Examination of Performance of Water Mist Fire Suppression Systems under Ventilation Conditions

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ABSTRACT: This paper describes water mist fire suppression effectiveness under various ventilation conditions. The full-scale fire test series were conducted in an empty enclosure and in a simulated machinery space. Fire scenarios in the tests included small and large pool fires, spray fires and wood crib fires that were placed at different locations within the compartment. The ventilation conditions varied from no ventilation, natural ventilation to forced ventilation. A single-fluid/high pressure and a twin-fluid/low pressure water mist systems were used, respectively, in the tests.

The test results showed that water mist suppression effectiveness was dependent on ventilation rates, fire size, type and location in the compartment as well as the characteristics of the water mist system used. During tests, both single- and twin-fluid water mist systems effectively extinguished fires under natural ventilation. Under forced ventilation, however, water mist fire suppression effectiveness was substantially reduced due to the strong mass exchange between the room and its surroundings.

KEY WORDS: fire suppression, water mist, ventilation.

INTRODUCTION

When gaseous agents are used to extinguish fires, ventilation systems in the compartment must be shut down, otherwise the fire protection system can be expected to fail. As reported in a study of fire protection of gas turbine installations [1], a 37% failure rate for total flooding halon or carbon dioxide systems was attributed to the extinguishment agent leaking from the protected compartment through open doors or vents. Water mist fire suppression systems have already demonstrated their efficacy for fire protection in a wide range of applications, including the protection of machinery spaces, gas turbine enclosures, and computer rooms [2–8]. Recent research further showed that water mist fire sup-

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pression systems were able to extinguish fires effectively with a definable degree of ventilation, such as with open doors or vents in a compartment, while gaseous agents could not work effectively under such ventilation conditions [9–11]. These studies suggested that the suppression effectiveness of water mist under ventilation conditions would further increase the range of water mist applications for fire protection. However, up to now, the capability and limitation of water mist fire suppression under a wide range of ventilation conditions, including both natural and forced ventilation, have not been investigated systematically, and the relationship between fire location and size, water mist characteristics and various ventilation conditions has not been analyzed.

In order to systematically understand and investigate the performance of water mist fire suppression systems under various ventilation conditions, a series of full-scale fire tests of water mist were carried out by the National Research Council of Canada. The fire scenarios used in the tests included small and large pool fires, spray fires and wood crib fires. These fires were placed in different locations within the compartment and some fires were shielded from the direct hit of water mist. The ventilation conditions in the compartment included non-ventilation (door closed), natural ventilation (door open) and forced ventilation (door open and an exhaust fan running). Two types of water mist systems (single-fluid and twin-fluid) were used in the tests. This paper reports the test results.

TEST FACILITY AND FIRE SCENARIOS

The test facility consisted of a specially-constructed compartment, a water distribution network and appropriate instruments to monitor and record test results.

Test Room

The test room was an irregular-shaped, rectangular room with dimensions of 9.7 m × 4.9 m × 2.9 m high, and with a corner (2.9 m × 2.2 m) removed. The test room had a 2.0 m × 0.9 m door and three 0.56 m^2 viewing windows. The room also had a 0.5 m × 0.5 m pressure relief vent attached to a fan in the south wall near the floor. Plan and elevation views of the room are shown in Figures 1 and 2.

Water Mist Systems

Two types of water mist systems were used in the tests: a single-fluid/high pressure system and a twin-fluid system. The detailed parameters of these two water mist systems are listed in Table 1.

The nozzle layout (number and location) of the two water mist systems was based on the guidelines provided by the manufacturers. For the single-fluid/high

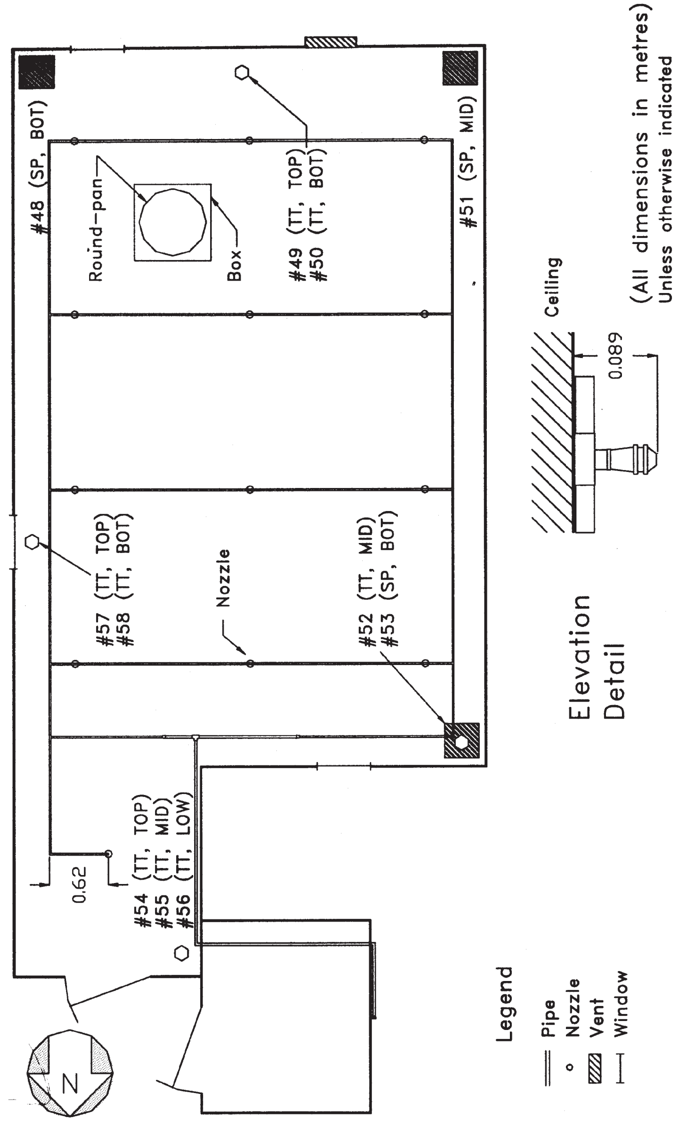

Figure 1. *Fire locations and a single-fluid water mist system in an empty enclosure (plan).*

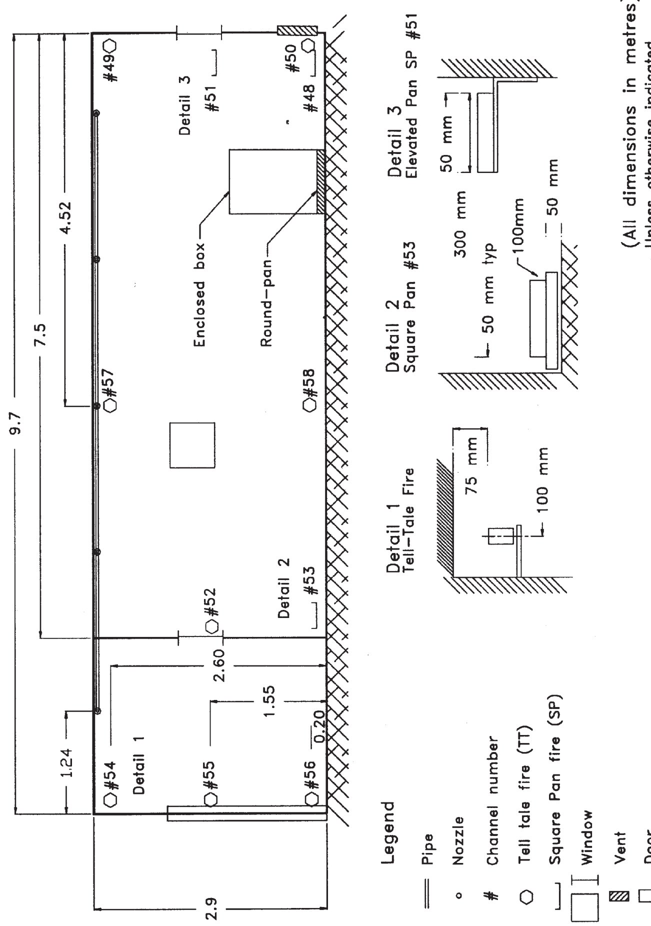

Figure 2. *Fire locations and a single-fluid water mist system in an empty enclosure (elevation).*

Table 1. Characteristics of the single-fluid and twin-fluid water mist systems.

System Types	Water Flow Rate (Lpm)	Pressure (bar)	Spray Cone Angle (degree)	Droplet Size ($D_{v0.9}$ microns)
Single-fluid (Reliable/Baumac)	6	70	90	200–400
Twin-fluid (Securiplex)	5	5.78 (water) 6.67 (air)	90	200–400

pressure water mist system, thirteen nozzles were installed on the ceiling, as shown in Figures 1 and 2. The spacing of the nozzles was 1.83 m × 1.83 m. The distance from the side nozzles to the south and north walls was 1.05 m, and to the east and west walls the distance was 0.95 m. One nozzle was located 1.24 m from the door. The total water discharge rate of the system was 78 Lpm.

