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# Full-Scale Experimental Study on Fire Suppression Performance of a Water Mist System for Large Shipboard Machinery Spaces

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Xiaowei Wu and Shouxiang Lu

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## Abstract

As a clean fire extinguishing agent, water mist has been considered to be an alternative to Halon 1301 on shipboard. Recently, a new water mist system was designed for large shipboard machinery spaces. In order to test the fire suppression performance of this system, a full-scale shipboard machinery compartment having a volume of 1200 m<sup>3</sup> was built. In this compartment, five fire scenarios, including diesel spray fires, diesel tray fires, and wood crib fires, were designed, and fire suppression parameters, including extinguishment time, compartment temperature, and gas concentrations, were measured. For all the scenarios, extinguishment times were typically less than 1 min, except for small fires. Average compartment air temperatures dropped to 70 °C within seconds after mist was activated. The CO concentrations of all the scenarios were below 4000 ppm, which was not life-threatening for short-term exposures. The test results indicated that this water mist system had an excellent ability to extinguish both obstructed and unobstructed Class B tray fires, Class B spray fires, and Class A fires in large machinery spaces. Meanwhile, the system could minimize the thermal damage to the compartment and its infrastructure and provide favorable conditions for personnel evacuation and firefighting. In conclusion, this newly designed water mist system was a viable alternative to Halon 1301 system for protecting large machinery spaces.

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## Keywords

Fire • Extinguishment • Halon alternatives • Water mist • Machinery space

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## 90.1 Introduction

Fires on shipboard may lead to a loss of capability, function, and life and, in extreme situations, the loss of the ship. Machinery spaces are high fire risk areas where flammable liquids are pumped and piped under pressure in the presence of ignition sources. Thus, installed fire protection systems are required in these spaces. As a very effective extinguishing agent, Halon 1301 has been widely used for

protecting ship machinery spaces since the late 1970s [1]. But Halon 1301 has ozone-depleting effect, which could decompose into chlorine, fluorine, and carbon components that react with the ozone in the atmosphere to eliminate it. In 1987, the provision of the Montreal Protocol was adopted to ban the use of Halon 1301 [2]. Faced with the inability to utilize Halon 1301 for future designs, considerable efforts were expended on halon replacement. One excellent candidate of the halon alternatives is water mist. The abundance of water, its lack of toxicity, and its environmental acceptability offered attractive incentives to pursue a water mist system.

The initial studies of water mist for fire protection applications started from 1978 to 1980 by the US Navy

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X. Wu • S. Lu (✉)  
State Key Laboratory of Fire Science, University of Science and  
Technology of China, Hefei, Anhui 230027, China  
e-mail: [sxlu@ustc.edu.cn](mailto:sxlu@ustc.edu.cn)

[3, 4]. In this period, the research was focused on calculations that illustrated how small water droplets, as contained in “water fog” or “fine water spray,” could achieve fire extinguishment by gas phase cooling. Then some experiments were carried out to validate the theoretical calculations.

From 1990 to 1994, water mist research entered into a prosperous period; the US Naval Research Laboratory conducted a series of small-scale testing in a  $3 \times 3 \times 2.4$  m steel compartment [5]. Parameters such as fire size and location, nozzle spacing, mist application rates, mist characteristics, ventilation, degree of obstructions, corner effects, and oxygen depletion were analyzed.

Following small-scale tests, full-scale tests were conducted to develop fundamental water mist system design parameters for protecting ship machinery spaces. But most of these tests were conducted aboard the US Navy’s fire research vessel, the Ex-Shadwell [6–13]. The Shadwell tests were run in a two-level compartment having a gross volume of  $960 \text{ m}^3$ . Thus, a question was posed: “if the shape of the test compartment changes and its volume is larger than  $1000 \text{ m}^3$ , are the conclusions of the Shadwell tests still working?” Meanwhile, the performance of nozzles and the technique of piping works are developing. Recently, a new water mist system was designed, whose fire suppression performance needed to be tested.

For the reasons above, a test compartment having a volume of  $1200 \text{ m}^3$  was built, which simulated a real shipboard machinery space. Five full-scale tests were conducted to study the suppression performance of the newly designed water mist system in the large compartment.

In this article, the test compartment, the configuration of the newly designed water mist system, the test fire scenarios, and the measure instrumentation were introduced. Then, the impact of water mist injection on extinguishment time, compartment temperature, and concentrations of combustion products was studied. A series of full-scale test data was obtained, providing relating reference for such engineering applications.

## 90.2 Experimental

### 90.2.1 Experimental Compartment

The tests were conducted in a full-scale compartment which was built to simulate a typical machinery space of ships (Fig. 90.1). The space was roughly  $21 \times 12 \times 6$  m ( $1200 \text{ m}^3$ ) and was bounded by metal bulkheads.

This space had three levels, i.e., a bilge level and two levels of catwalks, as shown in Fig. 90.1. These catwalks

allow easy access to critical areas in the space and, to some degree, serve as obstructions for the water mist systems. The catwalks located high in the space were constructed with metal grating, and the lower catwalks were constructed of steel plating. Typical machinery space equipments, such as engines, were simulated using sheet metal mock-ups as shown in Fig. 90.1. A  $2 \times 2$  m door was added in the aft bulkhead on the lower catwalk level, and a similar door was added in the forward bulkhead on the lower catwalk level. Four  $1.2 \times 1.3$  m vents and two  $1.8 \times 1.1$  m vents were added on the roof.

### 90.2.2 Water Mist System

Three types of nozzles were used in this water mist system. All the nozzles were researched and developed by self, and their specifications are listed in Table 90.1.

