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WATER SPRAY PROTECTION OF MACHINERY SPACES

FINAL REPORT
March 2001

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NOTICE

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16. Abstract (MAXIMUM 200 WORDS)

This report provides an evaluation of the firefighting capabilities of fixed pressure water spray systems for machinery spaces as described in Regulation 10 of Safety of Life at Sea (SOLAS). The objective of this evaluation was to determine if a system meeting the minimum SOLAS requirement can provide adequate protection of shipboard machinery spaces.

To meet this objective, the capabilities and limitations of twelve water spray systems were determined using the International Maritime Organization (IMO) test protocol for water mist systems (MSC 668 and 728) as the basis for this analysis. The tests were conducted in a simulated 500 m^3 machinery space onboard the U.S. Coast Guard's test vessel STATE OF MAINE.

Generally speaking, the trends in performance of water spray systems were similar to those observed for water mist systems. All systems were capable of extinguishing larger fires (4 kW/m^3 and greater) with variations in system capabilities becoming apparent as the fire size was reduced (2 kW/m^3 and below). Only about half of the systems were capable of extinguishing the 1.0 MW obstructed spray fire located on the side of the engine mockup (similar to IMO-6). Water mist systems typically exhibit slightly better capabilities primarily against the smaller fires.

It was concluded that the capabilities of these systems cannot be associated with a single parameter such as application rate and must be determined empirically. As a result, the approval of these systems needs to be performance based as with all other fire suppression systems required by SOLAS. It was recommended that SOLAS Regulation 10 be re-written to cover all water based machinery space systems with the caveat that they pass a modified IMO test protocol based on the one currently used for approving water mist systems [MSC 668 and 728].

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EXECUTIVE SUMMARY

The United States Coast Guard (USCG) has been actively involved in evaluating alternative fire suppression methods and replacement agents for Halon 1301 total flooding systems for machinery space applications. The research conducted to date includes evaluations of both the gaseous halon alternatives (halocarbons and inert gases) and water mist fire suppression systems. This experimental program was a continuation of this research and looked at the capabilities of water spray systems for machinery space applications.

The International Maritime Organization (IMO) allows the use of fixed pressure water spray fire extinguishing systems in machinery spaces per Regulation 10 Chapter II-2 of SOLAS (Safety of Life at Sea). Currently, the Code of Federal Regulations does not permit the use of fixed pressure water spray systems for vessels registered in the United States. Therefore, it was USCG's desire to determine if the systems meeting this requirement can provide adequate protection of shipboard machinery spaces.

The capabilities and limitations of twelve water spray systems meeting the minimum SOLAS requirement were determined using the IMO test protocol for water mist systems (MSC 668 and 728) as the basis for this analysis. The tests were conducted in a simulated 500 m^3 machinery space onboard the test vessel STATE OF MAINE located at the U.S. Coast Guard's Fire & Safety Test Detachment in Mobile, AL.

The trends in performance observed during these tests were generally similar to those of water mist systems. Both water spray and water mist systems rely on oxygen depletion to extinguish obstructed fires making larger fires easier to extinguish and go out faster than smaller fires.

The distinction between the two types of systems (mist versus spray) was observed for the smaller fires. The water mist systems had better capabilities against small fires than water spray systems. All of the water spray systems were capable of extinguishing larger fires (with volumetric heat release rates of 4 kW/m^3 and greater) with variations in system capabilities

becoming apparent as the fire size was reduced (2 kW/m^3 and below). Only about half of the systems included in this evaluation were capable of extinguishing the 1.0 MW obstructed spray fire located on the side of the engine mockup (similar to IMO-6). Most of the commercially available water mist systems are capable of extinguishing this fire.

The performance/capabilities of these water spray systems were shown to be linked to two parameters; vapor production and vent flow effects. In an actual installation where the space would be secured during a fire, the production of water vapor is the key parameter. As a result, the smaller the drops, the better the performance of the system (assuming good mixing).

A droplet evaporation algorithm was developed and added to the water mist fire suppression model developed and validated during previous USCG investigations ("A quasi-steady-state model for predicting fire suppression in spaces protected by water mist systems"). The modified model showed good agreement with the results of these tests and was used to define the capabilities and limitations of these systems as a function of drop size.

It was concluded that the capabilities of these systems cannot be associated with a single parameter such as application rate and must be determined empirically. As a result, the approval of these systems needs to be performance based as with all other fire suppression systems required by SOLAS for this application. It was recommended that SOLAS Regulation 10 be re-written to cover all water based machinery space systems (water spray and water mist), and require that these systems successfully complete an IMO test protocol such as the one currently used for approving water mist systems [MSC 668 and 728] or one derived from those incorporating the recommendations put forth in this report.

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

Page

LIST OF FIGURES

LIST OF TABLES

Page

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1.0 INTRODUCTION

The United States Coast Guard (USCG) has been actively involved in evaluating alternative fire suppression methods and agents for Halon 1301 total flooding systems for machinery space applications. The research conducted to date includes evaluations of both the gaseous halon alternatives (halocarbons and inert gases) and water mist fire suppression systems. This experimental program was a continuation of this research and evaluated the capabilities of water spray systems for machinery space applications.

The International Maritime Organization (IMO) allows the use of fixed pressure water spray fire extinguishing systems in machinery spaces per Regulation 10 Chapter II-2 of SOLAS (Safety of Life at Sea). Currently, the Code of Federal Regulations does not permit the use of fixed pressure water spray systems for vessels registered in the United States. The goal of this effort was to determine if the fixed water pressure systems meeting this SOLAS regulation can provide adequate protection of shipboard machinery spaces.

This work was performed under a Research & Development project for the Life Saving and Fire Safety Division (G-MSE-4) of USCG Headquarters. This project was part of an ongoing investigation established to define the fire suppression requirements for shipboard machinery spaces.

2.0 OBJECTIVES

The overall objective of this evaluation was to identify the capabilities and limitations of fixed pressure water spray fire protection systems as applied to a range of machinery space applications. More specifically, our goal was to determine if a system meeting the minimum SOLAS requirements can provide adequate protection of shipboard machinery spaces.

3.0 TECHNICAL APPROACH

To meet the program objectives, a two-phase full-scale fire test series was conducted in a simulated machinery space onboard the USCG's test vessel, STATE OF MAINE. The firefighting capabilities of a group of representative water spray systems were determined using the IMO test protocol for evaluating water mist systems (MSC Circular 668 and 728). Although the protocol was written specifically for water mist systems, it contains typical machinery space fire scenarios and provided a direct comparison between these water spray systems and previously tested water mist systems. A copy of the test protocol is found in Appendix A.

The initial phase of this investigation focused on identifying the firefighting capabilities of a group of representative systems. These systems were selected to cover the range of typical design parameters currently used throughout the industry. The second phase consisted of a parametric study intended to identify the relative contribution of the various system parameters (spray characteristics and system discharge rate) on the overall capabilities of the system. During these parametric studies, the systems were designed (i.e., nozzles were selected) with the intent that only one parameter (discharge characteristic) was varied at a time.

Prior to conducting this investigation, a futile attempt was made to identify a "typical" set of design characteristics for these systems by soliciting information from people active in the maritime industry. The general lack of knowledge of these systems was attributed to the time frame when the requirement was first implemented. The regulation was adopted by SOLAS over thirty-five years ago before the development and wide spread use of Halon 1301. The superior capabilities of the gaseous extinguishing agents have apparently made these water spray systems obsolete.

Since a set of typical design characteristics for these systems could not be identified, the capabilities evaluation focused on the minimum design requirement (5 Lpm/m^2) as stated in SOLAS. It was assumed that increasing the flow rate would increase the capabilities of the system making the minimum SOLAS requirement the limiting case. Five systems were designed to meet this requirement. These systems consisted of two standard sprinkler systems (NFPA-13 listed by Underwriters Laboratories Inc. (UL)), a water spray system (NFPA-15 listed by UL), and two generic systems produced using off-the-shelf industrial spray nozzles. One of the generic systems produced a coarse spray and the other a fine spray. The range of spray characteristics of these five systems was selected with the intent to identify the effect that droplet size has on the firefighting capabilities of the system.

A Navigation and Vessel Inspection Circular (NVIC) issued in August 1972 (USCG, NVIC 6-72) provides a description of nine USCG approved water spray systems for shipboard pump rooms and paint lockers, as well as the required design/installation parameters for each system. This NVIC which serves as a guide for fixed firefighting equipment on merchant vessels is still in effect today. The nozzles/systems described in the NVIC served to some extent as the base line for the parametric study (Phase II).

The parametric study evaluated the effects that application rate, spray pattern angle and system operating pressure have on the firefighting capabilities of the system. The application rates included in the study ranged from 5.0-17.1 Lpm /m^2. Spray pattern angles included 60, 90 and 120 degrees. The system operating pressures ranged from 3.5-8.5 bar.

4.0 TEST COMPARTMENT

The tests were conducted in the simulated machinery space aboard the test vessel, STATE OF MAINE, at the USCG Fire and Safety Test Detachment located at Little Sand Island in Mobile, AL. The machinery space is located on the fourth deck of the Number 6 cargo hold. The compartment was constructed to meet the dimensional requirements of other IMO test protocols. The compartment volume is approximately 500 m^3 with nominal dimensions of 10 m × 10 m × 5 m as shown in Figure 1. The diesel engine mock-up described in the test protocol is located on the fourth deck in the center of the compartment as shown in Figure 2. Air to support combustion was provided naturally through two 2 m^2 vent openings located on the fourth deck forward in the compartment. This ventilation configuration is slightly different than the

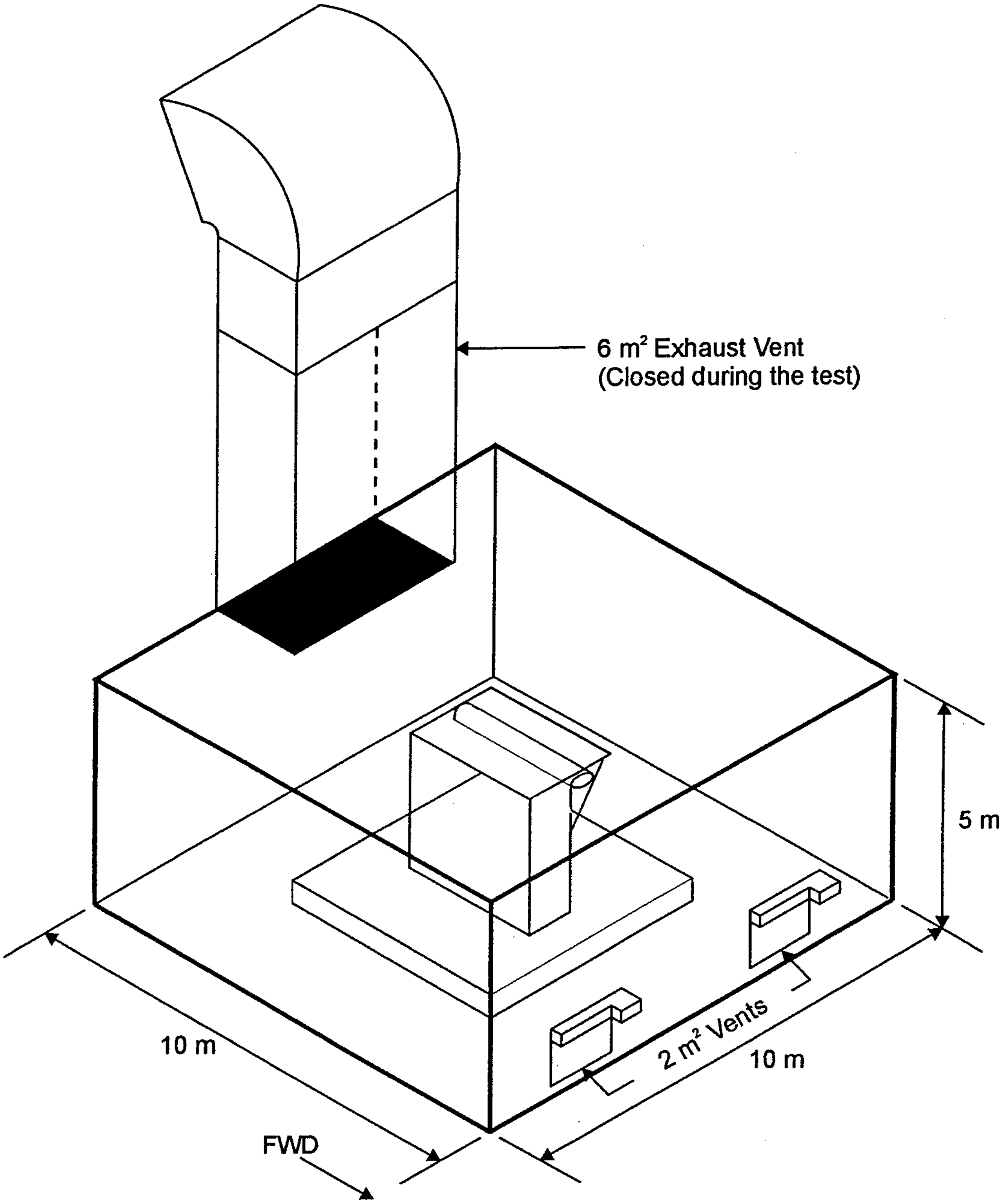
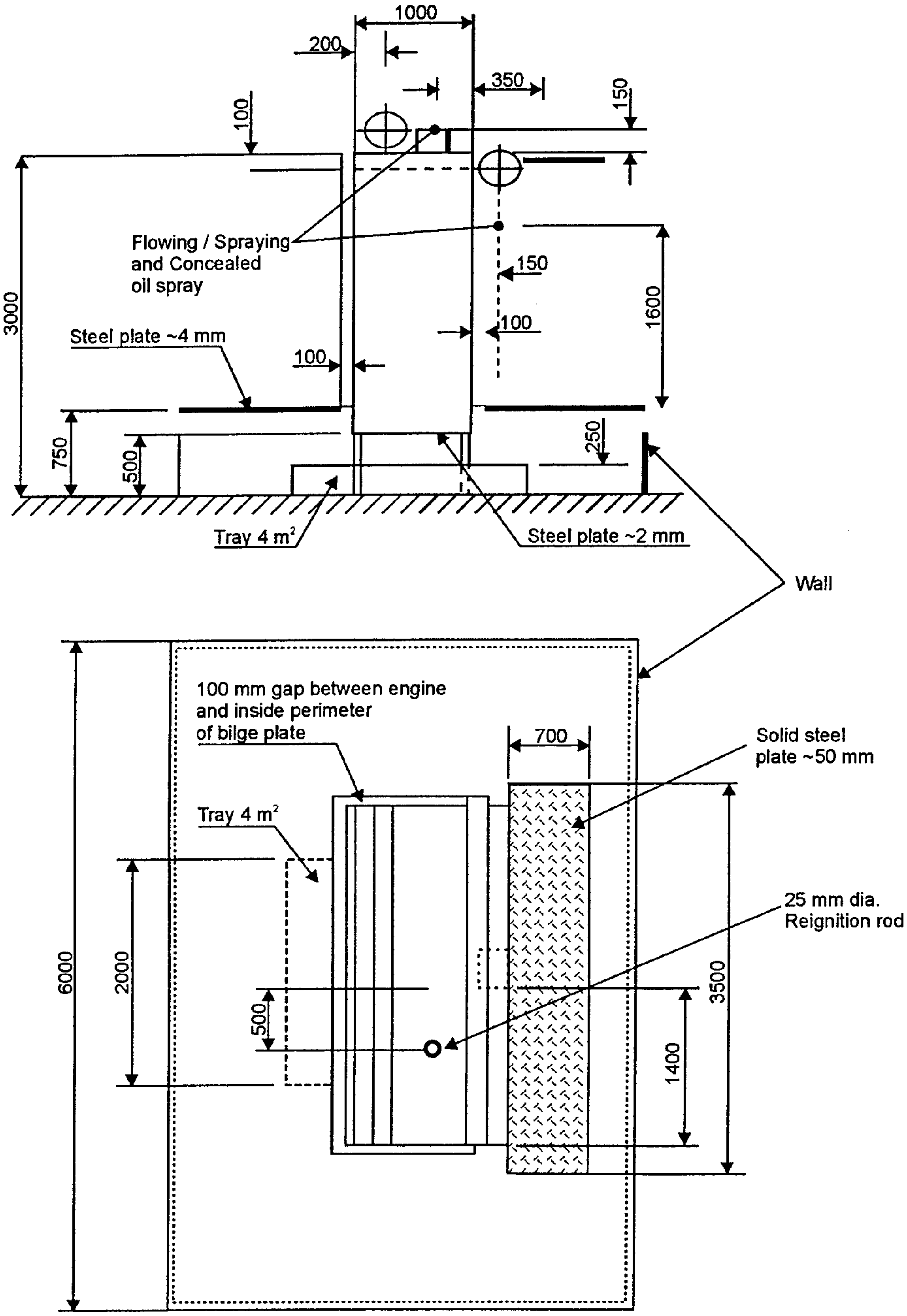


Figure 1. Machinery space configuration.



(All measurements are in mm, unless otherwise noted.)

Figure 2. Diesel engine mock-up.

single 4 m^2 vent opening described in the test protocol but did not appear to adversely affect the results of these tests.

5.0 WATER SPRAY SYSTEMS

5.1 Nozzles

Twelve water spray nozzles were evaluated in this test program. Five nozzles/systems were evaluated in the first phase and seven additional nozzles/systems were evaluated in the second phase of this investigation. The capabilities of all twelve nozzles/systems were however included in the parameter analysis (Phase II). All nozzles were installed in a pendent orientation and evaluated with either a 1.5 or 3 m spacing. A brief description of each nozzle is given in the following sections of this report. The spray characteristics of these nozzles stated in the following sections were provided by the manufacturer [Bete 1994; Grinnell 1994; Viking 1995] and validated in the laboratory at Hughes Associates, Inc. (HAI).

5.1.1 Phase I Nozzles (System Capabilities)

Five water spray nozzles/systems were evaluated in the initial phase of this test program. All five nozzles have a 90° spray pattern. The systems produced using these nozzles met the minimum application rate defined in SOLAS Regulation 10 (5.0 Lpm/m^2). The first three systems consist of two UL listed sprinklers (NFPA-13) and one water spray system (NFPA-15). The last two systems cover the range of drop sizes from coarse to fine with the same spray patterns and flow rates as the other three systems. A description of these nozzles and how they were tested is given in the following paragraphs.

5.1.1.1 Grinnell Model A (Pendent)

The Grinnell Model A is a UL listed NFPA-13 sprinkler head. The Model A is available with a variety of orifice sizes. The nozzle used in this evaluation had a nominal k-factor of 60.0 Lpm/bar$^{1/2}$. To produce the minimum application rate of 5.0 Lpm/m^2 specified in SOLAS, the nozzles were installed with a 3.0 m nozzle spacing and operated at a pressure of 0.9 bar. At this pressure, each nozzle flowed approximately 45 Lpm with a mean drop size (Sauter Mean) of 1000 microns.

5.1.1.2 Viking Model M (Pendent)

The Viking Model M is a UL listed NFPA-13 sprinkler head. The Model M is available with a variety of orifice sizes. The nozzle used in this evaluation had a nominal k-factor of 40.0 Lpm/bar$^{1/2}$. To produce the minimum application rate of 5.0 Lpm/m^2 specified in SOLAS, the nozzles were installed with a 3.0 m nozzle spacing and operated at a pressure of 1.3 bar. At this pressure, each nozzle flowed 45 Lpm with a mean drop size (Sauter Mean) of 900 microns.

5.1.1.3 Bete Fog Nozzle Model N2

The N2 nozzle is a UL listed NFPA-15 water spray nozzle. The N2 nozzle has a nominal k-factor of 24.0 Lpm/bar$^{1/2}$. To produce the minimum application rate of 5.0 Lpm/m^2 specified in SOLAS, the nozzles were installed with a 3.0 m nozzle spacing and operated at a pressure of 3.5 bar. At this pressure, each nozzle flowed 45 Lpm with a mean drop size (Sauter Mean) of 520 microns.

5.1.1.4 Bete Fog Nozzle Model WL15

The WL15 is a large drop water spray nozzle with a similar spray pattern as the other nozzles included in this evaluation. The WL15 has a nominal k-factor of 33.0 Lpm/bar$^{1/2}$. To produce the minimum application rate of 5.0 Lpm/m^2 specified in SOLAS, the nozzles were installed with a 3.0 m nozzle spacing and operated at a pressure of 1.9 bar. At this pressure, each nozzle flowed 45 Lpm with a mean drop size (Sauter Mean) of 850 microns.

