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WATER MIST (FINE SPRAY) FIRE PROTECTION IN LIGHT HAZARD OCCUPANCIES

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ABSTRACT

The capability of impingement type water mist (fine spray) nozzles, with operating pressures lower than 12 bar, was investigated in full-scale fire tests using light hazard scenarios. In these tests, four prototype nozzles were evaluated; however, only one of the nozzles (Nozzle A) provided satisfactory protection. The results of the tests, with Nozzle A, are reported as an indication of the capabilities of impingement type water mist nozzles in light hazard occupancies. Nozzle A was typically operated at a flow rate of 15 Lpm and a pressure of 10 bar. The fire tests were conducted in a room 5.5 m x 5.5 m with openings to two adjacent rooms (and in one test, an opening to a corridor). The fuel packages used in the fire tests were: the residential fuel package of Underwriters Laboratories (UL), a living room fuel package, a bedroom fuel package, and a shielded heptane pool fire. The UL and the living room fuel packages were used in a room corner and along a wall between two nozzles. Gas temperature measurements indicated that Nozzle A provided acceptable protection in the fire tests of this study with a total water flow rate of 45 Lpm. Based on the results of this study and a review of previous work with water mist systems, recommendations for approval testing and installation standards have been made for light hazard scenarios.

INTRODUCTION

Water Mist (fine spray*) systems for fire protection have been extensively investigated in the last several years, due in part to the phasing out of halon and the need to find alternatives. For example, halon alternatives are being sought for shipboard engine rooms, telecommunication central offices, combustion turbine enclosures, and other enclosures with flammable liquid hazards. Proposed water mist systems have been discussed at specialized technical conferences[2,3] and at conferences where details of other halon alternatives or other suppression systems have been presented (see, e.g., Refs. [4] and [5]). A comprehensive review of water mist technology was recently prepared by Mawhinney and Richardson.[6]

The potential of water mist for fire protection has been recognized for many years. For example, the Factory Mutual Engineering Division investigated the use of water mist for the protection of flammable liquid spray fires in the 1940s.[7] It was recognized that small water droplets could be entrained into the fire, producing cooling and oxygen dilution in the combustion zone. While potential advantages over the use of traditional sprinklers were revealed, the higher required operating pressures were considered to be a practical barrier at that time.

In studies such as that of Rasbash, Rogowski, and Stack[8], the role of drop size in flame cooling and oxygen dilution has been quantitatively investigated; however, understanding of the extinguishment mechanisms of water spray remains insufficient to design water mist systems. A review of water mist technology by Mawhinney, Dlugogorski, and Kim[9] states that the major extinguishment mechanisms are heat extraction, oxygen displacement, and blocking of radiant heat (reduced thermal feedback to burning and unburned surfaces), but no design

*Fine spray would seem to be a more appropriate term than mist since the term mist is typically used for water droplets that are much smaller than those generated by current commercial systems for fire protection. For example, Reference 1 indicates that drop sizes of mists range from 0.01 to 10 microns, while droplets for sprays range from 100 microns to about 3000 microns, a range that encompasses current water "mist" technology.

method is given. Observation of water mist protection of combustion turbine enclosures by the Factory Mutual Research Corporation (FMRC)[10] suggests that flame destabilization through the turbulent or mean flows generated by water mist systems may also be an important mechanism for some applications. Another important consideration in the performance is the oxygen consumption by the fire. Bill et al[11] observed in simulated engine room test fires with flammable liquids that extinguishment did not occur unless the compartment oxygen concentration was reduced to about 17%. The complex nature of the delivery of water mist to the combustion zone is primarily responsible for the difficulty in developing design criteria for water mist compared to inerting agents.

Because of the recognition that smaller droplets than those generated by traditional sprinklers would more effectively extract heat from the combustion zone (see, e.g., Ref. [8]), it has been anticipated that water mist systems, in addition to being a halon alternative, might provide protection superior to sprinklers in some occupancies by requiring smaller water supplies. Such considerations have led to the development and testing of water mist systems for cabins and public accommodation areas on passenger ships, where weight is an important consideration in the design of new ships or in retrofitting of fire protection onto existing ships. Examples of such systems are discussed by Turner (in Ref. [2]) and Arvidson[12]. The fire testing associated with cabins on passenger ships represents the most relevant information concerning the use of water mist in light hazard occupancies[13]. Furnishings in modern passenger ship cabins are similar to those of residential occupancies, such as homes or hotels. Fire experience on ships indicates the fire hazards are also similar in that fires can be fast growing and involve fire propagation along walls.

Fire test procedures for evaluating water mist systems have been developed by the International Maritime Organization[14] (IMO). These fire tests have been designed to establish whether water-based systems will provide protection equivalent to sprinkler systems regulated under Safety of Life at Sea (SOLAS) regulations.[15] For cabins between 12 m^2 and 50 m^2, the fuel packages from the FMRC[16] residential fire test, or equally acceptable, the Underwriters Laboratories (UL) residential fire test,[17] are prescribed. In the current study, the appropriateness of these tests for generic light hazard occupancies including residential occupancies was investigated.

In 1994, the U.S. Fire Administration sponsored a program[18] to investigate the use of water mist systems for residential protection. In an evaluation of five different water mist systems covering different technologies, it was concluded that "the feasibility of water mist as a residential fire suppression system has been demonstrated under a limited number of residential fire scenarios."

The objective of the current study was to continue to evaluate water mist protection for light hazard and residential occupancies and to develop a fire test protocol appropriate to test the performance of these systems in light hazard occupancies and to develop the related appropriate installation standards.

Water Mist Nozzle Characteristics

Water mist can be generated by a variety of technologies. These include impingement (sprinkler-like) nozzles at low pressures (less than 12 bar) and high pressure single fluid nozzles, and air atomization nozzles. A review of these technologies is given in Refs. [2] and [9]. This study only investigates the performance of prototype low pressure nozzles because low pressure single fluid nozzles can, in principle, use much of the equipment associated with sprinklers. Four prototypes were investigated in this study; however, only one nozzle (Nozzle A) provided acceptable performance. Details and test results for the other nozzles are available in the FMRC water mist study[19] for the USFA. The failure of the other nozzles is indicative of the need to evaluate water mist systems through full-scale fire testing. Characteristics of Nozzle A are given in Table 1.

Impingement nozzles are similar to sprinklers in that droplets are generated by the impingement of a water stream onto a deflector. These low pressure water mist nozzles may have a sprinkler-like appearance, but they have special

Table 1. Characteristics of Nozzle A

Nozzle style:	pendent, automatic (i.e., closed)
Nozzle flow rate:	15.1 Lpm
Operating pressure:	10 bar
K-factor:	4.7 Lpm/(bar)$^{1/2}$
Nozzle spacing:	2.44 m*
RTI:	40 (m-s)$^{1/2}$
C:	0.66 (m/s)$^{1/2}$
Temperature rating:	79.4°C

* Based on distance of corner nozzles from walls.

small orifices, i.e., K-factors* of the order of 14 Lpm/(bar)$^{1/2}$ or less and special deflectors to generate a water mist. While drop sizes are generally larger than for other water mist generating technologies, sufficient numbers of small droplets may be generated to allow flame cooling and oxygen displacement to occur. The existence of larger drops may be beneficial in that penetration of fire plumes and suppression through surface cooling, as with sprinklers, may also occur. Thus the impingement nozzle may be thought of as a hybrid water mist/sprinkler nozzle.

Nozzle A was a prototype which was commercially produced. The nozzles discharged vertically downward. In order to attempt to understand some aspects of the nozzle performance, characteristics of the water mist and the thermal response of the nozzle actuating elements have been measured. Although NFPA 750[20] states that "currently no general design method is recognized for water mist protection," NFPA 750 recommends that cumulative volumetric distributions of water droplets, horizontal water discharge distribution, profiles of the spray envelope, and spray thrust force be measured as a means of developing scientifically based system designs in the future. NFPA 750 defines water mist as a spray in which 99% of the volumetric flow, at a point 1 m below the nozzle in the coarsest part of the spray, is associated with droplets less than 1 mm in diameter. FMRC, however, in its approval process, has no restriction on drop size. Rather, water mist systems are identified through adequate suppression and/or extinguishment in fire tests. In particular, acceptable performance in shielded fires as described later in this paper is taken as evidence that the system responds as a water mist system.

*The nozzle K-factor is a discharge coefficient defined as the ratio of the flow rate to the square root of the operating pressure.

Measurements analogous to those recommended by NFPA have been made, along with others for use in the current program. Table 1 lists characteristics of Nozzle A: the K-factor, typical flow rates, operating pressure, nozzle spacing, and thermal response parameters (RTI, C, and nominal operating temperature). These thermal response parameters were measured following the ISO procedures for automatic sprinklers.[21]

Cumulative drop size distributions for Nozzle A, supplied by the manufacturer 3 were given at two pressures, 9 bar and 11 bar, at a point 1 m below the nozzle. Note that these two pressures bracket the operating pressures in this study. The volume median drop sizes were measured to be 180 microns at 9 bar and 225 microns at 11 bar. At the operating pressure used in this study, the volume median drop size is therefore approximately 200 microns. The drop sizes corresponding to a cumulative volume of 99% were 360 and 400 microns, respectively, for the 9 and 11 bar operating pressures. The increase of drop size with operating pressure appears to be an anomaly given the expected decrease in drop size with pressure. This result is possibly due to measurement at a single point and the change in spray pattern with increasing pressure.

Cumulative drop size distributions were also reported by the manufacturer at radii of 0.36 m and 0.78 m in the same plane. As would be expected due to the increased effect of drag on the radial throw of smaller droplets, the median drop size increases with radius. The median drop size increased to approximately 280 and 500 microns, respectively.

The horizontal water densities of Nozzle A were measured in one quadrant of the coverage area of each nozzle at a distance of 2 m below the nozzle. This elevation was selected because the seat of the upholstered chair used in the living room fire test is at this elevation. The tests were conducted in a room approximately 7.0 m x 7.0 m, with densities collected in 0.093 m^2 pans. The flow rate for each nozzle was 15.1 Lpm, as shown in Table 1. The results are given in Fig. 1. (Note that the orientation of the frame arms is shown schematically.)