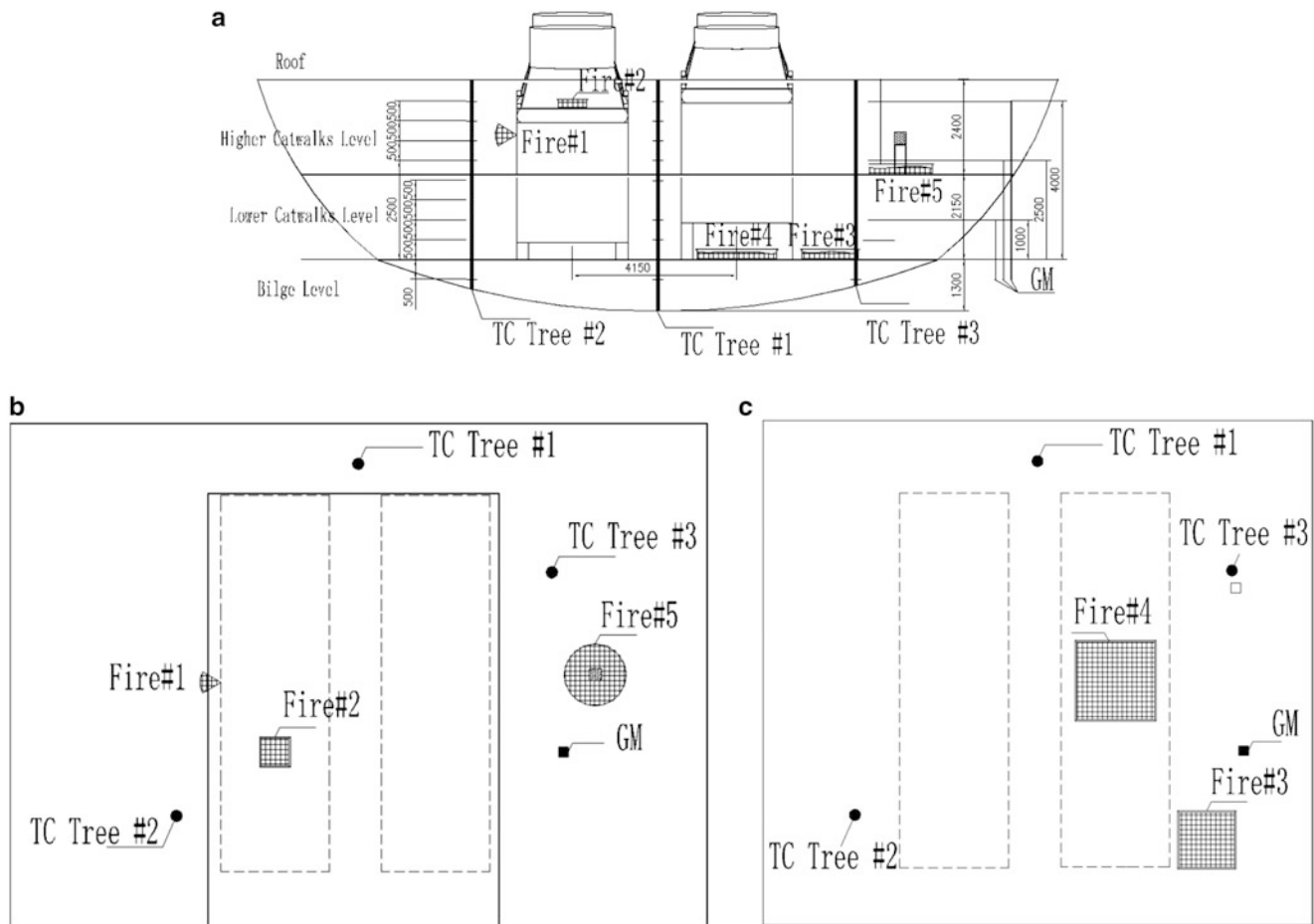
In order to improve the suppression capabilities of the system, the piping network was divided into three layers. The upper layer consisting of 31 nozzles was installed under roof. The middle layer consisting of 23 nozzles was installed under catwalks of grating, i.e., higher catwalks. The lower layer consisting of 16 nozzles was installed under catwalks of plate, i.e., lower catwalks. The piping network with nozzle locations was shown in Fig. 90.2.

The nozzle placement rules were followed. Under each platform of the compartment, a layer of nozzles should be installed. The spacing between nozzles should be less than the effective operating diameter of the nozzle. More nozzles should be considered in zones at high fire risk.

### 90.2.3 Fire Scenarios

To select fire scenarios reasonably, on the one hand, general standards, such as MSC/Circ.848, MSC/Circ.1165, and so on, were adopted. On the other hand, the possible fire scenarios of the simulated machinery compartment were analyzed.

Five types of fires were used in this study. The parameters of Fire #1–5 were listed in Table 90.2. Fire #1–4 were diesel fires to simulate Class B fires. Fire #1 was low-pressure horizontal spray with nominal fuel pressure 8 bar and fuel flow  $0.16 \pm 0.01 \text{ kg/s}$ . Fire #2 was an unobstructed small tray fire. Fire #3 was an unobstructed large tray fire. Fire #4 was obstructed by an engine mock-up. Fire #5 was a wood crib fire to simulate Class A fire. The locations of Fire #1–5 were shown in Fig. 90.1. With the combination of Fire #1–5, five fire scenarios are concluded, as shown in Table 90.3.