For the twin-fluid/low pressure water mist system, water and air were distributed in the compartment through the network, as shown in Figures 3 and 4. Fourteen twin-fluid nozzles were installed on the ceiling. The spacing of the nozzles was 1.63 m × 1.88 m. The distance from the side nozzles to the south and north walls was 0.94 m, and to the east and west walls the distance was 0.92 m. One nozzle was located 0.7 m from the door of the room. The total water discharge rate of the system was 70 Lpm.

Fire Scenarios

The full-scale tests were conducted in an empty enclosure and in a simulated machinery space. The test fires included tell-tale (TT) fires (each in a 75 mm diameter can), square-pan fires (each with dimensions of 0.3 m × 0.3 m), round-pan fires (0.7 m in diameter), spray fires and wood crib fires. The operating pressure of the heptane spray fire was 5.8 bar. The wood crib was made of 0.04 m thick pine sticks in 6 layers and was approximately 0.6 m × 0.6 m × 0.25 m high. These fires were placed at different locations within the compartment. Each type of fire size was determined by measuring its heat release rate in the open by oxygen consumption calorimetry. These fire sizes were the free burn levels and may be changed with surrounding conditions during fire suppression.

Fire Scenarios in an Empty Enclosure

For the test series in an empty enclosure, eight tell-tale heptane fires were placed strategically throughout the room at different elevations (see Figures 1 and 2). One tell-tale fire was placed in the center of the mock-up cabinet. The total heat output of the tell-tale fires was approximately 50 kW. Three square-pan heptane fires

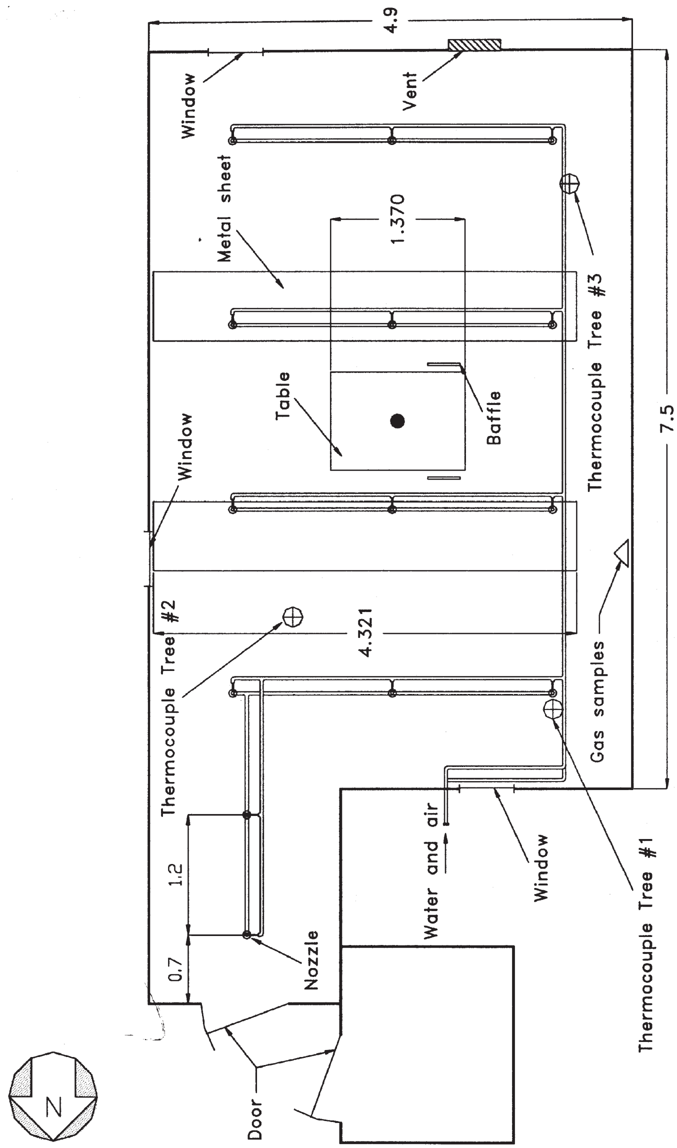

Figure 3. *Test facilities, fire locations and a twin-fluid water mist system in engine mock-up test (plan).*

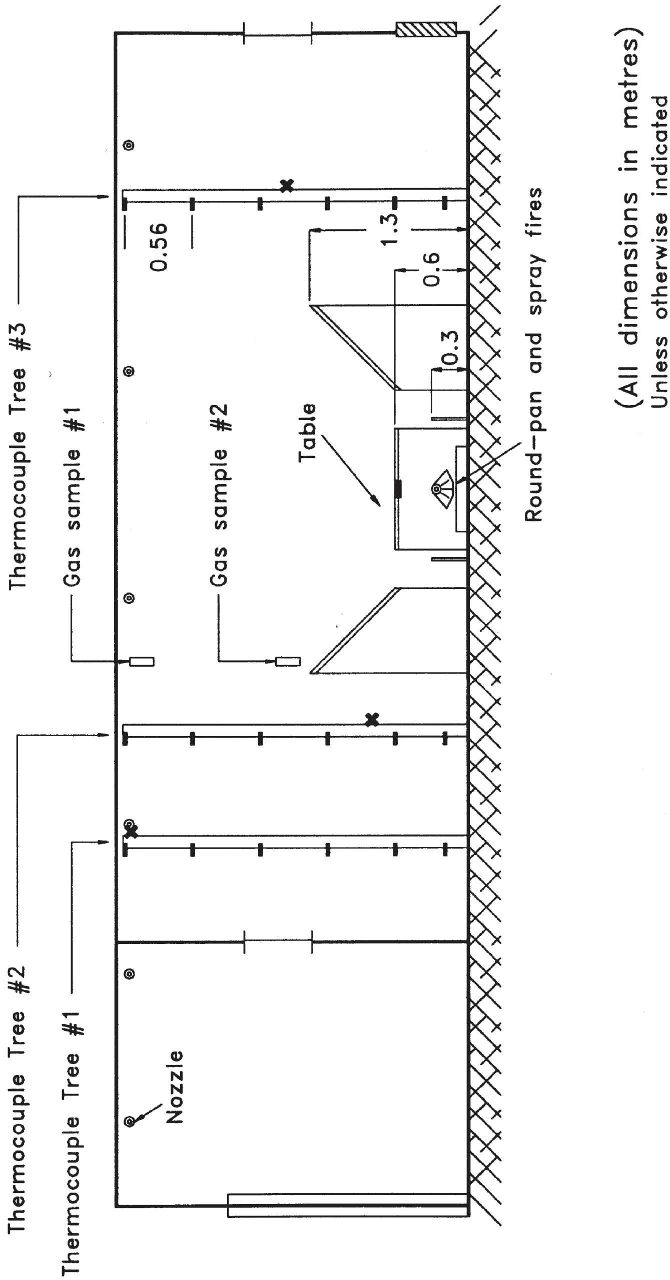

Figure 4. *Test facilities, fire locations and a twin-fluid water mist system in engine mock-up test (elevation).*

were placed in three corners. The heat output produced by each square-pan fire was approximately 50 kW. One round-pan heptane fire and one heptane spray fire, respectively, were placed close to the southeast corner of the room and covered with a perforated metal box so that these fires were shielded from direct water spray. The dimensions of the box were 0.80 m × 0.84 m × 0.94 m high. The top of the box was covered by a layer of sheet metal with holes that constituted a 6% opening ratio. The sides of the box were covered by metal meshes with a 33% opening ratio. The operating pressure of the heptane spray fire was 5.8 bar. The heat outputs of the round-pan and spray fires were approximately 500 kW and 520 kW, respectively. One wood crib was placed at the southwest corner of the room. It produced a heat output of approximately 450 kW. During the tests, these fires were selected to form specific fire scenarios that presented various fire challenges for water mist.

Fire Scenarios in a Simulated Machinery Space

For the test series in a simulated machinery space, a diesel engine mock-up, which was mainly based on the fire test protocol recommended by Factory Mutual Research Corporation (FMRC), was used (see Figures 3 and 4). To simulate the lower portion of a turbine casing, a solid metal table with a height of 0.6 m was placed in the center of the room while the perimeter of the table was fitted with 0.85 mm thick galvanized sheet metal. The sheet metal was installed at a 45° upward angle with respect to the table. The space below the table was partially shielded using two 0.3 m high × 0.3 m long vertical sheet metal baffles.

To simulate a large shielded pool fire, a heptane pool fire, 0.7 m diameter, was placed under the table and produced a heat output of approximately 500 kW. For the shielded heptane spray fire tests, one spray nozzle was placed under the table with an upward angle of 20° to strike the center of the table. The operating pressure of the spray fuel was 5.8 bar and the heat output of the spray fire was 520 kW. During the tests, only a twin-fluid water mist system was used.

Instrumentation

Three thermocouple trees, as shown in Figures 3 and 4, were set up in the room to measure room temperatures and the effect of ventilation on fire suppression. Each tree contained six thermocouples at approximately 0.56 m intervals vertically. Thermocouple Tree #2 was set up facing the door of the compartment and was 4.3 m from the door, which was used to measure the invasion of fresh air. To monitor the extinguishment of the fires, thermocouples were also placed at each fire location.

Nine pressure taps were installed on the west wall to monitor the pressure changes in the room during the activation of the water mist discharge and fire suppression period (see Figures 3 and 4). Three pressure taps were located at each of three elevations. The pressure taps at each location were manifolded to give an average pressure reading.