The thrust forces of the nozzles used in the study were measured using a load cell as in Ref. [22]. The force of the spray on a plate 0.33 m in diameter was measured approximately 25 mm from the tip of the nozzle. The weight of the water was estimated and subtracted from the thrust force.

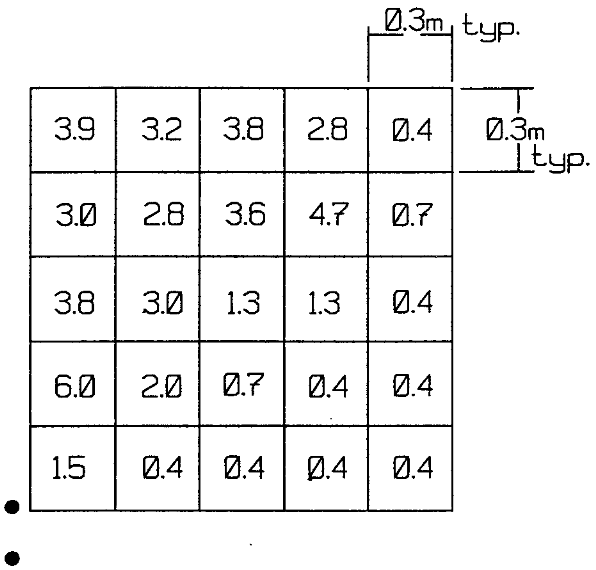

Figure 1. Horizontal water flux distribution for Nozzle A, 2 m below the deflector (flux in mm/min). (: indicates orientation of frame arms).

The thrust force was measured to be about 5 N at 10 bar.

Fire Test Facilities

Test Compartment

Fire testing was conducted within the "HUD" building located at FMRC headquarters in Norwood, MA. The facility had been previously used for fire testing, leading to the development of a prototype Limited-Water-Supply sprinkler[23]. The test area used in that study was re-compartmented for use in the current program. A schematic of the test facility is shown in Fig. 2 along with the nozzle configuration. The frame arms of nozzles were parallel to the north wall in all tests, except those in which the fuel package was placed between two nozzles, as shown in Fig. 2. In those tests, the frame arms were parallel to the east wall. It was observed that the frame arms did not significantly obstruct the water spray pattern.

Fire testing was conducted within the largest room in the facility. The room was 5.5 m x 5.5 m in area, with a ceiling height of 2.44 m. In addition to the main fire test room, the facility was constructed so that fire products could ventilate into connecting rooms (shown in Fig. 2 as an optional opening). A 12 m long, 1.5 m wide corridor was also constructed to simulate hallways common in offices, condominiums and apartment buildings with multiple residences. The purpose of the corridor, as with the rooms connecting to the main fire room, was to evaluate the effects of natural draft on the performance of the water mist system (number of actuating nozzles and required water supply).

The test room was fabricated using 5 cm x 10 cm studs and 5 cm x 20 cm ceiling joists. The walls and ceiling were covered with 1.3 cm thick plaster board. Combustible paneling and ceiling tiles were also used as part of the fuel packages, and will be discussed in the following section.

Fire Test Packages

Four different fuel packages were used in the current study: the UL 1626[17] corner residential package, an FMRC corner residential package[16], a bedroom fuel scenario, and a kitchen fuel scenario.

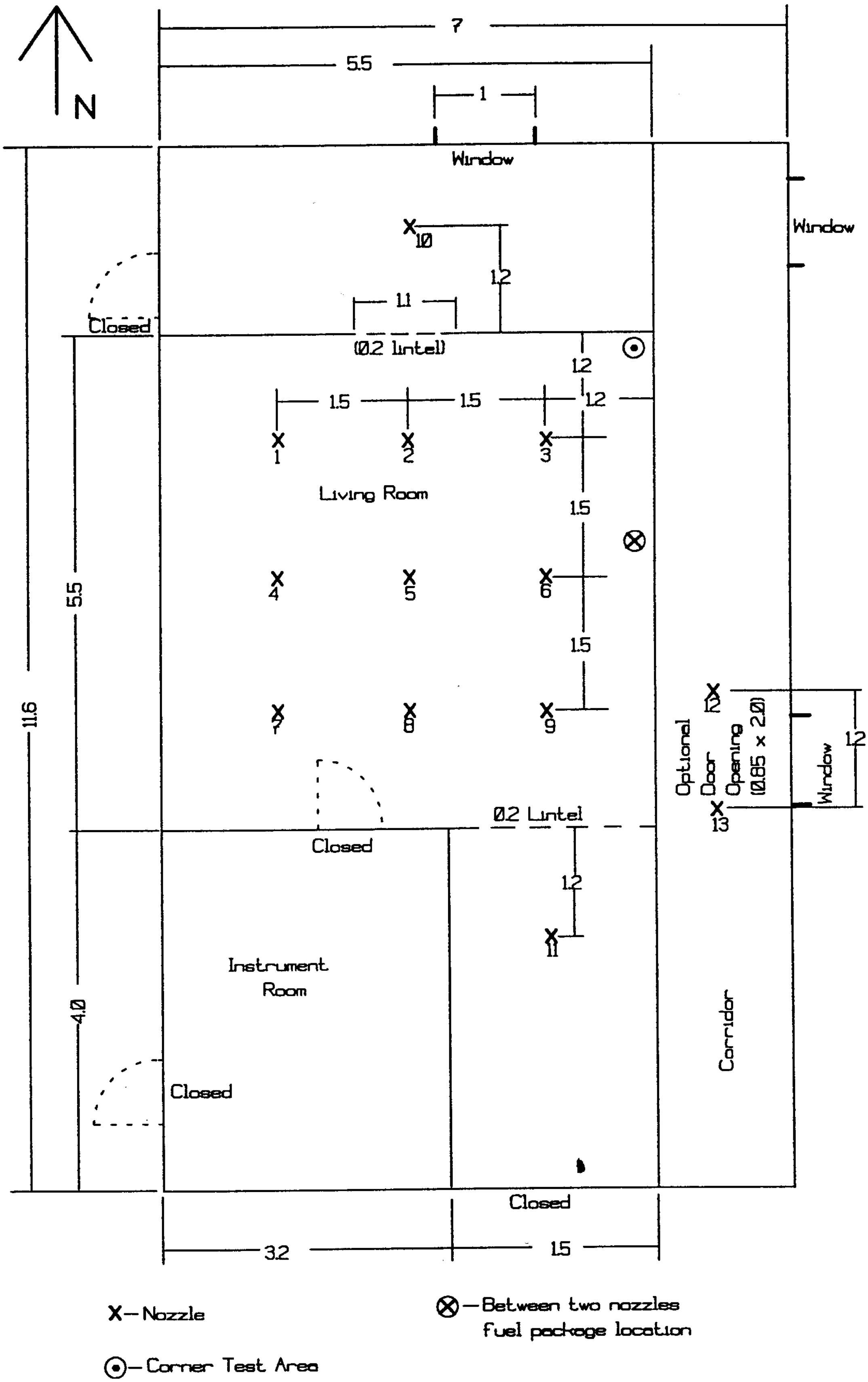

Figure 2. Schematic of test facility showing nozzle locations for Nozzles A (dimensions in meters).

The UL 1626 corner package consists of a wood crib and polyether foam attached to wood supports. Wood paneling with an ASTM E84 flame spread number of 200 is used along the walls, and combustible paneling with a flame spread number of 25 is used along the ceiling. Complete details of the fuel package are given in Ref. [16]. A schematic of the package as installed in the northeast corner of the main fire test room is shown in Fig. 3.

Originally, the FMRC residential fuel package[16] was based on a living room scenario using actual furnishings. Subsequent to this study, the FMRC residential fuel package has been revised to consist of simulated furnishings, such as used in UL 1626, rather than actual furnishings. The original FMRC residential fuel package has been used throughout this study. (It will be referred to herein as the FMRC residential fuel package.)[16] It consisted of a customized vinyl covered chair with polyurethane foam padding, two layers of curtains, a wooden end table, and a simulated end of a sofa. As in the UL package, combustible paneling and ceiling tiles are used. A schematic of the FMRC residential fuel package[16] is shown in Fig. 4. An analysis of sixty full-scale residential fire tests in the Los Angeles Residen-