**Fig. 90.1** Machinery space mock-up: (a) elevation view, (b) plan view of the higher catwalk level, (c) plan view of the lower catwalk level

**Table 90.1** Specifications of the water mist nozzles

Nozzle type	DV99 ( $\mu\text{m}$ )	Operating pressure (MPa)	K-factor	Cone angle ( $^\circ$ )	Flow rate (L/min)
#1	70–100	8–10	1.45	90	13
#2	70–100	8–10	1.45	120	13
#3	70–100	8–10	1.21	120	13

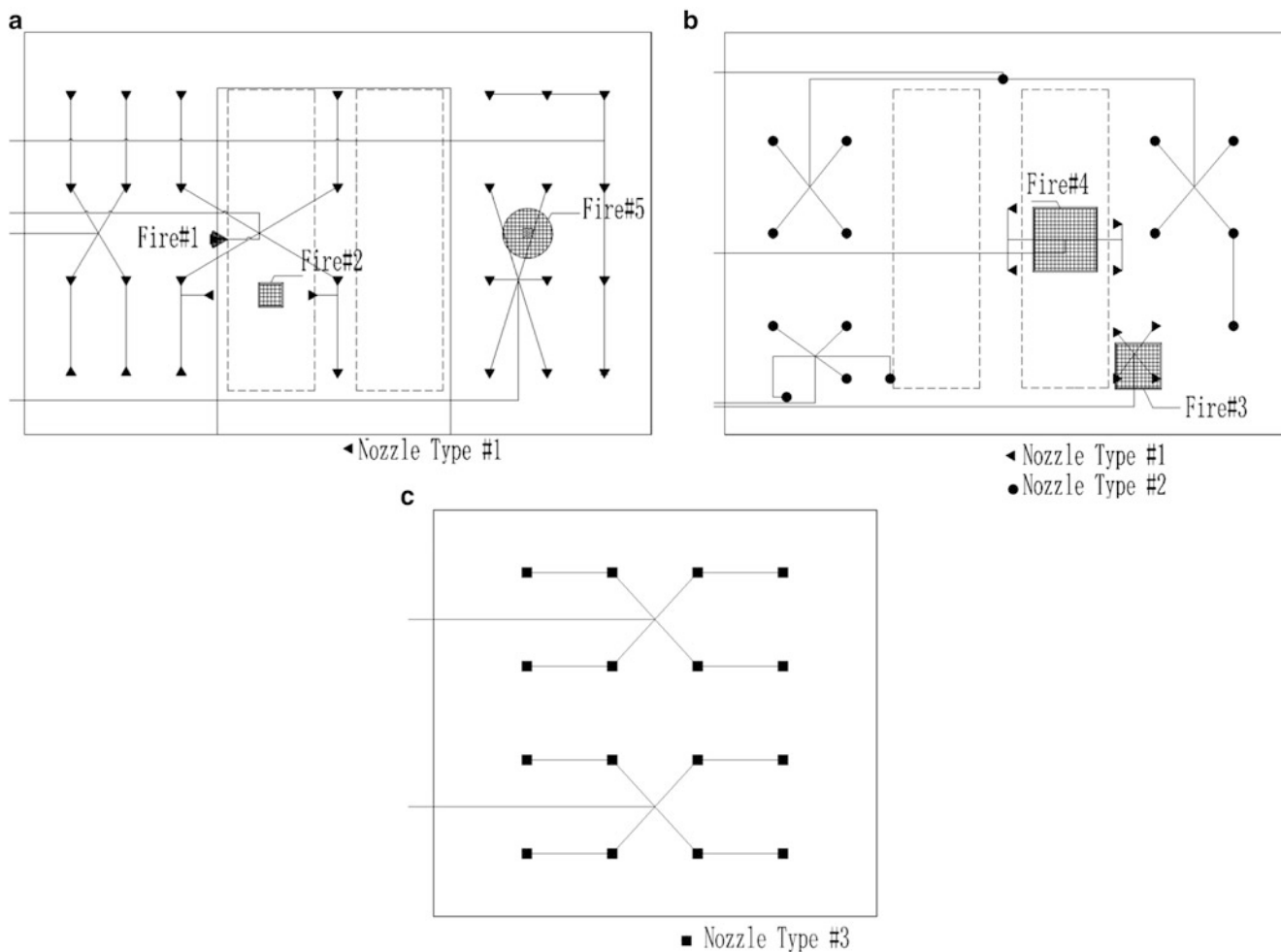
#### 90.2.4 Instrumentation

Three thermocouple trees were installed in the compartment. The thermocouple tree (TC Tree #1–3) layout was shown in Fig. 90.1. Each tree consisted of nine thermocouples. In order to measure the temperature at bilge, one thermocouple was set 0.5 m below the plates of the lower catwalks. The other eight thermocouples were poisoned at 0.5 m increments starting 0.5 m above the lower catwalk level. In order to determine the extinguishment time of each fire, thermocouples were located in the flame region of the fires. The thermocouples used in those tests were inconel-sheathed type-K thermocouples with 1.0 mm in diameter and could measure temperature up to 1200 °C.

In order to study the impact of water mist discharge on combustion products, gas analyzer was set up to measure the concentrations of carbon monoxide, carbon dioxide, and oxygen at three elevations in the compartment. The three measure points were poisoned at 1.0 m, 2.5 m, and 4.0 m above the lower catwalk level. The gas measure point (GM) layout was shown in Fig. 90.1.

