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Full-Scale Testing of Water Mist Fire Extinguishing Systems for Machinery Spaces on U.S. Army Watercraft

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A series of tests was conducted to evaluate the capability of water mist nozzles for extinguishing fires in engine and generator rooms on U.S. Army watercraft. Three types of nozzles were evaluated: single fluid low pressure, single fluid high pressure and dual fluid (air/water) nozzles. The international Maritime Organization's (IMO) test protocol for halon alternatives in machinery spaces and pump-rooms was used. The tests were conducted in a simulated machinery space 9.1 x 9.1 x 4.6 m. The best performance was obtained with a single fluid high pressure nozzle which was able to extinguish all of the fires in the IMO test protocol except the bilge-fire mist nozzles in the bilge areas.

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1.0 INTRODUCTION

The U.S. Army is investigating the use of water mist as a replacement for Halon 1301 total flooding systems currently installed in both flammable liquid storerooms and machinery spaces on Army watercraft. This investigation is centered around four Army ship designs that currently have onboard Halon 1301 fire suppression systems: namely, LCU 1600, LCU 2000, LSV, and ROWPU Barge. Since these ships come under the purview of the U.S. Coast Guard, any alternative to Halon 1301 would have to be approved by the Coast Guard.

In December 1994, the Maritime Safety Committee of the International Maritime Organization (IMO) approved guidelines for alternative arrangements for halon fire extinguishing systems (MSC Circular 668 [1]). Annex B of the guidelines provides an interim test method for evaluating equivalent water-based fire extinguishing systems for Category A machinery spaces and cargo pump rooms. This interim test standard was selected as the baseline for testing and acceptance for this evaluation.

Earlier work conducted by the U.S. Navy [2,3] has demonstrated that, if properly designed and tested, water mist fire suppression systems can afford excellent protection for machinery spaces, and flammable liquid storerooms [4]. The essential difference between this program and the Navy machinery space program lies in the selection of the fire tests and the compartment configurations making up the acceptance criteria. The Navy program incorporated a combination of simultaneous spray, pool, and tell tale fires in the range of 2.5-10 MW, located in a highly obstructed, simulated machinery space, as the fire threat, as opposed to the individual fire threats of the IMO standard which are located in a relatively unobstructed machinery space. Other differences include ventilation conditions as well as water mist system design constraints. For most of the Navy tests, the water mist system was evaluated as if it were a gaseous system. That is, before the mist system was activated, the forced ventilation in the space was shut down and the space secured (all compartment openings were closed to produce a relatively airtight enclosure). In comparison, the IMO tests are conducted in an open compartment containing a 2 m x 2 m (6.5 ft x 6.5 ft) vent opening. During the Navy tests, the mist system design evolved from an overhead uniform nozzle spacing type system similar to that required by the IMO protocol, to a multilevel system designed around the space and the obstructions therein. The net result of the approach taken by the Navy was a water mist system design that was capable of extinguishing all of the test fires in the space within 30 seconds of system activation. While these results are not directly comparable to the approach taken by the IMO, the Navy results represent the higher end of the performance curve and in some cases may be more representative of an actual Army machinery space application.

Manuscript approved December 20, 1995.

This report addresses the results of the tests conducted to evaluate the use of water mist technologies in Army machinery space applications in accordance with the approved test plan [5]. These tests were conducted by the Naval Research Laboratory (NRL) at its Chesapeake Beach Detachment (CBD). The Army flammable liquid storeroom tests are covered in a separate report [4].

2.0 OBJECTIVES

The objective of this test series was to evaluate the feasibility of using a water mist total flooding system as a replacement for the currently installed Halon 1301 system used in Army watercraft machinery spaces. This evaluation focussed primarily on the fire extinguishment capabilities of the "state of the art" water mist technologies as applied to machinery space applications. An assessment of water mist system parameters (i.e., flow rates, pressures, nozzle spacings, etc.) was also conducted to optimize the fire extinguishment capabilities of each system as well as add robustness to the system's performance. Ultimately, a performance specification was developed and is currently being reviewed for approval by the U.S. Coast Guard.

Other, more specific objectives include an evaluation of the following:

(1) the system's firefighting capabilities against a range of fuel types and fire scenarios including Class A fires and Class B pool, cascading, and spray fires;

(2) the system performance as a function of fire location within the protected space (i.e., corners, high elevations, etc.);

(3) the limits of the system with respect to shielding and fire obstruction(s); and

(4) the impact of water mist nozzle spray pattern obstructions on system performance.

3.0 WATER MIST OVERVIEW

3.1 Background

In general, the efficiency of a particular water mist system is strongly dependent on the system's ability to not only generate sufficiently small droplet sizes, but to distribute "critical concentrations" of droplets throughout the compartment. It is worth remarking that a widely accepted "critical concentration" of water droplets required to extinguish a fire is yet to be determined. Factors that contribute to the distribution of this critical concentration of water mist throughout the compartment consist of droplet size, velocity, the spray pattern geometry as well as the momentum and mixing characteristics of the spray jet, and the geometry and other characteristics of the protected area. Hence, water mist must be evaluated in context of a system rather than an extinguishing agent.

3.2 Current Water Mist Technologies

There are currently over twenty manufacturers of water mist hardware, some of which are commercially available as fire suppression systems while others are still under development or being used in other applications. For the purpose of more general discussion, these candidate systems can be broken down into three distinct categories: single-fluid low-pressure, single-fluid high-pressure, and twin-fluid systems. The droplet size distributions produced by similar technologies fall into discrete ranges. These ranges are shown as the volumetric mean droplet sizes (D_{V50}) in Fig. 1. All three system categories have been demonstrated as effective fire suppression technologies [4]. A brief description of the three general categories is given in the following paragraphs.

3.2.1 Single-fluid Low-pressure Nozzles

Single-fluid low-pressure nozzles operate at or below 175 psi. Because of this relatively low operating pressure, these nozzles often utilize the same piping and materials as conventional sprinkler systems. This translates into a relatively simple, lower cost system. The lower pressure nozzles also utilize larger orifice sizes to produce the same water flow rates. This increased orifice size can be an advantage in reducing the need for corrosion prevention and water supply filtration (to some extent).

The disadvantages of these nozzles are larger average droplet sizes and higher water flow rates. The larger droplet sizes reduce the systems' capabilities against obstructed/shielded fires. Also, the larger droplets have a higher terminal velocity than smaller droplets due to the mass of water contained in the droplet. This results in a higher fall out rate of droplets from the mist. This fall out significantly reduces the amount of mist that effectively mixes throughout the space, especially in higher elevations and around obstructions. The low pressure nozzles utilize higher flow rates in an attempt to negate these increased fall out losses.

3.2.2 Single-fluid High-pressure Nozzles

The single-fluid high-pressure nozzles, to date, have proven to be the most effective fire extinguishing mist system technology. As with the single-fluid low-pressure nozzles, these nozzles use a single-fluid (water or water plus an additive) but operate at pressures up to 200 bar (3000 psi). These high operating pressures provide an effective means of generating high concentrations of small droplets. The smaller droplet sizes exhibit more gaseous-like behavior and superior mixing characteristics. These characteristics increase the systems' capabilities against shielded/obstructed fires. The smaller droplets also have superior heat transfer characteristics due to greater surface area to volume ratios. This allows the high pressure nozzles to utilize water more efficiently and consequently use less water.

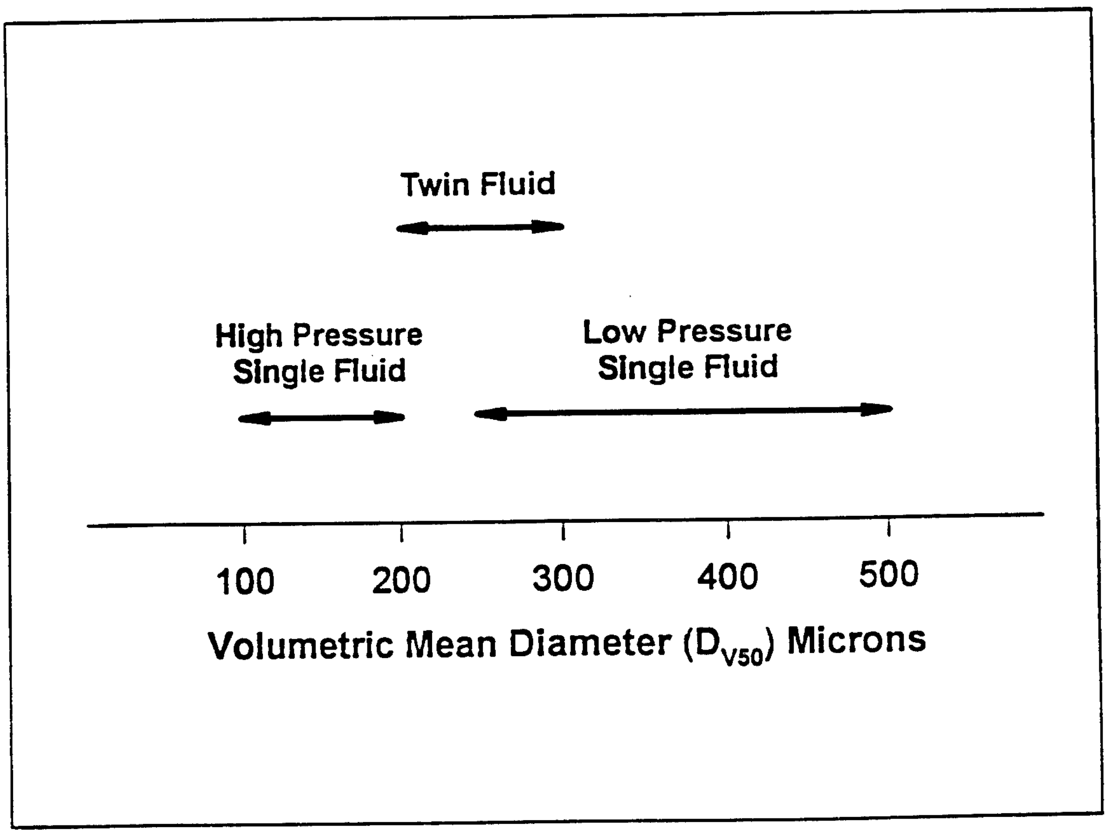


Figure 1. Droplet size comparison

The disadvantage of these nozzles is an increased cost due to the need for high-pressure system components (i.e., pipes, fittings, valves, pumps, etc.). Power requirements associated with the high-pressure pumps may in many cases also prove to be a severe disadvantage.

3.2.3 Twin-fluid Nozzles

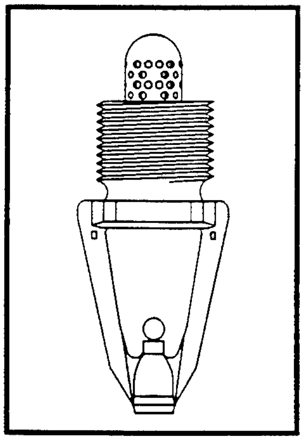
Twin-fluid nozzles require two fluids, water and an atomizing fluid, both being supplied to the nozzle using separate piping networks. These nozzles utilize a high velocity stream of air or nitrogen to shear the water into small droplets. This process usually takes place in or directly in front of the nozzle. One advantage of this technology is that it produces large quantities of small water droplets at low operating pressures, usually less than 7 bar (100 psi). The disadvantage of this technology is the additional piping, storage volume, and associated cost of the atomizing fluid.

3.3 Candidate Water Mist Systems

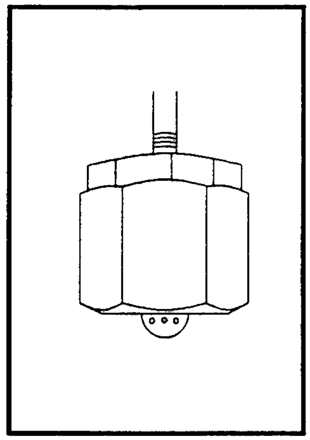
Six commercially available water mist fire suppression nozzles and two generic nozzles produced using off-the-shelf industrial spray nozzles were originally considered for this evaluation based on the tests conducted during the flammable liquid storeroom evaluation [4]. The candidate nozzles cover the range of available technologies from high and low-pressure single-fluid systems to twin-fluid systems. The generic nozzles were evaluated to identify any variations in performance between the "state of the art" water mist technologies and off-the-shelf industrial water spray nozzles with similar droplet size distributions and water usage rates. The commercially available nozzles were evaluated at the manufacturer's recommended design parameters (i.e., pressure and flow rate, but not necessarily nozzle spacing). Based on the results of the flammable liquid storeroom evaluation, and on recommendations from the manufacturers, all of the candidate nozzles were evaluated using a 1.5 m (5.0 ft) nozzle spacing. The nozzles evaluated during this test series include Grinnell AquaMist, Kidde-Fenwal, Securiplex, and Spraying Systems. The two Marioff nozzles as well the Senco Sensafe Nozzle were not evaluated during this test series due to either time or availability constraints. The five candidate nozzles are shown in Fig. 2. A brief description of each system is as follows:

3.3.1 Grinnell AquaMist Nozzle (AM-10)

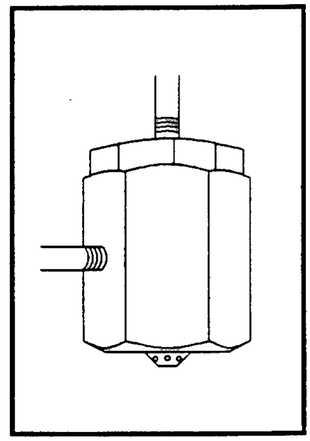
Grinnell AquaMist nozzle is a single-fluid, low-pressure nozzle which has a working pressure of 12 bar (175 psi) and is similar to a standard automatic sprinkler system in terms of system hardware and operating principles. It produces small droplets by impinging a water stream on a spherical deflector plate. The relatively low-pressure AquaMist nozzle substitutes efficiency in producing small droplets (produces larger droplets than the high-pressure nozzles) for the cost and commercial advantages of using standard hardware (hardware used by conventional sprinkler systems). The nozzle recommended for this evaluation (AM-10) has a nominal k-factor of 3.5 Lpm/bar$^{1/2}$ (0.26 gpm/psi$^{1/2}$) and is typically installed with a 2.0 m (6.0 ft) nozzle spacing. During these tests, the nozzles were installed with a 1.5 m (5.0 ft) nozzle spacing which corresponds to a mist application rate (flow rate per unit area) of 4.46 Lpm/m^2 (0.138 gpm/ft^2).



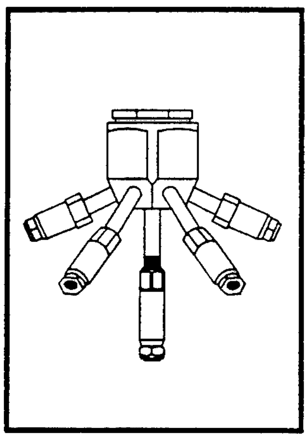
Grinnell
Aquamist
AM-10



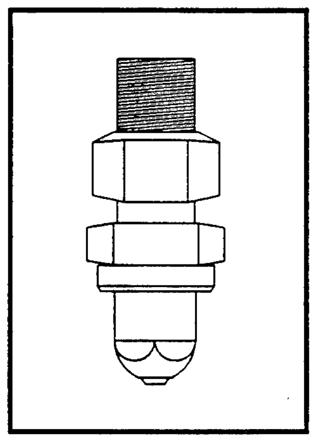
Kidde Fenwal
Mist Nozzle



Securiplex
(BP Technology)



Modified
Cluster Head
Spraying
Systems



Spraying
Systems
Pressure Washer
Nozzle

Figure 2. Candidate water mist systems (nozzles)

3.3.2 Kidde-Fenwal Nozzle

The Kidde-Fenwal mist nozzle is a low-pressure, single-fluid nozzle which has a working pressure of 12 bar (175 psi). It produces small droplets by impinging two water streams upon one another. As with the Grinnell AquaMist nozzle, the low system design pressure sacrifices efficiency in producing small droplets for cost and commercial advantages of using standard sprinkler-type hardware. The Kidde-Fenwal nozzle has a nominal k-factor of 3.4 Lpm/bar$^{1/2}$ (0.23 gpm/psi$^{1/2}$) and is typically installed with a 2.0 m (6.0 ft) nozzle spacing. During these tests, the nozzles were installed with a 1.5 m (5.0 ft) nozzle spacing which corresponds to a mist application rate of 3.5 Lpm/m^2 (0.1 gpm/ft^2).

3.3.3 Securiplex System 2000

The Securiplex System 2000 is a low-pressure, twin-fluid system. Twin-fluid nozzles incorporate a secondary or atomizing fluid (air or nitrogen) to shear the water into small droplets. The nozzle operates at 5.5 bar (80 psi) for both fluids and produces medium-size droplets (200 microns) with moderate momentum. It has a k-factor of 2.25 Lpm/bar$^{1/2}$ (0.15 gpm/psi$^{1/2}$) and has a recommended nozzle spacing of 1.5 m (5.0 ft). This corresponds to an application rate of 1.9 Lpm/m^2 (0.054 gpm/ft^2).

3.3.4 Two Generic Systems

3.3.4.1 Modified Spraying Systems 7N Nozzle

The modified Spraying Systems nozzle is a single-fluid, high-pressure nozzle which was developed for the U.S. Navy. The nozzle was evaluated at a pressure of 70 bar (1000 psi). The nozzle body is comprised of a Spraying Systems Model 7N nozzle body with seven model 1/4LN nozzle tips installed on 7.6 cm (3 in.) long brass nipples. The six 1/4LN nozzle tips installed around the perimeter are Model 1/4LN2, and the one in the center is a Model 1/4LN8. The purpose of the varying sizes of these nozzle tips is to produce droplets of different size and momentum: the perimeter nozzle tips produce small droplets with low momentum, and the center nozzle tips produce larger droplets with high momentum which serves to mix the mist throughout the space. With this configuration, the nozzle has a k-factor of 0.75 Lpm/bar$^{1/2}$ (0.05 gpm/psi$^{1/2}$). These nozzles were installed with a 1.5 m (5.0 ft) nozzle spacing. This corresponds to a mist application rate of 2.4 Lpm/m^2 (0.07 gpm/ft^2).

3.3.4.2 Pressure Washer Nozzles

The final nozzle was constructed using off-the-shelf pressure washers nozzles (T12W) also manufactured by Spraying Systems Inc. The resulting nozzle is a single-fluid high-pressure system that was evaluated at a pressure of 70 bar (1000 psi). The T12W nozzle has a k-factor of 0.45 Lpm/bar$^{1/2}$ (0.030 gpm/psi$^{1/2}$). These nozzles produce small droplets with high momentum. These nozzles were installed with a 1.8 m (5.0 ft) nozzle spacing. This corresponds to a mist application rate of 1.1 Lpm/m^2 (0.032 gpm/ft^2).

4.0 TEST PROTOCOL

The approval criteria for this evaluation developed during Task 3B [5] focussed on the International Maritime Organization, Marine Safety Committee, Circular 668, Alternative Arrangements for Halon Fire Extinguishing Systems in Machinery Spaces and Pump Rooms. The IMO test protocol was developed to evaluate the extinguishing effectiveness of water-based, total flooding fire extinguishing systems for Category A engine rooms and cargo pump rooms. Category A engine rooms are divided into three classes as shown in Table 1. For Class 1 engine rooms, tests are to be performed in a 100 m^2 enclosure having a 5 m ceiling height. For Classes 2 and 3 engine rooms, the tests are to be conducted in a space with a minimum floor area of 300 m^2 and a ceiling height in excess of 10 m.

Table 1. Classification of Category A Engine Rooms

Class	Typical Engine Facts	Typical Net Volume
1	Auxiliary engine room, small main machinery or purifier room, etc.	500 m^3
2	Main diesel machinery in medium sized ships such as ferries	3000 m^3
3	Main diesel machinery in large ships such as oil tankers and container ships	> 3000 m^3

The standard adequately addresses the evaluation of both small engine rooms with relatively low ceiling heights and extremely large engine rooms with high ceilings. However, the standard does not adequately address the evaluation of medium-size machinery spaces (1000-1500 m^3) and/or machinery spaces with larger floor areas (> 100 m^2) and low (< 5 m) ceiling heights. As shown in Table 2, all but one of the U.S. Army watercraft meet both the volume and ceiling height requirements for Class 1 engine rooms and thus are adequately covered under the less than 500 m^3 test protocol. The only exception is the main engine room of the LSV. The main engine room meets the ceiling height requirements, but it exceeds the volume limitation. It is believed that the ceiling height parameter is of equal importance as the volume of the space. It is also believed that neither the test protocol for Class 1 or Classes 2 and 3 adequately represents the machinery space of the LSV. The lack of an enclosure in the Classes 2 and 3 test protocol may result in such high mist/steam losses that it is unlikely that any water mist system can meet these requirements. In addition, there is little or no experimental work to support the applicability of the IMO test results to actual machinery space applications. For these reasons, the evaluation of the system for the LSV main engine room was based on the extrapolation of the results of the less than 500 m^3 tests to larger spaces with similar ceiling heights.

Table 2. Army Watercraft Engine Compartment Volumes*

Vessel	Application	Dimensions (m)	Volume (m^3)	Meets <500 m^3 Volume	Meets <5 m Ceiling Height
ROWPU	Engine Room #1	6.8 x 4.9 x 2.4	97.3	Yes	Yes
ROWPU	Engine Room #2	6.8 x 4.9 x 2.4	97.3	Yes	Yes
LSV	Main Engine Room	18.3 x 18.3 x 3.2	1256.1	No	Yes
LSV	Emergency Generator	3.9 x 4.8 x 3.5	62.2	Yes	Yes
LSV	Bow Thruster	8.2 x 7.3 x 3.0	218.9	Yes	Yes
**LCU 2003	Engine Room	12.8 x 9.7 x 2.9	464.5	Yes	Yes
**LCU 2003	Electrical & Storage Room	12.8 x 6.1 x 2.5	195.2	Yes	Yes
LCU 1675	Engine Room #1	8.5 x 3.7 x 2.1	135.9	Yes	Yes
LCU 1675	Engine Room #2	8.5 x 3.7 x 2.1	135.9	Yes	Yes

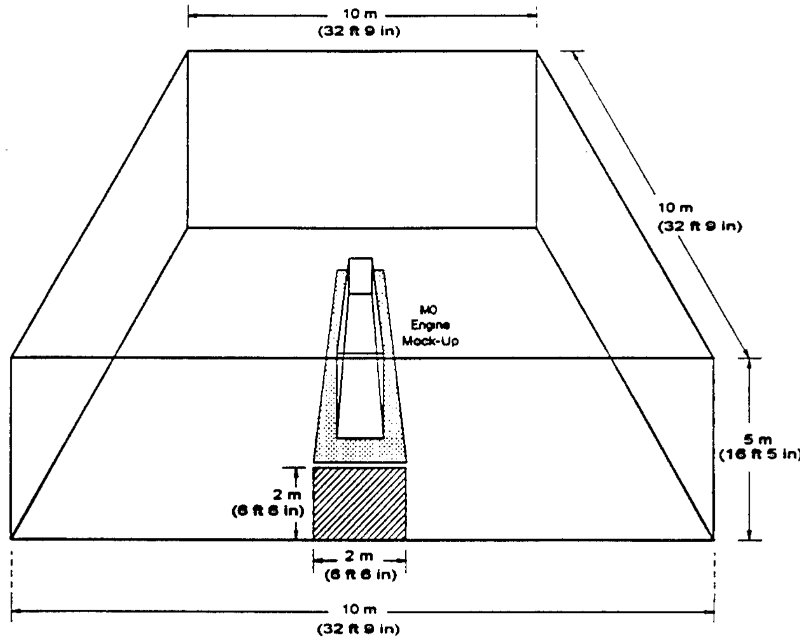
* Prior to conducting these tests, a survey was made of machinery spaces on Army watercraft. That survey is included as Appendix A of this report.

** Based on previous water mist test results, there is believed to be adequate separation between these two spaces to address them individually.

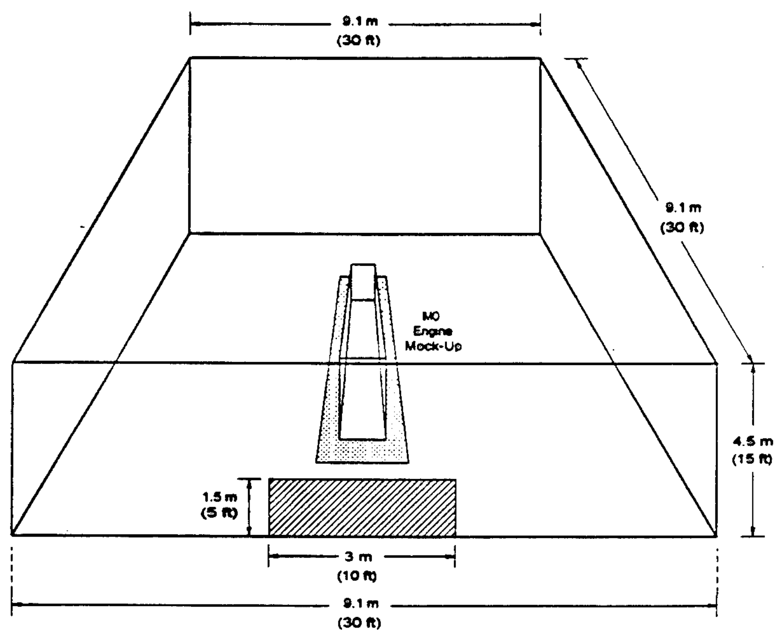
5.0 TEST PARAMETERS

5.1 Simulated Machinery Space

The tests were conducted in a machinery space mock-up located at the Chesapeake Beach Detachment (CBD) of the Naval Research Laboratory (NRL). The mock-up was a compromise between an easy fabrication and the letter-of-the-law IMO test enclosure. The machinery space measured approximately 9.1 m x 9.1 m x 4.6 m (381 m^3) (30 ft x 30 ft x 15 ft) (13,500 ft^3) as compared to the IMO mock-up of 10 m x 10 m x 5 m (500 m^3) (33 ft x 33 ft x 16 ft) (17,500 ft^3). The 2 m x 2 m IMO vent was simulated by removing one 3 m x 1.5 m (10 ft x 5 ft) steel panel from the center of one bulkhead/wall of the space. The mock-up and vent configuration as tested in this evaluation as well as the one specified in the test protocol are shown in Fig. 3.



IMO test configuration



Army test configuration

Figure 3. Machinery space configuration

The IMO engine mock-up was constructed in the center of the compartment for these tests. The engine mock-up (Fig. 4) was constructed per the specifications listed in the IMO test protocol and measured 1 m x 3 m x 3 m (3.3 ft x 9.8 ft x 9.8 ft). Around the top perimeter of the mock-up is a 100 cm (4.0 in.) lip which produces a 3 m^2 (32 ft^2) fire tray/pan. A notch located on the center of one side of the tray allowed fuel to flow down the side of the mock-up during cascading fuel fire scenarios. Two 250 mm (10 in.) diameter pipes, 3 m (9.8 ft) long, were installed on the top of the mock-up (one located above the tray and the other along the side of the tray) to simulate exhaust manifolds. A steel plate, measuring 0.7 m x 3.5 m (2.3 ft x 11.5 ft), was also attached to the side of the mock-up, adjacent to one of the pipes described previously. The combination of the pipe and steel plate created a 1.0 m horizontal obstruction for the spray fires located on the side of the engine mock-up.

A bilge was simulated by the addition of a raised deck 0.75 m (2.5 ft) above the lower deck. The deck was constructed of solid steel plating and was installed completely around the engine mock-up taking up over a quarter of the floor space of the test compartment. The dimensions of the raised deck were 4 m x 6 m (13.1 ft x 19.7 ft). There was a 100 mm (4 in.) gap around the mock-up and the raised deck to allow mist to reach the bilge. The bilge was partially enclosed by side walls which extended 0.5 m (1.6 ft) above the lower deck. This created a 250 mm (10 in.) gap between the bottom of the raised deck and the top of the side plates, also for mist to enter. Two fire trays producing pan/pool fires of the following sizes (0.5 and 4.0 m^2 (5.3 and 43 ft^2)) were also installed in the center of bilge located directly under the mock-up. The small pan was installed in the larger pan as shown in Fig. 4.

5.2 Water Mist System Description

5.2.1 Piping Network

The piping network designed for these tests is shown in Fig. 5. The system was constructed of 2.5 cm (1 in.) stainless steel tubing (AISI 316, welded seam tubing with a 1.65 mm (0.065 in.) wall thickness) and connected together using stainless steel single-ferrule compression fittings (DIN 2353). Stainless steel tubing and fittings were selected to prevent rust and/or corrosion from developing inside the piping network. As installed, this system has a working pressure of 200 bar (3000 psi) and a burst pressure of 800 bar (12000 psi). As shown in Fig. 5, the system consisted of 36 nozzles installed 1.5 m (5 ft) on center. This spacing relates to an individual nozzle coverage area of 2.3 m^2 (25 ft^2). The flow rate of the nozzles ranged from 6.2 to 13.6 Lpm (1.6 to 3.5 gpm), producing a water application rate (total flow/protected area) of 1.75 to 3.5 Lpm/m^2 (0.05 to 0.1 gpm/ft^2). The piping network was installed tight to the ceiling using 2.5 cm (1 in.) clevis hangers.

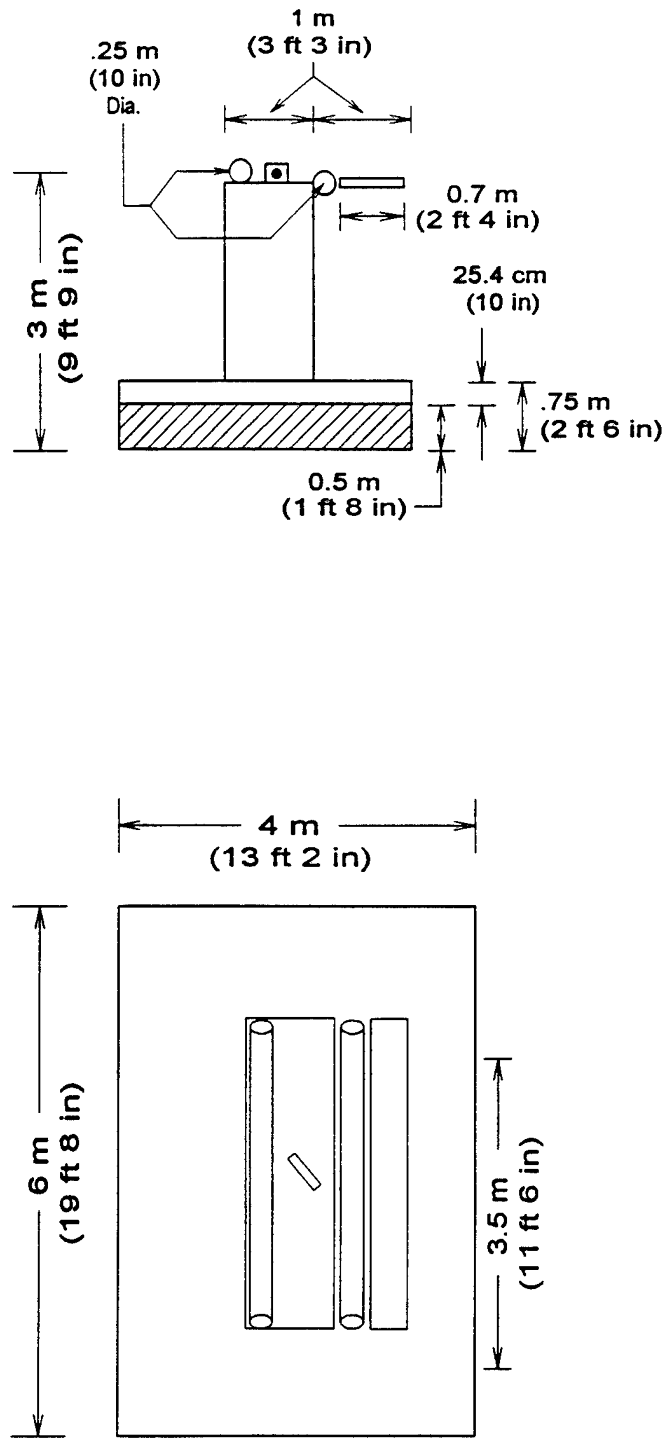


Figure 4. IMO engine mock-up

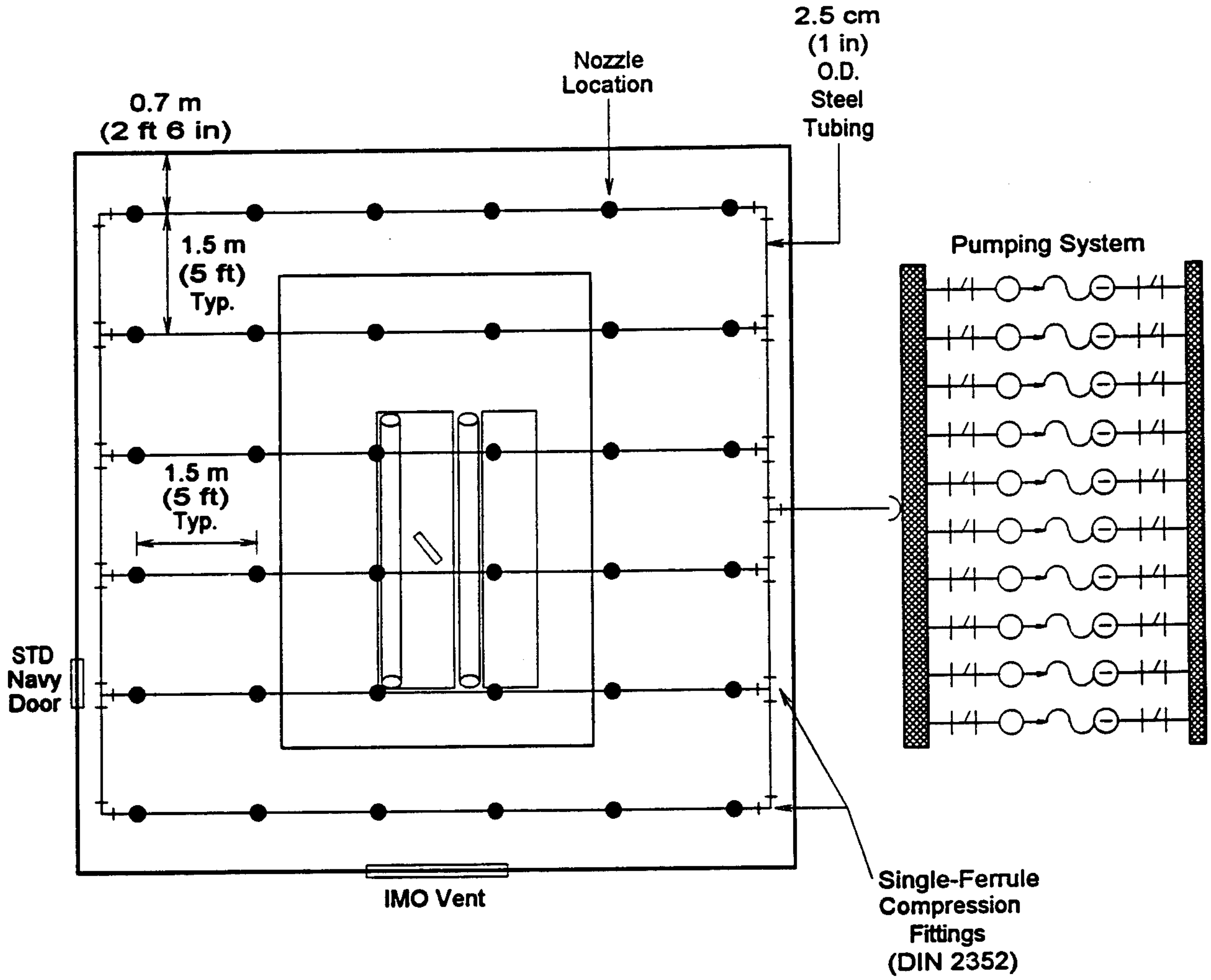


Fig. 5 - Water Mist Pipe Network

5.2.2 Pumping System

The high-pressure water mist systems evaluated during this test series were supplied using the supply and pumping system shown in Fig. 6. The pumping system consisted of ten gasoline combustion engine driven, pressure washers capable of delivering a total flow rate of 300 Lpm (75 gpm) at a pressure of 200 bar (3000 psi). The manifold supplying the pressure washers was connected to CBD's domestic water supply. The low-pressure single-fluid systems and twin-fluid system were supplied using a conventional fire truck also shown in Fig. 6. As with the high-pressure systems, the low-pressure single-fluid and twin-fluid systems both used potable water.