5.1.1.5 Bete Fog Nozzle Model P120

The P120 is a fine atomizing mist nozzle that produces small drops at relatively low pressures. The P120 was evaluated to bound the range of capabilities of these systems by producing a low pressure water mist system designed to operate at relatively the same pressure as the other water spray systems (fireman pressures). The P120 has a nominal k-factor of 5.5 Lpm/bar$^{1/2}$ producing a flow rate of 11.4 Lpm at a pressure of 4.3 bar. These nozzles were installed with a 1.5m spacing producing the 5.0 Lpm/m^2 application rate required by SOLAS.

During the second Phase of this investigation, the P120 was evaluated at the same nozzle spacing (1.5m) but at a higher pressure (8.5 bar vs. 4.3 bar). At this pressure, the system produced an application rate of 7.1 Lpm/m^2. At 4.3 bar the nozzle produces a mean drop size (Sauter Mean) of 350 microns and at 8.5 bar a mean drop size of 300 microns

5.1.2 Phase II Nozzles (Parametric Studies)

Seven water spray nozzles/systems were evaluated in the second phase of this test program. All seven nozzles were manufactured by Bete Fog Nozzle Inc. Initially, two nozzles (Models N3 and N5) currently approved in NVIC 6-72 were evaluated. The system produced with the N3 nozzles has the lowest application rate approved by the USCG while the system produced with the N5 nozzles has the highest. Two reduced flow rate systems/nozzles were also evaluated (TF6-120 and TF10-120). These nozzles are similar in design to the N series nozzles but are available with a wider range of flow rates and spray patterns. Two additional nozzles (a Model TF16 with a 60° spray pattern and a Model TF16 with a 120° spray pattern) were also evaluated. A description of these nozzles and how they were tested is given in the following paragraphs.

5.1.2.1 Bete Fog Nozzle Model N3

The N3 nozzle is a water spray nozzle currently USCG approved for use in fixed firefighting systems in pump rooms and paint lockers on merchant vessels. The N3 nozzle has a nominal k-factor of 38.2 Lpm/bar$^{1/2}$. To produce the minimum application rate of 8.5 Lpm/m^2 specified in NVIC 6-72, the nozzles were installed with a 3.0 m nozzle spacing and operated at a pressure of 4.3 bar. At this pressure, each nozzle flowed 79.2 Lpm with a mean drop size (Sauter Mean) of 600 microns.

5.1.2.2 Bete Fog Nozzle Model N5

The N5 nozzle is a water spray nozzle also currently USCG approved for use in fixed firefighting systems in pump rooms and paint lockers on merchant vessels. The N5 nozzle has a nominal k-factor of 76.5 Lpm/bar$^{1/2}$. To produce the minimum application rate of 17.0 Lpm/m^2 specified in NVIC 6-72, the nozzles were installed with a 3.0 m nozzle spacing and operated at a pressure of 4.3 bar. At this pressure, each nozzle flowed 158.6 Lpm with a mean drop size (Sauter Mean) of 850 microns.

5.1.2.3 Bete Fog Nozzle Model TF6

The TF nozzles are water spray nozzles similar in design to the N series nozzles but are available in a wider range of flow rates. The TF6 has a nominal k-factor of 3.2 Lpm/bar$^{1/2}$. The nozzles were installed with a 3.0 m spacing and operated at a pressure of 7.0 bar to produce an application rate of 0.9 Lpm/m^2. At this pressure, each nozzle flowed 8.4 Lpm with a mean drop size (Sauter Mean) of 250 microns.

5.1.2.4 Bete Fog Nozzle Model TF10

The TF nozzles are water spray nozzles similar in design to the N series nozzles but are available in a wider range of flow rates. The TF10 has a nominal k-factor of 9.0 Lpm/bar$^{1/2}$. The nozzles were installed with a 3.0 m spacing and operated at a pressure of 7.0 bar to produce an application rate of 2.7 Lpm/m^2. At this pressure, each nozzle flowed 24 Lpm with a mean drop size (Sauter Mean) 325 microns.

5.1.2.5 Bete Fog Nozzle Model TF14

The TF nozzles are water spray nozzles similar in design to the N series nozzles but are available in a wider range of flow rates. The TF14 has a nominal k-factor of 18.3 Lpm/bar$^{1/2}$. The nozzles were installed with a 3.0 m spacing and operated at a pressure of 7.0 bar to produce an application rate of 5.0 Lpm. At this pressure, each nozzle flowed 45 Lpm with a mean drop size (Sauter Mean) of 375 microns.

5.1.2.6 Bete Fog Nozzle Model TF16

As with the other TF nozzles, the TF16 is a water spray nozzle similar in design to the N series nozzles but is available in a wider range of spray patterns. The TF16 has a nominal k-factor of 24.0 Lpm/bar$^{1/2}$. To produce the minimum application rate of 5.0 Lpm/m^2, the nozzles were installed with a 3.0 m spacing and operated at a pressure of 3.5 bar. At this pressure, each nozzle flowed 45 Lpm. Both 60° and 120° spray pattern nozzles were evaluated. The 60° nozzle produces a spray with a mean drop size (Sauter Mean) of 550 microns and the 120° spray with a mean drop size of 500 microns.

5.2 Discharge System

The discharge system consisted of uniformly spaced nozzles installed in the overhead of the test space as shown in Figure 3. A grid system design with 25 nozzle ports was selected for this application. The nozzle ports were spaced 1.5 m apart with the appropriate nozzle locations plugged when a 3.0 m nozzle spacing was evaluated. The pipe network was installed approximately 0.3 m below the overhead to ensure that the structural members (stiffeners) in the space did not interfere with the spray patterns of the nozzles.

The pipe network was constructed of schedule 40 galvanized pipe and connected together with galvanized threaded fittings (Class 150). The system consisted of a 10 cm diameter supply line, two 6.35 cm diameter cross mains, and five 3.8 cm diameter branch lines as shown in Figure 3.

The system was pressurized using a Carver self-priming centrifugal pump. The pump was capable of providing a minimum flow rate of 1900 Lpm at 10 bar. The system pressure was regulated by directing a percentage of the pump discharge through a bypass line during the test. The water discharged by the system during the test was drawn directly from Mobile Bay.

A hydraulic analysis was conducted on the system to ensure that the nozzle pressures and flow rates did not significantly vary across the system. The hydraulic analysis was conducted

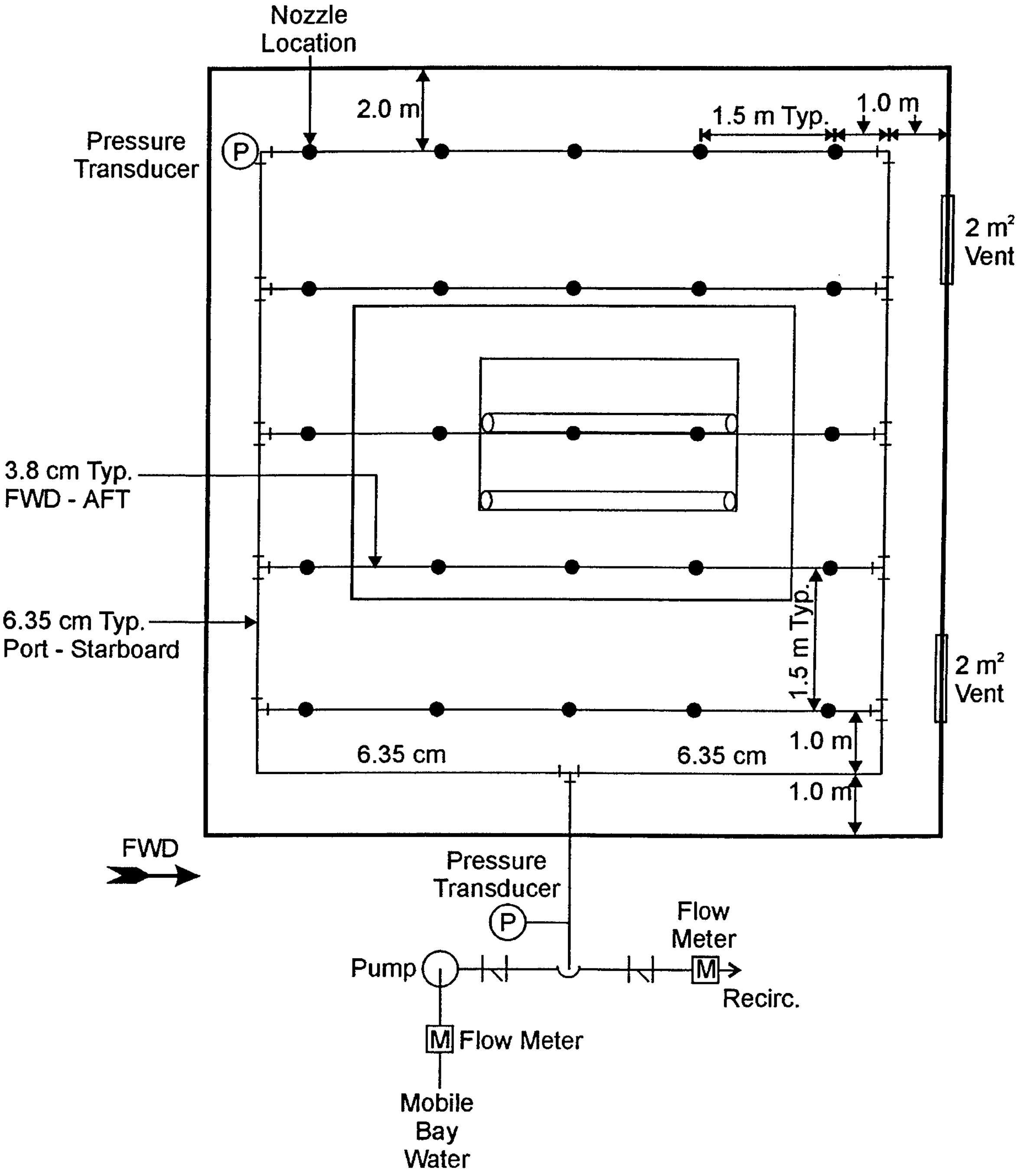


Figure 3. Discharge system.

using the computer model HASS (Hydraulic Analysis for Sprinkler Systems (HASS, 1996)). In the worst case scenario when all of the water supplied by the pump (1900 Lpm at 10 bar) was discharged through the nozzles, the nozzle flow rate only varied by approximately 7%. This variation was reduced to less than 5% for the actual system flow rates included in this evaluation.

6.0 FIRE SCENARIOS

The IMO test protocol for evaluating water mist systems (MSC Circular 668 and 728) was selected as the basis of this evaluation. A copy of this protocol is found in Appendix A. The thirteen tests included in the protocol are listed in Table 1. In order to successfully complete the protocol, all fires must be extinguished within 15 minutes of mist system activation. Four of these tests (IMO 4, 7, 8, and 13) are intended to evaluate the capabilities of a bilge fire suppression system but were still conducted during this investigation. Only a limited number of nozzles/systems were evaluated against the complete IMO test protocol.

Previous studies have identified five specific IMO tests or derivations thereof that appear to distinguish between the higher and somewhat lower performance water mist systems [Back et al. 1998]. These tests consist of the two larger spray fires, IMO-2 and IMO-3; the two smaller spray fires, IMO-5 and IMO-6; and the small pan fire, IMO-9. All twelve water spray systems were initially evaluated against these five fire scenarios using heptane as the fuel. Heptane is a lower flashpoint fuel that burns cleaner than diesel which allows a faster turnaround between tests. The lower flashpoint also makes these fires slightly more difficult to extinguish. This subset of tests provided the data for the parametric evaluation (Phase II) and allowed for the selection of two systems to be thoroughly evaluated against the complete test protocol. After completion of these tests, the two selected water spray systems were evaluated against the required thirteen IMO tests to provide a direct comparison between the extinguishing capabilities of these systems and the previously evaluated water mist systems.

Table 1. 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 fuel
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 fuel
IMO-3	Low-pressure, concealed horizontal spray fire on side of simulated engine with oil spray nozzle positioned 0.1 m in front of the engine (6.0 MW)	Commercial fuel oil or light diesel fuel
IMO-4	Combination of worst spray fire from Tests 1-3 and fires in trays under and on top of the simulated engine	Commercial fuel oil or light diesel fuel
IMO-5	High pressure horizontal spray fire on top of simulated engine (2.0 MW)	Commercial fuel oil or light diesel fuel
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 fuel
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	Heptane
IMO-11	Class A fires UL 1626 wood crib in 2 m^2 pool fire with 30-second pre-burn	Heptane
IMO-12	A steel plate (30 cm × 60 cm × 5 cm) offset 20° to the spray is heated by the top low-pressure, low-flow spray nozzle. When 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 fuel

The fuel pans used during these tests were square in shape and were constructed of 3.2 mm steel plate with welded joints. The pans were 15 cm in depth with side dimensions of 74.0 cm, 120 cm and 144 cm for the 0.5 m^2, 1 m^2 and 2 m^2 pans, respectively. These pans were filled with a 2.5 cm deep layer of water and a 5 cm deep layer of fuel. The pan fires pre-burned (fire allowed to burn without suppression applied) for one minute prior to system activation.

Each wood crib consisted of nine layers of six members. Each member was trade size 5 × 5 × 45 cm (actual 3.8 × 3.8 × 45 cm) fir with a moisture content between 4% and 7%. The wood crib was placed on an angle iron frame 0.3 m above the deck. The crib was ignited using a

$2.0\ m^2$ heptane pan fire. The wood crib/pan combination pre-burned for 30 seconds prior to system activation.

The spray fire parameters are given in Table 2. The low pressure spray fires were produced using a pressurized fuel tank and a pipe network constructed of 1.2 cm stainless steel tubing. The fuel flow was controlled by both a manual quarter-turn ball valve and a remotely actuated solenoid valve. The fuel tank was pressurized with nitrogen from a regulated cylinder. The high pressure spray was produced using a positive displacement pump and a similar pipe network constructed of 1.2 cm stainless steel tubing. The fuel flow was again controlled by both a manual quarter-turn ball valve and a remotely actuated solenoid valve. The fuel spray fires pre-burned for 5-15 seconds before system activation.

Table 2. Spray fire parameters.

Fire Type	Low Pressure	Low Pressure, Low Flow	High Pressure
Spray nozzle	Wide spray angle (120-125) full cone type	Wide spray angle (80) full cone type	Standard angle (at 6 bar) full cone type
Nozzle make and model	Bete Fog Nozzle P120	Bete Fog Nozzle P-48	Spray Systems LN-8
k-factor	5.5 Lpm/bar$^{1/2}$	0.9 Lpm/bar$^{1/2}$	0.3 Lpm/bar$^{1/2}$
Pressure	3.5 bar	3.5 bar	100 bar
Fuel flow rate	0.16 ± 0.01 kg/s	0.03 ± 0.005 kg/s	0.050 ± 0.002 kg/s
Fuel temperature	20 ± 5 °C	20 ± 5 °C	20 ± 5 °C
Nominal heat release rate	5.8 ± 0.6 MW	1.1 ± 0.1 MW	1.8 ± 0.2 MW

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, and carbon monoxide, carbon dioxide and oxygen gas concentrations as shown in Figure 4.

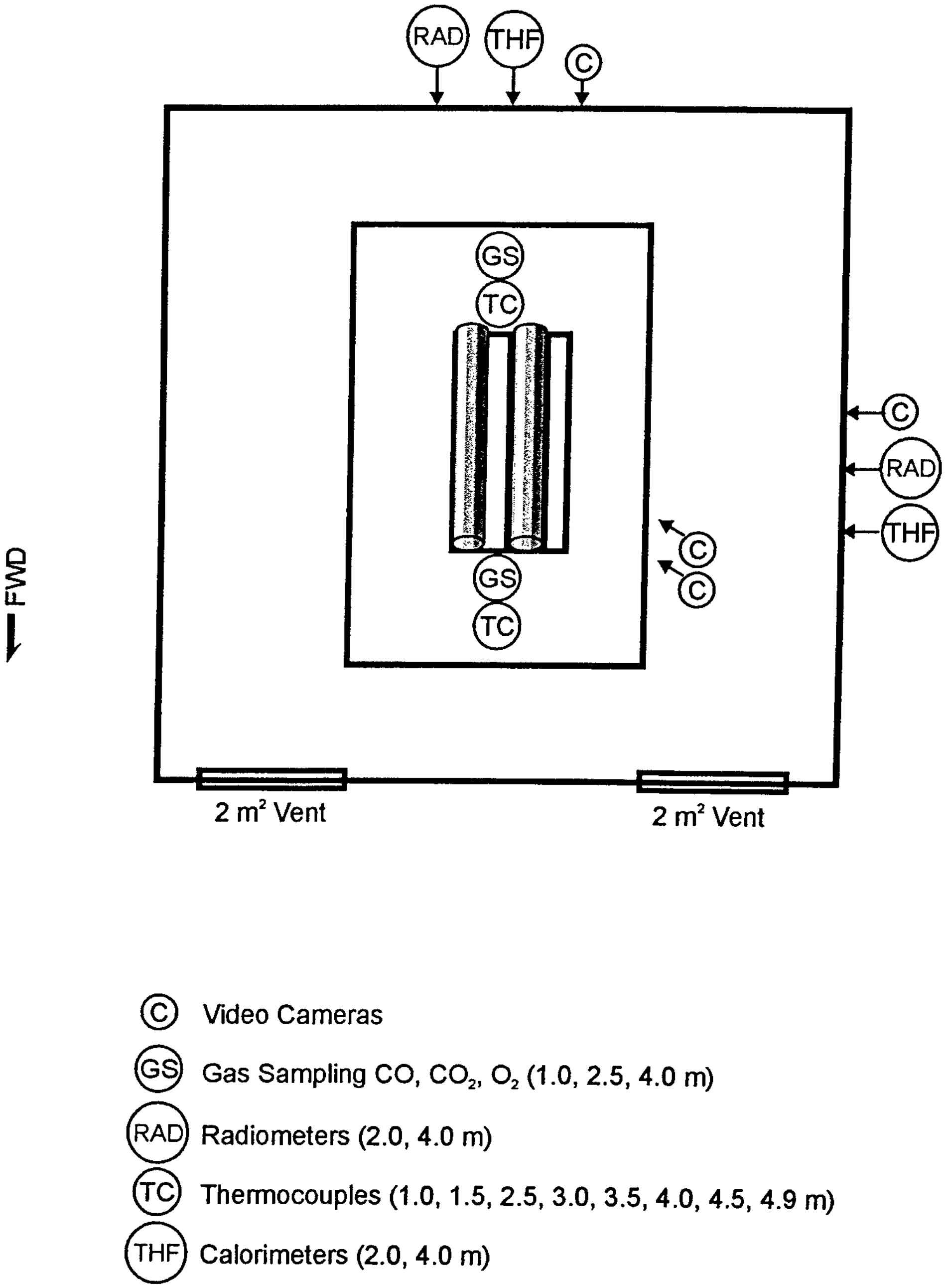


Figure 4. Instrumentation.

Measurements were recorded at a rate of one scan per second. A more detailed description of the instrumentation scheme is listed as follows.

7.1.1 Temperature Measurements

Two thermocouple trees were installed in the compartment. Each tree consisted of eight thermocouples positioned at the following heights above the lower deck: 1.0, 1.5, 2.5, 3.0, 3.5, 4.0, 4.5, and 4.9 m. Inconel sheathed type K thermocouples (0.47 cm diameter (Omega Model KQIN-18(G)-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 were measured at the centerline of the space, both forward and aft of the engine mock-up as shown in Figure 4. Measurements were made 1.0, 2.5, and 4.0 m above the lower deck. MSA Lira 3000 Analyzers with a full-scale range of 10% by volume was used to measure the carbon monoxide concentration. MSA Lira 303 Analyzers with a full-scale range of 25% by volume were used to monitor the carbon dioxide concentration. Rosemont 755 Analyzers were used to measure the oxygen concentration with a full-scale range of 25% by volume. All of the gas analyzers used during this investigation have an accuracy of 1% of the full-scale range.

The gas samples were pulled through 0.95 cm stainless steel tubing and a Drierite packed filter using a vacuum sampling pump at a flow rate of 1 Lpm/min, resulting in a 10 second transport delay.

