USING WATER MIST FOR FLASHOVER SUPPRESSION ON NAVY SHIPS

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ABSTRACT

The Damage Control for Automated Reduced Manning (DCARM) program is a three-year multidisciplinary program funded by the Navy Technology Center for Safely and Survivability. One aspect of the program is directed at optimizing the use of fine water mist (FWM) for fire control and boundary cooling in berthing compartments (non-machinery spaces) on Navy ships. The first-year fire test program evaluated the use of water mist for flashover suppression, in which the fire is confined to a small area. the combustion gases are cooled, and fire is prevented from spreading from the compartment of origin. The study confirmed that in low-ceiling, ventilation-limited shipboard spaces. flashover suppression can be achieved easily using low water application rates and widely spaced nozzles. Achieving flashover suppression also achieves boundary cooling. because the compartment of fire origin does not become hot enough for heat to ignite material in adjacent compartments.

INTRODUCTION

This paper describes the test results obtained during the first year of an experimental program aimed at developing a prototype water mist fire suppression (WMFS) system for integration with DCARM objectives [1]. The DCARM (Damage Control for Automated Reduced Manning) program is a multidisciplinary, three-year program funded by the Navy Technology Center for Safety and Survivability. One aspect of the program is directed at optimizing the use of water mist (WM) for fire control and boundary cooling in berthing and general-use compartments (non-machinery spaces) on ships. The objective of the first-year fire test program was to evaluate the use of water mist for flashover suppression in single-deck high compartments. "Flashover" is understood to be the condition in which heat from a fire radiates into every object in the room, eventually causing all combustibles to ignite and burn [2]. A WM system designed for flashover suppression is intended to cool the gases and smoke layer. limit the fire to a small area, and prevent fire from spreading beyond the compartment of origin.

It is proposed to utilize low water-demand, automatic fixed WMFS systems throughout the next generation of Navy ships to provide, as a minimum. flashover suppression and boundary cooling. The objective is to confine a fire to the compartment of origin for an extended period using a minimal amount of water. When damage-control crews arrive, they will encounter small fires that can be extiguished using a minimum of manpower. In this manner, the number of persons required for a damage control response team will he reduccd from current levels.

The Year 1 DC ARM Water Mist test program was subdivided into Task 1 and Task 2. Task 1 involved characterization of water mists which were used in the experiments. Measurements were taken to quantify the spray characteristics of drop size distribution (DSD), mass discharge rate (Q), cone angle, spray velocity, and representative flux density distribution (V_i). Task 2 involved fire testing to establish performance benchmarks for use of water mist for flashover suppression, fire control, and smoke scrubbing. The results of Task 1 and 2 are the basis for design criteria for a shipboard WMFS system intended for flashover suppression.

Task 1: Spray Characterization

Water mist nozzles manufactured by Grinnell, Kidde International, Marioff Hi-fog, and Spraying Systems Company were selected for fire testing. These manufacturers have developed different nozzles for application against Class **A** or Class B fuels. In general, nozzles intended for Class **A** fuels require a higher mass fraction of larger drop sizes than nozzles intended for liquid fuels (Class B) fires. Control over fire in Class A fuels benefits from fuel wetting much more than Class B fuels [3]. The nozzles intended for Class **A** applications, therefore, tend to have higher discharge rates and coarser sprays than nozzles intended for application in machinery spaces where Class B fuels are expected. For the DC ARM application, the fire scenario involved Class A fuels. The test objective, however, was to examine "flashover suppression" in compartments containing Class **A** fuels, rather than extinguishment. Because a spray with a higher content of fine droplets is likely to be more effective at cooling than a spray with a lower fraction, the nozzles intended for Class **B** fuel hazards were selected for fire testing.

The nozzles used in this test program are referred to as **A, B,** C, and D. Single-fluid nozzles only were selected. Two of the nozzles (**A** and B) operate in the "intermediate pressure" range (12 bar to 34 bar (175 psi to < 500 psi)): and two of the nozzles (C and D) operate in the "high pressure" range (>34 bar (500 psi)) [4]. **A** test apparatus was set up to measure spray characteristics. Each nozzle in turn was mounted 1.6 m above the floor in a 4 by 6 by 3 m high closed room to minimize disturbances to the spray cone. Instrumentation to measure water flow rate. nozzle pressure, spray velocity, and drop size distribution (DSD) was applied. Flux density distributions were collected on a plane 1 m below the nozzle tip using an array of collector cups with openings of 0.083 m in diameter, spaced 0.150 m apart in an orthogonal grid. This spacing allowed enough accuracy to be able to determine the spray cone diameter and estimate the flux density at the locations for drop size measurement.

