the starboard side of the compartment 4.0 m from the centerline of the space. The forward tree was located 5.0 m aft of the forward bulkhead. The aft tree was located 2.0 m forward of the aft bulkhead. Inconel sheathed type K thermocouples (3.2 mm diameter (Omega Model KMQIN-125G-600)) were used for this application.

7.1.2 Gas Concentration Measurements

Carbon monoxide, carbon dioxide, and oxygen concentrations were sampled at two locations and three elevations in the compartment. These concentrations measured 3.5 m starboard of the center line of the space adjacent to the thermocouple trees. These measurements

Figure 9. Instrumentation.

were made at the following heights above the lower deck: 1.4, 4.1, and 6.8 m. MSA Lira 3000 analyzers with a full-scale range of 10 percent by volume were used to measure the carbon monoxide concentration. MSA Lira 303 analyzers with a full-scale range of 25 percent by volume were used to measure the carbon dioxide concentration. Rosemont 755 analyzers with a full-scale range of 25 percent by volume were used to measure the oxygen concentration.

The gas samples were pulled through 9.5 mm stainless steel tubing and a Drierite packed filter using a vacuum sampling pump at a flow rate of 1.0 Lpm, resulting in a 10 second transport delay.

7.1.3   Heat Flux Measurements

Both radiant and total heat flux measurements were recorded at one location and three elevations in the compartment. Pairs of transducers (radiant and total heat flux) were installed on the forward bulkhead of the aft stair tower. The transducers were installed three heights above the lower deck (1.4, 4.1, and 6.8 m). Schmidt Boelter transducers manufactured by Medtherm Co. having a full-scale range of 0-50 kW/m^2 were used for this application. The radiometers were equipped with 150E sapphire windows. Both the radiometers and total heat flux transducers were calibrated to NIST standards and had a calibration accuracy of $\pm$ 3%.

7.1.4   Compartment Pressure Measurements

The compartment pressures were measured 2.5 m starboard of the centerline of the space on the aft bulkhead at three heights above the lower deck (1.4, 4.1, and 6.8 m). Setra Model 264 pressure transducers with a full-scale range of $\pm$ 2.48 kPa were used for this application. These instruments had an accuracy of 0.01% of the full-scale range.

7.2   Water Mist System Instrumentation

The water mist system was instrumented to provide the system operating pressures and the discharge rate of the system. The locations of these instruments were shown in Figures 4, 5 and 6.

7.2.1 Pressure Measurements

System pressures were measured at four locations: at the pump discharge and at the most hydraulically remote nozzle on each of the three decks. Setra Model 280E pressure transducers were used for this application. These transducers had a range of 0-150 bar with an accuracy of 0.01% full-scale.

7.2.2 Water Flow Rate Measurements

The flow rate of the water mist system was measured using two Flow Technologies Inc. paddle wheel type flow meters. The flow meters were installed just upstream of the pump inlet and in the bypass line. Each flow meter had a full-scale range of 0-1900 Lpm and an accuracy of 1.0% of the measured value.

7.3 Fire Instrumentation

The fires were instrumented to note extinguishment and to 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 (Omega Model KMQIN-1256-600)) were used for this application.

7.3.2 Fire Oxygen Concentration

An oxygen sampling probe was located adjacent to the base of the fire to determine the oxygen concentration at this location during extinguishment. A Rosemont 755 analyzer with a full-scale range of 25 percent by volume was used to measure the oxygen concentration at this location.

7.3.3 Heat Release Rate Measurements and Estimations

7.3.3.1 Spray Fires

The nozzle pressure was used to estimate 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 combustion of the fuel. This approach assumes that all of the fuel is consumed as well as a 100 percent combustion efficiency. The fuel nozzle pressure for these spray fires was measured approximately 6 m upstream of the nozzle. The pressure was measured using a Setra Model 205-2 transducer with a range of 1.7 MPa and an accuracy of 0.01% full-scale.

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 Setra Model 264 pressure transducer installed in the bottom of each pan. This pressure transducer had a range of 0-1380 Pa and an accuracy of 0.01% full-scale.

7.4   Video Equipment

Two video cameras were used during each test. These two video cameras, one standard, and one infrared (IR), were movable and located inside the compartment adjacent to the fire location. The IR camera malfunctioned early into the test series and provided little information during the remainder of the tests. A microphone was installed in the center of the space to provide the audio for the two video cameras.

8.0   TEST PROCEDURES

The tests were initiated from the control room located on the second deck between Frames 135 and 145. Prior to the start of the test, the spray cups and/or pans were fueled (where applicable), 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 fire ignition sequence began, and the compartment was cleared of test personnel. The ignition sequence for pan fires consisted of a fire fighter dressed in protective clothing igniting the fires using a torch installed on a 3 m pole. Spray fires were initiated remotely by activation of a fuel supply valve on the pressurized fuel system. The fires were allowed to freeburn for one minute prior to mist system activation. The test continued until the fire was extinguished or until 15 minutes after discharge, at which point the mist system was secured. On completion of the test, the space was ventilated by opening the cargo hatch on the main deck to cool the compartment and to remove the remaining products of combustion. The compartment was also cooled using a 38 mm hoseline as necessary.

9.0   RESULTS

Forty-two full-scale fire suppression tests were conducted during this evaluation. Twenty of these tests were conducted using total protection system while 22 tests were conducted using zoned systems. The results of these tests are shown in Table 2.

Shown in Table 2 are the test parameters, fire extinguishment times, steady-state compartment temperatures and steady-state oxygen concentrations. The extinguishment times were determined using the thermocouples that were positioned in the flame. The steady-state compartment temperatures are the average of the 18 air thermocouples installed in the space 30 seconds prior to extinguishment. The steady-state oxygen concentrations (dry) are the average of the 6 oxygen concentrations measured in the space 30 seconds prior to extinguishment.

The systems were all capable of extinguishing the larger spray fires (5.0 MW and 10.0 MW) in the closed machinery space independent of the system design/approach. The addition of ventilation during the 10.0 MW spray fire tests typically doubled the extinguishment times and resulted in no extinguishment in one test (Test #10). The smaller spray fire (2.5 MW) and the 2.0 m^2 pan fire provided a significant challenge for the water mist systems/designs included in this evaluation. Only the zoned HPS was capable of extinguishing these fires. The specific test results will be discussed in the subsequent sections of this report.

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Table 2. Test results.

Test #	System	Design	Fire	Location	Vent	Extinguishment Time min:sec	Steady State	
							Temp. °C	O$_2$ Conc. % (dry)
1	LFHPS	Total	10 MW	2nd Deck	Closed	8:00	85	14.3
2	LFHPS	Total	5 MW	2nd Deck	Closed	13:15	70	15.0
3	LFHPS	Total	10 MW	4th Deck	Closed	4:00	75	15.0
4	LFHPS	Total	5 MW	4th Deck	Closed	7:40	65	15.3
5	LFHPS	Total	10 MW	2nd Deck	Open	NO	63	15.5
6	LFHPS	Total	10 MW	4th Deck	Open	9:20	60	15.5
7	LFHPS	Zoned	10 MW	4th Deck	Closed	Aborted	--	--
8	LPS	Zoned	10 MW	4th Deck	Closed	4:35	76	13.0
9	LPS	Zoned	5 MW	4th Deck	Closed	10:30	70	12.0
10	LPS	Zoned	10 MW	4th Deck	Open	NO	80	11.0
11	LPS	Zoned	10 MW	2nd Deck	Closed	3:00	67	16.5
12	LPS	Zoned	5 MW	2nd Deck	Closed	5:30	64	17.5
13	LPS	Zoned	10 MW	2nd Deck	Open	6:15	62	17.4
14	IPS	Zoned	10 MW	2nd Deck	Closed	2:00	47	18.5
15	IPS	Zoned	5 MW	2nd Deck	Closed	4:15	47	19.0
16	IPS	Zoned	10 MW	2nd Deck	Open	3:30	43	19.0
17	IPS	Zoned	10 MW	4th Deck	Closed	5:30	68	14.0
18	IPS	Zoned	5 MW	4th Deck	Closed	5:50	62	15.8
19	IPS	Zoned	10 MW	4th Deck	Open	13:00	70	11.5
20	HPS	Zoned	10 MW	4th Deck	Closed	3:45	68	15.5
21	HPS	Zoned	5 MW	4th Deck	Closed	3:45	62	16.5
22	HPS	Zoned	10 MW	4th Deck	Open	5:40	70	15.3
23	HPS	Zoned	2.5 MW	4th Deck	Closed	9:00	62	16.5
24	HPS	Zoned	2 m^2	4th Deck	Closed	9:45	56	17.0
25	HPS	Zoned	2 m^2	4th Deck	Closed	9:25	56	17.0
26	HPS	Zoned	10 MW	2nd Deck	Closed	3:40	68	17.0
27	LPS	Total	10 MW	2nd Deck	Closed	8:00	73	13.0
28	LPS	Total	10 MW	4th Deck	Closed	6:45	70	14.2
29	IPS	Total	10 MW	4th Deck	Closed	5:30	59	15.3
30	IPS	Total	5 MW	4th Deck	Closed	8:10	60	15.0
31	IPS	Total	5 MW	4th Deck	Closed	8:45	55	15.3
32	IPS	Total	10 MW	4th Deck	Open	7:10	55	15.5
33	IPS	Total	2.5 MW	4th Deck	Closed	NO	45	15.0
34	IPS	Total	2 m^2	4th Deck	Closed	NO	45	15.0
35	HPS	Total	2 m^2	4th Deck	Closed	NO	58	16.7
36	HPS	Total	10 MW	4th Deck	Closed	4:30	75	15.6
37	HPS	Total	10 MW	4th Deck	Closed	4:00	76	15.0
38	HPS	Total	10 MW	4th Deck	Closed	6:00	75	14.5
39	HPS	Total	5 MW	4th Deck	Closed	6:00	70	16.0
40	HPS	Total	10 MW	4th Deck	Open	14:15	70	15.5
41	LPS	Total	5 MW	4th Deck	Closed	9:00	70	14.8
42	LPS	Total	10 MW	4th Deck	Open	9:30	80	15.5

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9.1   Total Protection System Results

Only a limited number of tests were conducted using the total protection systems with the fires located high in the space. This was due to the location of the fire with respect to the water mist nozzles. The nozzle grid installed in the overhead of the second deck was positioned below the stiffeners around the hatch. As a result, the nozzles were only installed approximately 2 m above the deck. With the fire located in the center between four nozzles at a height of 1.5 m above the deck, the flames from the fire extended into the void area between the nozzles and the cargo hatch almost completely unabated by the water mist. The low concentration mist in conjunction with the lack of mixing produced in this area allowed the fire to burn almost completely unabated. As a result, only a limited number of fires were conducted high in the space.

When a direct comparison was available, the low fires were extinguished faster than the fires conducted high in the space. This was attributed to better mixing (higher velocities) and higher mist concentrations at the fire location. The mist concentrations were much higher at lower elevations in the space (based on visual observations) due to the fallout of the mist (gravity).

Independent of the fire location, the extinguishment times, as expected, were observed to be a function of fire size with the larger fire extinguished faster than the smaller ones. This was attributed to the need for oxygen depletion to extinguish these obstructed fires.

The results of the tests conducted low in the space are shown in Table 3. In general, the extinguishment times were similar between the four systems. In the closed compartment, the 10.0 MW spray fire was extinguished in approximately five minutes and the 5.0 MW spray fire was extinguished in approximately eight minutes. The smaller fires (2.5 MW spray and the 2.0 m^2 pan) were never extinguished. All four systems were also capable of extinguishing the 10.0 MW spray fire in the ventilated compartment with extinguishment times ranging from 7 to 14 minutes.

Table 3. Extinguishment times (total protection systems).

	Low Fire Location				
Fire Vents	2 m^2 Pan Closed	2.5 MW Spray Closed	5.0 MW Spray Closed	10.0 MW Spray Closed	10.0 MW Spray Open
System	Extinguishment Times min:sec				
LPS			9:00	6:45	9:30
IPS	NO	NO	8:10 8:45	5:30	7:10
HPS	NO		*6:00	*6:00	*14:15
LFHPS			7:40	4:00	9:20

*Tests conducted at 35 bar.
NO-No extinguishment in 15:00
Blank-test not conducted

9.2   Zoned System Results

The extinguishment times for the zoned systems are shown in Table 4. The Low Flow High Pressure System (LFHPS) was not tested because the total flow rate of this system was less than the minimum discharge capacity of the pump package/piping arrangement (i.e., insufficient bypass flow resulting in over pressurization of the system).

Generally speaking, the extinguishment capabilities of the zoned systems were similar or superior to the total protection systems. The extinguishment times for the 10.0 MW spray fires in the closed machinery space ranged from two to five minutes while the extinguishment times for the 5.0 MW spray fires ranged from five to ten minutes. The extinguishment times for the 10.0 MW spray fires in the open machinery space varied from system to system. The 10.0 MW ventilated fire located low in the space proved to be very challenging for the zoned systems. The extinguishment time for the zoned IPS was almost twice that of the total protection IPS (7:10 vs. 13:00). The zoned LPS was not capable of extinguishing this fire. A direct comparison between

Table 4. Extinguishment times (zoned systems).

	Low Fire Location					High Fire Location		
Fire Vents	2 m² Pan Closed	2.5 MW Spray Closed	5.0 MW Spray Closed	10.0 MW Spray Closed	10.0 MW Spray Open	5.0 MW Spray Closed	10.0 MW Spray Closed	10.0 MW Spray Open
System	Extinguishment Times min:sec							
LPS		NO	10:30	4:35	NO	5:30	3:00	6:15
IPS		NO	5:50	5:30	13:00	4:15	2:00	4:00
HPS	9:30	9:00	3:45 5:15	3:45	5:40	4:00	2:15	3:30

NO-no extinguishment in 15:00
Blank-test not conducted

the zoned and total protection HPS is not appropriate due to the reduced system pressure used during the total protection system tests.

The zoned high pressure system demonstrated superior capabilities during this evaluation. The system typically produced faster extinguishment times than the other systems and was capable of extinguishing at least one fire (i.e., 2.5 MW spray or 2.0 m² pan) the other three systems could not extinguish.