7.1.3 Heat Flux Measurements

Both radiant and total heat flux measurements were recorded at four locations in the compartment. These transducers were installed on the port and aft bulkheads 2.0 m and 4.0 m above the lower deck as shown in Figure 4. These instruments were water cooled Schmidt

Boelter transducers manufactured by Medtherm Co. (Medtherm 64 Series Transducers) with a full-scale range of 0-100 kW/m^2. The radiometers were equipped with 150° sapphire windows. Both the radiometers and total vent flux transducers were calibrated to National Institute of Standards and Technology (NIST) standards and had a calibration accuracy of ± 3% of the measured valued.

7.2 Water Spray System Instrumentation

The water spray system was instrumented to provide the operating pressure and the discharge rate of the system. The locations of these instruments are shown in Figure 3.

7.2.1 Pressure Measurements

System pressures were measured at two locations: at the pump discharge and at the most hydraulically remote nozzle. Setra Model 205-2 pressure transducers were used for this application. These transducers have a range of 0-2 MPa with an accuracy of 0.01% full-scale.

7.2.2 Water Flow Rate Measurements

The flow rate of the water spray system was measured using two Flow Technologies Inc. paddlewheel flow meters. The flow meters were installed just downstream 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 (0.47 cm diameter (Omega Model KQIN-18(G)-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% 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 (Table 2). The energy release rates of the spray fires were calculated using the fuel flow rate and heat of combustion of the fuel. This approach assumes that all of the fuel is consumed at a 100 percent combustion efficiency. The fuel nozzle pressure for these spray fires was measured approximately six meters upstream of the nozzle. The two low-pressure spray fires were monitored using a Setra Model 205-2 pressure transducer with a full-scale range of 1.7 MPa and an accuracy of 0.1% full-scale. The high pressure spray fire was monitored using a Setra Model 205-2 pressure transducer with a full-scale range of 20.7 MPa and an accuracy of 0.1% 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 has a range of 0-3735 Pa and an accuracy of 0.01% full-scale.

7.4 Video Equipment

Four video cameras were used during each test: two located outside the compartment at fixed locations and two portable ones located inside the compartment. The two fixed cameras (both standard) were located on the port and aft bulkheads as shown in Figure 4. The two cameras located inside the compartment (one standard and one infrared (IR)) were movable and were typically positioned adjacent to the fire location. A microphone was also installed in the center of the space to provide the audio for the four video cameras.

8.0 TEST PROCEDURES

The tests were initiated from the control room located on the second deck level forward of the test compartment. Prior to the start of the test, the pans were fueled (where applicable), and the compartment ventilation condition set (forced ventilation was secured and the stack damper was closed). 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 was initiated, and the compartment was cleared of test personnel. The fires were allowed to free burn for the required time prior to spray system activation. The test continued until the fire was extinguished or until 15 minutes after discharge, at which point the spray system was secured. On completion of the test, the space was ventilated (the stack damper was opened and the forced ventilation system was activated) to cool the compartment and to remove the remaining products of combustion.

9.0 RESULTS

Ninety-one full-scale fire suppression tests were conducted during this evaluation. Approximately half of them focussed on defining the capabilities of water spray systems for machinery space applications (Phase I). The other half consisted of parametric studies to evaluate the effects that application rate, drop size, spray pattern and system operating pressure have on the fire extinguishing capabilities of the system (Phase II). The results of all ninety-one tests are shown in Table 3.

Shown in Table 3 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. Shortly after system activation, the conditions in the space became well mixed (uniform temperatures and gas concentration) and remained fairly constant for the duration of the test. These fairly constant conditions are referred to as the steady-state value. The steady-state compartment temperatures shown in Table 3 are the average of the eighteen air thermocouples installed in the space thirty seconds prior to extinguishment. The steady-state oxygen concentrations (dry) are the average of the six oxygen concentrations measured in the space thirty seconds prior to extinguishment.

Generally speaking, the capabilities and trends in performance of these systems were similar to those observed for water mist systems. The primary reason for this is that both types of systems employ the same extinguishment mechanisms. Both types of systems extinguish obstructed fires as a result of a reduction in oxygen concentration in the space caused by both the consumption of oxygen by the fire and the dilution of oxygen with water vapor.

Both water spray and water mist system are also capable of thermally managing the conditions in the space during the extinguishment process. Immediately after system activation, the temperatures in the space were dramatically reduced and maintained for the duration of the test. In a majority of the tests, the space became well mixed with a uniform temperature between 50-70 °C. An example of these conditions are shown in Figure 5.

Table 3. Test results.

Test #	Nozzle	Spacing (m)	Pressure (bar)	App. Rate (Lpm/m^2)	Fire (size & loc.)	Ext Time (min:sec)	Steady-State	
							Temperature (C)	Oxygen (% Dry)
1	M	3	1.3	5.0	6 MW Top	0:36	NA	NA
2	M	3	1.3	5.0	6 MW Side	3:14	55.0	13.0
3	M	3	1.3	5.0	2 MW Side	7:05	63.0	14.0
4	M	3	1.3	5.0	1 MW Side	13:36	53.0	14.4
5	M	3	1.3	5.0	1 m^2 Floor	8:00	61.0	14.0
6	M	3	1.3	5.0	1 m^2 Side	7:58	64.0	13.6
7	N2	3	3.5	5.0	6 MW Top	1:00	NA	NA
8	N2	3	3.5	5.0	6 MW Side	0:55	NA	NA
9	N2	3	3.5	5.0	2 MW Side	10:28	64.0	15.0
10	N2	3	3.5	5.0	1 MW Side	NO	50.0	16.0
11	N2	3	3.5	5.0	1 m^2 Side	ABORTED	NA	NA
12	N2	3	3.5	5.0	1 m^2 Side	11:04	61.0	16.0
13	N3	3	4.3	8.5	1 m^2 Side	ABORTED	NA	NA
14	N3	3	4.3	8.5	6 MW Side	0:24	NA	NA
15	N3	3	4.3	8.5	2 MW Side	6:39	57.0	14.6
16	N3	3	4.3	8.5	1 MW Side	9:51	44.0	14.8
17	N3	3	4.3	8.5	6 MW Top	0:04	NA	NA
18	TF16-120	3	3.5	5.0	6 MW Top	0:55	NA	NA
19	TF16-120	3	3.5	5.0	6 MW Side	0:35	NA	NA
20	TF16-120	3	3.5	5.0	2 MW Side	4:39	56.0	15.2
21	TF16-120	3	3.5	5.0	1 MW Side	11:01	45.0	14.8
22	TF16-120	3	3.5	5.0	1 m^2 Side	5:17	52.0	16.0
23	TF16-120	3	3.5	5.0	1 m^2 Side	5:11	52.0	16.0
24	TF16-60	3	3.5	5.0	6 MW Side	0:36	NA	NA
25	TF16-60	3	3.5	5.0	2 MW Side	4:22	60.0	15.2
26	TF16-60	3	3.5	5.0	1 MW Side	NO	46.0	14.6
27	TF16-60	3	3.5	5.0	6 MW Top	0:37	NA	NA
28	TF14-120	3	7.0	5.5	6 MW Top	0:03	NA	NA
29	TF14-120	3	7.0	5.5	6 MW Side	0:13	NA	NA
30	TF14-120	3	7.0	5.5	2 MW Side	0:28	NA	NA
31	TF14-120	3	7.0	5.5	1 MW Side	NO	48.0	15.0
32	TF14-120	3	7.0	5.5	1 m^2 Side	3:38	55.0	16.8
33	TF14-120	3	7.0	5.5	2 MW Side	NO	56.0	16.4
34	N5	3	3.5	17.0	6 MW Top	0:33	NA	NA
35	N5	3	3.5	17.0	6 MW Side	0:11	NA	NA
36	N5	3	3.5	17.0	2 MW Side	NO	49.0	15.6
37	N5	3	3.5	17.0	1 m^2 Side	3:16	50.0	17.2
38	WL	3	1.9	5.0	1 m^2 Side	14:38	63.0	13.0
39	WL	3	1.9	5.0	6 MW Side	3:07	58.0	13.0
40	WL	3	1.9	5.0	2 MW Side	6:17	61.0	13.0
41	WL	3	1.9	5.0	1 MW Side	NO	47.0	14.7
42	WL	3	1.9	5.0	6 MW Top	0:17	NA	NA
43	TF6-120	3	7.0	0.9	6 MW Top	0:16	NA	NA
44	TF6-120	3	7.0	0.9	6 MW Side	ABORTED	NA	NA
45	TF6-120	3	7.0	0.9	6 MW Side	1:32	NA	NA
46	TF6-120	3	7.0	0.9	2 MW Side	3:50	73.0	15.2
47	TF6-120	3	7.0	0.9	1 MW Side	8:05	70.0	15.6
48	TF6-120	3	7.0	0.9	1 m^2 Side	9:47	72.0	15.0
49	TF10-120	3	7.0	2.7	1 m^2 Side	6:33	66.0	16.4
50	TF10-120	3	7.0	2.7	6 MW Side	0:55	NA	NA

ABORTED – Test Terminated Due To Technical Difficulties
NO – Fire Not Extinguished
NA – Steady-State Conditions Not Achieved

Table 3. Test results (continued).

Test #	Nozzle	Spacing (m)	Pressure (bar)	App. Rate (Lpm/m^2)	Fire (size & loc.)	Ext Time (min:sec)	Steady-State	
							Temperature (C)	Oxygen (% Dry)
51	TF10-120	3	7.0	2.7	2 MW Side	2:48	NA	NA
52	TF10-120	3	7.0	2.7	1 MW Side	12:41	59.0	15.6
53	TF10-120	3	7.0	2.7	6 MW Top	0:01	NA	NA
54	P120	1.5	4.3	5.0	6 MW Top	0:01	NA	NA
55	P120	1.5	4.3	5.0	6 MW Side	0:51	NA	NA
56	P120	1.5	4.3	5.0	2 MW Side	2:34	NA	NA
57	P120	1.5	4.3	5.0	1 MW Side	6:51	55.0	16.0
58	P120	1.5	4.3	5.0	1 m^2 Side	7:11	64.0	16.0
59	P120	1.5	8.5	7.1	1 m^2 Side	5:03	59.0	16.0
60	P120	1.5	8.5	7.1	2 MW Side	4:07	56.0	16.2
61	P120	1.5	8.5	7.1	1 MW Side	11:28	46.0	16.4
62	P120	1.5	4.3	5.0	IMO-2	0:01	NA	NA
63	P120	1.5	4.3	5.0	IMO-3	0:45	NA	NA
64	P120	1.5	4.3	5.0	IMO-6	7:51	58.0	16.2
65	P120	1.5	4.3	5.0	IMO-5	0:02	NA	NA
66	P120	1.5	4.3	5.0	IMO-12	0:01	NA	NA
67	P120	1.5	4.3	5.0	IMO-11	1:46	NA	NA
68	P120	1.5	4.3	5.0	IMO-9	NO	57.0	16.8
69	P120	1.5	4.3	5.0	IMO-10	0:25	NA	NA
70	P120	1.5	4.3	5.0	IMO-13	NO	59.0	16.4
71	P120	1.5	4.3	5.0	IMO-7	NO	51.0	16.8
72	P120	1.5	4.3	5.0	IMO-1	0:02	NA	NA
73	P120	1.5	4.3	5.0	IMO-8	NO	42.0	18.8
74	A	3	0.8	5.6	IMO-1	1:09	NA	NA
75	A	3	0.8	5.6	6 MW Side	3:04	53.0	13.0
76	A	3	0.8	5.6	2 MW Side	4:01	60.0	14.8
77	A	3	0.8	5.6	IMO-3	2:51	44.0	13.0
78	A	3	0.8	5.6	IMO-6	13:12	49.0	14.0
79	A	3	0.8	5.6	IMO-10	3:29	63.0	13.0
80	A	3	0.8	5.6	IMO-13	NO	44.0	15.4
81	A	3	0.8	5.6	IMO-12	5:02	44.0	15.4
82	A	3	0.8	5.6	1 MW Side	8:37	46.0	14.0
83	A	3	0.8	5.6	IMO-9	NO	52.0	15.2
84	A	3	0.8	5.6	1 m^2 Side	5:50	55.0	14.8
85	A	3	0.8	5.6	IMO-11	3:35	59.0	15.6
86	A	3	0.8	5.6	IMO-7	NO	46.0	16.8
87	A	3	0.8	5.6	IMO-8	NO	43.0	18.4
88	A	3	0.8	5.6	IMO-2	0:01	NA	NA
89	A	3	0.8	5.6	IMO-5	0:21	NA	NA
90	N3	3	4.3	8.5	1 m^2 Side	7:04	58.0	15.2
91	N3	3	4.3	8.5	1 m^2 Side	4:10	56.0	15.6

ABORTED – Test Terminated Due To Technical Difficulties
NO – Fire Not Extinguished
NA – Steady-State Conditions Not Achieved

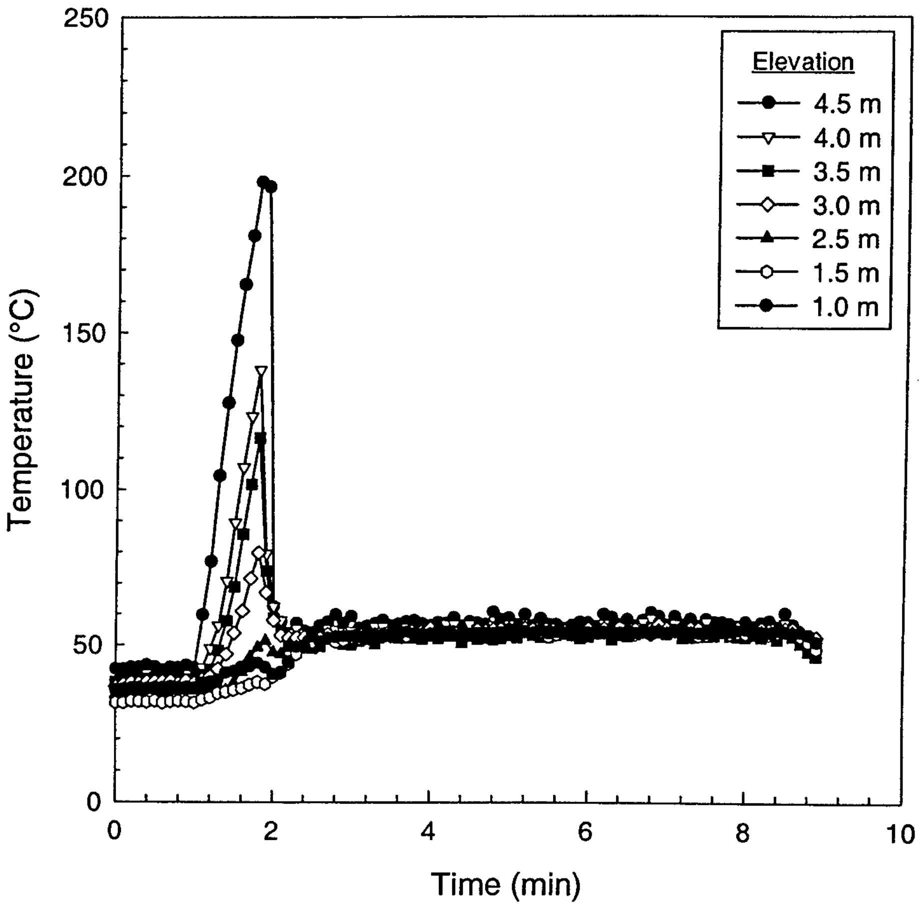


Figure 5. Typical compartment temperature histories.
(Test 15 – N3 nozzle – 8.5 Lpm/m^2 – 2 MW side)

The extinguishment times for the spray fire tests conducted during the capabilities evaluation are plotted in Figure 6. As with the water mist systems, the larger fires were easier to extinguish with extinguishment occurring faster than the smaller fires. This was attributed to the consumption of the oxygen in the space by the fire, the generation of steam, and the turbulence created by the fire. All the water spray systems were capable of extinguishing the 6.0 MW spray fires with variations in system capabilities becoming apparent as the fire size was reduced. Only about half of the systems were capable of extinguishing the 1.0 MW obstructed spray fire located on the side of the engine mock-up (similar to IMO-6).

9.1 General Capabilities Evaluation (Phase I)

The capabilities evaluation began with a series of scoping tests conducted against five systems designed to operate at or below fire main pressure (3.5 bar) and discharge the minimum application rate required by SOLAS (5 Lpm/m^2). The spray characteristics of these five systems covered the range from mist type sprays to very large drops (> 1000 microns). The results of these tests are shown in Table 4.

Two systems were then selected to be evaluated against the complete set of tests required by IMO for water mist systems (MSC 668 and 728). The best performer, the P120 nozzle (smallest drops) and the lowest pressure system, the Grinnell Model A pendant sprinkler, were selected for this evaluation. The results of these tests are shown in Table 5.

The capabilities of these two systems as demonstrated by the results shown in Table 5 are, in many respects, similar to conventional water mist systems. Both systems failed IMO tests 7, 8 and 13 and as a result would require a separate bilge system for approval. This leaves only the small obstructed heptane pan fire (IMO-9) from preventing these two systems from successfully completing the IMO test protocol (for this compartment volume). This small obstructed heptane pan fire has been shown to be the most challenging fire independent of the system type, with some water mist systems requiring additives such as AFFF to successfully pass this test.

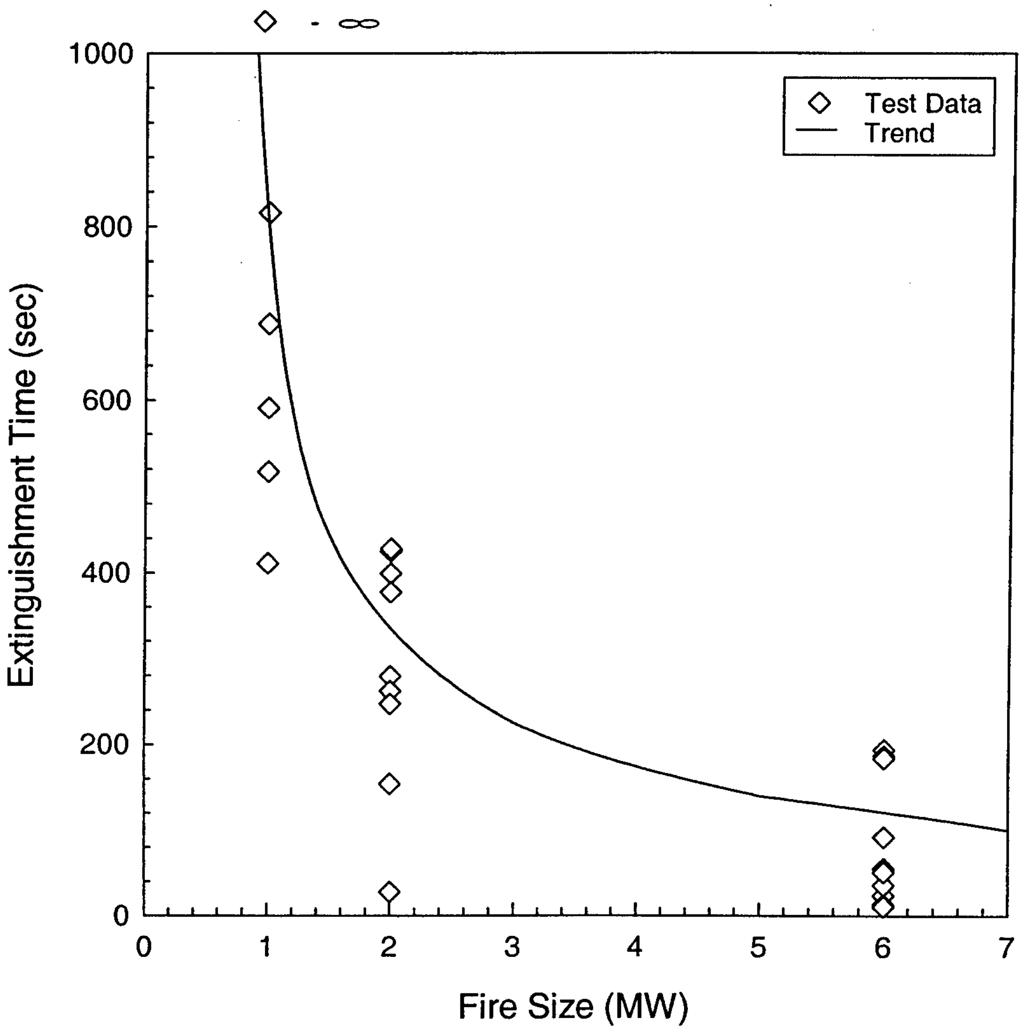


Figure 6. Extinguishment trends.
(General Capabilities Evaluation Spray Fire Tests)

Table 4. SOLAS system evaluation.

