

"CRITICAL CONCENTRATION' MEASUREMENTS AND LAB-TO-ROOM SCALE-UP WATER MIST FIRE TESTING

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ABSTRACT

The de novo thickness (**DNT**) i.e., the minimum product of extinguishment time and water flow rate required to extinguish the fire, for incipient heptane fires was determined. Although water mists were able to extinguish heptane telltale fires (5-cm diameter) with water fluxes as low as 0.025 L/min-m^2 , significant variations occurred in extinguishment times until the water flux exceeded 0.60 L/min-m^2 for a DNT of 0.3 Um' . Above this level, water use increased at a rate significantly greater than the corresponding decrease in extinguishment times.

Additionally, scale-up testing to determine whether laboratory-scale results would correlate with room-scale results was investigated. Room-scale testing used the findings from the laboratory-scale tests to design a room-scale system which successfully extinguished unobstructed, partially obstructed, and fully obstructed Class A (wood and paper) and Class B (heptane) fires.

INTRODUCTION

During the development of water mist systems, several basic concepts have arisen which impact the design, development, and marketing of water mist systems. Among the concepts worth investigating are the following:

1. Determination of the "critical concentration," i.e., the minimum total mass of water in droplets per unit volume required to extinguish various Class **A**, **B**, and **C** fires.
2. Effect of droplet size, size distribution, droplet velocity, and obstacles on "critical concentration."
3. Effect of droplet size, size distribution, and droplet velocity on the ability of the mist to penetrate complex spaces.
4. Determination of droplet lifetime and droplet suspension lifetime with regard to inertia.

No widely accepted method has as yet been developed to obtain reproducible volumetric concentrations in operating water mist systems. Work that has been reported normally used water **flux** rates required to extinguish various fires. This work comes one step closer to critical

concentration by introducing the concept of a “de novo thickness” (L/m^2) which is defined as the minimum product of extinguishment time (min) and water flow rate ($L/min\cdot m^2$) required to extinguish various Class A, B, and C fires.

Recent articles have indicated that application rates for water mist technologies usually fall in the range of $0.35 L/min\cdot m^2$ to $1.75 L/min\cdot m^2$ with the lowest successful application rate being $0.80 L/min\cdot m^2$ (1). As part of a program to study the feasibility and economics of water mist systems as potential replacements for some halon systems, several different single-fluid water mist nozzles were used to determine the lowest water flux rate which would effectively extinguish incipient fires as represented by 5-cm diameter heptane telltale fires. Heptane fueled telltale fires were chosen to represent incipient fires since the literature and researchers presently performing room-scale fire extinguishment testing have indicated that telltale fires are the hardest to extinguish.

Upon determining the de novo thickness (DNT) required to extinguish heptane telltale fires, attention was turned toward determining whether small-scale laboratory studies could be used successfully to design a room-scale fire suppression system. Laboratory studies determined the nozzle spacing, operating pressure, and water flux rates used to develop a room-scale fire suppression system. Room-scale experiments were proof-of-concept and scale-up tests. These experiments were conducted using the operating parameters determined during the laboratory studies to test the overall effectiveness of the water mist system in actual use. Assessments were made of the system’s ability to suppress fire, to protect against reignition, and to measure water damage to powered equipment, paper records, and electronic data storage contained in the room.

EXPERIMENTAL APPARATUS AND TEST PROCEDURES

Laboratory-Scale Experiments

The aerosol test chamber (ATC) used for the laboratory-scale testing measured 1.07 m by 1.07 m by 2.06 m and encompassed $2.3 m^3$ of volume. The incipient fires represented by five 5.08 cm diameter by 4 cm tall telltales (steel cups) used 10 mL of heptane floated on water. The water used to extinguish the fires was supplied by a $0.108\text{-}m^3/min$ high pressure metering pump capable of 10.3 MPa and controlled by a 60-Hz AC variable speed controller (0 to 5 gpm at pressures from 0 to 1500 psig), and was recycled within the system using a spill containment pallet as the reservoir.