10.0 DISCUSSION

10.1 General

The trends in the extinguishment times observed during these tests follow those found throughout literature; the larger the fire, the shorter the extinguishment time. This trend is shown in Figure 10 and is associated with the need for oxygen depletion to extinguish obstructed fires. In this figure, the extinguishment times for the spray fires are plotted versus fire size for the tests
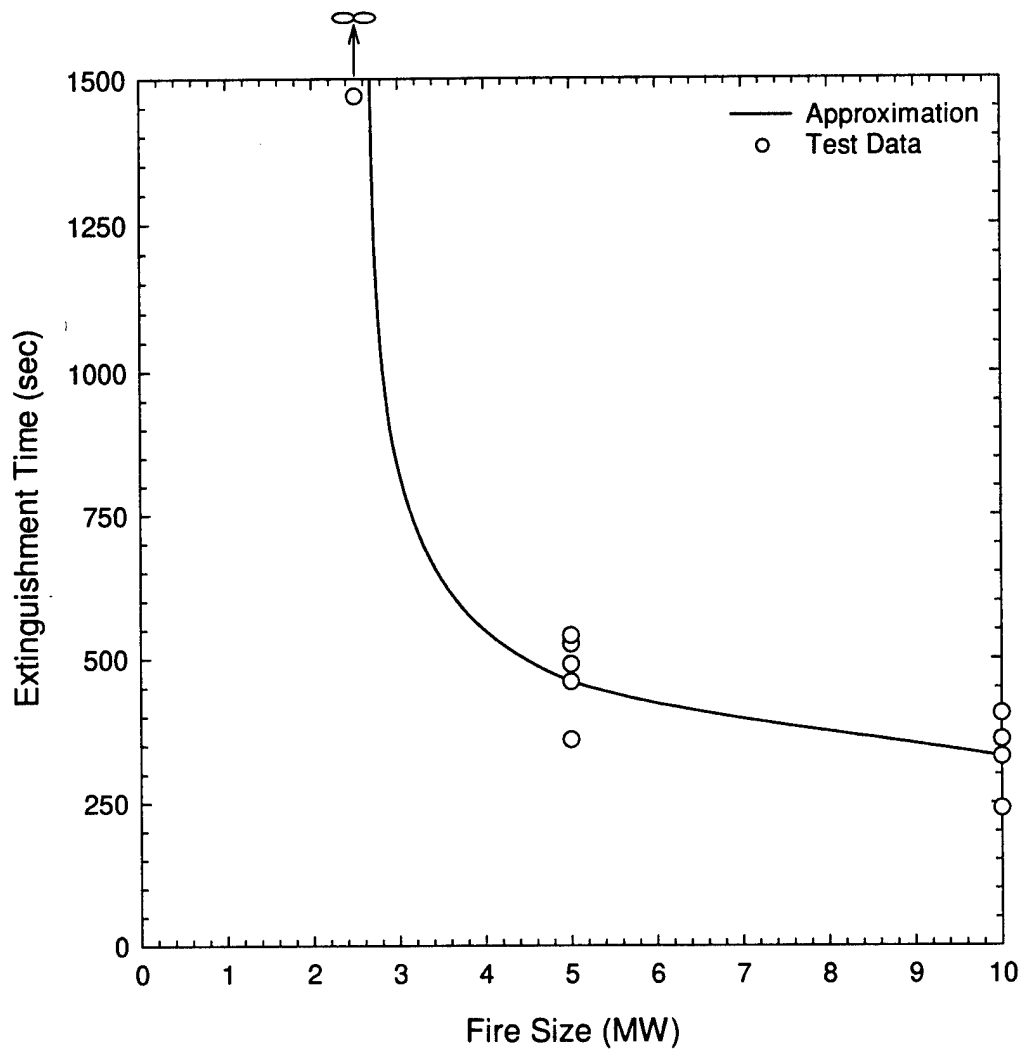
Figure 10. Extinguishment time relation.

conducted with the total protection water mist systems in the closed 3000 m^3 machinery space. The extinguishment time/fire size relation shown in this figure is associated with both the oxygen consumption and steam generation created by the larger fires. These trends, for the most part, were observed for each of the four systems included in this evaluation independent of the system design (total protection or zoned).

The effect of compartment volume on the extinguishment capabilities of the system (extinguishment times) also follow the trends found throughout the literature. A review of previous test data (Back et al., 2000) identified a normalization technique where the extinguishment times for obstructed spray fires were plotted versus the fire size divided by the compartment volume for all of the tests conducted in closed compartments. The net result was a relation that could be used to predict (within reasonable accuracy) the extinguishment times of fires in machinery spaces with a range of volumes. The results of the tests conducted with the total protection systems follow those same trends and are shown in Figure 11. The longer extinguishment times observed for these tests were attributed to a large leakage area in the compartment and will be discussed in the modeling section of this report (Section 10.3).

The ventilation condition also produced trends in the extinguishment time data. Opening the doors to the space typically doubled the extinguishment times for a given fire size (10.0 MW) and in many cases made these fires too difficult to extinguish. These trends were observed for each of the systems and system designs included with this evaluation. A more detailed discussion of the effects of ventilation on extinguishment time is found in the modeling section of this report (Section 10.3).

As shown in previous investigations, the pan fires were more difficult to extinguish than spray fires for a given fire size (heat release rate under ambient conditions). 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 rate of the fire is
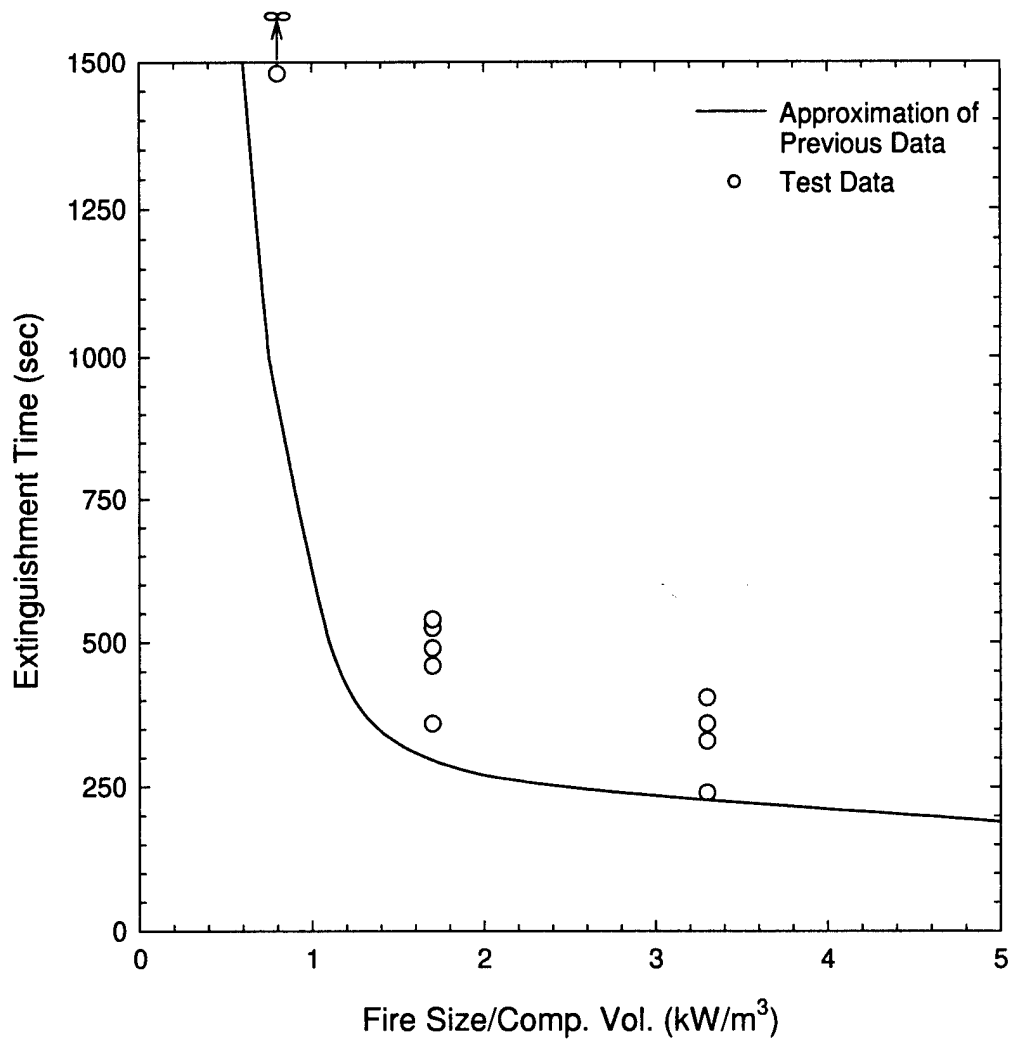
Figure 11. Normalized extinguishment times.

reduced. This variation in fire size changes the oxygen concentration history in the space, resulting in a longer time to reduce the oxygen concentration to a given value. Third, the spray fires have a higher strain rate than pool fires (higher strain rates denote lower flame stability) and consequently are much easier to extinguish. The high sides of the fuel pans may also shield the fires from any horizontal dispersion of mist.

Throughout this test series, the zoned systems demonstrated similar if not superior capabilities to the total protection systems produced with the same nozzles. This was attributed to better mixing characteristics and potential localized effects resulting from the entrainment of the upper layer (ventilated gases). The zoned systems included in this evaluation also discharged approximately 30 percent more water per unit volume than the total protection systems produced with the same nozzles. This higher flow rate may have also contributed to the increase in performance. These results suggest that a zone water mist system can provide the same level of protection as a standard total protection system. The zoned system should be more economical due to the lower flow rates and should reduce the impact of the system on the ship. As a result, the IMO test protocol should be modified to include zoned total protection systems.

During previous tests conducted in smaller machinery spaces (Back et al., 1998, 1999a, and 1999b), immediately after the water mist system was activated, the gases in the space became well-mixed producing uniform temperatures and gas concentrations throughout the space. During these tests, there appeared to be some degree of stratification in the compartment depending on the type of system (total protection or zoned) being evaluated.

The zoned total protection systems produced superior mixing inside the protected area but allowed some degree of stratification in the areas away from the nozzles. An example of this is shown in Figure 12. Shown in this figure are the gas/air temperatures measured in the compartment during a test conducted with the zoned HPS against the 10.0 MW spray fire in the closed compartment (Test #20). The forward thermocouple tree is located inside the zone and is fairly uniform, and the aft tree is located away from the nozzles and is somewhat stratified. The gas concentrations in the space followed the same trends.
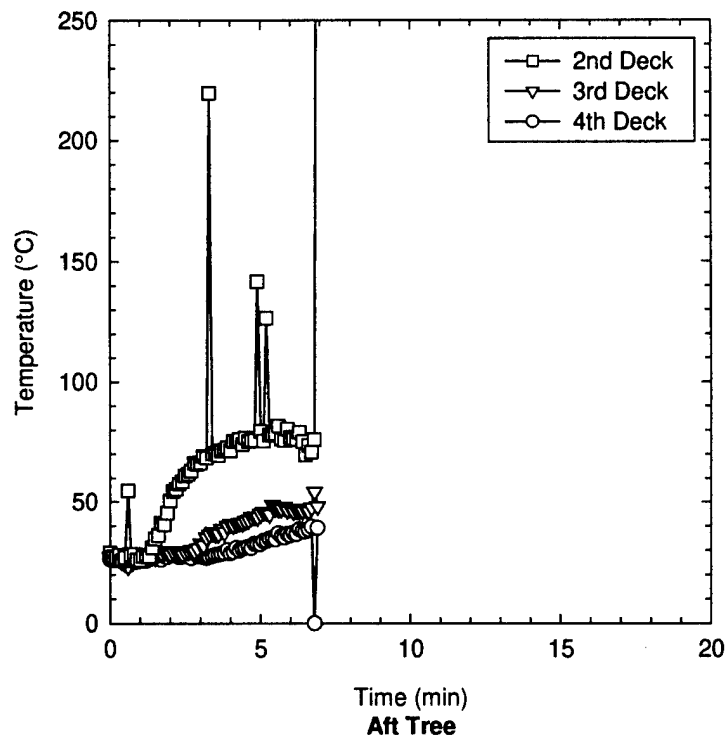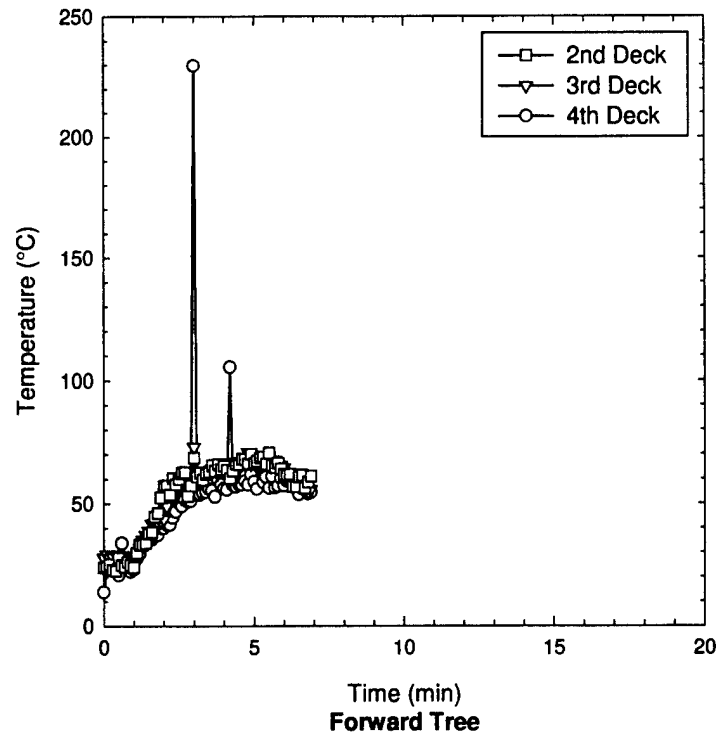
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Figure 12. Test #20 compartment temperatures.

The total protection systems produced more uniform mixing horizontally in the space with the degree of stratification being a function of the fire size and the ventilation conditions during the test. The larger fire sizes and higher ventilation rates increased the degree of stratification.

Figure 13 shows the gas/air temperatures measured in the compartment during a test conducted with the total protection HPS against the 5.0 MW spray fire in the closed compartment (Test #39). Figure 14 shows the gas/air temperatures measured during a test conducted with the total protection HPS against the 10.0 MW spray fire in the closed compartment (Test #38). The higher degree of stratification observed in Figure 14 is the result of doubling the size of the fire.

Figure 15 shows the gas/air temperatures measured in the compartment during a test conducted with the total protection HPS against the 10.0 MW spray fire in the open compartment (Test #40). The higher degree of stratification observed in Figure 15 as compared to Figure 14 is the result of increasing the ventilation conditions in the compartment. The gas concentrations in the space follow the same trends.

10.2 Design Considerations

During the development of a water mist system for U.S. Navy machinery spaces (Leonard et al., 1994; Back et al., 1997a, 1997b, and 1999c), it was shown that minor modifications in the design would increase the fire suppression capabilities of the systems. These modifications would have also increased the capabilities of the total protection systems included in this evaluation. Some of these design considerations are not specifically addressed in the IMO test protocol and are addressed here.