Two copper gas sampling ports, 12 mm in diameter, were located in the west wall as shown in Figures 3 and 4. One sampling port, 1.5 m above the floor and projecting 0.3 m into the room, was used to measure the concentrations of CO and CO_2. Another sampling port, 2.8 m above the floor and projecting 0.3 m into the room, was used to measure the concentrations of O_2, CO and CO_2. The gases were drawn through copper condensing coils immersed in water to remove water vapor and then measured by two Siemens Ultramat 22P Series** for CO_2 and CO concentrations and one Siemens Oxymat 5E O_2 analyzer for O_2 concentrations.

Two video cameras were set up at the south and north windows to obtain visual records of the water mist discharge and the behavior of the fires during suppression.

Test Procedure

During the tests, ventilation conditions included the door closed, the door open (natural ventilation) and the combination of the door being open with an exhaust fan running (forced ventilation). The flow rate of the exhaust fan was 0.737 m^3/s.

Test fires were allowed at least a 30 s pre-burn period before suppression commenced. During the pre-burn period, the door was kept open to allow fresh air to enter the room. At the beginning of the water mist discharge, the door was either kept open or closed, depending on the ventilation conditions for the test. For the tests with forced ventilation conditions, the exhaust fan was turned on at the same time as the water mist system was activated.

Fire suppression processes were directly observed through three windows of the compartment and monitored by thermocouples placed at each fire location. Test data were recorded at 1 s intervals. Visual observation and fire temperatures measured at each of the fire locations determined fire extinguishment. Before it was assumed that the water mist system was unable to extinguish the fire, the fire was allowed to burn for 7 to 16 minutes, depending on fire conditions and the changes in oxygen concentration in the compartment.

RESULTS AND DISCUSSION

The full-scale test series with two types of water mist systems were divided into three phases: tests with no ventilation, natural ventilation and forced ventilation. The extinguishing time is defined as the time interval between the activation of the water mist system and the instant of fire extinguishment. The average water den-

**Certain commercial products are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendations or endorsement by the National Research Council, nor does it imply that the product or material identified is the best available for the purpose.

sity (W_d) per area is introduced to measure the quantity of water required for fire extinguishment. It is defined as the ratio of the total amount of water discharged (W_t) over the compartment area (A_c):

$$W_d = \frac{W_t}{A_c} \quad (\mathrm{L/m^2}) \tag{1}$$

Water Mist Performance under No Ventilation

Table 2 lists the test results obtained from Phase I of the test series with two types of water mist systems in the empty enclosure and in the simulated machinery space, when there was no ventilation in the compartment. Figures 5 to 8 show the changes in the gas temperature and CO_2 concentration in the compartment during non-ventilated pool and wood crib fire tests, when the single-fluid/high pressure water mist system was employed. Pre-burn periods for the pool fire test and the wood crib fire test were 30 s and 90 s, respectively. During the pre-burn period, the room was heated and hot gases from the fires tended to concentrate near the ceiling. The gases in the room could be characterized in terms of two zones: an upper zone with hot combustion products and a lower zone with less affected air. As shown in Figures 7 and 8 during the wood crib fire test, with the longer pre-burn period, the thickness of the upper zone was increased and gas temperatures in the upper zone were also substantially high, compared to a short pre-burn period in the pool fire test (Test 1-1). When water mist was discharged downward from the ceiling level, it took 10 to 15 s for water mist to cool the gases in the upper zone as fine water droplets absorbed heat from their hot surroundings and quickly evaporated. At the same time, the discharge of water mist created a strong dynamic mixing in the compartment. The combustion products and water vapor in the hot layer near the ceiling were pushed downward by water mist to mix with the gases near the floor of the compartment, resulting in the rise of the gas temperatures and CO_2 concentration near the floor. As shown in Figures 5 to 8 for both pool and wood crib fire tests, gas temperatures and CO_2 concentrations tended to be uniform throughout the compartment due to the dynamic mixing, after the activation of the water mist system for about 20 to 30 s. The gases in the room could be characterized in terms of one zone that consisted of combustion products, water vapor and air.

As a result, with the discharge of water mist, the compartment was cooled down and oxygen and fuel vapor available for combustion were reduced due to the displacement by water vapor, but the effectiveness of water mist in suppressing fires was strongly dependent on the fire size and its location in the compartment. As shown in Table 2, during 4 full-scale tests (Test 1-1 to Test 1-4) in the empty enclosure involving different fire size, type and location in the compartment, tell-tale

Table 2. Summary of full-scale test results under non-ventilation (door closed).

Recorded Event	Test 1-1	Test 1-2	Test 1-3	Test 1-4	Test 1-5	Test 1-6
System Types	Single-fluid	Single-fluid	Single-fluid	Twin-fluid	Twin-fluid	Twin-fluid
Mock-Up in the Compartment	Empty	Empty	Empty	Empty	Machinery	Machinery
Fire Types	8 TTs 3 SPs 1 shielded pool fire	9 TTs 2 SPs 1 wood crib fire	8 TTs 1 shielded spray fire	8 TTs 3 SPs 1 shielded pool fire	1 shielded pool fire	1 shielded spray fire
Fire Size	700 kW	600 kW	570 kW	700 kW	500 kW	500 kW
TT 49—Ext. Time (s)	73	55	80	100		
TT 50—Ext. Time (s)	46	40	65	54		
TT 52—Ext. Time (s)	48	25	22	74		
TT 54—Ext. Time (s)	200	205	225	153		
TT 55—Ext. Time (s)	82	57	65	35		
TT 56—Ext. Time (s)	160	133	165	175		
TT 57—Ext. Time (s)	88	20	115	95		
TT 58—Ext. Time (s)	22	30	37	65		
TT 64—Ext. Time (s) (in the cabinet)		195				
SP 48—Ext. Time (s)	127	No ext.		225		
SP 51—Ext. Time (s)	40			105		
SP 53—Ext. Time (s)	177	No ext.		163		
Round-Pan Fire Ext. Time (s)	210			300	114	
Wood Crib Fire Ext. Time (s)		95				
Spray Fire Ext. Time (s)			140			113
Water Quantity (L/m^2)	6.4		6.8	8.2	3.1	3.1

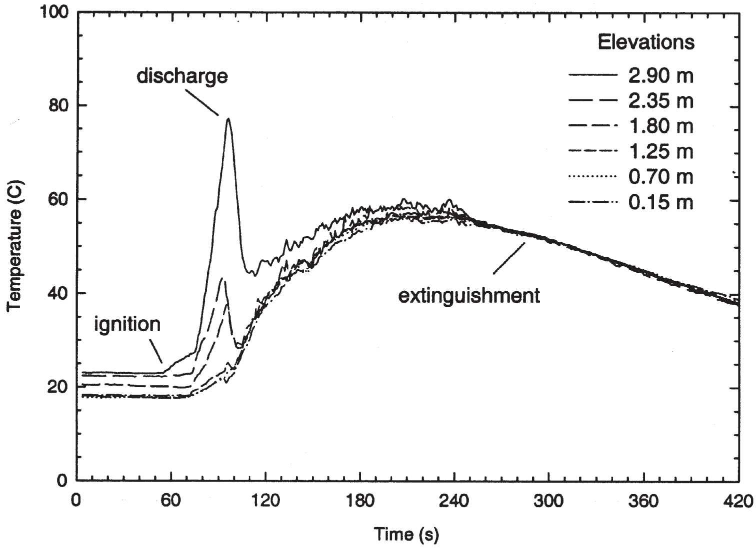

Figure 5a. *Room temperatures measured at Thermocouple Tree #1 in Test 1-1 with pool fires, when the single-fluid/high pressure water mist system was employed and the door was closed.*

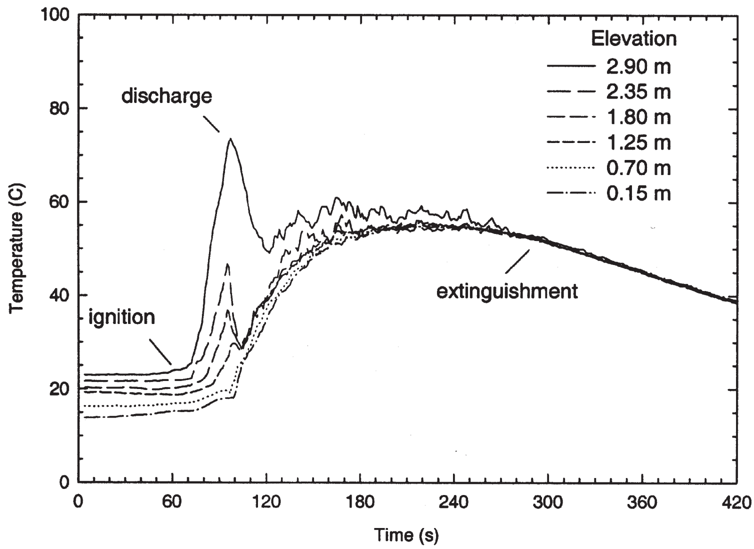

Figure 5b. *Room temperatures measured at Thermocouple Tree #2 in Test 1-1 with pool fires, when the single-fluid/high pressure water mist system was employed and the door was closed.*