Nozzle System	P120	N2	A	M	WL
Type	Mist	Spray	Sprinkler	Sprinkler	Spray
Drop Size (microns)	350	520	1000	900	850
Fire Scenario					
6 MW Spray Fire Top					
Ext. Time (min: sec)	0:01	1:00	1:09	0:36	0:17
SS Temperature (C)	NA	NA	NA	NA	NA
SS Oxygen (% Dry)	NA	NA	NA	NA	NA
6 MW Spray Fire Side					
Ext. Time (min: sec)	0:51	0:55	3:04	3:14	3:07
SS Temperature (C)	NA	NA	53	55	58
SS Oxygen (% Dry)	NA	NA	13.0	13.0	13.0
2 MW Spray Fire Side					
Ext. Time (min: sec)	2:34	10:28	4:01	7:05	6:17
SS Temperature (C)	NA	64.0	60.0	63.0	61.0
SS Oxygen (% Dry)	NA	15.0	14.8	14.0	13.0
1 MW Spray Fire Side					
Ext. Time (min: sec)	6:51	NO	8:37	13:36	NO
SS Temperature (C)	55.0	50.0	46.0	53.0	47.0
SS Oxygen (% Dry)	16.0	16.0	14.0	14.4	14.7
1 m^2 Pan Fire Side					
Ext. Time (min: sec)	7:11	11:04	5:50	10:58	14:38
SS Temperature (C)	64.0	61.0	55.0	64.0	63.0
SS Oxygen (% Dry)	16.0	16.0	14.8	13.6	13.0

NO – Fire Not Extinguished
NA – Steady-State Conditions Not Achieved

Table 5. IMO test results.

	Nozzle / System	P120	A
	Type	Mist	Sprinkler
	Drop Size (microns)	350	1000
Fire Scenario			
IMO-1	Ext. Time (min: sec)	0:01	1:09
	SS Temperature (C)	NA	NA
	SS Oxygen (% Dry)	NA	NA
IMO-2	Ext. Time (min: sec)	0:01	0:01
	SS Temperature (C)	NA	NA
	SS Oxygen (% Dry)	NA	NA
IMO-3	Ext. Time (min: sec)	0:45	2:51
	SS Temperature (C)	NA	44
	SS Oxygen (% Dry)	NA	13.0
IMO-5	Ext. Time (min: sec)	0:02	0:21
	SS Temperature (C)	NA	NA
	SS Oxygen (%Dry)	NA	NA
IMO-6	Ext. Time (min: sec)	7:51	13:12
	SS Temperature (C)	58.0	49.0
	SS Oxygen (% Dry)	16.2	14.0
IMO-7	Ext. Time (min: sec)	NO	NO
	SS Temperature (C)	51.0	46.0
	SS Oxygen (% Dry)	16.8	16.8
IMO-8	Ext. Time (min: sec)	NO	NO
	SS Temperature (C)	42.0	43.0
	SS Oxygen (% Dry)	18.8	18.4
IMO-9	Ext. Time (min: sec)	NO	NO
	SS Temperature (C)	57.0	52.0
	SS Oxygen (% Dry)	16.8	15.2
IMO-10	Ext. Time (min: sec)	0:25	3:29
	SS Temperature (C)	NA	63.0
	SS Oxygen (% Dry)	NA	13.0
IMO-11	Ext. Time (min: sec)	1:46	3:35
	SS Temperature (C)	NA	59.0
	SS Oxygen (% Dry)	NA	15.6
IMO-12	Ext. Time (min: sec)	0:01	5:02
	SS Temperature (C)	NA	44
	SS Oxygen (% Dry)	NA	15.4
IMO-13	Ext. Time (min: sec)	NO	NO
	SS Temperature (C)	59.0	44.0
	SS Oxygen (% Dry)	16.4	15.4

NO – Fire Not Extinguished
NA – Steady-State Conditions Not Achieved

9.2 Parametric Studies (Phase II)

Parametric studies were conducted to identify the effects that application rate, spray angle and system operating pressure have on the capabilities of the system. The nozzles used in each study were selected in an attempt to maintain the drop size distribution of the system while systematically varying only one parameter. The results of these studies are presented in the following sections. While the trends in the test data appear to be unapparent or confusing, the results can, to some degree, be explained by the analysis presented in the discussion section of this report (Section 10).

9.2.1 Application Rate

Two application rate evaluations were conducted during this test series. The first evaluation consisted of maintaining the original system operating pressure used during the systems capabilities evaluation (3.5 bar) while systematically increasing the application rate (by up to a factor of three greater than the minimum required by SOLAS). This was accomplished through the use of larger orifice nozzles. The results of these tests are shown in Table 6a. The second evaluation was conducted at a higher system operating pressure (7 bar) and consisted of reducing the application rate (by up to a factor of five less than the minimum required by SOLAS). This was accomplished through the use of smaller orifice nozzles. The results of these tests are shown in Table 6b.

As shown in these tables, the two lowest (0.9 and 2.7 Lpm/m^2) and one of the highest (8.5 Lpm/m^3) application rates successfully extinguished all of the fires in this evaluation.

9.2.2 Spray Pattern (Angle)

The spray pattern evaluation was conducted at the minimum application rate required by SOLAS (5 Lpm/m^2) and at an operating pressure of 3.5 bar (the pressure used during the system capabilities evaluation). The spray patterns (angles) evaluated included 60, 90 and 120 degrees. The results of these tests are shown in Table 7.

Table 6a. Application rate evaluation (higher application rates).

Nozzle / System	N2	N3	N5
App. Rate (Lpm/m^2)	5.0	8.5	17.0
Fire Scenario			
6 MW Spray Fire Top			
Ext. Time (min: sec)	1:00	0:04	0:33
SS Temperature (C)	NA	NA	NA
SS Oxygen (% Dry)	NA	NA	NA
6 MW Spray Fire Side			
Ext. Time (min: sec)	0:55	0:24	0:11
SS Temperature (C)	NA	NA	NA
SS Oxygen (% Dry)	NA	NA	NA
2 MW Spray Fire Side			
Ext. Time (min: sec)	10:28	6:39	NO
SS Temperature (C)	64.0	57.0	47.0
SS Oxygen (% Dry)	15.0	14.6	15.6
1 MW Spray Fire Side			
Ext. Time (min: sec)	NO	9:51	--
SS Temperature (C)	50.0	44.0	--
SS Oxygen (% Dry)	16.0	14.8	--
1 m^2 Pan Fire Side			
Ext. Time (min: sec)	11:04	7:04	3:16
SS Temperature (C)	61.0	58.0	50.0
SS Oxygen (% Dry)	16.0	15.2	17.2

NO – Fire Not Extinguished
NA – Steady-State Conditions Not Achieved
--- Test not conducted

Table 6b. Application rate evaluation (lower application rates).

Nozzle / System	TF-6-120	TF10-120	TF14-120
App. Rate (Lpm/m^2)	0.9	2.7	5.5
Fire Scenario			
6 MW Spray Fire Top			
Ext. Time (min: sec)	0:16	0:01	0:03
SS Temperature (C)	NA	NA	NA
SS Oxygen (% Dry)	NA	NA	NA
6 MW Spray Fire Side			
Ext. Time (min: sec)	1:32	0:55	0:13
SS Temperature (C)	NA	NA	NA
SS Oxygen (% Dry)	NA	NA	NA
2 MW Spray Fire Side			
Ext. Time (min: sec)	3:50	2:48	---
SS Temperature (C)	73.0	NA	---
SS Oxygen (% Dry)	15.2	NA	---
1 MW Spray Fire Side			
Ext. Time (min: sec)	8:05	12:41	NO
SS Temperature (C)	70.0	59.0	48.0
SS Oxygen (% Dry)	15.6	15.6	15.6
1 m^2 Pan Fire Side			
Ext. Time (min: sec)	9:47	6:33	3:38
SS Temperature (C)	72.0	66.0	55.0
SS Oxygen (% Dry)	15.0	16.4	16.8

NO – Fire Not Extinguished
NA – Steady-State Conditions Not Achieved
--- Test not conducted

Table 7. Spray pattern evaluation.

Nozzle / System	TF16-60	N2	TF16-120
Spray Pattern Angle	60°	90°	120°
Fire Scenario			
6 MW Spray Fire Top			
Ext. Time (min: sec)	0:37	1:00	0:55
SS Temperature (C)	NA	NA	NA
SS Oxygen (% Dry)	NA	NA	NA
6 MW Spray Fire Side			
Ext. Time (min: sec)	0:36	0:55	0:35
SS Temperature (C)	NA	NA	NA
SS Oxygen (% Dry)	NA	NA	NA
2 MW Spray Fire Side			
Ext. Time (min: sec)	4:22	10:28	4:39
SS Temperature (C)	60.0	64.0	54.0
SS Oxygen (% Dry)	15.2	15.0	15.2
1 MW Spray Fire Side			
Ext. Time (min: sec)	NO	NO	11:01
SS Temperature (C)	46.0	50.0	54.0
SS Oxygen (% Dry)	14.6	16.0	14.8
1 m^2 Pan Fire Side			
Ext. Time (min: sec)	5:11	11:04	5:17
SS Temperature (C)	52.0	61.0	45.0
SS Oxygen (% Dry)	16.0	16.0	16.0

NO – Fire Not Extinguished
NA – Steady-State Conditions Not Achieved

As shown in Table 7, only the system with 120 degree nozzles could successfully extinguish all of the fires included in this evaluation. The remaining two systems (60 and 90 degree nozzles) had trouble extinguishing the obstructed 1.0 MW spray fire on the side of the engine mock-up.

9.2.3 System Operating Pressure

Two evaluations, looking at the effects of system operating pressures, were conducted during this test series. The first one consisted of increasing the pressure of a selected system/nozzle (P120) from 3.5 to 8.5 bar. The increase in pressure consequently increased the application rate and potentially reduced the drop sizes of the system. The second evaluation consisted of changing the nozzles (selecting a smaller orifice nozzle of the same type) with the intent of maintaining a constant application rate and (similar) drop size distribution for the two systems. The results of these tests are shown in Table 8.

As shown in Table 8, increasing the pressure had negative effects in both evaluations. This is unprecedented in the literature and must be associated with the complex relation/balance of spray angle, drop size and velocity. For example, in many cases, increasing the pressure not only reduces the drop size but also reduces the spray pattern angle.

Table 8. System pressure evaluation.

Nozzle / System	P120	P120	TF16-120	TF14-120
Pressure (Bar)	3.5	8.5	3.5	7.0
App. Rate (Lpm/m^2)	5.0	7.1	5.0	5.5
Fire Scenario				
6 MW Spray Fire Top				
Ext. Time (min: sec)	0:01	---	0:55	0:03
SS Temperature (C)	NA	---	NA	NA
SS Oxygen (% Dry)	NA	---	NA	NA
6 MW Spray Fire Side				
Ext. Time (min: sec)	0:51	---	0:35	0:13
SS Temperature (C)	NA	---	NA	NA
SS Oxygen (% Dry)	NA	---	NA	NA
2 MW Spray Fire Side				
Ext. Time (min: sec)	2:34	4:07	4:39	---
SS Temperature (C)	NA	58.0	56.0	---
SS Oxygen (% Dry)	NA	16.2	15.2	---
1 MW Spray Fire Side				
Ext. Time (min: sec)	6:51	11:28	11:01	NO
SS Temperature (C)	55.0	46.0	45.0	48.0
SS Oxygen (% Dry)	16.0	16.4	14.8	15.6
1 m^2 Pan Fire Side				
Ext. Time (min: sec)	7:11	5:03	5:17	3:38
SS Temperature (C)	64.0	59.0	52.0	55.0
SS Oxygen (% Dry)	16.0	16.0	16.0	16.8

NO – Fire Not Extinguished
NA – Steady-State Conditions Not Achieved
--- Test not conducted

Table 9. System spray characteristics.

Nozzle	Pressure (bar)	App. Rate (Lpm/m^2)	Drop Size Sauter Mean (microns)	Drop Size Designation	Water Vapor Conc. (%)	Term. Vel. m/s	Momentum App. × Vel.	Vent Efficiency (%)
M	1.3	5.0	900	Large	0.5	5.4	27.0	70
N2	3.5	5.0	520	Medium	2.0	3.1	15.5	90
N3	4.3	8.5	600	Medium	1.5	3.6	30.6	60
TF16-120	3.5	5.0	500	Medium	2.0	3.0	15.0	95
TF16-60	3.5	5.0	550	Medium	2.0	3.3	16.5	95
TF14-120	7.0	5.5	375	Small	2.5	2.2	11.0	100
N5	3.5	17.0	850	Large	0.0	5.1	86.7	70
WL	1.9	5.0	850	Large	0.0	5.1	25.5	70
TF6-120	7.0	0.9	250	Small	3.0	1.5	1.4	100
TF10-120	7.0	2.7	325	Small	2.5	2.0	5.4	100
P120	4.3	5.0	350	Small	2.5	2.1	10.5	100
P120	8.5	7.1	300	Small	3.0	1.8	12.8	100
A	0.8	5.0	1000	Large	0.5	6.0	30.0	60

10.0 DISCUSSION

10.1 Interpretation of the Results

The previous results/systems capabilities are best explained with respect to two parameters; how much water vapor is produced by the system for a given fire scenario and how well the system disrupts the air flow through the vent openings. These two parameters are associated with the spray characteristics of each system/nozzle (drop size and momentum).

The spray characteristics for each system/nozzle are summarized in Table 9. The drop-size values were provided by the manufacturers and verified in the laboratory at Hughes Associates Inc. (HAI) [Bete 1994; Grinnell 1998; Viking 1995]. To aid in the analysis, the drop sizes have been categorized into three ranges; small – less than 400 microns; medium – between 400 microns and 800 microns; and large – greater than 800 microns. The terminal velocities were determined based on the simplified linear relation developed by Yao [Yao 1980] shown in Figure 7. The vent efficiency was based on the oxygen concentration histories recorded in the space during the tests and will be discussed in Section 10.1.2 of this report.

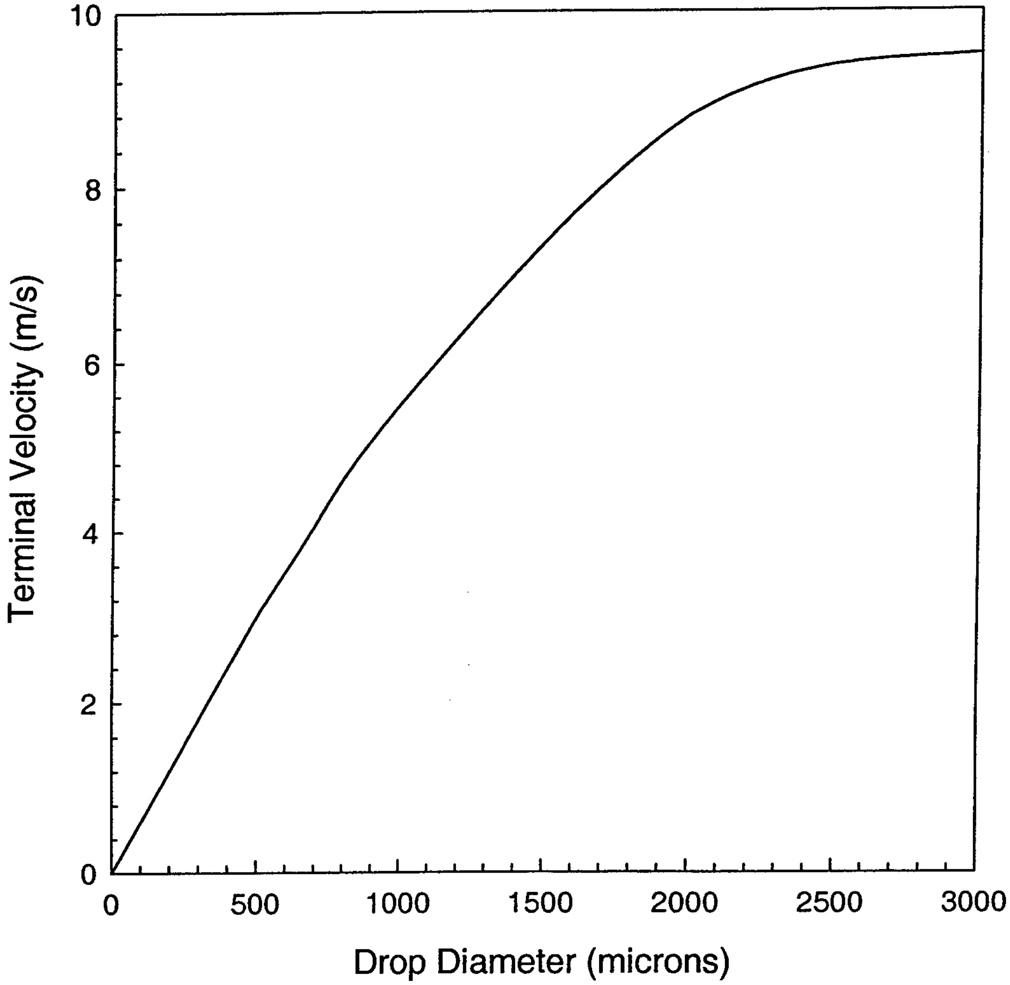


Figure 7. Terminal velocity relation developed by Yao.

10.1.1 Water Vapor Production

The amount of water vapor produced by each system appears to be primarily a function of drop size and was estimated based on the oxygen concentrations (dry) measured at the fire location just prior to extinguishment. The term "dry oxygen concentration" means that the water vapor has been removed from the sample. Filtering and drying the sample is required to protect the analyzers from damage. As a result, the dry concentrations are typically higher than the actual concentrations that occurred in the space. (The dry oxygen concentration minus the water vapor concentration equals the actual oxygen concentration). These dry oxygen concentrations were plotted as a function of the steady-state compartment temperature in Figure 8.

As shown in Figure 8, the small drop systems typically extinguished the fire when the dry oxygen concentration was reduced to 16%. The medium drop systems extinguished the fire when the dry oxygen concentration was reduced to 15% and the large drop systems when the oxygen concentration dropped to 13.5%. If we assume the fires were extinguished when the actual oxygen concentration was reduced to 13% (the limiting oxygen concentration of most hydrocarbon fuels is approximately 13% [Beyler 1988]), the small drop systems produced a 3% water vapor concentration, the medium drop systems a 2% concentration, and the large drop systems virtually no water vapor (0.5%).

It is surprising that the oxygen concentrations were fairly constant as a function of steady-state compartment temperature. One would expect these oxygen concentrations to increase as a function of temperature. This would be expected since the ability of air to contain water vapor is greater for higher temperatures (the partial pressure of water vapor increases with temperature). This may be related to changes in the ventilation conditions since the flow rate of air through the vent opening also increases proportionally with temperature.