A Malvem Model 2600 particle size measurement instrument [5] was used to measure the DSD of each nozzle at the design operating pressure and flow rate. The DSD varies considerably depending on where in the spray the measurement is taken. **A** single measurement of DSD is not statistically representative of the spray. **A** calculated average DSD was obtained by taking measurements at many points within the spray (I m below the nozzle), and weighting those readings according to the flux density at each location. Equation 1 was used to obtain a weighted average representation of the drop size distribution of the spray [6].

$$R_k = \frac{\sum_i (R_{j,i} \times A_i \times V_i)}{\sum (A_i \times V_i)}$$

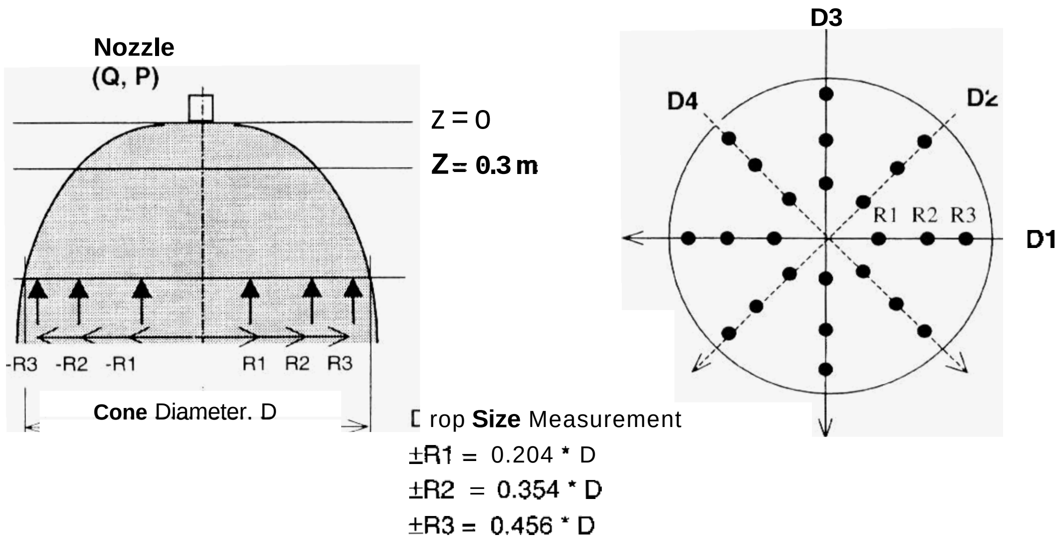
R_k = weighted cumulative volume percent readings for sizes equal to and less than d_{upper}

$R_{j,i}$ = cumulative volume percent readings for sizes equal to and less than d_{upper} at location "i"

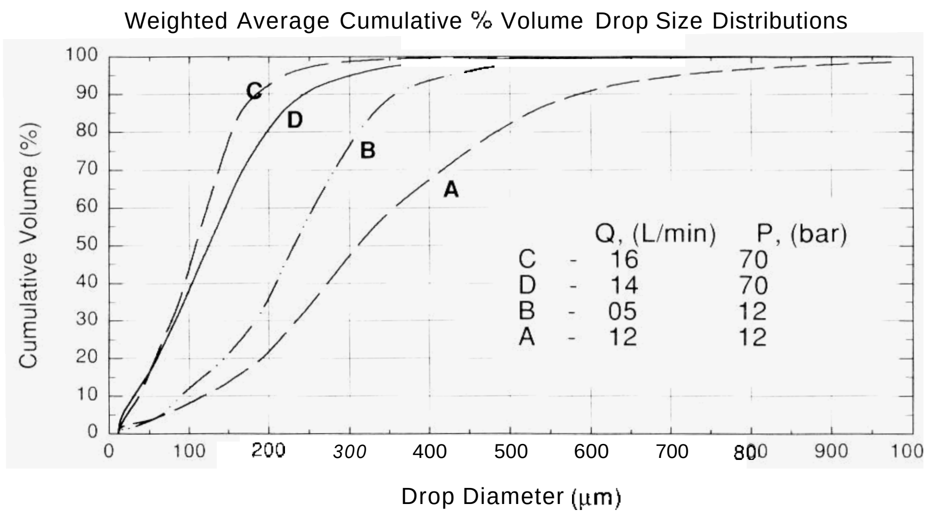
A_i = area centered at location "i" in which the size distribution is represented by R_k

V_i = the water flux density measured at location 'i'

As shown in Figure 1, up to 24 drop size distribution measurement\ were taken within each spray cone. Equation (1) was applied to weight numerically each reading according to the tlux density at the point of measurement [6]. Figurc 2 compares the weighted cumulative vol.% drop size distribution curves for the four nozzles investigated.