A range of single-fluid nozzles allowed a wide spread in water mist characteristics without the additional variables added with dual-fluid systems. The selected nozzles represented the range of products available— low pressure/high momentum nozzles (2.7-mm orifice diameter), intermediate pressure/momentum impingement nozzles (1.0-mm and 1.4-mm orifice diameter), and low-momentum humidification nozzles (0.2-mm and 0.5-mm orifice diameter). Table 1 lists the nozzles, number of nozzles used in an array, and the operating pressures used in the testing.

For each nozzle array and test condition, 470-mL (16-oz) water tumblers were placed across the floor of the ATC in an 11 by 11 array (A1 to K11). At the desired operating pressures,

gravimetric samples were collected in each tared tumbler. From the operating time and the weight of the water collected in each tumbler, the spray pattern above the tumbler in $L/min\cdot m^2$ was determined. After a full matrix was determined for the spray chamber, two vertical and two horizontal rows were checked twice **for** reproducibility of the array and flow rate to determine the statistical variances of the measurements. The flow test operating times varied with the number of nozzles, but were long enough to minimize startup and shutdown effects.

TABLE 1. MANUFACTURERS AND OPERATING DATA FOR NOZZLES SELECTED FOR TESTING

Manufacturer	Drop size range*	Number of nozzles	Operating pressure, MPa	
			Lower limit	Upper limit
Grinnell Aqua Mist AM-11	10-325 μm	1	0.7	1.2
Bete P 54	25-400 μm	3	1.4	2.8
Bete PJ 40	<50 μm	3, 1	1.4	6.9
Baumac International MX-20	10-200 μm	14	3.4	6.9
Baumac International MX-8	10-180 μm	14, 7, 4, 1	3.4	6.9

* Based upon manufacturers' sales literature.

The results of the flow analysis were plotted and five positions were chosen for the placement of the 5.08-cm telltales, based upon the different spreads (ranges) in water flux for the nozzle arrays. Each telltale was filled to within 3 mm of the rim with water; then 10mL of heptane was added and ignited. After a 30-s preburn, the door to the ATC was closed, the water mist system was started, and the times required to extinguish the flames were recorded. To determine the statistical variances of the measurements, 10 extinguishment tests were run for each water mist flux rate and nozzle array.

Upon completing the extinguishment tests, additional water flux testing was conducted to obtain a uniform water flux across a room with a ceiling water mist system. The nozzle array design giving the most uniform water flux for nozzles having a circular spray pattern was a rhombohedral patterned array with a 39.4-cm nozzle spacing on a 30.5-cm pipe run spacing which minimized the space between nozzle spray patterns (Figure 1).

Room-Scale Experiments

Room-scale experiments were proof-of-concept and scale-up tests using the laboratory-developed operating parameters to determine the overall effectiveness of the water mist system in actual use. Assessments were made of the system's ability to suppress fire, to protect against reignition, and to minimize or measure water damage to powered equipment, **paper** records, and electronic data storage media contained in the room.

The internal dimensions of the test chamber are 3.18 m long x 2.34 m wide x **2.40** m high for an internal volume of 18.3 m^3 . The test chamber is equipped with an automatic ventilation

system, motorized exhaust fan, and two motorized dampers, that can be used to sustain the internal oxygen concentration to support combustion during preburn. In addition to a camera providing video coverage, the tests were monitored by a data acquisition and equipment control system using a National Instruments Lab Windows software-based 486-DX33-MHz personal computer (PC) data acquisition and control system to scan and record four sensor input/output control circuits. Additionally, the test data were displayed on screens in real time for viewing and interpretation of results.

A ceiling array of 53 Baumac MX-8 nozzles, made from 12.5-mm outside diameter 304 stainless steel pipes and set in a rhombohedral pattern with a 39.4-cm nozzle spacing on a 30.5-cm pipe run spacing, provided the most complete and uniform coverage for the 3.18 m x 2.34 m room. Water was supplied to the nozzle system by the same pumping system used for laboratory testing. The nozzle array was fed from the center to minimize pressure differentials. The metering pump and water supply system were in the adjacent spaces (Figure 1).