#### 90.2.5 Experimental Procedures

The data acquisition system was activated prior to the test. Then the test fires were ignited leaving the compartment vents open. Fires were allowed a certain preburn period before the water mist is discharged. A 120-s preburn time is required for the tray fire and 5–15 s for the spray fire. For the wood crib fire, the preburn time is 30 s for Fire Scenarios #4 and 360 s for Fire Scenarios #5. After the preburn, the compartment was then sealed, and the mist system was activated. The mist system remained activated for a period of 15 min during each test or until all of the fires had been extinguished, whichever came first. At the completion of the



**Fig. 90.2** Piping network with nozzle locations: (a) higher catwalk level, (b) lower catwalk level, (c) bilge level

**Table 90.2** Parameters of fires

Fire no.	Type	Fuel	Fire size (MW)
#1	Spray	Diesel	6.0
#2	0.5 m <sup>2</sup> tray	Diesel	0.71
#3	2.0 m <sup>2</sup> tray	Diesel	3.0
#4	4.0 m <sup>2</sup> tray	Diesel	6.0
#5	Wood crib	Spruce	0.6

**Table 90.3** Fire scenarios

Scenario no.	Fire combinations
#1	Fire #1
#2	Fire #2
#3	Fire #3+ Fire #4
#4	Fire #5
#5	Fire #1+ Fire #3+ Fire #4+ Fire #5

discharge, the mist system was secured marking the end of the test. The space remained off-limits until cleared by the safety officer and the test director.

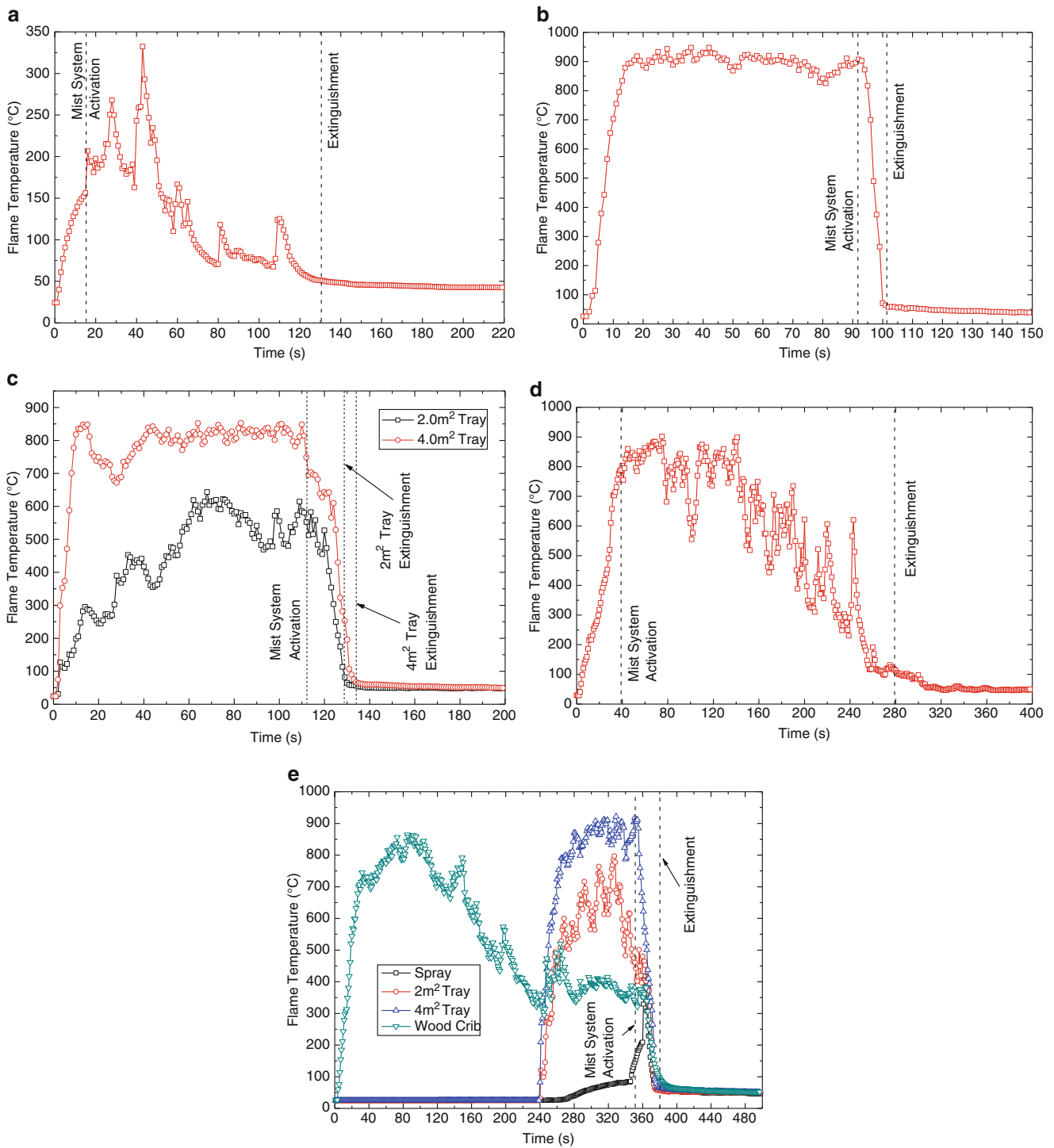
## 90.3 Results and Discussions

### 90.3.1 Flame Temperature and Fire Extinguishment Time

Extinguishment time was an important parameter to evaluate the suppression performance of a water mist system. In this article, the extinguishment time was defined as the time

between the injection of the water mist and the instant of fire extinguishment. The extinguishment of fires was determined based on temperature measurements recorded in the flame during each test. The flame temperature of each fire for each fire scenario was shown in Fig. 90.3. Extinguishment time for each fire scenario was shown in Fig. 90.4.