5.3 Fire Scenarios

The evaluation focussed primarily on the tests required by the IMO FP39 Draft Standard for Machinery Space Testing. A copy of this draft standard is found in Appendix B. The 13 tests required by this standard are listed in Table 3. The relative locations of each fire are shown in Fig. 7. Specifics on the exact locations of each fire and how these fires were produced can be found in Appendix B.

Table 3. 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 oil
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 oil
IMO-4	Combination of worst spray fire from Tests 1-3 and fires in trays (4 m^2) under and on top of the simulated engine (3 m^2)	Commercial fuel oil or light diesel oil
IMO-5	High-pressure horizontal spray fire on top of simulated engine (2.0 MW)	Commercial fuel oil or light diesel oil
IMO-6	Low-pressure low flow concealed horizontal spray fire on the side of simulated engine (1.0 MW)	Commercial fuel oil or light diesel oil
IMO-7	0.5 m^2 central under mock-up	Heptane
IMO-8	0.5 m^2 central under mock-up	SAE 10W30 mineral-based lubrication oil
IMO-9	0.1 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

Table 3. IMO Test Protocol (Cont'd)

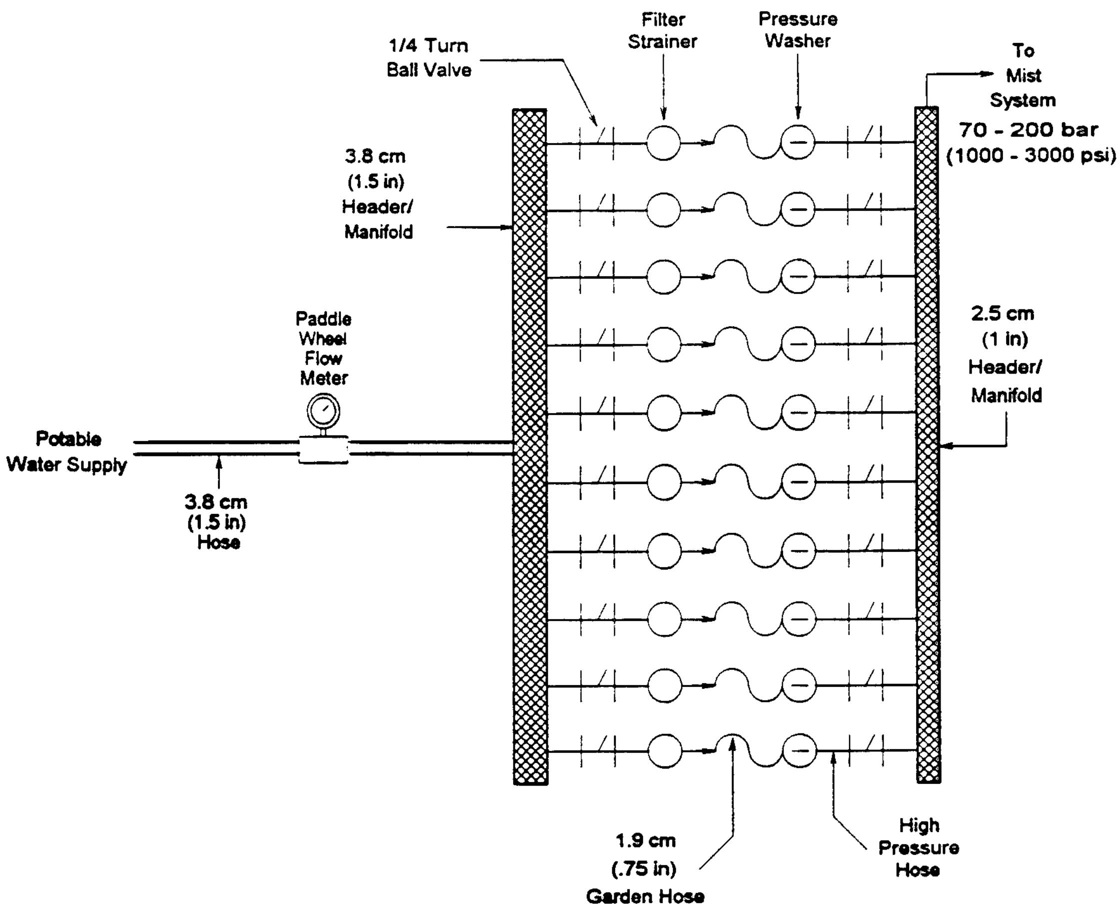
Test Number	Fire Scenario	Test Fuel
IMO-12	A steel plate (30 cm x 60 cm x 5 cm) offset 20° to the spray is heated to 350°C by the top low pressure, low flow spray. Then the plate system shutoff, no reignition of the spray is permitted.	Heptane
IMO-13	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil

Five additional fire scenarios, designated NRL 1-5 in Fig. 7, were also conducted during this evaluation. For the most part, these tests were variations of IMO fire scenarios with the only modification being the substitution of a lower flash point fuel (heptane) for the higher flash point diesel or commercial fuel oil. The lower flash point fuels have similar characteristics (extinguishment difficulty) to higher flash point fuels that have been heated (due to spilling on a hot surface) to temperatures above their flash point. The substitution of heptane for diesel fuel creates a worst case scenario and also allows for visual observation of the test due to lower smoke production. These five modified tests were conducted using the IMO test configuration and are listed in Table 4. These tests include two unobstructed heptane spray fires (NRL-1 and NRL-2), two shielded heptane spray fires (NRL-3 and NRL-4), and a large heptane pool fire (NRL-3).

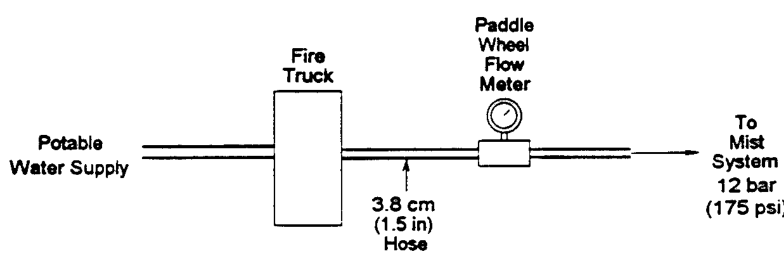
Table 4. Additional NRL Test Protocol

Test Number	Fire Scenario	Test Fuel
NRL-1	Low-pressure spray fire on top of simulated engine between agent nozzles (6.0 MW)	Heptane
NRL-2	Low-pressure low flow spray fire on top of simulated engine between agent nozzles (1.0 MW)	Heptane
NRL-3	3 m^2 pan fire on top of simulated engine	Heptane
NRL-4	Low-pressure low flow spray fire on side of simulated engine (1.0 MW)	Heptane
NRL-5	Low-pressure spray fire on side of simulated engine (6.0 MW)	Heptane

The spray fires were produced by pressurizing a fuel storage tank (230 l (60.0 gal) pressure vessel) with nitrogen. The system was located just west of the test compartment. The fuel system was designed to operate at low pressures and consists of a storage tank with a pressure range of 5.1-6.9 bar (75-100 psi) and an approximate nozzle pressure ranging from 3.4-5.1 bar (50-75 psi). These pressures are lower than those stated in the IMO test protocol,



High Pressure Pump Configuration



Low Pressure Pump Configuration

Figure 6. Water Mist System Pump Configuration

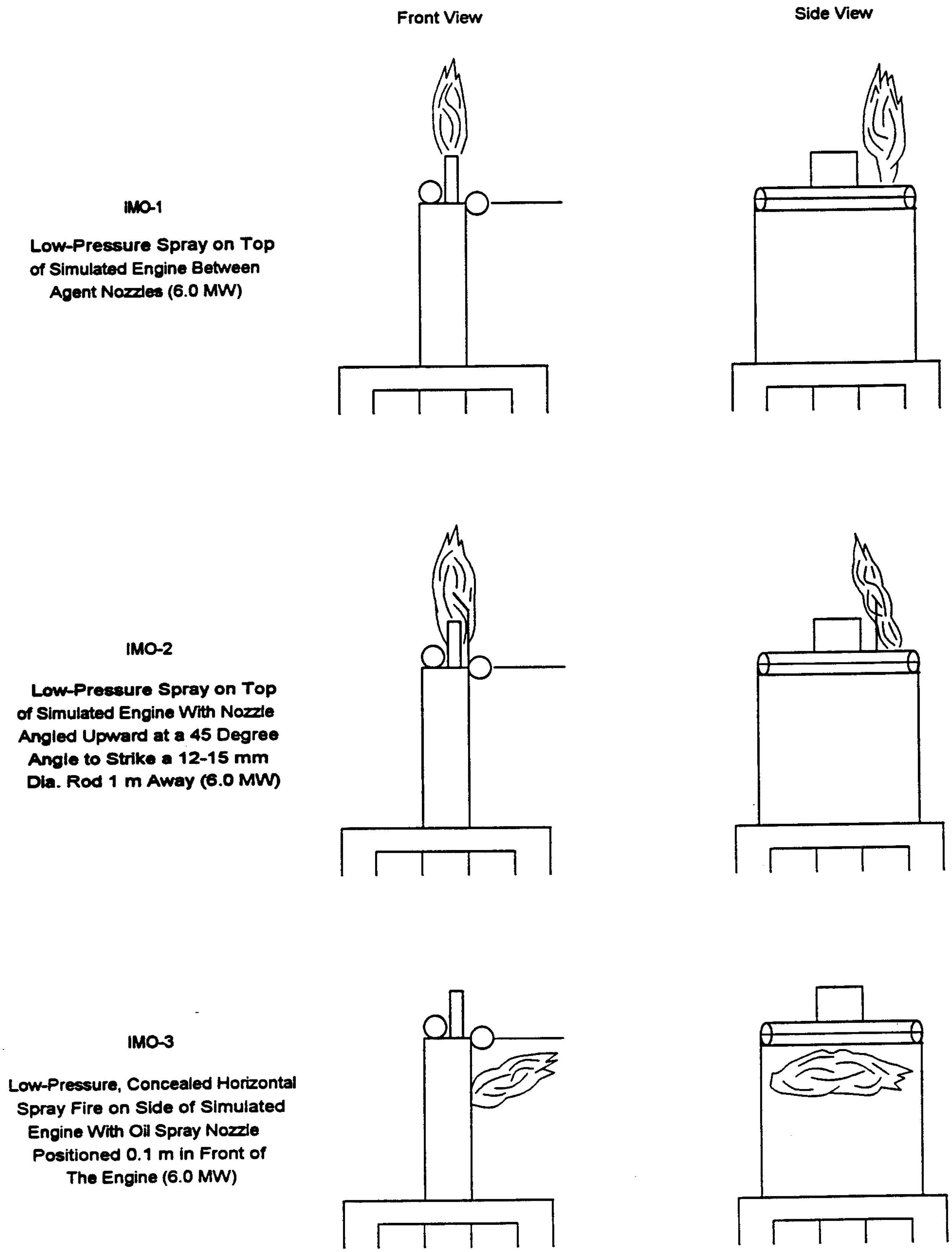


Figure 7. Fire scenarios

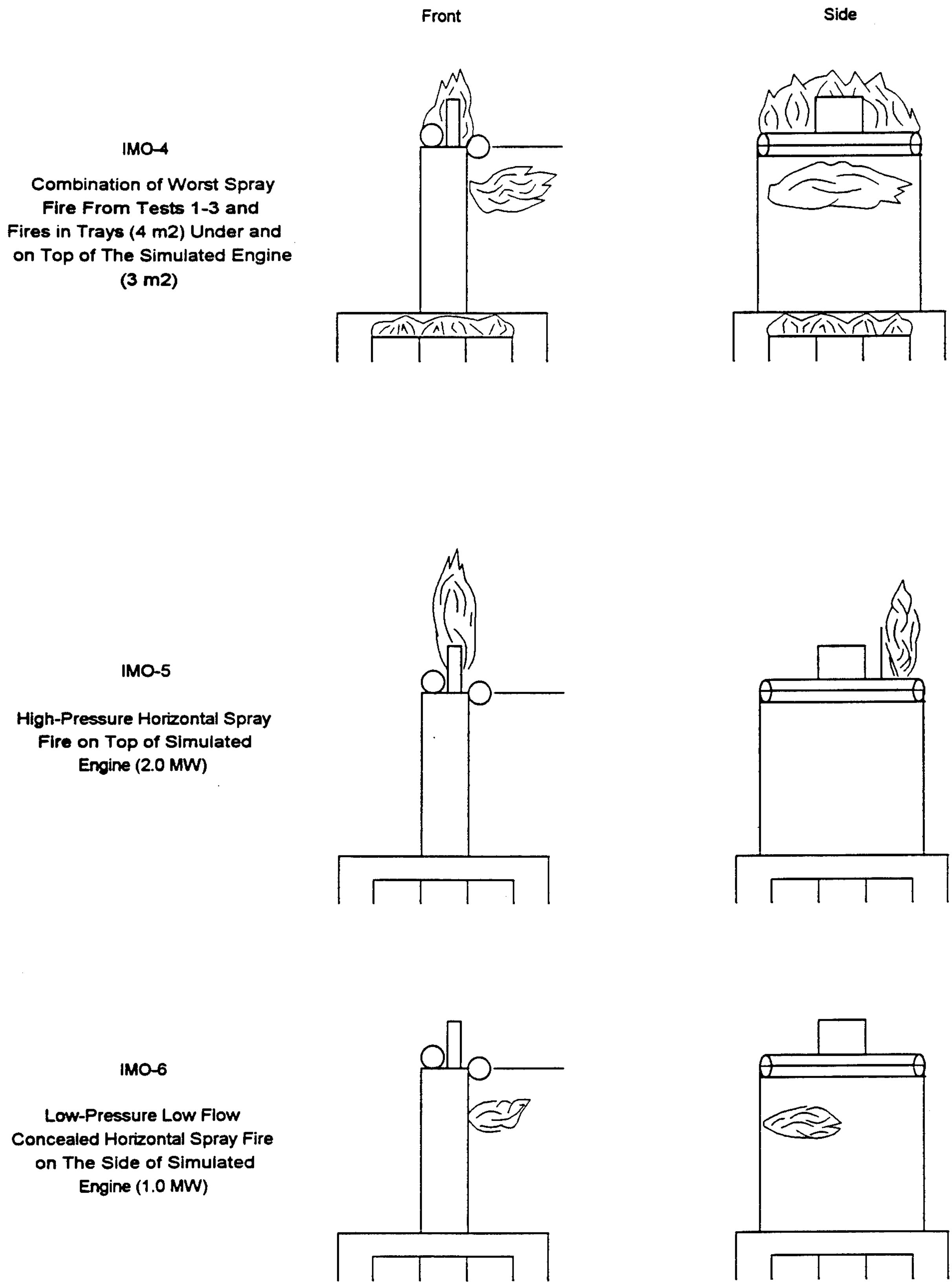


Figure 7. Fire scenarios (cont'd)

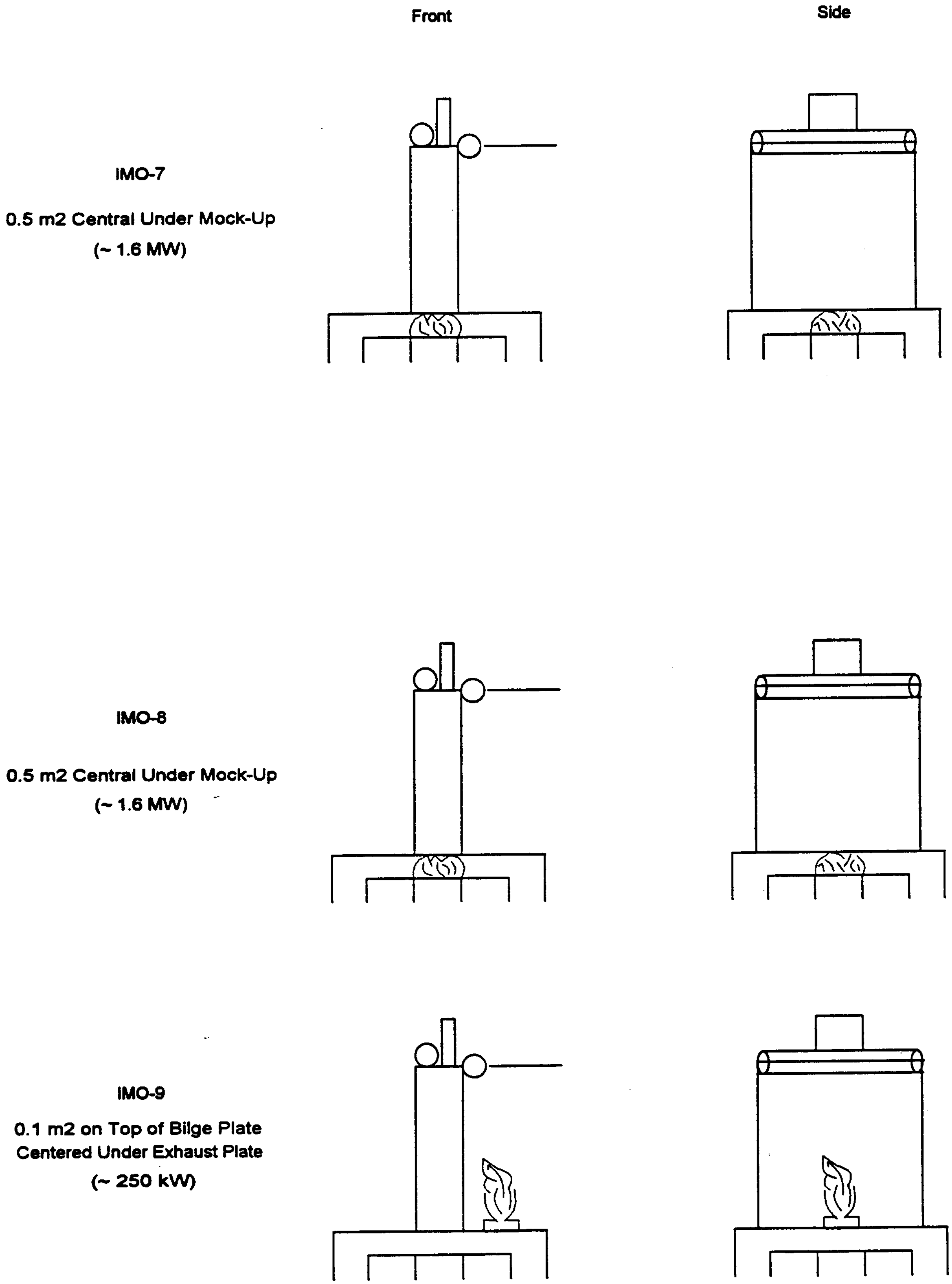


Figure 7. Fire scenarios (cont'd)

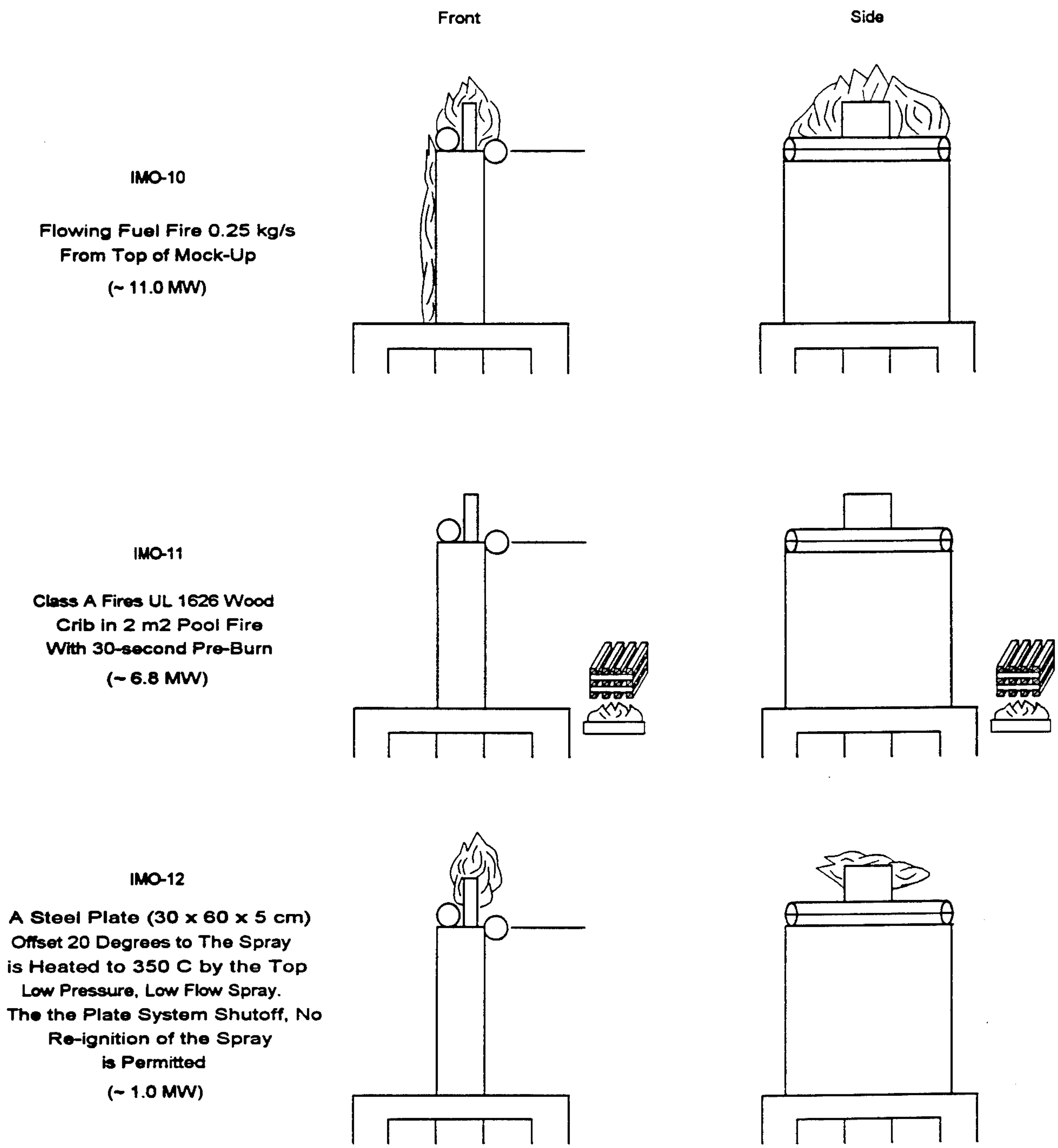


Figure 7. Fire scenarios (cont'd)

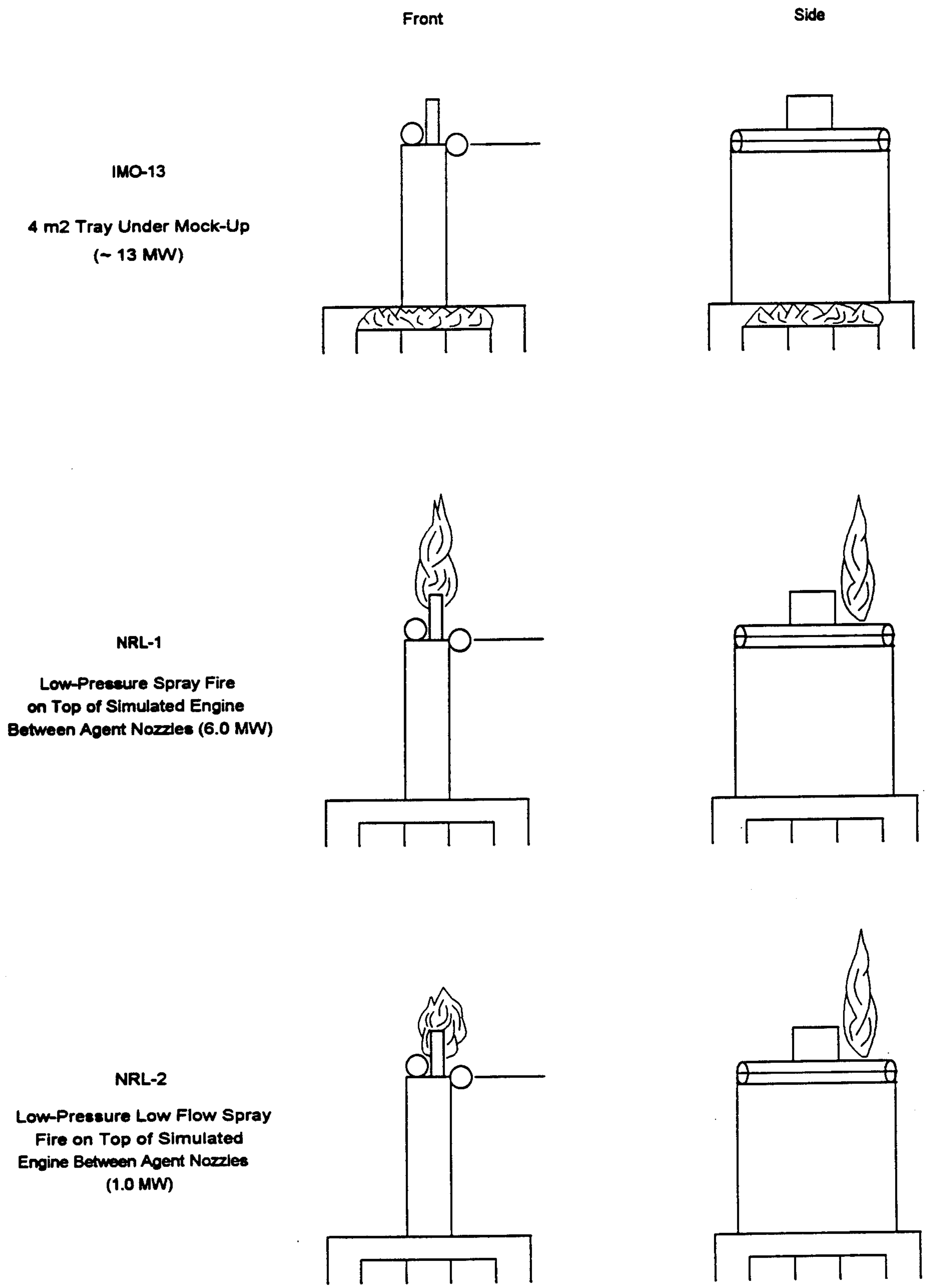


Figure 7. Fire scenarios (cont'd)

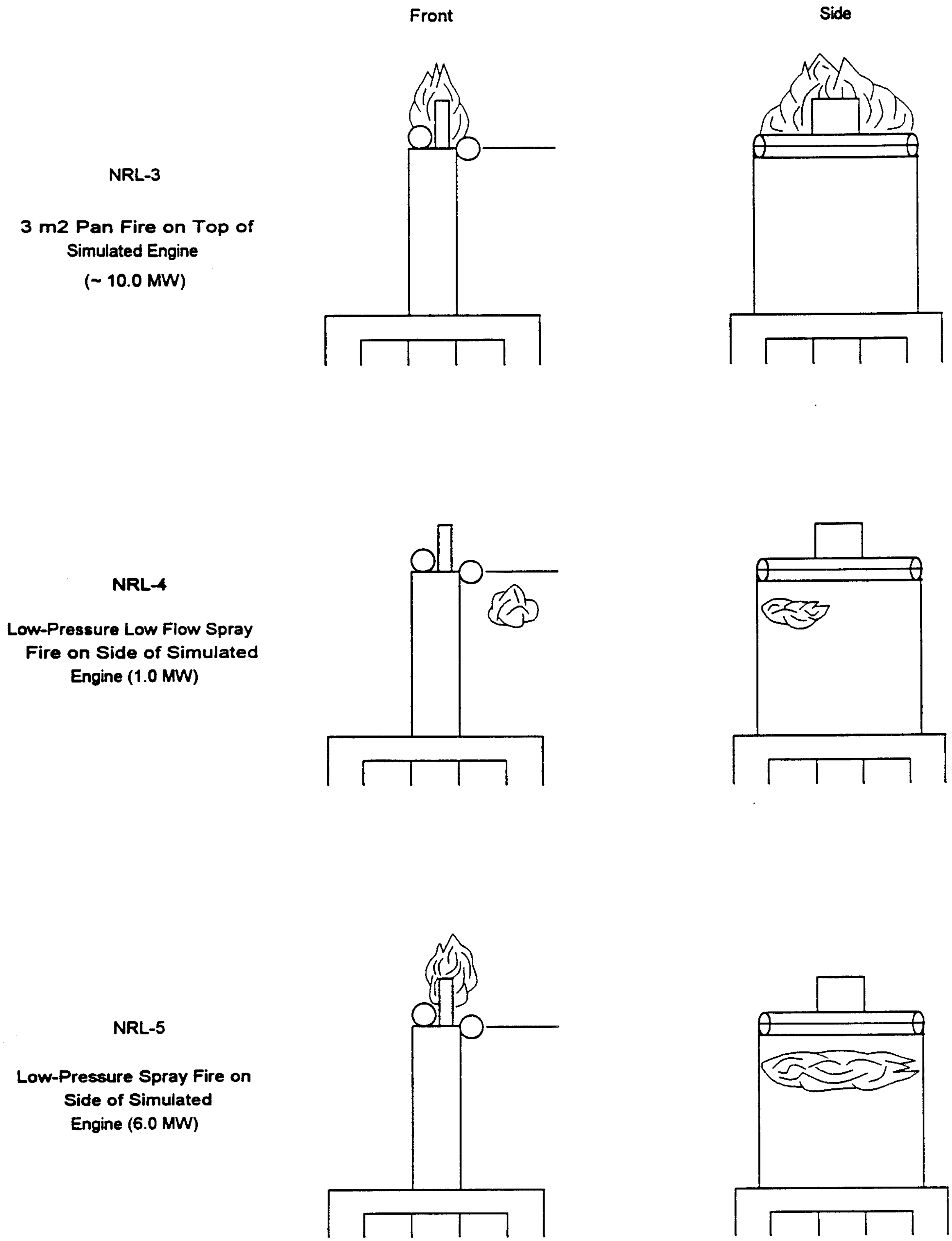


Figure 7. Fire scenarios (cont'd)

but previous studies have shown little, if any, variation in extinguishment difficulty between spray fires of various pressures for a given heat release rate (fire size). The fuel system was produced using 1.3 cm (0.5 in.) steel tubing with standard single-ferrule compression fittings. A schematic of the fueling system is shown in Fig. 8. The system was controlled from the instrumentation trailer via solenoid valves. The fuel spray nozzles used during these tests were produced by Bete Fog Nozzle, Inc. ("P" series nozzles). Model numbers P54, P80, and P120 were required for the three spray fires used in this test series. These nozzles operated in the previously mentioned pressure ranges to produce the 1.0, 2.0, and 6.0 MW spray fires respectively.

In addition to the fires described previously, six small heptane cup fires, referred to as "tell tales," were included in each test. These fires were positioned at various locations throughout the test compartment to provide an indication of mist concentrations throughout the space. These fires were fueled with 114 ml (4 oz.) of heptane contained in 227 ml (8 oz.) cups which were manually ignited prior to the test. The cups were 5.0 cm (2.0 in.) in diameter and were approximately 10.0 cm (4.0 in.) high. In this configuration, these small cup fires had a 5.0 cm (2.0 in.) freeboard (the distance between the fuel surface and the top lip ledge of the pan). These cups were located on two vertical arrays as shown in Fig. 9. The array consisted of a fire located every 1.5 m (5.0 ft) beginning 0.91 m (3.0 ft) above the deck.

6.0 INSTRUMENTATION

6.1 Water Mist System Instrumentation

The water mist system used during these tests was instrumented to measure both system pressures and system flow rates as shown in Fig. 10. A further description of the water mist system instrumentation is listed as follows.

6.1.1 Pressure Measurements

System pressures were measured at two locations: at a representative location in the pipe network, and at the discharge manifold as shown in Fig. 10. Setra Model 206E pressure transducers were used for this application. These transducers had a pressure range of 0-200 bar (0-3000 psi) with an accuracy of 0.01 percent full-scale or 0.02 bar (0.3 psi).

6.1.2 System Flow Rate Measurements

The amount of water discharged by the water mist systems was measured using a paddle wheel type flow meter. The flow meter was located just upstream of the supply manifold as shown in Fig. 10. The flow meter was an Omega Model FP-6000 which has an operating rate of 75-775 lpm (20-200 gpm).