The first modification would be to install the nozzles with an adequate spacing to ensure complete spray pattern coverage over the protected area. The 3.0 m nozzle spacing used during this test series was a compromise between economic and performance considerations. The
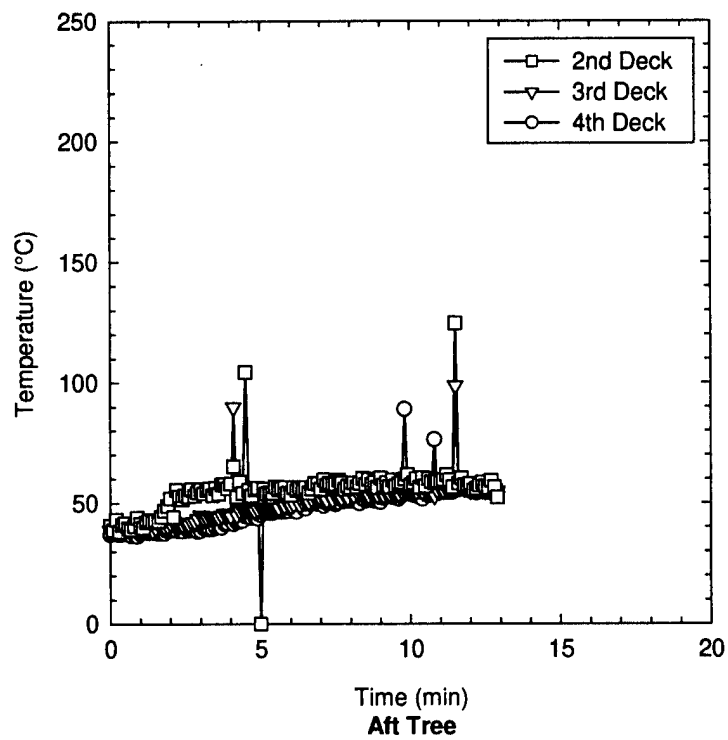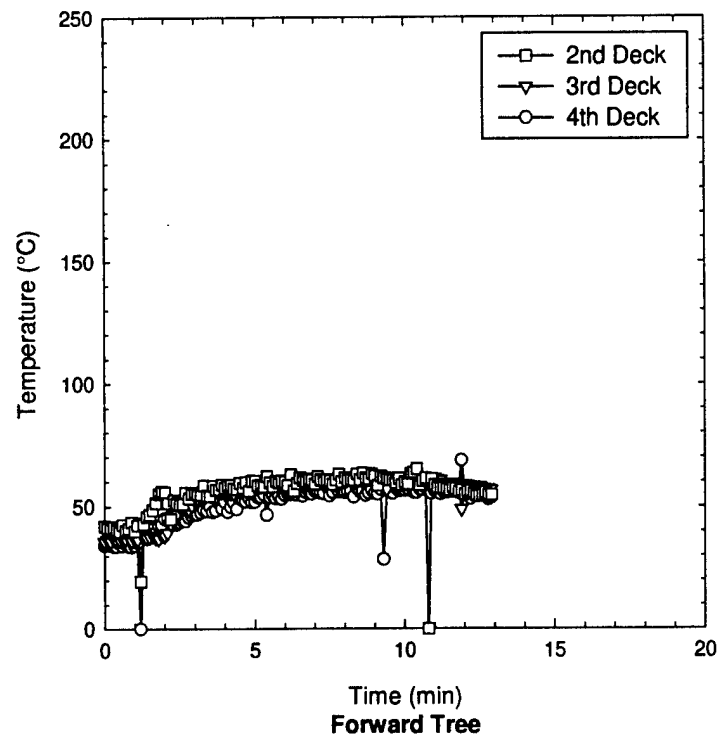
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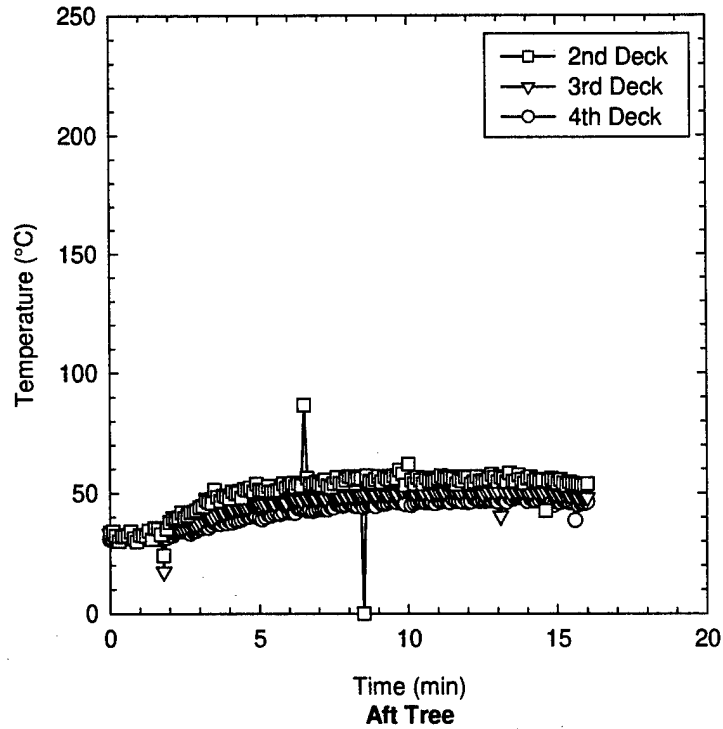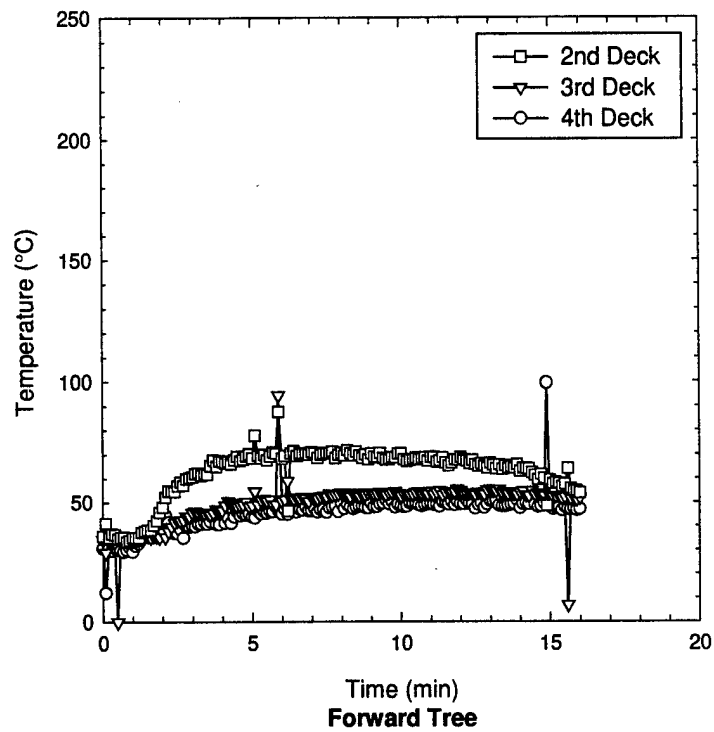**Figure 13. Test #39 compartment temperatures.**

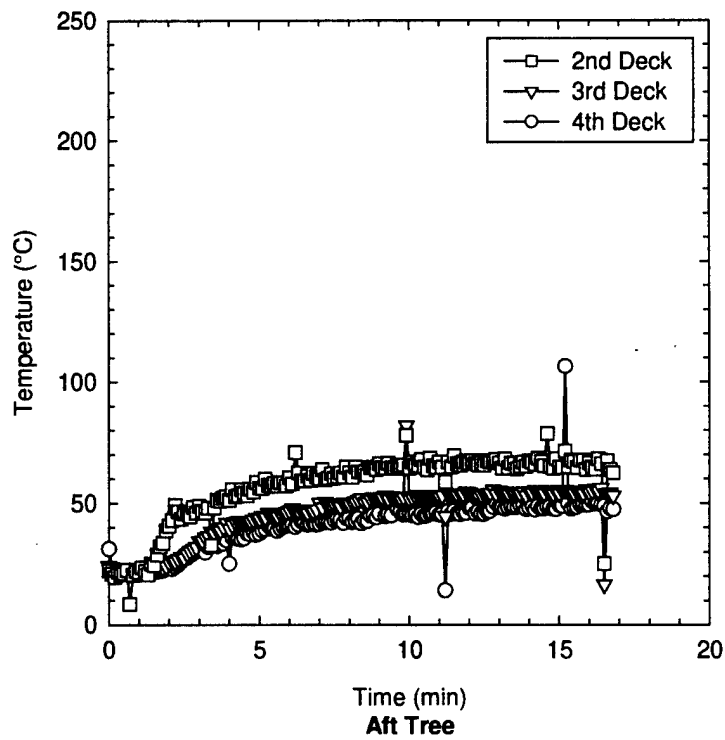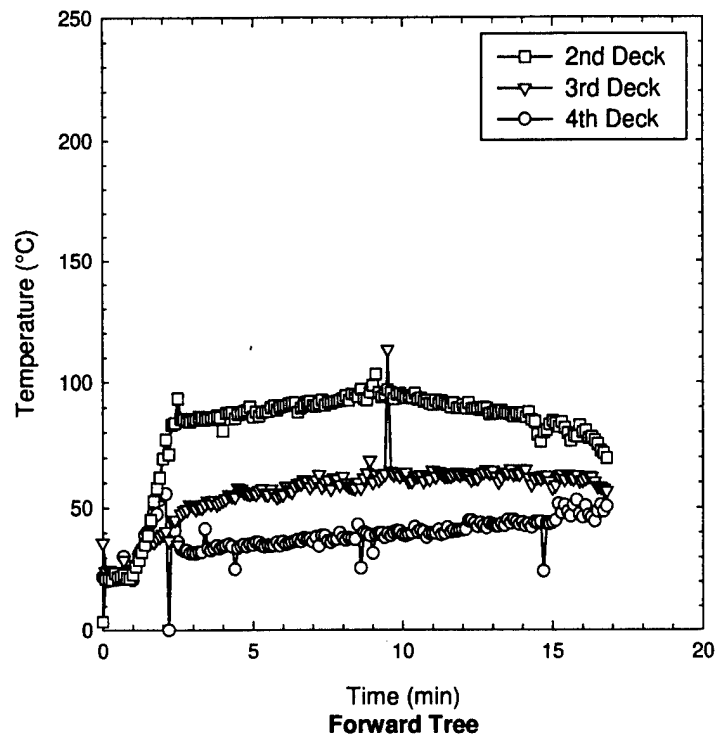**Figure 14. Test #38 compartment temperatures.**

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Figure 15. Test #40 compartment temperatures.

combination of the generic nozzles selected for this evaluation and the 3.0 m nozzle spacing resulted in incomplete spray pattern coverage of the protected area.

Another potentially advantageous design approach is to discharge more water high in the space to produce a more uniform mist concentration. This can be accomplished by incorporating nozzles with different flow characteristics (K-factors) or by using a tighter nozzle spacing high in the compartment. When each level of nozzles discharges the same quantity of water, the mist concentration varies with elevation, with higher concentrations occurring low in the space. This was shown during the tests conducted with the total protection systems. A tighter nozzle spacing in the upper grid may ensure the complete pattern coverage mentioned previously and create a more uniform mist concentration throughout the space.

Staggering the nozzle locations between levels (i.e., installing the nozzles in the lower grid such that the next lower level of nozzles are located in the center between four nozzles in the upper grid) is also a recommended practice. This tends to fill holes that may exist in the spray patterns and creates a more uniform mist concentration horizontally across the space.

As a final consideration, when the upper level of nozzles cannot be installed reasonably close to the overhead (i.e., within 0.5 m), it is recommended that additional nozzles be installed in the grid aiming upward to protect the area above the nozzles.

10.3   Modeling Comparison

The steady-state extinguishment model developed previously (Back et al., 1998) was used to analyze the results of these tests. The model assumes that water mist systems extinguish obstructed fires through a reduction in oxygen concentration resulting from both the consumption of oxygen by the fire and the dilution of the oxygen with water vapor.

The model is based on conservation of energy and mass and requires the following input parameters: fire size, compartment volume and geometry, vent area and height, and water mist system flow rate. From these conditions, the model can predict the steady-state compartment

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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 initial step in using the model to analyze the test data was to determine the ventilation conditions (i.e., leakage area) in the test compartment. As written, the model calculates the air flow through the compartment using a ventilation factor $(A\sqrt{H})$ correlation that assumes that the air enters and the vitiated gases exit through a single vent opening. This correlation does not specifically apply to complex ventilation configurations with multiple vent openings located at different elevations as was the case during these tests, but can be used as a first order approximation knowing the narrow range of steady-state compartment temperatures and air flow rates observed during these tests.

Using the conditions measured in the space during these tests, the equivalent ventilation factor was determined for both the closed and ventilated compartments. The measured steady-state conditions (oxygen concentration and temperature) that occurred in the compartment during the tests were used in this calculation.

The ventilation factor was determined by using a two step process. First, the mass flow rate of air flowing through the compartment required to produced the measured steady-state oxygen concentration for the size of the test fire was determined using the following equation:

$$\dot{Q}_{Fire} = \dot{m}_{air} \, \Delta H_{R_{O_2}} \left(\gamma_{O_2(in)} - \gamma_{O_2(out(dry))} \right) \tag{1}$$

where $\dot{Q}_{Fire}$ is the heat release rate of the fire, $\dot{m}_{air}$ is the mass flow rate of air through the compartment, $\Delta H_{R_{O_2}}$ is the heat of reaction of oxygen and the gammas are the mass fractions of oxygen in the air flow into $(\gamma_{O_2(in)})$ and out of $(\gamma_{O_2(out(dry))})$ the compartment. The dry concentration was selected since the majority of the water vapor in the compartment was the result of mist evaporation and not the combustion process.

Knowing the mass flow rate of air, the ventilation factor can be determined using the following vent flow equation (Drysdale, 1985):

$$\dot{m}_{air} = \frac{2}{3} A H^{1/2} C_d \rho_O (2g)^{1/2} \left(\frac{(\rho_O - \rho_F)/\rho_O}{[1 + (\rho_O/\rho_F)^{1/3}]^3} \right)^{1/2} \tag{2}$$

where A is the area of the openings, H is the height of the opening, ρ_O is the density of air at ambient temperature, ρ_F is the density of the gases inside the compartment, $C_d = 0.7$ and $g = 9.81 \ m/s^2$. The density of the gases is a function of temperature and must be calculated using the measured steady-state compartment temperature.

For the closed compartment, the data from the test conducted with the total protection IPS against the 5.0 MW spray fire (Test #31) was used to determine the equivalent leakage area. Using the steady-state oxygen concentration (15.3% dry) and compartment temperatures (55 °C) measured during the test, the equivalent ventilation factor was determined to be approximately 21 $m^{5/2}$. Assuming the vent height equals the height of the compartment, this equates to an equivalent leakage area of approximately 7.3 m^2.

For the ventilated compartment, the data from the test conducted with the total protection IPS against the 10.0 MW spray fire (Test #32) was used to determine the equivalent ventilation factor and leakage area. Using the test data (55 °C and 15.5% dry) yields an equivalent ventilation factor and leakage area for the ventilated compartment of 44 $m^{5/2}$ and 15.3 m^2 respectively. It was these leakage areas that were used as inputs to the model.

The ability to accurately represent the complex ventilation configuration used during these tests with a ventilation factor ($A\sqrt{H}$) is shown in Figure 16. The solid line on this figure is the calculated air flow rate (mass) through the compartment using the leakage area previously determined for the closed compartment combined with a buoyancy driven orifice flow model representing the ventilation configuration used during these tests. The ventilation condition produced by the leaks in the compartment was approximated using a vertical vent opening (slit)
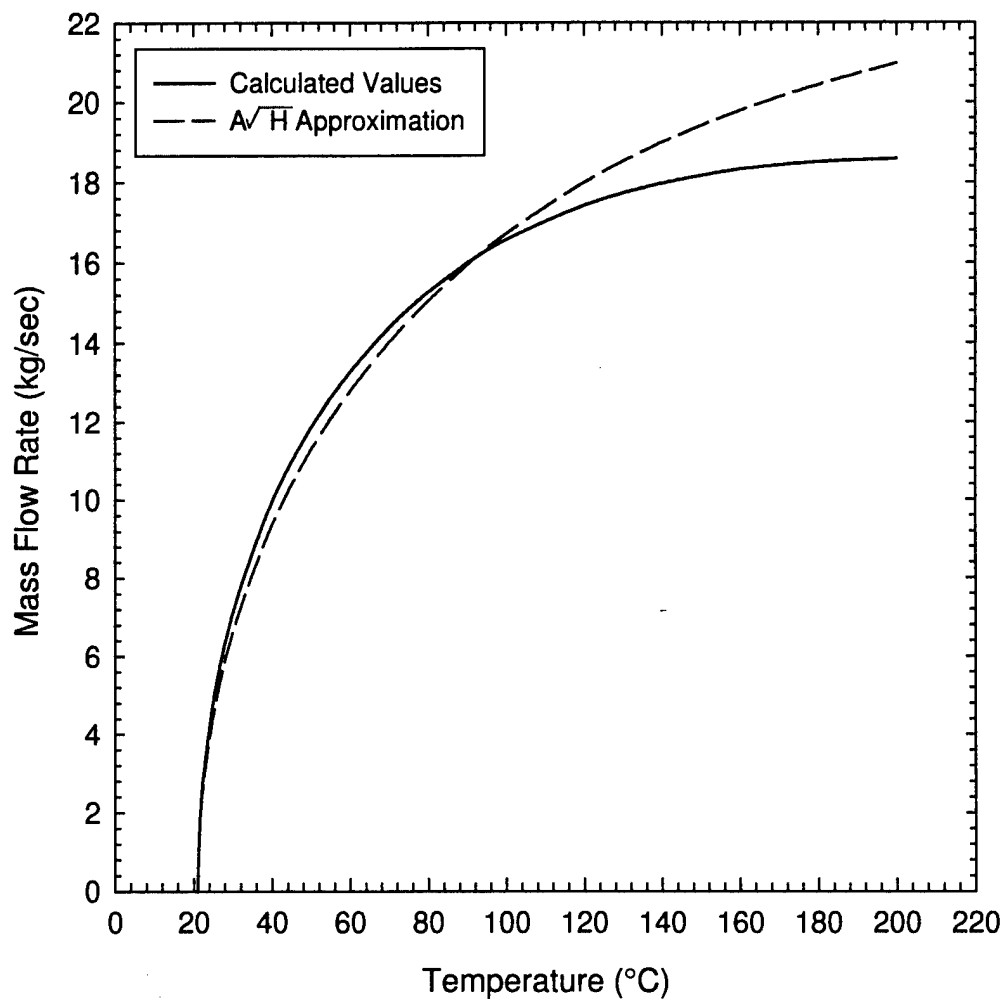
Figure 16. Vent flow analysis.