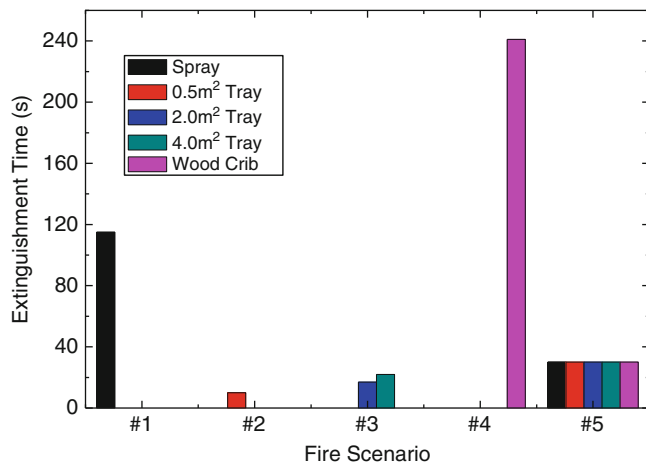
For Fire Scenario #1, the flame temperature of the spray fire was relatively low, about 160 °C before the system activation. After water mist injection, the temperature decreased while oscillating. This indicated that the water mist formed a relatively sealed space around the



**Fig. 90.3** Time history of flame temperature: (a) Fire Scenario #1, (b) Fire Scenario #2, (c) Fire Scenario #3, (d) Fire Scenario #4, (e) Fire Scenario #5

spray fire and the flame burnt as in a poor ventilation enclosure. Thus, the spray fire turned to be a small fire which was more difficult to extinguish than larger fires. So the extinguishment time for this scenario was relatively longer, about 115 s.

For Fire Scenario #2, the flame temperature of the small tray fire was about 900 °C before the system activation and dramatically decreased in a short time after water mist injection. The extinguishment time for this scenario was about 10 s.



**Fig. 90.4** Extinguishment time comparison for all the fire scenarios

For Fire Scenario #3, the 2.0 m<sup>2</sup> tray fire was unobstructed, and the 4.0 m<sup>2</sup> tray fire was obstructed by an engine mock-up. The extinguishment times of the two fires were both very short, 17 s for the 2.0 m<sup>2</sup> tray fire and 22 s for the 4.0 m<sup>2</sup> tray fire.

For Fire Scenario #4, the flame temperature of the wood crib fire was about 900 °C before the system activation. After water mist injection, the temperature decreased relatively slowly. The extinguishment time was about 241 s. Why Class A fires were so difficult to extinguish? Perhaps because the water mist could only put out the outer surface flame of the wood crib, and it was still high temperature in its inner part.

For Fire Scenario #5, fire resources included spray fire, unobstructed tray fire, obstructed tray fire, and wood crib fire. After water mist injection, all the fires extinguished in a short time, approximately 30 s. This indicated that although fires like Fire #1 and Fire #5 were difficult to extinguish alone, in the presence of larger fires, they were much easier to extinguish.

### 90.3.2 Compartment Temperature

Water mist could remove heat from a system because of its high specific heat and latent heat of vaporization. Thus, water mist systems could be used to thermally manage the conditions in machinery spaces.

In order to analyze the temperature changes in the test compartment, Fire Scenario #1 was taken, for example. The time history of compartment temperature at different heights for Fire Scenario #1 was shown in Fig. 90.5.

With regard to one thermocouple tree, before mist discharge, temperatures of higher thermocouples were higher

than those of lower thermocouples. It was in accordance with the fact that the upper room was filled with hot smoke and the lower room filled with cool air.

After water mist activation, the temperatures of higher thermocouples decreased, and those of lower thermocouples increased. This illustrated that the upper smoke layer and down cool air were mixed because of water mist injection.