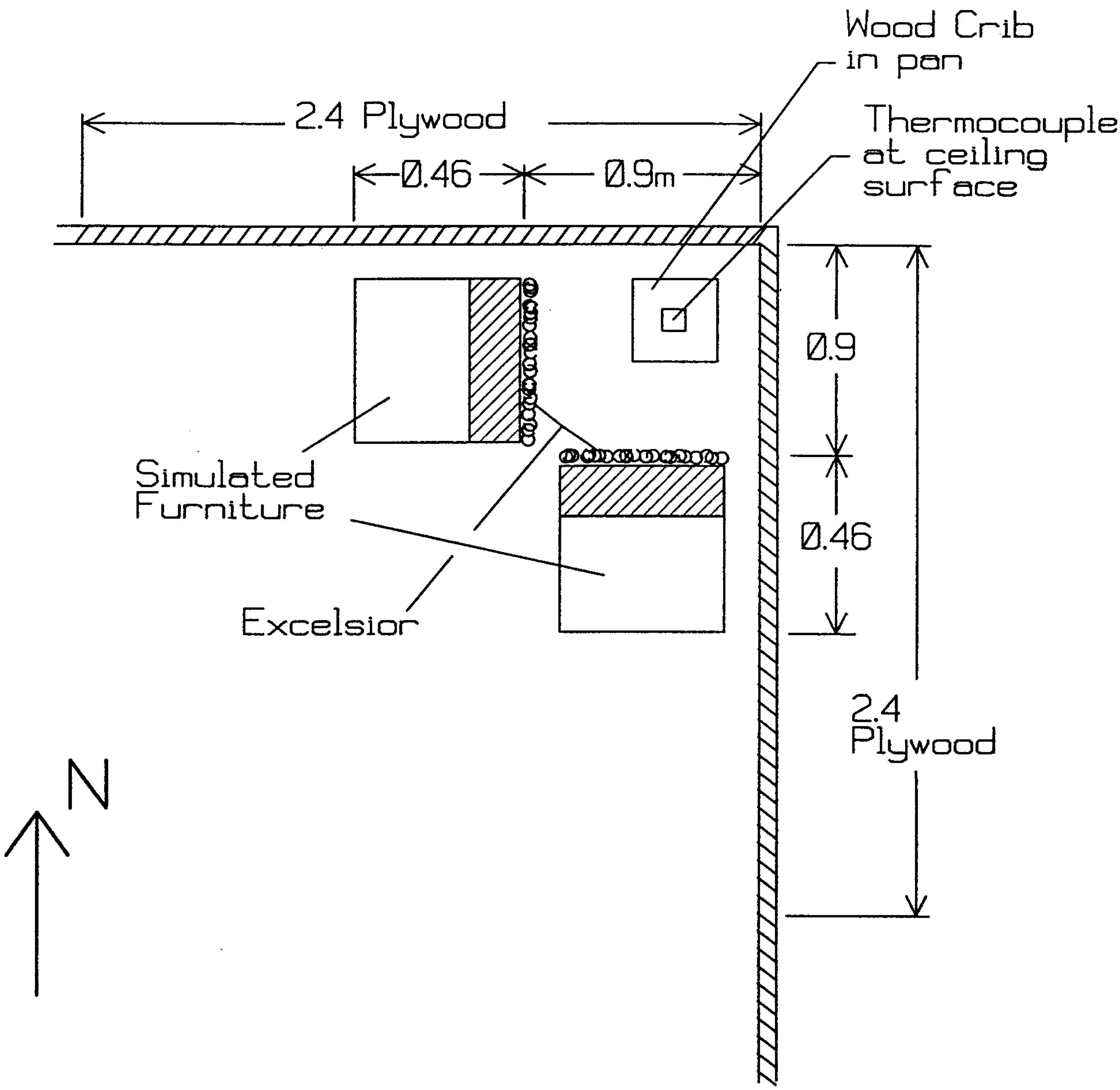

Figure 3. Schematic of UL 1626 corner residential fuel package (dimensions in meters).

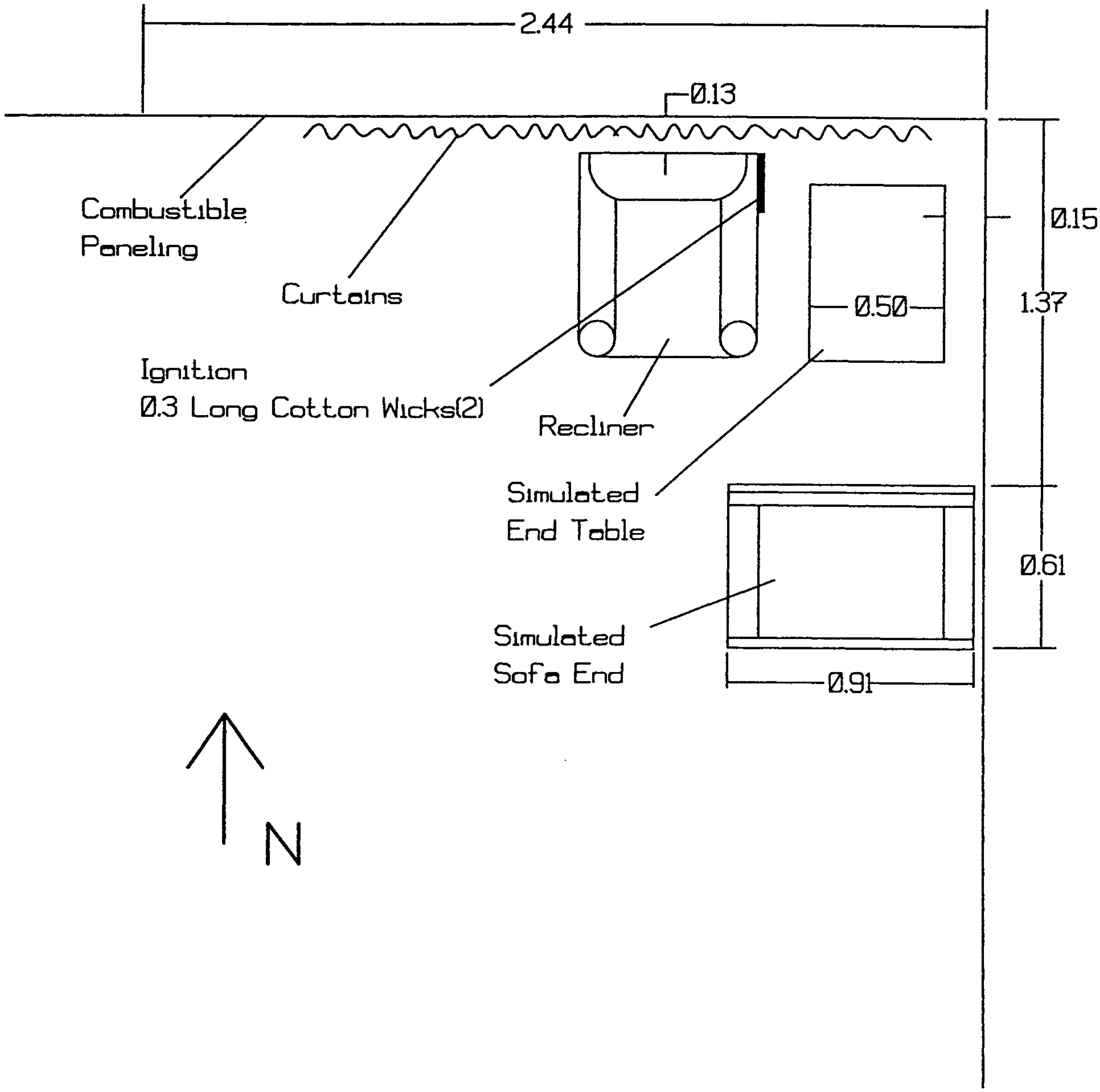

Figure 4. Schematic of FMRC corner residential fuel package (dimensions in meters).

tial Test Program[24] has shown that the FMRC residential fire test represents a worst case fire scenario for residential sprinkler protection. In addition to these fire tests, FMRC has also investigated fire scenarios in hotel rooms[25] and offices.[26] A comparison of sprinklered fire test results indicates that the corner living room scenario of the Los Angeles Residential Test Program is an appropriate worst case scenario for light hazard occupancies. FMRC has also used this scenario in the development of FMRC Approvals criteria for use with extended coverage sprinklers in light hazard occupancies.[27]

Details covering the burning characteristics of the upholstered chair are given in Refs. [23] and [28]. A listing of contents of the FMRC residential fuel package[16] is given in Table 2.

The bedroom fuel package scenario consisted of a standard commercially available bed placed in the northeast corner of the main fire test room. The contents of the bed are listed in Table 3.

A fourth fuel package consisted of a shielded heptane pool fire on a counter above the floor. This

Table 2. Description of FMRC Residential Fuel Package

Item	Units	Dimensions and Description
Simulated Sofa End	1	1.9 cm (¾ in.) plywood structure, open top and bottom, 61 x 91 x 61 cm high (24 x 36 x 24 in.).
Chair (Recliner)	1	Custom-made reclining chair, approximately 76 cm (w) x 91 cm (l) x 99 cm (h) (30 x 36 x 39 in.). All new materials consisting of vinyl covering with cotton backing, 4.5 kg (10 lb); shredded polyurethane foam (chair back, 3.6 kg (8 lb)); polyurethane foam (seat, 2.3 kg, 13 cm thick (5 lb, 5 in.)); polyurethane (arms, 1.4 kg, 2.5 cm thick (3 lb, 1 in.)) pine structure; total weight 23.8 kg (52.5 lb).
End Table	1	Table top, 1.9 cm (¾ in.) particleboard, 66 x 50 cm (26 x 19½ in.); table legs, soft wood, i.e., pine, fir, etc., 30 x 30 x 51 cm (12 x 12 x 20 in.)
Curtains	4	2 panels, rod pocket panels, 102 cm (w) x 183 cm (l) (40 x 72 in.), fabric blend: 50% polyester, 50% cotton. 2 panels, sheer, rod pocket panels, 102 cm (w) x 183 cm (l) (40 x 72 in.), 100% polyester batiste.

Table 3. Standard Bed Contents

1. Bed frame steel (1.8 m long by 1.4 m wide)
2. Box spring wood frame covered with corrugated fiber board
3. Mattress innerspring unit covered with resin treated pad consisting of textile chippings and fiber and urethane foam.
4. Sheets (2) no iron percale
5. Pillows (2) polyester fiber
6. Pillow cases 60% cotton, 40% polyester
7. Blanket 100% acrylic
8. Comforter 100% polyester

hazard was much more severe than would be expected for light hazard occupancies and provided an indication of the capabilities of the water mist system.

Water Supply System

Water was supplied in all fire tests to the water mist nozzles by an electric motor (20 HP) driven centrifugal pump rated for 492 Lpm at a pressure of 13 bar. Water was supplied to the water mist nozzles through a 2.54 cm (1 in.) CPVC feed line connecting to 2.54 cm (1 in.) branchlines above the ceiling. The water mist nozzles, all discharging with their deflectors about 50 mm below the ceiling, were connected to the water supply system using 1.27 cm (½ in.) CPVC couplings connecting to 1.27 cm (½ in.) CPVC nipples; CPVC tees and elbows were used and all joints were bonded with CPVC cement. The locations of water mist nozzles are shown in Fig. 2. Flow rates were controlled by monitoring water supply pressure. The appropriate system pressure was determined by flowing open nozzles and measuring the volume of flow over a 1 min time interval. This established the operating pressure for the desired flow of a single nozzle. When multiple nozzles operated, the pressure was manually adjusted to maintain the supply pressure. The centrifugal pump was operated prior to nozzle actuation by the use of a bypass line and by flow through an orifice (external to the test facility) at the end of the main feed line. Flow and pressure determinations were made with these established flows.