Figurc 1. Locutions within spray cones for measurement of flux density distribution and drop size distribution. The positions shown are the centroids of segments of equal area [7].



Figurc 2. Comparison of statistically weighted cumulative vol.% versus drop size distribution plots for four commercial water-mist nozzles.

Measurements of vertical-downward velocity profiles were taken at two distances from the nozzle. At least eight readings were taken across the spray profile at a distance 0.3 m below the nozzle, and again 1.0 m below each nozzle. A vane-type anemometer was inserted into the spray cone to measure downward velocity of the water particles and entrained air at different points. The velocity measured is that of the air entrained by the spray. Individual drops will have velocities greater than the average air velocity measured. Figure 3 compares the downward velocity profiles of a high pressure and a low pressure nozzle measured 0.3 m below the nozzle. This data provide a qualitative, but nonetheless useful, measure of the difference between a HP and LP water mist nozzle. The HP nozzles have more energy momentum than the LP nozzles available to promote mixing and cooling of hot gases in the compartment.

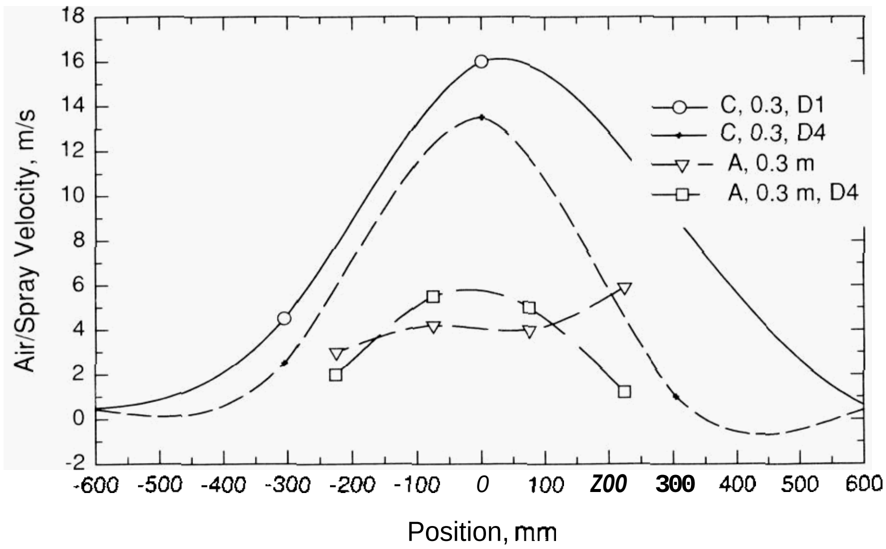


Figure 3. Downward spray velocity, 0.3 m below Nozzles A (LP) and C (HP).

FIRE TESTING FOR FLASHOVER SUPPRESSION

Test Structure

The test structure was approximately representative of a berthing compartment in the lower deck levels of a ship. The combustion air supply must come from the corridor within a single deck level. Combustion gases have no place to vent other than into the same corridor. The geometry leads to a ventilation-limited fire in a low-ceiling space, with a smoke-logged corridor. One feature that was not modeled in the test structure was the intra-deck pressure condition. The elevation of the neutral plane in a ship. with closed hatches between decks, will affect the overall ventilation conditions. A single *story* structure inside a larger open laboratory will have better ventilation/exhaust capacity than a below-deck compartment on a ship.