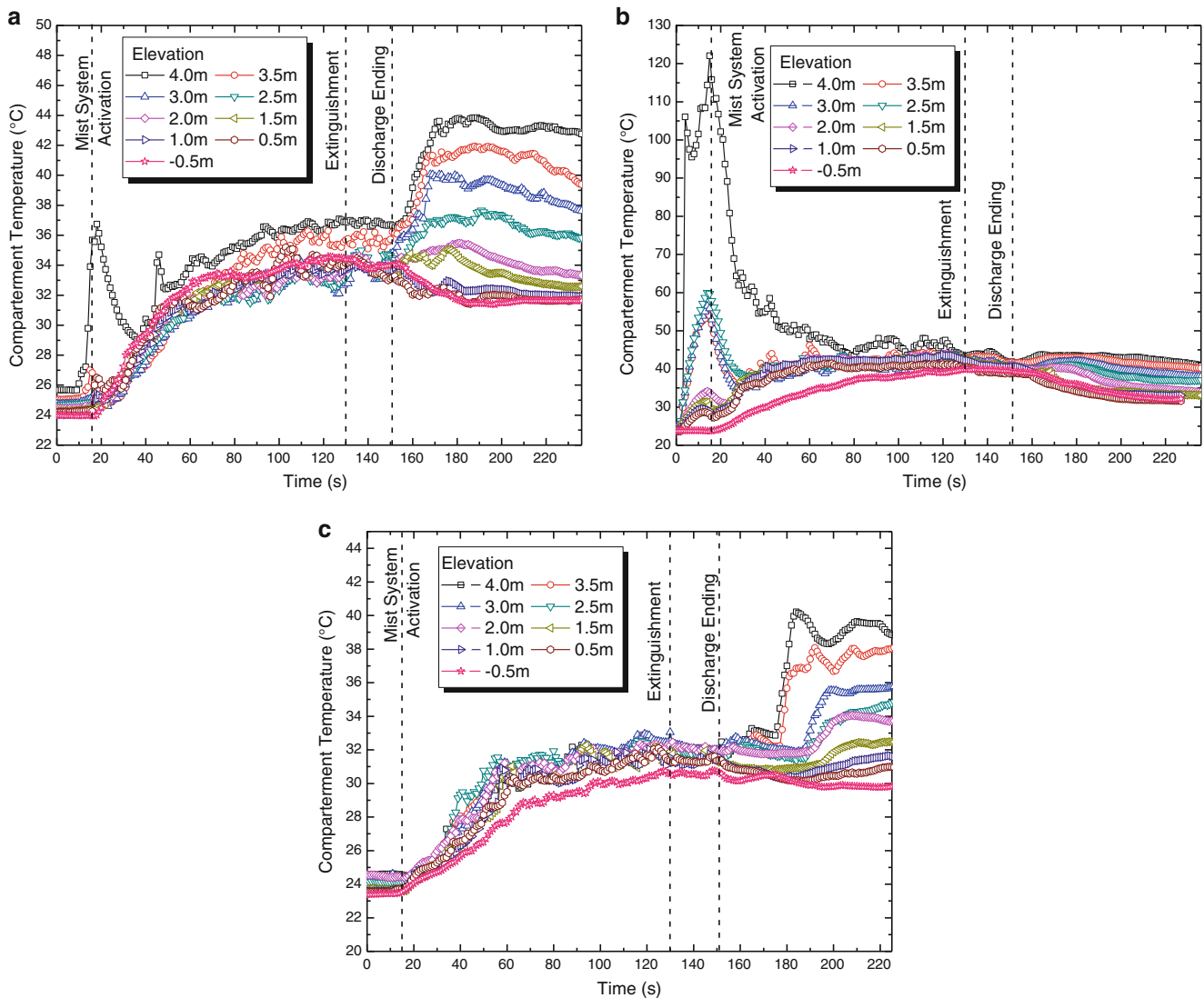
After mist injection ending, the temperature gradient at different levels reappeared. Perhaps this phenomenon was caused by the air mixing effects of water mist injection.

As shown in Fig. 90.5, for one thermocouple tree, the temperatures at different heights exhibited almost the same trend. Thus, average temperature was employed here. The time history of average compartment temperature of different thermocouple trees for all the fire scenarios was shown in Fig. 90.6. For all the fire scenarios, the compartment temperature reduced below 70 °C. According to US naval ships' technical manual, human would be incapable in 5 min and died in 30 min, and electronics would be permanent damaged when temperature was above 150 °C. Thus, the compartment temperature in our tests would help manual intervention, minimize thermal damage, and prevent fire spread from the compartment of origin.

### 90.3.3 Gas Concentration

The results of gas concentration measurement indicated that, for all cases, very slight variations were found in the O<sub>2</sub> and CO<sub>2</sub> concentrations, so only the changes in CO concentrations were analyzed in the following. The concentrations of CO at three measure points were shown in Fig. 90.7. The changes at three measure points exhibited almost the same trend for all the scenarios. The amounts of CO produced during the preburn remained fairly constant at low value, about 30 ppm, because the combustion was oxygen enriched in this period. During the extinguishment process, the amounts of CO were observed to dramatically increase in a certain time and then decreased. This indicated that water mist injection really brought incomplete combustion at the beginning, but it could then dilute CO with the continuing discharge. Compared to all the scenarios, the CO concentration was larger when fire HRR was higher.

While the extinguishment of these fires produced significantly higher CO concentrations, the amount of CO for each scenario was below 4000 ppm. According to US naval ships' technical manual, human would be incapable in 5 min and died when CO concentration was above 4000 ppm. Thus, the CO concentration in our tests was not life-threatening for short-term exposures. It would provide favorable conditions for personnel who remained staying in the space.