Instrumentation

Instrumentation to measure gas temperature, ceiling temperature, and gas concentrations of oxygen, carbon monoxide, and carbon dioxide were installed in the test facility. Thermocouples fabricated from Inconel sheathed 30 gauge chromel-alumel wire were used to measure gas temperatures. Thermocouples were installed in the center of the main fire test room 76 mm below the ceiling and 1.5 m above the floor. In each fire scenario, a thermocouple was installed over the ignition point, 76 mm below the ceiling. A thermocouple was also embedded 1 mm in the ceiling over ignition.

Gas sampling occurred at an elevation of 1.5 m in the room center. The gas flow rate was 8 Lpm with a lag time to the gas analyzers of about 30 s. The gas samples were drawn through a tube with a glass wool filter, and a desiccant. Concentrations of carbon monoxide and carbon dioxide were obtained using infrared analyzers. Oxygen concentrations were obtained using a paramagnetic analyzer.

The times of nozzle actuation were determined through recording of a voltage drop due to the breaking of an electrical circuit caused by the actuation of the nozzle. Data was obtained through computerized data acquisition at a rate of 1 scan per second.

Description of Fire Tests

The four fuel packages described previously were used in six fire scenarios. These scenarios were the FMRC corner residential fire test,[16] the FMRC residential fire test with fuel package between two sprinklers, the UL 1626 corner residential fire test,[17] a fire scenario using a modified UL fuel package between two sprinklers, a bedroom scenario, and a high challenge scenario consisting of a shielded heptane pool fire.

The procedure for supplying water to the water mist systems was similar in all tests. Water flow to the nozzles was maintained for at least 10 min unless damage to the test facility was anticipated. If it appeared, through monitoring of the gas temperature over ignition, that the fire was extinguished, the water flow was discontinued 10 min after the first nozzle actuation with data from the room being acquired for up to a total test time of 20 min. Otherwise, the water supply pressure was maintained after initial nozzle actuation up to a total test time of 20 min.

The FMRC residential fuel package[16] is shown in Fig. 4. Ignition was achieved through the use of two 0.30 m long cotton wicks which had absorbed 40 mL of methanol. The wicks were placed adjacent to the chair, as shown in Fig. 4. Ignition was initiated with a match. In this test scenario, the optional opening to the corridor shown in Fig. 2 was closed.

In a second scenario, the FMRC test package was installed along the east wall between two sprinklers, as shown in Fig. 2. In this scenario, however, the simulated sofa end was not used. The chair and cotton wicks used for ignition were located so as to be equidistant from the closest nozzles. The optional door opening, shown in Fig. 2, was used in this scenario.

The UL 1626[17] corner residential package, shown in Fig. 3, was installed in the northeast corner of the main burn room. As described in Ref. [17], 0.2 L (8 oz) of n-heptane were placed in a pan directly below the wood crib, and 113 g (4 oz) of excelsior were located on the floor adjacent to each section of simulated furniture (foam attached to wood supports). The n-heptane was ignited and, 40 s later, the excelsior was also ignited.

As with the FMRC residential fuel package[16], a second scenario between two nozzles was investigated using the UL residential fuel package. In this scenario, the crib was located as in the second FMRC scenario, i.e., between the two nozzles as indicated in Fig. 2. The wood crib was located 25 mm from the wall, as in the corner test with the crib center equidistant from the two closest nozzles (Fig. 5). The wooden supports, with polyether foam attached, were located as shown in Fig. 5. The distance between the supports along the wall was 1.4 m. Excelsior was placed on the floor as in the corner test. Ignition of the fuel package was as in the standard UL residential corner test.

The bedroom scenario was conducted with the bed (contents described in Table 3) located in the northeast corner of the main fire test room. The head of the bed was 76 mm from the north wall and the right side of the bed was 0.36 m from the east wall (see Fig. 2). A trash can (180 mm in diameter) was filled with 10 sheets of newspaper and placed adjacent to the head of the bed on the right side. Ignition was by a match placed in the bottom of the trash can through a 25 mm x 25 mm opening on the side.

The final scenario was a high challenge test incorporating a shielded heptane pool fire placed on a counter with simulated cabinets above. The scenario is not representative of residential or other light hazard scenarios, however, it provided a means of investigating the limitations of water mist systems. The counter/cabinet assembly was placed in the northeast corner of the main fire test room with the counter/cabinets running 2.1 m longitudinally along the north wall. The counter top was 0.91 m high and 0.61 m deep. The cabinets were 0.5 m above the counter top and were 0.91 m high and 0.4 m deep.

Using the counter/cabinet assembly, a high challenge shielded flammable liquid fire was developed. A 0.3 m diameter pan, filled with 600 mL of heptane, was raised 0.1 m above the counter top. The pan, placed 0.2 m from the east wall, was situated so that the bottom of the cabinets, 0.4 m above the pan, covered one half of the pan. A cabinet door, 0.6 m by 0.6 m, was simulated above the pan with a vertical 0.63 cm (¼ in.) plywood panel which was attached to the cabinets' surface on one edge and was propped open at a 30° angle with respect to the cabinet. The simulated door opening shielded a portion of the fire from droplets discharged by the water mist nozzles. (Note, however, no opening was cut into the cabinet surface).

The fire tests, utilizing Nozzle A, are listed in Table 4. The table indicates the fire scenario, number of nozzles actuated, and fire test results. Unless otherwise noted, nozzle flow rates, spacing and other characteristics were as in Tables 1 and 2. Details of all the fire tests are discussed in the following section.

Fire Test Results

As indicated in Table 4, eleven fire tests were conducted in the program using Nozzle A (and, in Test 10, a prototype limited-water-supply sprinkler) and the fire scenarios were described in the previous section. The fire tests were designed to last 20 min; however, some tests were aborted earlier using hose streams to avoid excessive damage to the test facility (Tests 8b and 15). When significant suppression occurred, the water supply was disconnected 10 min after first nozzle actuation (Tests 2, 3, 6, 7, 10 and 12). The 10 min period corresponds to the minimum sprinkler water supply duration under NFPA 13D[29] for one- and two-family dwellings. (The water supply requirement under NFPA 13[30] for light hazard occupancies is 30 min). In Test 7, fire regrowth occurred and the water supply was reconnected, resulting in fire suppression. The water supply was also reconnected in Test 3, but room tenability was not maintained. In the remaining tests (Tests 4, 9, and 13), the water supply pressure was maintained after nozzle actuation throughout the entire test period.

Test results were judged following the room tenability criteria of the Los Angeles Residential Test Program:[24] gas temperatures over ignition, 76 mm below the ceiling, are not to exceed 316°C; the ceiling surface temperature over ignition is

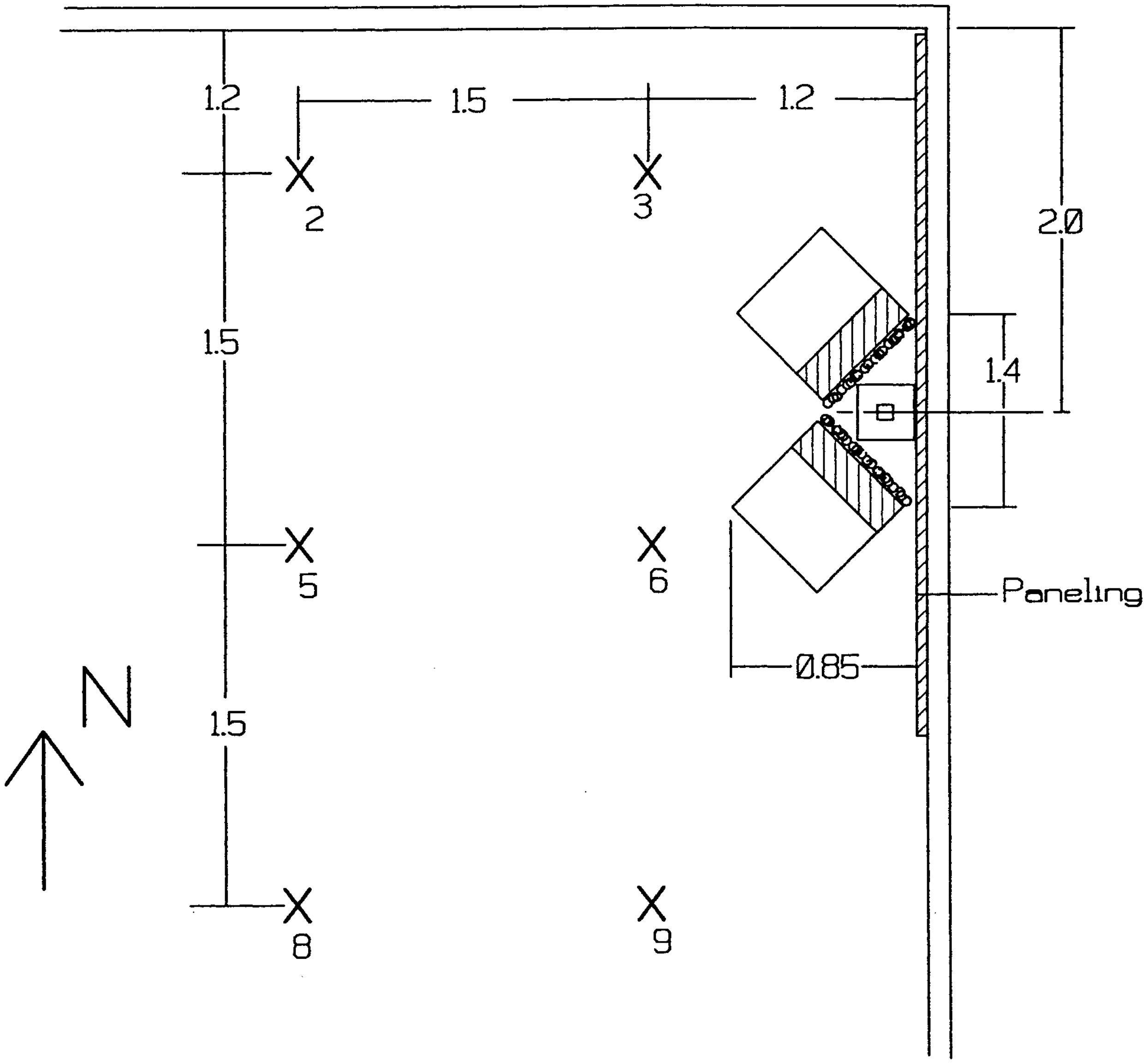

Figure 5. Schematic of modified UL 1626 residential package with ignition between two nozzles (dimensions in meters).

not to exceed 260°C; and the gas temperature in the room center at an elevation of 1.5 m is not to exceed 93°C. Gas temperatures at a height of 1.5 m in the room center did not exceed 51°C in any test. Although water spray did not impinge directly on the thermocouple at that location, a general build-up of fine droplets in the room may have wetted the thermocouple; hence, these results are not considered to be reliable and are not used further in the analysis of the test results. The maximum allowed carbon monoxide concentration is 3000 ppm. In Table 4, when these criteria are satisfied, the test result is listed as "suppression" or "extinguishment." Extinguishment implies no flames were observed at the conclusion of the test. The nozzle actuation times in each test are given in Table 5. Maximum temperature and gas concentrations (minimum for oxygen) are given in Table 6.