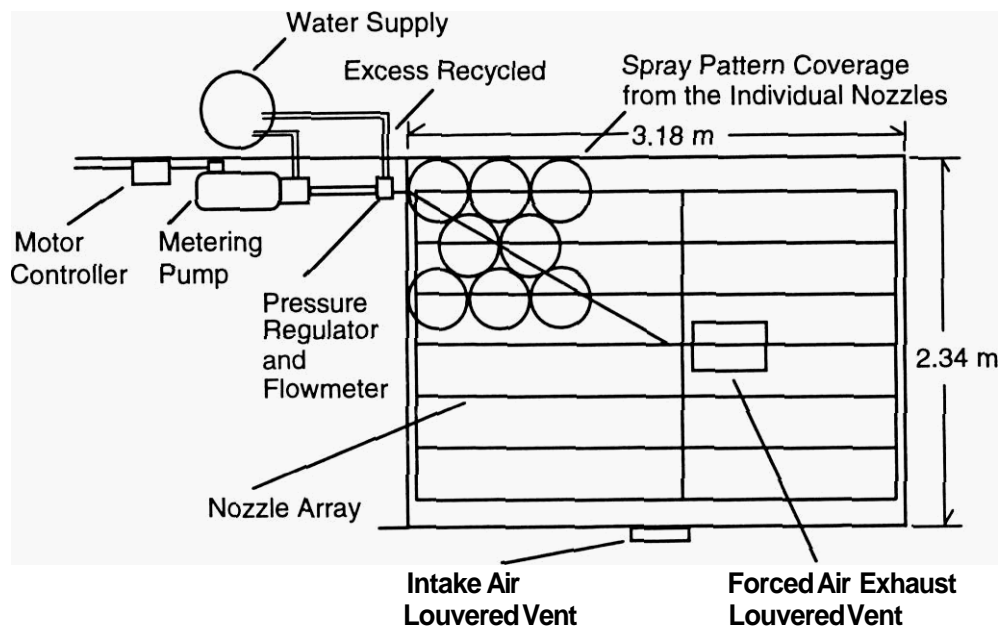


Figure 1. Baumac MX-8 System layout for room-scale tests.

The water mist fire testing used the same obstructions, 7.6-cm diameter heptane-fueled telltales, pool fire pans (21.0 cm and 45.7 cm), and wood cribs normally used for halon and halon replacement testing. All pans and telltales were 10.2 cm tall with 5.1 cm of water and 2.5 cm of heptane. The obstruction feature used in this testing was open on top and only partially open on the sides (10 to 15% of the sides are open), since the halon replacement test nozzle directs the gas/liquid stream horizontally along the top of the test chamber, and the momentum carries the vapor down the walls and back across the floor (Figure 2). Under halon replacement test conditions, obstruction from the sides was considered more important. Since this test feature allows water mist to fall into it but restricts the water mist entering from the sides, these fires were considered partially obstructed in the tests where the pans were centered near one side of

the feature. Table 2 lists the test scenarios used during the proof-of-concept and scale-up testing for the Baumac MX-8 nozzle based water mist system.