0.9 m wide by the height of the compartment (8.25 m). The air flow through the open doors (Figure 3) was determined using a buoyancy driven orifice flow model with three orifices driven by the buoyancy forces produced by the hot gases in the compartment. The location of the neutral plane was determined by requiring the inflow to equal the outflow. The dotted line is the calculated air flow rate (mass) using the ventilation factor previously determined for the open compartment. As shown in this figure, the two approaches produced almost identical results.

The steady-state temperatures measured during the tests conducted with the total protection systems are listed in Table 5. The steady-state temperatures ranged from 45-80 °C, depending on the fire size, ventilation condition, and water mist system flow rate. The steady-state temperatures varied by 10-15 °C between systems (due to differences in system discharge rates).

Table 5. Steady-state compartment temperatures (total protection systems).

Low Fire Location					
Fire Vents	2 m² Pan Closed	2.5 MW Spray Closed	5.0 MW Spray Closed	10.0 MW Spray Closed	10.0 MW Spray Open
System	Temperature (°C)				
LPS			70	70	80
IPS	45	45	55	59	55
HPS	58		*70	*75	*70
LFHPS			65	75	60

* Tests conducted at 35 bar

The model was used to accurately predict the steady-state compartment temperatures for all the tests conducted during this evaluation. Figure 17 shows a comparison of the predicted temperatures and the temperatures measured during these tests. As shown in Figure 17, the temperatures predicted by the model are similar to the measured values but begin to lose accuracy for the higher heat release rates. This is attributed to the fact that these larger fires were extinguished before steady-state conditions were achieved.

Figure 17. Steady-state temperature comparison.

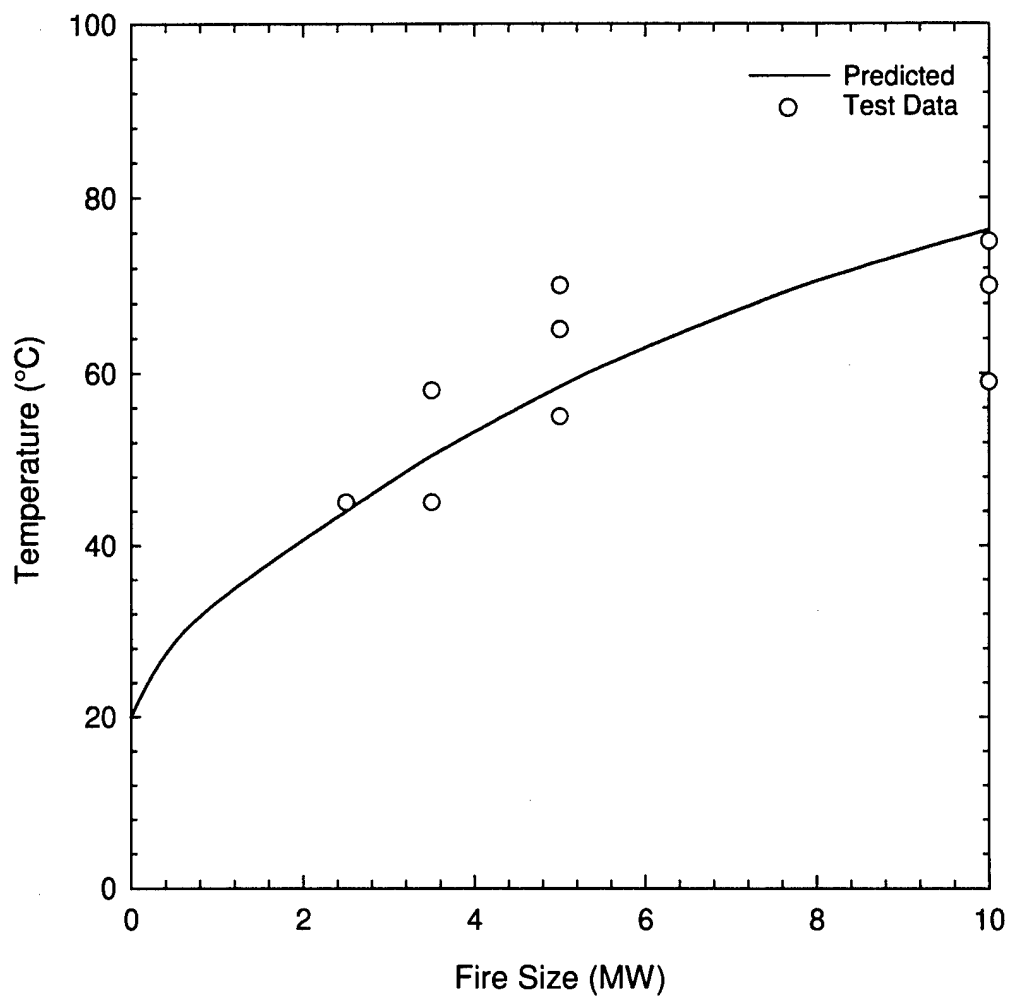The minimum oxygen concentrations measured in the compartment during the tests conducted with the total protection systems are shown in Table 6. The oxygen concentrations typically ranged from 14-17 percent by volume (dry). The measured dry concentrations were adjusted to include water vapor, assuming that the gases were saturated, and are also shown in Table 6.

Table 6. Minimum oxygen concentrations (total protection systems).

	Low Fire Location				
Fire Vents	$2 m^2$ Pan Closed	2.5 MW Spray Closed	5.0 MW Spray Closed	10.0 MW Spray Closed	10.0 MW Spray Open
System	Concentration (%)				
LPS			(12.5) [14.8]	(11.9) [14.2]	(12.6) [15.5]
IPS	(14.4) [15.0]	(14.2) [15.0]	(13.5) [15.3]	(12.1) [15.3]	(13.3) [15.5]
HPS	(14.3) [16.7]		(13.7) *[16.0]	(12.0) *[15.0]	(12.9) * [15.5]
LFHPS			(12.4) [15.3]	(11.9) [15.0]	(12.6) [15.5]

( ) Wet Concentrations
[ ] Dry Concentrations
* Tests conducted at 35 bar

These data suggest that a conservative estimate for the LOI of heptane using the products of combustion and water vapor as the diluent is approximately 14 percent by volume. All of the fires conducted during this evaluation were extinguished when the wet oxygen concentrations approached 14 percent by volume. This compares favorably to the results found in the literature (Beyler, 1988) and in the previous three phases of this investigation (Back et al., 1998, 1999a, and 1999b).

The model was also used to predict the steady-state oxygen concentrations for the tests conducted during this evaluation. These concentrations are shown in Figure 18. As determined in the initial calculation, a 21 $m^{5/2}$ ventilation factor was used for the closed compartment and an 44 $m^{5/2}$ ventilation factor for the open compartment. A comparison between the predicted and

measured oxygen concentrations is inappropriate due to the fact that a majority of these fires were extinguished before steady-state oxygen concentrations were achieved.

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 our 3000 m^3 machinery space can be determined from Figure 18. 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. The critical fire size is also the value that the extinguishment times measured during these tests asymptotically approach as the fire size is reduced. Figure 18 shows that the critical fire size for our 3000 m^3 closed compartment is approximately 4.0 MW and 7.0 MW for the ventilated compartment.

The model was also used to estimate the extinguishment times for these fires. The extinguishment times predicted by the model for the closed compartment are shown as the line on Figure 19. Also shown on Figure 19 is the range of extinguishment times recorded during these tests. As shown in this figure, the extinguishment times predicted by the model are similar to those measured during this evaluation.

The scatter in the total 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 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 suggest that well-mixed conditions were not always achieved and may be system dependent. For example, the LFHPS did not produce well-mixed conditions during the test. This was attributed to the lower water flow rate of the system. Consequently, systems that do not produce well-mixed conditions may require longer to extinguish the fire than that predicted by the model.

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, 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.
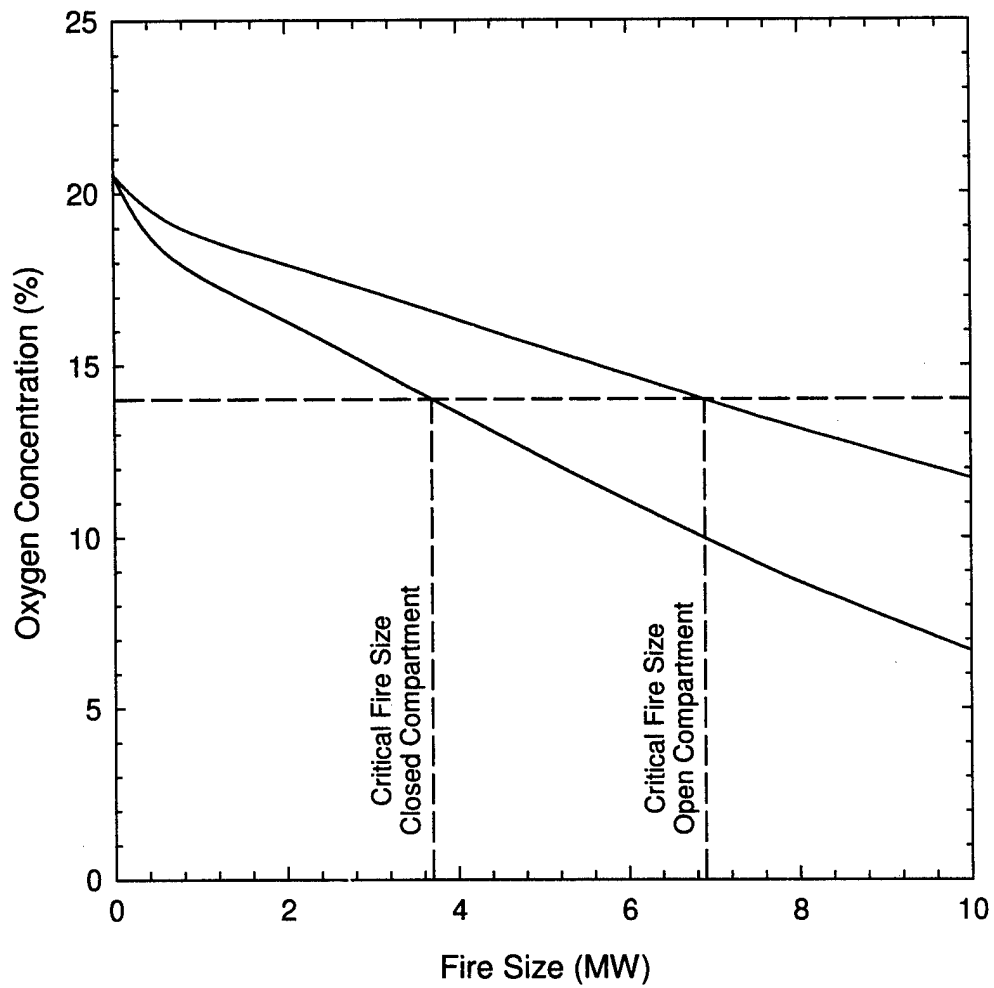
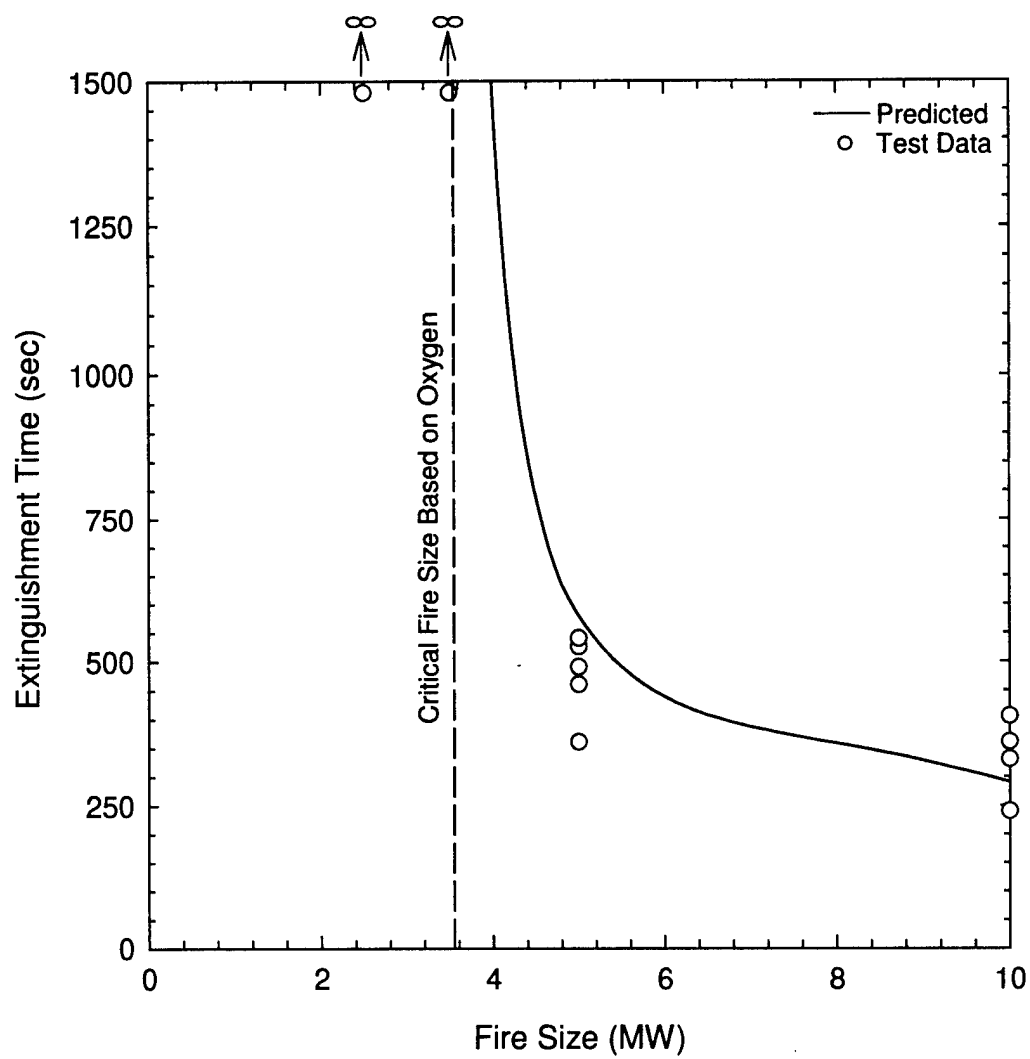**Figure 18. Predicted steady-state oxygen concentration.**

Figure 19. Extinguishment time comparison.

Previous studies (Peatross et al., 1997) have shown that the heat release 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 is 50 percent of the expected value. The predictions made by the model also support this assumption. If the heat release rates of the pan fires are reduced by 50 percent (i.e., 7.5 MW to 3.75 MW), the steady-state compartment temperatures and the extinguishment times show better agreement with the model predictions. These values were also shown in Figures 17 and 19.

10.4 Analysis of Prior Large Space (> 500 m³) Test Results

During a previous investigation conducted by the U.S. Coast Guard at Factory Mutual Research Corporation (FMRC) (Bill et al., 1998), it was concluded that water mist systems could not adequately protect Class II and III machinery spaces due to the need for some degree of oxygen depletion required to extinguish obstructed fires. This conclusion was based on a series of tests conducted in a 940 m³ enclosure constructed of corrugated metal and plastic curtains. During these tests, only a limited number (one) of fires were extinguished. While the final conclusion may or may not be accurate, the results of these tests do not accurately depict the capabilities of water mist in this application. The steady-state model can also be used to explain these results.