In the first test of Nozzle A, Test 2, the FMRC corner residential package[16] was used and rapid suppression occurred after the actuation of the nozzle closest to the fire. The water supply was disconnected 10 min after nozzle actuation. No fire regrowth occurred and the fire was seen to be extinguished at the end of the 20 min test. Temperature results are shown in Fig. 6. Nozzle A extinguished the FMRC residential fuel package at a flow rate of 15.1 Lpm. For compari-

Table 4. Fire Test Summary

Test No.	Fire Scenario	Nozzle Type	No. Nozzles Actuated	Duration of Water Flow (min)[1]	Result
2	FMRC (corner)	A	1	10	Extinguish
3	UL 1626 (corner)	A[2]	3	10 + 7	Failure
4	UL 1626 (corner)	A	2	19	Suppression
6	Bedroom	A	1	10	Extinguish
7	FMRC package (between 2 nozzles)	A	2	10 + 6.5	Suppression
8b	Shielded Heptane Pool Fire	A	2	18	Failure[4]
9	UL 1626 (corner)	A[2]	3	19	Failure
10	UL 1626 (corner)	Limited-Water-Supply Sprinkler	1	10	Suppression
12	UL package between 2 nozzles	A	3	10	Extinguish
13	UL 1626 (corner)	A	3	19	Suppression (Repeat of Test 4)
15	UL 1626 (corner)	A[3]	3	10	Failure[4]

[1] Initial period plus additional time if fire regrowth occurred and water turned on again.
[2] Flow rate varied between 11 and 15 Lpm per nozzle (below minimum specified by manufacturer).
[3] Bulb actuating element with 68°C temperature rating.
[4] Test aborted because of severe fire development.

son, fire regrowth has been observed to occur in this fire scenario with residential sprinklers operating at 68 Lpm.[24] The severity of the fuel package is indicated by the Required Delivered Density (RDD) of the FMRC chair which has been measured to be between 9 and 15 mm/min.[28]

Tests 4 and 13 were conducted at the manufacturer's specified flow rates using Nozzle A with the UL 1626 corner package, and provided a comparison between the FMRC residential fuel package and that used by UL. In Test 4, the fire growth was arrested when the first nozzle actuated at 1 min after ignition; however, the fire size was maintained. A second nozzle then operated 1 min 34 s after ignition, and fire suppression occurred followed by regrowth at about 4 min (see Fig. 7). Because the fire size was significant (as judged from the gas temperature) 10 min into the test, the water supply pressure was maintained throughout the remaining test period. The fire was suppressed and no other nozzles actuated.

Because of the symmetry of the nozzles with respect to the fire location in Test 4 (see Fig. 2), it was expected that a third nozzle might operate. To investigate this possibility, the conditions of Test 4 were repeated in Test 13. In this test, the three nozzles closest to the fire actuated. After actuation, the fire was initially suppressed; however, the fire then regrew, followed again by suppression.

The maximum gas temperature over ignition in Test 13 was 399°C, 84°C above the tenability limit. However, the maximum ceiling surface temperature and carbon monoxide concentrations were acceptable (216°C and 2086 ppm). Given the brief nature of the temperature peak (see Fig. 8) and the acceptable value of the other tenability factors, the fire is considered to be sup-

Table 5. Actuation Times (min:s)

Test No.	Nozzle Location		
	3*	2*	6*
2	1:00	DNO	DNO
3	0:46	1:16	1:08
4	1:00	DNO	1:34
6	1:16	DNO	DNO
7	1:54	DNO	4:40
8b	7:01	7:47	DNO
9	0:55	1:15	1:13
10	0:58	DNO	DNO
12	0:55	DNO	0:46 (0.55**)
13	1:03	1:34	1:30
15	0:31	3:36	2:02

* See Fig. 2 for location of nozzles.
** Nozzle No. 9 operated (see Fig. 2).
DNO = Did not operate.

Table 6. Gas Concentration and Temperature Results

Test No.	Max. CO (ppm)	Max. CO_2 (%)	Min. O_2 (%)	Max. Ceiling Surface Temperature (°C)	Max. Ceiling Gas Temperature (°C)
2	211	0.1	20.4	81	256
3	2207	2.7	18.2	200	518
4	1780	2.6	17.3	204	258
6	194	0.3	20.1	58	177
7	938	1.1	19.4	111	246
8b	3923	2.4	17.7	673	934
9	4131	3.9	15.7	599	857
10	*	0.7	19.8	90	233
12	868	1.5	19.2	106	270
13	2086	2.2	18.3	216	399
15	1279	2.4	18.2	523	*

* Instrument malfunction

pressed for the purposes of this study. The difference in the results between Test 4 and 13 may possibly be due to slight differences in the nozzles due to their fabrication as prototypes rather than production nozzles.

In order to provide some insight into the performance of the water mist nozzles, Test 10 was conducted with the UL corner package using prototype Limited-Water-Supply sprinklers. The prototype was developed by FMRC in a program[23]

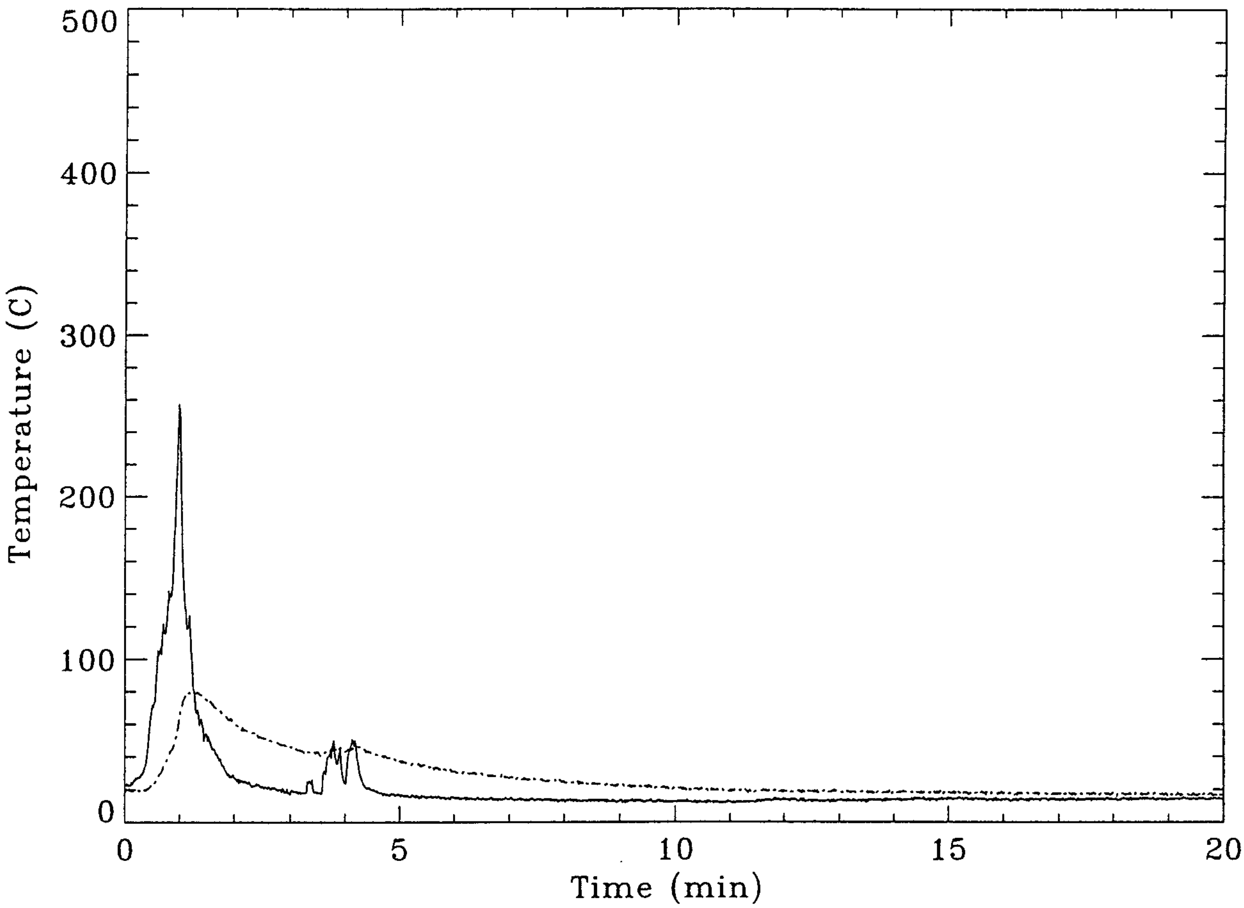

Figure 6. Temperature results for FMRC residential corner test (Test 2); ___, ceiling gas temperature; ___.___, ceiling surface temperature.

sponsored by the USFA to develop a sprinkler system for manufactured homes requiring a total water supply of 380 L. The sprinklers were installed at the same locations as Nozzle A, shown in Fig. 2. The design flow rate of 38 Lpm was provided upon sprinkler actuation. The fire was suppressed with only a single sprinkler actuation, and suppression was maintained when the water supply was discontinued after 10 min. This contrasts sharply with the test reported in Ref. [23], in which three sprinkler actuations occurred with the FMRC package and control was lost after the water supply was discontinued.