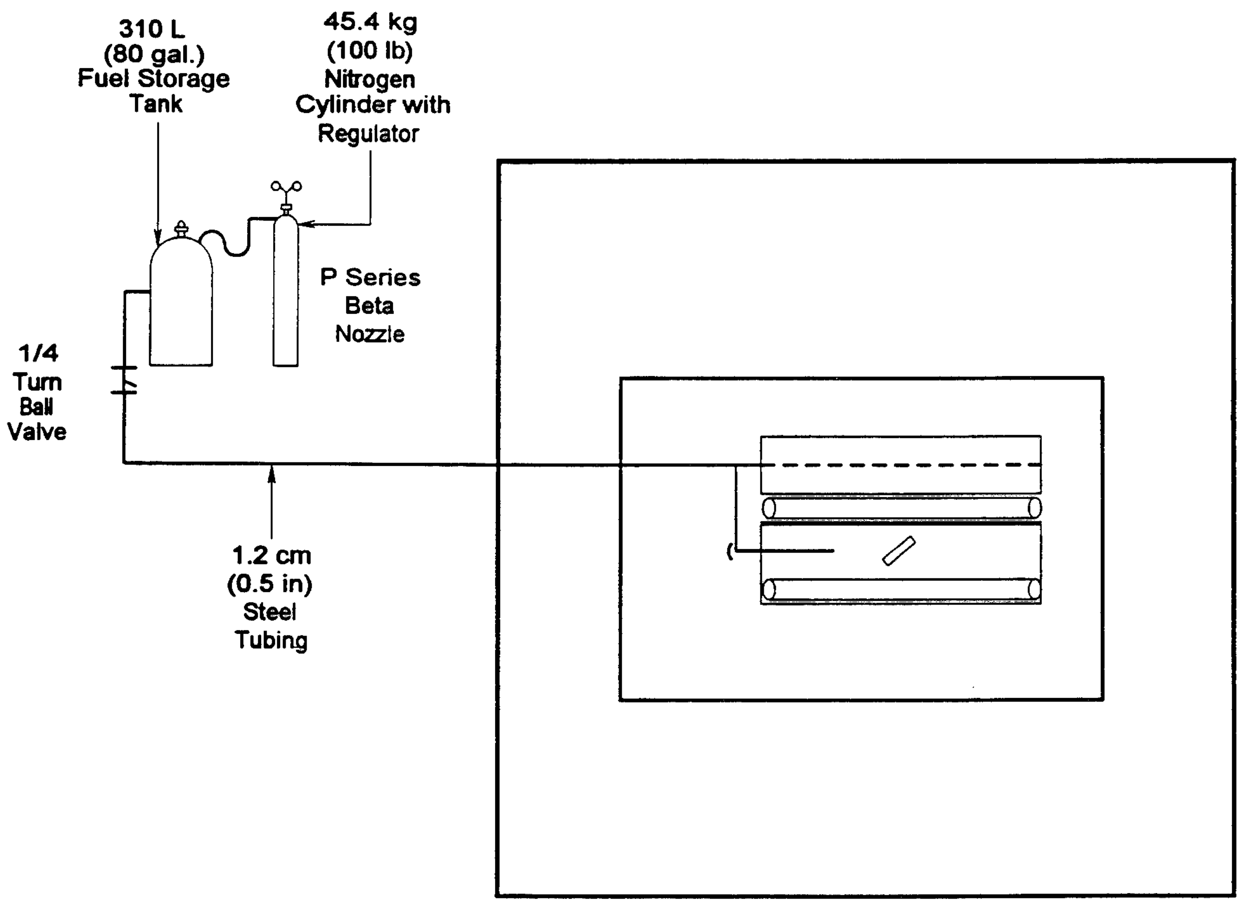


Figure 8. Spray fire fuel system

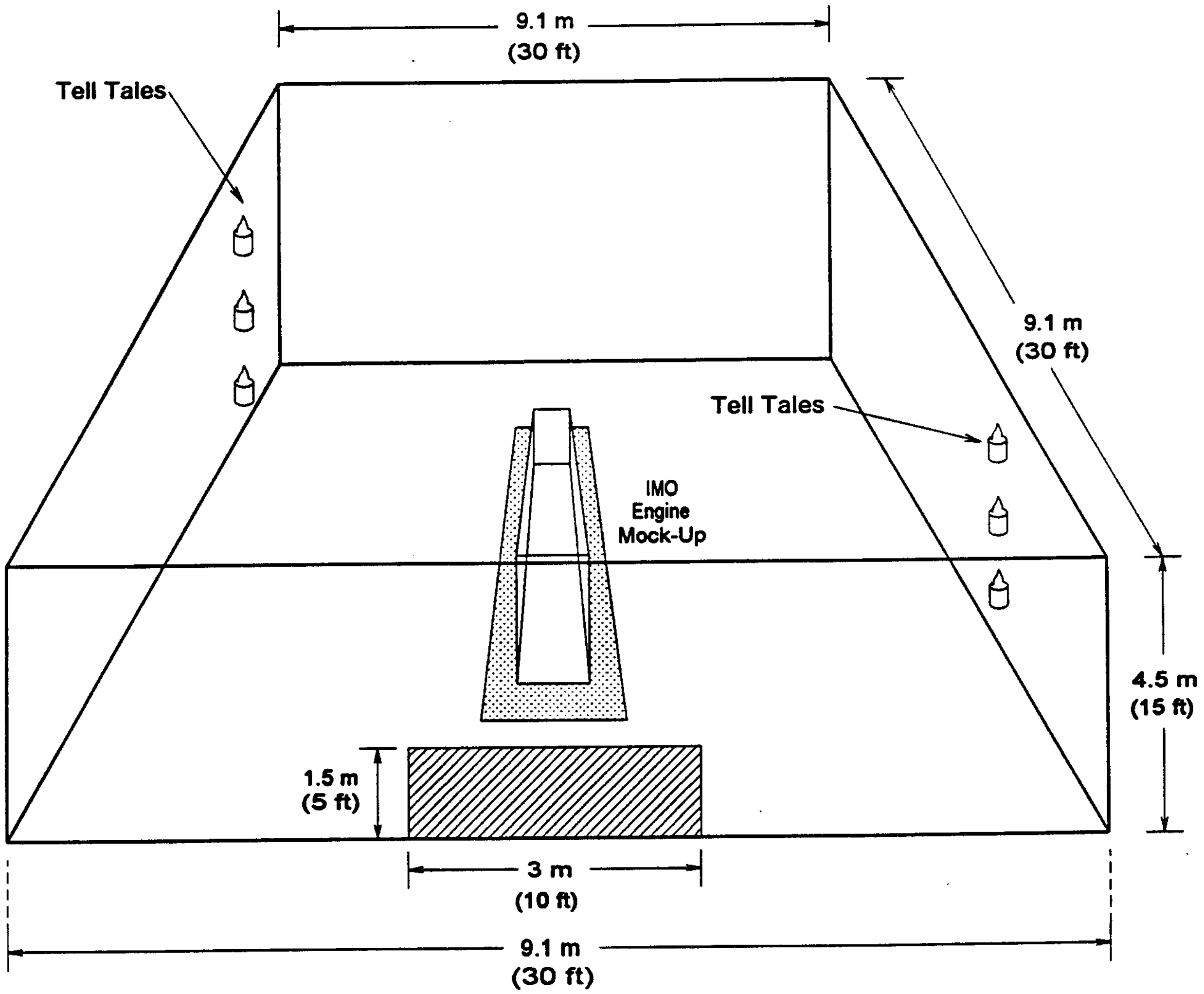


Fig. 9 - Tell-tale fire locations

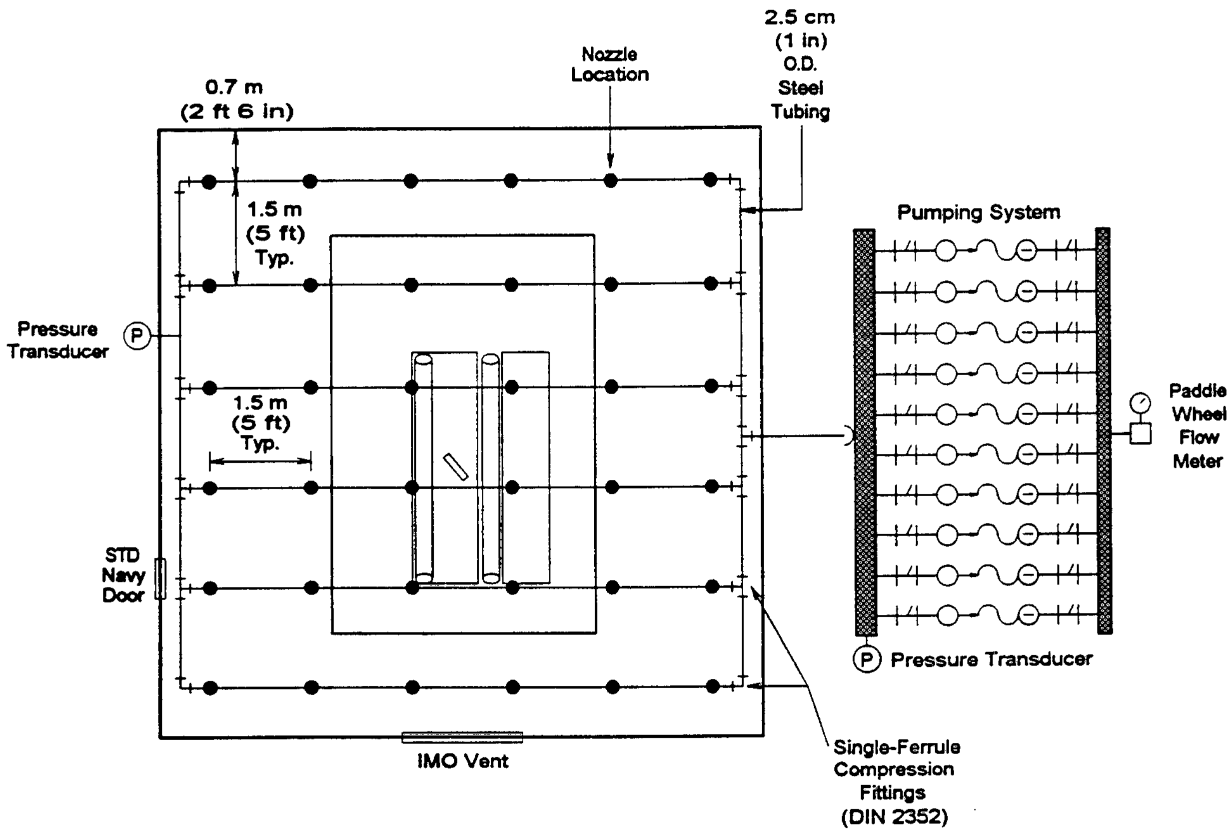


Figure 10. Pressure and flow rate measurement locations of water mist system

6.2 Machinery Space Instrumentation

The machinery space was instrumented to measure both the thermal conditions in the compartment as well as the typical fire gas species concentrations (CO, CO_2, and O_2). Instruments were installed to measure air temperature, fire temperature (to note extinguishment times), radiant and total heat flux, and fire gas concentrations. Data were collected using a PC-based data acquisition system at a rate of one scan per second. The instrumentation scheme is shown in Fig. 11. A more detailed description of the instrumentation follows.

6.2.1 Air Temperature Measurements

Four thermocouple trees were installed in each corner of the compartment in the space to measure air temperature. Each tree consisted of seven (7) thermocouples positioned at 61 cm (2.0 ft) increments starting 61 cm (2.0 ft) above the lower deck. Twenty-four gauge, inconel-sheathed type-K thermocouples were used for this application.

6.2.2 Gas Concentration Measurements

Carbon monoxide, carbon dioxide, and oxygen concentrations were measured in the overhead of the space (in the hot layer). Various model Beckman analyzers were used for this application. The sample was taken 61 cm (2.0 ft) below the ceiling in approximately the center of the space as shown in Fig. 11.

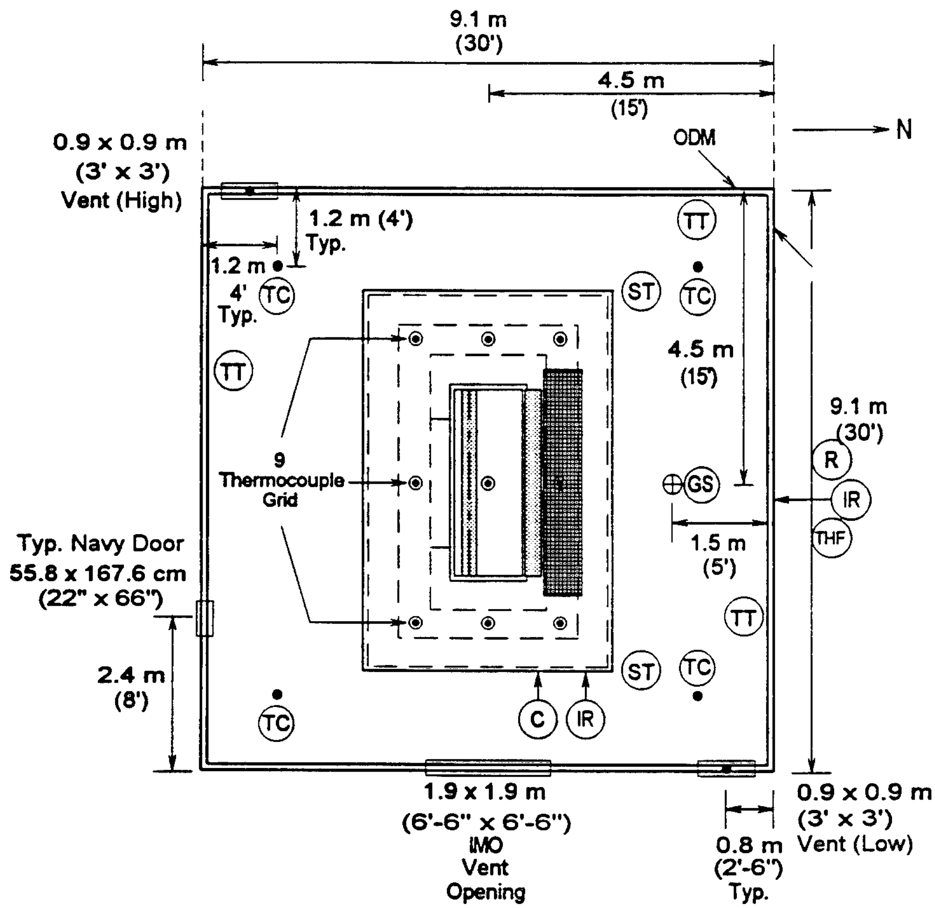
6.2.2.1 Oxygen Concentration (Fire Location)

In addition to the above fire gas concentration measurements, oxygen was measured at the base of each fire. The sampling system was designed to allow the measurement location to be easily moved between tests.

Note: Additional water traps were installed to assure the water mist entrained into the sampling line was removed before the sample reached the analyzers.

6.2.3 Heat Flux Measurements

Both radiant and total heat flux were measured at three locations (elevations) in the compartment. These transducers were installed on the centerline of the north bulkhead and spaced 1.5 m (5.0 ft) apart beginning 0.91 m (3.0 ft) above the lower deck. These instrumentations were Schmidt Boelter transducers manufactured by Medtherm Co. and have a full-scale range of 0-50 kW/m^2. Each radiometer was equipped with a 150° sapphire window.



- FTC - Fire Thermocouple
- (TC) TC Tree - Thermocouples 0.6,1.2,1.8,2.4,3.0,3.6,4.2 m (2,4,6,8,10,12,14')
- (GS) GS - Gas Sampling 4.2 m (14') Elevation O2,CO,CO2 Total Hydrocarbon
  0.6 m (2') Elevation O2,CO,CO2
- (ODM) Optical Density Meter 0.9,2.4,3.9 m (3',8',13')
- (C) Video Camera
- (IR) Infrared Video Camera
- (THF) Total Heat Flux Meters 0.9,2.4,3.9 M (3',8',13')
- (R) Radiometers 0.9,2.4,3.9 m (3',8',13')
- (TT) Tell Tale Tree 0.9,2.4,3.9 m (3',8',13')

Figure 11. Machinery space instrumentation

6.2.4 Optical Density Meters

Three optical density meters were installed to measure the mist concentration across the northwest corner of the compartment during these tests. These measurements aided in a relative estimation of mist concentrations at various elevations in the compartment. The optical density meters consisted of a laser and an LED. The meters were installed with 1.5 m (5.0 ft) spacings starting at 0.91 m (3.0 ft) above the deck.

6.3 Fire Instrumentation

6.3.1 Flame Temperature

Each fire was instrumented for temperature to identify extinguishment time. Thermocouples were located in the flame region of both the main fires and the tell tale fires to determine extinguishment times. These thermocouples were 24-gauge, inconel-sheathed type-K thermocouples.

6.3.2 Fuel System Nozzle Pressure

The fuel system nozzle pressure was measured to estimate the heat release rate of each spray fire. Nozzle pressure was measured using a Setra Model 280E pressure transducer having a range of 0-680 kPa (0-100 psi). The heat release rate of each spray fire was estimated using the fuel flow rate and heat of combustion of the fuel. The calculation assumed that all of the fuel is consumed and the fuel was burned with a 100 percent combustion efficiency.

6.4 Video Cameras

The main fire in each fire scenario was videotaped using both a standard and infrared (NFTI) video camera. The cameras were located close to the fire to insure that the view was not obscured by mist and that the fire status (extinguishment) could be determined. The infrared camera was particularly useful in determining extinguishment times of the diesel fuel fires, due to the poor visibility resulting from the increased smoke production of these fires. The actual locations of these cameras varied, depending on the fire scenario.

7.0 TEST OVERVIEW

7.1 Test Sequence

A matrix including all of the tests conducted during this evaluation is found in Table 5. An explanation of the general test groupings is listed as follows.

Table 5. Global Test Matrix

System	Scenario	Compartment Dimensions (m)	Ventilation Dimensions (m)	Operating Pressure (bar psi)	Application Rate (Lpm/m^2 (gpm/ft^2))
Phase I. IMO Compliance Tests – Space < 500 m^3					
Grinnell AquaMist	13 IMO / 5 NRL	9.1 x 9.1 x 4.6	1.5 x 3.0	12 (175)	5.3 (0.124)
Kidde-Fenwal	13 IMO / 5 NRL	9.1 x 9.1 x 4.6	1.5 x 3.0	12 (175)	4.2 (0.10)
Securiplex	13 IMO / 5 NRL	9.1 X 9.1 X 4.6	1.5 X 3.0	5.5 (80)	2.2 (.053)
Spraying Systems (Mod. 7N)	13 IMO / 5 NRL	9.1 x 9.1 x 4.6	1.5 x 3.0	70 (1000)	2.7 (0.064)
Spraying Systems (T12RW)	13 IMO / 5 NRL	9.1 x 9.1 x 4.6	1.5 x 3.0	70 (1000)	1.5 (0.036)
Phase II. Horizontal Extrapolation					
Spraying Systems (Mod. 7N)	13 IMO / 5 NRL	9.1 x 9.1 x 4.6	9.1 x 4.6	70 (1000)	2.7 (0.064)
Spraying Systems (Mod. 7N)	13 IMO / 5 NRL	12.1 x 9.1 x 4.6	1.5 x 3.0	70 (1000)	2.7 (0.064)
Spraying Systems (Mod. 7N)	13 IMO / 5 NRL	18.2 x 9.1 x 14.6	1.5 x 3.0	70 (1000)	2.7 (0.064)

(1) IMO Compliance Tests – Space < 500 m^3

The initial set of tests consisted of evaluating the candidate water mist systems against the thirteen IMO tests for machinery spaces less than 500 m^3. As shown in Table 2, all of the machinery spaces in the Army watercraft surveyed except the engine room in LSV, are less than 500 m^3. The systems were also evaluated against an additional five NRL tests described in Section 5.3 of this report. The objectives of these tests were to determine which, if any, of the candidate water mist technologies meet the requirements listed in the IMO FP39 Draft Standard for Machinery Spaces. Many of the strengths and weaknesses of each technology were also identified during these tests.

(2) Volumetric Extrapolation of Results

The second set of tests consisted of evaluating a selected water mist technology against the 13 IMO tests in larger test volumes with similar ceiling heights. The objectives of these tests were to determine if the results obtained during the less than 500 m^3 tests are indicative of the systems' capabilities in larger spaces with similar ceiling heights. Specifically, these tests were conducted to determine if the nozzles that pass Phase I of this program can adequately protect the main engine room of the LSV.

The initial approach to extrapolating the data required the removal of the east wall of the test space. Preliminary scoping tests were so adversely affected by ambient conditions (wind) that a new approach was implemented. To minimize the effects of the weather and excessive mist losses, additions were made to the compartment. The first addition (Modified IMO I) extended the compartment about 3 m (9.8 ft) to the east. The modified test compartment measured 12 m x 9 m x 4.5 m (40 ft x 30 ft x 15 ft) as shown in Fig. 12. The second addition (Modified IMO II) extended the compartment another 6 m (19.7 ft) resulting in a compartment measuring 18 m x 9 m x 4.5 m (60 ft x 30 ft x 15 ft).

7.2 Test Procedures

Prior to the beginning of this test series, a procedure list was developed to insure the safety of all test participants and to maintain consistency between tests. The procedure checklist was used to verify the proper operation of all instrumentation, fuel, and water mist system components. A test summary data sheet was also developed prior to the beginning of this test series. The test summary sheets served an accurate record of the test configuration, including fire scenario, mist system, compartment configuration, etc.

The tests were initiated from the instrumentation trailer located just east of the test enclosure. All key test personnel were located in the instrumentation trailer during each test with the exception of one pump operator located at the pump station and a firefighter wearing protective clothing positioned at the entrance to the space. The water mist systems' pumps were started prior to each test. The video cameras were initiated and the tell-tale fires ignited. The data acquisition system was activated one minute prior to the ignition of the main fire. The test fires were ignited by the firefighter using a torch and allowed to burn freely for one minute before the mist system was activated. The mist system remained activated for a duration of 15 minutes or until all of the fires had been extinguished, whichever came first. At the completion of the 15-minute discharge, the mist system was shut down marking the termination of the test. The space remained off-limits until cleared by the safety officer (firefighter) and the test director. Communication with all participants was maintained via hand-held radios.

8.0 RESULTS AND DISCUSSION

8.1 General Overview

Over 200 full-scale fire extinguishment tests were conducted during this test series. The extinguishment times for the five candidate nozzles (Modified Spraying Systems SS-7N nozzle, Pressure washer nozzle SS-T12W, Grinnell AquaMist nozzle, Kidde-Fenwal nozzle, and Securiplex nozzle) are listed in Table 6 and shown in Fig. 13 for both the IMO and NRL fire test scenarios. The extinguishment times were determined based on visual observations and on temperature measurements recorded in the fire flame during each test. An example of a typical flame temperature history is shown in Figure 14. During this test, the Grinnell AquaMist system was capable of extinguishing the 6.0 MW diesel spray fire on top of the mock-up (IMO-1) in less than two minutes of system activation.

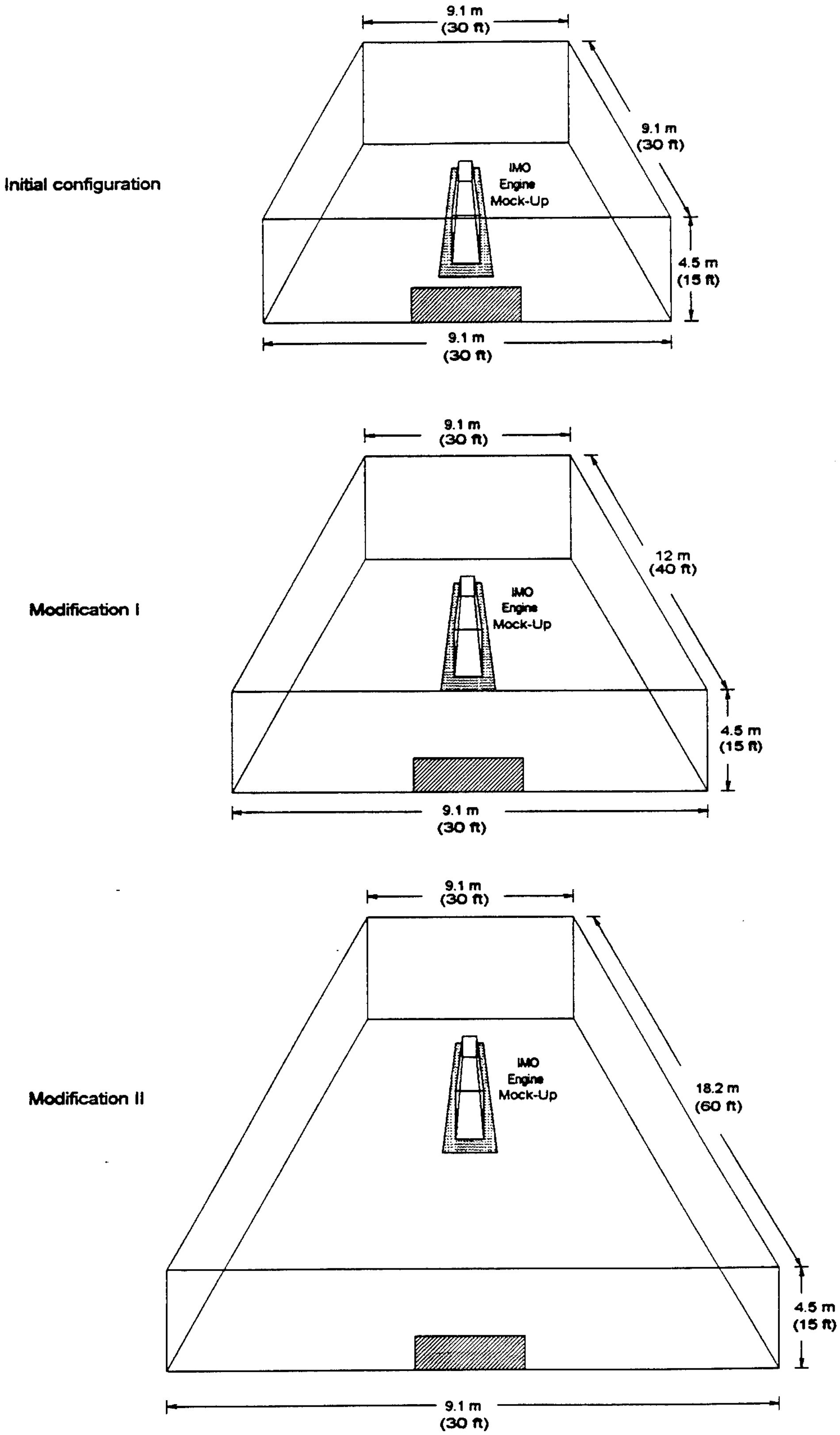


Figure 12. Machinery space modifications.

Table 6. Army Water Mist Machinery Space Tests - System Comparison
IMO and NRL Test Protocol

Test Number	Fire Scenario	Test Fuel	Extinguishment Times (min./sec.)				
			SS-MOD.7N	SS-T12 W	G-AM10	KF	Securiplex
IMO-1	Low-pressure spray on top of simulated engine between agent nozzles (6.0 MW)	Commercial fuel oil or light diesel fuel	1:42	3:00	1:24	1:20	1:15
IMO-2	Low-pressure spray on top of simulated engine with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1 m away (6.0 MW)	Commercial fuel oil or light diesel oil	2:10	4:30	1:50	1:25	1:00
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 oil	2:26	4:00	7:16	8:55	5:35
IMO-4	Combination of worst spray fire from Tests 1-3 and fires in trays (4 m^2) under and on top of the simulated engine (3 m^2) (bilge test)	Commercial fuel oil or light diesel oil	NO	NO	NO	NO	NO
IMO-5	High-pressure horizontal spray fire on top of simulated engine (2.0 MW)	Commercial fuel oil or light diesel oil	1:36	3:00	1:12	4:15	2:12
IMO-6	Low-pressure low flow concealed horizontal spray fire on the side of simulated engine (1.0 MW)	Commercial fuel oil or light diesel oil	3:43	6:30	9:03	NO	8:10
IMO-7	0.5 m^2 central under mock-up (bilge test)	Heptane	NO	NO	NO	NO	NO
IMO-8	0.5 m^2 central under mock-up (bilge test)	SAE 10W30 mineral-based lubrication oil	NO	NO	NO	NO	NO
IMO-9	0.1 m^2 on top of bilge plate centered under exhaust plate	Heptane	4:15	5:30	NO	NO	NO
IMO-10	Flowing fuel fire 0.25 kg/s from top of mock-up	Heptane	9:20	9:50	NO	NO	NO
IMO-11	Class A fires UL 1626 wood crib in 2 m^2 pool fire with 30-second preburn	Heptane	9:20	8:00	7:00	8:40	8:40
IMO-12	A steel plate (30 cm x 60 cm x 5 cm) offset 20° to the spray is heated to 350°C by the top low pressure low flow spray. Then the plate system shutoff, no reignition of the spray is permitted.	Heptane	4:50	3:40	1:42	3:30	5:20
IMO-13	4 m^2 tray under mock-up (bilge test)	Commercial fuel oil or light diesel oil	NO	NO	NO	NO	NO
NRL-1	Low-pressure spray fire on top of simulated engine between agent nozzles (6.0 MW)	Heptane	2:15	6:20	1:52	5:30	1:43
NRL-2	Low-pressure low flow spray fire on top of simulated engine between agent nozzles (1.0 MW)	Heptane	3:00	9:40	3:30	NO	NO
NRL-3	3 m^2 pan fire on top of simulated engine	Heptane	2:30	4:05	NO	NO	1:15
NRL-4	Low-pressure low flow spray fire on side of simulated engine (1.0 MW)	Heptane	8:45	NO	NO	NO	NO
NRL-5	Low-pressure spray fire on side of simulated engine (6.0 MW)	Heptane	4:30	6:30	10:07	NO	6:00

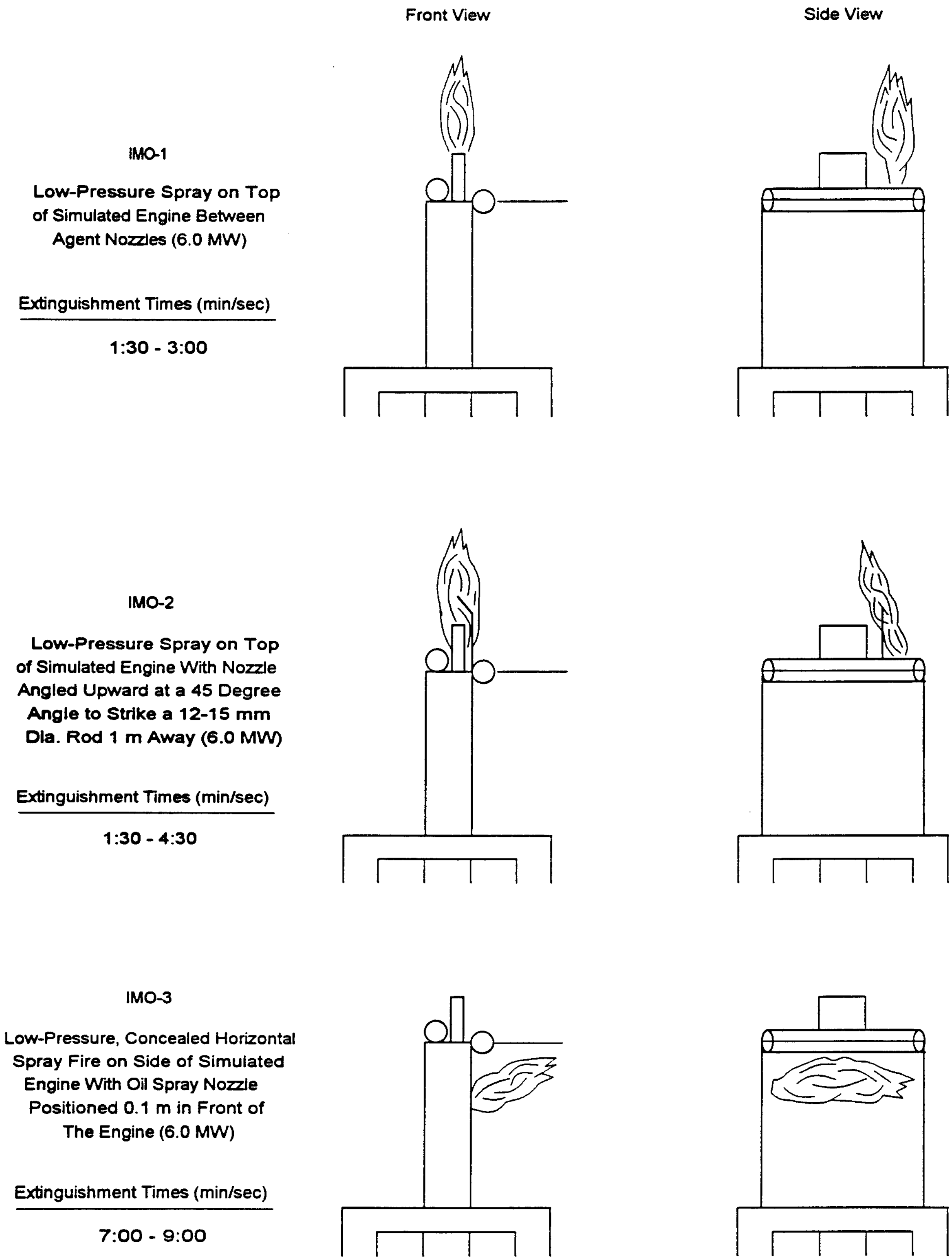


Figure 13. Fire scenario extinguishment times

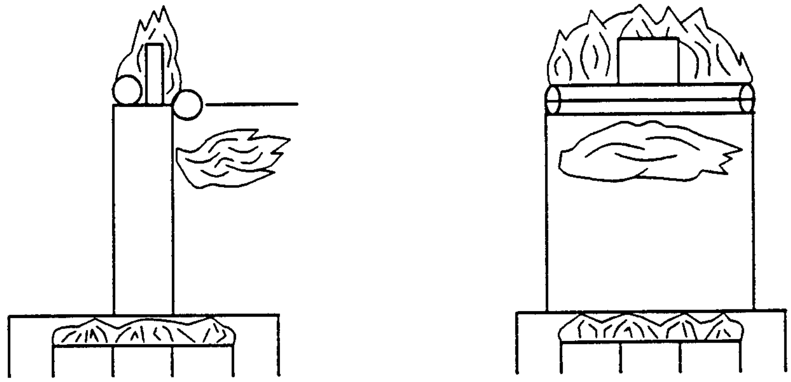
Front | Side

IMO-4

Combination of Worst Spray
Fire From Tests 1-3 and
Fires in Trays (4 m2) Under and
on Top of The Simulated Engine
(3 m2)

Extinguishment Times (min/sec)

No

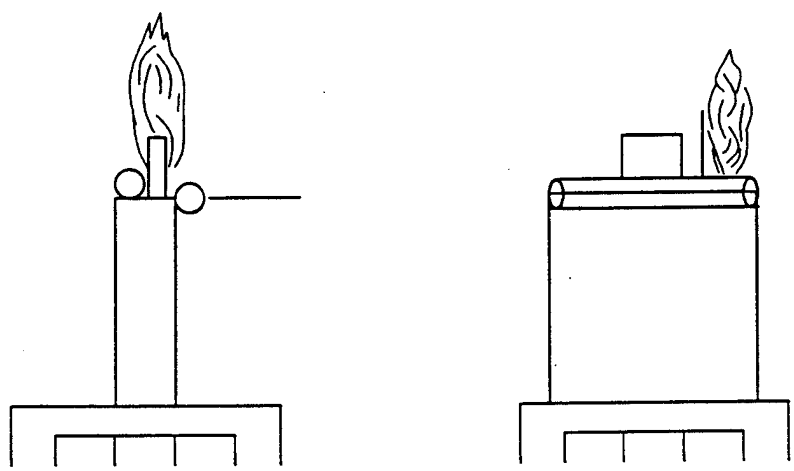


IMO-5

High-Pressure Horizontal Spray
Fire on Top of Simulated
Engine (2.0 MW)

Extinguishment Times (min/sec)

1:30 - 4:00



IMO-6

Low-Pressure Low Flow
Concealed Horizontal Spray Fire
on The Side of Simulated
Engine (1.0 MW)

Extinguishment Times (min/sec)

9:00 - No

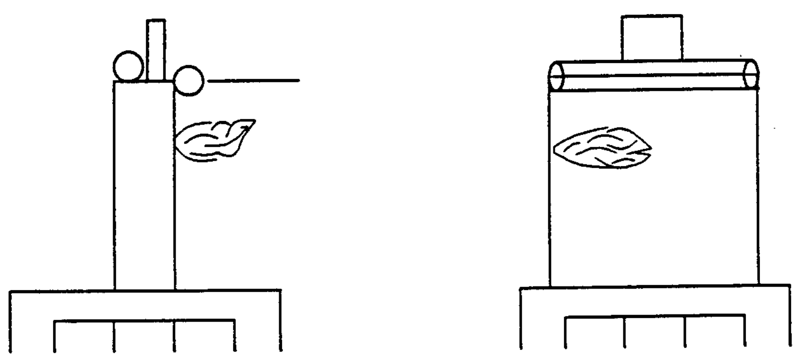


Figure 13. Fire scenario extinguishment times (cont'd)

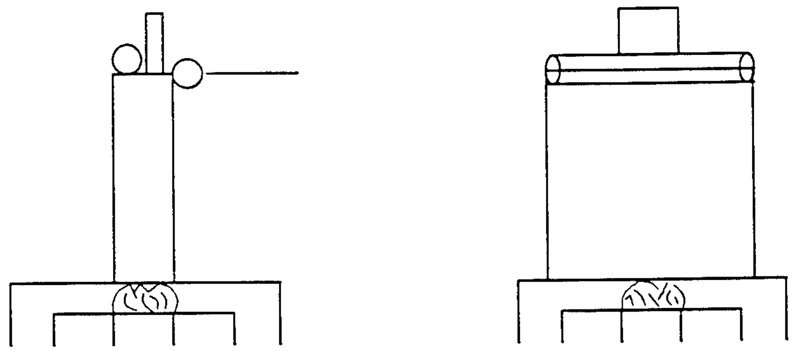
Front Side

IMO-7

0.5 m2 Central Under Mock-Up

Extinguishment Times (min/sec)

No

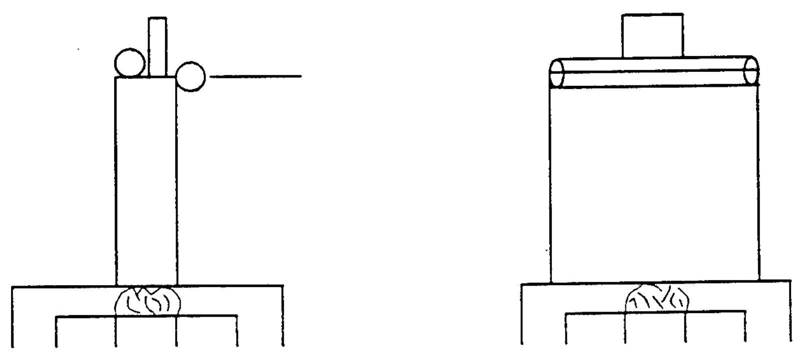


IMO-8

0.5 m2 Central Under Mock-Up

Extinguishment Times (min/sec)

No



IMO-9

0.1 m2 on Top of Bilge Plate
Centered Under Exhaust Plate

Extinguishment Times (min/sec)