Similar to the previous analysis, the initial step required the determination of an equivalent ventilation factor and leakage area for the FMRC test compartment. The ventilation conditions were determined using the actual test data for both the closed and open compartments. Using the steady-state oxygen concentrations and compartment temperatures measured during Test #23 to determine the closed compartment conditions and Test #20 for the open compartment, the equivalent ventilation factors were determined. The equivalent ventilation factors were determined to be 33 $m^{5/2}$ for the closed compartment and 45 $m^{5/2}$ for the open compartment. Assuming the height of the vent equaled the height of the compartment (5 m), this corresponds to leakage areas of 15 m^2 and 20 m^2 respectively. The difference between the two is

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in reasonable agreement with the size of the actual vent opening (2 m × 2 m) added to the compartment.

Using these ventilation conditions in conjunction with the actual test parameters as input to the model, the steady-state conditions for the two compartment configurations can be predicted. These predictions are shown in Figures 20, 21, and 22 for the closed compartment and in Figures 23 and 24 for the open compartment.

As shown in Figures 20 and 23, the predicted steady-state compartment temperatures are in agreement with the values recorded during the tests. The inability of the two water mist systems to extinguish these fires can be explained using Figures 21 and 24. Assuming an LOI of 14 percent, the critical fire size was approximately 5.0 MW for the closed compartment and over 6.0 MW for the open compartment. Only one fire conducted during the FMRC test series was above these critical values (Test #21). During this test (6.0 MW shielded spray fire in the closed compartment), the fire was extinguished in approximately five minutes. This extinguishment time is also similar to the value predicted by the model (Figure 22).

While the steady-state model was used to explain the results of the FMRC test series, the conclusions and recommendations developed during this investigation still apply. In summary, the ability of water mist to protect large machinery spaces is a function of the ventilation conditions in the space. Provisions should be considered to allow the approval of these systems with representative ventilation conditions.

10.5   General Capabilities

The tests conducted to date form a substantial database for water mist systems installed in machinery spaces with volumes ranging from 100 m^3 to 3000 m^3 and varying degrees of ventilation. These tests have also identified the strengths and limitations of water mist in these applications.

A basic understanding of the mechanisms of extinguishment associated with water mist was developed approximately 40 years ago (Braidech et al., 1955; Rasbash et al., 1960). The

Figure 20. FMRC steady-state temperature comparison (closed compartment).

Figure 21. FMRC steady-state oxygen concentration predictions (closed compartment).

Figure 22. FMRC extinguishment time predictions (closed compartment).
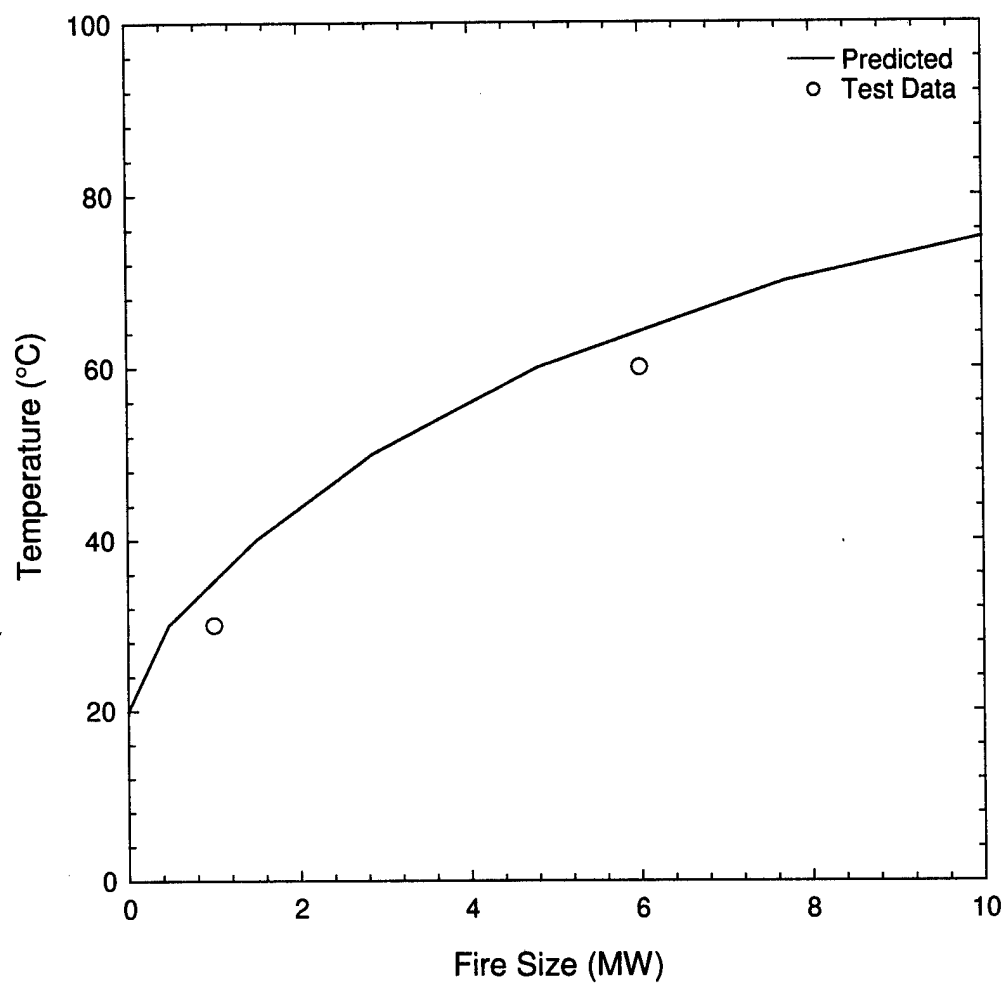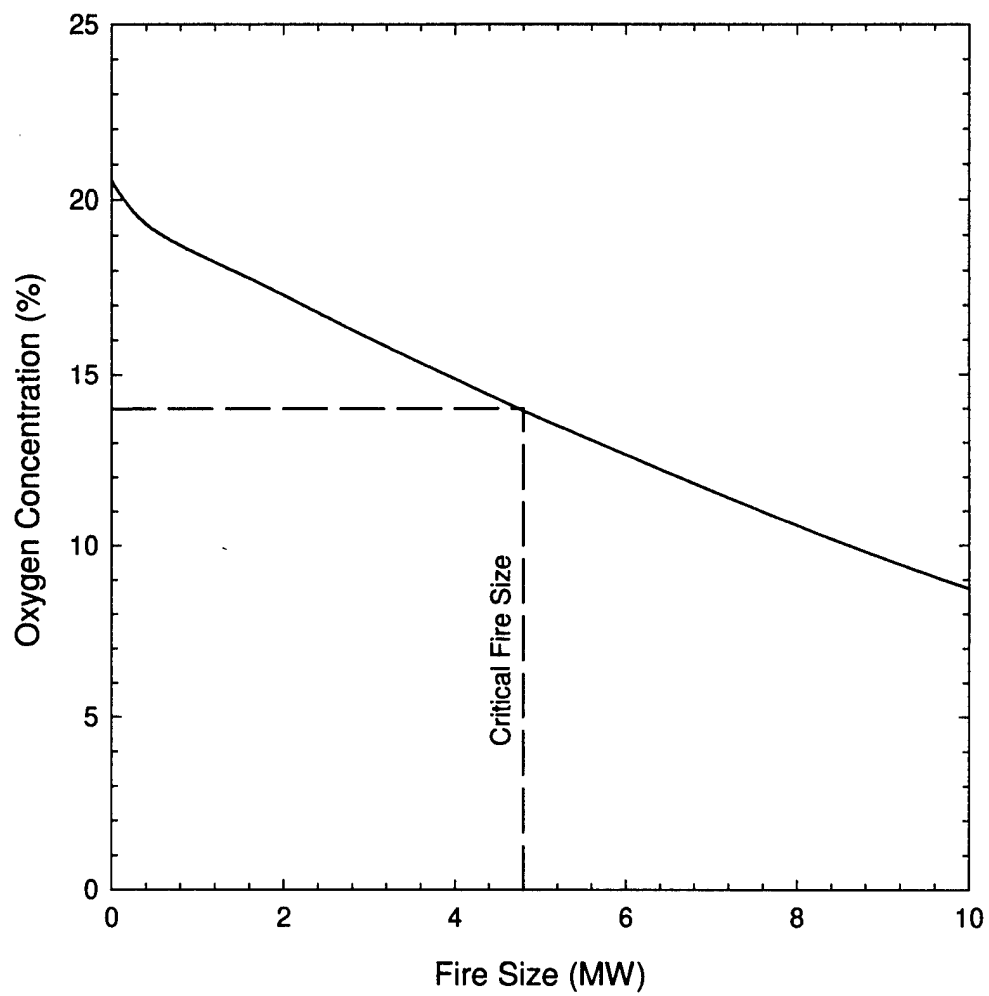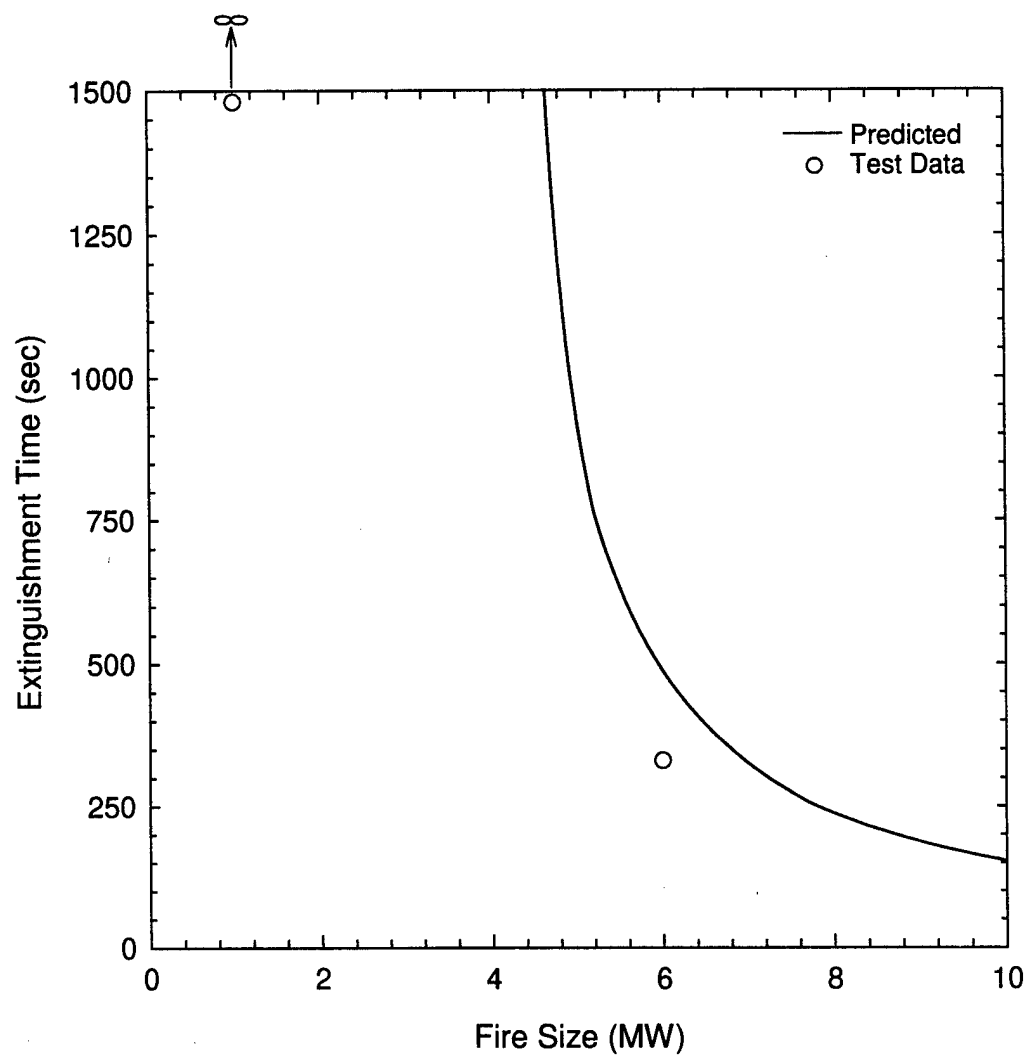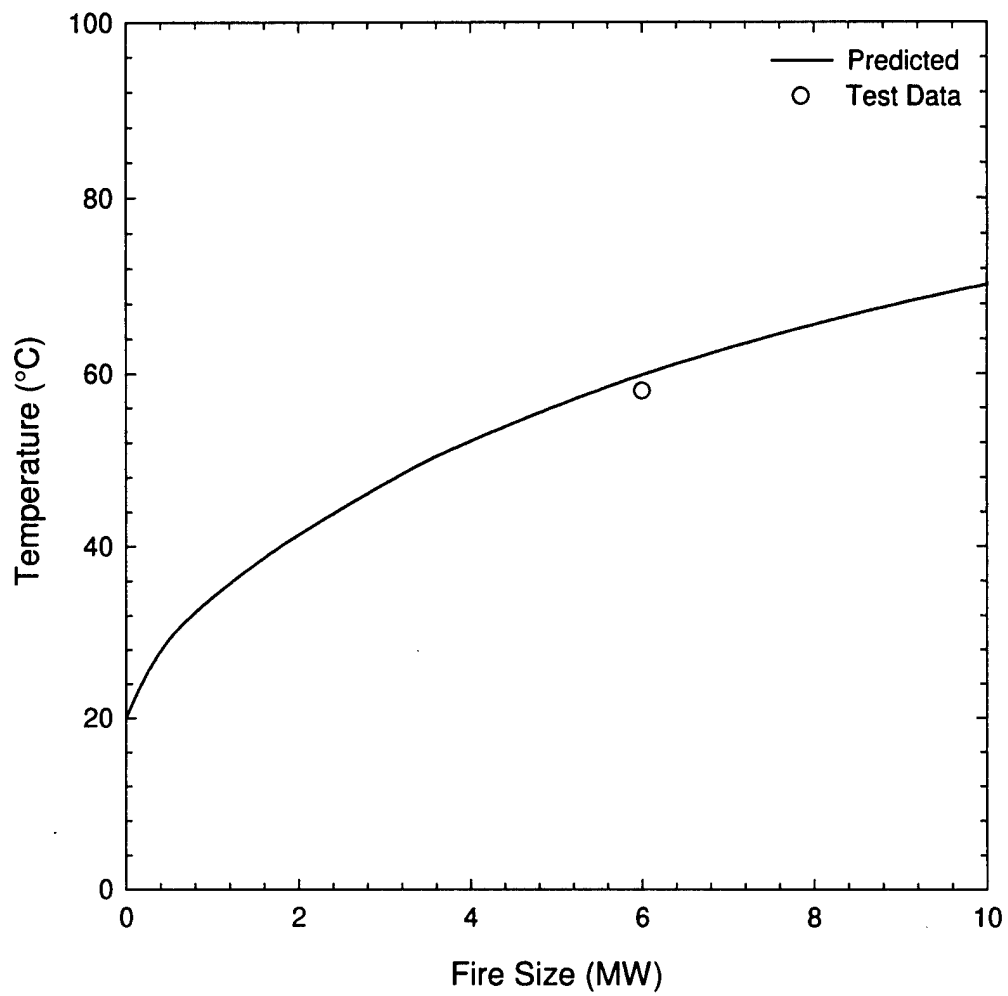
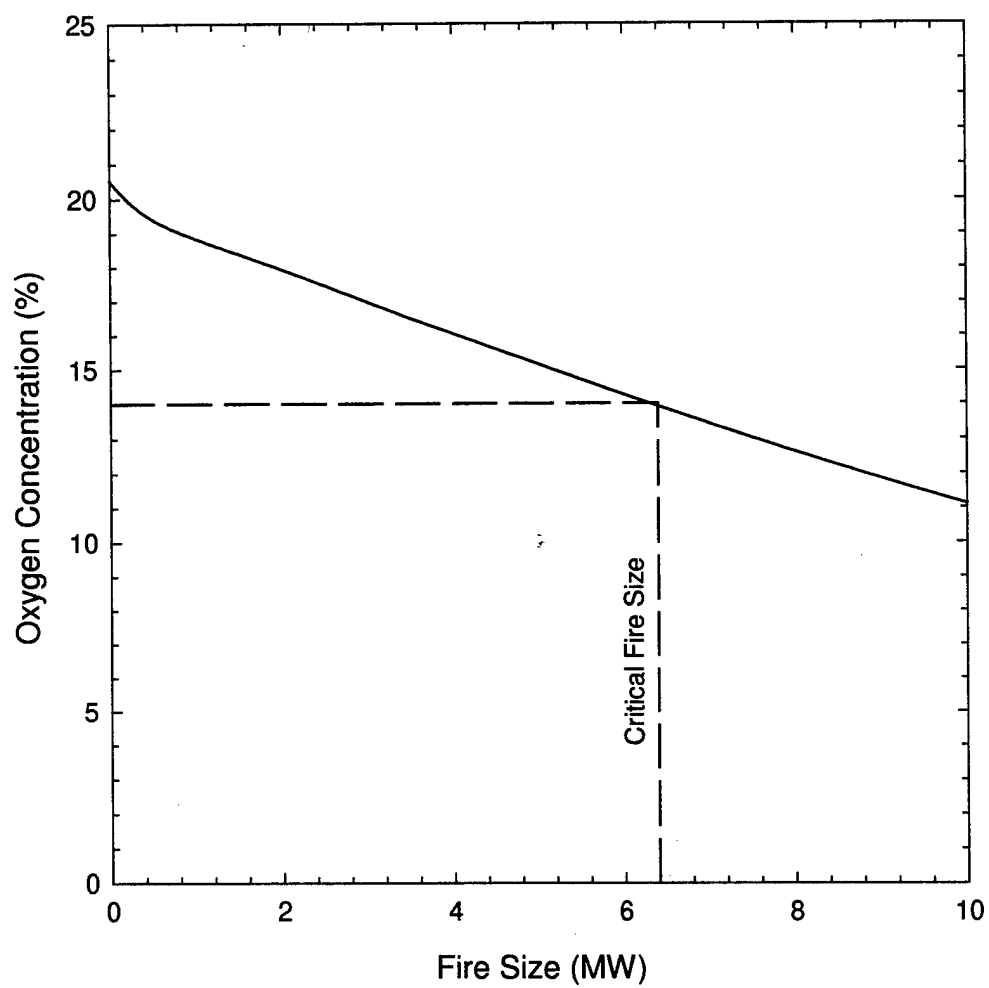**Figure 23. FMRC steady-state temperature comparison (open compartment).**