The above results are indicative of the different suppression mechanisms employed by sprinklers and water mist systems. In the UL scenario, the burning crib, being close to the wall, is a reliable ignition source for the combustible paneling. In contrast, in the FMRC scenario, the chair is the primary hazard with the paneling becoming involved only after considerable fire development in the chair. Sprinklers with relatively large droplets, and a spray pattern designed to have high wall wetting, may easily prevent propagation up the wall paneling if sprinkler actuation is early enough. Water mist nozzles, however, with smaller droplets and lower flows provide less wall wetting, and are therefore more vulnerable to vertical fire propagation on combustible surfaces. The superior performance of the water mist system in the FMRC scenario suggests that the cooling of flames above the chair, absent with larger sprinkler droplets, is significant to suppression in this scenario.

Compared to the FMRC residential fuel package[16], the UL package is more easily specified and constructed, and represents a more challenging light hazard fire test for water mist systems. (The FMRC residential package appears to be more severe for automatic sprinklers). It was therefore recommended that a UL 1626 type corner test

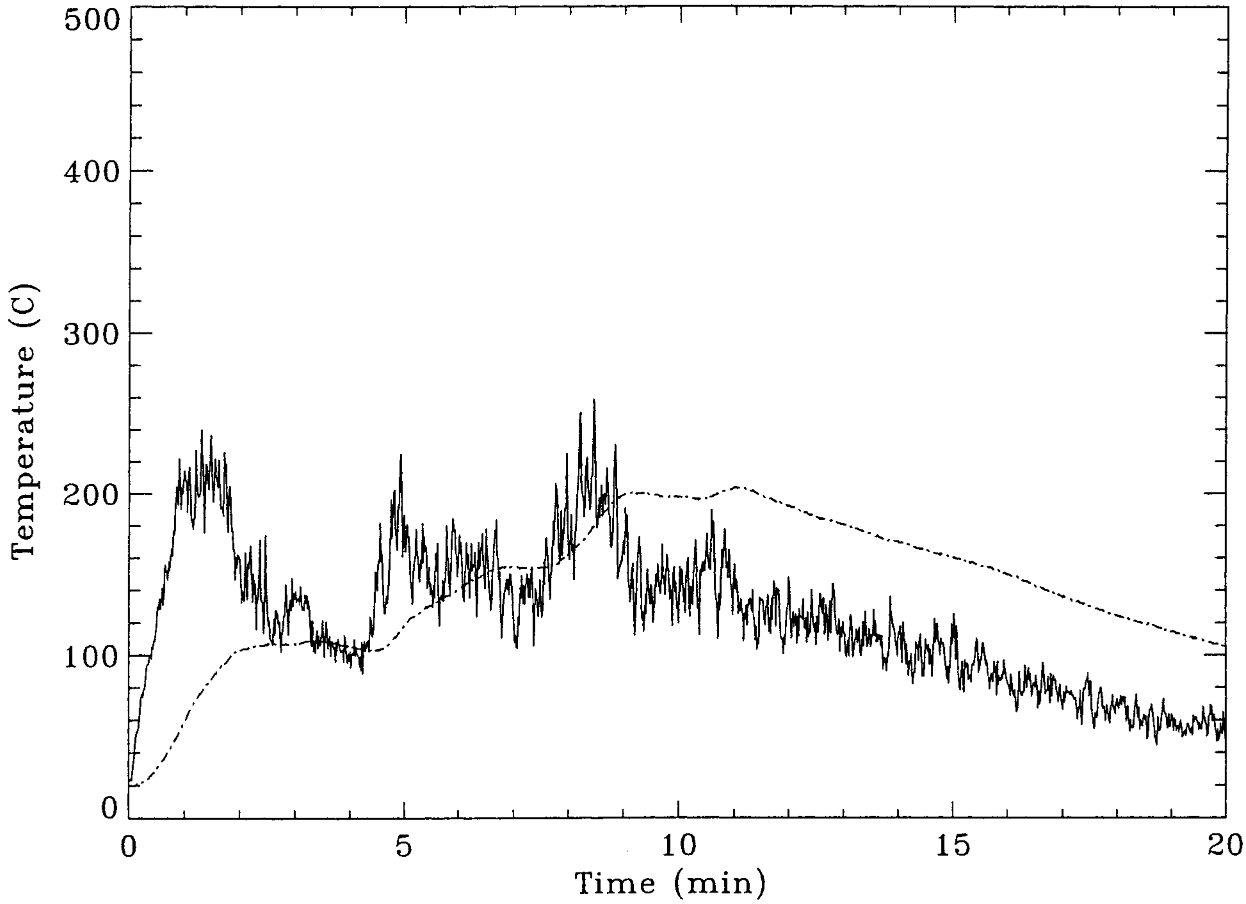

Figure 7. Temperature results for UL residential corner test (Test 4); ___, ceiling gas temperature; ___.___, ceiling surface temperature.

be adopted as part of a water mist system FMRC Approval test.

Two other tests, Tests 3 and 9, were conducted using the UL 1626 corner scenario with Nozzle A. In these tests, the flow rate was not steady due to varying supply pressures. The flow varied between 11 and 15 Lpm. In both tests, 3 nozzles actuated and the fire was not controlled. For comparison, results of Test 9 are shown in Fig. 9. This indicates that a minimum flow rate higher than 11 Lpm is needed for acceptable performance by Nozzle A. In Test 15, Nozzle A was installed with a 68°C temperature rated bulb compared to 79°C used in the other tests with this nozzle. Although the nozzle flows were the same as in successful Tests 4 and 13, the test had to be aborted to avoid damage to the facility. It is unclear why this failure occurred, particularly considering the successful use of 68°C temperature rated water mist nozzles in similar testing[31]. Test 15 appears to be an anomaly which unfortunately could not be further investigated in this program.

A maximum of three nozzles actuated in any of the corner tests using Nozzle A. In order to investigate if additional nozzles could actuate in other scenarios, the FMRC package and a modified UL package were used in two tests with ignition between two nozzles. The details of the fire scenario are described in the previous section. In Test 7, the FMRC package was used and Nozzle Type A was installed as in Fig. 2. The nozzle in the northeast corner actuated 1 min 54 s after ignition (Fig. 10). The fire was rapidly suppressed; however, fire regrowth occurred and a second nozzle actuated 4 min 40 s after ignition. The fire was again suppressed and the water flow was discontinued 10 min after the first nozzle actuation. Fire regrowth occurred 13 min after ignition and the fire was suppressed when the water flow was reestablished.

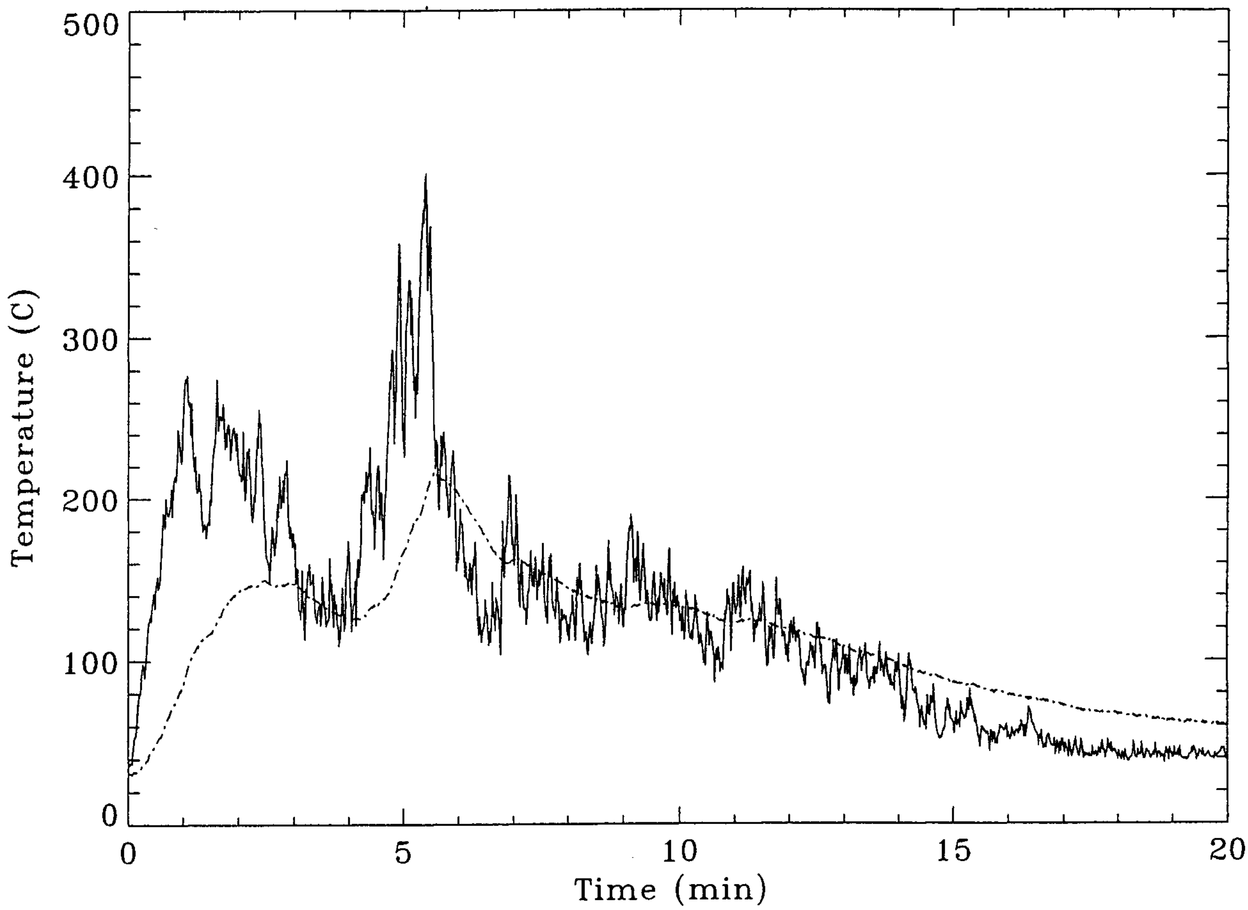

Figure 8. Temperature results for UL residential corner test (Test 13); ___, ceiling gas temperature; ___.___, ceiling surface temperature.