5:30 - No

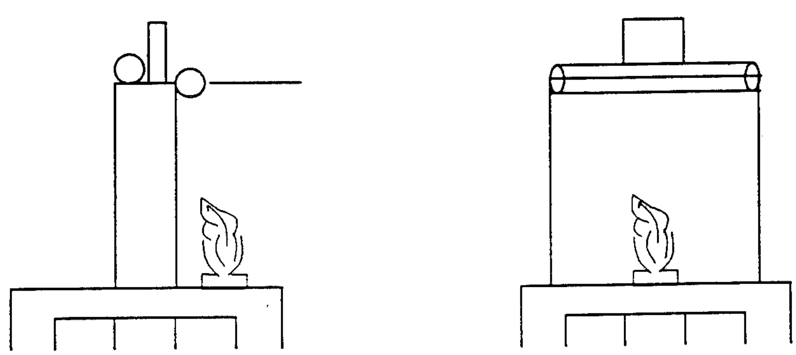


Figure 13. Fire scenario extinguishment times (cont'd)

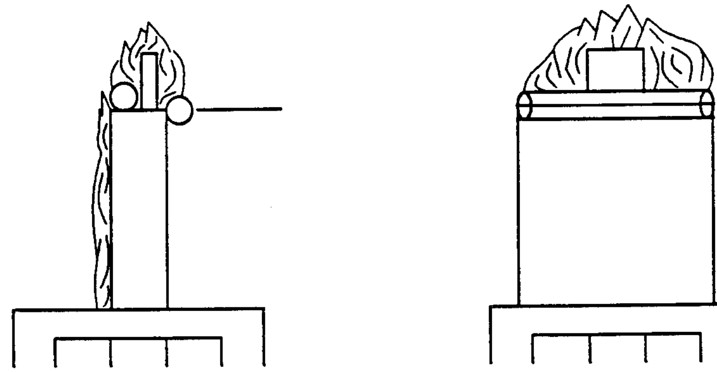
Front Side

IMO-10

Flowing Fuel Fire 0.25 kg/s
From Top of Mock-Up

Extinguishment Times (min/sec)

10:00 - No

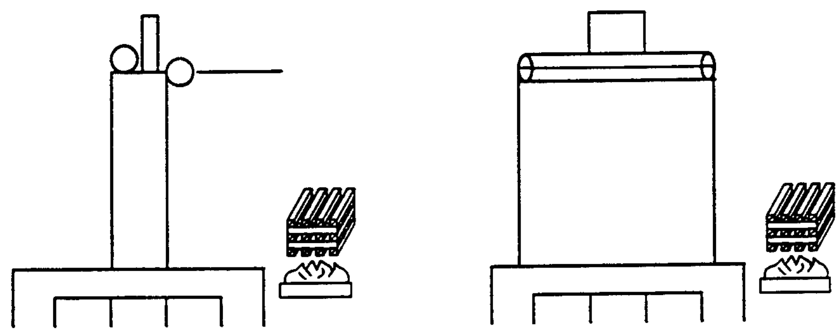


IMO-11

Class A Fires UL 1626 Wood
Crib in 2 m2 Pool Fire
With 30-second Pre-Burn

Extinguishment Times (min/sec)

7:00 - 9:30



IMO-12

A Steel Plate (30 x 60 x 5 cm)
Offset 20 Degrees to The Spray
is Heated to 350 C by the Top
Low Pressure, Low Flow Spray.
The the Plate System Shutoff, No
Re-ignition of the Spray
is Permitted

Extinguishment Times (min/sec)

1:30 - 5:00

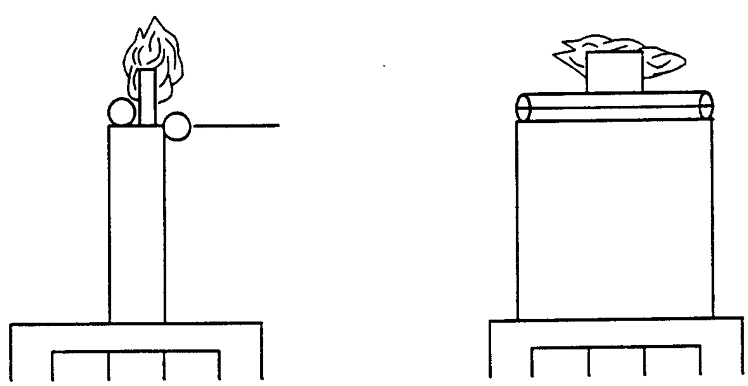
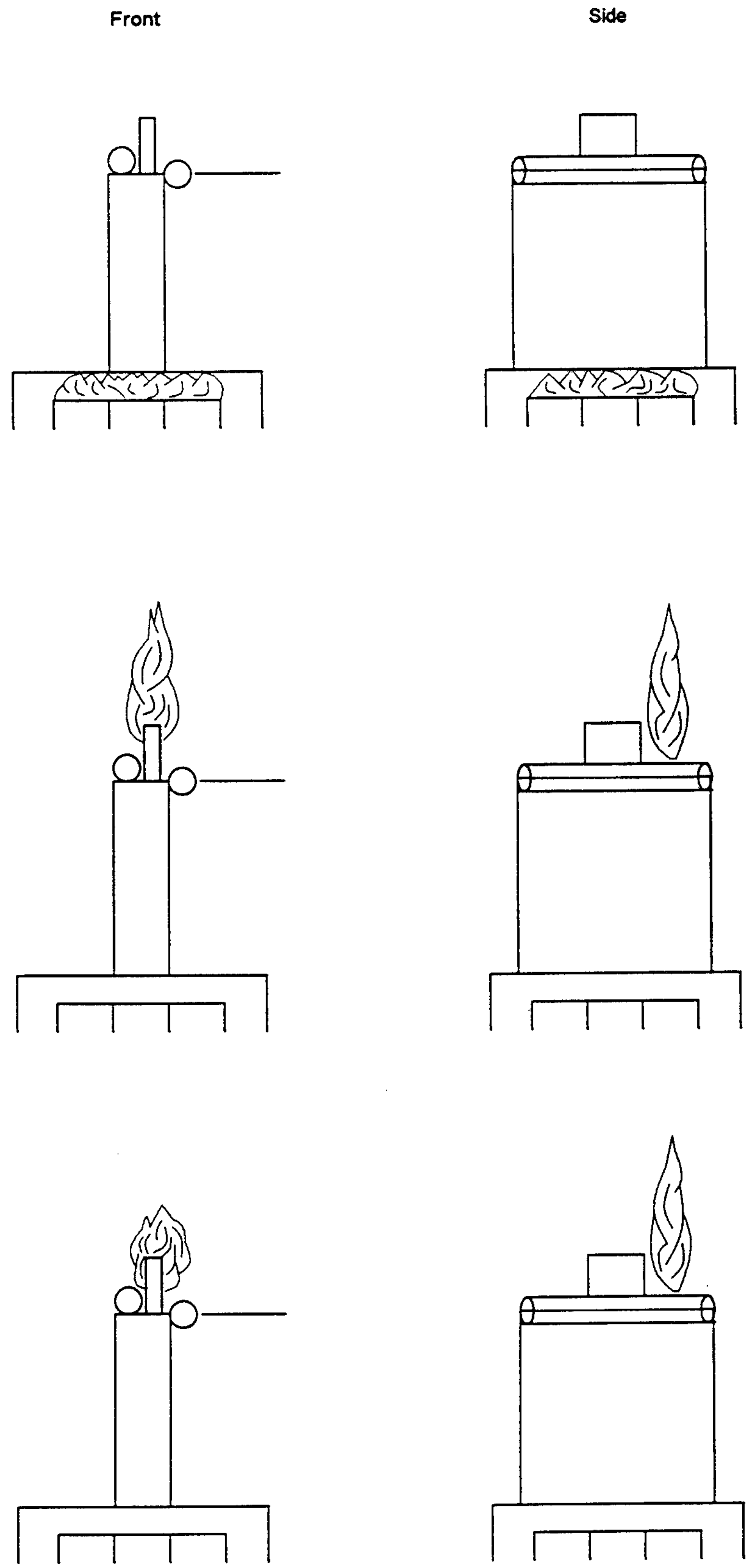


Figure 13. Fire scenario extinguishment times (cont'd)



IMO-13

4 m2 Tray Under Mock-Up

Extinguishment Times (min/sec)

NO

NRL-1

Low-Pressure Spray Fire on Top of Simulated Engine Between Agent Nozzles (6.0 MW)

Extinguishment Times (min/sec)

6:30 - No

NRL-2

Low-Pressure Low Flow Spray Fire on Top of Simulated Engine Between Agent Nozzles (1.0 MW)

Extinguishment Times (min/sec)

9:30 - No

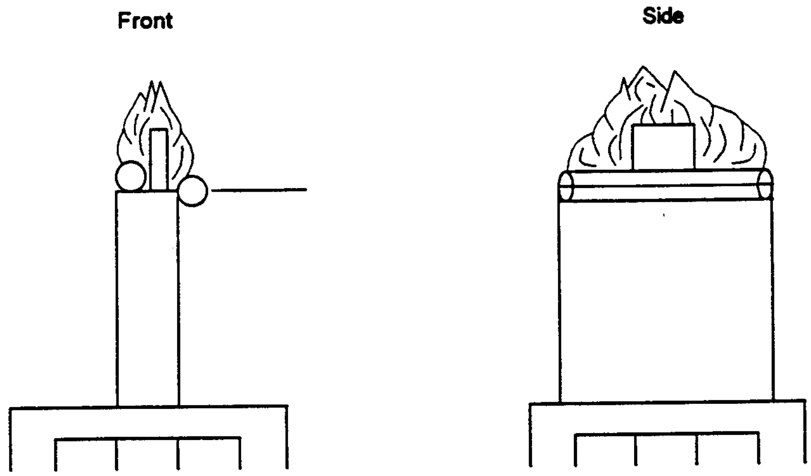
Figure 13. Fire scenario extinguishment times (cont'd)

NRL-3

3 m2 Pan Fire on Top of Simulated Engine

Extinguishment Times (min/sec)

4:00 - No

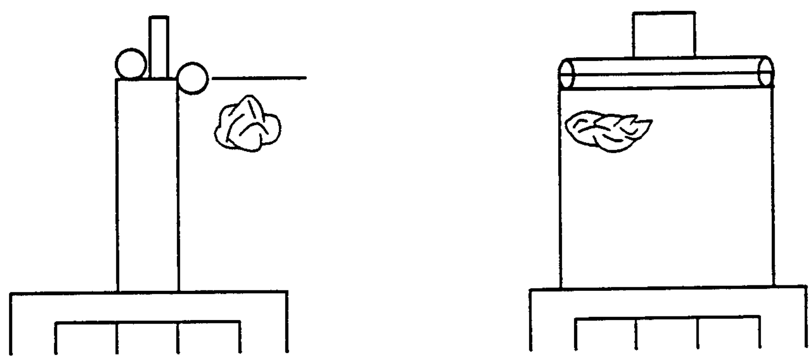


NRL-4

Low-Pressure Low Flow Spray Fire on Side of Simulated Engine (1.0 MW)

Extinguishment Times (min/sec)

8:30 - No



NRL-5

Low-Pressure Spray Fire on Side of Simulated Engine (6.0 MW)

Extinguishment Times (min/sec)

10:00 - No

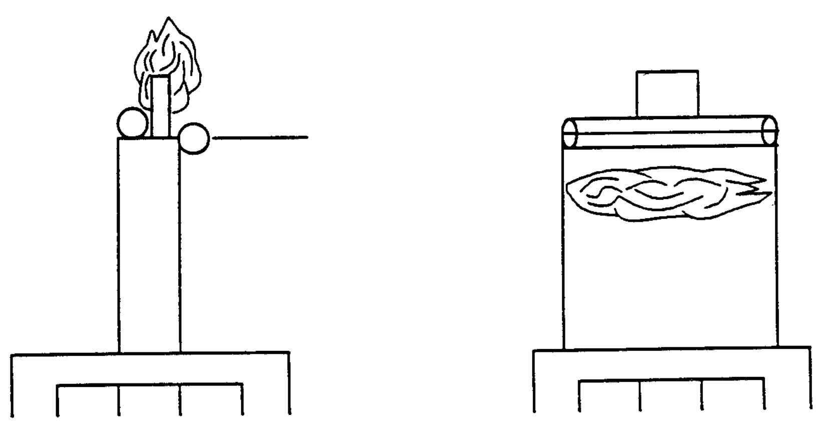


Figure 13. Fire scenario extinguishment times (cont'd)

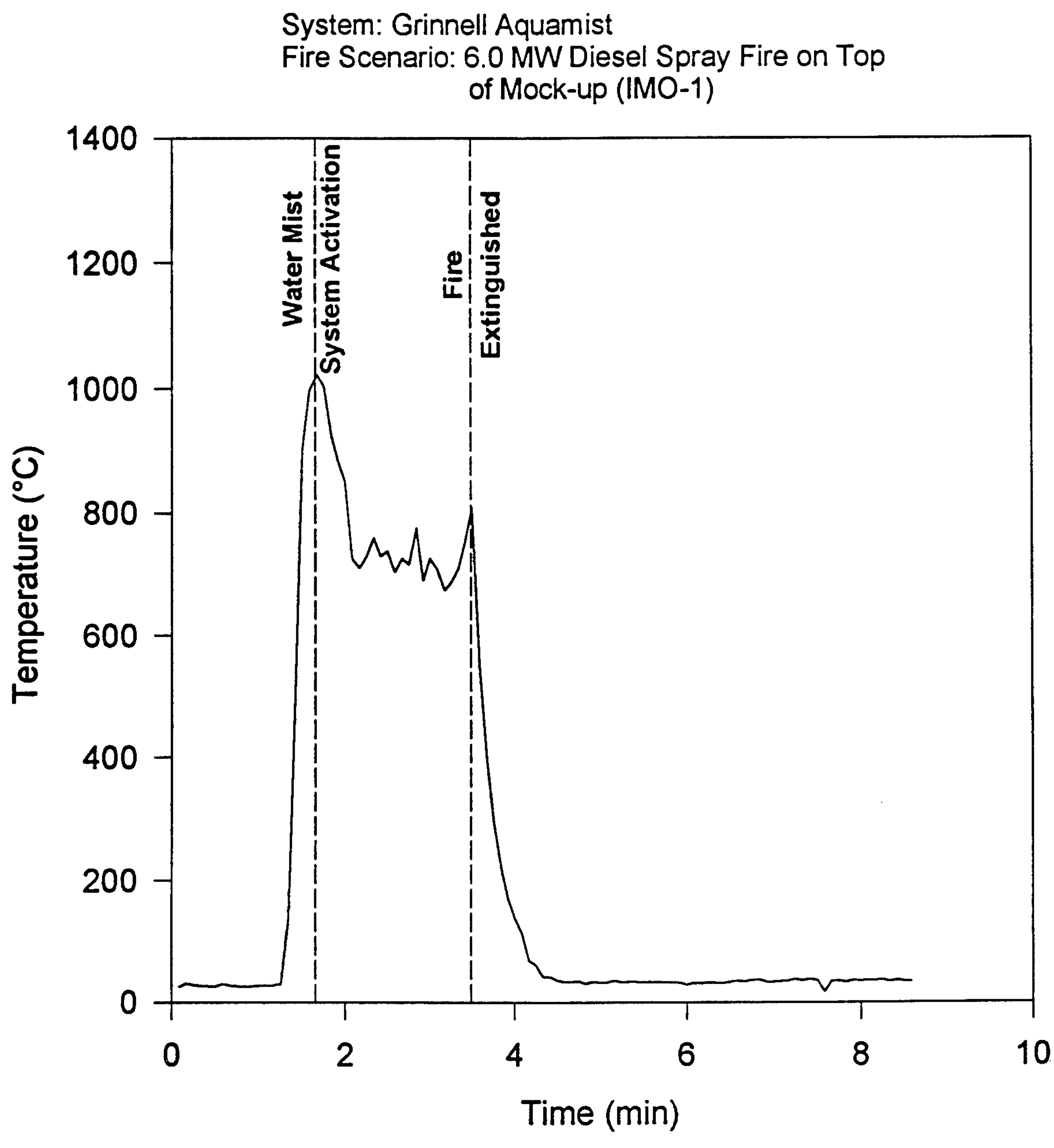


Fig. 14 - Fire Temperature (used to determine extinguishment time)

The following observations can be made concerning the overall performance of water mist technologies in this application.

The primary result of interest pertains to the time required to extinguish the fire since the IMO requirements state that extinguishment must occur in less than 15 minutes. In a majority of the tests, the candidate water mist systems required significant amounts of time (minutes) to extinguish the fire. This compares to the prominent gaseous halon alternatives that usually extinguish the fire within seconds (usually on the order of less than 30 seconds [7]) of agent discharge. However, these shorter extinguishment times are for tests conducted in closed spaces. One would not expect gaseous agents, including Halon 1301, to be effective in an open space such as the IMO test enclosure. The extinguishment times recorded during these tests range from just over one minute to as long as ten minutes as shown in both Table 6 and Fig. 13. These times would be reduced by installing water mist nozzles at multiple elevations in the space as well as under obstructions as illustrated during the Navy test program [3]. Reducing the vent losses could also reduce the extinguishment times.

Although these systems required minutes to extinguish the test fires, immediately after the water mist system was activated, the temperatures in the space were dramatically reduced. This temperature reduction was observed to be relatively equal for the five systems evaluated during this test series (independent of the type/category of system). The temperatures measured in the compartment for each of the five systems during the 1.0 MW and 6.0 MW heptane spray fires located on the side of the mock-up (NRL-4 & NRL-5) are found in Appendix C. These plots illustrate the magnitude of the temperature reduction produced by each system. The obstructed heptane spray fires were selected for this illustration due to their typically longer extinguishment times. An example of this temperature reduction is shown in Fig. 15. During this test, the Grinnell AquaMist system was activated one minute after ignition of the main fire (6.0 MW diesel spray fire (IMO-3)). The fire was not extinguished for over seven minutes after mist system activation. During this eight-minute discharge, the temperatures were reduced and maintained below 50°C (122°F) until the fire was extinguished. This reduction in temperature would help minimize the thermal damage to the space, prevent fire spread beyond the space, and aid in manual intervention.

An interesting phenomenon was also observed during the extinguishment of the obstructed spray fires. After the mist system was activated and the mist concentration began to increase and the oxygen concentration began to decrease, the spray fire flame began to behave differently. Initially, the flame became less turbulent. Once the oxygen concentration dropped below approximately 19.0 percent, the flame began to change color (turned from the bright yellow luminous flame to a bluish-purple flame) and was observed to separate from the fuel spray source (Blow-off). At this point, only the far edges of the fuel spray were burning. Many times during the test, the flame actually became completely detached from the fuel spray. This flame separation and reattachment continued until the fire was extinguished or the test was terminated. This phenomenon was also observed for the unobstructed fires but to varying degrees depending on the water mist system being evaluated, the fire size, and fuel type. As a rule, the phenomenon was more pronounced when heptane was used rather than diesel fuel.

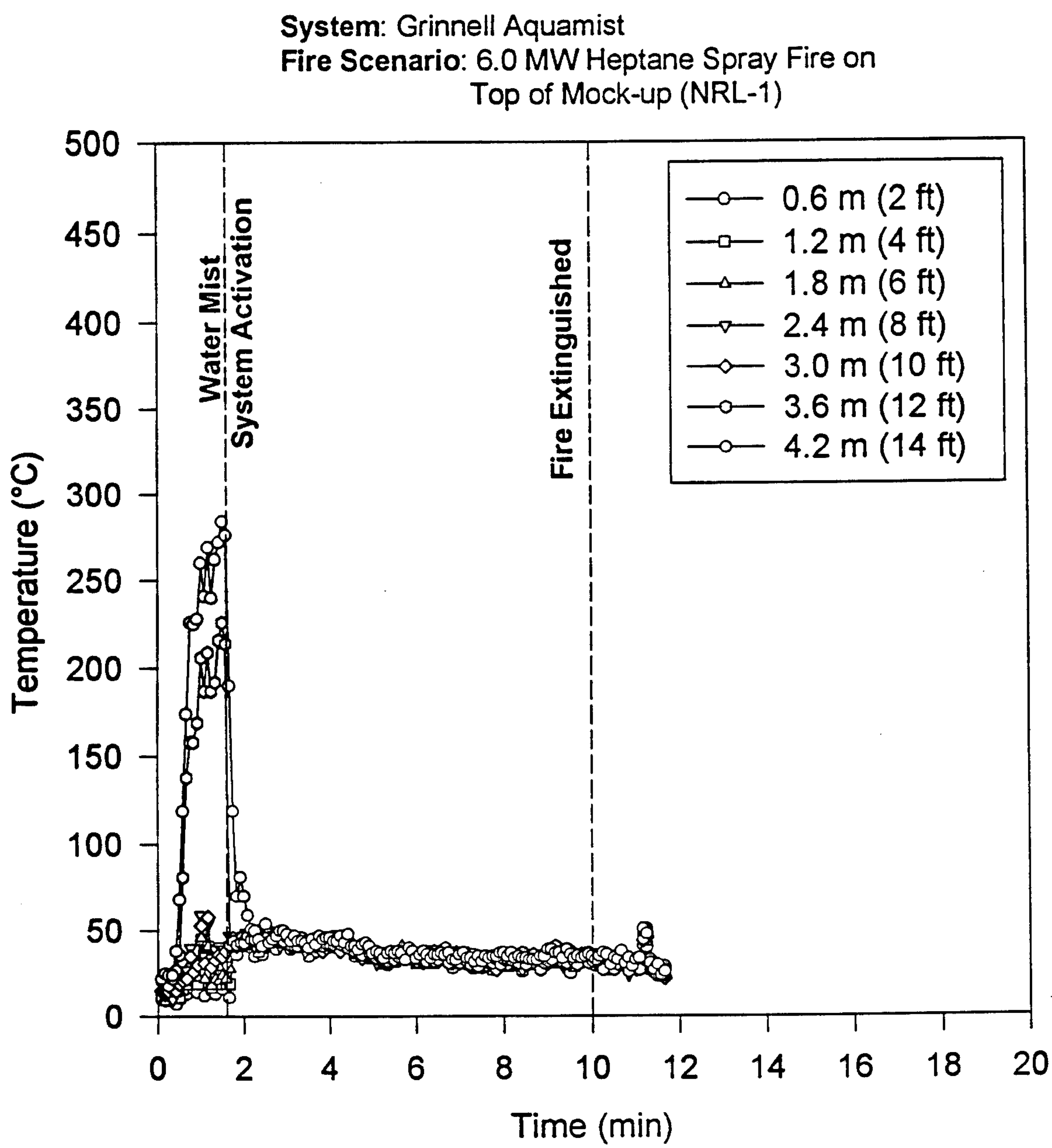


Figure 15. Compartment temperatures (reduction due to mist system)

These tests also illustrated that water mist nozzles strictly installed in the overhead of the space are unable to protect the bilge of the space with overhead nozzles (Tests IMO-4, IMO-7, IMO-8, and IMO-13). During these tests, none of the bilge fires were extinguished. Observations made during the bilge fire tests indicate that very little, if any, mist was reaching the fire under the bilge plating. In this configuration, the bilge represents a substantially large horizontal obstruction (on the order of two plus meters (over 6 feet)). Large horizontal obstructions are a significant challenge to water mist technologies due to gravity fall-out of the mist. In addition, the mist must enter the bilge area throughout a .25 m (10 in) vertical opening located around the perimeter of the bilge .50 m (1 ft 8 in) above the deck (Fig. 4). This configuration was shown to be too challenging for the water mist nozzles evaluated during these tests. These tests demonstrate the need to further evaluate bilge applications in more representative configurations as well as the need to evaluate a wide range of obstructions.

As a general rule, the spray fires on the top of the engine mock-up (particularly IMO-1, IMO-2, IMO-5, IMO-12, and NRL-1) are easier to extinguish than those located elsewhere in the space. This is attributed to two interrelated variables. First, these fires are located high in the compartment in close proximity to the water mist nozzles, resulting in a large portion of the mist being discharged directly into the spray fire plume. Secondly, the upper portions of the compartment are exposed to a greater accumulation of fire gases and steam thus reducing the oxygen concentration at the base of the fire. This becomes apparent during IMO-12 (1.0 MW heptane spray fire with reignition source). During this test, the prolonged pre-heating (on the order of 10-12 minutes) of the steel plate (to 350°C (662°F)) reduces the oxygen concentration in the space and increases the temperature of both the surface of the mock-up and the air in the space (develops a hot layer) as shown in Figure 16. Once the mist system is activated, the fire is extinguished in about 2-5 minutes due to both a significant amount of mist being converted to steam and the reduced oxygen concentration as a result of the long preburn time.

The obstructed fires (the fires located on the side of the mock-up) (IMO-3, IMO-4, IMO-6, IMO-10, NRL-4, and NRL-5) are substantially more difficult to extinguish than fires located elsewhere in the space as shown in Figure 17. In general, there are two primary variables which contribute to the extinguishment of these obstructed spray fires. These variables include both mist and oxygen concentration at the fire location. The mist concentration at a given obstructed location is a function of the droplet size, distribution, spray momentum characteristics, and the ability of the system to mix/distribute the spray around obstructions. The smaller droplet size/higher momentum nozzles usually produce increased mixing characteristics as compared with the low pressure nozzles. This results in increased capabilities against obstructed fires. The oxygen concentration at the base of the fire with respect to time is a function of the size of the fire, compartment volume, and ventilation parameters of the space. In other words, consumption of oxygen by the fire, and the dilution of the oxygen in the space by steam, both contribute to reducing the oxygen available for combustion. Consequently, larger fires are usually easier to extinguish than smaller fires due to higher oxygen consumption rates, increased steam production rates, better mixing due to increased turbulence created by the fire and greater entrainment rates. This is illustrated by comparing the results of IMO-3 and IMO-6. The larger spray fire (IMO-3, 6.0 MW), as a rule, is usually extinguished two or three minutes faster than the smaller spray fire (IMO-6, 1.0 MW).

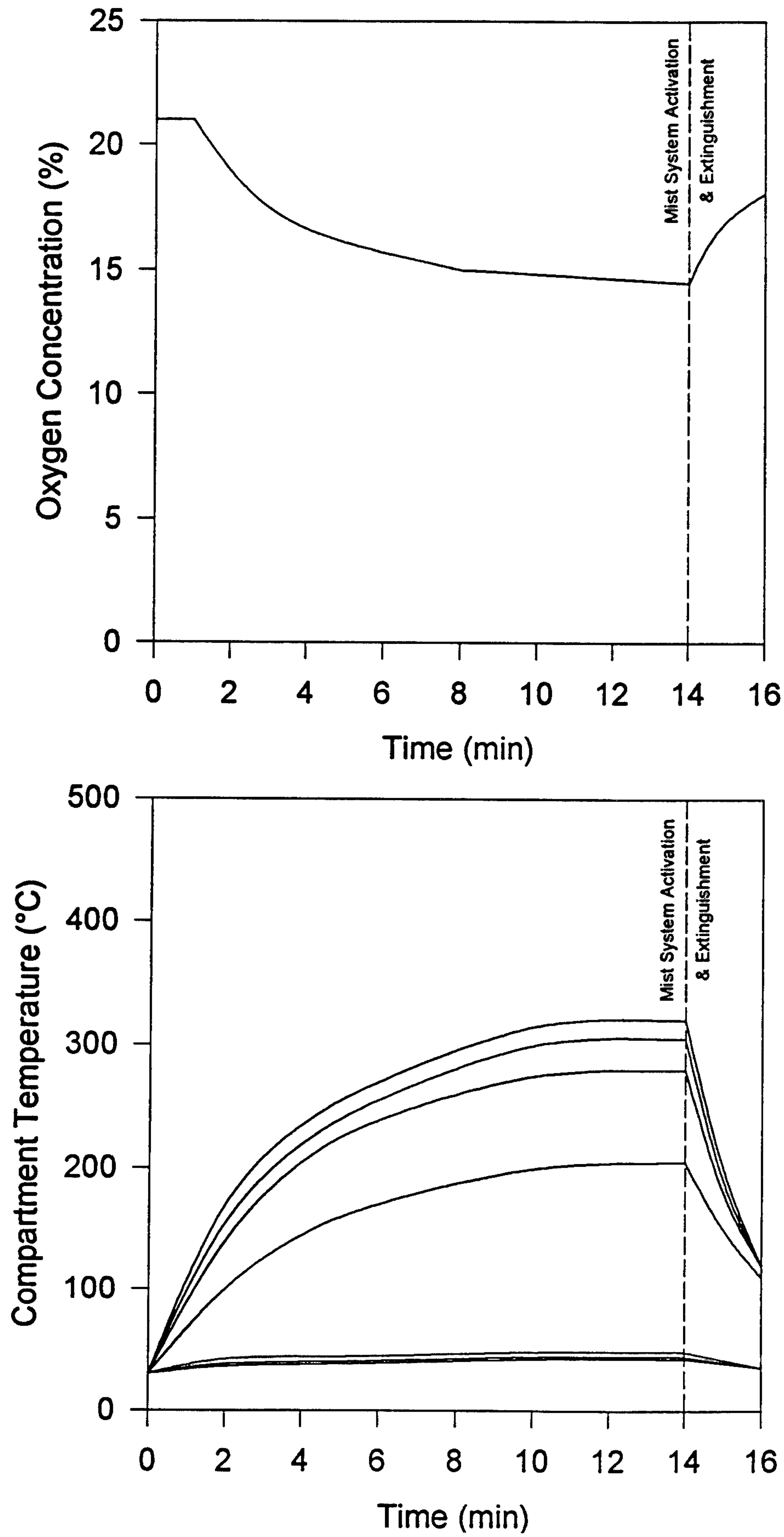


Figure 16. Compartmental condition during IMO test #12 (IMO-12)

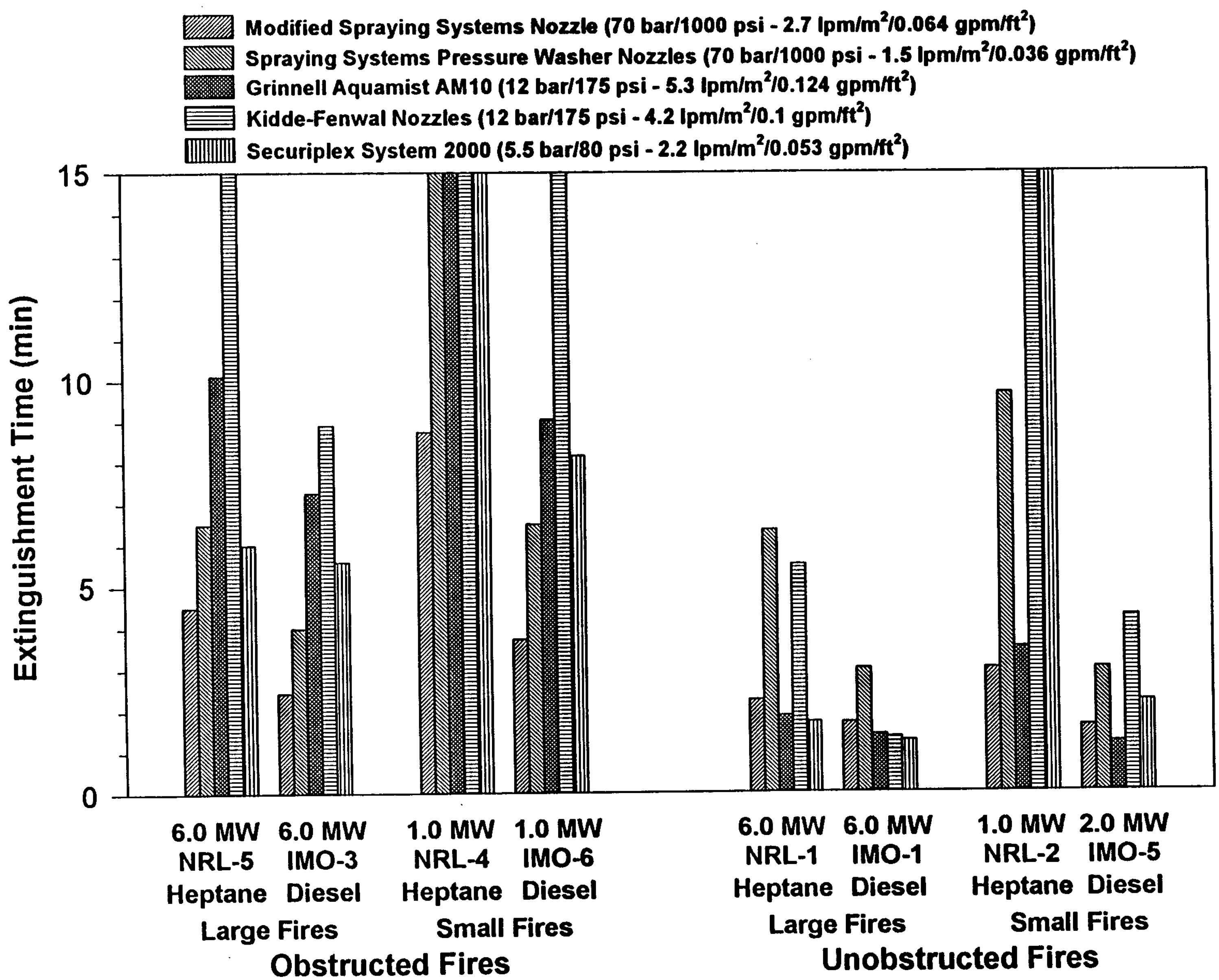


Fig. 17 - Extinguishment summary

Smaller fires are more difficult to extinguish than larger fires. This was illustrated by the poor performance exhibited by the water mist systems against the 0.1 m^2 (IMO-9) heptane pan fire and 1.0 MW spray fires located under the obstruction plate (IMO-6 and NRL-4). As stated previously, the smaller fire usually required two to three minutes longer to extinguish. The 0.1 m^2 heptane pan fire and the 1.0 MW heptane spray fire located on the side of the mock-up were observed to distinguish the higher performance water mist systems from the lower performance systems. Only the modified spraying systems nozzle was able to extinguish all of these fires.

The large heptane pan fire on the top of the mock-up (IMO-10) was one of the more difficult fires to extinguish. Based on the results of the spray fire tests conducted on top of the mock-up, it was anticipated that the pan fire scenario would not pose a challenge to the candidate systems. However, the large pipe (simulating a manifold) located along the top of the mock-up presented a significant obstruction to the water mist systems. During the tests when the fire was not extinguished, the mist system was capable of extinguishing the areas of the pool fire open to the mist, but could not extinguish the flames beneath the obstruction. These small residual fires consequently kept spreading back across the fuel surface.

In general, the fires conducted with lower flash point fuel [Heptane -4°C (25°F)] were more difficult to extinguish than those conducted with the higher flash point fuel [Diesel 52°C (126°F)]. This is illustrated by comparing the extinguishment times of the tests conducted with heptane (NRL-1 and NRL-5 tests) to the ones conducted with diesel fuel (IMO-1 and IMO-3) Figure 17. Some of the fires extinguished when diesel was used as the fuel were not extinguished when heptane was used as the fuel. During the tests conducted with both heptane and diesel fuel, the heptane fires usually required two to four minutes longer to extinguish. The increased difficulty with lower flash point fuels is attributed to the high potential for reignition, the constant production of flammable vapor mixtures above the fuel surface in the absence of flame radiation and the inability of water mist to cool the fuel surface below the flash point of the fuel.

8.2 Enclosure Effects

The extinguishment of fires with water mist is somewhat dependent on the characteristics of the enclosure (i.e., volume, shape, clutter and ventilation conditions). These parameters have varying effects on the extinguishment process and the conditions in the space. First, the enclosure confines the mist allowing the build-up of a mist concentration. Second, the enclosure confines heat, thus aiding in the production of steam. Third, the enclosure confines the products of combustion and steam thus contributing to the depletion of oxygen in the space.