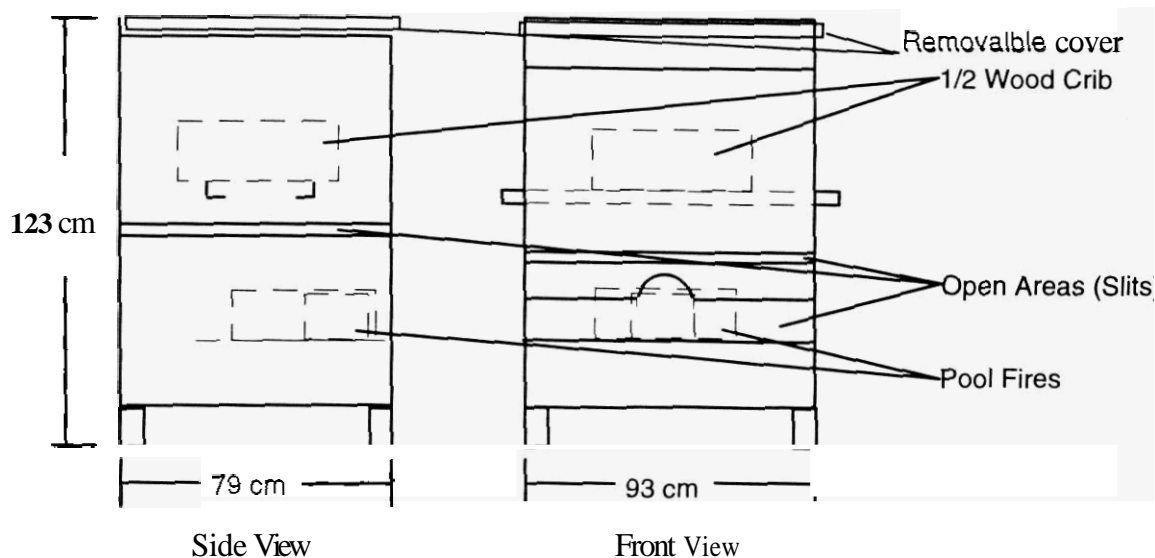


Figure 2. Partially and fully obstructed water mist test feature.

TABLE 2. ROOM-SCALE TEST SCENARIOS FOR THE BAUMAC MX-8 WATER MIST SYSTEM

Test Scenario	Conditions	Fuel	Pool Fire Size (W)	Repeats
1	Unobstructed with Telltales	Heptane	32	6
2	Reignition	Heptane	32	2
3	Partially Obstructed	Heptane	32	2
4	Partially Obstructed with Telltales	Heptane	292	3
5	Cabinet	Heptane	32	1
6	Partially Obstructed	Paper		4
7	Partially Obstructed	1/2 Wood Crib		3
8	Unobstructed	1/2 Wood Crib		2

The two Class A fire extinguishment test scenarios involved (1) shredded paper in a 31-cm² wastepaper basket and (2) the NEMER 1/2 wood crib. Temperature monitoring for the wastepaper basket consisted of a thermocouple placed in the geometric center of the basket, a thermocouple centered 61 cm above the basket, and thermocouples in both a floor corner and an opposite ceiling corner. The wood crib was constructed of 25 Douglas fir boards (3.65 cm by 3.65 cm by 50.8 cm) layered cross-wise and stacked 5 high with five boards in each layer. The final wood crib size (50.8 cm by 50.8 cm by 18.6 cm) was placed 46 cm above a 61 cm by 61 cm heptane pool fire. The heptane pool fire ignited the wood crib and exhausted its fuel before the crib preburn time was finished and the water mist system was started. Temperature monitoring

consisted of a thermocouple located 7 cm above the heptane pool fire, a second thermocouple 7 cm above the wood crib, and two thermocouples in upper and opposite lower corners of the room.

RESULTS AND DISCUSSIONS

Laboratory-Scale Results

A primary goal of a water mist system is to suppress or extinguish fires with minimal amounts of water. After the first round of testing, the small size and flow rates of the Baumac MX-8 nozzles allowed progressively fewer numbers of nozzles to be used in the ATC to find the lower effective limit of fire extinguishment. Based on sales literature, the Baumac MX-8 nozzles were initially tested at 6.90 MPa with a nozzle spacing of 15 to 18 cm. Using a Malvem Series 2600 particle analyzer, droplet size analysis of the MX-8 nozzles at 6.90 and 3.45 MPa, measured at 40.6 cm below the nozzle on the center line, showed similar droplet size distributions (Figure 3). Only the flow rate changed with pressure, ranging from an average of 0.132 ± 0.003 L/min at 6.90 MPa to 0.081 ± 0.002 L/min at 3.45 MPa. Lowering the pressure and repeatedly halving the number of nozzles and rerunning the water flux and extinguishment tests allowed the determination of the minimum water flux required to extinguish the heptane telltales effectively. The data indicated the fires could be extinguished with very small amounts of water (0.02 to 0.03 L/min-m²).

The most effective water flux rate for extinguishing heptane cup fires with a water mist system was 0.60 L/min-m². Increasing water fluxes above 0.6 L/min-m² did not significantly decrease extinguishment times in comparison with total water usage. Although water flux levels below this range were able to extinguish the telltales, the extinguishment times became longer and more erratic (Figure 4). Extinguishment times for water fluxes between 0.025 and 0.60 L/min-m² showed standard deviations on the order of their extinguishment times. Further studies in this water flux range should elucidate the mechanism of fire extinguishment with water mists. Water fluxes below 0.025 L/min-m² were not able to extinguish the fires.