Figure 24. FMRC steady-state oxygen concentration predictions (open compartment).

mechanisms of extinguishment can be broken down into two basic groups: direct and indirect flame interaction. Direct flame interaction includes gas phase cooling and localized oxygen depletion, and indirect effects include global oxygen depletion and surface wetting/cooling effects.

Gas phase cooling is defined as the removal of heat from the flame and hot gases. As the heat is removed from the flame, the temperature of the flame is reduced. If the calculated adiabatic flame temperature is reduced below the critical value necessary to sustain combustion (limiting adiabatic flame temperature), the flame will be extinguished. The calculated limiting adiabatic flame temperature for a number of hydrocarbon gases is approximately 1600 K (1326 °C). The cooling of the flame also reduces the radiation back to the fuel surface, reducing the pyrolysis rate of the fuel.

Recent investigations have bounded some of the parameters associated with gas phase cooling. The concentration of water mist required to extinguish hydrocarbon fires has been identified in two independent studies (Anderson et al., 1996; Leonard et al., 1994). Both studies have determined that the extinguishment concentration of a relatively low velocity mist is approximately 150 g/m^3 (Volumetric Mean Diameter (Dv$_{50}$) . 100 microns). This extinguishment concentration is reduced as the velocity of the mist is increased.

The difficulty in predicting extinguishment by gas phase cooling is associated with being able to predict and/or measure the amount of mist reaching the fire. The ability of mist to diffuse into all areas in the space is significantly limited in the range of drop sizes produced by current commercially available hardware. Recent studies (Leonard et al., 1994) have shown that the concentration of mist decreases by more than a factor of two after traveling about one-half meter horizontally away from the spray pattern of a nozzle. To compensate for this limitation, the higher performance water mist systems rely on high velocity sprays to mix the mist through the compartment. To complicate this issue even further, the fire tends to alter these conditions by changing the drop size distribution in the space (vaporization and condensation) and affecting the flow patterns throughout the space due to the plume and ceiling jets.

Oxygen depletion and dilution can occur on either a localized or global scale. As the water droplets are converted to steam, the volume occupied by the water can increase by over three orders of magnitude. If the vaporization of the water occurs in the flame, the volumetric expansion can disrupt the entrainment of air (oxygen) into the flame. On a global or compartmental scale, the production of steam resulting from mist interactions with the flame, hot gases and/or hot surfaces can significantly reduce the oxygen concentration in the space. The oxygen available for combustion on a compartmental scale is a function of the size of the fire, the compartment volume, and the ventilation conditions in the compartment. As the size of the fire increases, the average temperature in the space increases, and the oxygen concentration decreases due to both the consumption of the oxygen by the fire and dilution of the oxygen by water vapor (steam). If the combined effects of oxygen depletion and dilution can reduce the oxygen concentration below the critical value necessary to sustain combustion (Limiting Oxygen Index (LOI)), the fire will be extinguished. The LOI for most hydrocarbon fuels is approximately 13 percent using nitrogen as the diluent (Beyler, 1988). This value should be slightly higher using vitiated gases and water vapor as the diluent.

The final primary mechanism of extinguishment is the wetting/cooling of the fuel surface. This can be the predominant extinguishment mechanism for fuels that do not produce combustible mixtures of vapor above the fuel surface at ambient temperatures (i.e., solid fuels and liquid fuels with high flashpoints (i.e., diesel . 60 °C)). Wetting/cooling of the fuel surface reduces the pyrolysis rate of the fuel. If the vapor/air mixture above the fuel surface is reduced below the lower flammability limit (LFL) of the fuel, the flame is extinguished.

Typically, a combination of mechanisms is involved to some degree in the extinguishment process. During the full-scale machinery space investigations conducted by the U.S. Coast Guard, it was evident that specific fires were extinguished predominately by direct flame interaction and others through indirect effects.

Immediately after mist system activation, the temperatures in the space were dramatically reduced. If the fire was unobstructed and the spray characteristics (mist concentration and velocity) of the system were adequate to extinguish the fire by direct flame interaction, the fire

was quickly extinguished (typically less than one minute). The extinguishment times for these fires were relatively constant and did not vary significantly as a function of either fire size or compartment volume. About one half of the mist systems included in the U.S. Coast Guards' investigations were capable of extinguishing fires by direct flame interaction if the fire was located in close proximity to the grid of nozzles (i.e., fires located on top of the diesel engine mock-up in the IMO test protocol). Many of these systems had problems extinguishing fires with direct flame interaction if the fires were located in the center between two or four nozzles. The minimum mist flow rate per unit volume of protected space for a system that could consistently extinguish the fire by direct flame interaction was on the order of 0.3 Lpm/m^3.

A majority of the systems had difficulties extinguishing fires that were located away from the nozzles (distances greater than three meters) by direct flame interaction. This is related to the velocity of the mist at the fire location. The smaller droplets that are characteristic of water mist systems are more efficient in absorbing heat/energy from hot gas due to their high surface area to volume ratios. However, these small droplets have low terminal velocities. The droplet is typically discharged from the nozzle with a high velocity, which tends to decrease with distance away from the nozzle as the droplet approaches its terminal velocity. Only a limited number of the systems included in these evaluations could extinguish a spray fire located greater than three meters away from the nozzle without the help of oxygen depletion (Back et al., 1996a).

If the conditions required to extinguish the fire through direct flame interaction were not achieved, a reduction in oxygen concentration was required to aid in the extinguishment process. For these fires, a well-mixed steady-state thermal environment was produced and maintained in the space until the oxygen concentration dropped below the critical value. In all tests where steady-state conditions occurred, the steady-state temperatures ranged from 30-75 °C.

The significance of these steady-state temperatures became apparent when evaluating the oxygen concentration in the space during extinguishment. It was determined that the dilution of oxygen by saturated water vapor at these temperatures can significantly reduce the oxygen available for combustion. In fact, it was determined that the water vapor in saturated air at temperatures above 80 °C is sufficient to dilute the oxygen concentration below the LOI for most

fuels (Figure 25) (Keenan, 1969). This information defines the maximum steady-state temperatures that can be produced and maintained in spaces protected by water mist systems.

The extinguishment times for fires that require some degree of oxygen depletion are a function of the fire size, the compartment geometry (volume, surface area, and ventilation rate/conditions), and the amount of mist reaching the fire. For a given water mist system and set of compartment conditions, as the fire size is reduced, the extinguishment times tend to asymptotically approach a critical fire size below which the fire cannot be extinguished. This trend in extinguishment time was shown in Figure 10.

For a given fire scenario, the amount of mist reaching the fire is a function of the spray characteristics of the mist system, the location of the fire with respect to the water mist nozzles and the degree of fire obstruction. If more mist reaches the fire, the dependency on oxygen depletion is reduced and the fires are extinguished faster. The higher the degree of fire obstruction, the lower the amount of mist that reaches the fire and the lower the oxygen concentration required to extinguish the fire.

The limiting case for these obstructed fires is a scenario where little if any mist actually reaches the fire. During a majority of the obstructed fires conducted during these investigations, only a limited amount of mist actually reached the fire. These fires were extinguished primarily by a reduction in oxygen concentration caused by the consumption of oxygen by the fire and the dilution of oxygen with water vapor.

The oxygen concentrations and steady-state compartment temperatures can be predicted for a given set of parameters using first principles: conservation of energy and mass. As a result, the model described in Section 10.2 of this report was developed to predict this limiting case. The model uses the compartment geometry, vent area, and water mist system flow rate to predict both the steady-state temperatures and oxygen concentrations in the space for a range of fire sizes. These predictions are then used to determine the smallest fire that will reduce the oxygen concentration in the space by consumption and dilution to below the LOI of the fuel. The results
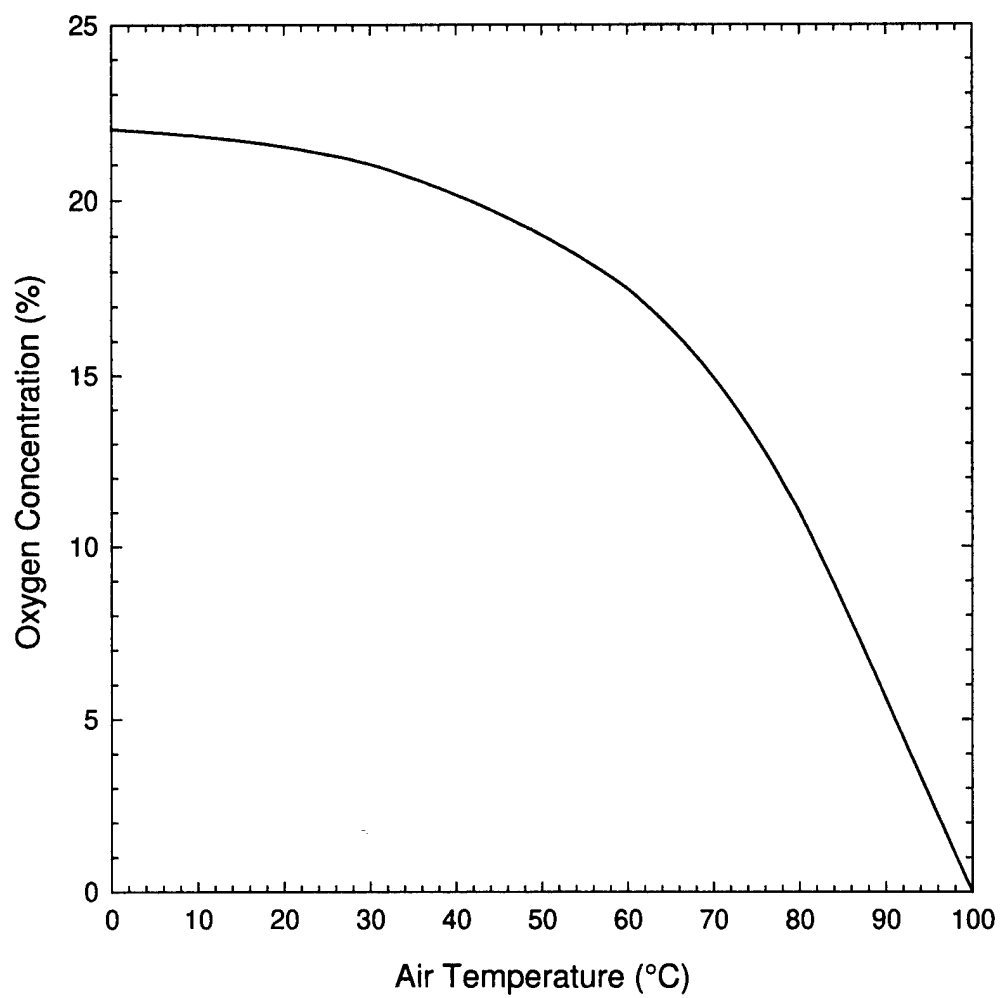
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Figure 25. Oxygen concentration in air saturated with water vapor.

of these tests suggest the LOI of the fuels used during these investigations was 14 percent using saturated water vapor as the diluent.

The results of these tests and the predictions made by the model provide insight into how various compartment conditions (i.e., compartment size/volume and ventilation conditions) affect the capabilities of water mist in this application. The following discussion focuses on the scenario where some degree of oxygen concentration reduction is required to extinguish the fire. If extinguishment occurs solely by direct flame interaction, the capabilities of the system should be unaffected by the various compartment conditions.

For fires that require some degree of oxygen depletion to aid in extinguishment as the size of the fire is reduced, the extinguishment times asymptotically approach a value that is driven primarily by the opening/leakage areas in the space. If the space were air tight, these times would asymptotically approach the Y-axis (zero heat release rate). As the vent area is increased, the critical fire size increases shifting the original plot to the right. This is shown in Figure 26 for a 100 m^3 machinery space under two ventilation conditions (a closed compartment with a small leakage area (ventilation factor $A\sqrt{H}$ = 0.1 $m^{5/2}$) and a compartment with one standard shipboard door opened (ventilation factor $A\sqrt{H}$ = 2.3 $m^{5/2}$)). As shown in this figure, opening a standard shipboard door to the compartment only increases the critical fire size by approximately 100 kW. This illustrates the robustness of the extinguishment capabilities of water mist as a function of doors being left opened to the space. Without the mist system operating, a standard shipboard door could support almost a 4.0 MW fire. Due to the cooling provided by the mist, the flow rate of air/oxygen through the door into the compartment is dramatically reduced, as well as the size of the fire this air can support.