Oxygen depletion and dilution has been identified as one of the contributing factors in extinguishing shielded/obstructed fires [3,8]. These tests illustrate that fires can still be extinguished in locations of lower mist concentrations with some help from oxygen depletion. The oxygen concentrations at the base of each fire during extinguishment are shown in Table 7. The effects of oxygen depletion are best illustrated by comparing the results of the test conducted with the spray fires located on the side of the mock-up (IMO-3, IMO-6, NRL-4, and NRL-5) as shown in Figure 18. The obstructed spray fires were extinguished when the oxygen

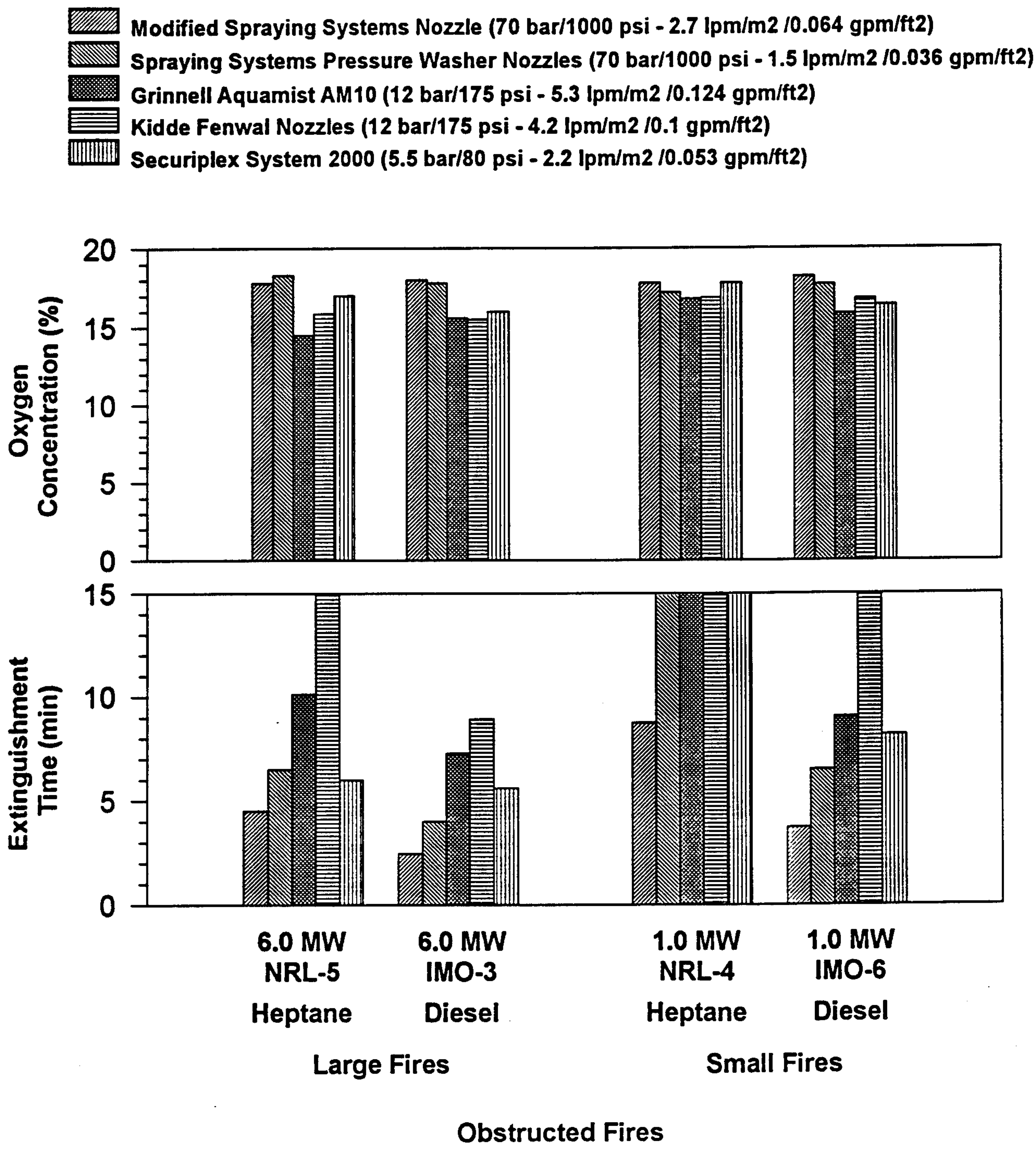


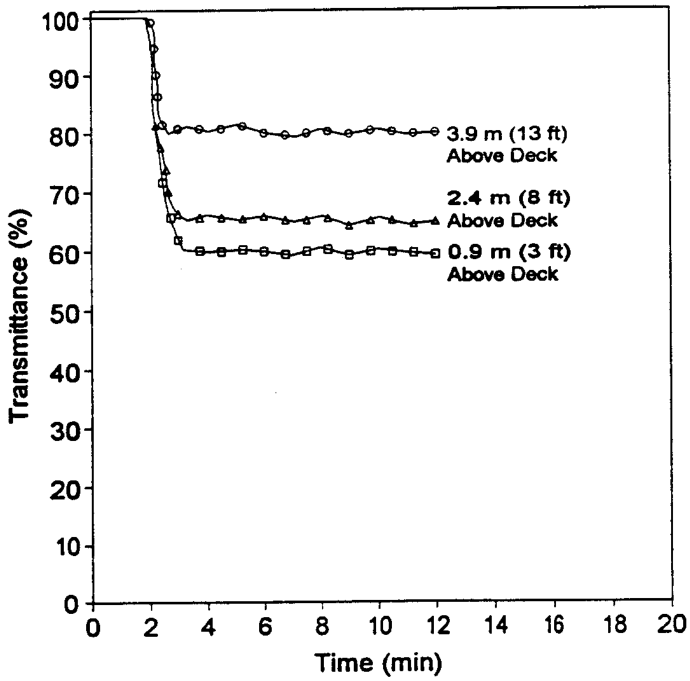
Figure 18. Obstructed Fire Test Results

concentration dropped below 15-16 percent for the low-pressure single-fluid nozzles and when the oxygen concentration dropped below 18-19 percent for the high-pressure nozzles. (Thirteen percent is the limiting oxygen index for most hydrocarbon fuels [9].) The unobstructed fires (fire located on top of the mock-up) were extinguished with oxygen concentrations anywhere between 16 to 21 percent.

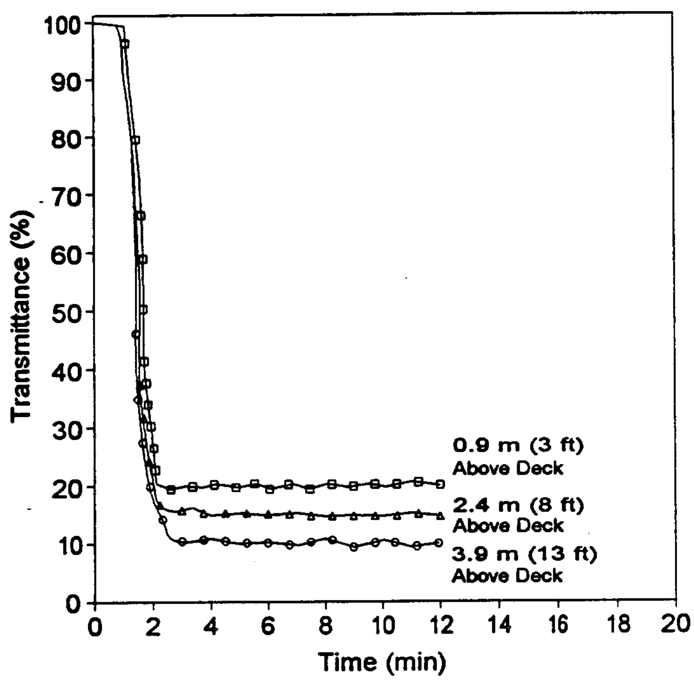
Steam production and recondensation may also be a contributing factor in the extinguishment process. The production of steam can aid in extinguishment in many ways. First, steam reduces the oxygen concentration due to dilution effects. Dilution can occur on both a localized or global scale. This oxygen dilution is difficult to accurately measure using standard oxygen analyzers. In order to make this measurement accurately, the sample must be maintained at a constant temperature (the temperature at which the sample was taken) as it is drawn from the test compartment to the analyzer to assure the water vapor remains as a gas. In addition, the liquid droplets in the sample also need to be removed. Secondly, as the steam cools, it condenses back into mist (very small droplets). The condensing steam effectively changes the dropsize characteristics in the space. Also, the gaseous behavior of the steam (and the small droplets being condensed out of the steam) increases the mist system's capabilities against obstructed fires.

An estimation of recondensed steam being produced during the extinguishment of a large fire can be seen by comparing the optical density measurements (ODM) recorded during two tests conducted with the Grinnell AquaMist nozzles (a cold discharge test (no fire) and a 2.0 MW heptane spray fire located on the top of the mock-up). This comparison is shown in Fig. 19. As shown in Fig. 15, during the cold discharge test, the mist concentration reduces transmittance of the ODMs on the order of 10-40 percent. The obscuration range is related to a gradient in the mist concentration with the highest concentration located low in the space (greatest reduction in transmittance) and decreases with elevation (lowest reduction in transmittance). During the fire test (2.0 MW heptane spray fire), the reduction of transmittance was more uniform and was observed to be on the order of 80 percent. This was primarily due to the production of steam and recondensing steam during the test. The products of combustion (primarily soot) produced by the heptane spray fire itself tend to reduce the optical density at the 4.0 m (13.0 ft) elevation by 10 percent but usually have little or no effect on the ODM's at the 2.5 m (8.0 ft) and 1.0 m (3.0 ft) levels. Also note in Fig. 19 that during the fire test, the concentration gradient was reversed with higher concentrations observed at the higher elevations in the space. The reversal of the concentration gradient is related to both the in-flow of cool air low in the space and the heated steam rising and recondensing.

The net effects of the fire (i.e., oxygen depletion, steam production and recondensation, and better mixing due to increasing turbulance) are best illustrated by evaluating the mist system's capabilities against the small tell tale fires. The number or percent of tell tale fires extinguished during a given test has been identified to be a function of the heat release rate of the main fire (primary fire). As shown in Fig. 20, on an average, the four mist systems were capable of only extinguishing 50 percent of the tell-tale fires during the cold discharge tests (tell tale fires only/no primary fire). As the size of the primary fire was increased, the number of tell tale fires



Grinnell Aquamist System (No Fire)



Grinnell Aquamist System with 2.0 MW Fire

Figure 19. Optical density comparison (steam production and condensation)

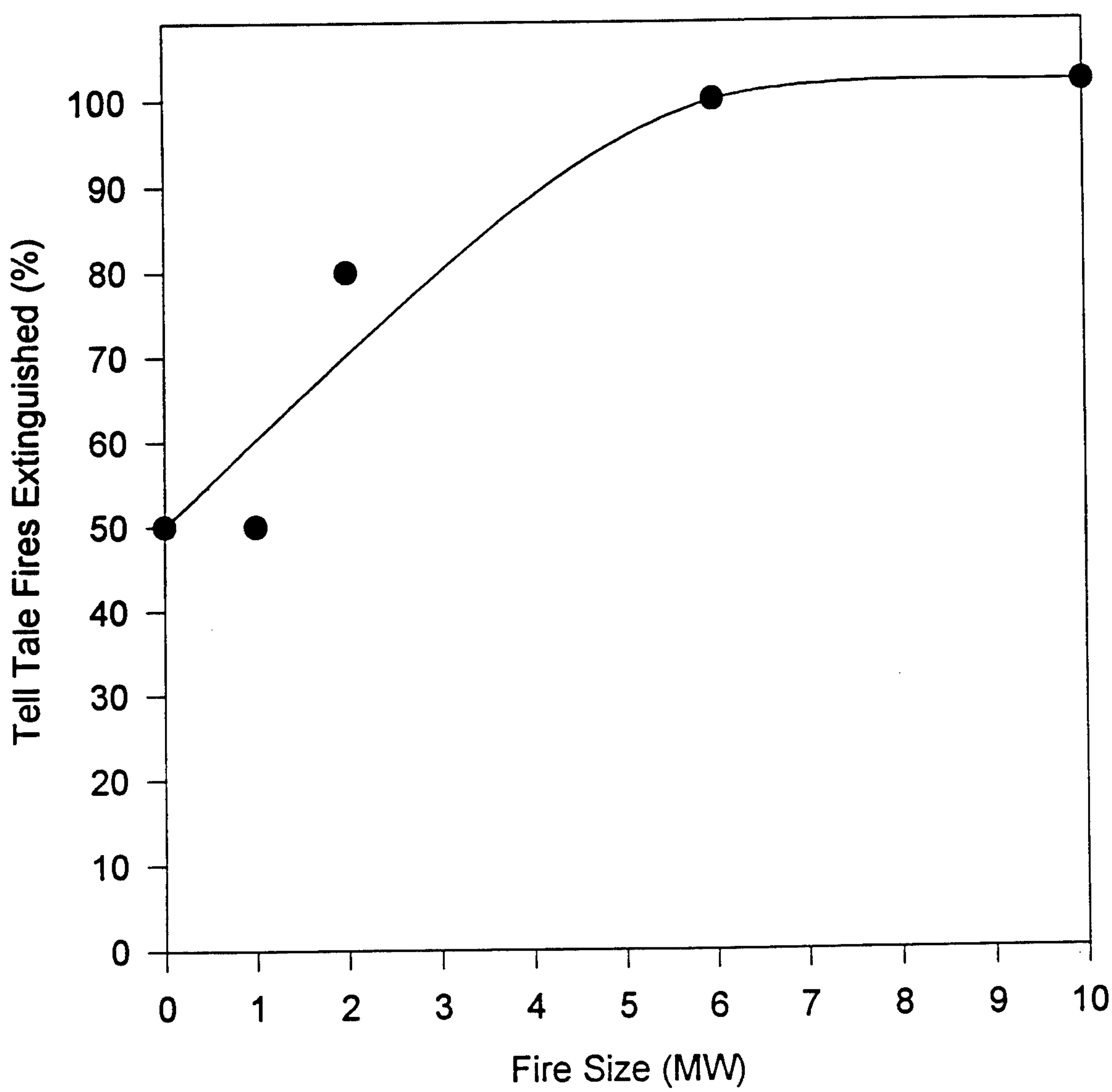


Fig. 20 - Tell tale extinguishment as a function of primary fire size

extinguished increased until all of the tell tale fires were extinguished. This occurred during the tests conducted against the 6.0 MW fire tests. During the tests conducted with large fires (6.0 MW or larger), all of the tell tales were extinguished independent of the extinguishment status of the large primary fire.

8.3 Individual Water Mist System Performance

The following discussion does not include the bilge fire scenarios. Discussion of the bilge tests was intentionally omitted due to the inability of the overhead water mist nozzles evaluated during this test series to extinguish these fires. It was determined during this test series that the bilge areas of the space require additional protection. Further work in this area is needed. It may be advantageous to protect these areas with a separate extinguishing system having the ability to operate independently of the system installed in the main space.

8.3.1 Grinnell AquaMist (G-AM10)

The Grinnell AquaMist nozzle is a single-fluid low pressure nozzle that operates at pressure of 12 bar (175 psi). At this pressure, the individual nozzles flow approximately 12 Lpm (3.1 gpm) producing a total system flow rate of 440 Lpm (112 gpm). This flow rate corresponds to an application rate of 5.3 Lpm/m^2 (0.124 gpm/ft^2), the highest application rate evaluated during this test series.

Results of the Grinnell AquaMist tests are shown in Table 6. Throughout this test series, the AquaMist system was capable of extinguishing a majority of the fires located on top of the mock-up (unobstructed fires; see IMO-1, IMO-2, IMO-5, IMO-12, NRL-1 and NRL-2) within one to four minutes of system activation. These particular extinguishment times were comparable to the other nozzles evaluated during this test series. The limits of the AquaMist nozzles were revealed during the obstructed fire tests (fires located on the side of the mock-up). The AquaMist system was capable of extinguishing both large obstructed spray fires (6.0 MW heptane and diesel spray fires (IMO-3 and NRL-5) and the small, 1 MW concealed spray fire (IMO-6)) but could not extinguish the 1.0 MW heptane spray fire (NRL-4). As mentioned previously, the extinguishment of the obstructed spray fires was observed to be related to the oxygen concentration at the base of the fire. For the AquaMist nozzles, the fires were extinguished when the oxygen concentration dropped to 14.5 - 16.0 percent at the base of the fire. During the 1.0 MW diesel fuel fire (IMO-6), the oxygen dropped to 15.9 percent before extinguishment. During the heptane spray fire (NRL-4), the oxygen remained at 16.8 percent for the duration of the test. The mist concentration plus any effects of the reduced oxygen concentration (16.8 percent) apparently were insufficient to extinguish the heptane spray fire.

The AquaMist nozzles' long extinguishing times (7-10 minutes) for these partially obstructed fires may be related to the larger droplet sizes produced by the low-pressure systems. These larger droplets have limited capabilities against partially obstructed fires due to their high gravity losses (fall-out rates/terminal velocities). The AquaMist nozzles also failed to extinguish the 0.1 m^2 heptane pan fire (IMO-9) located on the bilge plate under the 1.0m (3.05 ft.) obstruction on the side of the mock-up. This small pan fire could not be extinguished with the amount of mist reaching the fire, and the fire was too small to deplete the oxygen concentration in the space (the oxygen concentration remained at 21 percent, see Table 7). The 3 m^2 heptane pan fire (NRL-3) and pan fire/flowing fuel combination (IMO-10) also proved too difficult for the AquaMist nozzles. The inability to extinguish these fires was attributed to the spray pattern characteristics of the nozzle. There appeared to be a hole in the coverage of the spray patterns located at the center of the four nozzles. The spray pattern coverage was adequate to knock down these fires, but not to completely extinguish them. During these tests, a small residual flame remained in an obstructed area (behind the exhaust manifold - pipe) between the four nozzles which continually spread back across the fuel surface.

8.3.2 Kidde-Fenwal (KF)

The Kidde-Fenwal nozzle is also a single-fluid low-pressure nozzle that operates at a pressure of 12 bar (175 psi). At this pressure, the individual nozzles flow approximately 10 Lpm (2.5 gpm) producing a total system flow rate of 350 Lpm (90 gpm). This flow rate corresponds to an application rate of 4.2 Lpm/m^2 (0.1 gpm/ft^2) which is slightly less than the Grinnell AquaMist nozzles.

The Kidde-Fenwal nozzles produced extinguishment characteristics similar to the Grinnell AquaMist nozzles. During these tests, the Kidde-Fenwal nozzles did well against the diesel fires located on top of the mock-up (open fires), but had difficulty extinguishing the unobstructed heptane fires and the obstructed fires located on the side of the mock-up. The Kidde-Fenwal nozzles were capable of extinguishing the large (6.0 MW) obstructed diesel spray fires (IMO-3) but could not extinguish the 6.0 MW heptane spray fire (NRL-5), nor the two smaller obstructed spray fires (IMO-6 and NRL-4) as well as the obstructed pan fire (IMO-9). These nozzles also failed to extinguish heptane fires located on top of the mock-up (NRL-2 and NRL-3). This was, again, attributed to holes in the spray patterns between the four nozzles. In short, the Kidde-Fenwal nozzles could not produce an adequate concentration of mist either high in the space or under the obstructed plate. Interestingly, during the tests when the fires were extinguished, the extinguishment times were comparable to the other candidate systems.

8.3.3 Securiplex

The Securiplex nozzle is a twin-fluid nozzle that operates at a pressure of 5.5 bar (80 psi) for both fluids. Each fluid (water and air) is supplied to the nozzle via a separate set of piping. At this operating pressure, the individual nozzles flow approximately 5.0 Lpm (1.32 gpm) of water and 0.23 m^3 (8.0 ft^3) of air. This water flow rate corresponds to an application rate of 2.2 Lpm/m^2 (0.053 gpm/ft^2).

The Securiplex nozzles produced extinguishment characteristics somewhere between the single-fluid, low-pressure nozzles (Grinnell AquaMist and Kidde-Fenwal) and the single-fluid, high-pressure nozzles (the two spraying systems nozzles). These results were anticipated based

Table 7. System Comparison - Oxygen Concentration at Extinguishment

Test Number	Fire Scenario	Test Fuel	Oxygen Concentration (%) (Extinguishment Times (min./sec.))				
			SS-MOD.7N	SS-T12W	G-AM10	KF	Securiplex
IMO-1	Low-pressure spray on top of simulated engine between agent nozzles (6.0 MW)	Commercial fuel oil or light diesel fuel	16.8 (1:42)	16.8 (3:00)	17.0 (1:24)	17.2 (1:20)	17.8 (1:15)
IMO-2	Low-pressure spray on top of simulated engine with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1 m away (6.0 MW)	Commercial fuel oil or light diesel oil	18.6 (2:10)	18.1 (4:30)	16.8 (1:50)	17.3 (1:25)	18.0 (1:00)
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 oil	18.0 (2:26)	17.8 (4:00)	15.6 (7:16)	15.5 (8:55)	16.0 (5:35)
IMO-4	Combination of worst spray fire from Tests 1-3 and fires in trays (4 m²) under and on top of the simulated engine (3 m²)	Commercial fuel oil or light diesel oil	-- (NO)	-- (NO)	-- (NO)	-- (NO)	-- (NO)
IMO-5	High-pressure horizontal spray fire on top of simulated engine (2.0 MW)	Commercial fuel oil or light diesel oil	18.8 (1:36)	18.0 (3:00)	17.7 (1:12)	16.9 (4:15)	17.4 (2:12)
IMO-6	Low-pressure low flow concealed horizontal spray fire on the side of simulated engine (1.0 MW)	Commercial fuel oil or light diesel oil	18.2 (3:43)	17.7 (6:30)	15.9 (9:03)	16.8 (NO)	16.4 (8:10)
IMO-7	0.5 m² central under mock-up	Heptane	21.0 (NO)	21.0 (NO)	21.0 (NO)	21.0 (NO)	21.0 (NO)
IMO-8	0.5 m² central under mock-up	SAE 10W30 mineral-based lubrication oil	21.0 (NO)	21.0 (NO)	21.0 (NO)	21.0 (NO)	21.0 (NO)
IMO-9	0.1 m² on top of bilge plate centered under exhaust plate	Heptane	21.0 (4:15)	21.0 (5:30)	21.0 (NO)	21.0 (NO)	21.0 (NO)
IMO-10	Flowing fuel fire 0.25 kg/s from top of mock-up	Heptane	-- (9:20)	-- (9:50)	-- (NO)	-- (NO)	-- (NO)
IMO-11	Class A fires UL 1626 wood crib in 2 m² pool fire with 30-second preburn	Heptane	19.6 (9:20)	19.4 (8:00)	19.4 (7:00)	19.5 (8:40)	18.2 (NO)
IMO-12	A steel plate (30 cm x 60 cm x 5 cm) offset 20° to the spray is heated to 350°C by the top low pressure low flow spray. Then the plate system shutoff, no reignition of the spray is permitted.	Heptane	19.2 (2:50)	19.2 (3:40)	19.8 (1:42)	18.4 (3:30)	18.8 (5:20)
IMO-13	4 m² tray under mock-up	Commercial fuel oil or light diesel oil	19.4 (NO)	19.2 (NO)	19.0 (NO)	19.4 (NO)	19.5 (NO)

Table 7. System Comparison – Oxygen Concentration at Extinguishment (Continued)

Test Number	Fire Scenario	Test Fuel	Oxygen Concentration (%) (Extinguishment Times (min./sec.))				
			SS-MOD.7N	SS-T12W	G-AM10	KF	Securiplex
NRL-1	Low-pressure spray fire on top of simulated engine between agent nozzles (6.0 MW)	Heptane	16.7 (2:15)	15.7 (6:20)	16.8 (1:52)	15.9 (5:30)	16.2 (1:43)
NRL-2	Low-pressure low flow spray fire on top of simulated engine between agent nozzles (1.0 MW)	Heptane	18.8 (3:00)	16.0 (9:40)	18.4 (3:30)	16.7 (NO)	17.5 (NO)
NRL-3	3 m^2 pan fire on top of simulated engine	Heptane	18.75 (2:30)	17.4 (4:05)	16.2 (NO)	16.4 (NO)	18.6 (1:15)
NRL-4	Low-pressure low flow spray fire on side of simulated engine (1.0 MW)	Heptane	17.8 (8:45)	17.2 (NO)	16.8 (NO)	16.9 (NO)	17.8 (NO)
NRL-5	Low-pressure spray fire on side of simulated engine (6.0 MW)	Heptane	17.8 (4:30)	18.3 (6:30)	14.5 (10:07)	15.9 (NO)	17.0 (6:00)

on the fact that the drop size distribution of the twin-fluid systems lies between that of the high and low pressure single-fluid systems. During these tests, the Securiplex nozzles did well against the large fires (i.e., 6.0 MW fires) but showed mixed results against the smaller fires (i.e., 1.0 MW fires). The Securiplex nozzles were capable of extinguishing all of the large fires on top of the mock-up (IMO-1, IMO-2, IMO-5 and NRL-1), with the exception of the 1.0 MW heptane spray fire (NRL-2). The Securiplex nozzles also could not extinguish the two small heptane fires located on the side of the mock-up (the 0.1 m^2 heptane pan (IMO-9) and the 1.0 MW heptane spray fire (NRL-4)). The difficulties in extinguishing these two fires appears to be related more to the oxygen concentration at the base of the fire than with the drop size characteristics of the nozzle. The data suggest that the Securiplex nozzles produce adequate amounts of small droplets to extinguish these fires. This is illustrated by the capabilities exhibited by these nozzles in extinguishing the remaining obstructed fires (IMO-3, IMO-6, and NRL-5). During the three tests when the fires were not extinguished, the oxygen concentration at the base of the fire never dropped below 17.5 percent. These higher oxygen concentrations were related both to the size of the fire and the amount of air supplied to the compartment by the system (atomizing fluid flow rate). It appears that if nitrogen would have been used as the secondary/atomizing fluid, the performance of the nozzles could have been improved.

8.3.4 Spraying System's Pressure Washer Nozzles (SS-T12W)

A single-fluid high-pressure nozzle system was produced using Spraying Systems T12W nozzles. The system was evaluated using a nozzle operating pressure of 70 bar (1000 psi). At this pressure, an individual nozzle flowed approximately 3.5 Lpm (0.9 gpm) producing a total system flow rate of 126 Lpm (32.4 gpm). This flow rate corresponds to an application rate of 1.5 Lpm/m^2 (0.036 gpm/ft^2), the lowest application rate evaluated during this test series. This application rate is approximately one-third that of the pervious two systems (low pressure, single fluid).

The system produced using the Spraying Systems T12W nozzles performed extremely well against most of the fire scenarios evaluated in this test series except the small obstructed heptane spray fire (1.0 MW) located on the side of the mock-up (NRL-4). At many times during this test, the fire was completely extinguished but was then reignited by the hot metal surfaces on the side of the mock-up. A lack of cooling associated with the extreme low flow rates of water mist may have been a predominant variable. The system also had difficulty extinguishing (required a longer period of time to extinguish) the fires located on top of the mock-up between four nozzles. This was due to holes in the spray patterns between the nozzles as observed with the previous two systems. Using a lower pressure (say 35 bar (500 psi)) would widen the spray pattern, but also reduce the flow rate of the system. Although this system extinguished more fires than the two low pressure nozzles, the extinguishment times produced with this system were up to two minutes longer than the other systems evaluated during this test series.

8.3.5 Spraying System's Modified Cluster Nozzle (SS-MOD.7N)

A second single-fluid high-pressure system developed during the Navy test program (3) was produced using a modified Spraying Systems nozzle (Model 7N). This system was also evaluated using a nozzle pressure of 70 bar (1000 psi). At this pressure, an individual nozzle flowed approximately 6.2 Lpm (1.6 gpm) producing a total system flow rate of 223 Lpm (58 gpm). This flow rate corresponds to an application rate of 2.7 Lpm/m^2 (0.064 gpm/ft^2) which is twice that of the previous system (T12W) but approximately half that of the single-fluid low-pressure nozzles.

The system produced using the modified Spraying System nozzles performed extremely well during this test series. The system was capable of extinguishing all of the test fires within the prescribed amount of time (15 minutes). The superior performance exhibited by this system was attributed to the nozzle's ability to produce large quantities of small droplets with high momentum. These smaller droplets with high momentum mix well throughout the compartment increasing the system's capabilities against partially obstructed fires. As identified during the evaluation of the low-pressure systems, the extinguishment of the obstructed fires appears to be related to the oxygen concentration at the base of the fire. During the tests conducted with both generic high-pressure systems, the obstructed fires were extinguished when the oxygen concentration at the base of the fire dropped to approximately 18 percent. This suggests that these two systems produce higher mist concentrations at the base of the fire but are still dependent on oxygen depletion to aid in extinguishment. They are, however, somewhat less dependent on oxygen depletion than the two low-pressure single-fluid systems. The extinguishment times produced by this system were about one-half of the times for the SS-T12W (see IMO-1, IMO-2, IMO-5, IMO-6, and NRL-3) which is what one would have predicted since the application rate is twice that of the SS-T12W.

8.3.6 System Performance Summary

The two high-pressure single-fluid systems exhibited superior extinguishment capabilities throughout this test series as shown in Figure 21. The twin fluid and low-pressure single-fluid nozzles do not produce sufficient quantities of smaller droplets which reduces the capabilities of the nozzles against the obstructed fires. Although the twin fluid and the low pressure single-fluid nozzles had difficult extinguishing many of the obstructed fires, the extinguishment times for many of the unobstructed fires were comparable if not superior to the high-pressure systems. Only the system produced with the modified Spraying Systems nozzles was capable of extinguishing all of the fires evaluated during this test series, thus passing the IMO test protocol for all but the bilge fire scenarios. This nozzle was selected as the basis for developing the U.S. Army water mist performance specification and was incorporated in the scaling/horizontal extrapolation portion of this program (to verify the use of water mist in a larger space (LSV main engine room)).

8.4 Bilge Fire Tests

A series of test was also conducted to evaluate the effectiveness of using water mist to separately protect the machinery space bilge areas. The series consisted of installing six modified Spraying Systems nozzles uniformly spaced (nominal 2.0 m (6.5 ft)) in the bilge area under the IMO mock-up as shown in Fig. 22.

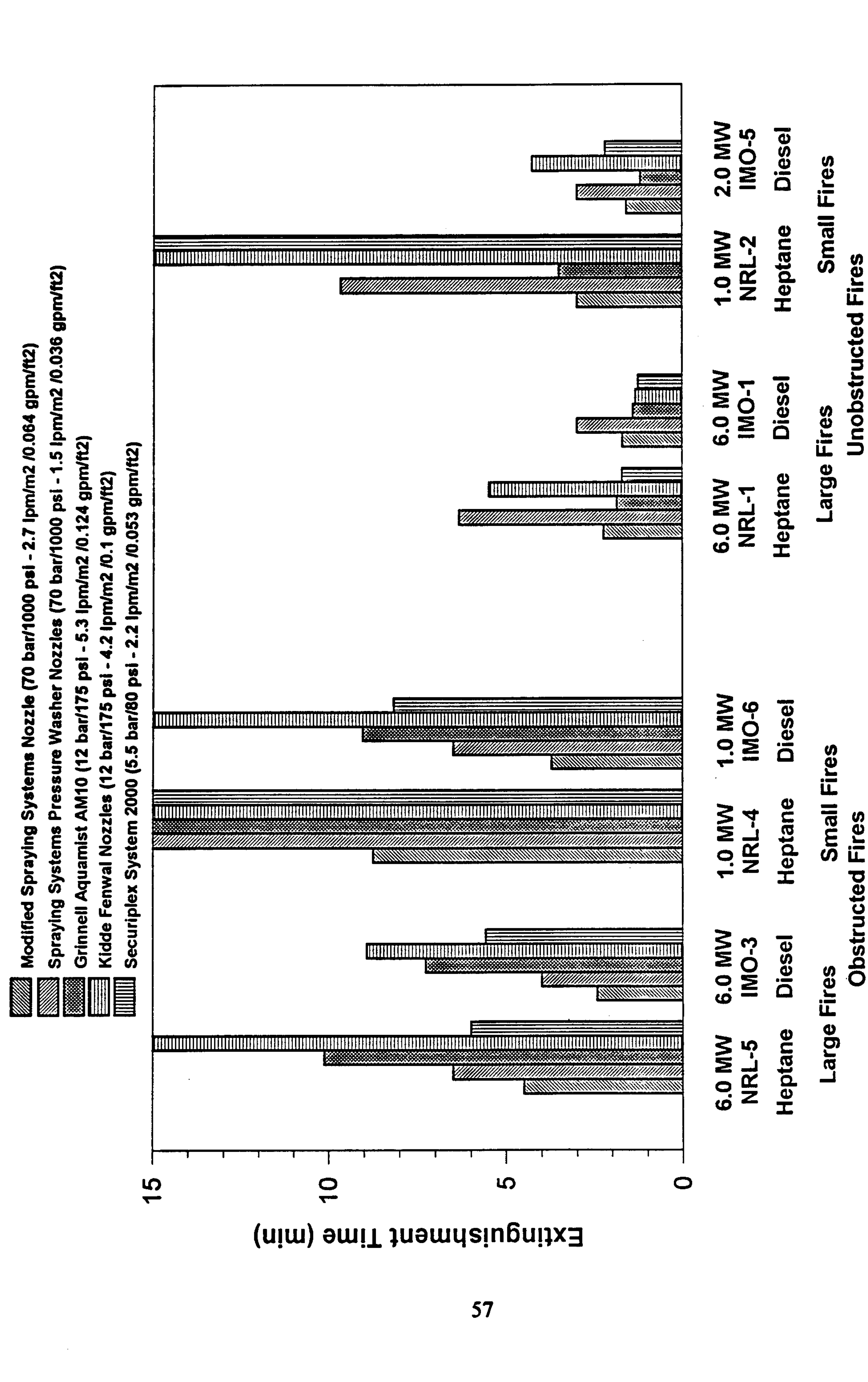


Fig. 21 - System performance comparison

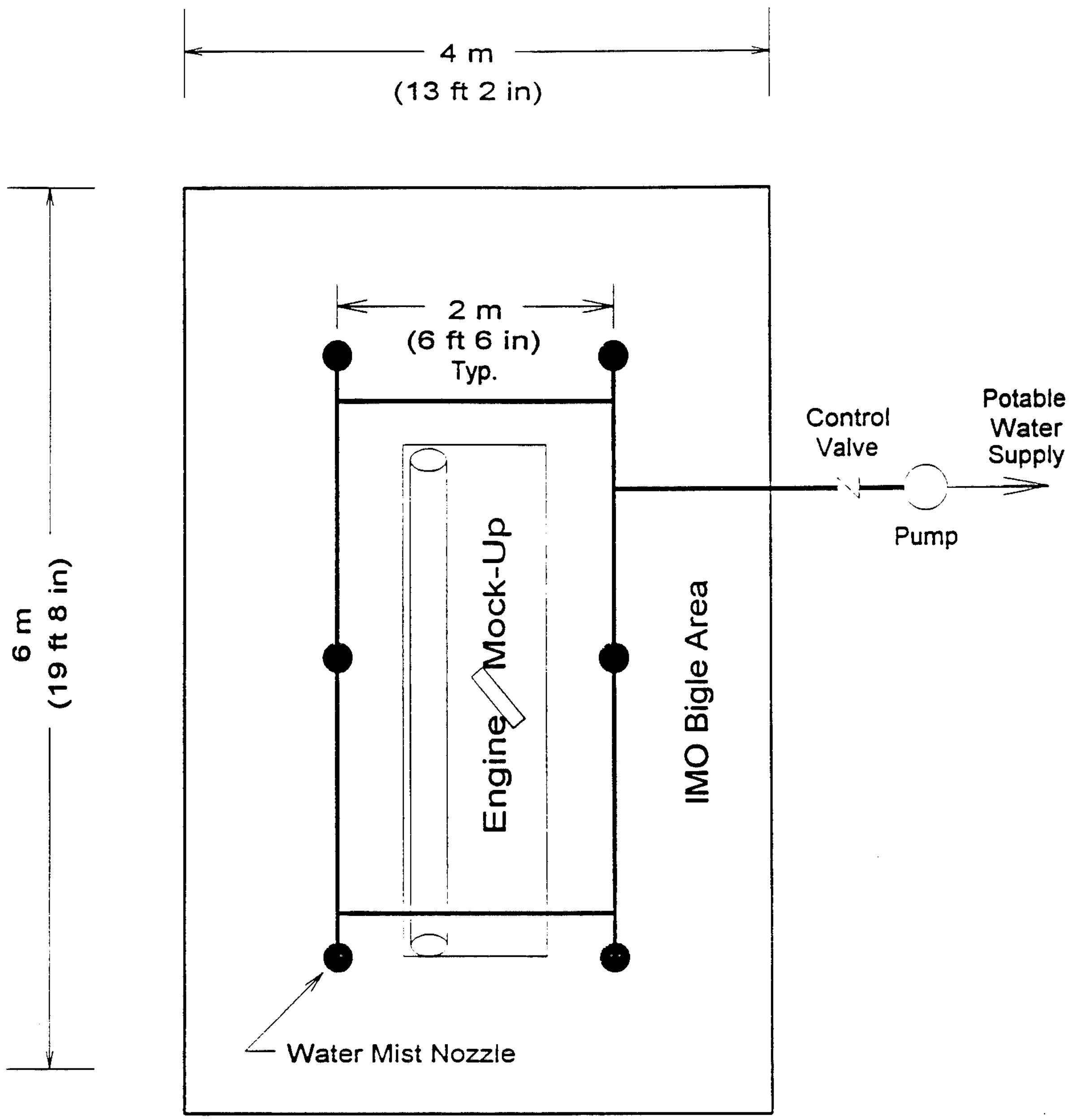


Figure 22. Bilge water mist system configuration

Additional modifications were made to the original nozzles prior to the bilge installation. The first modification consisted of replacing the 1/4LN2 orifices installed around the perimeter of the nozzle with 1/4LN4 orifices. The 1/4LN8 orifice in the center of the nozzle was also replaced with a 1/4LN2 orifice. The net result of these modification was to change the spray pattern characteristics of the nozzle from a narrow pattern, high downward momentum nozzle to a wide pattern, high/medium horizontal momentum nozzle. As configured, the nozzle had a k-factor of 0.98 Lpm/bar^{½} (0.069 gpm/psi^{½}) producing a nominal application rate similar to that of the overhead system (2.0 Lpm/m^2 (0.06 gpm/ft^2)). As with the overhead system, the bilge nozzles were operated at 70 bar (1000 psi).