A 6.7 by 3.7 by 2.4 m high (60 m^3) test structure was constructed in the Calorimetry Building at Naval Research Laboratory Chesapeake Bay Detachment test site (CBD). The Test Room (Figure 4) consisted of a 2 by 4 ft wood frame covered on the inside walls and ceiling with Type X gypsum board. The floor was constructed of plywood on 2 by 4 ft joists on a concrete slab. An opening (0.56 by 1.68 m) in the north wall of the room, with 0.30 m sill height, represented a

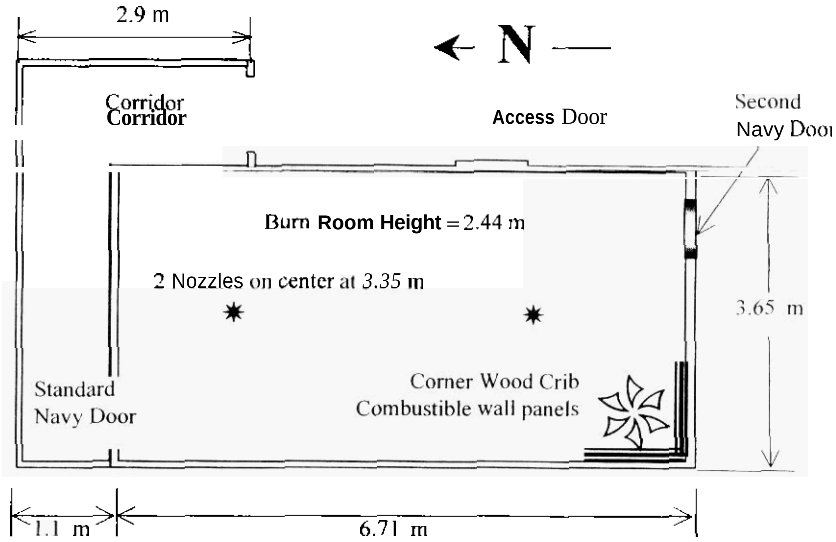


Figure 4. Dimension.; and arrangement of the fire test room.

typical navy door in a berthing space. This navy door was the primary sourcc of' ventilation air to support combustion in the compartment (apart from room leakage). Ventilation air from the attached corridor had to pass over the 0.30 m high sill to enter the room. All smokc left the compartment via the navy door. creating **an** uppcr gas layer in the corridor before escaping into the building and being captured by the building hood/fan system.

The gypsum hoard walls. plywood floor. and gaps above the access door, contributed to a relatively high degree of room leakage. No door-fan test was done to quantify room leakage area. It is expected that a berthing compartment below-decks on a ship, with steel deck, ceiling and bulkheuds, will havc a lower leakage area than the test facility.

As the firc testing progressed. a second navy door was introduced in the south wall in order to examine the effects of cross ventilation on the nozzle performance. In addition, a large door in the east wall of the compartment was used for access for setting up the fuel packages and igniting the fires. This door was also used in several tests to simulate a major change in the availability of ventilation air, e.g., opening a large hatch for entry by a damage control crew.

The tcst plan incorporated a variety offire scenarios. including **Class** B fuel pan fires at various locations in the compartment. The fire test that presented the greatest challenge to the WM system involved Class **A** combustibles in the southwest corner of the test room. Figure 4 illustrates the location of the Class **A** fuel comer fire.

INSTRUMENTATION

Instrumentation in the test facility, shown in Figures 5 and **6.** is described below.

1. Thermocouple trees (TR) consisted of 8 thermocouples (TC) each, spaced 0.3 m apart from the ceiling down to 0.3 m above the floor. TCs wcre type K, chromel alumel thermocouple

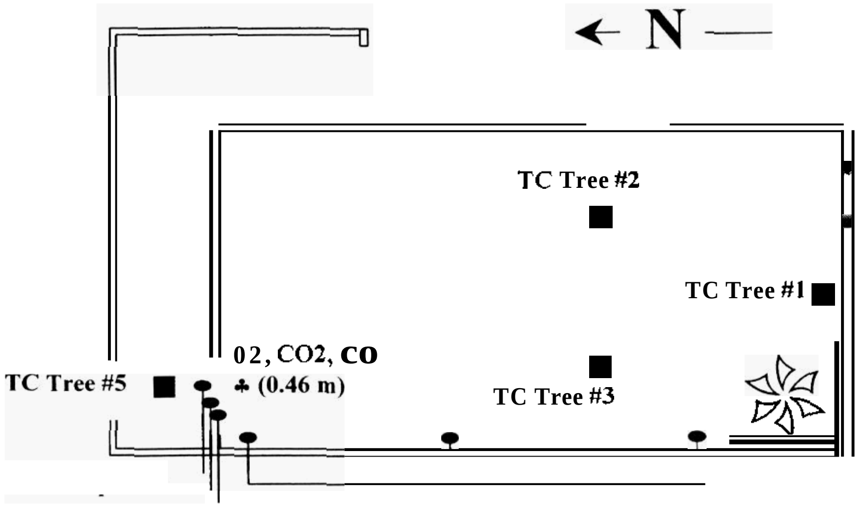


Figure 5. General arrangement of selected instrumentation.

wire. Tree TCs were sheathed. Ceiling mounted TCs (not shown) were exposed bead. The locations of TR-I, 2, **3,** and *5* are shown in Figure 5.