Because this scenario was more challenging for Nozzle A than the FMRC corner scenario, a modified UL package was installed in Test 12 as shown in Fig. 5. In this test, three nozzles actuated. Nozzles 3, 6 and 9, as shown in Fig. 5, actuated at 55 s, 46 s, and 55 s, respectively. The fire was suppressed and the water supply disconnected 10 min after the first actuation (Fig. 11). A comparison of the results shown in Figs. 7 and 11 indicates that the UL corner test was a more severe challenge than the modified UL test between two nozzles. The three-nozzle actuation in Test 12, however, underlines the conclusion from Test 13 that, for Nozzle A, a water supply of at least 15 Lpm for each of three nozzles is needed for adequate performance.

Two other fire scenarios were conducted with Nozzle A. In Test 6, the bedroom scenario was used. One nozzle actuated and extinguished the fire. Water flow was discontinued in this test, 10 min after nozzle actuation.

In Test 8b, a shielded heptane pool fire was used, as described in the previous section. It was envisioned that the small droplets would be entrained into the pool fire and result in extinguishment. About 6 min into the test, the wood paneling of the cabinet, shielded by an open cabinet door, began to burn vigorously. Nozzle actuations occurred at 7 min 1 s and 7 min 47 s; however, the fire was not suppressed. Despite gas temperatures exceeding 900°C under the ceiling over ignition, no additional nozzles operated. The ceiling surface temperature, however, was as high as 673°C and the carbon monoxide concentration maximum was 3923 ppm. The test was aborted 18 min after ignition using a hose stream.

The small number of actuated nozzles attest to the very effective cooling of the small droplets generated by the water mist nozzles. After the test, the nozzles were actuated to see if droplets were impinging on the unactuated nozzles.

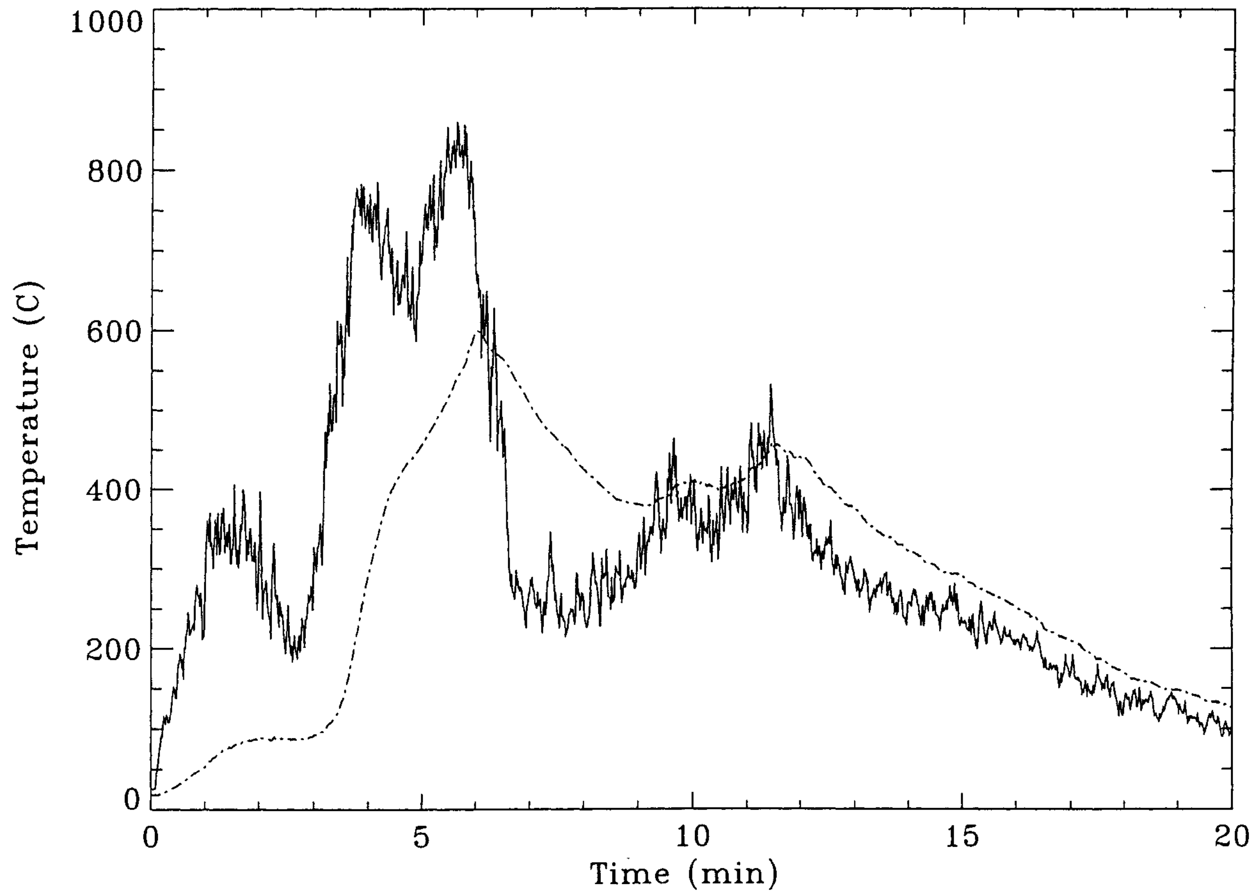

Figure 9. Temperature results for UL residential test (Test 9) with low water flow rate; —, ceiling gas temperature; —·—, ceiling surface.

Although no droplet impingement was visible, a general build-up of water mist in the room was observed, which may account for the small numbers of nozzles actuated. For residential protection with a limited water supply or light hazard occupancies where it is critical to limit water damage, this may be advantageous in that the fire is localized while cooling throughout the room reduces nozzle actuation.

Discussion of Results

The fire test results presented above indicate that water mist systems have the potential to provide protection for light hazard occupancies comparable to sprinklers as used in commercial or residential applications. The maximum number of nozzles operating in any test was three with a total application of 45 Lpm (Tests 3 and 12). The tests in which three nozzles operated involved simulated furnishings; however, when realistic furnishings were used (Tests 2 and 7) the performance was improved. The excellent performance of the water mist systems with real furnishings provides a high level of confidence that water mist systems have the capability of protecting light hazard occupancies at reduced water supply levels compared to traditional sprinkler systems. Finally, in Test 8b, in which a shielded heptane spray fire was used, only two nozzles operated due to the high cooling at the ceiling even though the hazard was well beyond that of a light hazard occupancy. This test result suggests that a further benefit of water mist systems compared to sprinklers is reduced area of water damage.

In contrast to the water mist performance summarized above, current FMRC sprinkler standards for unconfined light hazard occupancies require a total water flow of 568 Lpm (4.1 mm/min over 139 m^2 area). FMRC Approved extended coverage (EC) sidewall sprinklers may be used in compartments up to 150 m^2 in area, at

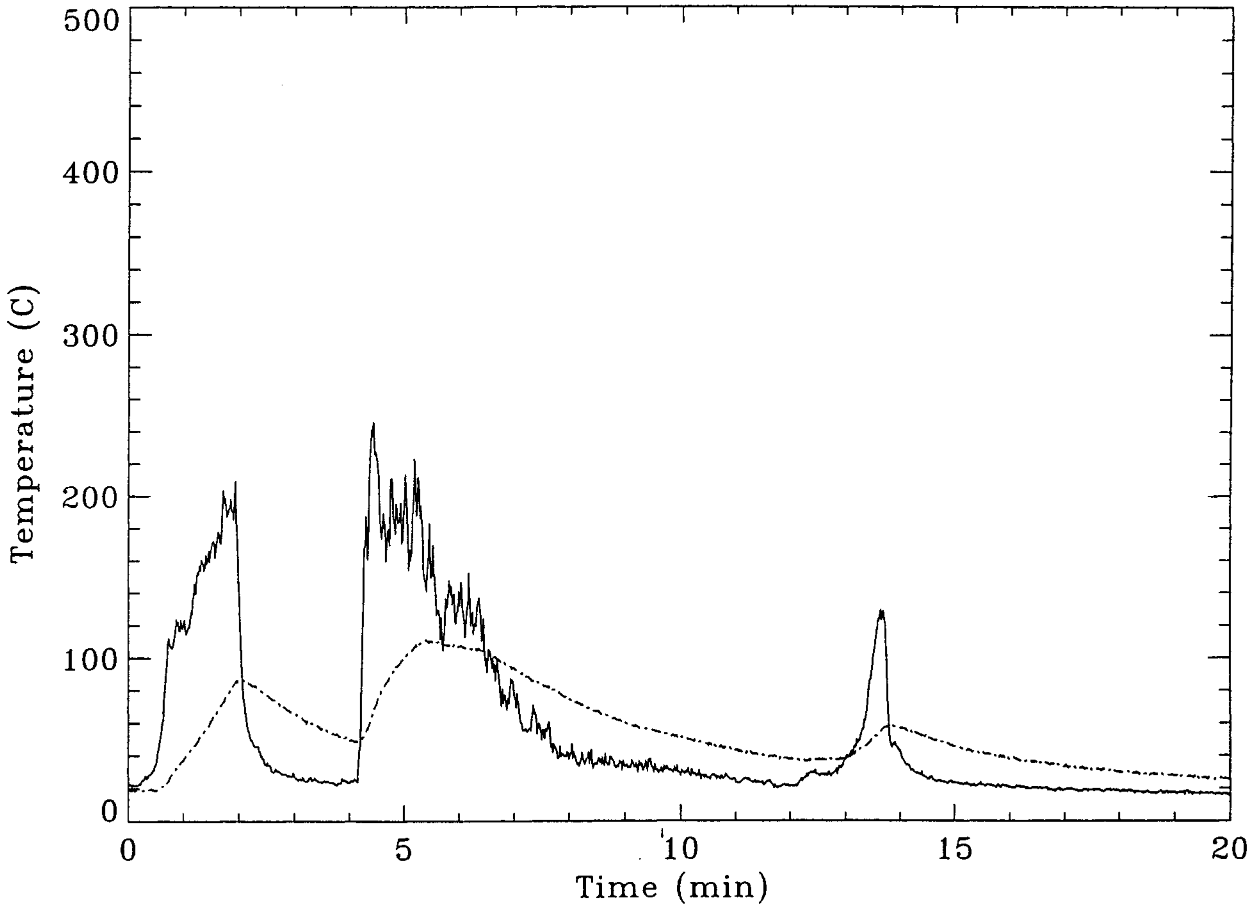

Figure 10. Temperature results from testing using FMRC fuel package placed between two nozzles (Test 7); __, ceiling gas temperature; __.__, ceiling surface temperature.

a density of about 4.1 mm/min and a maximum coverage area of 37 m^2. (Sidewall sprinkler water supplies are governed by end pressures).[25] For a compartment the same size as that tested in this study (30 m^2), the required total flow rate would be 124 Lpm.