To support this hypothesis, the previous results have been replotted in terms of the percent saturation (Figure 9). This figure suggests that as the temperature is increased above a value specific to the spray characteristics (drop size) of the system, the water vapor production

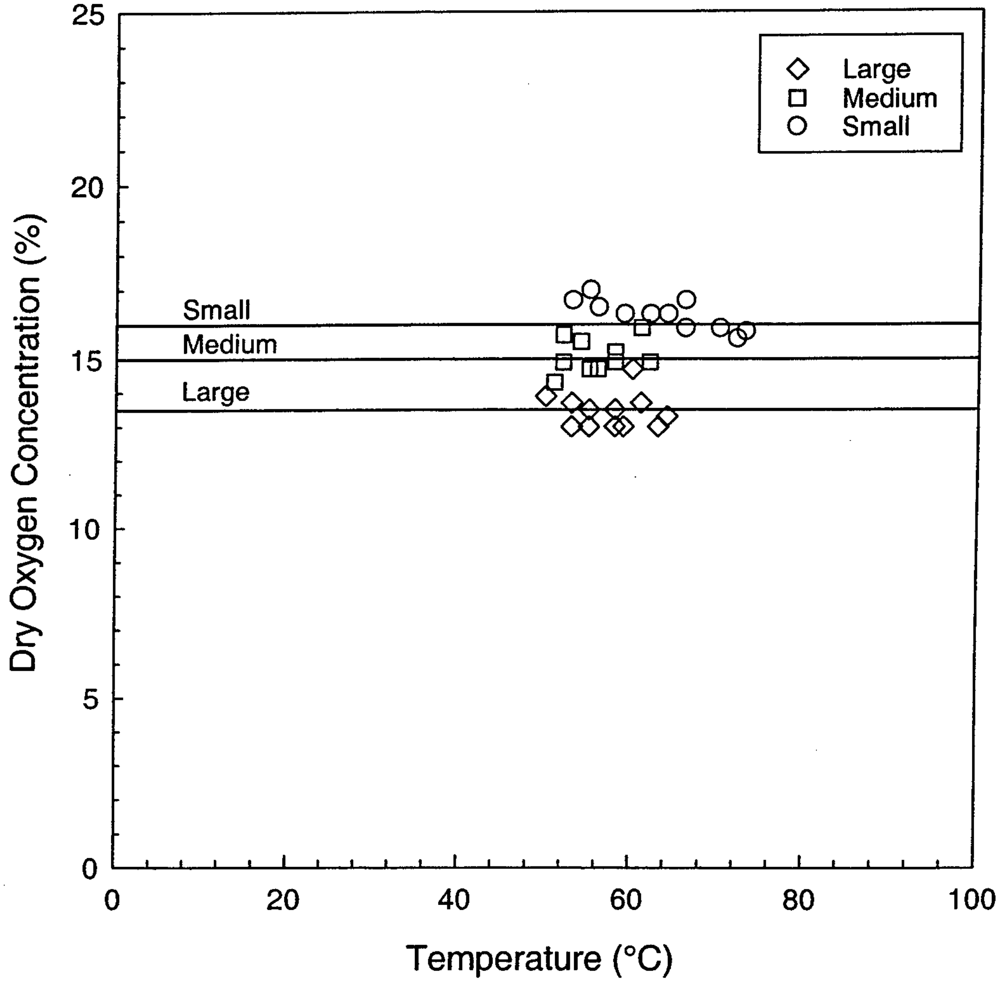


Figure 8. Oxygen concentrations (dry) at extinguishment.
(Grouped by drop size: small, medium and large)

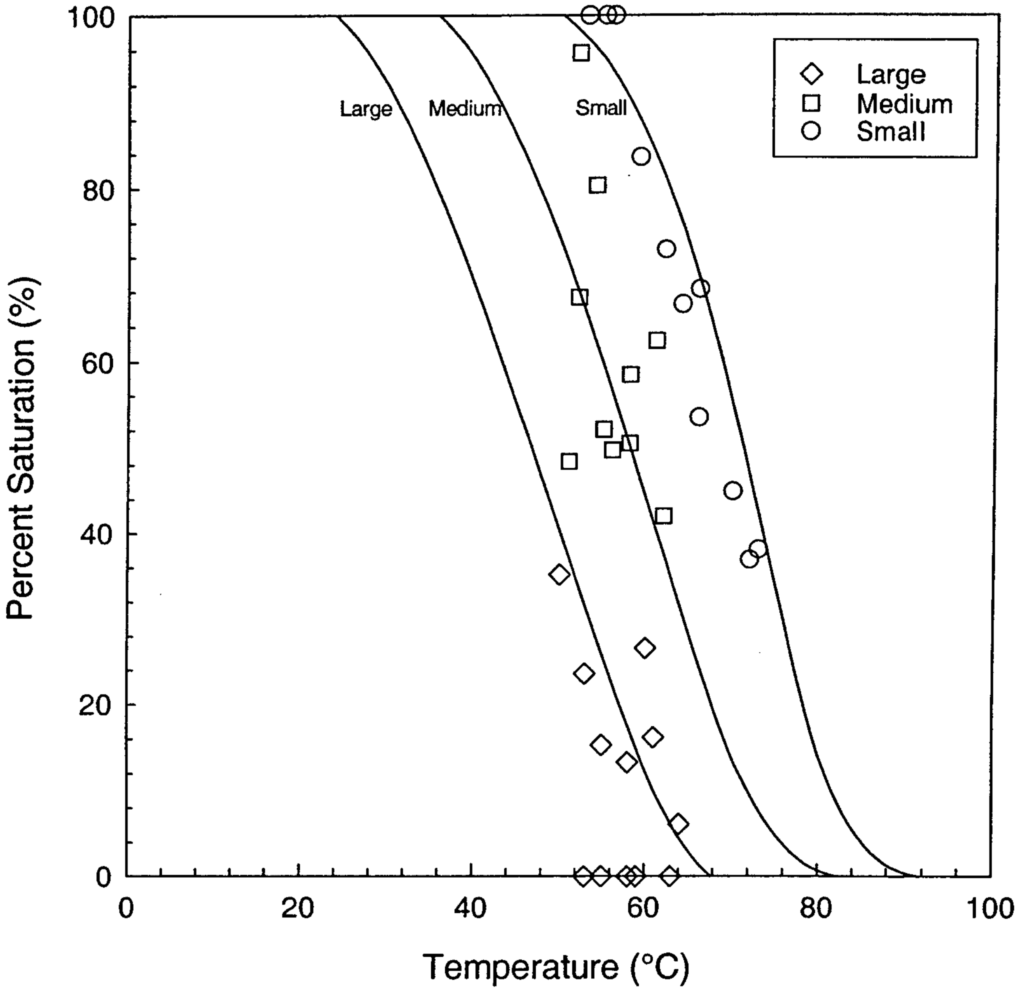


Figure 9. Percent saturation of the gases with water vapor.
(Grouped by drop size: small, medium and large)

rate (evaporation/vaporization rate) is inadequate to completely saturate the air/gases in and flowing through the compartment due to the higher vent flow rate.

In summary, the smaller drop systems have higher evaporation rates than the large drop systems but still have difficulty completely saturating the gases in a well ventilated compartment. In the absence of the vent opening, the vapor concentrations in the space should increase for all systems allowing even the larger drop systems to approach saturated conditions.

10.1.2 Vent Flow Effects

Many of the systems were capable of disrupting the air flow through the vent opening similar to screening nozzles although only overhead nozzles were used during these tests. The ability of a system to disrupt the flow of air through the vent (similar to a water curtain) appears to be a function of the spray momentum of the system. The spray momentum term contains both mass (flow rate of the system) and velocity (terminal drop velocity) parameters. The measured disruption of air flow through the vent was based on the oxygen concentration histories measured in the compartment. The six oxygen concentration histories were averaged and used in a conservation of mass (oxygen) analysis conducted on the compartment. The analysis determined the amount of oxygen that needed to flow through the vent in order to achieve the measured average oxygen concentration history. This value was then compared to the expected vent flow rate based on a temperature-dependent orifice flow correlation applicable to well mixed compartments.

The actual flow rate of oxygen into the compartment required to produce the measured air concentration history was determined using the following equation.

$$\rho_{comp} Vol_{comp}\left(\gamma_{O_{2(2)}} - \gamma_{O_{2(1)}}\right) = \left(\dot{m}_{air}\, \gamma_{O_{2\infty}} \frac{\dot{Q}_{Fire}}{\Delta H_{R_{O_2}}}\right)\left(t_{(2)} - t_{(1)}\right) \qquad (1)$$

Where ρ_{comp} is the density of the gas in the compartment (as a function of temperature), Vol_{comp} is the compartment volume, $\dot{m}_{air}$ is the vent flow rate, $\dot{Q}_{Fire}$ is the heat release rate of the fire,

$\Delta H_{R_{O_2}}$ is the heat of reaction of oxygen (13 MJ/kg) and $\gamma_{O_{2(1)}}$ and $\gamma_{O_{2(2)}}$ are the mass fractions of oxygen in the compartment at times one and two ($t_{(1)}$ and $t_{(2)}$) respectively. For this analysis, a delta t of 120 seconds was selected ($t_{(2)}$ = 180 seconds after discharge and $t_{(1)}$ = 60 seconds after discharge).

The expected mass flow rate of air was determined using the vent flow correlation listed as follows:

$$\dot{m}_{air} = \frac{2}{3} A_v H^{\frac{1}{2}} C_d \rho_o (2g)^{\frac{1}{2}} \left(\frac{(\rho_o - \rho_{comp}) / \rho_o}{\left[1 + (\rho_o / \rho_{comp})^{\frac{1}{3}}\right]^3} \right) \tag{2}$$

where A_v is the area of the vent opening, H is the height of the vent opening, ρ_o is the density of air at ambient temperature, ρ_{comp} is the density of the gases inside the compartment, C_d = 0.7 and g = 9.81 m/s^2.

The results of this analysis are shown in Table 9 in terms of vent efficiency. (An efficiency of 100% means the spray had no effect while 0% means the vent flow was completely shut-off by the spray). As shown by these values listed in Table 9, the higher the spray momentum, the greater the effect on the vent flow rate. It is believed that the higher momentum sprays produced turbulent flow conditions near the vent effecting the pressures that drive the flow of gases through the opening.

This knowledge can now be used to interpret the test results. For example, the results shown in Table 4 can now be explained. The system consisting of P120 nozzles (smallest drops) exhibited superior capabilities by producing the highest water vapor concentration even though the system had little effect on the vent flow rate (other than by reducing the compartment temperature). The system consisting of N2 nozzles (medium drops) performed the worst because it neither produced adequate amounts of saturated vapor nor shut-off the vent. The three large drop systems performed fairly equally with the highest momentum systems performing the best due to their ability to reduce the flow of air through the vent openings.

10.2 Application of Results

The previous discussion identified two parameters (vapor production and vent flow effects) associated with the performance of these systems. The large vent opening in the IMO test enclosure may be a useful safety factor with respect to approving systems but in an actual situation is somewhat artificial. In an actual installation where the machinery space doors are typically kept closed, or are closed when the fire suppression system is activated (as is the case with gaseous agents or water mist), the water vapor production becomes the predominant parameter. This suggests that the smaller the drops, the better the performance of the system.

The results of these tests can be used to estimate the capabilities of water spray systems in an actual application (closed machinery space). This assumes that the oxygen concentration/ vapor production measured during these tests is representative of what would occur in an actual machinery space. Using the oxygen/vapor concentrations measured during these tests, the expected extinguishment times for fires in closed compartments can be determined and expressed in terms of fire size to compartment volume ratio.

The extinguishment times were estimated using the following equation.

$$\Delta t \;=\; \dot{m}_{air}\,\Delta H_{R_{air}}\,\frac{\chi_{O_2} \quad \chi_{O_{2\,ext}}}{\chi_{O_2}} \Big/ \dot{Q}_{Fire} \tag{3}$$

Where $\dot{m}_{air}$ is the mass of air, $\Delta H_{R_{air}}$ is the heat of reaction of air (3 MJ/kg), $\chi_{O_{2\infty}}$ is the oxygen concentration in ambient air (21%), $\chi_{O_{2ext}}$ is the oxygen concentration at extinguishment (13% was assumed for this calculation) and $\dot{Q}_{Fire}$ is the heat release rate of the fire. The above calculation was conducted per unit volume by expressing the mass of air and fire size in per unit volume terms.

The estimated extinguishment times for the three-drop size ranges used during this investigation are shown in Figure 10. This figure illustrates the increased capabilities of the smaller drop systems. As shown in this figure, the critical fire size for a small drop systems is almost half that of the larger drop systems. As one would expect, the small drop correlation is very similar to the capabilities observed for water mist systems in this application [Back et al. 2000].

10.3 Modeling

The quasi steady-state model developed during a previous investigation [Back et al. 2000] was modified so it could be used to predict the capabilities of water spray systems as well as the water mist systems for which it was originally intended. One of the limitations of the model was the assumption that all water mist systems produced saturated vapor. This assumption has never been validated. The saturated vapor assumption negated the need for an evaporation model but prevented the steady-state model from being able to distinguish between two systems with similar discharge rates but different spray characteristics (drop size). In order to apply the steady-state model to larger drop systems, an evaporation algorithm needed to be developed and added to the model.

The evaporation of drops in a spray involves simultaneous heat and mass transfer processes in which the heat for evaporation is transferred to the drop surface by conduction and convection from the surrounding hot gas, and vapor is transferred by convection and diffusion back into the gas stream. The overall rate of evaporation depends on the pressure, temperature, and transport properties of the gas; the temperature, volatility and diameter of the drops in the spray; and the velocity of the drops relative to that of the surrounding gas.

For this application, a steady-state evaporation algorithm was selected. The term steady-state is used to describe the stage in the drop evaporation process where the drop surface has attained its wet-bulb temperature and all of the heat reaching the surface is utilized in providing the latent heat of vaporization.

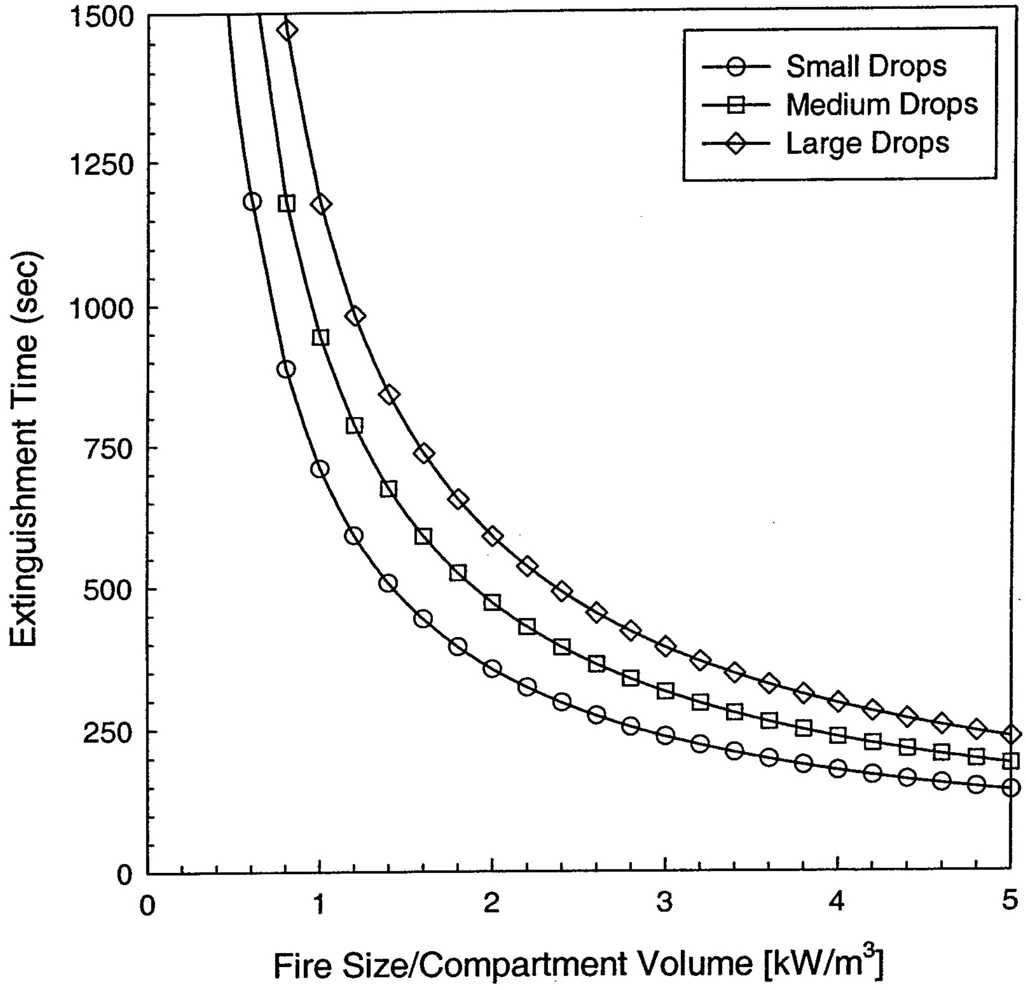


Figure 10. Estimated capabilities as a function of fire size to compartment volume ratio. (Based on an extrapolation of the test data to closed machinery spaces)

The first step in the calculation is to determine the heat transfer number *(B_T)* for the gas liquid combination. The heat transfer number B_T denotes the ratio of the available enthalpy in the surrounding gas to the heat required to evaporate the liquid. As such, it represents the driving force for the evaporation process and is given in the following equation.

$$B_T = \frac{c_{p_g}\left(T_\infty - T_s\right)}{L} \tag{4}$$

where c_{p_g} is the specific heat of the gas (air) and L is the latent heat of vaporization corresponding to the liquid surface temperature T_s.

Where the heat transfer rates are the controlling parameter, the evaporation rate for a single droplet can be determined using the following equation:

$$\dot{m} = 2\pi D \left(\frac{k}{c_p}\right)_g ln\left(1 + B_T\right) \tag{5}$$

where D is the drop diameter, k and c_p are the thermal conductivity and specific heat of the gas (air) respectively, and B_T is the heat transfer number as determined using equation (4). It should be noted that equation (5) assumes the Lewis number is one and only applies to steady-state evaporation. When used in the quasi steady-state model, the results of equation (5) are multiplied by the total number of drops in the compartment.

The total number of droplets suspended in the compartment at any given time is determined by first calculating the droplets concentration in the compartment.

The droplet concentration is estimated by dividing the system application rate (kg/sec·m^2) by the terminal velocity (m/s) of the mean drop size. The concentration is then divided by the weight of an average size drop and multiplied by the compartment volume to obtain the total number of drops in the space.

The previous calculation illustrates the advantages for using small drop systems for this application. Small drop systems produce higher droplet concentrations due their significantly lower terminal velocities. This relation is shown in Figure 11. Due to the reduced volume/weight of the smaller drops, the number of drops required to produce this concentration is significantly higher as shown in Figure 12. The higher surface area per unit volume of the small drops, combined with the larger number of drops suspended in the air, make the smaller drop systems significantly more efficient for producing water vapor than the larger drop systems.

To illustrate this point further, the evaporation rate as a function of drop size has been plotted in Figure 13 for the 500 m^3 test compartment filled with droplets with a steady-state air temperature of 50 °C. As shown in this figure, the evaporation rate significantly increases once the drop sizes are reduced below 500 microns.

Prior to inserting the evaporation algorithm into the model, the algorithm was validated using the results of these tests. During the previous analysis, water vapor concentration of gases in the compartment (percent saturation) was estimated based on the assumption that all fires were extinguished when the wet oxygen concentration in the compartment was reduced to 13.0 percent. These results were shown in Figure 9. The evaporation algorithm combined with a vent flow correlation applicable to well stirred compartments (the one used in the quasi steady-state model) were used to reproduce these measured values.