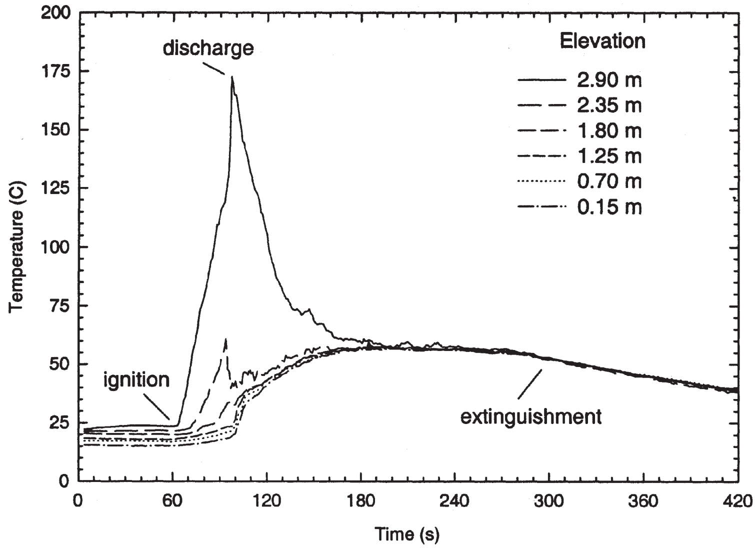

Figure 5c. *Room temperatures measured at Thermocouple Tree #3 in Test 1-1 with pool fires, when the single-fluid/high pressure water mist system was employed and the door was closed.*

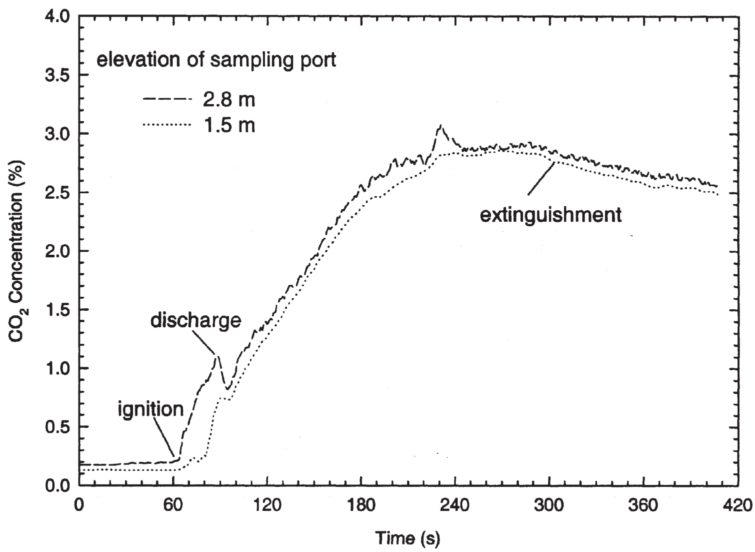

Figure 6. CO_2 *concentrations in the compartment in Test 1-1 with pool fires, when the single-fluid/high pressure water mist system was employed and the door was closed.*

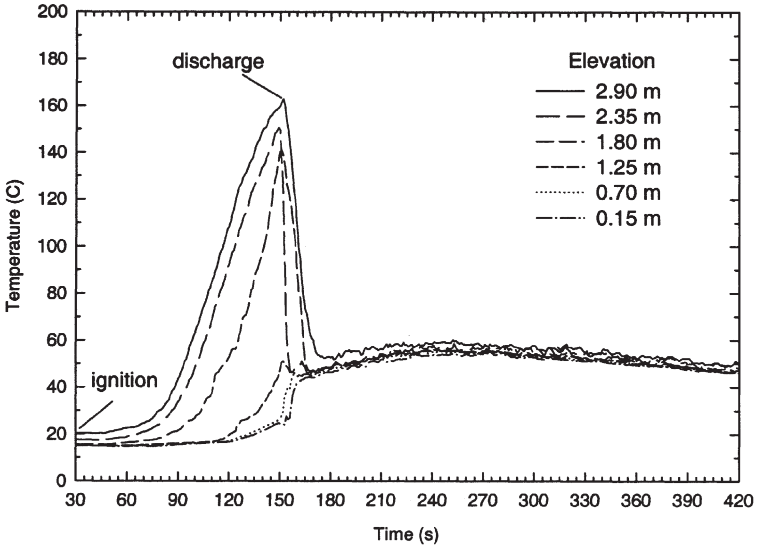

Figure 7a. *Room temperatures measured at Thermocouple Tree #1 in Test 1-2 with wood crib fires, when the single-fluid/high pressure water mist system was employed and the door was closed.*

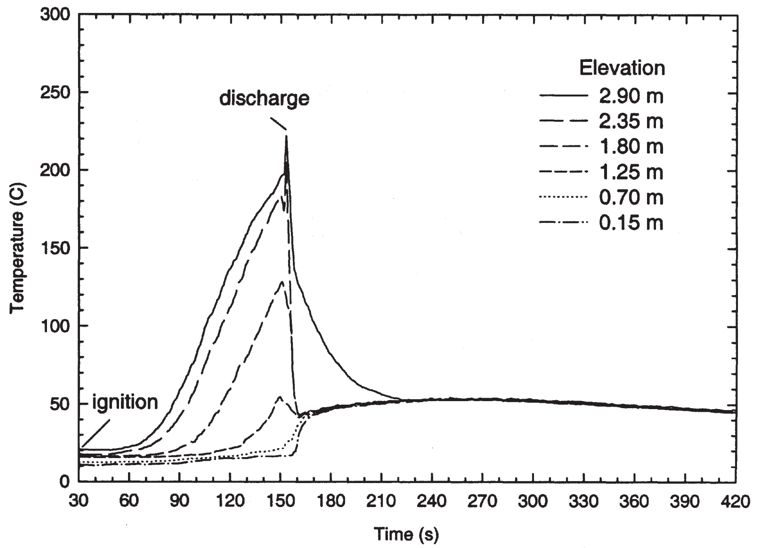

Figure 7b. *Room temperatures measured at Thermocouple Tree #2 in Test 1-2 with wood crib fires, when the single-fluid/high pressure water mist system was employed and the door was closed.*

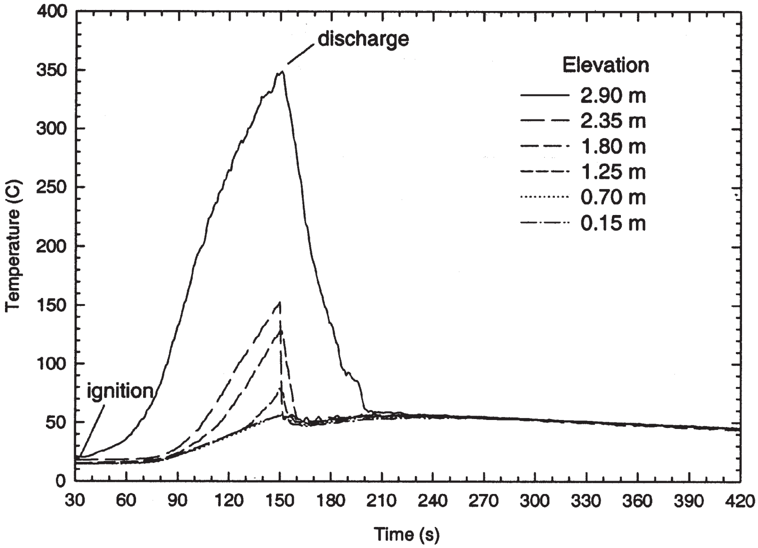

Figure 7c. *Room temperatures measured at Thermocouple Tree #3 in Test 1-2 with wood crib fires, when the single-fluid/high pressure water mist system was employed and the door was closed.*

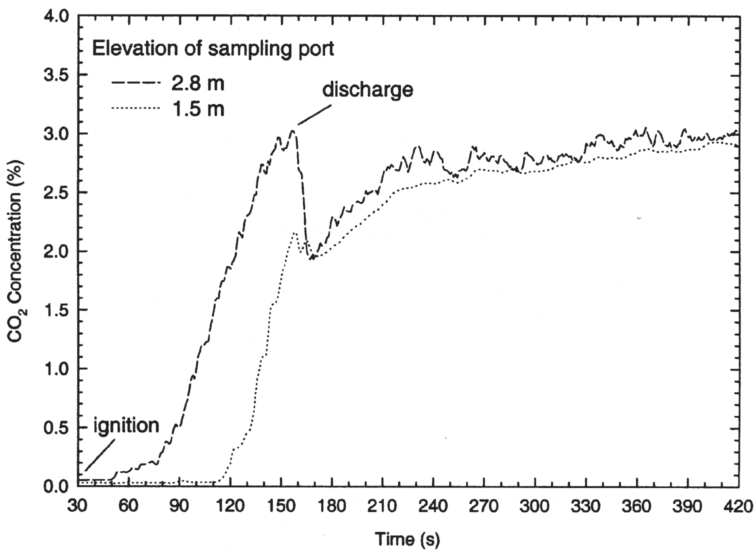

Figure 8. CO_2 *concentrations in the compartment in Test 1-2 with wood crib fire, when the single-fluid/high pressure water mist system was employed and the door was closed.*

fires located near the ceiling (#49, #54 and #57) and a tell-tale fire (#56) at the bottom of the corner near the door were the most difficult tell-tale fires to extinguish. They were far from nozzles and hardly hit by water mist. Two square-pan fires located in the two corners at floor level were also difficult to extinguish, because the corner effects restricted water vapor entering into the fire plume from its surroundings. In addition, the shielded round-pan fire in Test 1-1 was also difficult to extinguish, compared to the unshielded wood crib fire in Test 1-2 and the shielded spray fire in Test 1-3.