In order to establish nozzle flow and spacing requirements along with total flow requirements for water mist systems in light hazard occupancies, FMRC has established three full scale fire tests: 1) a compartment test similar to those reported here in which the UL residential package is installed in the room corner, 2) a fire test with bunk beds which demonstrates the capability of the water mist to suppress fires where direct spray impingement is not possible, and 3) an "unconfined" space test using simulated couches. These tests have been adopted from the IMO standard for water based systems.[14] Two types of FMRC Approval are available for water mist systems protecting light hazard occupancies: systems restricted for use in compartments to a maximum size of 37 m^2 and systems which can be installed without any restriction in regard to area. In the former case, only the first two types of fire tests must be conducted. All three types of fire tests must be conducted for systems with no restriction on compartment area. Key details of the three tests are given below. Further details are available in the FMRC Water Mist Light Hazard Standard.[32]

The bunk bed test is adopted from a series of such tests intended to simulate small cabin fires in the IMO standard. A fire is ignited in a lower bunk bed mattress in a room 12 m^2. The mattress is made of polyether foam with a cotton fabric cover. In the FMRC test, a single nozzle is placed in the room center. Damage to the cushion of the lower bunk bed is to be limited to 40% by volume. In addition, the maximum ceiling surface and gas temperature (76 mm below the ceiling) over ignition are to be less than 260°C and 315°C,

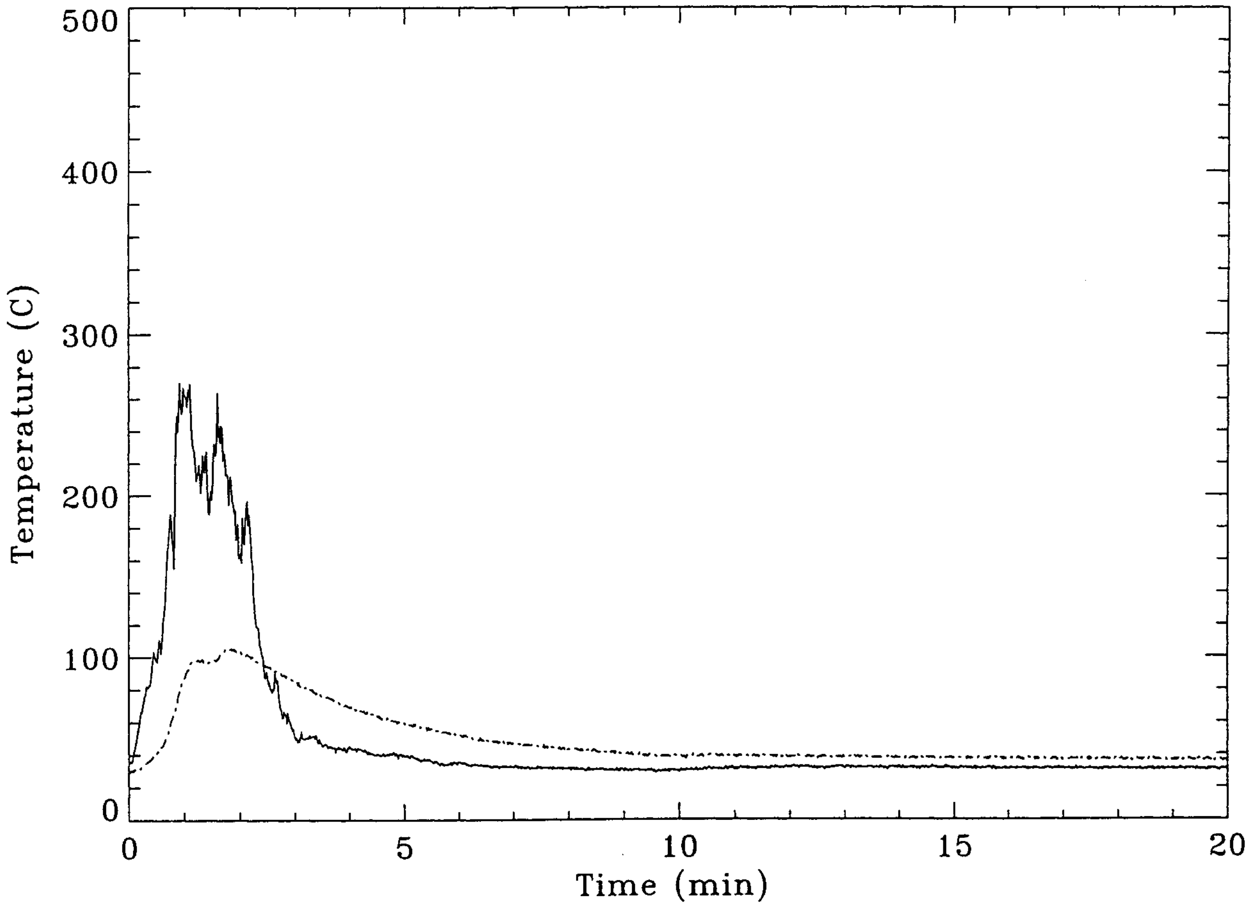

Figure 11. Temperature results from testing using modified UL residential fuel package between two nozzles (Test 12); ___, ceiling gas temperature; ___.___, ceiling surface temperature.

respectively. Testing[3] has shown that sprinklers will not typically provide this level of protection; hence, this test is a means of differentiating water mist systems and sprinklers in light hazard applications.

A compartment test, similar to the corner tests with the UL fuel package described in this study, is to be conducted in a square room no greater than 37 m^2 and a ceiling height of 2.5 m. The fuel package, however, should have more precise and controllable flammability characteristics, measurable using small-scale calorimetry. The compartment size, selected by the manufacturer, will be the largest size compartment that can be protected by the mist system unless the unconfined space fire test is conducted. Nozzles are to be installed at the maximum spacing and supplied with the minimum water flow specified by the water mist system manufacturer. A nozzle is also to be installed in a doorway diagonally across from the simulated furniture fuel package. For systems only FMRC Approved for protection of compartments 37 m^2 or less (i.e., without the "unconfined" space test), the doorway nozzle is not to actuate. Water supply requirements are based upon all the nozzles in the compartment actuating. Other criteria for approval are that the gas temperature at 76 mm below the ceiling and the ceiling surface temperature over ignition should not exceed 315°C and 265°C, respectively. Based on these tests, water mist systems are to be FMRC Approved for use in compartments with ceiling heights no greater than 3 m, a modest extrapolation of the test condition.

Water mist systems to be FMRC Approved for use in spaces without area restriction are to pass the IMO Public Space Test[14]. In this test, simulated couches with polyether cushions and cotton fabric covers are placed below nozzles in three ceiling configurations: couches centered under one nozzle, between two nozzles, and between four nozzles. In tests with a ceiling height of

2.5 m at the Swedish National Testing and Research Institute (SP), it was observed that the Public Space Test resulted in the actuation of six standard sprinklers [RTI = 300 $(m\text{-}s)^{1/2}$] installed at a 4 m spacing using a density of 4.4 mm/min when the couches were centered between two sprinklers.[33] This indicates that the Public Space Test is a severe test for light hazard occupancies.

The ceiling height in the FMRC Approval test for "unconfined" spaces is 5 m. No more than five nozzles are allowed to actuate with at least one nozzle observed to remain unactuated beyond each actuated nozzle. In addition, over ignitions the maximum ceiling surface temperature and gas temperature at 76 mm below the ceiling are to be no more than 260°C and 315°C, respectively. Damage to the couches is restricted to 50% by volume.

Water Supply and System Demand

In the successful tests conducted during this study, water supply duration varied from 10 min to 19 min. However, because in some fire tests extinguishment did not occur, a minimum water supply of 60 min is required for the operation of the water mist system protecting light hazard occupancy occupancies, the same as required by FMRC for sprinklers. The water supply is to be capable of supplying the hydraulically most remote nine nozzles for mist systems approved for use in "unconfined" spaces. This nine nozzle design approach corresponds to a design involving a ring of nozzles operating beyond that of a fire centered under one nozzle. Such a design may prove conservative, as indicated by the test results of this study, but a margin of safety is appropriate until further experience is gained with this new technology. In the case of mist systems that are only approved for use in compartments, the water supply must be sufficient to supply the maximum number of nozzles in any compartment.

Conclusions

This study shows low pressure water mist technology to be a viable alternative to automatic sprinklers in the protection of areas of light hazard occupancies, such as in offices, hotel rooms, residences, and other similar areas. When compared to automatic sprinkler protection in compartmented areas, tests conducted by FMRC showed that low pressure water mist systems have potential for offering protection using less water, hence, with reduced water damage at equivalent fire damage areas. Water mist nozzle design characteristics and operating parameters were found to have significant impact on the ability of this new technology to suppress or extinguish the test fires; consequently, a full-scale fire test protocol is required for evaluation of different nozzles and system designs for light hazard occupancy applications.

Based on the results of the FMRC fire tests in a compartmented area and on a review of the IMO fire test protocol for water mist in unconfined areas, a comprehensive fire test protocol has been recommended in this paper for water mist systems in compartmented and "unconfined" areas of light hazard occupancies.

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