2. Bidirectional probes in the north navy door measured air/gas velocities in and out of the compartment.
3. Pressure transducers in the micromanometer range measured the buoyancy-induced pressure difference (ΔP) across the wall separating the bum room from the surrounding laboratory area. AP was measured at three elevations: the ceiling, mid-room height, and SO mm above the floor.
4. Optical density meters (ODM) were installed (Figure 6)—two at eye-level, one in the bum room, and one outside the bum room in the corridor. Two more were placed in ceiling mounted "smoke wells." The smoke-well arrangement measured differences in the opacity of smoke without the complicating factors such as changes in height of the neutral plane in the compartment, or different degrees of stirring or mixing of smoke, which affected conditions at eye-level [1].

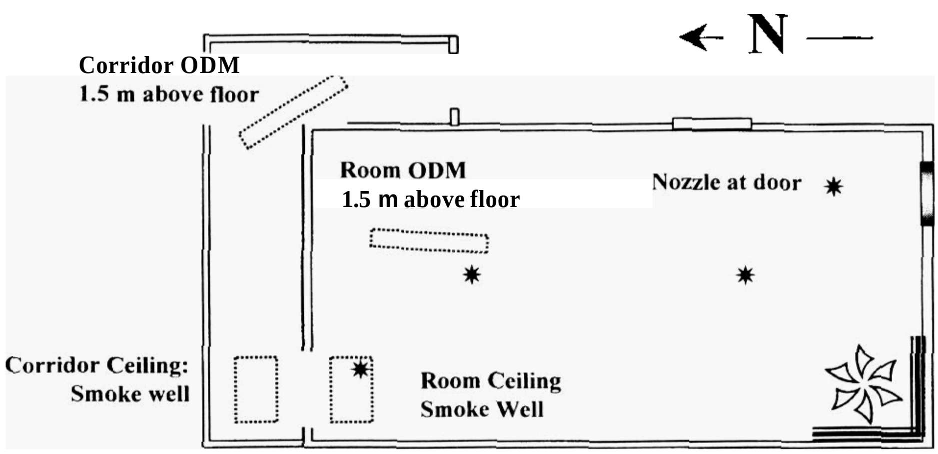


Figure 6. Location of optical density meters (ODM), ceiling smoke wells, and nozzles.

Oxygen, carbon dioxide, and carbon monoxide concentration in the room gases werc measured. Gases were sampled from 0.46 m below thc ceiling at the lintel of the navy door outlet from the room. A condenser and soot filter removed moisture from the gas stream bcfore it entered the gas analyzers.

5. Flow and pressurc measurements on the water distribution systcrn used Sponsler flow meters and Omega pressure transducers. Water prcssure readings were made on the riser and at two points on the ceiling tubing grid, to ensure that all nozzles were operating at the samc prcssure.

Fire Scenario

The fire scenario was designed to meet the following conditions:

1. The size of fuel package should be large enough that the fire could bring the compartment to flashover beforc all of the fuel was consumed.
2. The fire should hc as large as could he supported by the natural ventilation through the singlc navy door under unsuppressed conditions.
3. The fire should not be so large that it self-extinguishes by consuming **all** of the available oxygen.
4. The fire would be suppressed hut not extinguished by the mist. due to shielding or thc manner of application of WM. Heat would continue to be generated at a reduced rate throughout the application of mist.
5. If the degree of control by WM is marginal or insufficient, the fire should grow slowly and involve fuel not involved in the original ignition. This pattern of fire growth is typical of Class **A** fuels. Performance of different WM systems could be compared by quantifying the extent offire spread in the fuel package.