The tests consisted of evaluating the bilge water mist system against the three bilge fire scenarios required in the IMO Test Protocol (IMO-7, IMO-8, and IMO-13). The results of these tests are listed in Table 8.

Table 8. Bilge Water Mist System Fire Tests

Test Number	Fire Scenario	Test Fuel	Extinguishment Time (min:sec)	Oxygen Concentration
IMO-7	0.5 m^2 central under mock-up	Heptane	5:20	19.2
IMO-8	0.5 m^2 central under mock-up	SAE 10W30 mineral-based lubrication oil (diesel)	3:40	18.8
IMO-13	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil (heptane)	2:40	16.4

As shown in Table 8, the bilge water mist system was capable of extinguishing all three fires in less than six minutes of system activation. During the tests conducted against the small pan fires (IMO-7 and IMO-8), the mist system was capable of extinguishing these fires with only a minimum reduction in oxygen concentration (19 percent). When the larger fire (IMO-13) was extinguished, the oxygen concentration in the bilge was less than 17 percent. This major reduction in oxygen was driven primarily by the size of the fire with respect to the bilge volume (large fire, small volume).

In summary, an unobstructed bilge fire does not appear to be a challenge to the "state-of-the-art" water mist technologies. However, some of the technologies may need to modify their spray pattern characteristics to better fit the space. The geometry of the space is such that the fire will always be located in close proximity to a mist nozzle, and due to the size of the space (small volume), a fire of any size will always significantly reduce the oxygen concentration in the space. The problem lies in identifying the limits of these systems with respect to bilge depth and clutter/obstructions. A detailed discussion of these parameters is beyond the scope of this report. However, a better solution to the bilge fire problem would be to install an Aqueous Film Forming Foam (AFFF) System in the bilge. Tests conducted by the U.S. Navy have shown that an AFFF bilge sprinkling system provides excellent protection for these spaces.

8.5 Cable Tray Fire Tests

Two additional tests were conducted to evaluate the ability of water mist to extinguish cable tray fires. The tests consisted of evaluating the modified Spraying Systems nozzles against a cable tray located directly above the IMO mock-up as shown in Fig. 23. It should be noted that the horizontal run of the cable tray was located above the level of the water mist nozzles. The cables were ignited using a 1.0 MW heptane spray fire located on top of the mock-up (NRL-2). The first test consisted of impinging the 1.0 MW spray fire on the cable tray for a period of two minutes before the fuel spray was shut down and the mist system activated. During this test, the cable tray fire was extinguished immediately and did not reignite. It should be noted that the cables were not energized and that an energized cable could have resulted in a reignition. If the cable would have reignited, it is believe that the mist system would have again extinguished this fire.

The second test was conducted using the fire configuration described above except the fuel spray (heptane) remained activated for the duration of the test. During this test, the fire was extinguished in approximately one minute but kept reigniting due to the heated cables located above the spray. Apparently, the mist concentration in the area around the cable tray was adequate to extinguish both the cable tray and fuel spray fires but not adequate to cool the cables below the ignition temperature of heptane. Again, the scenario was exaggerated by the fact the cables and a majority of the fuel spray were located above the mist nozzles. It is believed that the reignition/extinguishment process could have continued indefinitely or until the oxygen concentration high in the space dropped to a level where the spray would not ignite.

8.6 Extrapolation of the IMO Test Protocol to Larger Compartment

The final phase of this test series was conducted to determine if the results from the less than 500 m^3 tests could be extrapolated to larger spaces with similar ceiling heights. The primary objective was to determine if water mist systems could adequately protect the main machinery space on the LSV which, as shown in Table 2, has a total volume of 1256 m^3. This objective was achieved by reevaluating the modified Spraying System's nozzle (the only system to pass the IMO test protocol (minus the bilge fires)) in a 9.1 m x 12.2 m x 4.6 m (30 ft x 40 ft x 15 ft) space and a 9.1 m x 18.2 m x 4.6 m (30 ft x 60 ft x 15 ft) space against the 13 IMO test fires (Fig. 12). These compartment sizes range from approximately one-quarter to approximately one-half the size of the machinery space on the LSV. It also needs to be noted that the additional area/volume of the space was protected using only two rows of nozzles or approximately 33 percent of the design mist application rate. Initially, the tests were conducted using heptane under the assumption that heptane is more difficult to extinguish than the higher flash point diesel fuel or light crude oil. If the heptane fires were not extinguished, the test was repeated using diesel fuel. The bilge water mist system described previously was also activated during these tests.

The results of these tests are listed in Table 9. In general, the extinguishment times recorded during these tests identified only random variations in the performance of the Modified Spray System nozzle evaluated over the range of the compartment sizes. The only significant variation occurred during 1.0 MW heptane spray fire tests located on the side of the mock-up

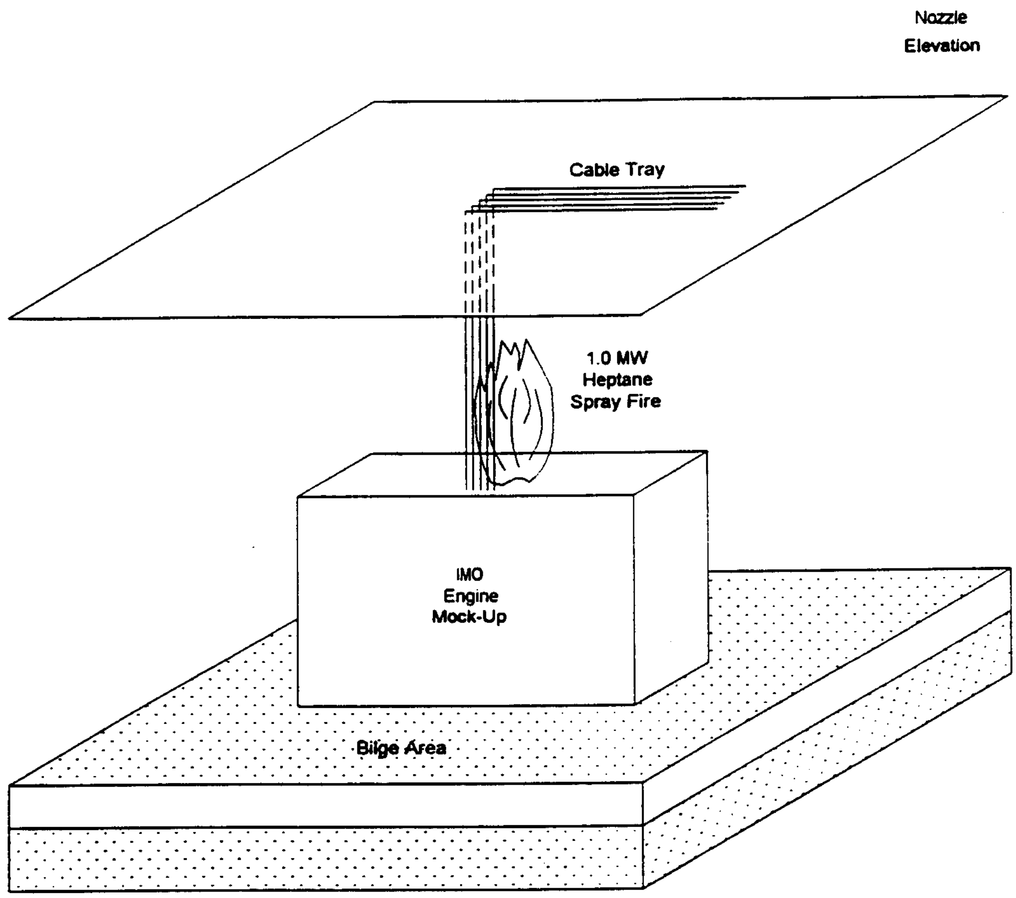


Figure 23. Cable tray fire scenario

Table 9. Army Water Mist Machinery Space Tests
(Compartment Size Comparison)
Oxygen Concentration at Extinguishment

Test No.	Fire Scenario	Test Fuel	Oxygen Concentration (%)		
			900 ft^2	1200 ft^2	1800 ft^2
			Extinguishment Times (min:sec)		
IMO-1	Low-pressure spray on top of simulated engine between agent nozzles (6.0 MW)	Commercial fuel oil or light diesel oil	16.8 (2:15 (H))	17.6 (2:30 (H))	17.4 4:45 (H)
IMO-2	Low-pressure spray on top of simulated engine with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1 m away (6.0 MW)	Commercial fuel oil or light diesel oil	17.4 (4:00 (H))	17.8 (2:45 (H))	17.9 (5:45 (H))
IMO-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 the engine (6.0 MW)	Commercial fuel oil or light diesel oil	17.8 (4:30 (H))	18.2 (6:00 (H))	18.4 (5:00 (H))
IMO-4	Combination of worst spray fire from Tests 1-3 and fires in trays (4 m^2) under and on top of the simulated engine (3 m^2)	Commercial fuel oil or light diesel oil	17.6 (3:00 (H)(B))	18.2 (4:50 (H)(B))	17.8 (5:00(H)(B))
IMO-5	High-pressure horizontal spray fire on top of the simulated engine (2.0 MW)	Commercial fuel oil or light diesel oil	18.2 (3:10 (H))	18.5 (2:20 (H))	18.0 (5:15 (H))
IMO-6	Low-pressure low flow concealed horizontal spray fire on the side of the simulated engine (1.0 MW)	Commercial fuel oil or light diesel oil	17.8 (8:45 (H))	17.5 (NO/9:15(H))	18.8 (NO/NO (H) 3:30/ 3:35 (D))
IMO-7	0.5 m^2 central under mock-up	Heptane	19.2 (5:20 (B))	18.8 (4:30 (B))	18.8 (5:00 (B))
IMO-8	0.5 m^2 central under mock-up	SAE 10W30 mineral-based lubrication oil	18.8 (3:40(D)(B))	19.0 (3:55(D)(B))	18.9 (3:30(D)(B))
IMO-9	0.1 m^2 on top of bilge plate centered under exhaust plate	Heptane	21.0 (4:15 (H))	21.0 (6:00 (H))	21.0 (4:20 (H))
IMO-10	Flowing fire 0.25 kg/s from the top of mock-up	Heptane	– (NO/9:20(H) 6:40(H)(B))	– (NO (H) 8:00 (H) (B))	– (NO (H) 7:30(H)(B))
IMO-11	Class A fires UL 1626 wood crib in 2 m^2 pool fire with 30-second preburn	Heptane	17.7 (9:20 (H))	18.2 (8:45 (H))	17.3 (10:00 (H))
IMO-12	A steel plate (30 cm x 60 cm x 5 cm) offset 20° to the spray is heated to 350°C by the top low-pressure low flow spray. When the plate reaches 350°C, the system is activated. Following system shutoff, no reignition of the spray is permitted.	Heptane	19.6 (2:50 (H))	18.2 (1:40 (H))	19.0 (2:00 (H))
IMO-13	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil	16.4 (2:40 (H)(B))	17.2 (2:30 (H)(B))	16.8 (1:55(H)(B))

Notes: H = heptane B = required the use of the bilge water mist system in addition to the overhead water mist system
D = diesel

(NRL-4). The mist system was capable of extinguishing this fire in both the 82.2 m^2 (900 ft^2) and the 120 m^2 (1200 ft^2) compartments but was unable to extinguish the fire in the 166 m^2 (1800 ft^2) space. The extinguishment times recorded during these tests suggest that this particular fire is borderline and that slight variations in compartment size/geometry and/or mist concentration may affect the results. The IMO version of this fire (diesel fuel, IMO-6) showed little, if any, variation in results over the range of compartment sizes. Additionally, as with the previously mentioned fire, the remaining IMO fires exhibited only slight random variations in extinguishment times which is believed to lie well within the scatter of data.

The oxygen depletion dependency for extinguishment of the obstructed fires was also observed for the larger spaces. The mist system usually extinguished these obstructed fires when the oxygen concentration at the base of the fire dropped below 18 percent as shown in Table 9. Interestingly, there does not appear to be a direct relation between the fire size to compartment volume ratio and the time required to deplete the oxygen to 18 percent. Variables which could impact this relation include ambient conditions (wind speed and direction), how well the mist alters the air flow through the vent opening, and how well the mist knocks down the fire (reduces the size of the fire) during the initial stages of the test.

Considering the randomness of the results, the high leakage rates in the extended portions of the compartment and the substantially lower mist application rate in these areas, it appears that the results from the less than 500 m^3 IMO test protocol can be extrapolated horizontally as long as the height of the space remains constant. Based on the need to deplete the oxygen in order to extinguish obstructed fires, limits must exist to this horizontal extrapolation and need to be identified. However, these results indicate that performance can be extrapolated to spaces on the order 2-4 times larger than the test compartment and that the LSV machinery space can be protected using the modified Spraying Systems nozzles.

9.0 SUMMARY AND CONCLUSIONS

These tests have demonstrated the effectiveness of using water mist technologies as a halon alternative in Army watercraft machinery space applications. The data also indicate the ability to extrapolate, within limits, the results of the IMO test protocol to larger spaces with similar ceiling heights.

The fire extinguishment capabilities of water mist systems observed during this test series follow many of the general trends found throughout the literature. These trends include the following:

1. Water mist systems require minutes to extinguish fires as opposed to fractions of minutes for the gaseous halon alternatives. (These times can potentially be reduced by designing the system around the space being protected and by securing the ventilation (forced and natural) to the space prior to system activation.);

2. Immediately after activation, water mist systems dramatically reduce the temperatures in the space, which will aid in manual intervention and minimize thermal damage;

3. The bilge of the space cannot be adequately protected using water mist nozzles installed only in the overhead of the space; however, the bilge can be protected using water mist if the nozzles are installed in the bilge. Further work in this area is needed;

4. Larger fires are easier to extinguish (with extinguishment occurring much faster) than smaller fires. (This is related to the consumption of oxygen by the fire, steam generation, and turbulence created by the fire.);

5. Lower flash point fuels represent a greater challenge to the current water mist technologies than higher flash point fuels. (This is attributed to the lack of fuel surface cooling effects and the reflash (reignition) potential of the lower flashpoint fuels.);

6. Obstructed fires are more difficult to extinguish than unobstructed fires. (This is attributed to the amount of mist actually reaching the fire (obstructed fires are usually located in areas of lower mist concentration).);

7. A single, small, obstructed fire may always be too challenging for the spectrum of available water mist technologies (smaller fires in the presence of larger fires do not pose the same threat); and

8. The high-pressure single-fluid systems exhibited superior fire extinguishing capabilities when compared to the twin fluid and low-pressure single-fluid systems (primarily due to superior capabilities against obstructed Class B fires). (This was attributed to these systems' ability to produce small droplets with high momentum.)

With respect to Army watercraft applications, the modified Spraying Systems' nozzle demonstrated superior fire extinguishment performance throughout this test series and was recommended for this application based on the current IMO test protocol. This was the only nozzle capable of passing all of the IMO tests per the letter-of-the-law with the exception of the bilge fires space. However, the ability to extinguish these fires with a bilge water mist system was also demonstrated. The U.S. Army water mist performance specification was developed [10] based on the performance exhibited by this nozzle and is currently being reviewed for approval by the U.S. Coast Guard.

10.0 PROPOSED MODIFICATIONS TO THE IMO TEST PROTOCOL

The IMO test protocol needs to be revised to address the inadequacies of the standard with respect to bilge areas, obstructions/shielding, water mist nozzle spray pattern obstructions, and the evaluation and acceptance of water mist systems for larger areas.

During these tests, it was determined that a water mist system installed in the overhead of the space could not adequately protect the bilge area. It was also demonstrated that water nozzles installed in the bilge were capable of extinguishing the three IMO bilge fires. The IMO test protocol needs to be revised to allow for separate protection of the bilge area independent of the main machinery space. Irregardless of the type of system (i.e., AFFF, CO_2 or water mist), the test protocol needs to be revised to evaluate the protection provided by the proposed bilge fire protection system.

The limits of each system with respect to fire obstructions and shielding also need to be identified. The protocol needs to be revised to evaluate the maximum horizontal obstruction under which the system is capable of extinguishing a fire of a given size (say, 1.0 MW). This data would be used to identify areas in the space requiring additional nozzles other than in the overhead of the space.

The protocol needs to be revised to evaluate the minimum water mist spray pattern obstruction (measured in percentage of spray pattern) required to significantly reduce the fire fighting capabilities of the system. This data would be used to identify areas in the space requiring additional nozzles due to clutter of as well as areas where nozzles need to be repositioned.

The ability to extrapolate the results of the less than 500 m^3 tests to larger volumes was also demonstrated during these tests. However, based on the need to deplete the oxygen in order to extinguish obstructed fires, limits to this extrapolation must exist and need to be identified. The oxygen depletion required to extinguish the obstructed fires also suggests that it is unlikely that any of the current technologies can meet the greater than 500 m^3 test protocol as it is currently written. In order to properly evaluate water mist systems for larger spaces, the system must be evaluated in a space of roughly the same size (volume). This will undoubtedly be costly, but until there is a better understanding of mist dispersion, flame interaction and the parameters associated with extrapolation/scaling-up to larger spaces, there appears to be no other alternative.

11.0 REFERENCES

1. International Maritime Organization, "Alternative Arrangements for Halon Fire-extinguishing Systems in Machinery Spaces and Pump-rooms," IMO FP39 MSC Circular 668, London, December 1994.

2. Leonard, J.T., Back, G.G., and DiNenno, P.J., "Full Scale Machinery Space Water Mist Tests: Phase I - Unobstructed Space," NRL Ltr Rpt Ser 6180/0713.1, October 5, 1994.

3. Leonard, J.T., Back, G.G., and DiNenno, P.J., "Full Scale Machinery Space Water Mist Tests: Phase II - Simulated Machinery Space," NRL Ltr Rpt Ser 6180/0868.2, 23 December 1994.

4. Back, G.G., DiNenno, P.J., Hill, S.A., and Leonard, J.T., "Evaluation of Water Mist Fire Suppression Systems for Flammable Liquid Storeroom Applications," NRL Report, in publication.

5. Leonard, J.T., "Engineering, Design, and Testing of Water Mist Fire Suppression Systems for the U.S. Army Watercraft: Full-scale Testing of Water Mist Suppression Systems for U.S. Army Watercraft: Task 3B - Prototype Design and Test Criteria for Machinery Space Systems," NRL Ltr. Rpt. Ser 6180/0806.1, November 17, 1994.

6. NFPA 750, "Standard for the Installation of Water Mist Fire Suppression Systems," National Fire Protection Association, Quincy, MA, Draft 05/05/95.

7. Sheinson, R.S., Williams, F.W., and Maranghides, A., and Peatross, M.J., "Real Scale Machinery Space Halon Replacement Agent Testing," NRL Ltr Rpt Ser 6180/0835.2, December 9, 1994.

8. Mawhinney, J.R., "Fine Water Spray Fire Suppression Project," *Proceedings of the First International Conference on Fire Suppression Research*, Stockholm and Borås, Sweden, May 5-8, 1992.

9. Beyler, C., "Flammability Limits of Premixed and Diffusion Flames," Section 1/Chapter 7, *The SFPE Handbook of Fire Protection Engineering*, National Fire Protection Association, Quincy, MA, 1988.

10. Leonard, J.T., "Draft Specifications for a Water Mist Fire Suppression System for Use in United States Army Vessels," NRL Ltr. Rpt. Ser 6180/0105.2, February 21, 1995.

Appendix A

Fire Hazard Analysis of Machinery Spaces on Army Watercraft

Appendix A

Fire Hazard Analysis of Machinery Spaces on Army Watercraft

INTRODUCTION

The Naval Research Laboratory is exploring the feasibility of employing water mist fire suppression systems for machinery and flammable liquid storage rooms on Army Watercraft under Department of Transportation Reimbursable Agreement DTRS-57-94-X-0066. Task 2 of the Project Work Plan for that contract includes an analysis of Army watercraft fire hazards, ignition scenarios, and physical attributes of the hazard areas. This report describes the analysis of the machinery spaces: flammable liquid storage rooms are the subject of a separate report.

FIELD INVESTIGATIONS

In order to establish the fire hazards, compartment configurations, and potential testing requirements, an on-site field investigation was conducted at Fort Eustis, Virginia, on June 6-7, 1994. A vessel representing each of the four major ship classes (LCU 2000 series, LCU 1600 series, LSV, and ROWPU Barge) containing Halon 1301 fire suppression systems was investigated. Each area that contained a Halon 1301 fire suppression system was documented for the following:

- overall interior dimensions;
- openings;
- special conditions;
- wall coverings;
- locations, dimensions, and construction of obstructions;
- locations and magnitude of potential hazards;
- existing fire suppression system scheme;
- storage area of Halon 1301 cylinders; and
- initial evaluation of potential cylinder and/or pump storage for the water mist systems.

The vessels visited were as follows:

- The LCU 2003 - "MACON",
- The LCU 1675,
- The LSV - "General George S. Besson Jr.," and
- The ROWPU Barge.

The results of the field investigation are summarized in Tables A1-A9 and the accompanying figures (Fig. A1-A9), The major fuel sources and scenarios encountered were as follows:

a) Marine diesel fuel, pool, spray and combination pool/spray;

b) Engine oil, pool, spray, and combination pool/spray;

c) Hydraulic oil, pool, spray, and combination pool/spray;

d) Variable flashpoint flammable liquids;

e) Electrical and miscellaneous cabling; and

f) General combustibles, such as cardboard boxes, oil soaked rags, wood pallets, etc.

The compartment sizes and total fuel loading varied widely from vessel to vessel. However, no compartment investigated exceeded a total height requirement of 4.5 m (15 ft).

Table A1

SURVEY SUMMARY CHART

Vessel: LCU 2003

Compartment: Main Engine Room - See Figure A1.

Room dimensions:

Length: 42'-0"
Width: 32'-0"
Main compartment height: 9'-7"
Bilge depth: 3'-0"
Overall height: 12'-7"

Potential hazards:

1. Diesel fuel (marine) - spray on hot engine surfaces; pool formation under engine (or generator) and in bilge; cascade along engine surface.
2. Engine oil - spray from the oil pumping unit or on hot engine surfaces; pool formation under engine, in bilge, from the oil separation unit, and from the oil pumping unit; cascade along engine surface.
3. Cables and electrical panels
4. Hydraulic oil - spray from feed and return lines; pool formation on main floor or in bilge.

Openings:

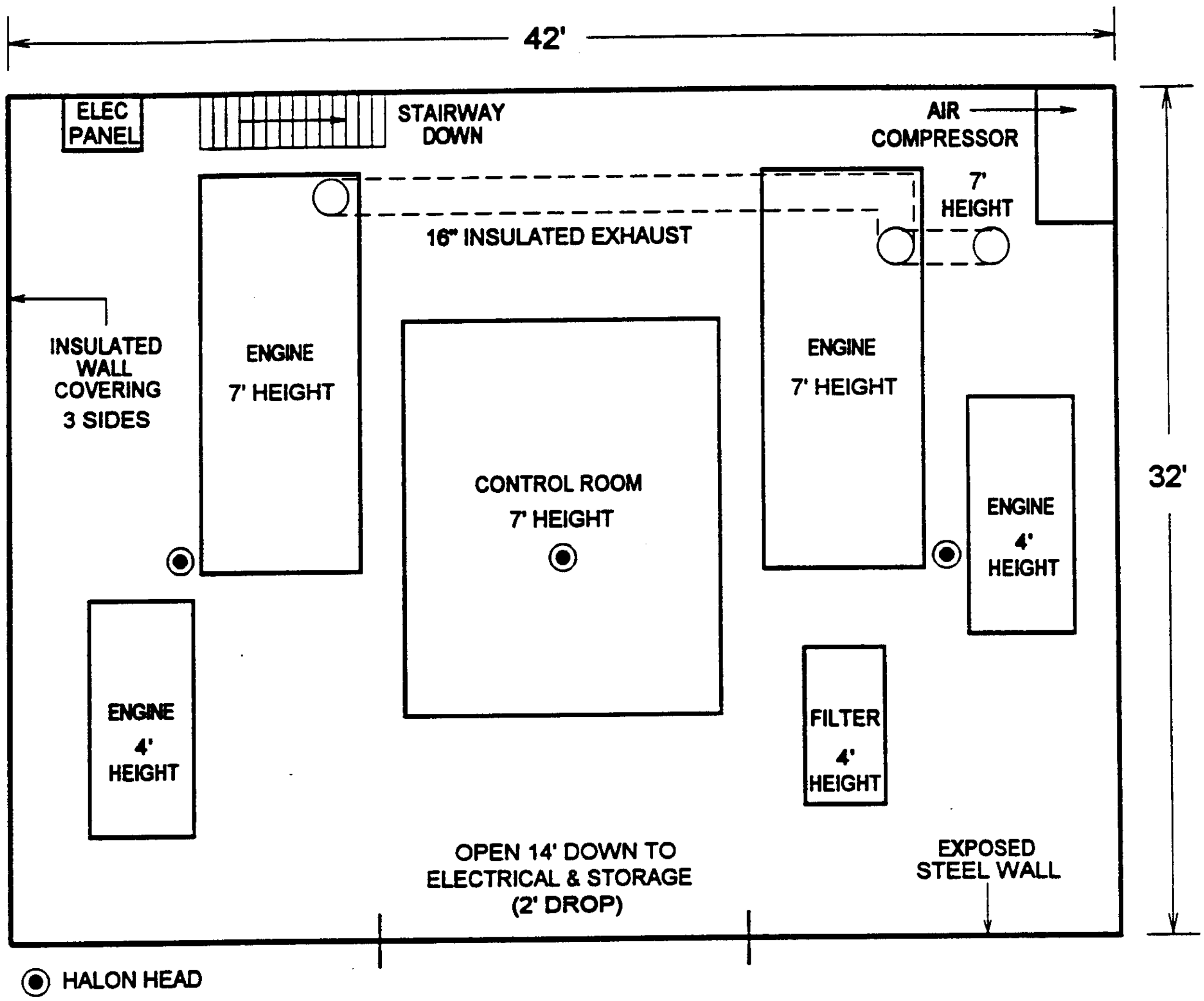
1. A 26" x 78" door at the top of the stairs.
2. A 14'-0" x 6'-2" opening to the electrical and storage areas.

Wall coverings:

1. Faced insulated wall covering.

Observations:

1. The engine room is protected by 680 lbs. (2 @ 340 lbs.) of Halon 1301. The cylinders are located one deck above in the emergency generator room. The space in which they are stored has very little tolerance for more storage.
2. Three heads protect the room, one in the center of the control room, and one each centered on the far side of each main engine.



LCU - 2003 - MAIN ENGINE ROOM
MAIN ROOM HEIGHT = 9'-7"
BILGE DEPTH = 3'
TOTAL: 12'-7"

Figure A1

Table A2

SURVEY SUMMARY CHART

Vessel: LCU 2003

Compartment: Main Engine Room Storage and Control Panel Area - See Figure A2.

Room dimensions:

Length: Overall 42'-0"
Width: 20'-0"
Main compartment height: 8'-2"
Bilge depth: N/A
Overall height: 8'-2"

Potential hazards:

1. Cables and electrical panels.
2. Combustibles - oily rags stacked in piles and in a plastic and steel trash barrels; dirty oil filters in the steel trash barrel; boxed new oil filters sitting on the deck; multiple cardboard boxes stacked on all of the storage shelves.
3. Oxygen/acetylene tanks for cutting torches.

Openings:

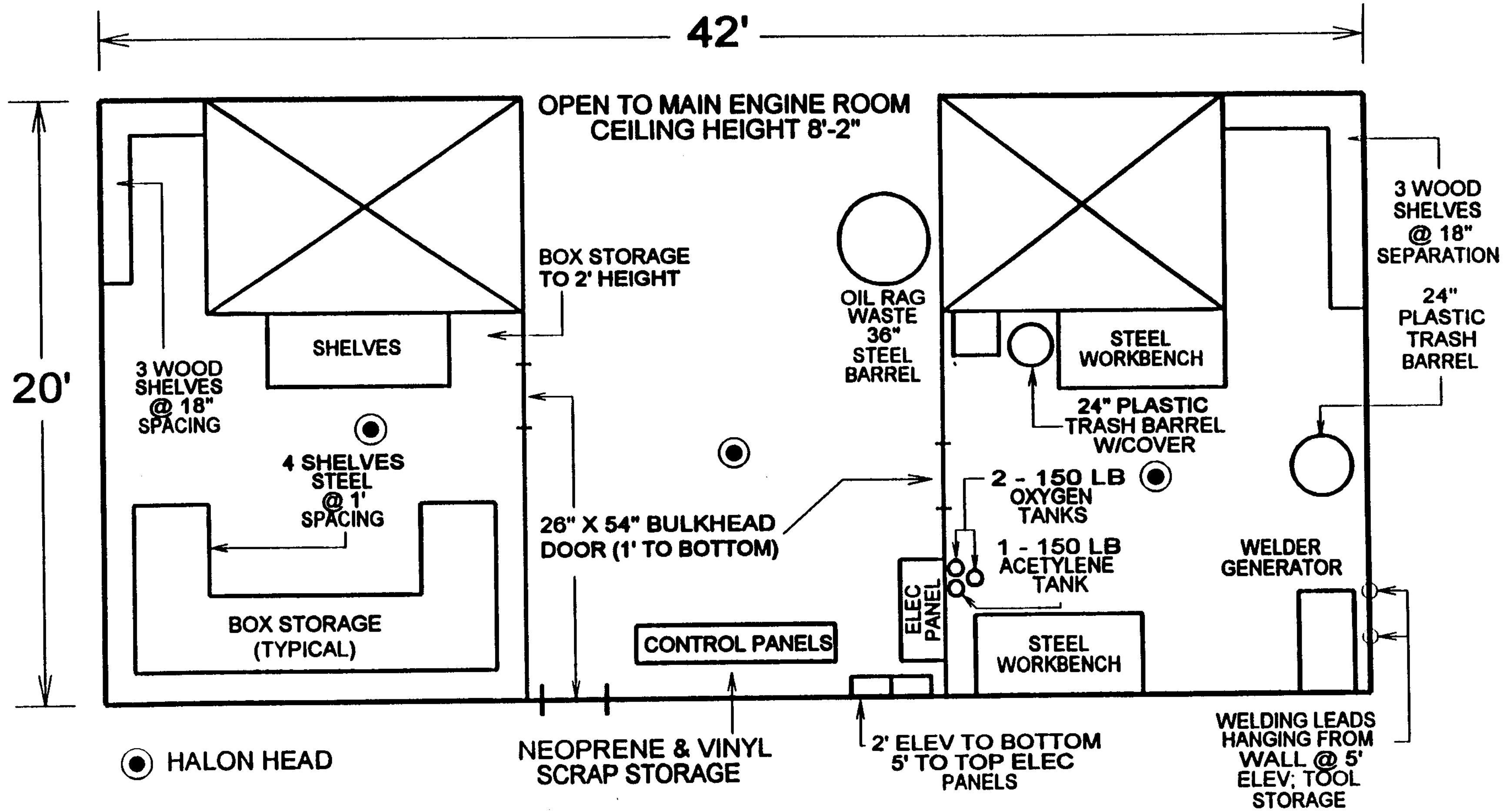
1. One 26" x 54" door leading into the storage room, the work room, and one out of the rear of the control panel area.

Wall coverings:

1. Faced insulated wall covering.

Observations:

1. This area is protected by 375 lbs. (5 @ 75 lbs.) of Halon 1301. Three heads protect this area, one in the center of each room.
2. The halon cylinders were located in the same area as the engine room cylinders.
3. The storage room contained a heavy fuel loading of boxes on all of the shelves.
4. All cables run out of the control and electrical panels ran up the walls and across the ceiling to a main cable tray into the main engine room. The tray was tight to the deck.



LCU 2003 - MAIN ENGINE ROOM AND CONTROL PANEL AREA

Figure A2

Table A3

SURVEY SUMMARY CHART

Vessel: LCU 1675

Compartment: Main Engine Room #1 - See Figure A3.

Room dimensions:

Length: 28'-0
Width: 12'-2"
Main compartment height: 7'-0"
Bilge depth: 1'-2"
Overall height: 8'-2"

Potential hazards:

1. Diesel fuel (marine) - spray on hot engine surfaces; pool formation under engine and in bilge; cascade along engine surface.
2. Engine oil - spray on hot engine surfaces; pool formation under engine and in bilge; cascade along engine surface.
3. Cables and electrical panels.
4. Hydraulic oil - spray from feed and return lines; pool formation on main floor or in bilge.
5. Other combustibles - oily rags stacked in piles; dirty oil filters on deck; paper storage; book cases with Tech Manuals; wood tool storage locker.

Openings:

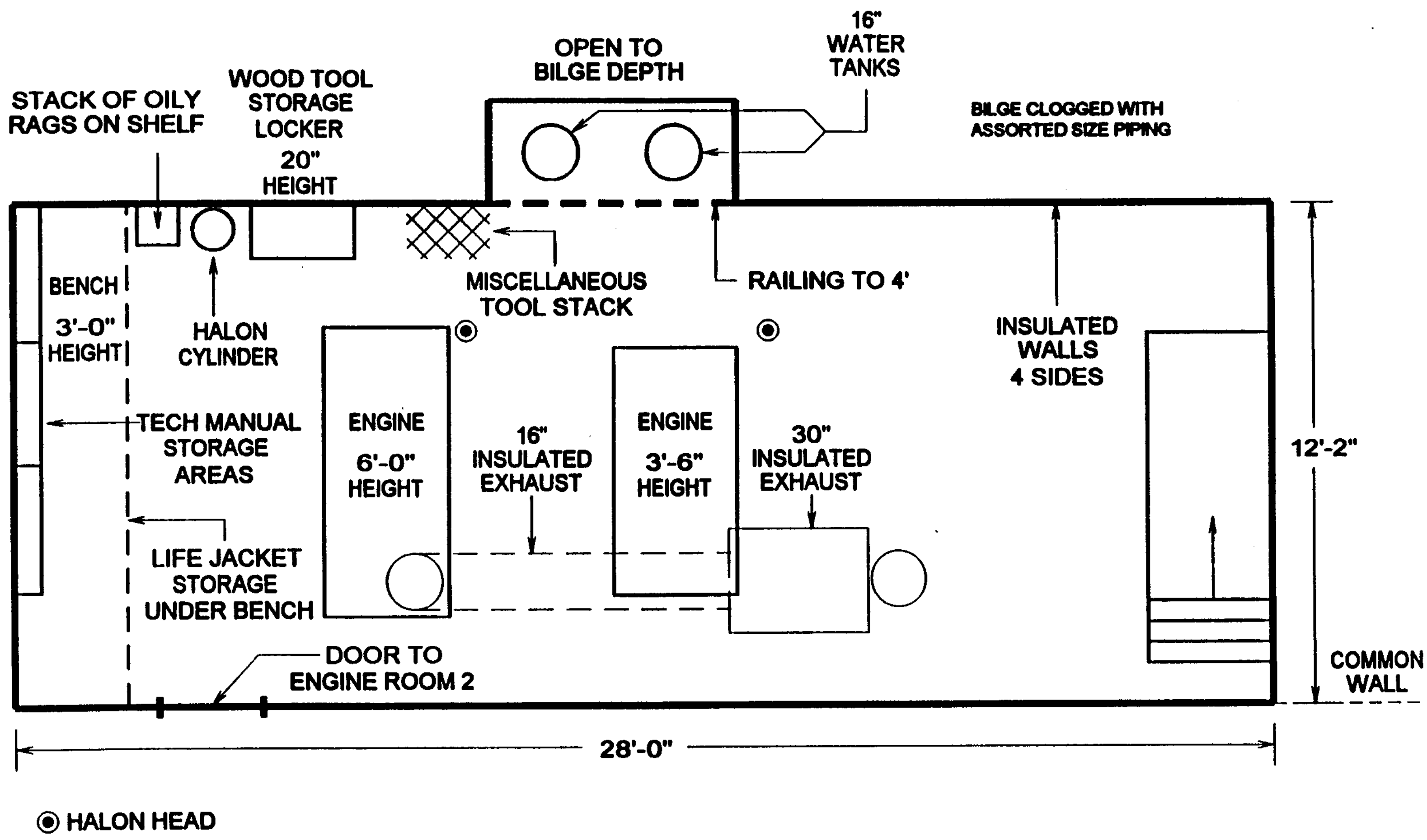
1. A 26" x 54" door to adjacent engine room.
2. Opening at the head of the stairway.