With a large total heat release rate (700 kW) in Test 1-1, all fires in the compartment were extinguished, no matter where they were located in the room. For the spray fire test (Test 1-3), all the fires in the room were also extinguished. However, extinguishing times for the tell-tale fires (#54 and/or #56) located near the door were increased, compared to test results in Test 1-1 with a large total heat release rate. For the test with an unshielded wood crib fire (Test 1-2), all the fires, except for two corner square-pan fires, were extinguished. The failure to extinguish two corner square-pan fires in Test 1-2 may be attributed to the fact that the unshielded wood crib fire, as a main heat release source in the room, was quickly extinguished (95 s of extinguishing time, compared to 210 s of extinguishing time for the shielded round-pan fire in Test 1-1). Without the existence of the main heat release source, the depleting of oxygen in the compartment was slowed down and less water vapor was produced, which increased difficulties to extinguish two corner square-pan fires.

Water mist effectiveness in fire suppression was also determined by characteristics of water mist systems. Tests 1-1 and 1-4 compared the effectiveness of two types of water mist systems (see Table 2), when the same fire scenarios were employed in the empty enclosure. Compared to the single-fluid/high pressure water mist system, the twin-fluid/low pressure water mist system also extinguished all the fires located at the different positions of the compartment (Test 1-4). However, extinguishing times were substantially increased. For example, extinguishing time for the shielded large round-pan fire was extended from 210 s to 300 s, and extinguishing times for two corner square-pan fires (#48 and #51) were also substantially increased. The lower effectiveness of the twin-fluid/low pressure water mist system in fire suppression was attributed to its lower discharge pressure that could not produce high water spray momentum and strong dynamic mixing in the compartment [12]. It may also be attributed to its lower total water discharge rate in the tests (70 Lpm), compared to the single-fluid/high pressure system (78 Lpm).

During the test series in the simulated machinery space, the twin-fluid/low pressure water mist system extinguished both shielded pool fire (Test 1-5) and shielded spray fire (Test 1-6) that were located under the metal table. As shown in Table 2, the extinguishing time and water required for both fires were almost equal, because heat release rates in the two tests were almost equal.

Water Mist Performance under Natural Ventilation

When there is an opening in the compartment, the temperature difference between the room (T_r) and its surroundings (T_a) creates a pressure difference that results in mass exchange at the opening [13]. The mass exchange between the room and its surroundings is mainly dependent on the temperature difference between the room and its surroundings as well as the size of the opening. The mass flow rate ($\dot{m}_{out}$) through the opening from the room can be calculated from an application of the Bernoulli equation and a flow coefficient for the vent [14]:

$$\dot{m}_{out} = W\rho_a T_a C\int_N^H \left[\left(\frac{2g}{T_r}\right)\int_N^z \left(\frac{1}{T_a} - \frac{1}{T_r}\right) dZ'\right]^{0.5} dZ \qquad (2)$$

where W and H are opening width and height, respectively, C is the opening flow coefficient, g is gravitational acceleration and ρ_a is density of gas in the surrounding area.

As shown in Figure 9, without water mist discharge, the hot gases in the upper layer flow out of the room at a rate of $\dot{m}_{out}$, while fresh air flows into the lower portion of the room at a rate of $\dot{m}_{in}$. When water mist was discharged, the mass exchange between the compartment and its surrounding through the opening was restricted. To examine the effectiveness of water mist under various ventilation conditions, the same fire scenarios as those used in Phase I of the test series were employed but the door of the compartment was kept open in Phase II

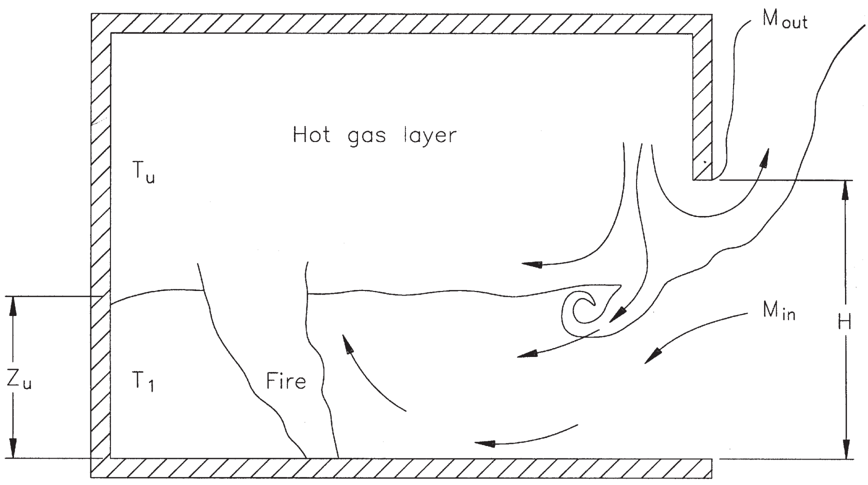

***Figure 9.** A schematic of convective mass transfer phenomena within a compartment.*

of the test series. Corresponding test results obtained from Phase II of the test series using two types of water mist systems in the empty enclosure and simulated machinery space with the door open (natural ventilation) are listed in Table 3.

Figures 10 and 11 show the changes in room pressure during Tests 2-1 and 2-2 involving pool and wood crib fires with the door open. When the pre-burn period in Test 2-2 with the wood crib fire was long (90 s), the upper zone of the room became thick and hot. The activation of the water mist system in Test 2-2 generated a sudden negative pressure change in the compartment due to the cooling by water mist (see Figure 11), resulting in some fresh air being drawn into the compartment. After the activation of the water mist system, the room pressure tended to be unchangeable in the subsequent water mist discharge. When the pre-burn period in Test 2-1 with pool fires was short (30 s), the upper zone of the room was not very hot and thick. As a result, the activation of the water mist system did not generate a sudden pressure change in the compartment (see Figure 10). This indicated that neither room gases containing water vapor and combustion products in Test 2-1 were substantially pushed out of the compartment through the opening nor was fresh air drawn into the compartment by the activation of the water mist system. Therefore, when there are openings, fire size and the length of the pre-burn period determine whether the activation of the water mist system may change fire suppression conditions in the compartment.

After the activation of the water mist system, continuing water mist discharge was able to restrict the mass exchange between the room and its surroundings. Figure 12 shows the changes in the gas temperature in the compartment during the pool fire test (Test 2-1) with the door open. Compared to the same fire scenarios with the door closed (Test 1-1), both gas temperature distributions measured at three locations of the room were very similar (see Figures 5 and 12). After a certain period of water mist discharge, the steady suppression condition in the compartment was achieved even if the door was open. The gas temperatures throughout the room were cooled to around 52°C and were about 30°C higher than the surrounding temperature of the room. Such a low temperature difference could only generate a small mass exchange between the compartment and its surroundings. As observed in tests, a small amount of room gases containing water vapor and combustion products were flowing out of the room through the upper portion of the opening door. At the same time, a small amount of fresh air was flowing into the compartment through the lower portion of the door. However, with the strong dynamic mixing generated by water mist discharge, this small amount of fresh air from outside of the room was quickly mixed with the gases in the room and lost its energy for subsequent penetration into the depth of the room. It had very limited impact on water mist fire suppression.

Such very limited impact of ventilation on fire suppression can be observed

Table 3. Summary of full-scale test results under natural ventilation (door open).