The first step in the calculation consisted of using evaporated algorithm to determine the evaporation rate (kg/s) of all the droplets in the space. The mass of water was then added to the mass of air flowing through the compartment as determined using the vent flow correlation (equation (2)). The calculated mass fraction of water vapor in this gas flow was then divided by the mass fraction of saturated gas to determine the percent saturation. This calculation was conducted for a range of compartment temperatures and three drop sizes representative of the systems evaluated during these tests (small – 400 microns, medium – 600 microns and large – 800 microns). The results of this analysis and a comparison with the measured values are shown in Figure 14. The lines on this figure are the calculated values and the symbols are the measured values

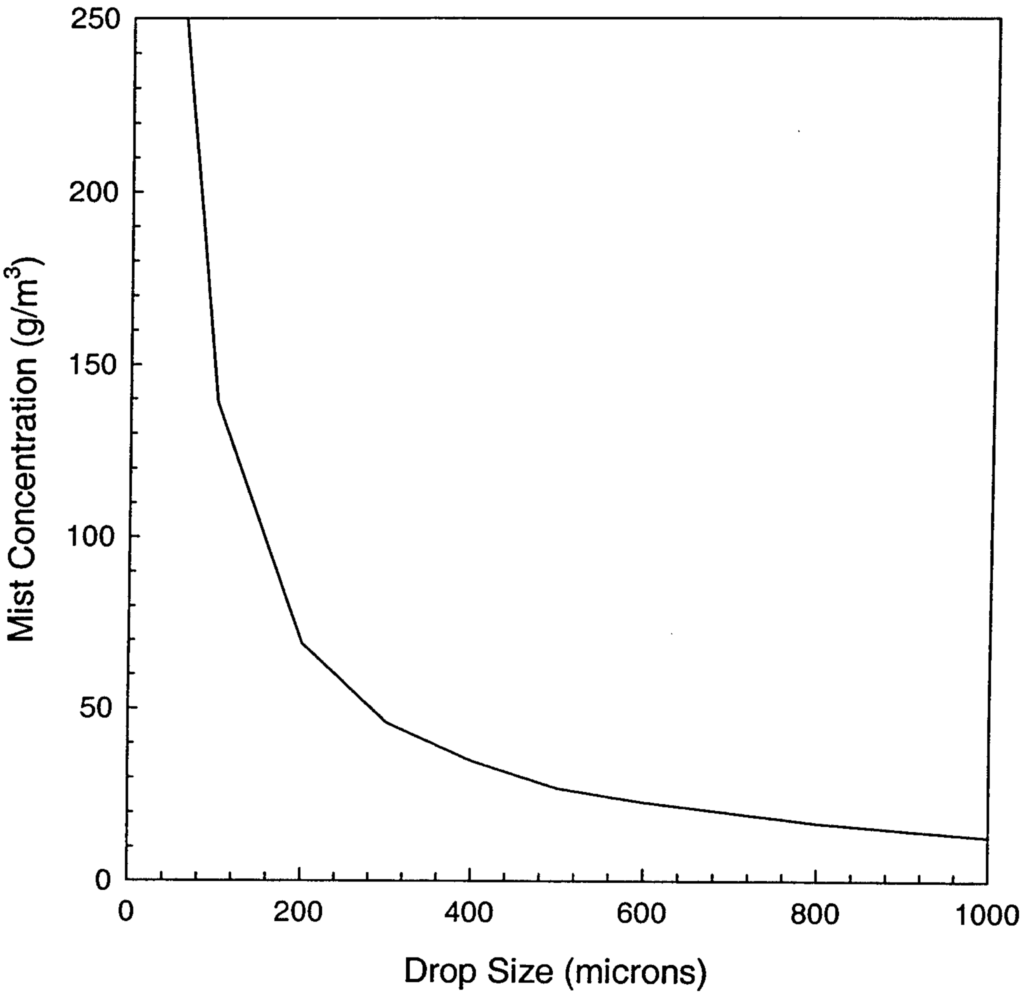


Figure 11. Calculated droplet concentrations as a function of drop size. (Determined for a system with an application rate of 5.0 Lpm/m^2)

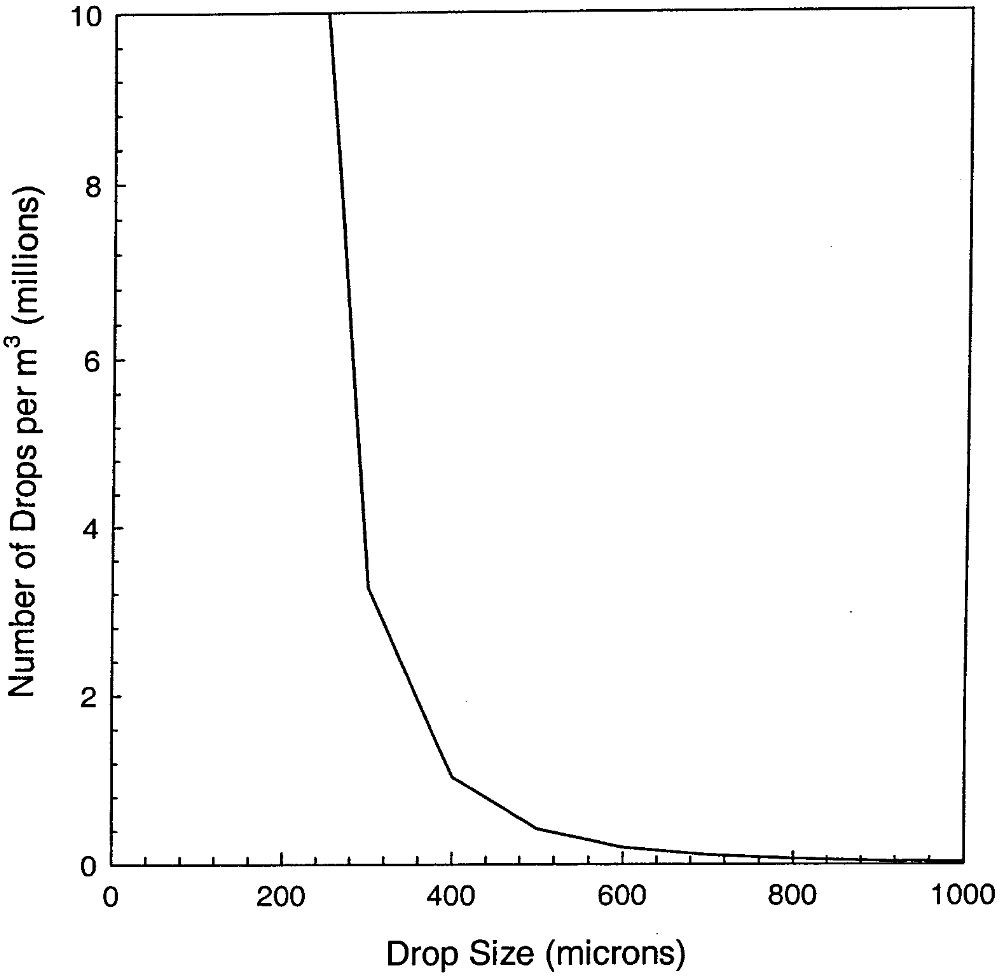


Figure 12. Number of drops per cubic meter.
(Based on the calculated concentrations shown in Figure 11.)

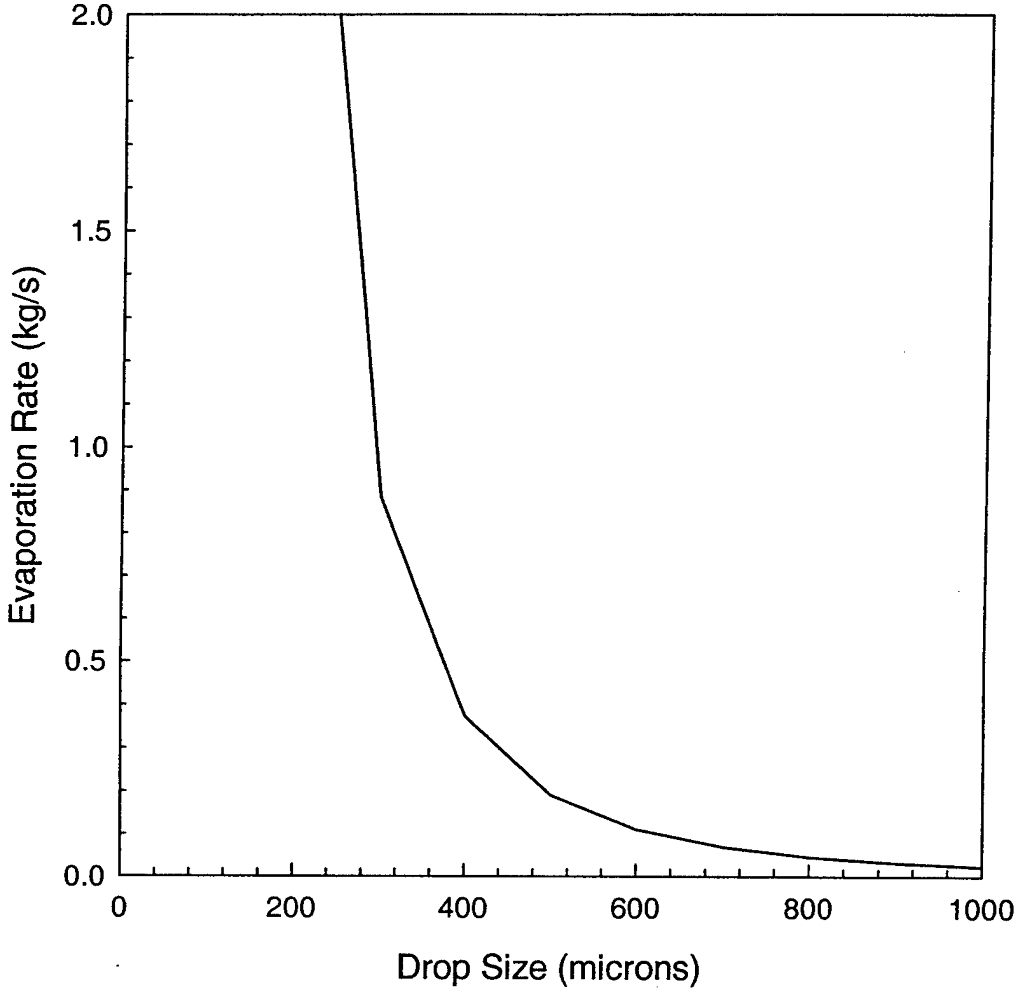


Figure 13. Evaporation rate as a function of drop size.
(For the concentrations shown in Figure 11 and an air temperature of 50 °C)

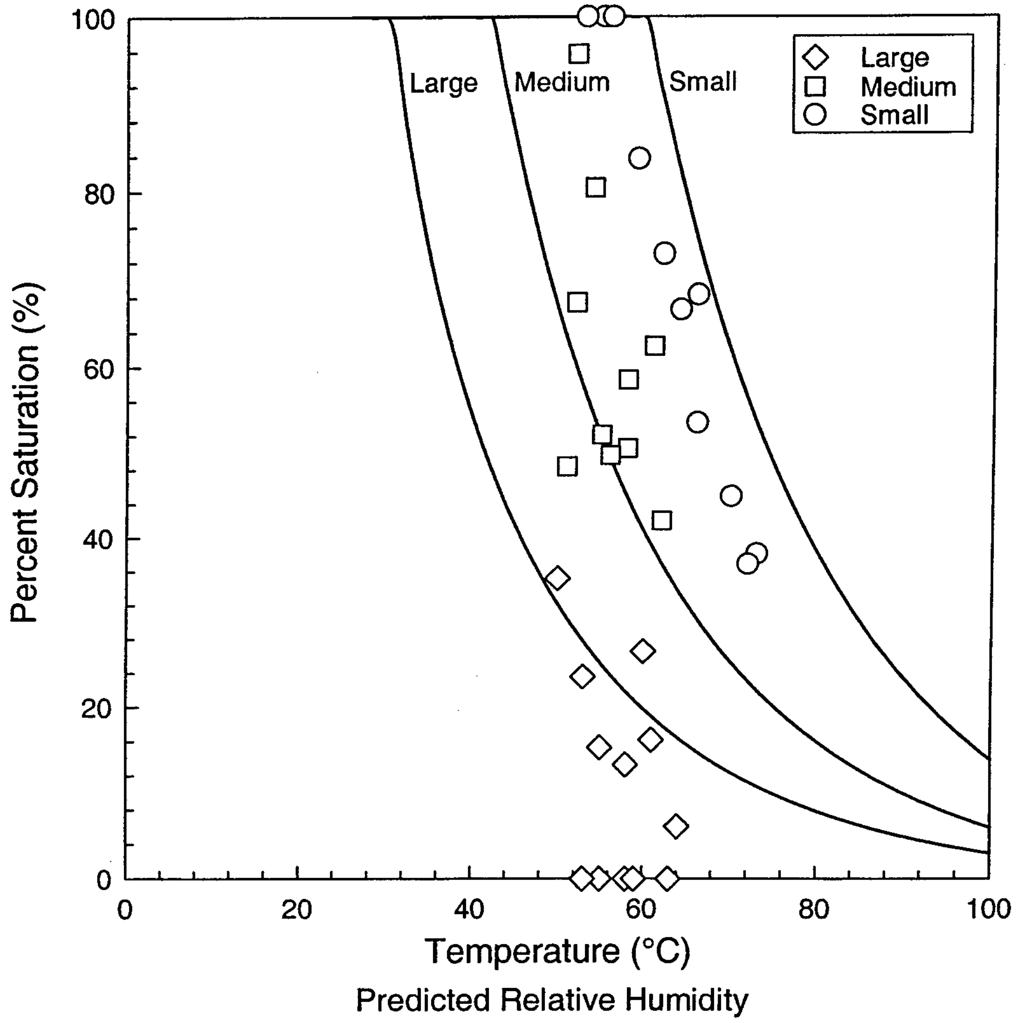


Figure 14. Vapor concentration comparisons.
(For systems with various size droplets: small, medium and large)

As shown in Figure 14, the predicted values are in good agreement with those measured during these tests. The measured concentrations however, were typically slightly less than the predicted values. The reason for this is that the fires were, in many cases, extinguished before the predicted steady-state conditions were achieved. The analysis also shows that the lines used to approximate the measured data in Figure 9 are not representative of the trends once the temperature is increased above 60-70 °C. Above these temperatures, the lines should asymptotically approach the y-axis not linearly approach as shown in Figure 8.

The evaporation algorithm was then inserted in the quasi steady-state model and used to predict the results of these tests. The steady-state temperatures and extinguishment times were predicted by the model for the systems discharging 5 $\mathrm{Lpm/m^2}$ (the minimum SOLAS requirement) and are shown in Figure 15. The ban of predicted results represents the range of drop sizes from 250-1000 microns.

As shown in Figure 15, the predicted results are again in good agreement with the measured values. The measured temperatures are similar for the systems included in this investigation and all lie in the ban of the predicted values. There is also reasonably good agreement with the extinguishment times although there are significant variations in the data. The extinguishment times that are less than the predicted values are attributed to a reduction in vent flow rate resulting from water curtain type effects. These are not addressed/ included in the model. The extinguishment times that are longer than the predicted values are attributed to reflashes/reignitions due to hot surfaces local to the fuel spray.

10.4 Drop Size Trade-offs

There are three aspects associated with the capabilities/performance of these systems: thermal management, water vapor production, and critical fire size. All three are associated with the energy absorption characteristics of the spray and are a function of the drop size and application rate of the system.

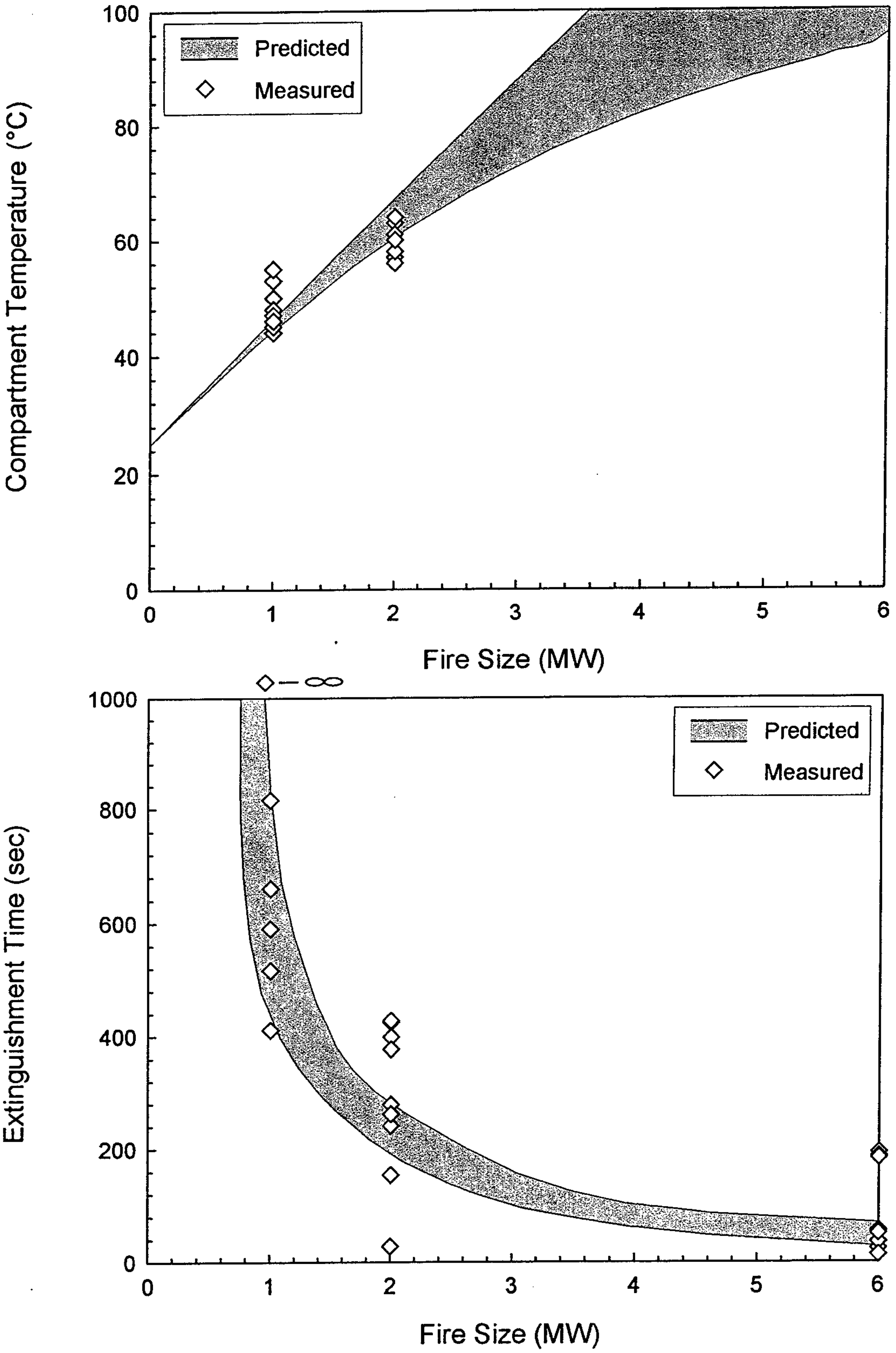


Figure 15. Model comparison for the systems discharging 5 Lpm/m^2.
(The ban represents the range of drop sizes from 250-1000 microns.)

The ability to manage the temperatures in the space is associated with the energy absorption characteristics of the system. This energy absorption consists of both heating the droplets to the surrounding gas temperatures and the production of water vapor. Systems that are inefficient in producing water vapor can still provide the same energy absorption by increasing the application rate. This is illustrated in Figure 16.

Shown in Figure 16 is the application rate (as a function of drop size) required to produce a steady-state compartment temperature of 60 °C for a 1.5 MW fire in the 500 m^3 IMO test compartment. As shown in this figure, an application rate of 3 Lpm/m^2 is adequate to maintain the temperature until the drop size exceeds 500 microns, at which point, the application rate needs to be increased. The required increase in application rate is on the order of 0.2 Lpm/m^2 per 100 micron increase in drop size above 500 microns.

The ability of a system to produce water vapor is primarily a function of drop size and increases exponentially as the drop size is reduced below 500 microns (as shown in Section 10.3). This exponential increase is associated with the lower terminal velocities of the smaller droplets resulting in a significant increase in droplet concentration as the drop sizes are reduced. The ability of a system to produce water vapor as a function of temperature for a range of drop sizes and application rates is shown in Figure 17. This figure shows the application rate required to saturate the gases flowing through the vent opening in the 500 m^3 IMO test compartment ($A\sqrt{H}$ = 4.7 $m^{3/2}$) as a function of temperature. As shown in this figure, the application rate needs to be increased significantly as the drop size of the system is increased.

The same type of analysis can be used to verify the assumption of saturated water vapor used when modeling the results of the previous water mist test series. Figure 18 shows the application rates (for a range of smaller size drops (mist)) required to saturate the gases in the compartment as a function of temperature.