Wall coverings:

1. Faced insulated wall covering.

Observations:

1. The room is protected by 125 lbs. of Halon 1301. The cylinder is located next to the work bench within the room.
2. Two heads protect the room, one foot diagonally off each engine corner closest to the water tanks, on the stairway side of the engine.
3. The bilge was approximately 75% filled with assorted sized piping.



LCU 1675 ENGINE ROOM #1
MAIN ROOM HEIGHT = 7'-0"
BILGE DEPTH = 1'-2"
TOTAL HEIGHT = 8'-2"

Figure A3

Table A4

SURVEY SUMMARY CHART

Vessel: LCU 1675

Compartment: Main Engine Room #2 - See Figure A4.

Room dimensions:

Length: 28'-0"
Width: 12'-2"
Main compartment height: 7'-0"
Bilge depth: 1'-2"
Overall height: 8'-2"

Potential hazards:

1. Diesel fuel (marine) - spray on hot engine surfaces; pool formation under engine and in bilge; cascade along engine surface.
2. Engine oil - spray from the oil separator units or on hot engine surfaces; pool formation under engine, in bilge, from the oil separation unit, and from the dirty oil storage unit; cascade along engine surface.
3. Cables and electrical panels
4. Hydraulic oil - spray from feed and return lines; pool formation on main floor or in bilge.
5. Other combustibles - oily rags stacked in piles; dirty oil filters on the deck.

Openings:

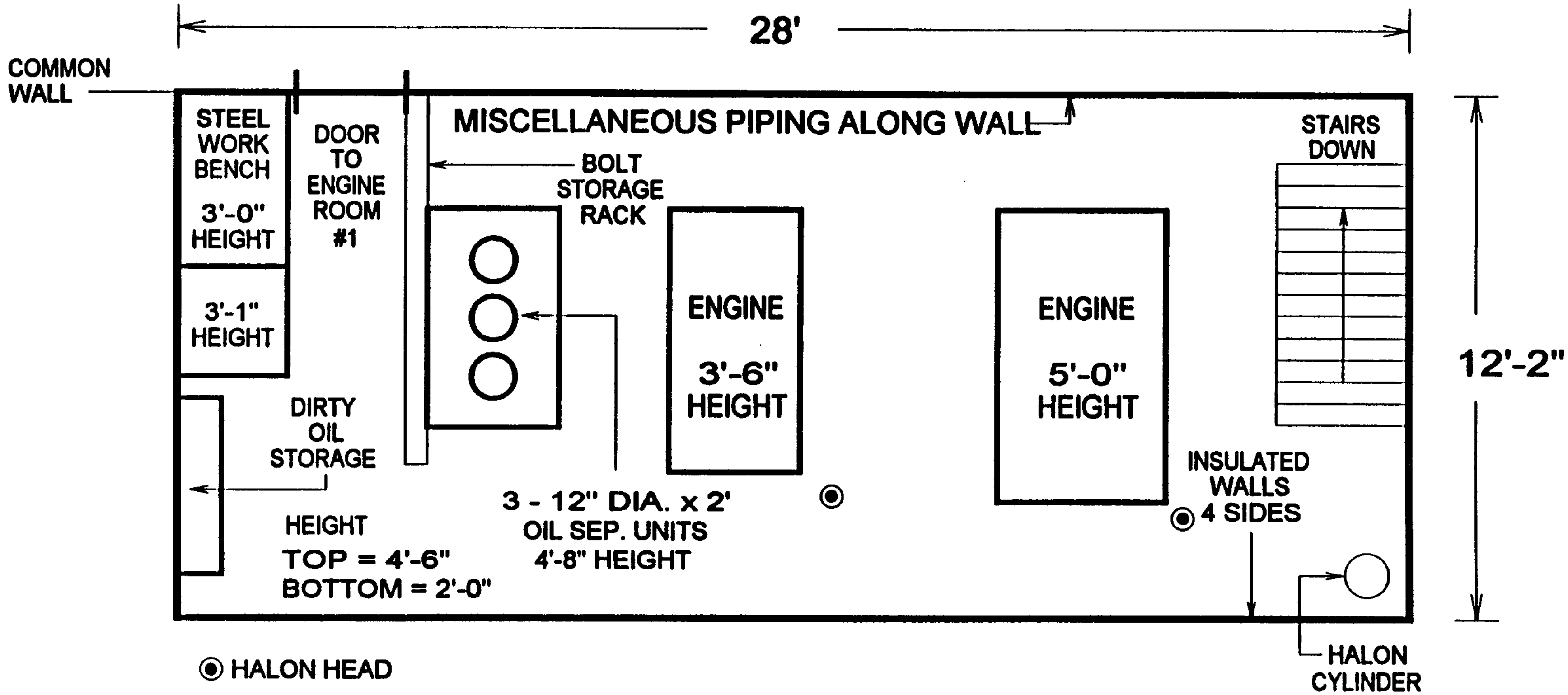
1. A 26" x 54" door to adjacent engine room.
2. Opening at the head of the stairway.

Wall coverings:

1. Faced insulated wall covering.

Observations:

1. The room is protected by 125 lbs. of Halon 1301. The cylinder is located in the corner under the stairs.
2. Two heads protect the room, one foot diagonally off each engine corner closest to the non-common wall, on the stairway side of the engine.
3. The bilge was approximately 75% filled with assorted sized piping.



LCU 1675 MAIN ENGINE ROOM 2
MAIN ROOM HEIGHT = 7'-0"
BILGE DEPTH = 1'-2"
TOTAL: 8'-2"

Figure A4

Table A5

SURVEY SUMMARY CHART

Vessel: LSV

Compartment: Main Engine Room - See Figure A5.

Room dimensions:

Length: 60'
Width: 60'
Main compartment height: 10'-5"
Bilge depth: 2'-6"
Overall height: 12'-11"

Potential hazards:

1. Diesel fuel (marine) - spray on hot engine surfaces; pool formation under engine (or generator) and in bilge; cascade along engine surface.
2. Engine oil - spray from the oil pumping unit or on hot engine surfaces; pool formation under engine, in bilge, from the oil separation unit, and from the oil pumping unit; cascade along engine surface.
3. Cables and electrical panels
4. Hydraulic oil - spray from feed and return lines; pool formation on main floor or in bilge.
5. Other combustibles - oily rags stacked in piles and in a plastic trash barrel; dirty oil filters in the plastic trash barrel; boxed new oil filters sitting on the deck; filed paper storage; book case with Tech Manuals.

Openings:

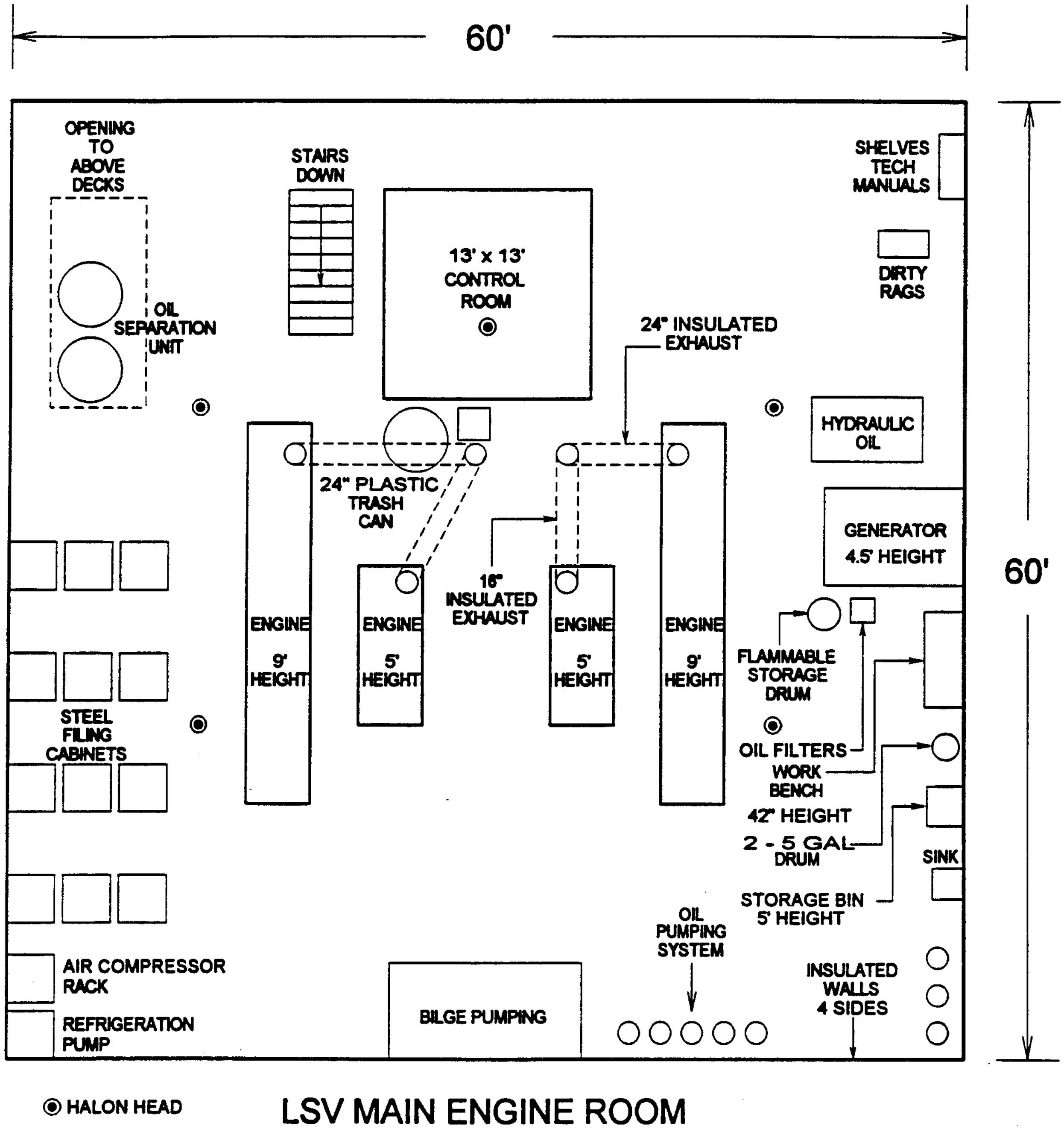
1. Stairway.
2. 6'-0" x 13'-6" open shaft to upper decks above oil separation unit.

Wall coverings:

1. Faced insulated wall covering.

Observations:

1. One set of two halon nozzles are located symmetrically on each sidewall parallel to the engine approximately 3'-0" off of the wall. The first is located 15'-3" from the control room end and the second is 41'-3" from the control room end. A fifth head is located in the center of the control room.
2. The engine room is protected by 3-432 lb. cylinders (total: 1296 lbs.) stored in a bank above the engine room next to the emergency generator room.
3. Cables run to all four engine and to all electrically powered pumping systems. All cables are run straight up an are in cable trays that are tight to the ceiling. The main cable tray run through the center of the two small engines to the control room where the electrical panels are located.



LSV MAIN ENGINE ROOM
MAIN ROOM HEIGHT = 10'-5"
BILGE DEPTH = 2'-6"
TOTAL HEIGHT = 12'-11"

Figure A5

Table A6

SURVEY SUMMARY CHART

Vessel: LSV

Compartment: Emergency Generator Room - See Figure A6.

Room dimensions:

Length: 15'-10"
Width: 12'-8"
Main compartment height: 11'-6"
Bilge depth: N/A
Overall height: 11'-6"

Potential hazards:

1. Diesel fuel (marine) - spray on hot engine surfaces; pool formation under engine and in collection pan; cascade along engine surface.
2. Engine oil - spray on hot engine surfaces; pool formation under engine and in collection pan; cascade along engine surface.
3. Cables and electrical panels.
4. Hydraulic oil - spray from feed and return lines; pool formation on main floor.

Openings:

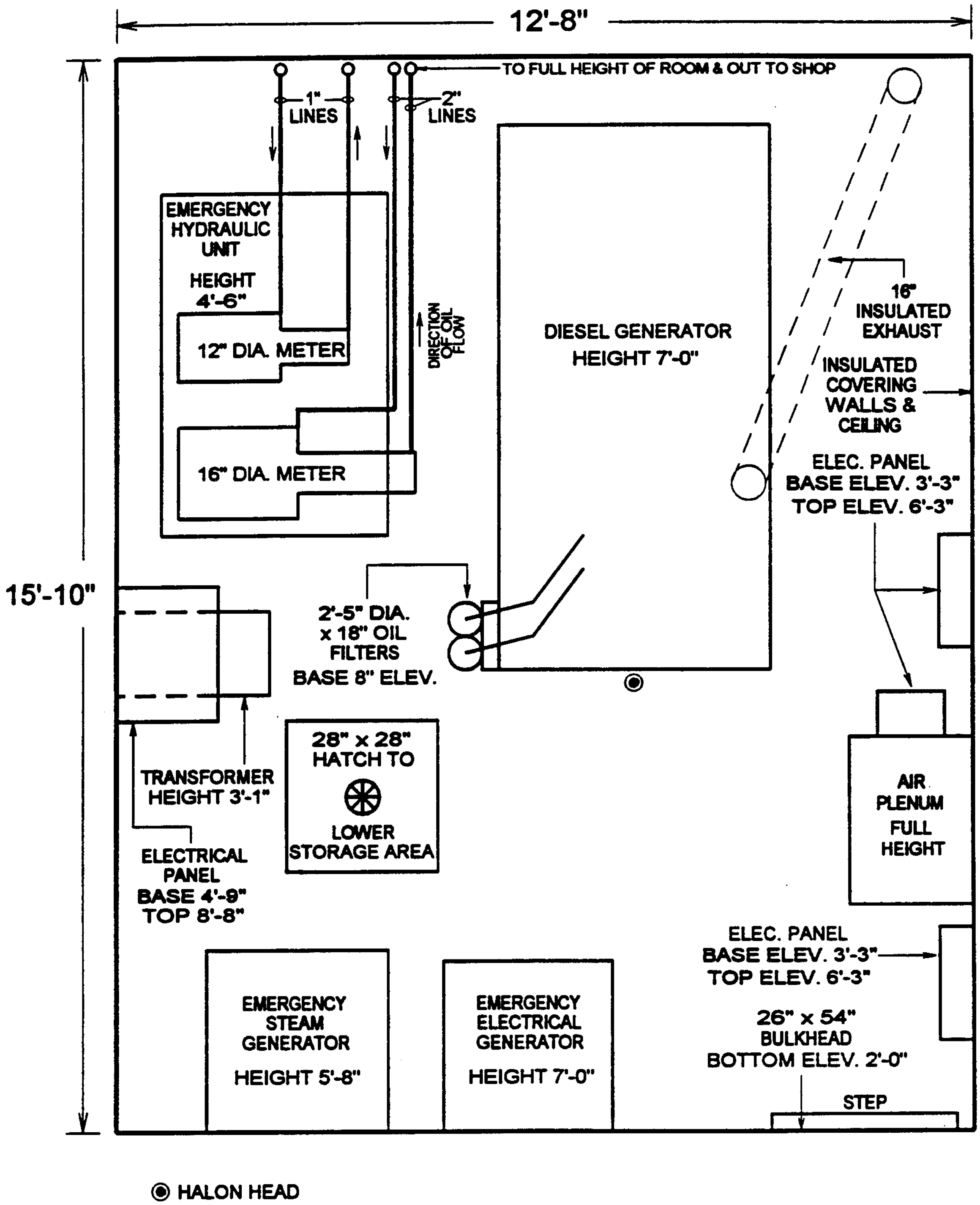
1. One 26" x 54" door opening.

Wall coverings:

1. Faced insulated wall covering.

Observations:

1. The room is protected by 450 lbs. of Halon 1301 stored in a bank above the engine room next to the emergency generator room.
2. Cables run in bundles up the sidewall and along the overhead from all electrical panels to the main emergency electrical generator.



LSV EMERGENCY GENERATOR ROOM
CEILING HEIGHT 11'-6"

Figure A6

Table A7

SURVEY SUMMARY CHART

Vessel: LSV

Compartment: Bow Thruster Room - See Figure A7.

Room dimensions:

Length: 27'-0"
Width: 24'-0"
Main compartment height: 7'-0"
Bilge depth: 2'-6"
Overhead depth: 3'-0"
Overall height: 12'-6"

Potential hazards:

1. Diesel fuel (marine) - spray on hot engine surfaces; pool formation under engine and in bilge; cascade along engine surface.
2. Engine oil - spray on hot engine surfaces; pool formation under engine and in bilge; cascade along engine surface, leaks from the storage drums onto the main floor.
3. Cables.
4. Other combustibles - oily rags stacked in piles and in a steel trash barrel; dirty oil filters in a steel trash barrel; boxed new oil filters sitting on the shelves; box and hose storage on shelves; penetrating fluid.

Openings:

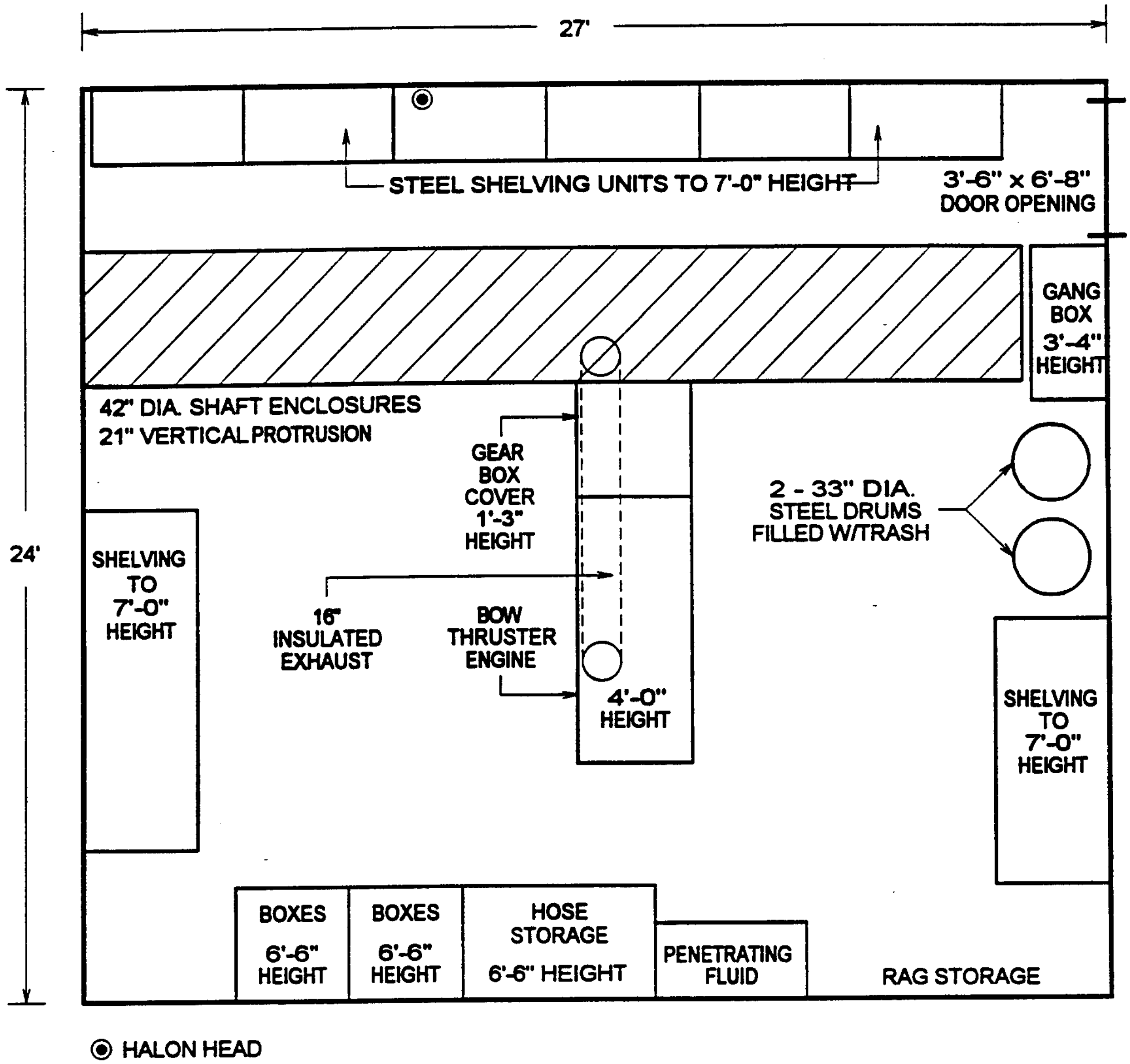
1. One 3'-6" x 6'-8" door opening.

Wall coverings:

1. Faced insulated wall covering.

Observations:

1. The room is protected by one 290 lb. Halon 1301 cylinder. The cylinder is located in the flammable liquid storage room.
2. Only one nozzle protects the room. It is located 13'-6" from the door across the 27'-0" wall at the top of the shelves. At the time of investigation it was blocked by boxes.
3. The overhead consists of a 36" deep steel beams in a 6'-0" x 6'-0" grid centered on the room. In the 24' direction subframing with 12" deep beams, 18" on center exists. The flange widths are 8" leaving a 12" gap. The crew has filled approximately 30% of the area within the subframing with cardboard boxes,



LSV BOW THRUSTER ROOM

MAIN ROOM HEIGHT: 7'-0"
OVERHEAD: 3'-0"
BILGE: 2'-6"
OVERALL HEIGHT: 12'-6"

Figure A7

Table A8

SURVEY SUMMARY CHART

Vessel: ROWPU Barge

Compartment: Engine Room #1 - See Figure A8.

Room dimensions:

Length: 22'-6"
Width: 16'-0"
Main compartment height: 8'-0"
Bilge depth: 2'-0"
Overall height: 10'-0"

Potential hazards:

1. Diesel fuel (marine) - spray on hot engine surfaces; pool formation under engine and in bilge; cascade along engine surface.
2. Engine oil - spray on hot engine surfaces; pool formation under engine and in bilge; cascade along engine surface, leaks from the storage drums onto the main floor.
3. Hydraulic oil - leaks from the storage drums onto the main floor.
4. Cables

Openings:

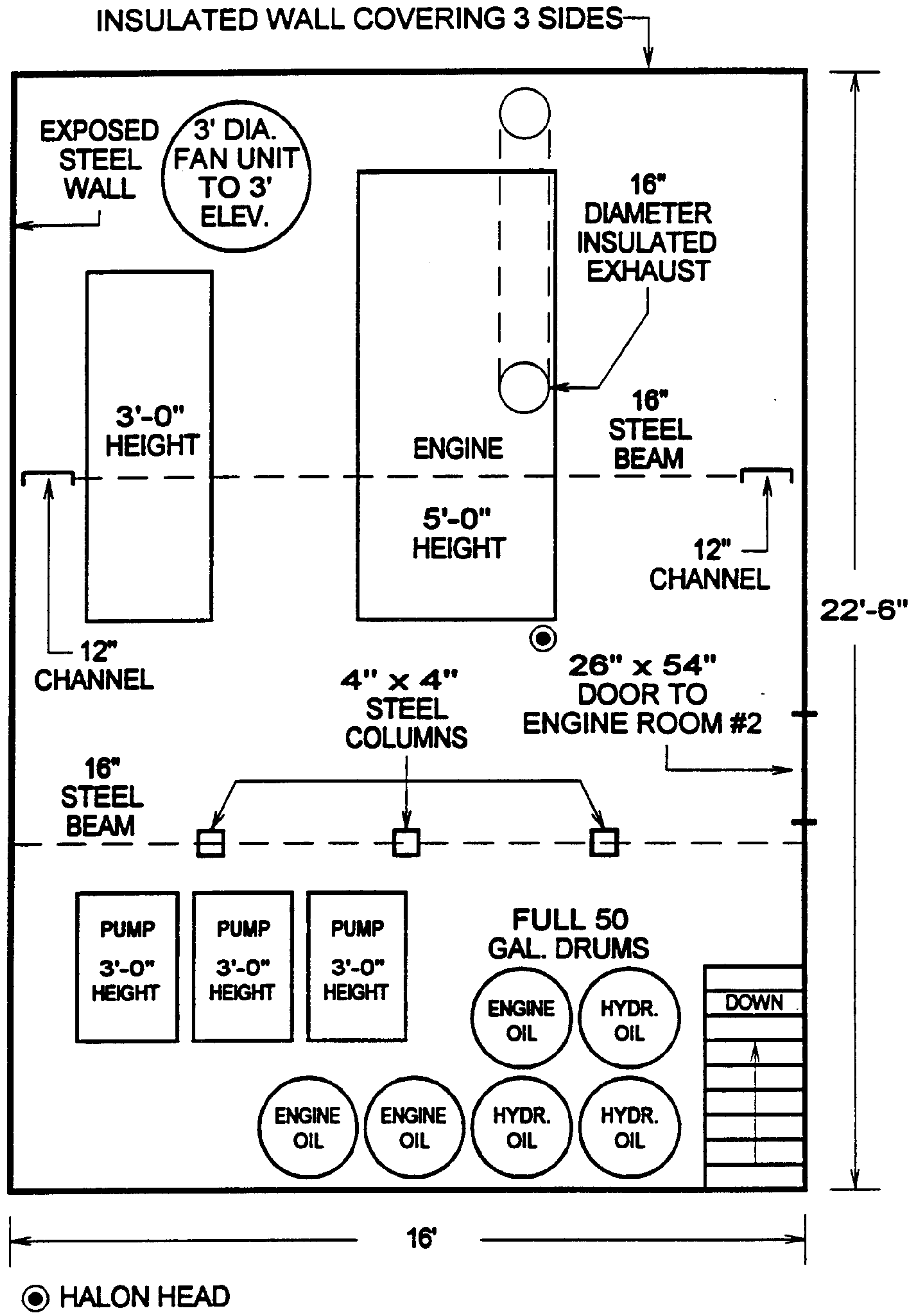
1. Door adjoining the two main engine rooms.
2. Opening in overhead at top of stairs.

Wall coverings:

1. Faced insulated wall covering.

Observations:

1. The dual engine room area is protected by a 580 lb. Halon 1301 system. Each engine room is protected by 290 lbs. The distribution nozzle is located above the corner of the main engine, closest to the center of the room. Cylinders are stored in the work area directly above the engine rooms.
2. Six cables run up from each engine to a common cable tray which runs along the overhead and in the open web of the 16" support beam (the beam supported by the 4x4 columns) to engine room #2. All cables are tight to the overhead and to the beam.
3. The room also contains a 3' diameter fan unit which is ducted down to the 3' elevation within the room.



ROWPU BARGE ENGINE ROOM #1
ENGINE ROOM HEIGHT: 8'-0"
BILGE DEPTH: 2'-0"
TOTAL: 10'-0"

Figure A8

Table A9

SURVEY SUMMARY CHART

Vessel: ROWPU Barge

Compartment: Engine Room #2 - See Figure A9.

Room dimensions:

Length: 22'-6"
Width: 16'-0"
Main compartment height: 8'-0"
Bilge depth: 2'-0"
Overall height: 10'-0"

Potential hazards:

1. Diesel fuel (marine) - spray on hot engine surfaces; pool formation under engine and in bilge; cascade along engine surface.
2. Engine oil - spray on hot engine surfaces; pool formation under engine and in bilge; cascade along engine surface.
3. Cables

Openings:

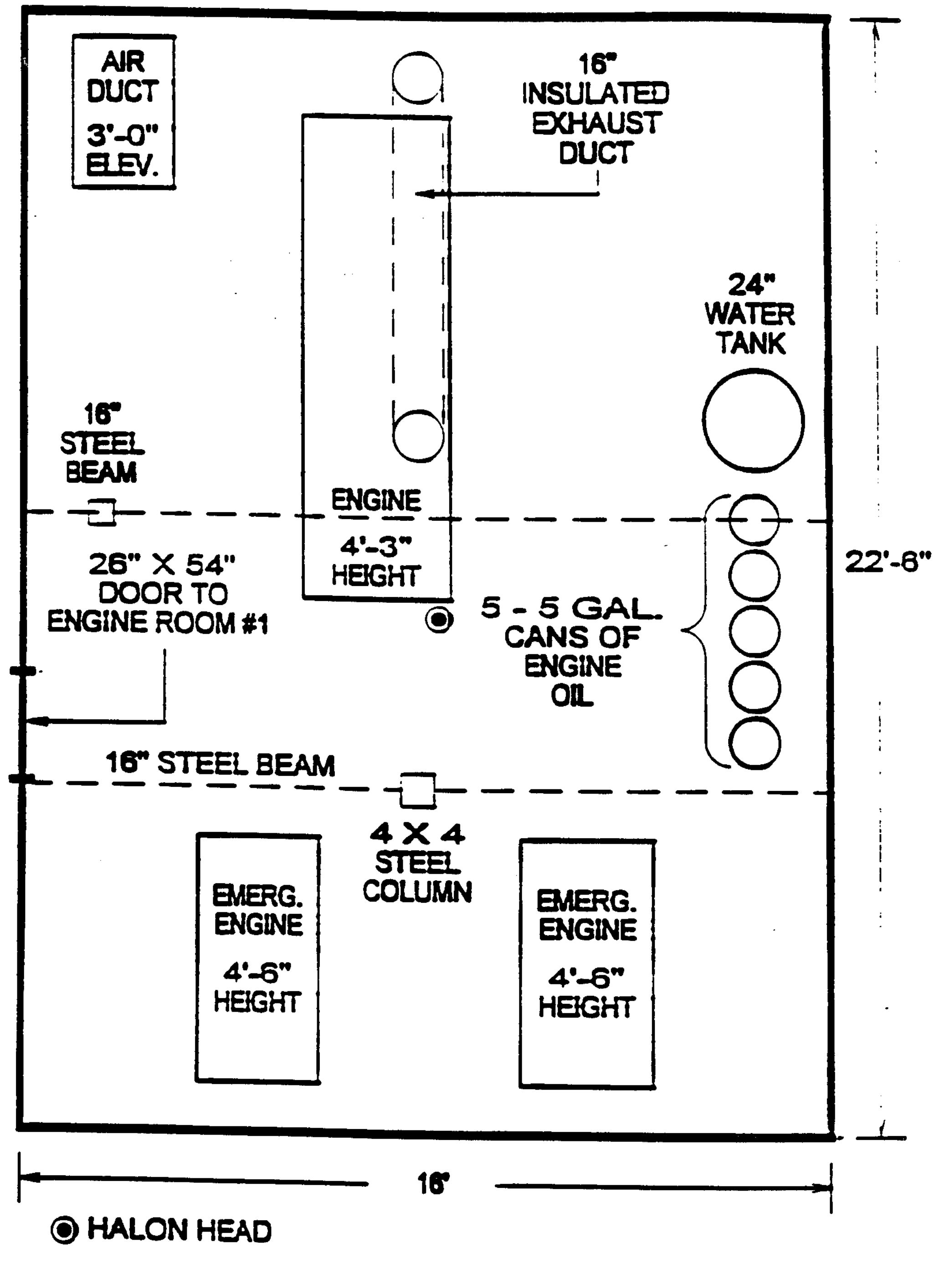
1. Door adjoining the two main engine rooms.

Wall coverings:

1. Faced insulated wall covering

Observations:

1. The dual engine room area is protected by a 580 lb. Halon 1301 system. Each engine room is protected by 290 lbs. The distribution nozzle is located above the corner of the main engine, closest to the center of the room. Cylinders are stored in the work area directly above the engine rooms.
2. Six cables run up from each engine to a common cable tray which runs along the overhead and in the open web of the 16" support beam to a main electrical panel in another space. All cables are tight to the overhead and to the beam.
3. The room also contains a 1'x2' ventilation duct down to the 3' elevation within the room.



ROWPU BARGE ENGINE ROOM #2
ENGINE ROOM HEIGHT: 8'-0"
BILGE DEPTH: 2'-0"
TOTAL: 10'-0"

Fig. A9 – ROWPU Barge Engine Room #2

Appendix B

IMO Interim Test Method

APPENDIX B

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-room of category A and cargo pump-rooms. In order to define the different engine-room 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. 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.

Table 1 - Classification of Category A 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 container ships	>3,000 m^3	Fuel: Low pressure 0.7-1.0 kg/s at 3-8 bar High pressure 0.20 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 II-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 x length x height) 1 m x 3 m x 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 x 6 m x 0.5 m high surrounding the mock-up with three trays, 2, 2, and 4 m^2, equalling a total area of 8 m^2, underneath. See figure 2.

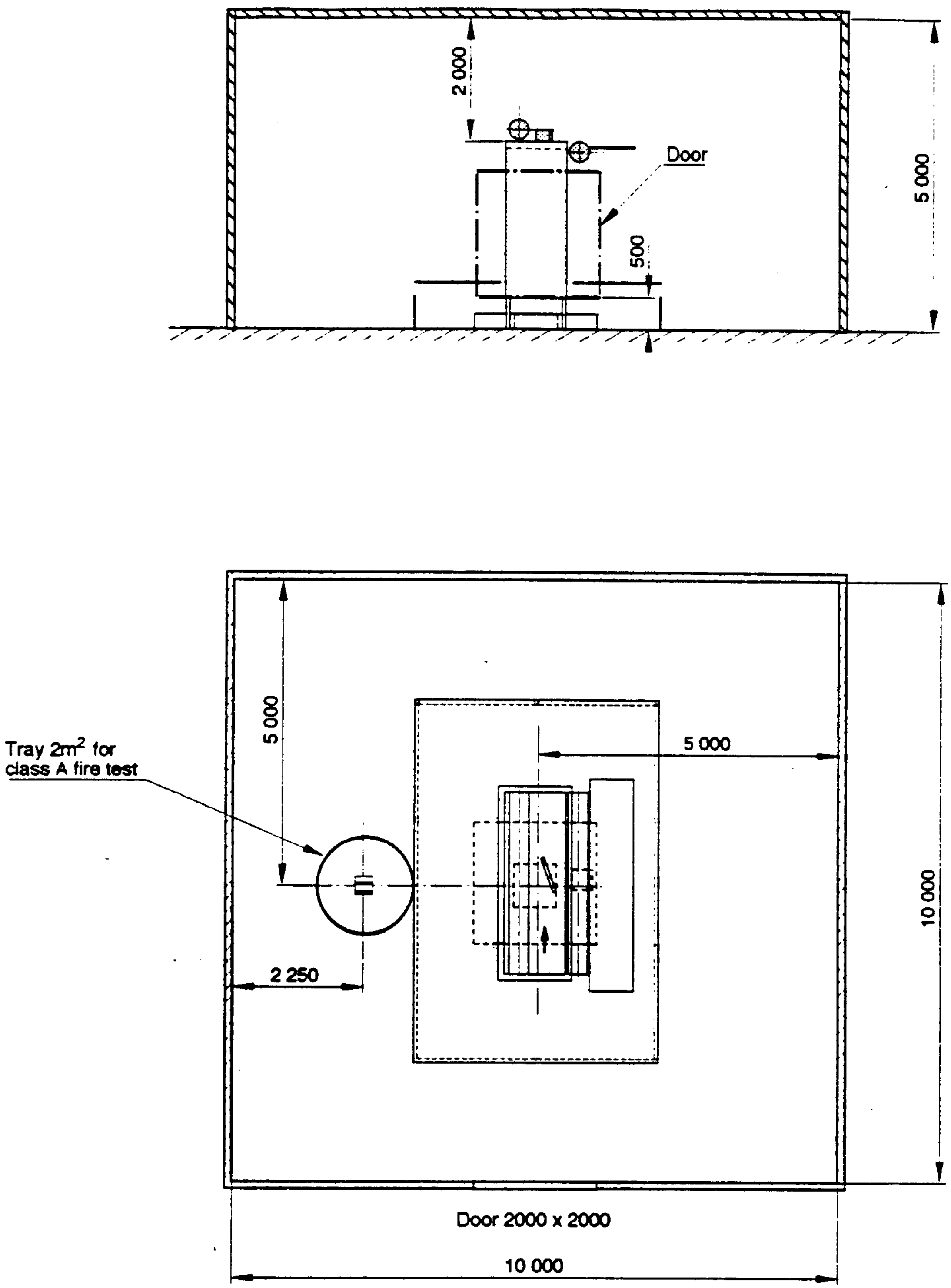
4.2.2 Test room

.1 Class 1 - Engine-rooms

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

.2 Class 2 and 3 - Engine-room

The test should be performed in a fire test hall with 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.