Recorded Event	Test 2-1	Test 2-2	Test 2-3	Test 2-4	Test 2-5
System Types	Single-fluid	Single-fluid	Single-fluid	Twin-fluid	Twin-fluid
Mock-Up in the Compartment	Empty	Empty	Empty	Machinery	Machinery
Fire Types	8 TTs 3 SPs 1 shielded pool fire	9 TTs 2 SPs 1 wood crib fire	8 TTs 1 shielded spray fire	1 shielded pool fire	1 shielded pool fire
Fire Size	700 kW	600 kW	570 kW	500 kW	500 kW
TT 49—Ext. Time (s)	50	55	115		
TT 50—Ext. Time (s)	55	40	65		
TT 52—Ext. Time (s)	30	35	20		
TT 54—Ext. Time (s)	No ext.	No ext.	No ext.		
TT 55—Ext. Time (s)	75	25	70		
TT 56—Ext. Time (s)	No ext.	100	No ext.		
TT 57—Ext. Time (s)	50	120	110		
TT 58—Ext. Time (s)	20	25	65		
TT 64—Ext. Time (s) (in the cabinet)		No ext.			
SP 48—Ext. Time (s)	128	No ext.			
SP 51—Ext. Time (s)	40				
SP 53—Ext. Time (s)	230	No ext.			
Round-Pan Fire Ext. Time (s)	120			420	
Wood Crib Fire Ext. Time (s)		120			
Spray Fire Ext. Time (s)			140		145
Water Quantity (L/m^2)				12	4.1

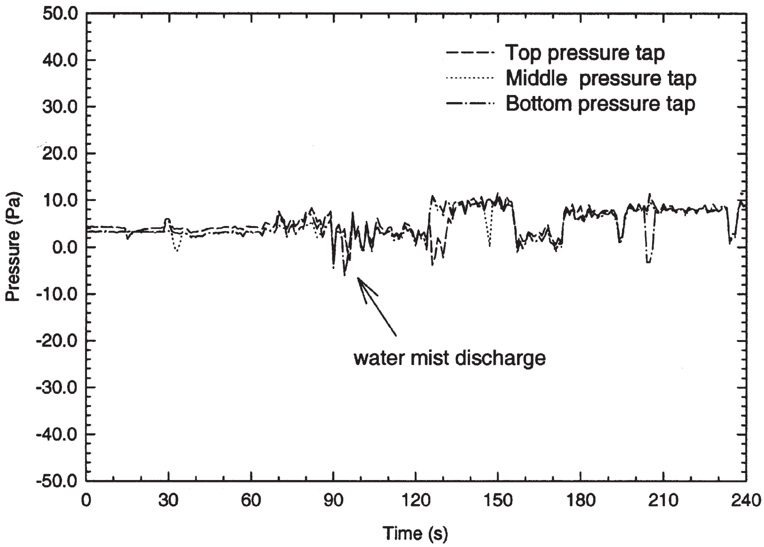

Figure 10. *Room pressures in Test 2-1 with pool fires and door open using single-fluid/high pressure water mist system.*

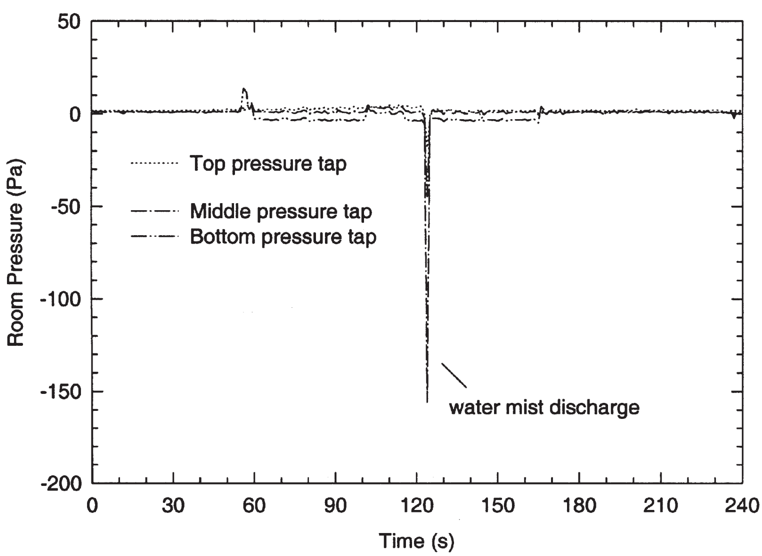

Figure 11. *Room pressures in Test 2-2 with wood crib fires and door open using single-fluid/high pressure water mist system.*

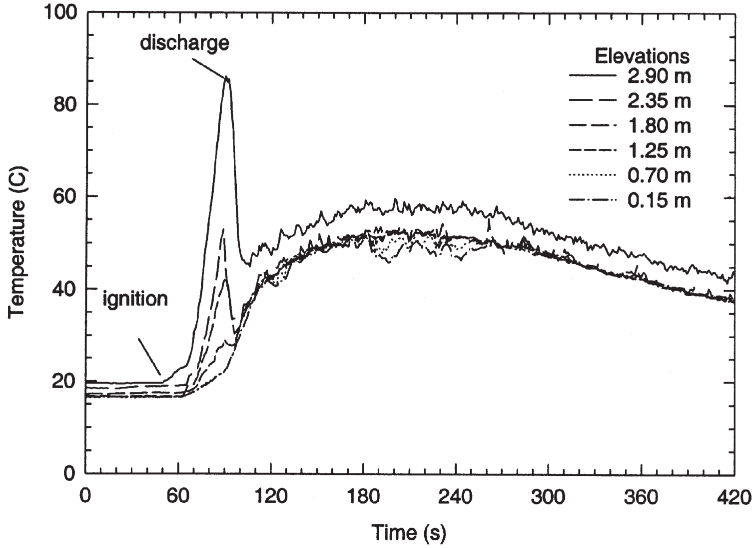

Figure 12a. *Room temperatures measured at Thermocouple Tree #1 in Test 2-1 with pool fires, when the single-fluid/high pressure mist system was employed and the door was open.*

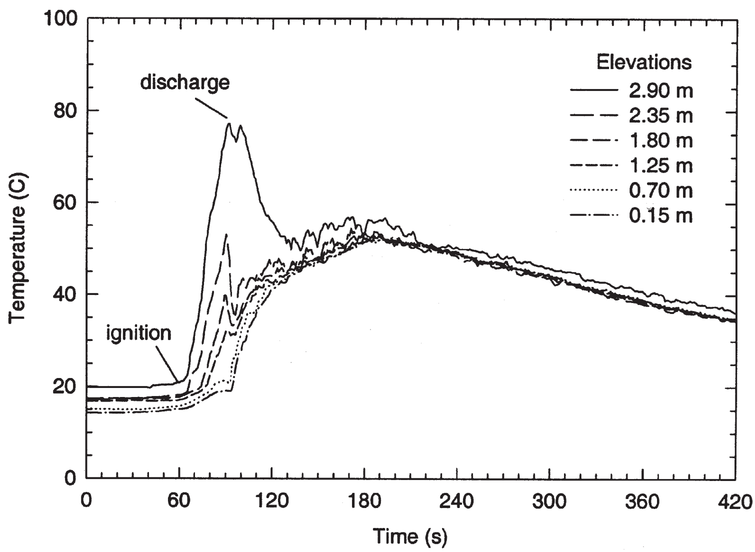

Figure 12b. *Room temperatures measured at Thermocouple Tree #2 in Test 2-1 with pool fires, when the single-fluid/high pressure mist system was employed and the door was open.*

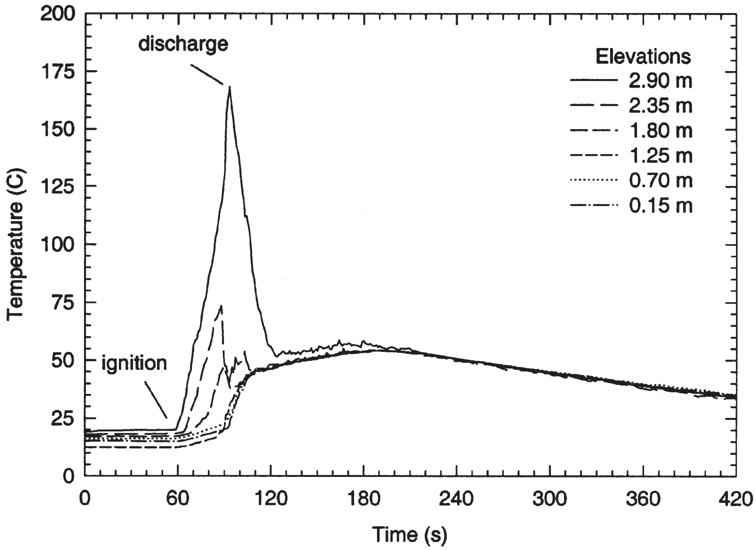

Figure 12c. *Room temperatures measured at Thermocouple Tree #3 in Test 2-1 with pool fires, when the single-fluid/high pressure mist system was employed and the door was open.*

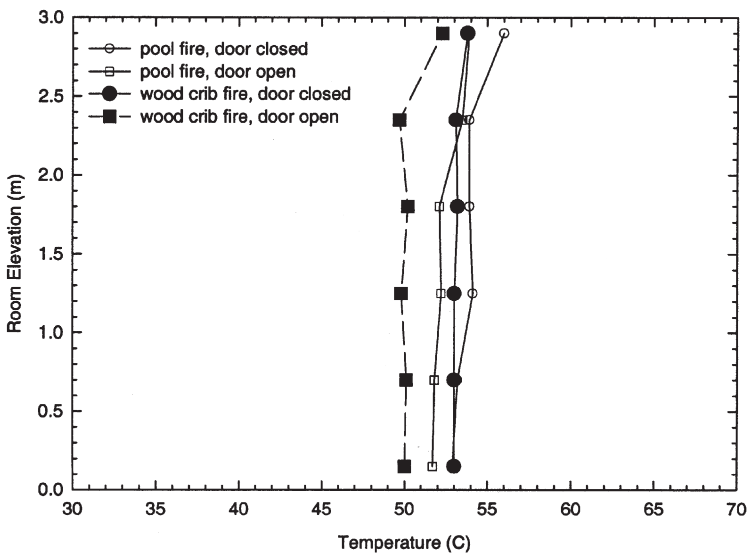

Figure 13. *Room temperature profiles along the elevations measured at Thermocouple Tree #2 with the door closed/opened at 90 s after discharge with single-fluid/high pressure water mist system.*

from the changes in air temperature and CO_2 and O_2 concentrations in the compartment. Figure 13 compares the temperature profiles measured at the location of Thermocouple Tree #2 close to the opening door, when the steady suppression conditions were achieved for both pool and wood crib fire tests with and without ventilation in the compartment. The temperature profiles measured in tests with ventilation also tended to be uniform vertically as observed in the test without ventilation, showing less effect of the door being open on gas temperatures in the room. In Figures 14 and 15, the changes in CO_2 and O_2 concentrations in the compartment with and without ventilation for the spray fire test were compared. The CO_2 concentration in Figure 14 was an averaged value measured at two elevation locations (1.5 and 2.8 m above the floor). As shown in Figures 14 and 15, the door being open did not change the CO_2 or O_2 concentrations in the compartment, indicating that fire suppression in the compartment was not interfered with by the door being open.