The extinguishment time for a given fire (type and size) is also a function of the size/volume of the compartment. For a given fire size and ventilation condition, increasing the size of the compartment proportionally increases the extinguishment time, but does not significantly change the critical fire size of the compartment. Consequently, for fire sizes above the critical value, doubling the compartment volume for a given fire scenario and ventilation condition typically doubles the extinguishment time (fire burn time).
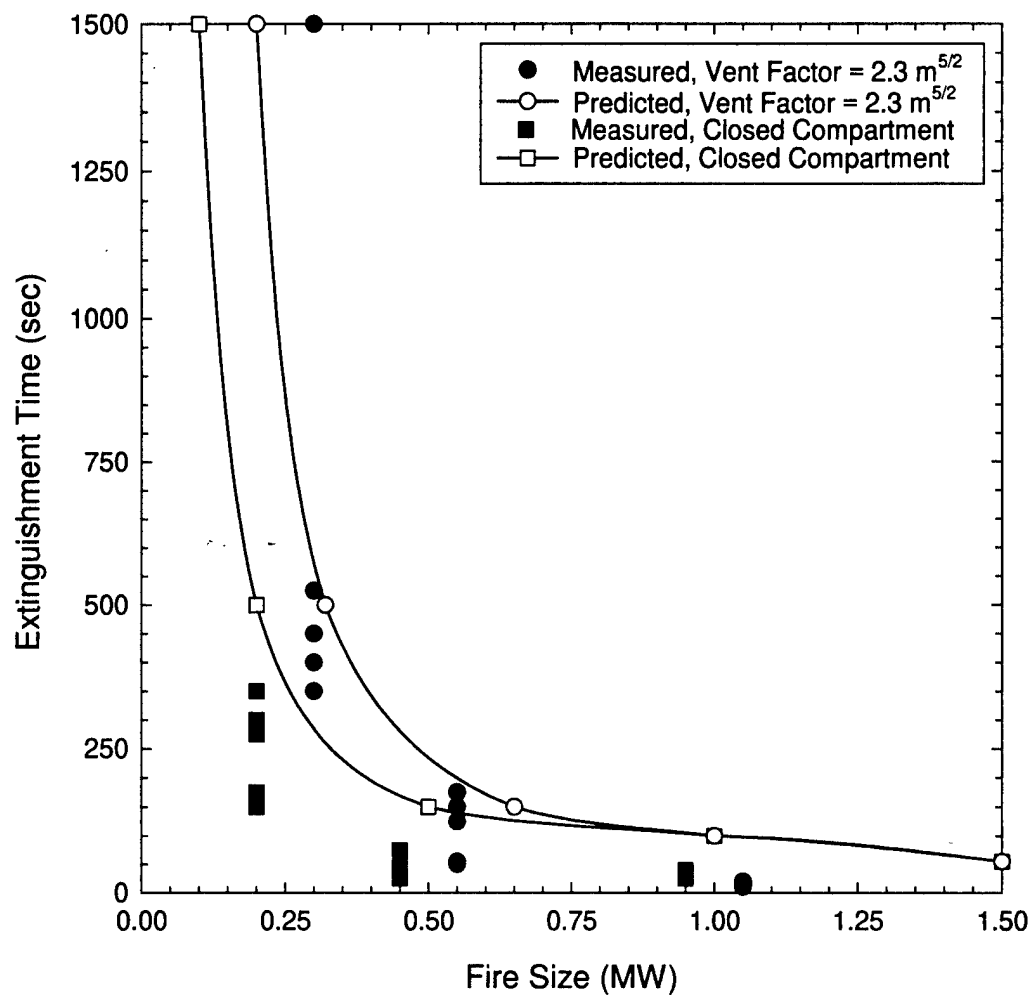
Figure 26. The effects of ventilation on extinguishment time.
(Back et al., 1999b)

Due to these trends, the general capabilities of water mist systems in machinery space applications can be expressed by plotting the extinguishment times versus the fire size to compartment volume ratios. This is shown in Figure 27 for the tests conducted by the U.S. Coast Guard in closed machinery spaces. Applying a curve fit to the data produces a relation that can be used to estimate the capabilities of a water mist system in closed machinery space for a range of compartment volumes. As stated previously, increasing the ventilation in the space tends to shift this curve to the right.

In summary, the strengths of water mist are associated with its ability to extinguish a wide range of larger Class B fires while thermally managing the conditions in the space. The reduced temperatures minimize the thermal damage and prevent fire spread to adjacent compartments. The lower temperatures also tend to reduce the air flow through vent openings in the space making these systems somewhat less affected by the ventilation conditions in the space than other total protection systems (gaseous agents).

The limitations of water mist are associated with difficulties extinguishing small-obstructed fires. The difficulty in extinguishing obstructed fires is associated with high mist fallout rates (due to gravity) which tend to significantly reduce the mist concentration in areas away from the spray patterns of the nozzles. Hence, water mist technologies may never exhibit the same capabilities against small-obstructed fires as the gaseous agents.

Although the gaseous behavior of water mist is severely limited, many obstructed fires can still be extinguished. The extinguishment of these fires is the result of a reduction in oxygen concentration in the space caused by the consumption of oxygen by the fire and a dilution of oxygen with saturated water vapor. In fact, if the fire size is above the critical value dictated by the conditions in the compartment, the fire can still be extinguished without any mist reaching the fire. The principles governing this phenomenon are well understood and a model has been developed to predict this limiting case.

The results of these tests and the predictions made by the model suggest that this critical fire size is primarily a function of the ventilation conditions in the space. If the space were
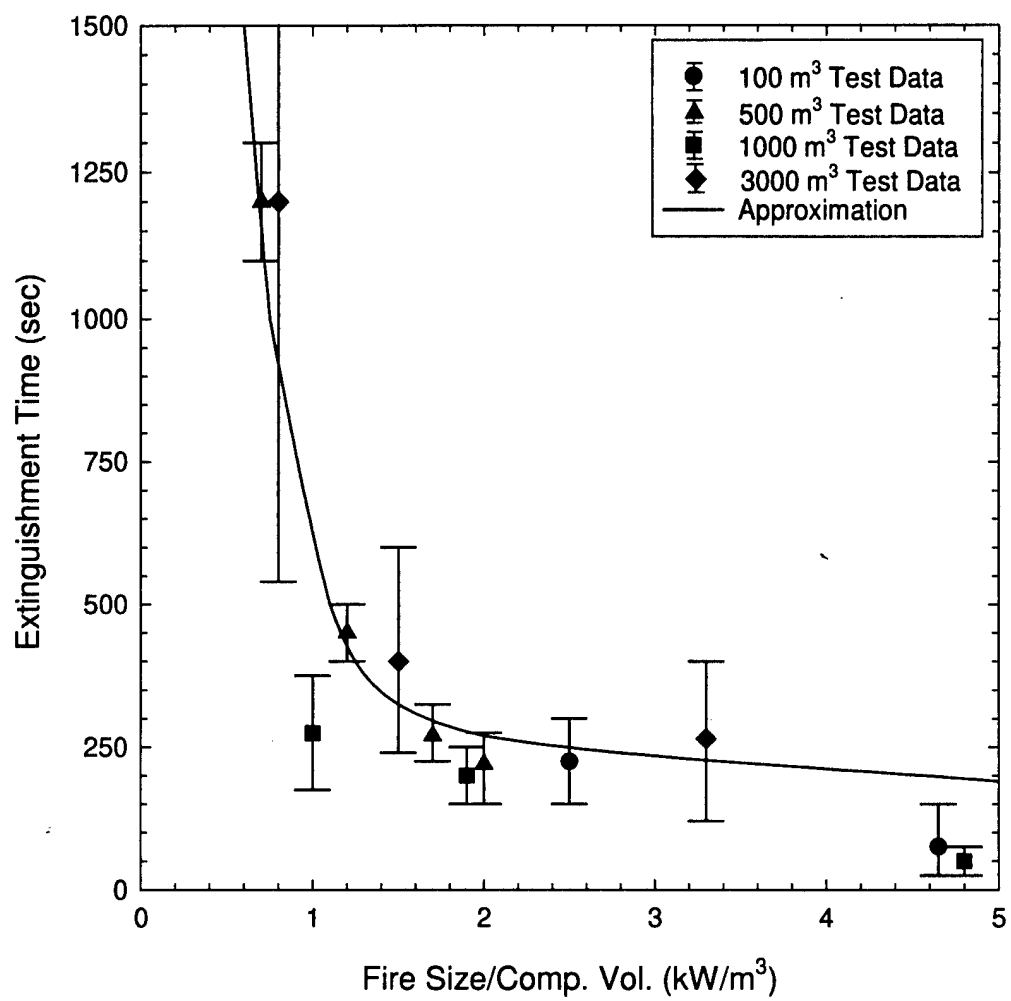
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Figure 27. Normalized extinguishment time curve.

secured prior to mist system activation (as would be done for the gaseous agents), the critical fire size would be driven by the leakage area in the space. For typical leakage areas of $0.1 - 0.3$ m^2 (Hiller, 1998), the critical fire size for the space would be less than 250 kW. Unfortunately, the time required to extinguish these small obstructed fires is a function of the size (volume) of the space and approaches infinity as the fire size is reduced to the critical value.

The limitations on fire size and the times required to extinguish small obstructed fires need to be assessed with respect to the fire hazard (typical fire scenarios) and the scenario when the system would actually be discharged. The typical hazard in a machinery space is a fast growing Class B fire which would be quickly extinguished. Small fires (fires with heat release rates near the critical value) are easily approached and extinguished using a portable extinguisher and would not warrant the activation of the total protection system. In any case, the space would remain tenable until the fire is extinguished and the likelihood of fire spread to adjacent space is minimal.

10.6   IMO Protocol

The IMO test protocol as described in MSC Circulars 668 and 728 requires the successful completion of 13 fire tests as listed in Table 7. These tests are conducted on and around a simulated diesel engine mock-up located in the center of the space. For Class 1 and 2 machinery spaces (Class 1 – less than 500 m^3 and Class 2 – greater than 500 m^3 but less than 3000 m^3), the tests are to be conducted in a well-ventilated compartment (i.e., containing a 2 m × 2 m vent opening). For Class 3 spaces, the tests are to be conducted basically without an enclosure (i.e., no walls or ceiling). The water mist system must be installed with a uniform nozzle spacing at a height of 5 m in a space with an overhead in excess of 10 m high. The protocol does not address innovative design approaches (i.e., zoned systems) and requires that all nozzles discharge mist simultaneously upon system activation. The protocol requires complete extinguishment of the test fires within 15 minutes of system activation.

The number of fire tests is quite excessive when compared to the gaseous agent test protocol MSC Circular 776 (IMO, 1996c) which only requires four tests. The research to

Table 7. IMO test protocol.

Test Number	Fire Scenario	Test Fuel
IMO-1	Low pressure spray on top of simulated engine between agent nozzles (6.0 MW)	Commercial fuel oil or light diesel oil
IMO-2	Low pressure spray on top of simulated engine with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1 m away (6.0 MW)	Commercial fuel oil or light diesel oil
IMO-3	Low pressure concealed horizontal spray fire on side of simulated engine with oil spray nozzle positioned 0.1 m in from of the engine (6.0 MW)	Commercial fuel oil or light diesel oil
IMO-4	Combination of worst spray fire from Tests 1-3 and fires in trays (4 m^2) under and on top of the simulated engine (3 m^2)	Commercial fuel oil or light diesel oil
IMO-5	High pressure horizontal spray fire on top of simulated engine (2.0 MW)	Commercial fuel oil or light diesel oil
IMO-6	**Low pressure, low flow concealed horizontal spray fire on the side of simulated engine (1.0 MW)**	**Commercial fuel oil or light diesel oil**
IMO-7	0.5 m^2 central under mock-up	Heptane
IMO-8	0.5 m^2 central under mock-up	SAE 10W30 mineral based lubrication oil
IMO-9	**0.5 m^2 on top of bilge plate centered under exhaust plate**	**Heptane**
IMO-10	Flowing fuel fire 0.25 kg/s from top of mock-up (see Figures 10 and 11)	Heptane
IMO-11	Class A fires UL 1626 wood crib 2 m^2 pool fire with 30-second preburn	Heptane
IMO-12	A steel plate (30 cm × 60 cm × 5 cm) offset 20° to the spray is heated to 350 °C by the top low pressure, low flow spray. Then the plate reaches 350 °C, the system is activated. Following system shutoff, no reignition of the spray is permitted.	Heptane
IMO-13	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil

date shows that the two most challenging tests are IMO-6 (a low pressure, low flow concealed spray fire) and IMO-9 (a 0.5 m^2 pan fire located under the exhaust plate) as shown in bolded type in Table 7. Assuming a separate bilge fire suppression system (water mist, gaseous agent, or AFFF) these may be the only two tests required. The pan fire in IMO-9 must be extinguished by direct flame interaction since the size of the fire is insufficient to reduce the oxygen concentration in the space (i.e., the heat release rate is below the critical value). This test assures that the system is designed with an adequate nozzle spacing and that the discharge nozzles produce the desired spray characteristics (i.e. droplet size, velocity, and spray pattern). The obstructed spray fire in IMO-6 must be extinguished by indirect effects and assures that the mist system discharges an adequate amount of water to provide the required cooling characteristics (thermal arrangement). The remaining fires are either unobstructed and located in close proximity to the water mist nozzles, or are relatively large and quickly reduce the oxygen concentration in the space.

The size of these fires may be an issue. The strength of water mist fire suppression systems lie in their ability to rapidly extinguish relatively large fires while minimizing the thermal exposures in the space. A 1.0 MW fire is a fairly large fire in a small space but in a Class 2 or 3 engine room, should be easily approachable and extinguished with a portable extinguisher.

To quantify this point even further, a 1.0 MW fire has a flame volume of approximately one cubic meter. This equates to two tenths of one percent of the volume for a Class 1 engine room and three hundredths of one percent for a Class 3 engine room. In order not to eliminate water mist from consideration in larger spaces, the minimum fire size required to be extinguished could be scaled as a function of compartment volume. For example, a constant value of 1-2 kW/m^3 could be adopted. Fire size to compartment volume ratios of this magnitude would only increase the compartment temperature to approximately 75 °C (assumes well-mixed) in the absence of mist and to less than 50 °C during mist discharge, assuming typical water discharge rates on the order of 0.3 Lpm/m^3.

The gaseous halon alternatives are designed and tested with the intent that the machinery space is secured (i.e., doors closed and ventilation systems shut down) prior to discharge. The IMO test protocol for water mist requires that the systems be evaluated in well-ventilated compartments. This has been a point of controversy for years. The size of the vent opening dictates the critical fire size (i.e., smallest fire that will reduce the oxygen concentration below the LOI of the fuel) for the compartment. The 4.0 m^2 vent opening (2 m × 2 m) required in the IMO test protocol results in a critical fire size of approximately 1.0 MW for the water mist system discharge rates typically used by commercially available systems. Without the water mist system to cool the space and reduce the flow of air through the vent, the IMO vent opening could support over an 8.0 MW fire.

The combination of the lower heat release rate fire(s) and the 4.0 m^2 vent opening will limit the use of water mist to smaller machinery spaces. Using the extinguishment model described in Section 10.3, the extinguishment times for 1000 m^3, 2000 m^3 and 3000 m^3 Class 2 machinery spaces were predicted. These extinguishment times are shown in Figure 28. Selecting the 1.0 MW shielded spray fire as the limiting case (IMO-6), it is unlikely that any water mist system discharging only water can successfully complete the protocol for spaces with volumes greater than 2000 m^3.

In summary, the IMO test protocol ensures that water mist systems are designed with the proper nozzle spacing and spray characteristics to have a high probability of extinguishing a wide range of fire sizes in machinery spaces with varying degrees of ventilation. The protocol also ensures that the discharge rate is adequate to provide the required thermal management needed to minimize the damage for the longer extinguishment times that are characteristic of water mist systems for smaller obstructed fires. The conservative nature of the protocol (due to the high ventilation rates and smaller fire sizes (i.e., 1.0 MW)) will limit the use of water mist in larger machinery spaces.