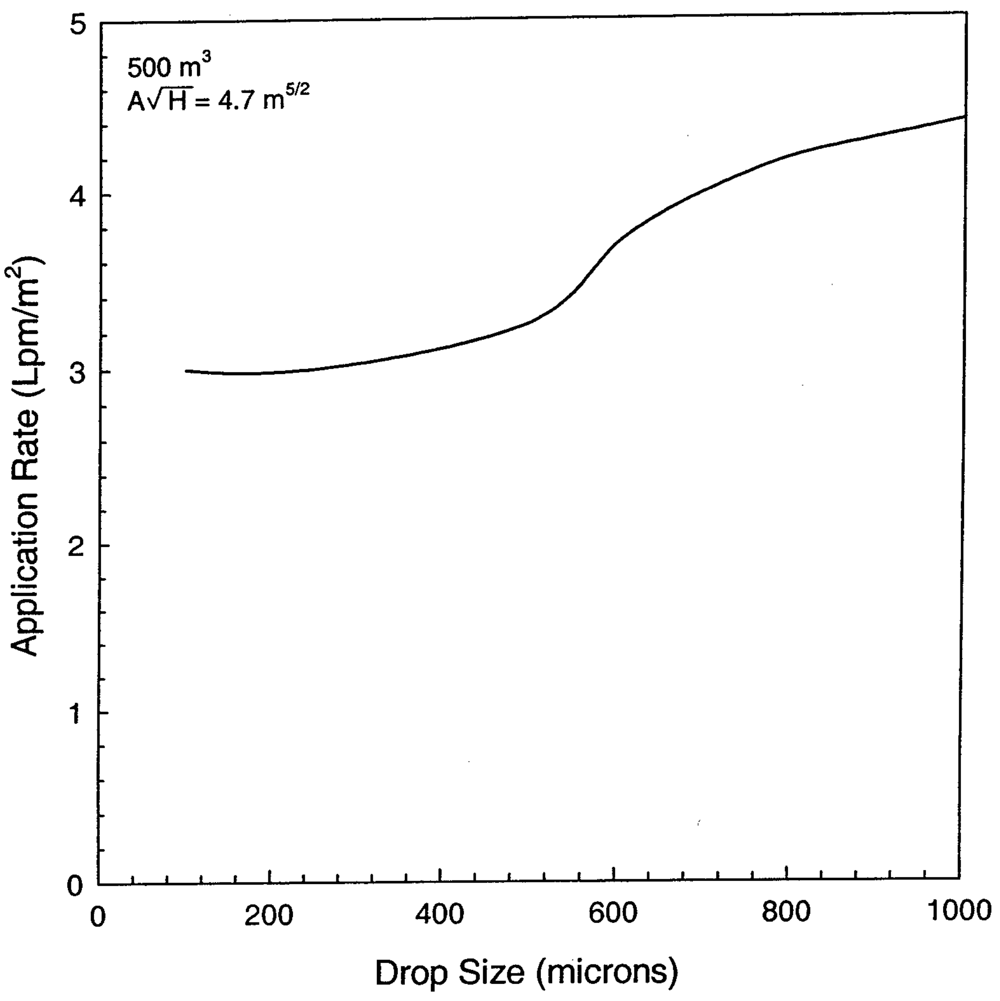


Figure 16. Thermal management comparison as a function of system application rate and spray characteristics.
(Parameters required to produce 60 °C for a 1.5 MW fire for the IMO $500\ m^3$ test compartment)

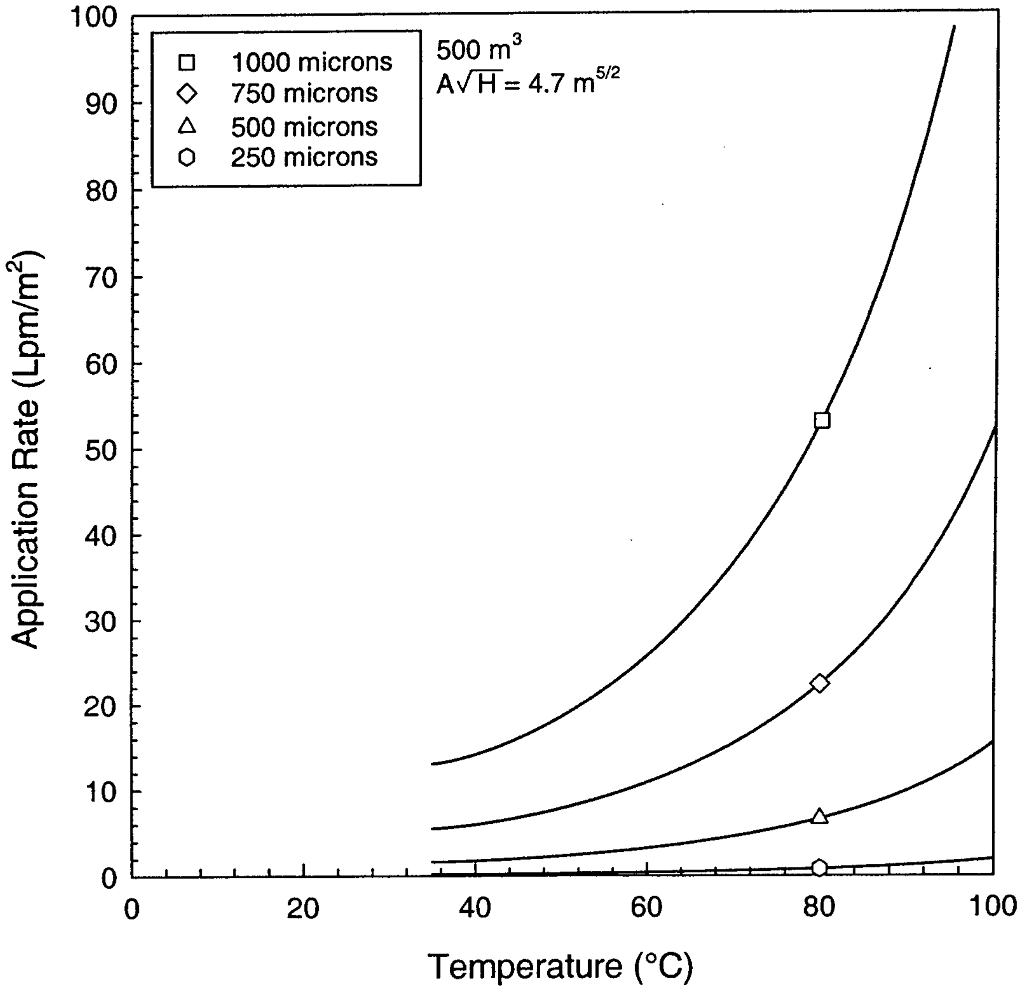


Figure 17. Parameters required for saturation (spray).

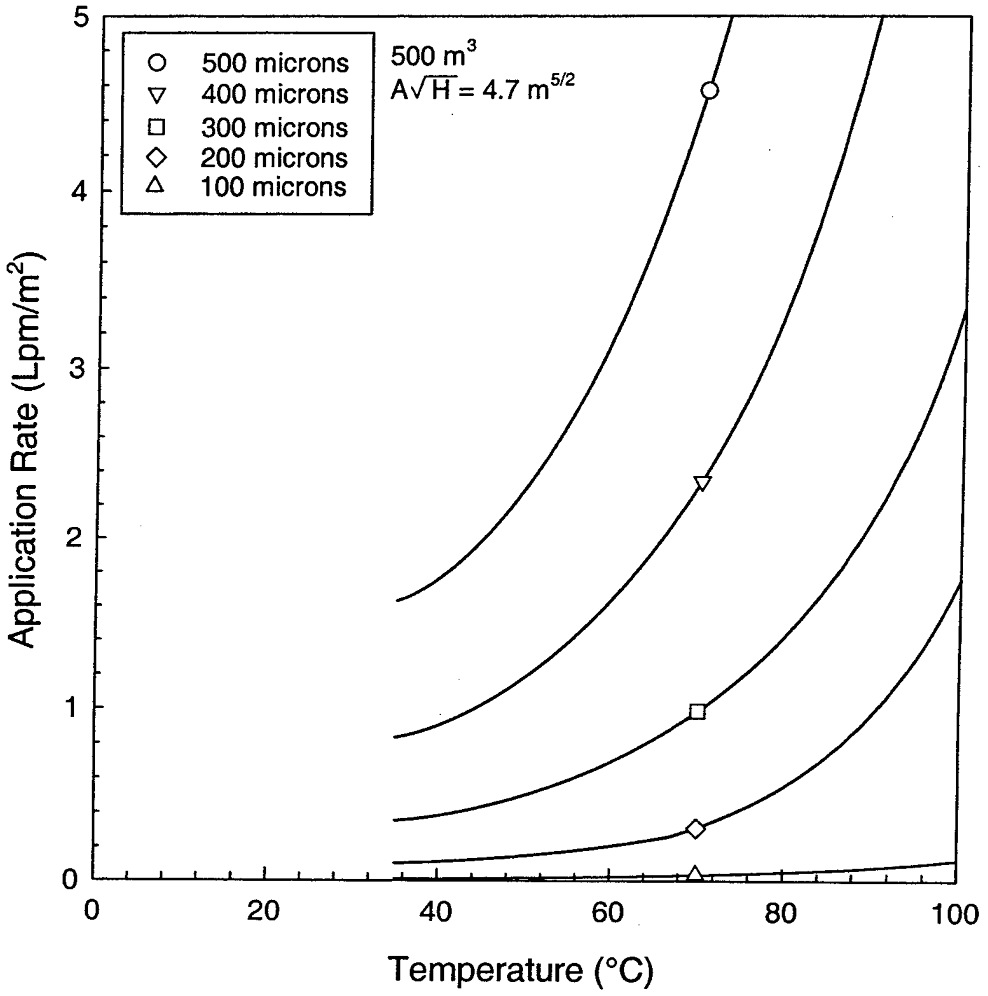


Figure 18. Parameters required for saturation (mist).

The saturated vapor assumption can be validated by comparing the required system parameters shown in Figure 18 to the ones previously tested/modeled. For example, the mist systems previously evaluated had mean drop sizes less than 300 microns and system application rates on the order of 3 Lpm/m^2 (± 1 Lpm/m^2). Based on Figure 18, a water mist system with a mean drop size of 300 microns discharging 2 Lpm/m^2 (the minimum previously tested) is adequate to produce saturated vapor in the 500 m^3 IMO test compartment for steady-state temperatures less than 90 °C. Typical compartment temperatures recorded during these previous tests ranged from 50–70 °C. This suggests that during all the water mist tests, the gases in the compartment were saturated.

10.5 Overall System Capabilities

The final and most important analysis is associated with how the production of water vapor effects the extinguishment capabilities of a system. All water spray systems are capable of reducing the compartment temperatures to acceptable levels but only the smaller drop systems (< 500 microns) are capable of producing saturated vapor at typically used application rates. The contribution of water vapor in the extinguishment process is illustrated in Figure 19, by comparing the critical fire size for the 500 m^3 IMO test compartment ($A\sqrt{H} = 4.7\ \text{m}^{3/2}$) as a function of both drop size and application rate.

As shown in Figure 19, increasing the application rate reduces the critical fire size independent of the spray characteristics of the system. This is a result of the increase in the cooling capabilities of the system. As the application rate of the system is increased, the compartment temperatures decrease reducing the flow rate of air through the vent opening. In the extreme case, when the gas temperatures in the space are reduced to ambient, the critical fire size is reduced to zero. Unfortunately, this occurs at unrealistically high application rates for these systems. It should also be noted that as the fire size is reduced to the critical value, the extinguishment times asymptotically approach infinity.

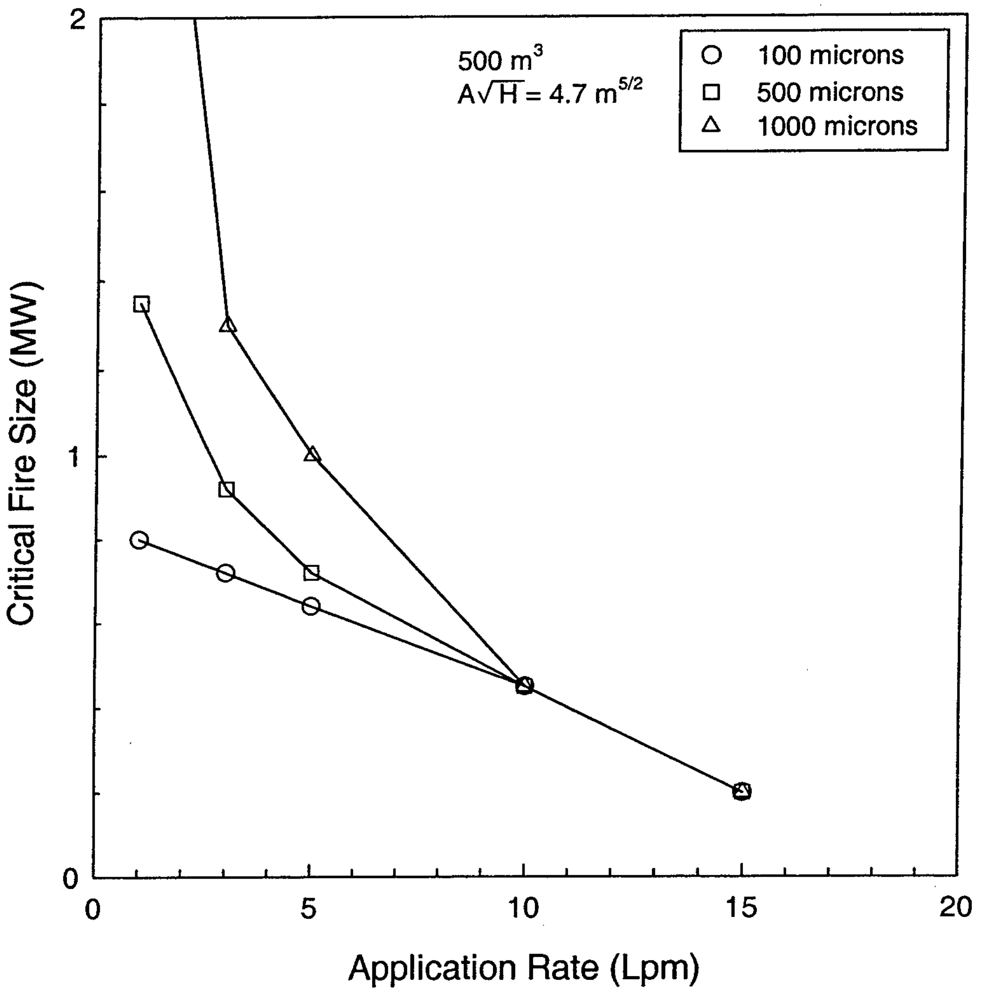


Figure 19. Critical fire size comparison.

As shown in Figure 19, as the application rate is reduced below 10 Lpm/m^2, the ability of the system to produce saturated vapor becomes the predominant variable associated with the critical fire size. For application rates of 5 Lpm/m^2 (the minimum SOLAS requirement), the difference in critical fire size between a mist type system (less than 250 microns) and a large drop system (~ 1000 microns) is on the order of 250 kW (750 kW for the mist system and 1.0 MW for the large drop system).

Based on the results shown in Figure 19, there is a high probability that any system designed to meet the minimum SOLAS requirements with a mean drop size less than 1000 microns could pass all the tests in IMO test protocol (MSC 668-728) for 500 m^3 enclosures with the exception of the small obstructed pan fire IMO-9. Even water mist systems require help (additives) to pass this test. Figure 19 also suggests that the borderline capabilities of the large drop systems would prevent them from succeeding in larger volume spaces whereas the smaller drop systems have a better chance to succeed.

10.6 Test Protocol Concerns

The final discussion needs to address the issues that have plagued the water mist industry over the past several years; "Is the inability of a system to extinguish a small obstructed fire and acceptable reason not to accept/approve a system?" "Is a small obstructed fire the primary hazard associated with a machinery space?" and "Should all the IMO tests be conducted in a well-ventilated compartment?" 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 based systems (mist and sprays) in larger machinery spaces unless these issues are addressed. Recommendations were made in a previous investigation (Back, et al 2000) to modify the protocol to address these issues. The following is the list of recommendations for improving the evaluation and approval process for water base systems in machinery space applications developed during that previous investigation.

- Reduce the number of tests in the protocol to the three or four most challenging;
- Allow the systems to be evaluated with more representative ventilation conditions;
- Scale the test fire size as a function of compartment volume. A 1-2 kW/m^3 scaling rule is recommended; and
- Allow the evaluation and approval of zoned total protection systems.

If these recommendations are adopted, there is reasonable probability that water base systems could be used to protect larger machinery spaces (greater then 1000 m^3).

11.0 SUMMARY AND CONCLUSIONS

Generally speaking, the trends in performance (extinguishment capabilities and thermal management) of water spray systems were similar to those previously observed for water mist systems. Both water spray and water mist systems rely on oxygen depletion to extinguish obstructed fires making larger fires easier to extinguish and go out faster than smaller fires. The water spray systems were capable of extinguishing larger fires (4 kW/m^3 and greater) with variations in system capabilities becoming apparent as the fire size was reduced (2 kW/m^3 and below). Only about half of the systems were capable of extinguishing the 1.0 MW obstructed spray fire located on the side of the engine mockup (similar to IMO-6). Water mist systems typically exhibit slightly better capabilities against these smaller fires with a majority of the commercially available systems capable of extinguishing this fire.

The water spray systems included in this evaluation were also capable of thermally managing the conditions in the space by producing a fairly well mixed environment and by reducing the compartment temperatures to 50-70 °C. The higher flow rates of the water spray systems apparently compensate for the lower evaporation efficiency associated with the larger drop sizes.

The performance/capabilities of these water spray systems were shown to be linked to two parameters; vapor production and vent flow effects. In an actual installation where the space would be secured during a fire, the production of water vapor is the key parameter. As a result, the smaller the drops, the better the performance of the system (assuming good mixing). This not only applies to extinguishment times but also to the critical fire size of the compartment.

A droplet evaporation algorithm was developed and added to the water mist fire suppression model developed and validated during previous USCG investigations (Back, et al 2000). The modified model showed good agreement with the results of these tests and was used to define the capabilities and limitations of water spray systems as a function of drop size.

It was concluded that the capabilities of these systems cannot be associated with a single parameter such as application rate and must be determined empirically. As a result, the approval of these systems needs to be performance based as with all other fire suppression systems required by SOLAS. It is recommended that SOLAS Regulation 10 be re-written to cover all water based machinery space systems with the caveat that they pass the IMO test protocol currently used for approving water mist systems [MSC 668 and 728]. Based on the results of these tests, it is likely that an optimized water spray system can successfully complete the test protocol for compartment volumes on the order of 500 m^3, but due to the large vent opening and/or smaller fire sizes included in the protocol, may have problems completing the requirements for larger machinery spaces.

12.0 RECOMMENDATIONS

It is recommended that SOLAS Regulation 10 be re-written to be performance based and be applied to all water based machinery space fire suppression systems (mist, water sprays, sprinklers etc.) The regulation should require successful completion of a test protocol based on MSC 668 and the revisions included in MSC 728. The following modifications to the protocol (s) are also recommended.

- Reduce the number of tests in the protocol to the three or four most challenging (The current protocol has tests that are redundant and do not differentiate system performance);
- Allow the systems to be evaluated with more representative ventilation conditions. (Remove the 2 m x 2 m vent opening and replace it with a leakage area typical to machinery space applications);
- Scale the test fire size as a function of compartment volume. A 1-2 kW/m^3 scaling rule is recommended. (Smaller fire sizes (less than 1 kW/m^3) do not significantly increase the temperature in the space and can be easily approached and extinguished using a portable extinguisher); and
- Allow the evaluation and approval of zoned total protection systems. (Previous studies [Back et al. 2000] have shown that zoned systems can be effective in this application and the current test protocol does not allow for approval of these systems).

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APPENDIX A – IMO TEST PROTOCOL

APPENDIX A – IMO TEST PROTOCOL
(MSC Circulars 668 and 728)

INTERIM TEST METHOD FOR FIRE TESTING EQUIVALENT WATER-BASED FIRE-EXTINGUISHING SYSTEMS FOR MACHINERY SPACES OF CATEGORY A AND CARGO PUMP-ROOMS

1 SCOPE

This test method is intended for evaluating the extinguishing effectiveness of water-based total flooding protect the volume fire-extinguishing systems for engine-rooms of category A and cargo pump rooms. In order to define the different engine-rooms and possible fire scenarios the engine types are divided into different Classes according to Table 1.

The test method covers the minimum fire-extinguishing requirement and prevention against reignition for fires in engine-rooms.

It was developed for Systems using ceiling mounted nozzles for Class 1 and Class 2 engine-rooms and multiple level nozzles for Class 3 engine-rooms, that may be utilized in conjunction with a separate bilge area protection system. In the tests, the use of additional nozzles to protect specific hazards by direct application is not permitted. However if referenced in the manufacturer's design and installation instructions, additional nozzles may be installed along the perimeter of the compartment to screen openings.

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* Except for coated and plated nozzles, the nominal release temperature range should be color-coded on the nozzle to identify the nominal rating. The color code should be visible on the yoke arms holding the distribution plate for fusible element nozzles, and should be indicated by the color of the liquid in glass bulbs. The nominal temperature rating should be stamped or cast on the fusible element of fusible element nozzles. All nozzles should be stamped, cast, engraved or color-coded in such a way that the nominal rating is recognizable even if the nozzle has operated. This should be in accordance with Table 1.

Table 1 - *Classification of Category An Engine Room*

Class	Typical engine facts	Typical Net Volume	Typical oil flow and pressure in fuel and lubrication system
1	Auxiliary engine-room, small main machinery or purifier room, etc.	500 m^3	Fuel: Low pressure 0.15-0.20 kg/s 3-6 bar High pressure 0.02 kg/s 200-300 bar Lubrication oil: 3-5 bar Hydraulic oil: 150 bar
2	Main diesel machinery in medium-sized ships such as ferries	3,000 m^3	Fuel: Low pressure 0.4-0.6 kg/s at 3-8 bar High pressure 0.030 kg/s at 250 bar Lubrication oil: 3-5 bar Hydraulic oil: 150 bar
3	Main diesel machinery in large ships such as oil tankers and containers ships	>3,000 m^3	Fuel: Low pressure 0.7-1.0 kg/s at 3-8 bar High pressure .020 kg/s Lubrication oil: 3-5 bar Hydraulic oil: 150 bar

2 FIELD OF APPLICATION

The test method is applicable for water-based fire-extinguishing systems which will be used as alternative fire-extinguishing systems as required by SOLAS regulation 11-2/7. For the installation of the system, nozzles shall be installed to protect the entire hazard volume (total flooding). The installation specification provided by the manufacturer should include maximum nozzle spacing, maximum enclosure height, distance of nozzles below ceiling, maximum enclosure volume and maximum ventilation condition.