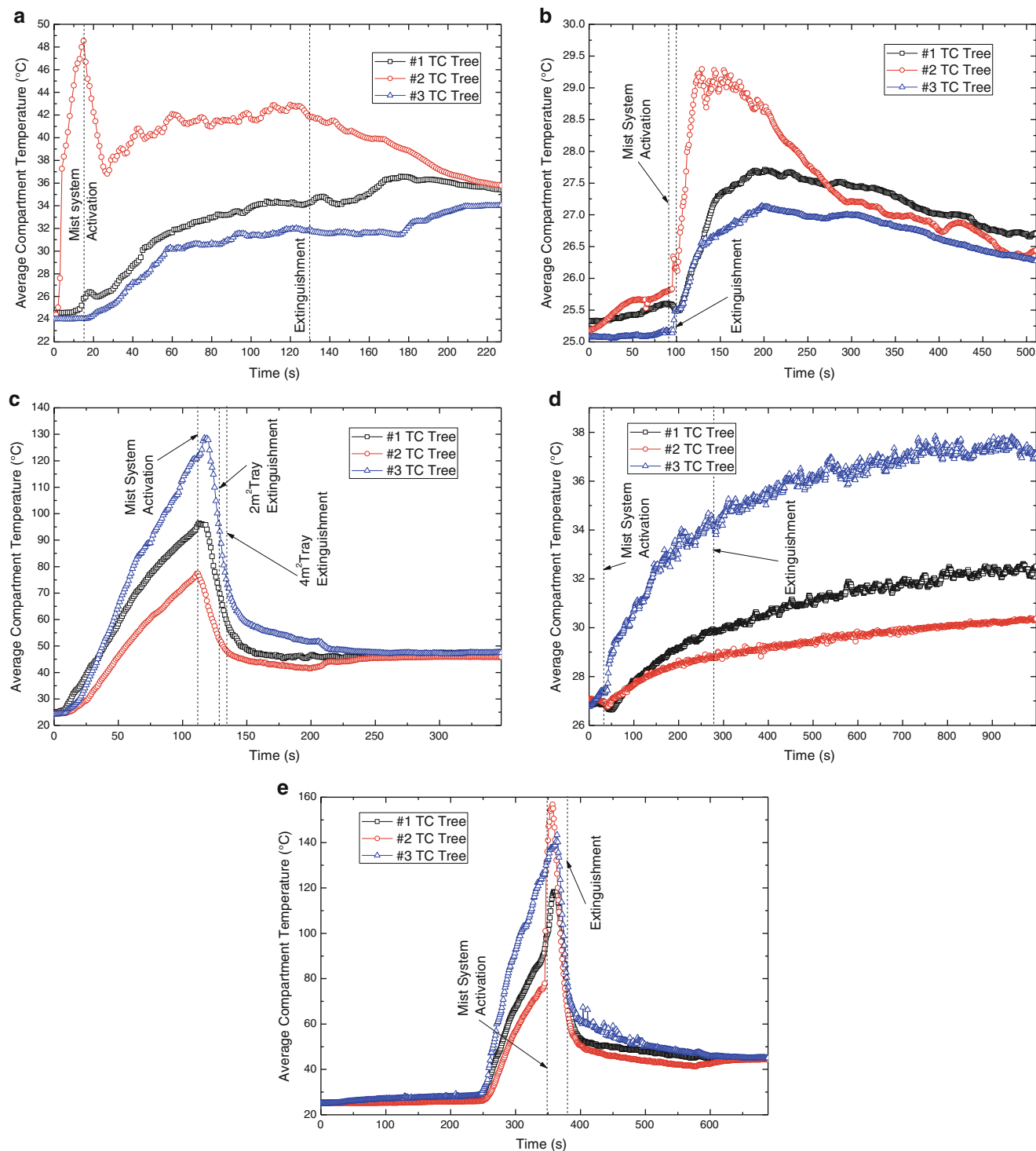


**Fig. 90.5** Time history of compartment temperature at different heights (Fire Scenario #1): (a) thermocouple tree #1, (b) thermocouple tree #2, (c) thermocouple tree #3

## 90.4 Conclusions

Water mist fire suppression systems are being seriously considered to replace Halon 1301 total flooding systems in machinery space applications. In this article, a full-scale experimental facility was built to study the fire suppression performance of a newly designed water mist system for large shipboard machinery spaces. A series of full-scale tests was carried out with different fire scenarios. The tests contributed valuable experimental data for water mist systems installed in large machinery spaces. Conclusions can be drawn as follows:

1. These tests have demonstrated the ability of the newly designed water mist system to extinguish both obstructed and unobstructed Class B tray fires, Class B spray fires, and Class A fires in large machinery spaces.
2. The system required minutes to extinguish fires as opposed to seconds for the gaseous halon alternatives.
3. The parameters of the water mist system nozzles and piping networks, the extinguishment experimental data, and the results provided in this article may serve as an available reference for such engineering applications.
4. The water mist system can be used to thermally manage the conditions in the machinery spaces. For all of the fire