Based on the discussion presented previously, it is unlikely that any system discharging only water will ever successfully complete the protocol for volumes greater than 2000 m^3. The
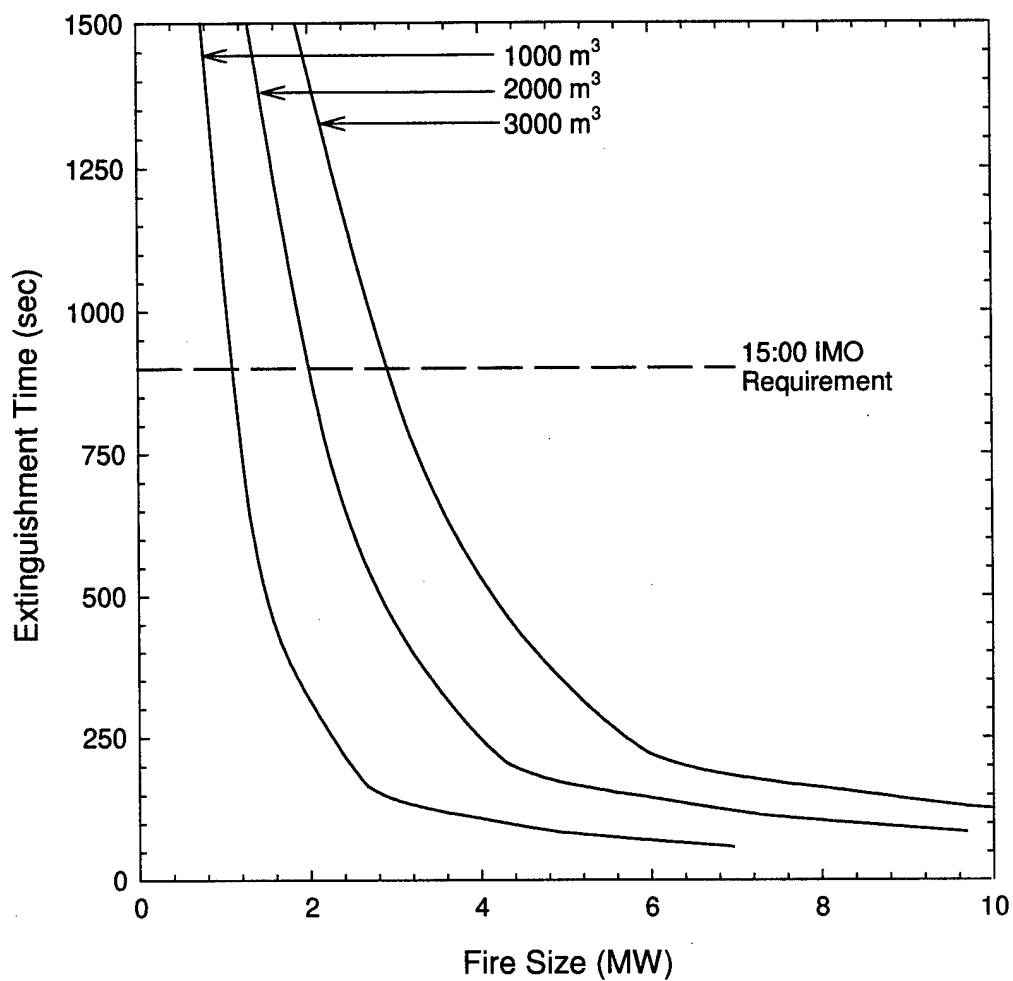
Figure 28. Compartment volume comparison.

lack of an enclosure for volumes greater than 3000 m^3 guarantees that water mist can never be used in these spaces.

11.0 CONCLUSIONS

The capabilities observed for the water mist systems (both zoned and total flooding) in the 3000 m^3 machinery space followed the same trends found throughout the literature. The small fires must be extinguished by direct flame interaction with the mist while the obstructed fires are extinguished primarily by oxygen depletion (indirect effects). Fires that are extinguished by direct flame interaction are typically extinguished in less than one minute and are relatively unaffected by compartment volume or ventilation conditions. Fires that require some degree of oxygen depletion to aid in extinguishment (obstructed fires) have longer extinguishment times which have been shown to be a function of fire size to compartment volume ratio (assuming a constant ventilation condition). The extinguishment times for these fires approach infinity as the size of the fire is reduced to the critical value. This critical value/size is primarily a function of the ventilation conditions in the space. These obstructed fires serve as the limiting case but are somewhat predictable using first principles.

The steady-state extinguishment model developed during previous phases with this investigation was further validated using the results of these tests. The model assumes that obstructed fires are extinguished through a reduction in oxygen concentration resulting from both the consumption of oxygen by the fire and dilution of the oxygen with water vapor. The predictions made by the model showed reasonably good agreement with the results of these tests. Variations between predicted and measured results were attributed to the lack of a well-mixed environment in the space during extinguishment, which is one of the primary assumptions used by the model.

The strengths and weaknesses of the IMO test protocol were also identified. As currently written, the protocol ensures that water mist systems are designed with the proper nozzle spacing and spray characteristics to have a high probability of extinguishing a wide range of fire sizes in

machinery spaces with varying degrees of ventilation. The protocol also ensures that the discharge rate is adequate to provide the required thermal management needed to minimize the damage for the longer extinguishment times that are characteristic of water mist systems for smaller obstructed fires. The conservative nature of the protocol (due to the high ventilation rates and smaller fire sizes (i.e., 1.0 MW)) will however limit the use of water mist in larger machinery spaces. Based on this analysis, it was concluded that it is highly unlikely that any system discharging only water will ever successfully complete the protocol for volumes greater than 2000 m^3.

12.0   RECOMMENDATIONS

The following is a list of recommendations for improving the evaluation and approval process for water mist systems in machinery space applications.

- ◆   Reduce the number of tests in the protocol to the three or four most challenging (Section 10.6);

- ◆   Allow the systems to be evaluated with more representative ventilation conditions (Section 10.5);

- ◆   Scale the test fire size as a function of compartment volume. A 1-2 kW/m^3 scaling rule is recommended (Section 10.6); and

- ◆   Allow the evaluation and approval of zoned total protection systems (Section 10.1).

The following is a list of considerations that might be applicable to the design of water mist systems in large machinery space applications.

- ◆   Install the nozzles with an adequately narrow spacing to ensure complete spray pattern coverage over the protected area;

- Discharge more water high in the space to produce a more uniform mist concentration at all elevations;

- Stagger the nozzle locations between levels; and

- When the upper level of nozzles cannot be installed reasonably close to the overhead (i.e., within 0.5 m), it is recommended that additional nozzles be installed in the grid aiming upward to protect the area above the nozzles.

13.0   REFERENCES

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APPENDIX A- INSTRUMENTATION AND CAMERA DETAILS

F.I.R.E.S.
INSTRUMENT LIST & TEST REQUIREMENTS

TEST NAME: WATER MIST/LARGE MACHINERY	SPACES	ORIGIN: LOWER AFT PORT CORNER

TEST SERIES: 99WM
TOTAL NUMBER OF TESTS: ~42
PROJECT NUMBER: 3308.1.98

TIME FOR EACH TEST: ~20 MIN
SCAN INTERVAL: 1 SEC

#	SP	RE	ID	INSTRUMENTATION DESCRIPTION	SERIAL NUMBER	DISPLAY RANGE / ACTUAL RANGE	LOCATION	REMARKS
0			X	Humidity	10004	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	Wind – Direction	04401A-D	0-360°	Portside, 02 DK	Ambient 0° = Bow
4			X	TC Reference Junction	TC-1	0-50 °C	Portside, 1 DK	Ambient
5		61	X	TC	K50FT 1/8IN.	0-800 °C	13.5, 15.0, 0.5	Fwd TREE
6		61		TC	K50FT 1/8IN.	0-800 °C	13.5, 15.0, 1.4	Fwd TREE
7		61		TC	K50FT 1/8IN.	0-800 °C	13.5, 15.0, 2.3	Fwd TREE
8		61		TC	K50FT 1/8IN.	0-800 °C	13.5, 15.0, 3.2	Fwd TREE
9		61		TC	K50FT 1/8IN.	0-800 °C	13.5, 15.0, 4.1	Fwd TREE
10		61		TC	K50FT 1/8IN.	0-800 °C	13.5, 15.0, 5.0	Fwd TREE
11		61		TC	K50FT 1/8IN.	0-800 °C	13.5, 15.0, 5.9	Fwd TREE
12		61		TC	K50FT 1/8IN.	0-800 °C	13.5, 15.0, 6.8	Fwd TREE
13		61		TC	K50FT 1/8IN.	0-800 °C	13.5, 15.0, 7.7	Fwd TREE
14		61		TC	K50FT 1/8IN.	0-800 °C	2.0, 17.8, 0.5	Aft TREE
15		61		TC	K50FT 1/8IN.	0-800 °C	2.0, 17.8, 1.4	Aft TREE
16		61		TC	K50FT 1/8IN.	0-800 °C	2.0, 17.8, 2.3	Aft TREE
17		61		TC	K50FT 1/8 IN.	0-800 °C	2.0, 17.8, 3.2	Aft TREE
18		61		TC	K50FT 1/8 IN.	0-800 °C	2.0, 17.8, 4.1	Aft TREE
19		61		TC	K50FT 1/8 IN.	0-800 °C	2.0, 17.8, 5.0	Aft TREE
20		61		TC	K50FT 1/8 IN.	0-800 °C	2.0, 17.8, 5.9	Aft TREE

F.I.R.E.S.
INSTRUMENT LIST & TEST REQUIREMENTS

TEST NAME: WATER MIST/LARGE MACHINERY	SPACES	ORIGIN: LOWER AFT PORT CORNER
TEST SERIES: 99WM		TIME FOR EACH TEST: ~20 MIN
TOTAL NUMBER OF TESTS: ~42		SCAN INTERVAL: 1 SEC
PROJECT NUMBER: 3308.1.98		

#	CHANNEL			INSTRUMENTATION DESCRIPTION	SERIAL NUMBER	DISPLAY RANGE ACTUAL RANGE	LOCATION	REMARKS
	SP	RE	ID					
21		61		TC	K50FT 1/8 IN.	0-800 °C	2.0, 17.8, 6.8	Aft TREE
22		61		TC	K50FT 1/8 IN.	0-800 °C	2.0, 17.8, 7.7	Aft TREE
23	X	61		TC	K50FT 1/8 IN.	0-800 °C	18.0, 11.0, 1.4	FIRE TC
24	X	61		TC	K50FT 1/8 IN.	0-800 °C	18.0, 11.0, 6.8	FIRE TC
25			X	CO	41092	0-5 % / 0-10 %	13.5, 14.5, 1.4	Fwd TREE
26			X	CO_2	1000694	0-15 % / 0-25 %	13.5, 14.5, 1.4	Fwd TREE
27	X		X	O_2	1001451	11-21 % / 0-25 %	13.5, 14.5, 1.4	Fwd TREE
28				CO	41093	0-5 % / 0-10 %	13.5, 14.5, 4.1	Fwd TREE
29				CO_2	1000695	0-15 % / 0-25 %	13.5, 14.5, 4.1	Fwd TREE
30	X			O_2	1001637	11-21 % / 0-25 %	13.5, 14.5, 4.1	Fwd TREE
31				CO	41094	0-5 % / 0-10 %	13.5, 14.5, 6.8	Fwd TREE
32				CO_2	1000696	0-15 % / 0-25 %	13.5, 14.5, 6.8	Fwd TREE

A-2

F.I.R.E.S.
INSTRUMENT LIST & TEST REQUIREMENTS

TEST NAME: WATER MIST/LARGE MACHINERY	SPACES	ORIGIN: LOWER AFT PORT CORNER
TEST SERIES: 99WM		TIME FOR EACH TEST: ~20 MIN
TOTAL NUMBER OF TESTS: ~42		SCAN INTERVAL: 1 SEC
PROJECT NUMBER: 3308.1.98		

CHANNEL				INSTRUMENTATION DESCRIPTION	SERIAL NUMBER	DISPLAY RANGE	ACTUAL RANGE	LOCATION	REMARKS
#	SP	RE	ID						
33	X			O_2	1001638	11-21 %	0-25 %	13.5, 14.5, 6.8	Fwd TREE
34				CO	41344	0-5 %	0-10 %	2.0, 17.5, 1.4	Aft TREE
35				CO_2	1000697	0-15 %	0-25 %	2.0, 17.5, 1.4	Aft TREE
36	X			O_2	1001641	11-21 %	0-25 %	2.0, 17.5, 1.4	Aft TREE
37				CO	41347	0-5 %	0-10 %	2.0, 17.5, 4.1	Aft TREE
38			X	CO_2	34056	0-15 %	0-25 %	2.0, 17.5, 4.1	Aft TREE
39				O_2	2002456	11-21 %	0-25 %	2.0, 17.5, 4.1	Aft TREE
40				CO	0103495	0-5 %	0-10 %	2.0, 17.5, 6.8	Aft TREE
41				CO_2	34057	0-15 %	0-25 %	2.0, 17.5, 6.8	Aft TREE
42				O_2	2002457	11-21 %	0-25 %	2.0, 17.5, 6.8	Aft TREE

INSTRUMENT LIST & TEST REQUIREMENTS

TEST NAME: WATER MIST/LARGE MACHINERY SPACES | ORIGIN: LOWER AFT PORT CORNER

TEST SERIES: 99WM

TOTAL NUMBER OF TESTS: ~42 | TIME FOR EACH TEST: ~20 MIN

PROJECT NUMBER: 3308.1.98 | SCAN INTERVAL: 1 SEC

#	SP	RE	ID	INSTRUMENTATION DESCRIPTION	SERIAL NUMBER	DISPLAY RANGE	ACTUAL RANGE	LOCATION	REMARKS
43	X			O_2	2002909	11-21 %	0-25 %	Fire Locations	FIRE O^2
44			X	RAD	682111	0-50 kW/m^2	0-113.5 kW/m^2	11.8, 11.0, 1.4	4TH DECK
45			X	CAL	87622	0-50 kW/m^2	0-113.5 kW/m^2	11.8, 11.0, 1.4	4TH DECK
46				RAD	924853	0-50 kW/m^2	0-56.5 kW/m^2	11.0, 9.5, 4.1	3RD DECK
47				CAL	72876	0-50 kW/m^2	0-113.5 kW/m^2	11.0, 9.5, 4.1	3RD DECK
48				RAD	682112	0-50 kW/m^2	0-113.5 kW/m^2	11.8, 11.0, 6.8	2ND DECK
49				CAL	68215	0-50 kW/m^2	0-113.5 kW/m^2	11.8, 11.0, 6.8	2ND DECK
50			X	PRESS	223787	+/-1244 Pa		0.0, 13.5, 1.4	4TH DECK
51				PRESS	223788	+/-1244 Pa		0.0, 13.5, 4.1	3RD DECK
52				PRESS	223789	+/-1244 Pa		0.0,13.5, 6.8	2ND DECK
53				PRESS	139969	1723 kPa		Outside Compt	FUEL PRESS
54	X			PRESS	586325	0-7000 kPa	0-20658 kPa	On Manifold	MIST PUMP

F.I.R.E.S.
INSTRUMENT LIST & TEST REQUIREMENTS

TEST NAME: WATER MIST/LARGE MACHINERY SPACES					ORIGIN: LOWER AFT PORT CORNER
TEST SERIES: 99WM					TIME FOR EACH TEST: ~20 MIN
TOTAL NUMBER OF TESTS: ~42					SCAN INTERVAL: 1 SEC
PROJECT NUMBER: 3308.1.98					

CHANNEL				INSTRUMENTATION DESCRIPTION	SERIAL NUMBER	DISPLAY RANGE / ACTUAL RANGE	LOCATION	REMARKS
#	SP	RE	ID					
55				PRESS	586326	0-7000 kPa / 0-20658 kPa	2.5, 2.5, 2.7	4TH DECK
56				PRESS	586327	0-7000 kPa / 0-20658 kPa	2.5, 2.5, 5.4	3RD DECK
57				PRESS	586328	0-7000 kPa / 0-20658 kPa	2.5, 2.5, 8.2	2ND DECK
58				PRESS	780521	0-3735 Pa	VARIABLE	FUEL REGRESSION
59			X	FLOW	259	0-1500 Lpm / 0-31.5 Lps	In Inlet Line	INLET FLOW
60			X	FLOW	258	0-1500 Lpm / 0-31.5 Lps	In Bypass Line	BYPASS FLOW
61				TC Reference Junction	TC-2	0-50 °C	I/O Patch Box	Ambient