3 SAMPLING

The components to be tested should be supplied by the manufacturer together with design and installation criteria, operational instructions, drawings and technical data sufficient for the identification of the components.

4 METHOD OF TEST

4.1 Principle

This test procedure enables the determination of the effectiveness of different water-based extinguishing systems against spray fires, cascade fires, pool fires, and Class A fires which are obstructed by an engine mock-up.

4.2 Apparatus

4.2.1 *Engine mock-up*

The fire test should be performed in a test apparatus consisting of:

.1 An engine mock-up of size (width × length × height) 1 m × 3 m × 3 m constructed of sheet steel with a nominal thickness of 5 mm. The mock-up is fitted with two steel tubes diameter 0.3 m and 3 m length that simulate exhaust manifolds and a grating. At the top of the mock-up a 3 m^2 tray is arranged. See Figure 2.

.2 A floor plate system 4 m × 6 m 0.5m high surrounding the mock-up with three trays, 2, 2, and 4 m^2, equaling a total area of 8 m^2, underneath. See Figure 2.

4.2.2 *Test room*

.1 Class 1 engine-room

The test should be performed in 100 m^2 room with 5 m ceiling height and ventilation through a 2 m × 2 m door opening. Fires and engine mock-up according to Tables 2, 3 and Figure 1.

.2 Class 2 engine-room

The tests should be performed in a room having a specified area greater than 100 m , specified height of from 5 to 7.5 m and ventilation through a 2 m × 2 m door opening up to a total volume for the room of 3,000 m^3. Fires and engine mock-up should be according to Tables 2, 3, and Figure 1.

.3 Class 3 engine-room

The test should be performed in a fire test hall with a minimum floor area of 300 m^2, and a ceiling height in excess of 10 m and without any restrictions in air supply for the test fires. Fires and engine mock-up should be according to Tables 2 and 3 and Figure 1.

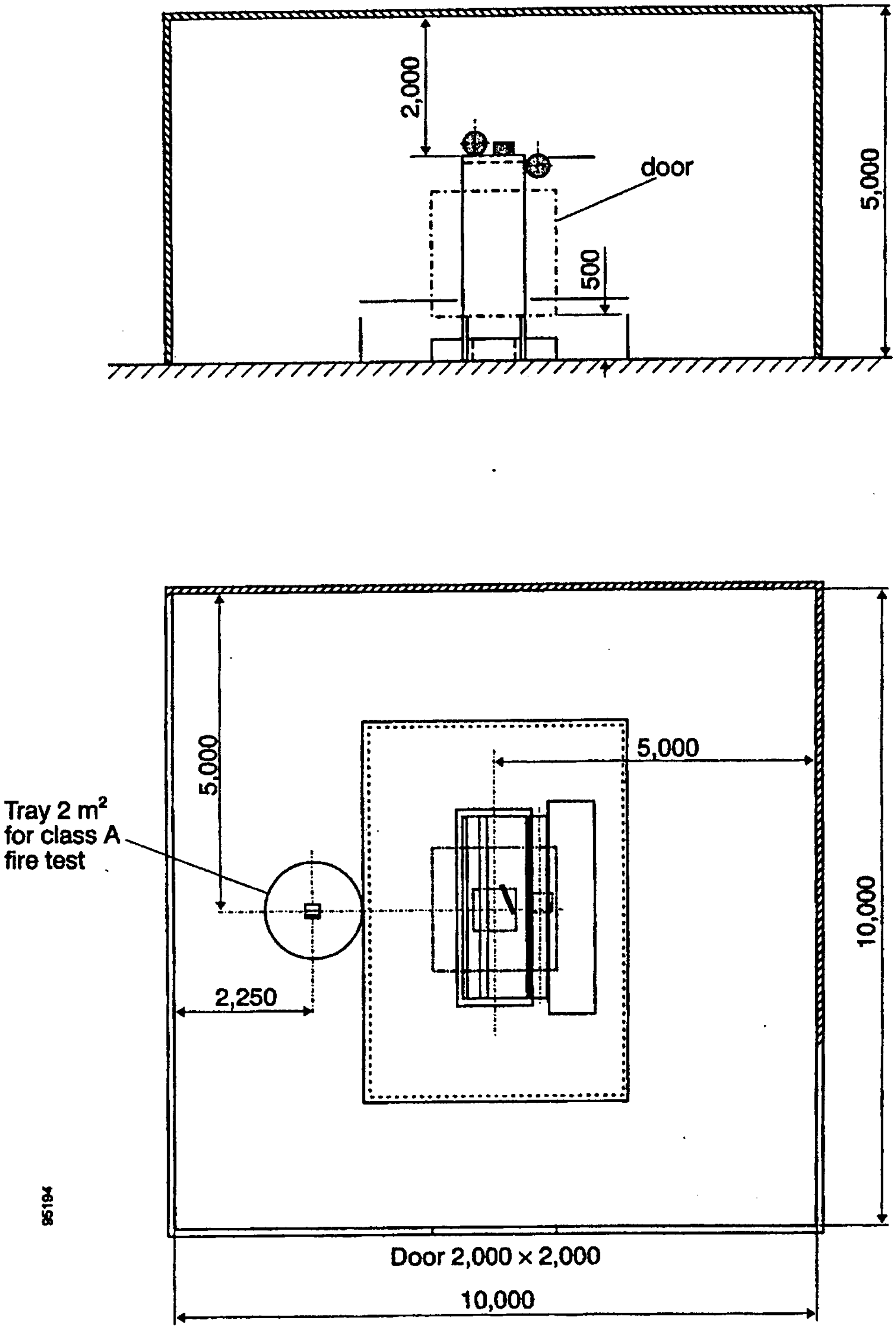
2,000
door
5,000
500
5,000
5,000
Tray 2 m²
for class A
fire test
10,000
2,250
Door 2,000 × 2,000
10,000
95194

Figure 1

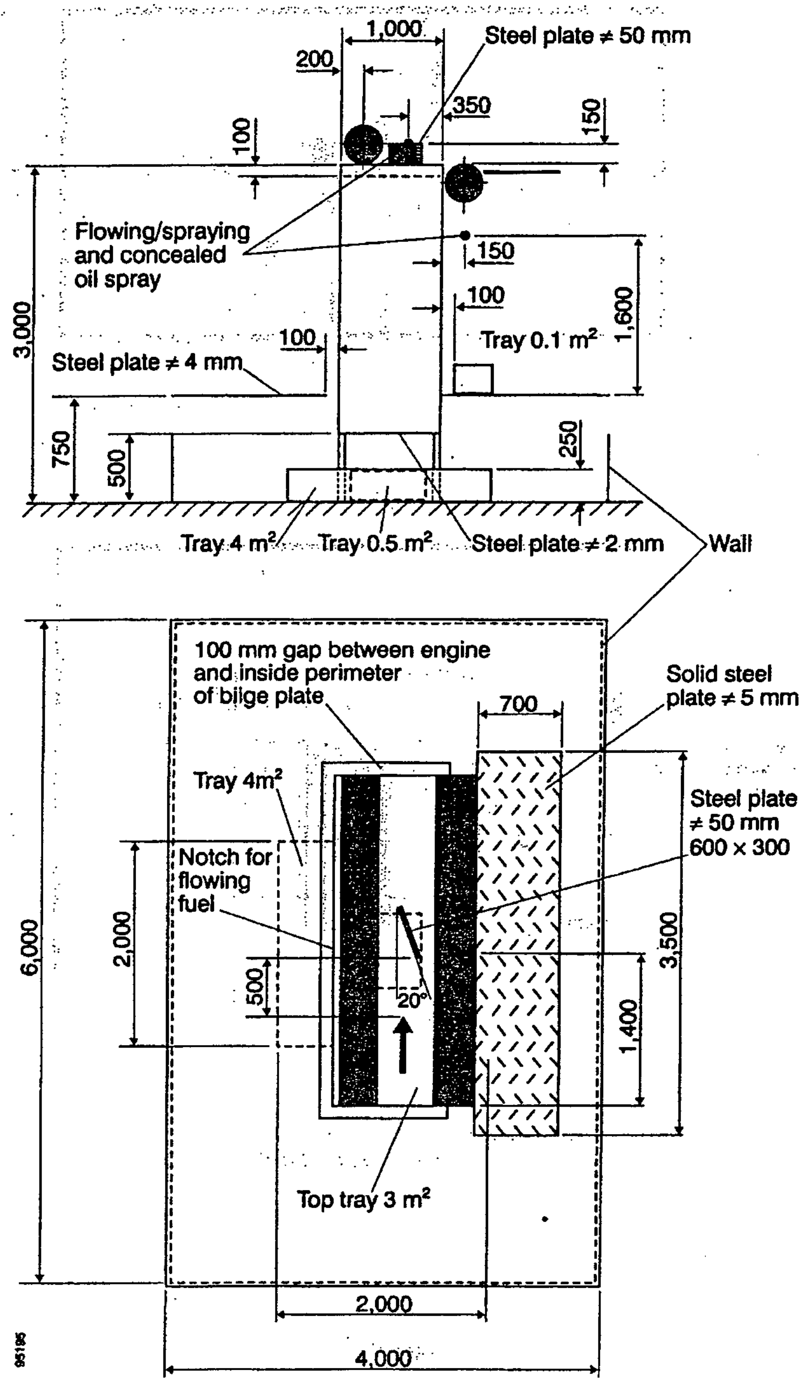
1,000
Steel plate ≠ 50 mm
200
350
150
100
Flowing/spraying and concealed oil spray
150
100
1,600
3,000
100
Tray 0.1 m²
Steel plate ≠ 4 mm
750
500
250
Tray 4 m²
Tray 0.5 m²
Steel plate ≠ 2 mm
Wall
100 mm gap between engine and inside perimeter of bilge plate
700
Solid steel plate ≠ 5 mm
Tray 4m²
Steel plate ≠ 50 mm 600 x 300
Notch for flowing fuel
2,000
500
20°
6,000
3,500
1,400
Top tray 3 m²
2,000
4,000
95195

Figure 2

Table 2 - *Test Programmer*

Test No.	Fire Scenario	Test Fuel
1	Low pressure horizontal spray on top of stimulated engine between agent nozzles	Commercial fuel oil or light diesel oil
2	Low pressure spray in top of stimulated engine centered with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1m away	Commercial fuel oil or light diesel oil
3	Low pressure concealed horizontal spray fire on side of simulated engine with oil spray nozzle positioned 0.1 m in from the end of engine	Commercial fuel oil or light diesel oil
4	Combination of worst spray fire from tests 1-3 and fires in trays under (4 m^2) an on top of the simulated engine (3 m^2)	Commercial fuel oil or light diesel oil
5	High pressure horizontal spray on top of the simulated engine	Commercial fuel oil or light diesel oil
6	Low pressure low flow concealed horizontal spray fire on the side of simulated engine with oil spray nozzle positioned 0.1 m in from the end of the engine end at the inside of floor plate	Commercial fuel oil or light diesel oil
7	0.5 m^2 central under mock-up	Heptane
8	0.5 m^2 central under mock-up	SAE 10W30 mineral based lubrication oil
9	0.5 m^2 on top of bilge plate centered under exhaust	Heptane
10	Flowing fire 0.25 kg/s from top of mock-up. See Figure 3	Heptane
11	Class A fires wood crib (see Note) in 2 m^2 pool fire with 30 s preburn. The test tray should be positioned 0.75 m above the floor as shown in Figure 2.	Heptane
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 nozzle positioned horizontally 0.5 m from the front edge of the plate. When the plate reaches 350 °C, the system is activated, Following system shutoff, no reignition of spray is permitted	Heptane
13	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil

Notes: 1 The wood crib is to weigh 5.4-5.9 kg and is to be dimensioned approximately 305 mm × 305 mm × 305 mm. The crib is to consist of eight alternate layers of four trade size 38.1 mm × 38.1 mm kiln-dried spruce or fir lumber 305 mm long. The alternate layers of the lumber are to be placed at right angles to the adjacent layers. The individual wood members in each layer are to be evenly spaced along the length of the previous layer of wood members and stapled. After the wood crib is assembled, it is to be conditioned at a temperature of 49 ± 5°C for not less than 16 h. Following the conditioning, the moisture content of the crib is to be measured with a probe type moisture meter. The moisture content of the crib should not exceed 5% prior to the fire test.

2 Test 4, 7, 8 and 13 are not required for bilges with a separate fire protection system and are not applicable to bilges with a depth of more than 0.75 m (see section 4.3).

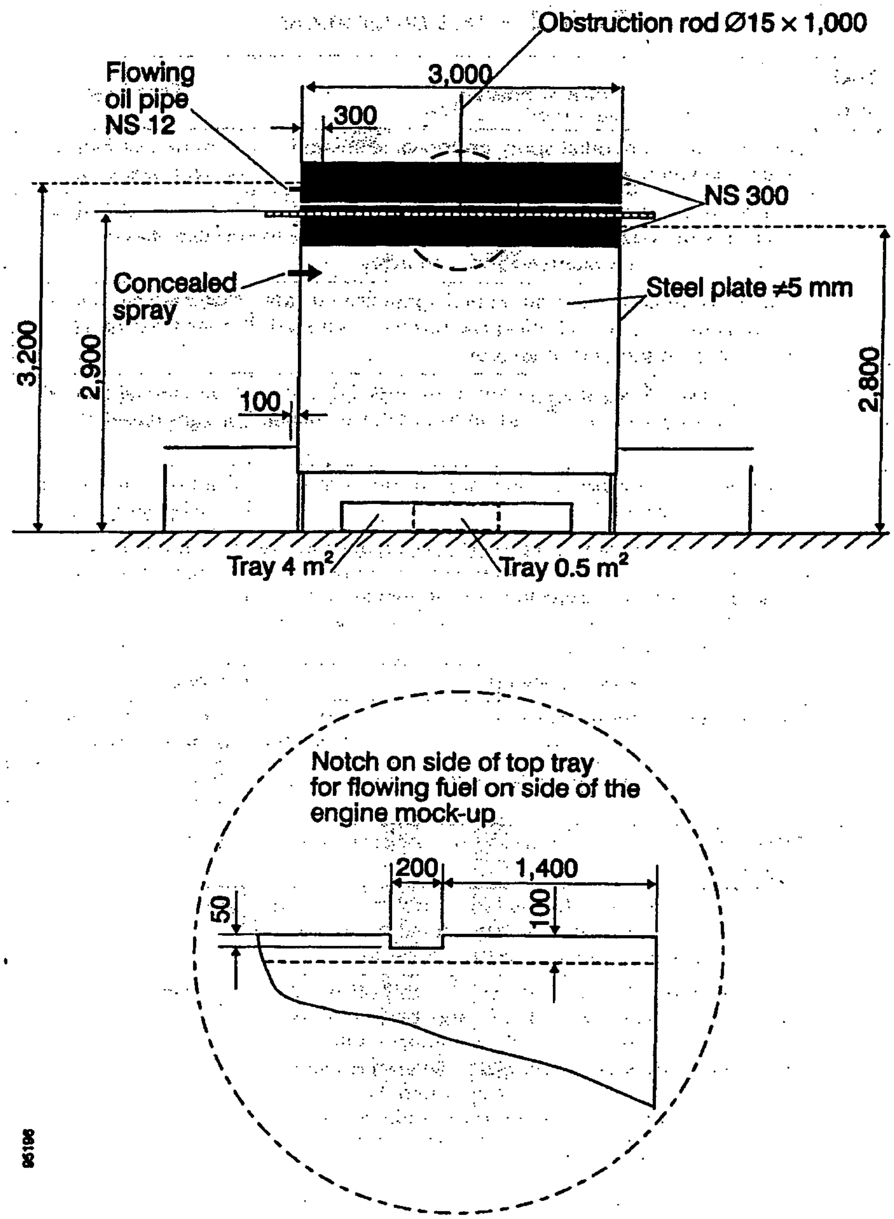
Obstruction rod Ø15 × 1,000
Flowing oil pipe NS 12
3,000
300
NS 300
Concealed spray
Steel plate ≠5 mm
3,200
2,900
100
2,800
Tray 4 m²
Tray 0.5 m²
Notch on side of top tray for flowing fuel on side of the engine mock-up
200
1,400
50
100
95196

Figure 3

Table 3 - *Oil spray fire test parameters*

Category A Engine-Room Class 1-3			
Fire type	**Low pressure**	**Low pressure, low flow**	**High pressure**
Spray nozzle	Wide spray angle (120° to 125°) full cone type	Wide spray angle (80°) full cone type	Standard angle (at 6 bar) full cone type
Nominal oil pressure	8 bar	8.5 bar	150 bar
Oil flow	0.16 ± 0.01 kg/s	0.03 ± 0.005 kg/s	0.050 ±0.002 kg/s
Oil temperature	20 ± 5°C	20 ± 5°C	20 ± 5°C
Nominal heat release rate	5.8 ± 0.6 MW	1.1 ± 0.1 MW	1.8 ± 0.2 MW

4.3 Extinguishing system

The extinguishing system should be installed according to the manufacturer's design and installation instructions. For Class 3 engine-rooms, the maximum vertical distance between levels of nozzles should be limited to 7.5 m and the lowest level of nozzles should be at a minimum height of 5 m above the floor. For actual installation with bilges more than 0.75 m in depth, nozzles must be installed in the bilges in accordance with manufacturer's recommendations as developed from representative fire tests.

4.4 Procedure

4.4.1 *Ignition*

The tray/s used in the test should be filled with at least 50 mm fuel on a water base. Freeboard is to be 150±10 mm.

4.4.2 *Flow and pressure measurements (oil system)*

The oil flow and pressure in the oil system should be measured before each test. The oil pressure should be measured during the test.

4.4.3 *Flow and pressure measurements (Extinguishing System)*

Agent flow and pressure in the extinguishing system should be measured continuously on the high pressure side of a pump or equivalent equipment at intervals not exceeding 5 s during the test, alternatively, the flow can be determined by the pressure and the *K* factor of the nozzles.

4.4.4 *Duration of test*

After ignition of all fuel sources, a 2 mm preburn time is required before the extinguishing agent is discharged for the oil tray fires and 5-15 s for the oil spray and heptane fires and 30 s for the Class A fire test (Test No. 11).

Extinguishing agent should be discharged for 50% of the discharge time recommended by the manufacturer or 15 mm whatever is less. The oil spray, if used, should be shut off 15 s after the end of agent discharge.

4.4.5 *Observations before and during the test*

Before the test, the test room, fuel and mock-up temperature is to be measured.

During the test the following observations should be recorded:

.1 the start of the ignition procedure;
.2 the start of the test (ignition);
.3 the time when the extinguishing system is activated;
.4 the time when the fire is extinguished, if it is;
.5 the time when the extinguishing system is shut off;
.6 the time of reignition, if any;
.7 the time when the oil flow for the spray fire is shut off; and
.8 the time when the test is finished.

4.4.6 *Observations after the test*

.1 Damage to any system components;

.2 The level of oil in the tray(s) to make sure that no limitation of fuel occurred during the test;

.3 Test room, fuel and mock-up temperature.

5 CLASSIFICATION CRITERIA

At the end of discharge of water-based fire-extinguishing media and fuel at each test, there should be no re-ignition or fire spread.

6 TEST REPORT

The test report should include the following information:

.1 Name and address of the test laboratory;
.2 Date and identification number of the test report;
.3 Name and address of client;
.4 Purpose of the test;
.5 Method of sampling;
.6 Name and address of manufacturer or supplier of the product;
.7 Name or other identification marks of the product;
.8 Description of the tested product:
  - drawings,
  - descriptions,
  - assembly instructions,
  - specification of included materials,
  - detailed drawing of test set-up.

.9 Date of supply of the product;
.10 Date of test;
.11 Test method;
.12 Drawing of each test configuration;
.13 Measured nozzle characteristics;
.14 Identification of the test equipment and used instruments;
.15 Conclusions;
.16 Deviations from the test method, if any;
.17 Test results including observations during and after the test; and
.18 Date and signature.