Therefore, Table 3 shows that, when the door was kept open during both pool and spray fire tests (Tests 2-1 and 2-3), the use of the single-fluid/high pressure water mist system extinguished all fires in the room, except for two tell-tale fires (#54 and #56) at the top and bottom of the room near the door. These two tell-tale fires were located too close to the door and their extinguishment was influenced by the door being open, as water vapor and combustion products escaped through the door. However, the local fire suppression conditions of other fires were not influenced by the door being open, as both quick cooling for the compartment and the creation of a strong dynamic mixing by water mist effectively restricted air convection between the compartment and its surroundings. The extinguishing time for the spray fire was the same as that when the door was kept closed (no ventilation). For the wood crib fire test with the door open (Test 2-2), the effectiveness of the single-fluid/high pressure water mist was similar to that when the door was closed. Two square-pan fires were not extinguished, as observed in the test with the door closed. In addition, one tell-tale fire (#54) near the top of the door and one tell-tale fire in the cabinet (#64) were also not extinguished due to the door being open. All other fires in the compartment were extinguished. The extinguishing time for the wood crib fire was delayed from 95 s to 120 s with the door open. This test result was consistent with the above discussion that with the long preburn period in the wood crib fire test and the door open, the activation of the water mist discharge created a negative impact on fire suppression, resulting in the prolongation of the extinguishing time.

When the twin-fluid/low pressure water mist system was employed in the tests with the door open, both shielded pool and spray fires (Tests 2-4 and 2-5) were extinguished, which were the same as in tests without ventilation. However, compared to water mist effectiveness under non-ventilation conditions in Table 2, the extinguishing time for the shielded spray fire was extended from 113 s to 145 s and the extinguishing time for the shielded pool fire was significantly delayed from

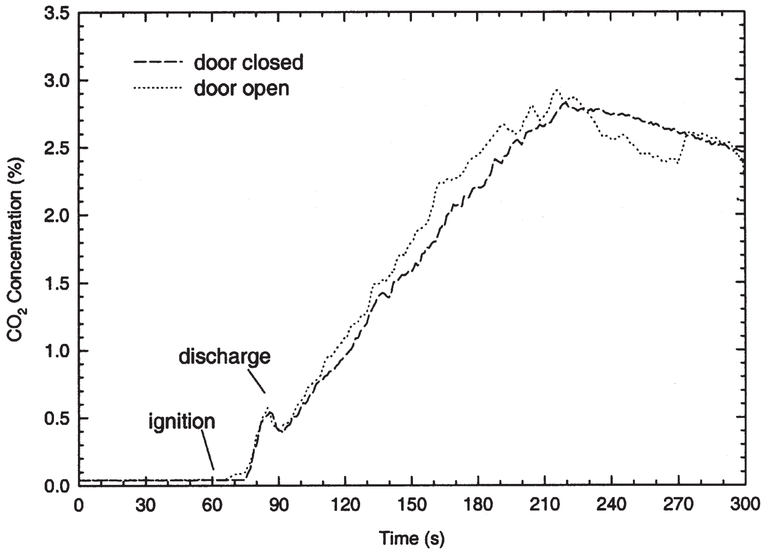

Figure 14. *CO_2 concentrations in the compartment with the door closed and open in the spray fire test, when the single-fluid/high pressure water mist system was employed.*

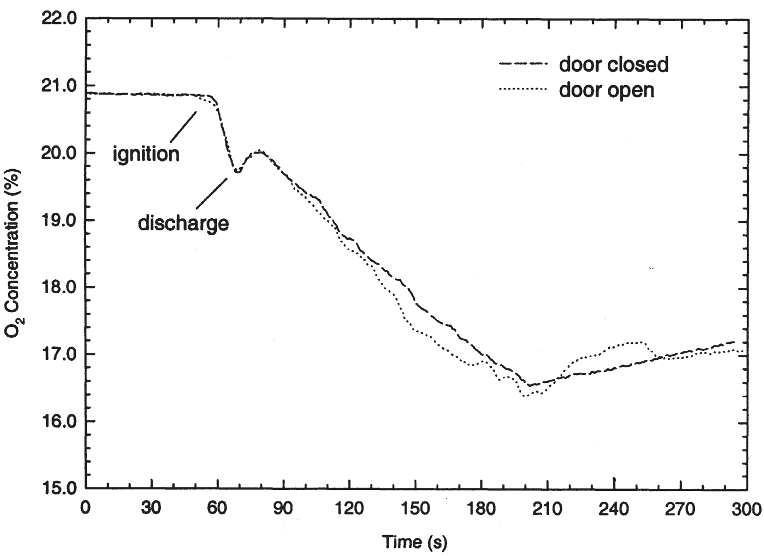

Figure 15. *O_2 concentrations in the compartment with the door closed and open in the spray fire tests, when the single-fluid/high pressure water mist system was employed.*

114 s to 420 s. The changes in extinguishing times suggested that the effectiveness of the twin-fluid water mist system was substantially affected by the door being open. This can be further analyzed from changes in air temperature and CO_2 concentration in the compartment. As shown in Figure 16, with the twin-fluid water mist system, the temperatures measured at the locations of Thermocouple Trees #1 and #3 still tended to be uniform vertically and had not been affected by the door being open, but the temperatures measured at the location of Thermocouple Tree #2 close to the door was no longer uniform vertically. The room temperatures near the floor were lower than temperatures in the upper portion of the compartment due to the cold fresh air flowing into the room. Also, Figure 17 shows that the averaged CO_2 concentration with the door open was substantially lower than that with the door closed, because a part of the gases in the compartment had been vented outside.

These test results indicated that, with the door open, water mist was still able to effectively control and extinguish the fires. For the single-fluid/high pressure water mist system, the effect of ventilation on fire suppression was mainly limited to the area close to the opening, while the effectiveness of water mist against other fires located at the interior of the room was not affected by the door being open. For the twin-fluid/low pressure water mist system, however, its performance was substantially affected by the changes in ventilation conditions due to its weak spray momentum, resulting in long extinguishing times.

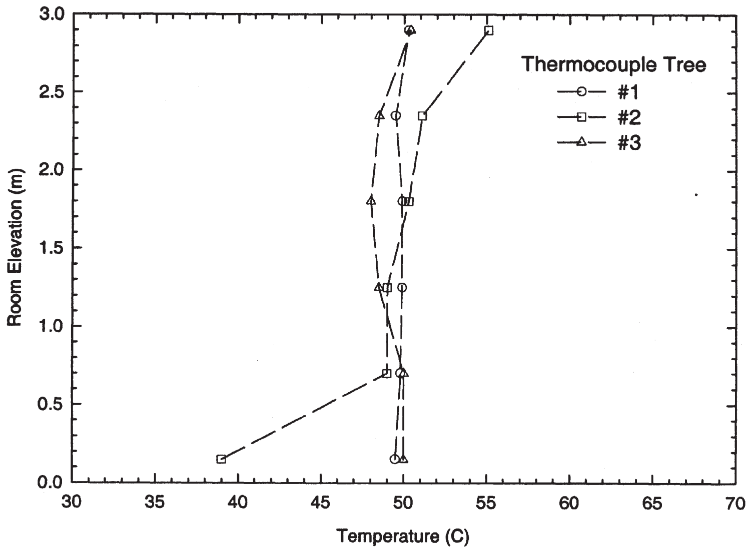

Figure 16. *Room temperature profiles along the elevations measured at thermocouple trees when the door was open for the pool fire tests with twin-fluid/low pressure mist system at 90 s after mist discharge.*

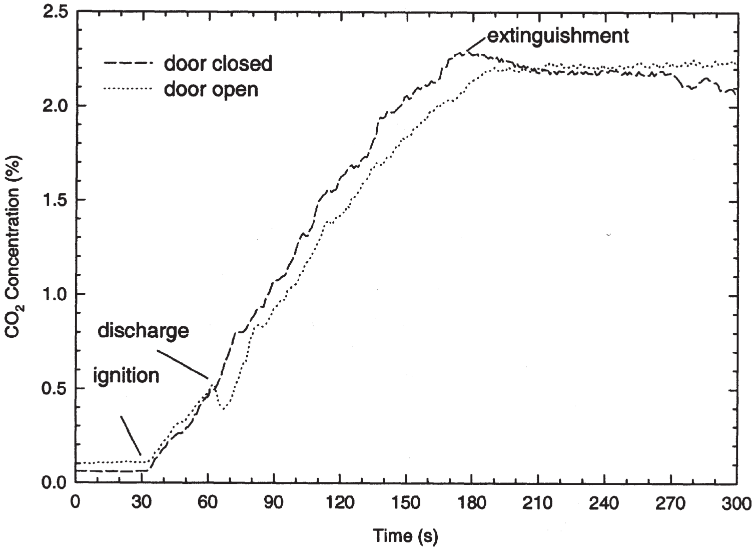

Figure 17. *CO_2 concentrations in the compartment with the door closed and open for the pool fire tests, when the twin-fluid/low pressure water mist system was employed.*

Water Mist Performance under Forced Ventilation

In Phase III of the test series, the impact of forced ventilation on water mist effectiveness was examined in the simulated machinery space, when the door was kept open and the exhaust fan was running. Table 4 lists the test results obtained from Phase III of the test series with the twin-fluid/low pressure water mist system.