Two types of fire sources were used in the test series: a square pan with 8.0 L of heptane fuel, and **a** UL-727-I-A wood crib with conibustiblc wood panels situated in a corner. The pan fires were unable to bring the compartment to flashover, however, and were relatively easily cxtinguished by the water-mist system [8]. The liquid fuel fire scenario did not meet condition 5, since the entire fuel surface burns on ignition. **A** wood crib with combustible wall panels scenario, however. satisfied all of the conditions descrihcd. Unsuppressed, it was able lo bring the compartment to tlashover: the burning rate (hence heat release rate) of the wood char responded to changes in water-mist application; there was enough fuel to allow “steady-state” conditions to develop **in** the compartment; and the amount of fuel physically consumed could be measured after the test werc completed.

The UL-722-I-**A** wood crib was constructed of 10 layers of five 38 by 38 by SOX mm long oven-dried pine sticks, with overall dimensions 508 by 508 by 380 mm high. It was placed on 3X mm brick supports in the southwest corner of the room with approximately 12 mm between the edge of the crib and the wall surfaces. The south and west walls of the corner were lined with I.2 m by 2.4 m by 3 mm (1/8 in) Georgia Pacific, medium-density fiberboard wall paneling mounted on 20 mm fir strapping. The crib was ignited using 100 ml of heptane in **a** 100 by 100 nim pan placed between the supporting bricks under the center of the crib.

SUPPRESSION STRATEGIES

Water-mist nozzles were installed in the test room ceiling at the positions shown in Figure *6***.** The distance between nozzles, or nozzles and walls, recommended by the manufacturers for their conventional systems, were not followed. The objective was to learn whether flashover suppression could be achieved using significantly less water than required for extinguishment. Several nozzle layouts were applied: (I) two nozzles spaced 3.35 m apart on the center line of the room, equidistant from each side wall; (2) one nozzle just inside the room in front of the standard navy door; and **(3)** one nozzle at mid-point of the ceiling. Several variations on the location of nozzles relative to ventilation openings occurred.

The comer test fire was out of range of the direct spray discharge from any of the nozzles. From water distribution measurements, it was evident that the nozzle spray pattern did not cover the entire floor area and never caused direct wetting of the combustible wall panels in the corner. In general, the spray pattern involved a measurable flux density within a 1.75 m diameter circle (or less) centered below the nozzle, with almost zero flux density outside of the spray cone. Spray cones from adjacent nozzles neither overlapped nor touched the walls. With such sparse spacing, i.e., with no overlap in spray cones, use of a nominal or average flux density based on the combined discharge rate of the nozzles divided by the floor area of the compartment is misleading. The "Cone Area Ratio" was proposed as a parameter that reflects the sparse spray coverage area relative to total floor area. This is the ratio of the sum of the spray cone areas to total compartment floor area, Cone Area Ratios used in these tests ranged between 0.09 and 0.20 (9 to 20%).

EVALUATING "FLASHOVER SUPPRESSION"

For this test series. flashover suppression is defined in terms of the ability of water mist to prevent ceiling temperatures in the compartment from exceeding 400 "C. The unsuppressed wood-crib/wall panel fire brought the compartment to the point at which an array of cardboard target boxes ignited. Figure 7(a), which shows temperature profiles in the compartment (TR2) and the corridor (TR5) at the peak of the fire, is deemed to represent the beginning of flashover with an unsuppressed fire. The benefits of applying water mist at different nozzle spacing and spray characteristics can be **seen** by comparing temperature profiles in the compartment under suppressed and unsuppressed fire conditions. Figure 7 (b) shows temperature profiles in the room and adjacent corridor with two nozzles on the room centerline. Figure 7(c) shows the temperature profiles with 2 nozzles mounted over the doors only. In both cases. compartment temperatures are significantly less than the near-flashover condition in Figure 7(a).

SUMMARY OF KEY FINDINGS

There is not enough room within the length-limit of a conference paper to present all the data upon which the conclusions of this study are based. The preceding information has described the test setup. The following highlights are selected from the list of key findings in the Interim Test Report [I]. The results of the analysis are presented as responses to pertinent questions.