1: 100

Figure 1

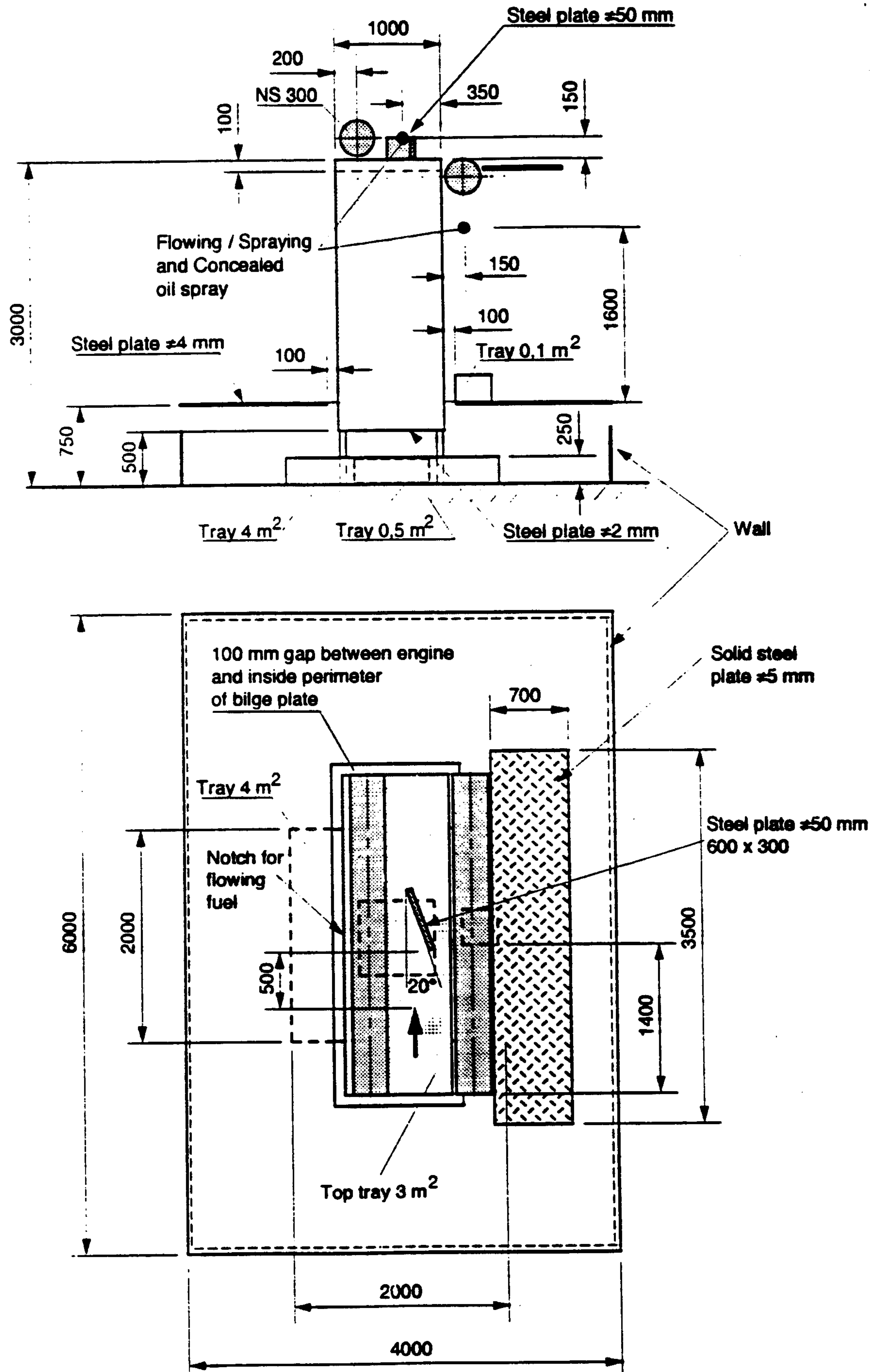

Steel plate ±50 mm
1000
200
NS 300
350
150
100
Flowing / Spraying
and Concealed
oil spray
150
100
1600
3000
Steel plate ±4 mm
100
Tray 0,1 m2
750
500
250
Tray 4 m2
Tray 0,5 m2
Steel plate ±2 mm
Wall
100 mm gap between engine
and inside perimeter
of bilge plate
700
Solid steel
plate ±5 mm
Tray 4 m2
Steel plate ±50 mm
600 x 300
Notch for
flowing
fuel
6000
2000
500
20°
1400
3500
Top tray 3 m2
2000
4000

Figure 5

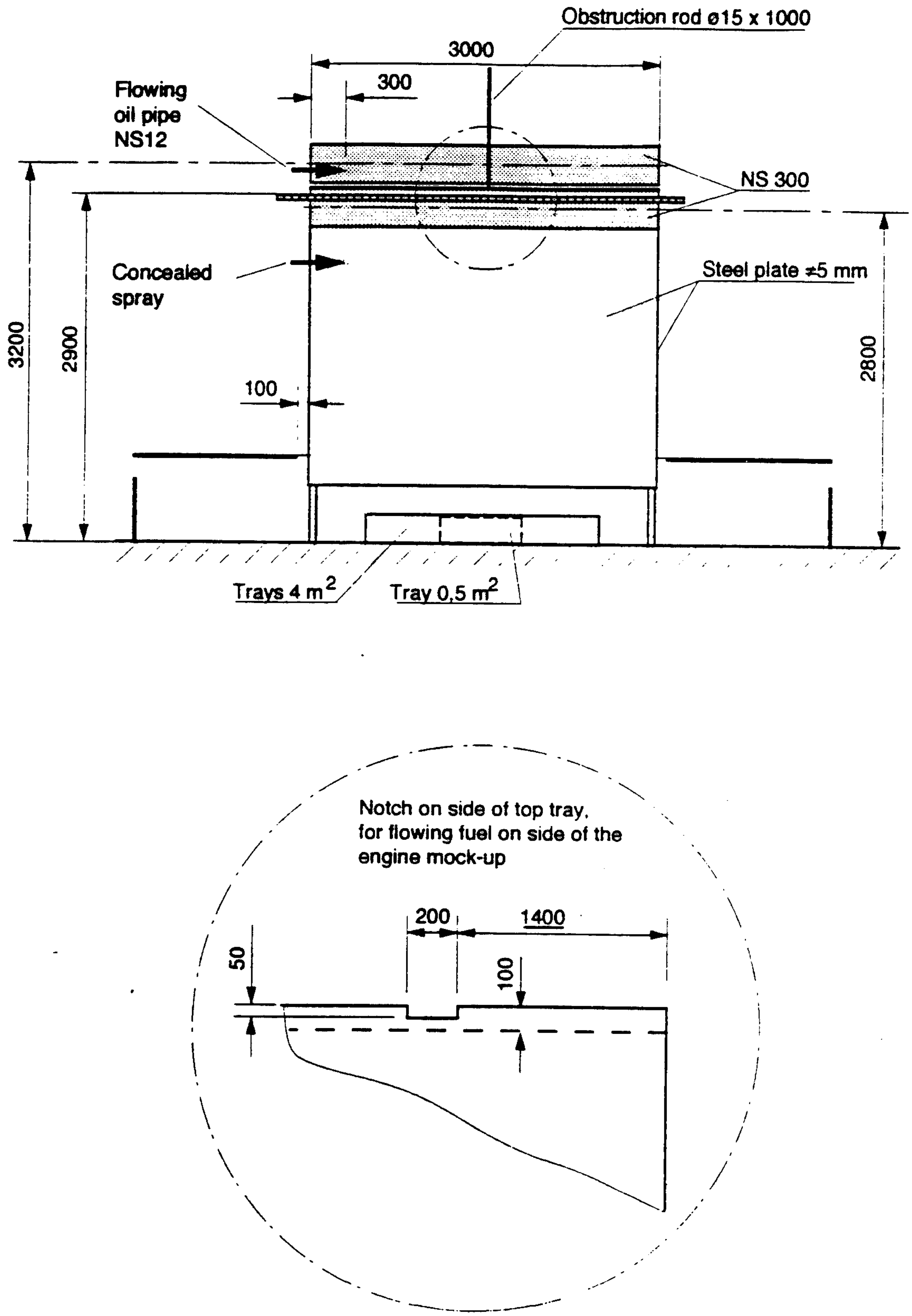

Obstruction rod ø15 x 1000
3000
300
Flowing
oil pipe
NS12
NS 300
Concealed
spray
Steel plate ≠5 mm
3200
2900
2800
100
Trays 4 m2
Tray 0,5 m2
Notch on side of top tray,
for flowing fuel on side of the
engine mock-up
200
1400
50
100

Figure 3

1:50

Table 2 - Test programme

Test No.	Fire Scenario	Test Fuel
1	Low pressure horizontal spray on top of simulated engine between agent nozzles	Commercial fuel oil or light diesel oil
2	Low pressure spray on top of simulated engine centred with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1 metre 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) and on top of the simulated engine (3 m^2)	Commercial fuel oil or light diesel oil
5	High pressure horizontal spray fire 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 engine and 0.1 m^2 tray positioned 1.4 m in from 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	0.1 m^2 on top of bilge plate centred under exhaust plate	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 sec. 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 x 60 cm x 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 shut off, no reignition of the spray is permitted	Heptane
13	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil

Note: The wood crib is to weigh 5.4 to 5.9 kg and is to be dimensioned approximately by 305 by 305 by 305 mm. The crib is to consist of eight alternate layers of four trade size 38.1 by 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 hours. 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.

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. The maximum vertical distance is limited to 5 m. 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 30 mm oil 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 seconds 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 minute preburn time is required before the extinguishing agent is discharged for the oil tray fires and 5-15 seconds for the oil spray and heptane fires and 30 seconds 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 minutes whatever is less. The oil spray, if used, should be shut off 15 seconds 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;

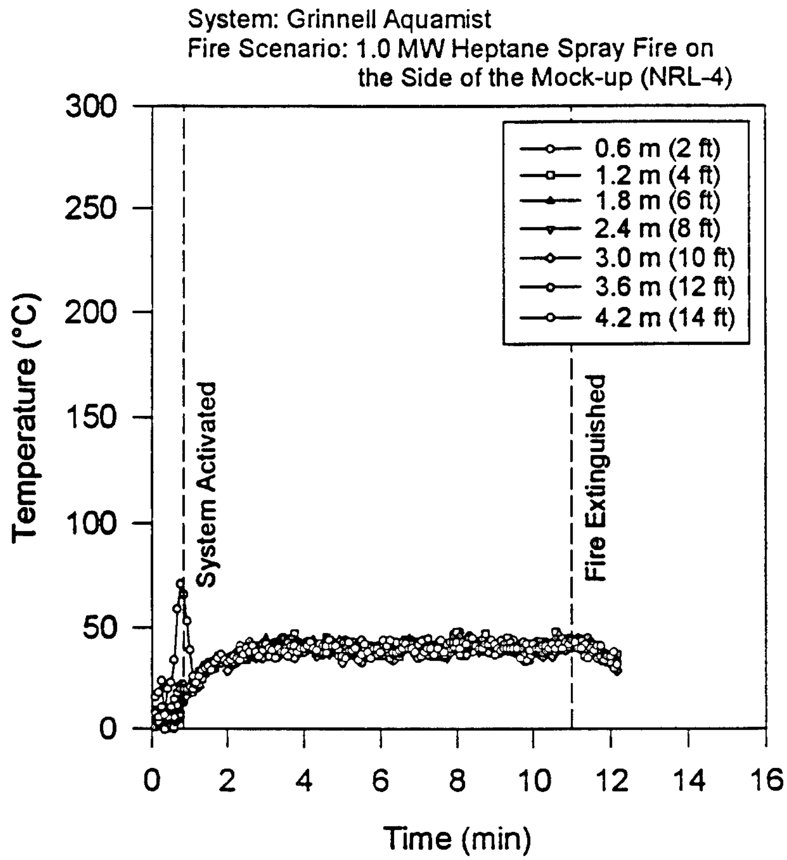
.16 Deviations from the test method, if any;

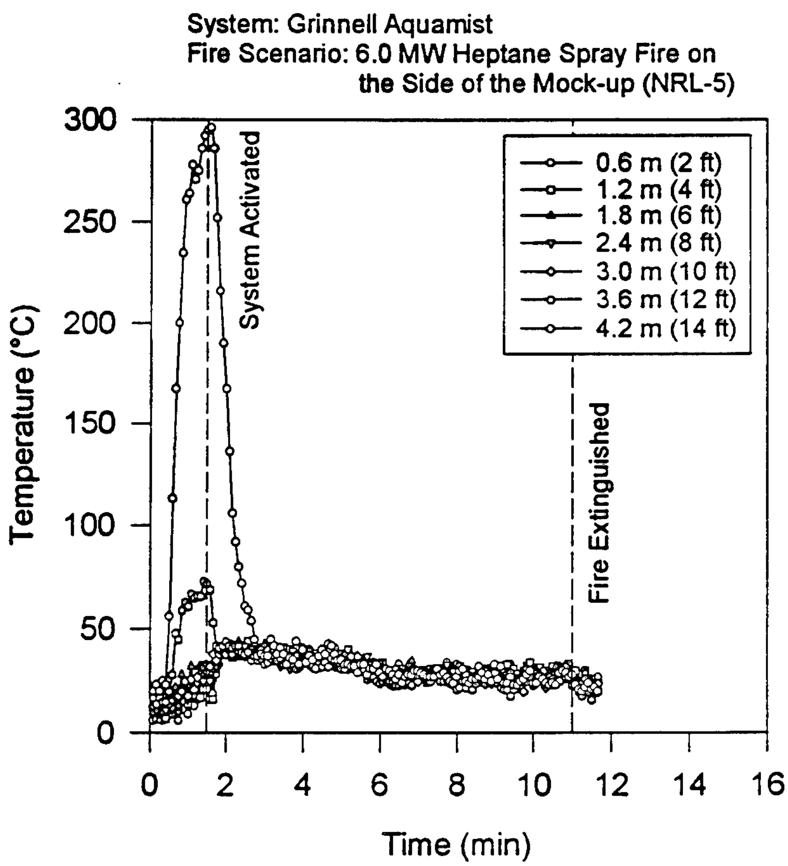
.17 Test results including observations during and after the test; and

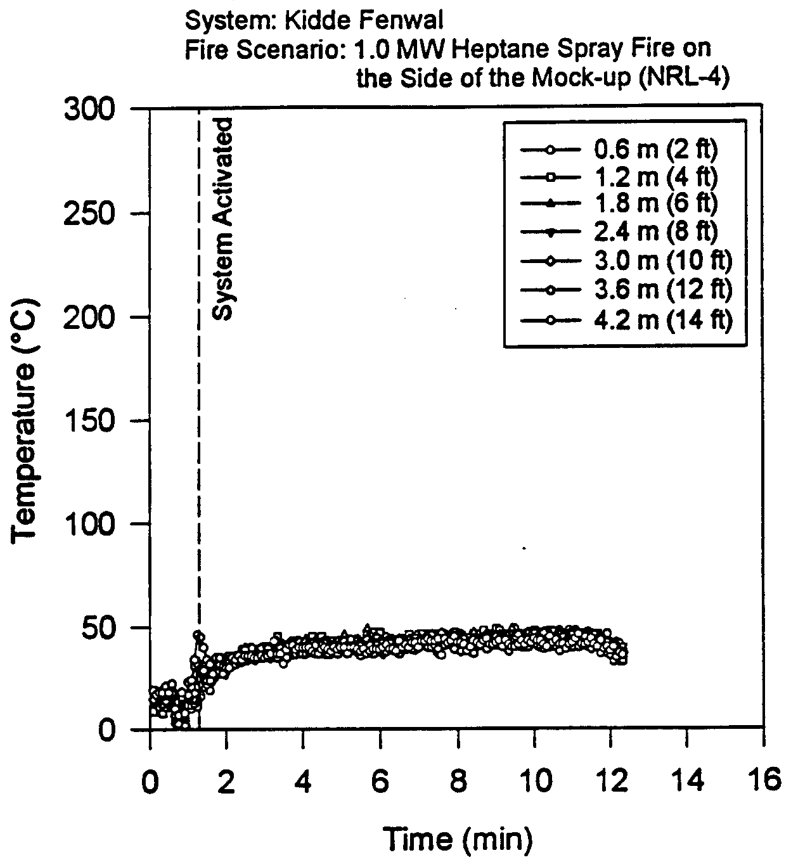
.18 Date and signature.

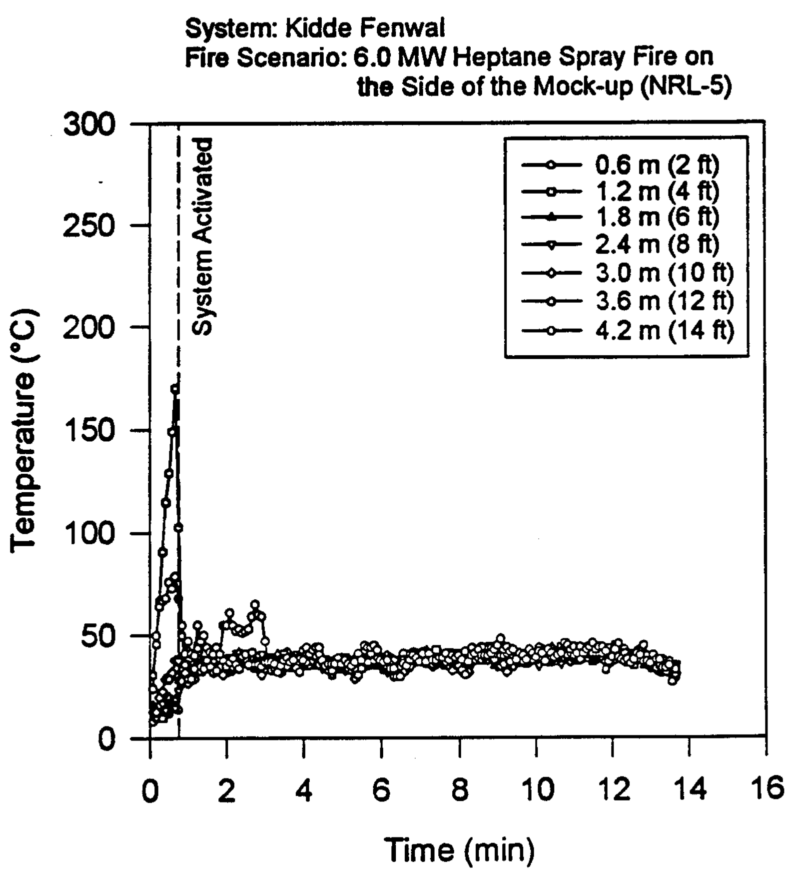
Appendix C

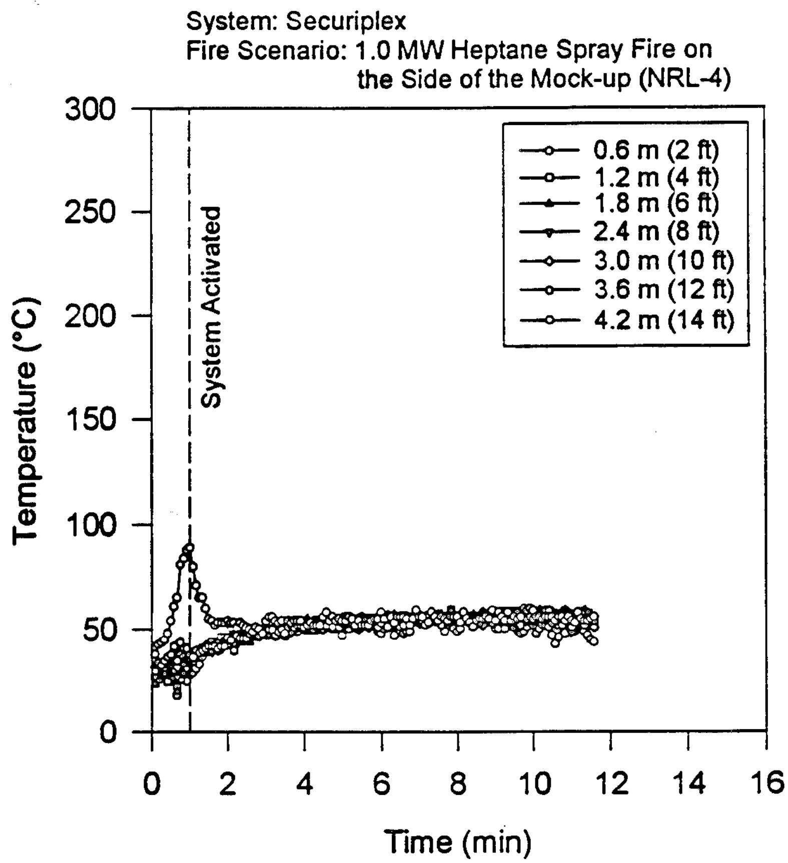
Compartment Temperature Plots

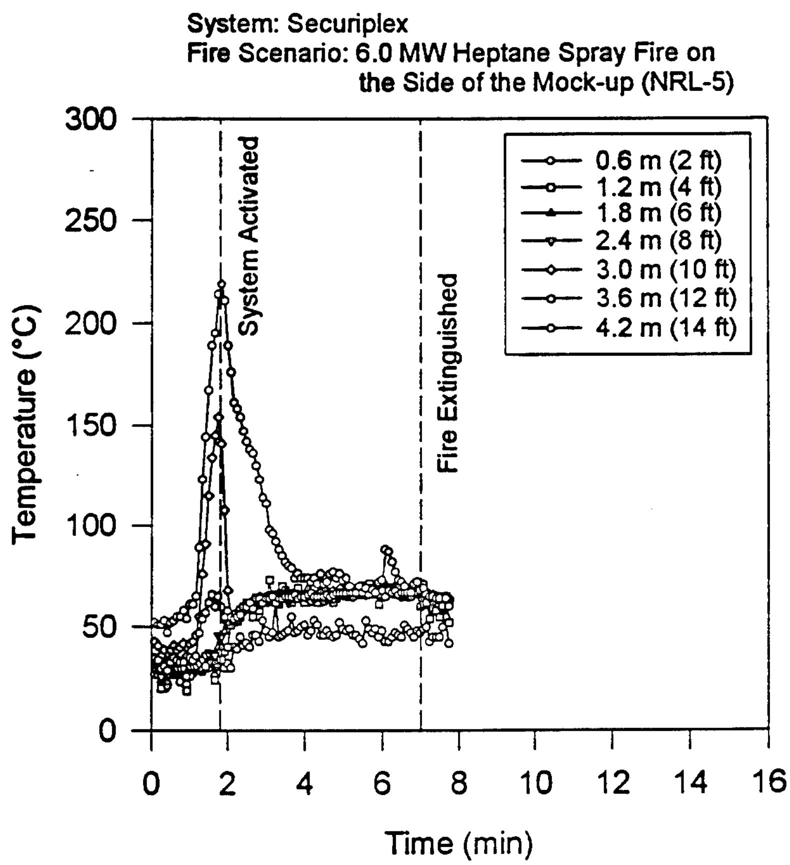

System: Grinnell Aquamist
Fire Scenario: 1.0 MW Heptane Spray Fire on
the Side of the Mock-up (NRL-4)
300
250
200
150
100
50
0
Temperature (°C)
0
2
4
6
8
10
12
14
16
Time (min)
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)
System Activated
Fire Extinguished

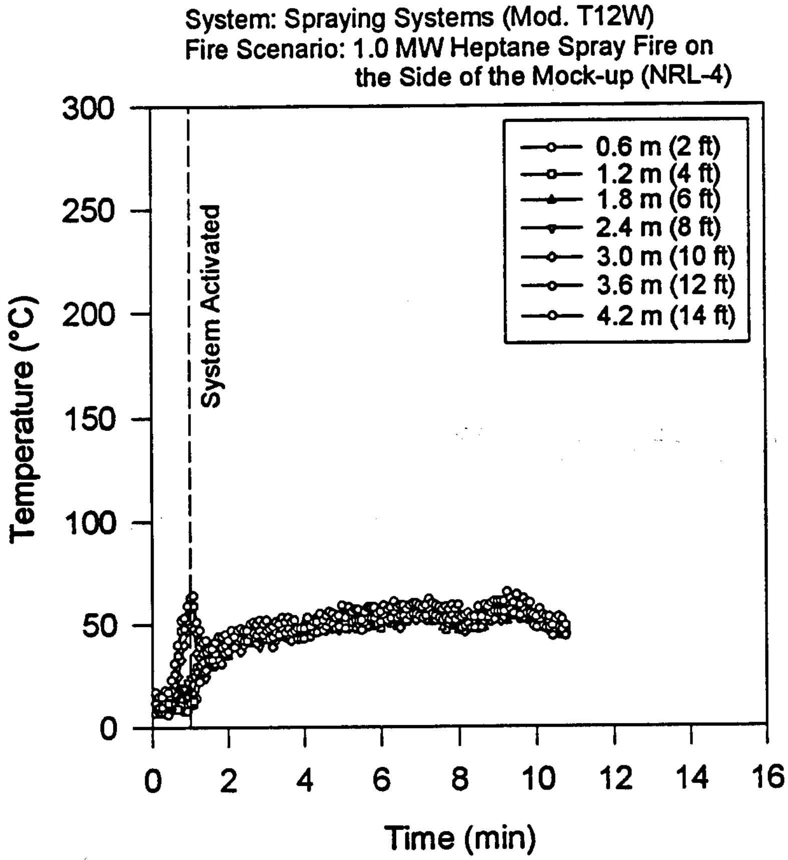

System: Grinnell Aquamist
Fire Scenario: 6.0 MW Heptane Spray Fire on
the Side of the Mock-up (NRL-5)
300
250
200
150
100
50
0
Temperature (°C)
0
2
4
6
8
10
12
14
16
Time (min)
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)
System Activated
Fire Extinguished

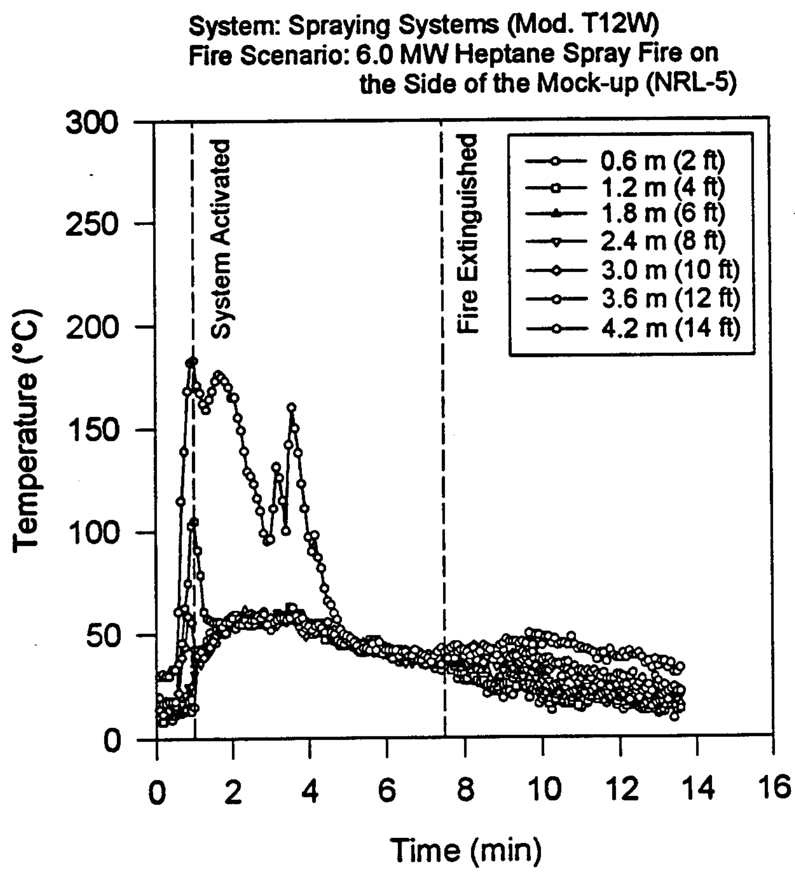

System: Kidde Fenwal
Fire Scenario: 1.0 MW Heptane Spray Fire on the Side of the Mock-up (NRL-4)
System Activated
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)
Temperature (°C)
Time (min)
0
50
100
150
200
250
300
2
4
6
8
10
12
14
16

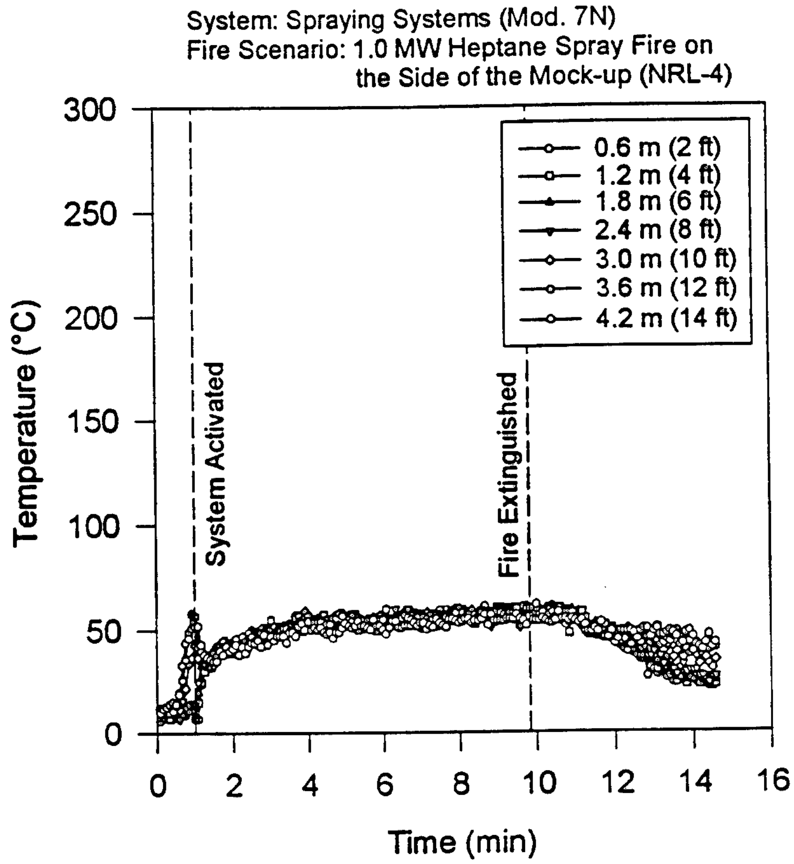

System: Kidde Fenwal
Fire Scenario: 6.0 MW Heptane Spray Fire on the Side of the Mock-up (NRL-5)
System Activated
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)
Temperature (°C)
Time (min)
0
50
100
150
200
250
300
2
4
6
8
10
12
14
16

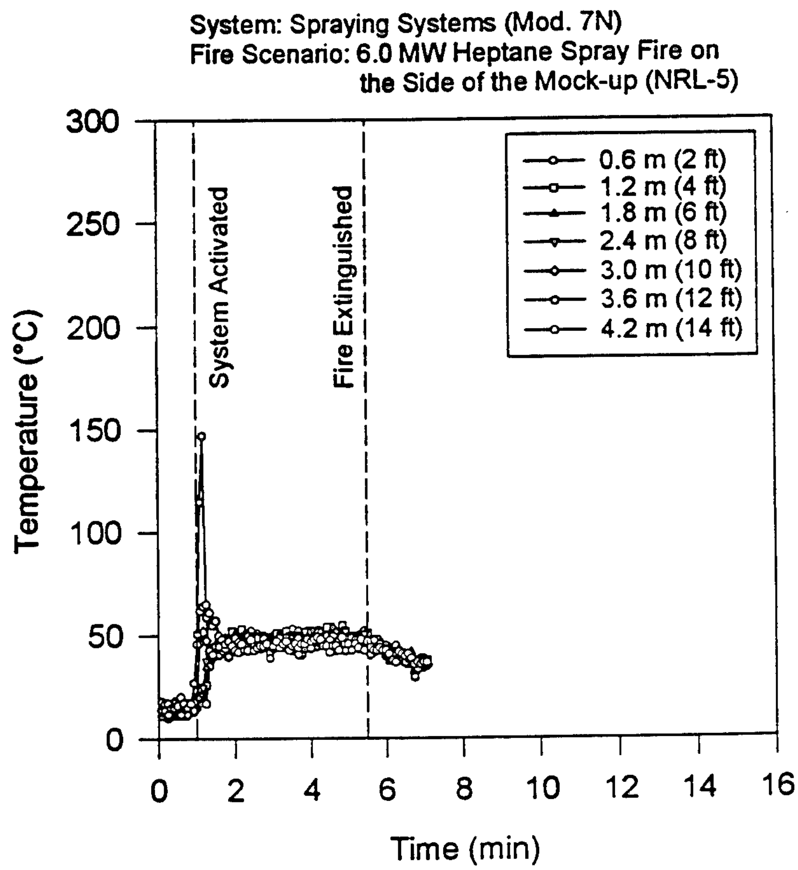

System: Securiplex
Fire Scenario: 1.0 MW Heptane Spray Fire on the Side of the Mock-up (NRL-4)
System Activated
Temperature (°C)
Time (min)
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)


System: Securiplex
Fire Scenario: 6.0 MW Heptane Spray Fire on the Side of the Mock-up (NRL-5)
System Activated
Fire Extinguished
Temperature (°C)
Time (min)
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)


System: Spraying Systems (Mod. T12W)
Fire Scenario: 1.0 MW Heptane Spray Fire on the Side of the Mock-up (NRL-4)
Temperature (°C)
Time (min)
System Activated
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)


System: Spraying Systems (Mod. T12W)
Fire Scenario: 6.0 MW Heptane Spray Fire on the Side of the Mock-up (NRL-5)
Temperature (°C)
Time (min)
System Activated
Fire Extinguished
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)


System: Spraying Systems (Mod. 7N)
Fire Scenario: 1.0 MW Heptane Spray Fire on the Side of the Mock-up (NRL-4)
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)
System Activated
Fire Extinguished
Temperature (°C)
Time (min)
0
50
100
150
200
250
300
2
4
6
8
10
12
14
16


System: Spraying Systems (Mod. 7N)
Fire Scenario: 6.0 MW Heptane Spray Fire on the Side of the Mock-up (NRL-5)
0.6 m (2 ft)
1.2 m (4 ft)
1.8 m (6 ft)
2.4 m (8 ft)
3.0 m (10 ft)
3.6 m (12 ft)
4.2 m (14 ft)
System Activated
Fire Extinguished
Temperature (°C)
Time (min)
0
50
100
150
200
250
300
2
4
6
8
10
12
14
16