As observed in tests, when there was forced ventilation in the compartment, the

Table 4. Summary of full-scale test results under forced ventilation.

Test Series	Test 3-1	Test 3-2
System Type	Twin-fluid	Twin-fluid
Mock-Up in the Compartment	Machinery	Machinery
Fire Type	1 shielded pool fire	1 shielded spray fire
Fire Size	500 kW	520 kW
Pool Fire	No ext.	
Spray Fire		Ext. at 510 s, 15.6 L/m^2 water

mass exchange between the room and its surroundings was significantly increased. Air inflow rate into the room through openings was proportional to the flow rate of the exhaust fan. As shown in Figure 18, during the test with the shielded spray fire, the room temperatures measured at Thermocouple Tree #1 that was away from the door opening and exhaust fan, remained uniform vertically and were not disturbed by the forced ventilation. However, the distribution of the room temperatures near both the door and the exhaust fan opening was considerably changed, showing much lower room temperatures near the floor and higher gas temperatures near the ceiling. This was because, with the forced ventilation, cold air in-flow through the door cooled the room temperatures near the floor and the loss of large quantities of fine water mist through the exhaust fan for cooling led to higher gas temperatures near the ceiling. Also, the burning rate of the fire was increased under forced ventilation due to more fresh air flowing into the compartment, which further resulted in higher gas temperatures near the ceiling.

Figures 19 and 20 compare the changes in O_2 and CO_2 concentrations in the compartment with and without forced ventilation. The O_2 concentration in the compartment with forced ventilation was higher than that with the door closed. This allowed the fire to burn efficiently and increased the difficulty for water mist to extinguish the fire. The CO_2 concentrations in the compartment with forced ventilation were also lower than the values without ventilation, as the com-

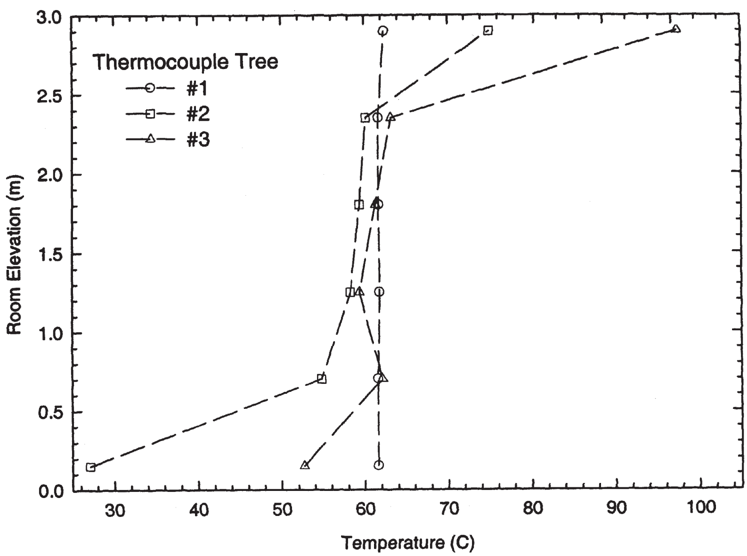

Figure 18. *Room temperature profiles along the elevations measured at thermocouple trees under forced ventilation for the spray fire test with twin-fluid/low pressure mist system at 50 s of discharge.*

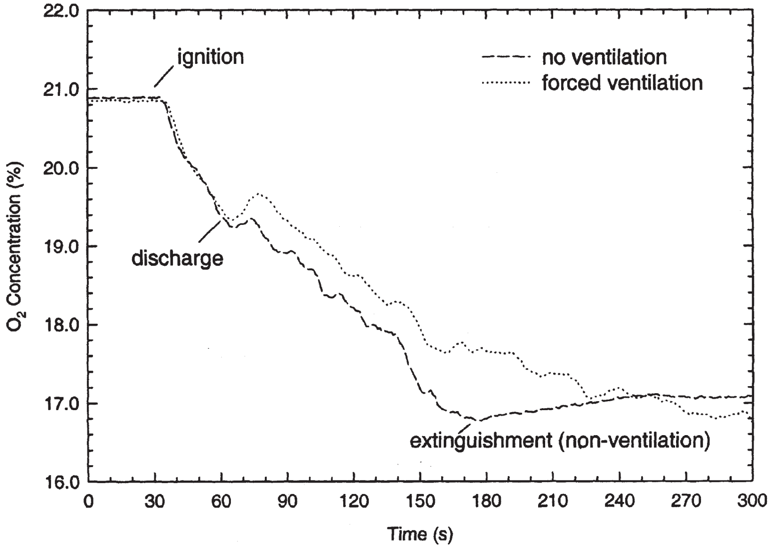

Figure 19. *O_2 concentrations in the compartment in the spray fire tests with no ventilation and with forced ventilation, when a twin-fluid/low pressure water mist system was employed in the machinery space.*

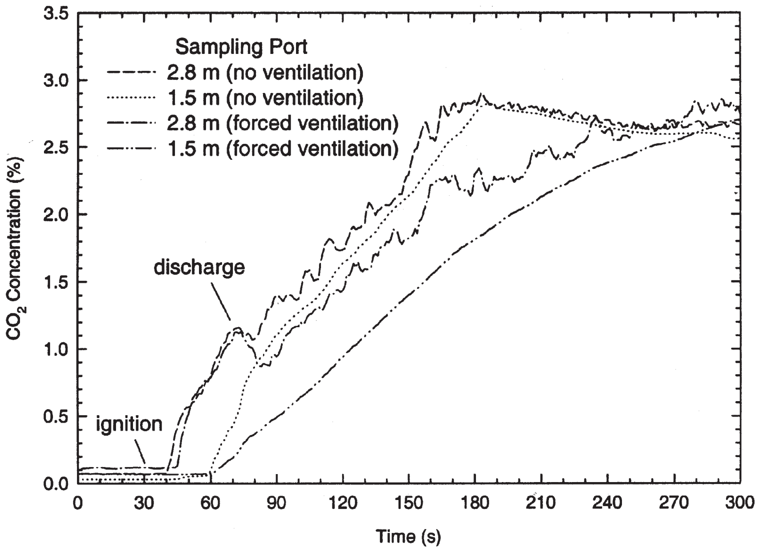

Figure 20. *CO_2 concentrations in the compartment during the spray fire tests with no ventilation and with forced ventilation, when the twin-fluid/low pressure water mist system was employed.*

bustion products were vented out of the room. In addition, the difference in CO_2 con-centration measured at the two elevation locations was substantially increased as the dynamic mixing in the room was interfered with and reduced by forced ventilation.

Therefore, as shown in Table 4, when there was forced-air convection in the room, the extinguishing time for the shielded spray fire (Test 3-2) was significantly increased from 113 s to 510 s and the water required for fire suppression was largely increased from 3.1 L/m^2 to 15.6 L/m^2, compared to no ventilation conditions. Furthermore, the use of the twin-fluid water mist system could not extinguish the shielded round-pan fire (Test 3-1).

SUMMARY

During fire suppression with ventilation in the compartment, water mist was still able to quickly control the fires and cool the compartment, which in turn reduced the mass exchange between the room and its surroundings caused by temperature differences. In addition, strong dynamic mixing, created by the water mist discharge, restricted the penetration of the outside air into the depths of the compartment, as a small amount of fresh air was quickly mixed with the gases in the room near the opening and loses its energy for subsequent convection.

The effect of ventilation on the effectiveness of water mist was dependent on the fire size and location in the compartment and the characteristics of the water mist system used. For the single-fluid/high pressure water mist system, which produced strong dynamic mixing by its high water spray momentum, only the fire extinguishment near the opening area was influenced by opening the door. The extinguishment of other fires located far from the door was not affected by the door being open. For the twin-fluid/low pressure water mist system, which produced a lower water spray momentum, the air from outside of the compartment could penetrate more deeply into the compartment and influenced fire suppression conditions, resulting in an extended extinguishing time. In addition, the activation of the water mist discharge may also change fire suppression conditions in the compartment, depending on fire size and the length of the pre-burn period.

Under forced ventilation, the loss of a large quantity of water vapor and combustion products through the openings reduced the extinguishing capability of the water mist system. Also, fresh air in-flow into the compartment through the opening allowed the fires to burn more efficiently and increased the difficulty for fire suppression.

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