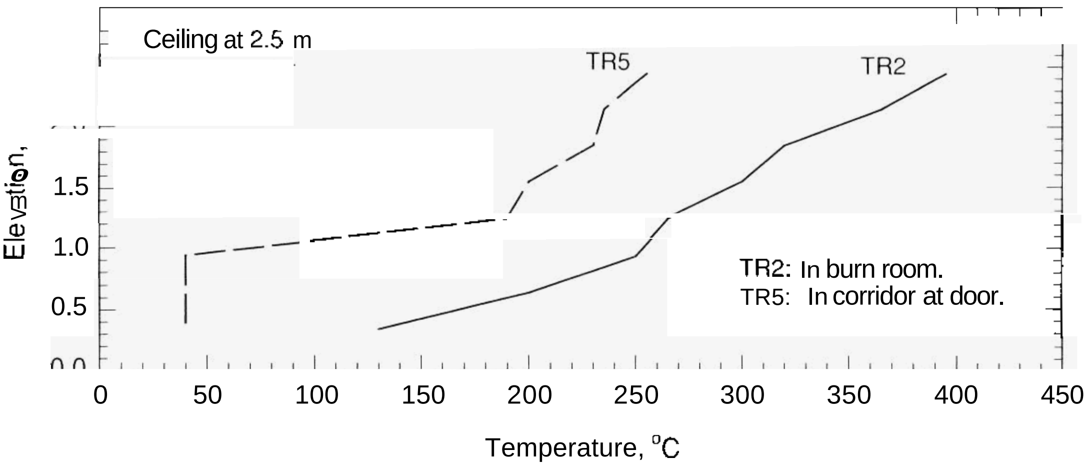


Figure 7(b): Test T18 K14 C3, Suppressed Wood Crib, t = 600 s

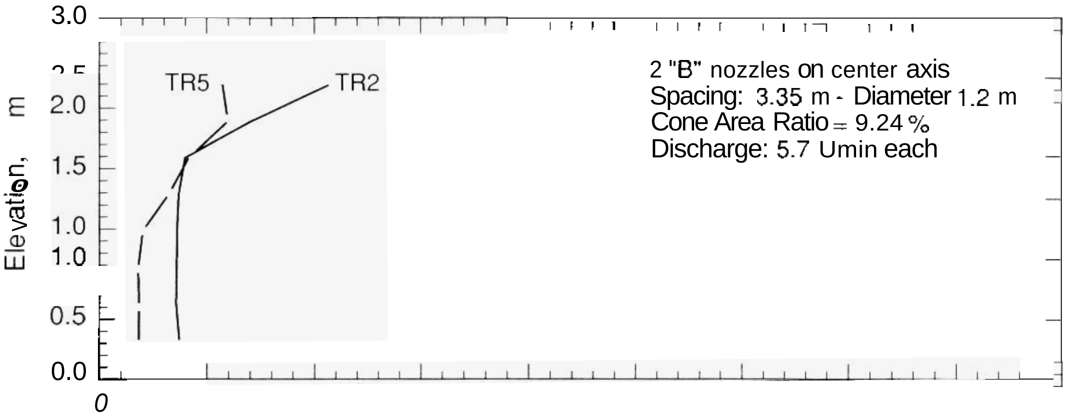


Figure 7(c): Test T26 K14 C3, Suppressed Wood Crib Fire, t = 720 s.

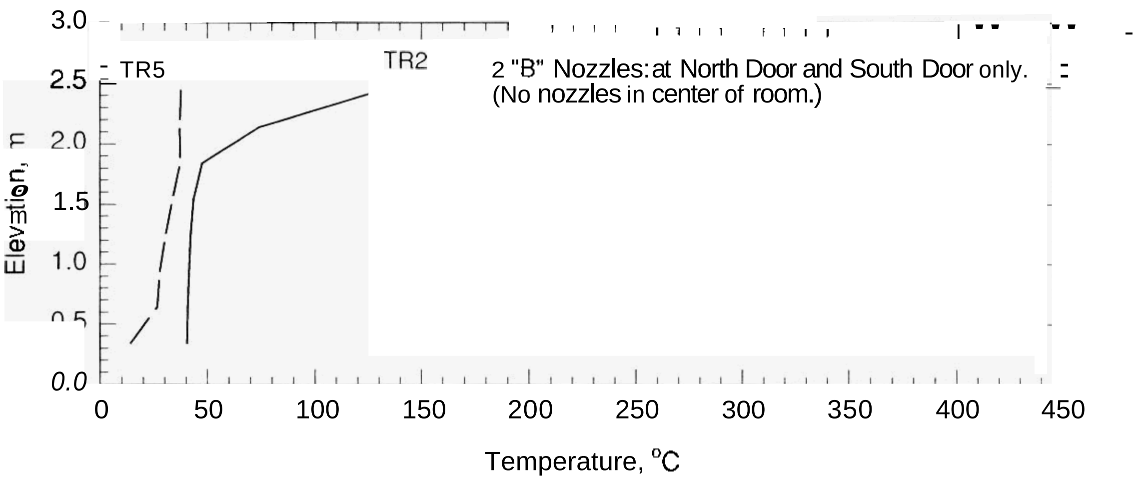


Figure 7. Temperature profiles in room and in corridor > 1 min duration.