Analysis of Figure 4 shows that the extinguishment times for water fluxes at and above 0.6 L/min-m² conservatively averages 20 s or 0.33 min, multiplying this by the above water flux rate yields a **DNT** of 0.3 L/m².

Partial and Fully Obstructed Fires

Table 3 shows the results for extinguishment testing of partially and fully obstructed heptane telltale fires. A 53 cm x 60 cm board bolted to the side of the ATC 96 cm above the floor at approximately a 45° angle covered a floor area measured at 51 cm x 60 cm. The fully obstructed telltale B6 was centered at the back of the covered area, while telltales D4 and D8 were partially obstructed by being placed 10 cm inside the covered area at the board's mid-point. Water flux tests indicated that partially obstructing the telltales reduced the water mist

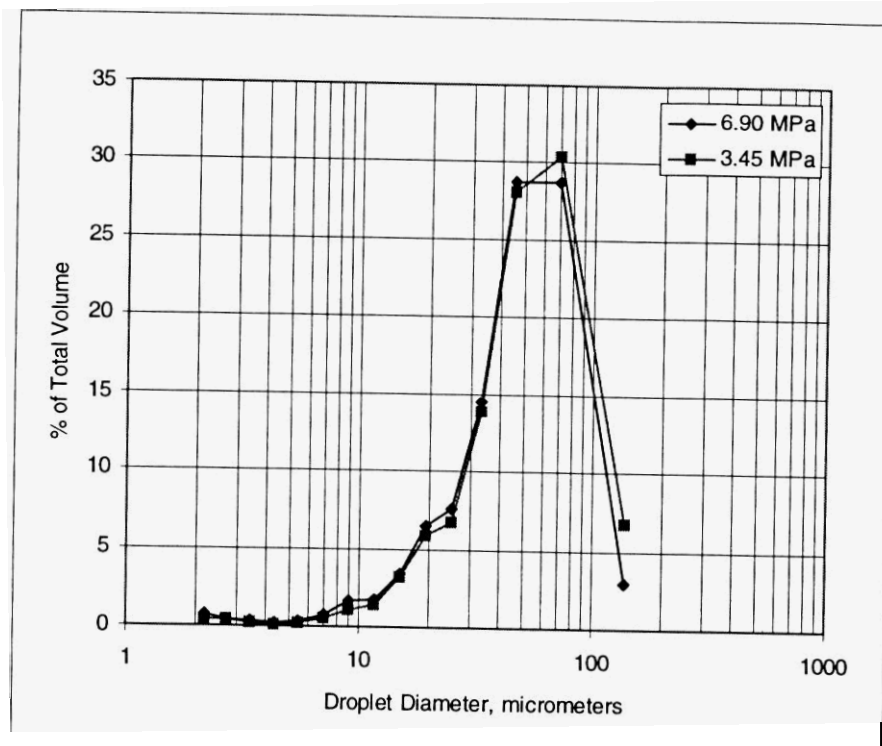
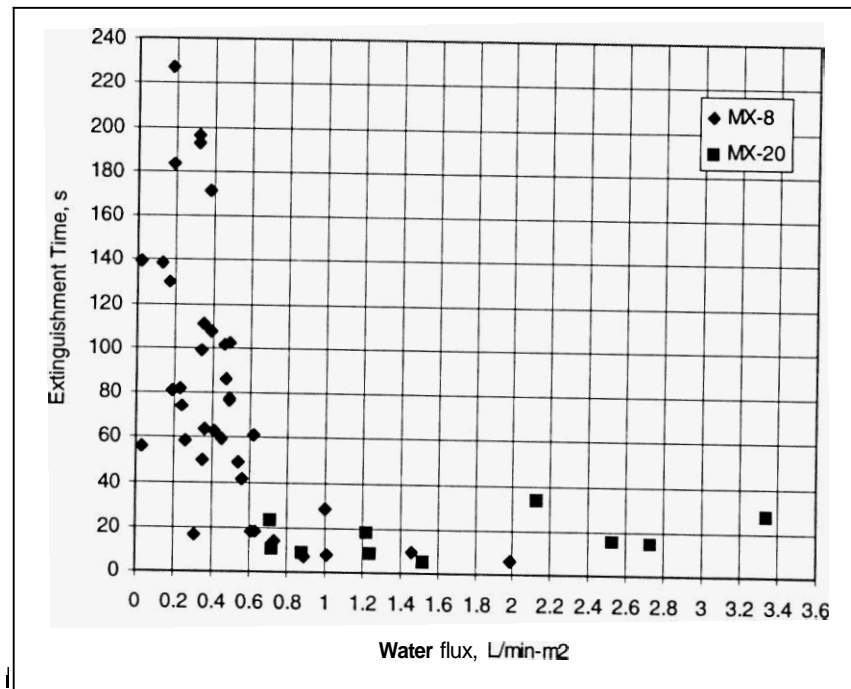