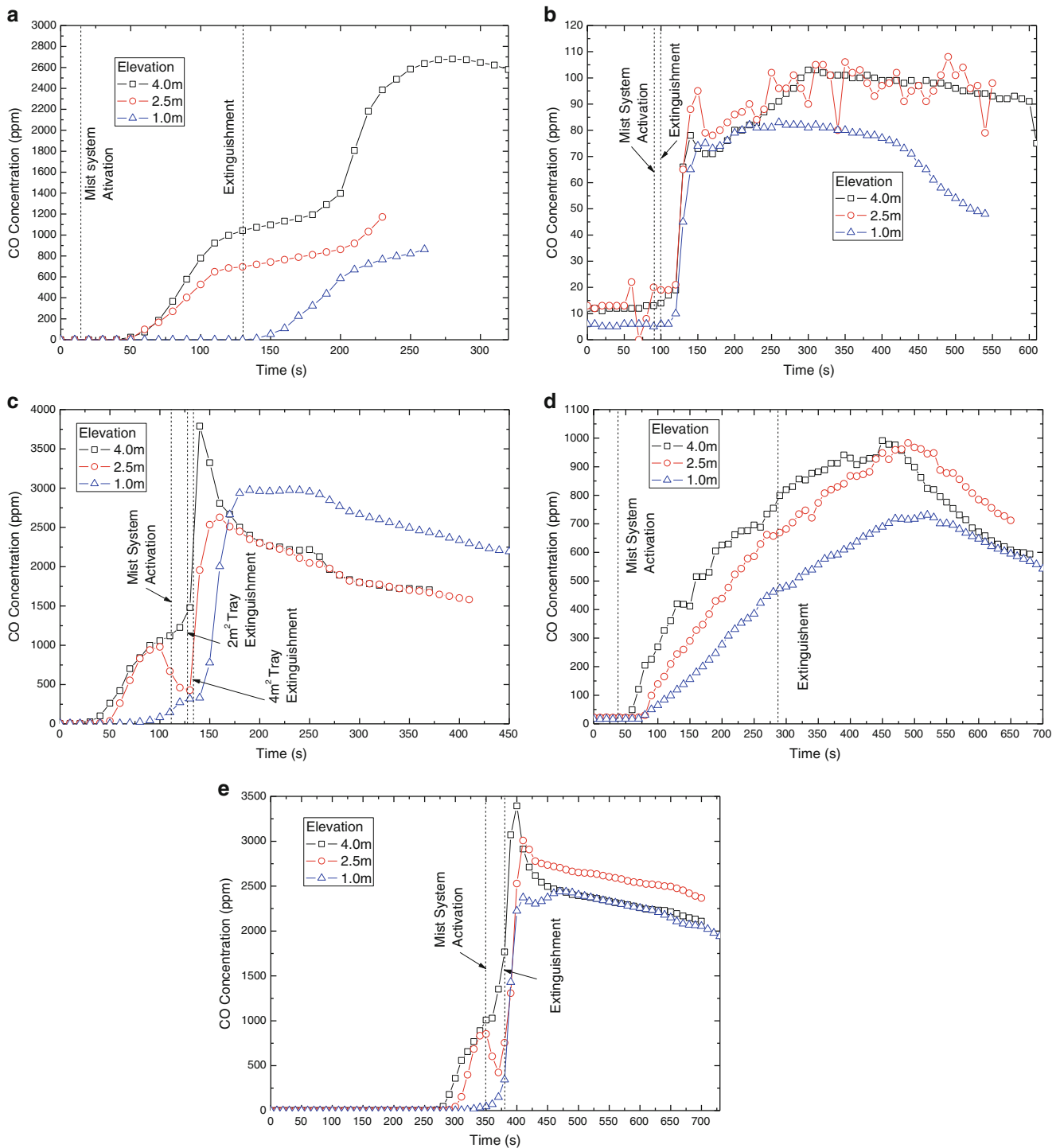
**Fig. 90.6** Time history of average compartment temperature of different thermocouple trees: (a) Fire Scenario #1, (b) Fire Scenario #2, (c) Fire Scenario #3, (d) Fire Scenario #4, (e) Fire Scenario #5

scenarios, the system dramatically reduced the temperature of the space almost immediately after activation, and the space became well mixed with a uniform temperature below 70 °C. This reduction in temperature will minimize the thermal damage to the compartment and its

infrastructure and provide favorable conditions for personnel evacuation and firefighting.

- For all of the fire scenarios, CO concentrations were below 4000 ppm. It would provide favorable conditions for personnel who remained staying in the space.





**Fig. 90.7** Time history of CO concentrations at different heights: (a) Fire Scenario #1, (b) Fire Scenario #2, (c) Fire Scenario #3, (d) Fire Scenario #4, (e) Fire Scenario #5.

In conclusion, this newly designed water mist system has an excellent ability to extinguish fires in the secured large compartment. However, ventilation was not considered in those tests. Thus, in the future, the ventilation effect on the fire suppression capabilities of the water mist system will be studied in the full-scale test compartment.

## References

1. Darwin RL, Williams FW (2000) The development of water mist fire protection systems for U.S. navy ships. *Navy Eng J* 11:49–57
2. United Nations Environment Program (1987) The montreal protocol on substances that deplete the ozone layer, Nairobi

3. Fielding, GH, Williams EW, Carhart HW (1977) Suppression – why not water? NRL Memorandum Report 3435, Washington, DC
4. Lugar JR, Fornslor RO, Carhart HW, Fielding GH (1978) Flame extinguishment by waterfogs and sprays, fifth quadripartite conference IEP ABCA-7
5. Hanauska CP, Back GG (1993) Halons: alternative fire protection systems, an overview of water mist fire suppression systems technology. Hughes Associates, Columbia
6. Leonard JT, Back GG (1994) Revised test plan: full-scale testing of total-flooding water mist system, NRL Ltr Rpt Ser 6180/0716.2
7. Leonard JT, Back GG, DiNenno PJ (1994) Full scale machinery space water mist tests: phase I – unobstructed space. NRL Ltr Rpt Ser 6180/0713.1. Naval Research Laboratory, Washington, DC
8. Leonard JT, Back GG, DiNenno PJ (1994) Full scale machinery space water mist tests: phase II – simulated machinery space. NRL Ltr Rpt Ser 6180/0868.2, Naval Research Laboratory, Washington, DC
9. Darwin RL, Leonard JT, Back GG (1995) Status report on the development of water mist systems for U.S. Navy shipboard machinery space, halon options technical working conference, final program/abstracts. Albuquerque
10. Leonard JT, Darwin RL, Back GG (1995) Full scale tests of water mist fire suppression systems for machinery spaces. In: Proceedings international conference on fire research and engineering, D.P Lund, Editor, Society of Fire Protection Engineers
11. Back GG, DiNenno PJ, Leonard JT, Darwin RL (1996) Full scale tests of water mist fire suppression systems for navy shipboard machinery spaces: phase I – unobstructed spaces. NRL/MR 6180-96-7830, Naval Research Laboratory, Washington, DC
12. Back GG, DiNenno PJ, Leonard JT, Darwin RL (1996) Full scale tests of water mist fire suppression systems for navy shipboard machinery spaces: phase II – obstructed spaces, NRL/MR/6180-967831. Washington, DC
13. Back GG, Darwin RL, Leonard JT (1996) Full scale tests of water mist fire suppression systems for navy shipboard machinery spaces. In: Proceedings INTERFLAM 96. St. Johns College, Cambridge