Was flashover suppression achieved? In all of the tests the potential for flashover was eliminated by injection of water mist. Ceiling temperatures dropped below 150 "C, whether two nozzles were distributed in the middle of the room, or one sprayed over the doorway. As Figures 7(b) and 7(c) illustrate, temperatures inside the compartment were better controlled with nozzles in the center of the room than at the door only, but by less than 20 "C. On the other hand, a nozzle in front of the door did a better job of cooling the gases that entered the corridor than nozzles in the room only.

Were boundary cooling objectives achieved? Achieving flashover suppression has a direct benefit for boundary cooling objectives. If a compartment is prevented from becoming hot, there will be insufficient heat transfer through boundaries to ignite combustibles in adjacent compartments. An exception to this is where a shielded fire is directly against an uninsulated bulkhead.

Which type of nozzle performed "best"? The HP nozzle (C) with the finest drop size distribution had a greater degree of suppression of the wood crib fire than the LP nozzles. For a comparable degree of temperature control, the steady state oxygen concentration in the compartment with the HP nozzle dropped to 18%, as opposed to 15% with LP nozzles.

Are the results sensitive to ventilation conditions? A breach in a compartment, designed for minimal flow rates for flashover suppression. could lead to quick re-growth in fire intensity, particularly where nozzles are installed over the door(s) only. This breach could be due to battle damage or to entry of a damage-control crew through a previously closed opening. Although flashover suppression can be achieved with very low application rates and very few nozzles per compartment, control over ventilation can be lost in a variety of ways. Where control over ventilation cannot be rigorously achieved, a design that relies on nozzles distributed in the space, rather than over doors only, is preferred.

Effect of water mist on smoke conditions. The optical density data in these experiments did not provide unambiguous evidence that the water mist improved visibility through scrubbing of the smoke. The following statements can be made:

- Water mist has a mitigating effect on smoke conditions during a fire, by reducing the amount of fuel burned and soot generated, and reducing buoyancy and air entrainment.
- Potential improvement in visibility in corridors is likely to be more influenced by the type of fuel, the gas layer temperature and elevation of the neutral plane, and the presence of steam, than by particular application of water mist.

Could performance be improved by earlier detectionlactivation? A water-mist system designed for flashover suppression will not necessarily perform better if activated earlier. Since the mist system is not designed to extinguish fire, but rather to prevent it from spreading within the compartment or beyond, the small fire. if not extinguished fortuitously, will continue to grow until temperature and oxygen concentrations reach a steady-state equilibrium. From this it is concluded that WM system activation on a thermal signal, rather than early detection based on smoke sensor, is adequate for flashover suppression.

Individual temperature sensor readings in a compartment may vary considerably, depending on proximity to the fire, or the distance below the ceiling. This study demonstrated that the pressure reading between the fire compartment and an adjacent space is less dependent on location of the fire in the compartment than point temperature readings, and hence may be easier to interpret as "fire or non-fire" than point-type temperature sensor data.

CONCLUSION

Task 1 of this research program collected data on the characteristics of water-mist sprays produced by four commercially available water mist nozzles. A method of generating weighted-average, drop-size distributions was applied. The commercial nozzles tested displayed a broad range of drop-size distributions. As expected, high-pressure nozzles produced finer water mist than low pressure nozzles. High-pressure nozzles also demonstrated significantly higher average spray velocity than low pressure nozzles, even with comparable mass discharge rates.

The Task 2 fire testing confirmed that in low-ceiling. ventilation-limited shipboard spaccs, flashover suppression can he achieved easily using low water application rates and widely spaced nozzles. Maximum temperatures below 150 °C are possible, even with nozzles installed over doorways only. If limited ventilation cannot be assured. however. nozzles should be distributed throughout the compartment rather than only at the openings. Achieving tlashover suppression to a large degree also achieves boundary cooling, because the compartment of fire origin does not becomc hot enough for heat to ignite material in adjacent compartments.

The experience gained from this study will form the basis for design criteria for a water-mist system that requires a lower discharge rate than commercial systems. but still provides a degree of fire control consistent with DCARM objectives.

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