Figure 3. MX-8 droplet size distribution at two pressures at 40.6 cm.



Additional data from testing with Baumac MX-20 nozzles included to provide information at higher flow rates.

concentration by approximately 60%. Increased coverage or distance from the edge of the obstruction further reduced the water mist by an additional 15% for a total decrease from the original concentration of 75% for the fully obstructed telltale (B6).

TABLE 3. EXTINGUISHMENT RESULTS FOR AN OBSTRUCTED BAUMAC MX-8 SYSTEM

Manufacturer's Model	No. of Nozzles	System Operating Pressure, MPa	Telltale Placement	Water Flux, L/min-m ²	Extinguishment Times, s
Baumac MX-8	7	3.45	B6	0.12 ± 0.02	Burned out*
			D8	0.19 ± 0.02	183 ± 52
			D4	0.18 ± 0.02	227 ± 68
			I4	0.49 ± 0.02	77 ± 57†
			J2	0.46 ± 0.02	102 ± 42

* Five of ten telltales burned until they ran out of fuel.

† One of ten telltales burned until it ran out of fuel.

Optimum Nozzle Layout for Room-scale Testing

Table 4 shows the effect nozzle spacing and layout has on extinguishing unobstructed heptane telltales. Results at two different water flux levels indicate that crowding the nozzles can have the effect opposite to that expected for fire extinguishment. The results show that as the nozzle separation increased, the fires were extinguished more quickly in spite of using less water. Table 4 indicates that an array of four nozzles spaced 40 cm apart set in a rhombohedral pattern extinguishes the telltale fire faster and more uniformly at a water flux of 0.1 to 0.2 L/min-m² than does the manufacturer's nozzle may having a 15 to 18 cm nozzle spacing and a water flux of 0.3 to 0.4 L/min-m². Additionally, Figure 5 shows that a nozzle spacing of 40.6 ± 5 cm yields a uniform water flux pattern for the seven nozzle array.

TABLE 4. EFFECT OF NOZZLE SPACING ON EXTINGUISHMENT FOR BAUMAC MX-8 NOZZLES

Number of Nozzles	14	7	4	1
Nozzle Spacing, cm	15.2- 19.0	40.6	40.6	--
Water Flux, L/min-m ²	0.619 ± 0.052	0.415 ± 0.010	0.359 ± 0.037	0.232 ± 0.021
Extinguishment Time, s	60.8 ± 51.9	63.2 ± 27.8	63.8 ± 28.0	82.0 ± 30.2
Water Flux, L/min-m ²	0.316 ± 0.052	0.319 ± 0.010	0.169 ± 0.037	0.021 ± 0.021
Extinguishment Time, s	196.2 ± 112.6	192.7 ± 105.1	129.6 ± 36.5	139.5 ± 60.3

During discussions regarding this phenomenon, it was proposed that the water mist at higher concentrations coalesces into larger drops. These larger drops fall straight down and have a reduced chance to interact with the flame or, if above the flame, may fall through the flame. At

lower concentrations, the smaller drops, in addition to falling into the fire, can be swept into the side of the fire from a greater (relative) distance, thereby aiding extinguishment by horizontal flame penetration and cooling at the flame/fuel interface. The distance the water mist can be pulled into a fire will depend on the fire size (draft) and the water mist droplet size.

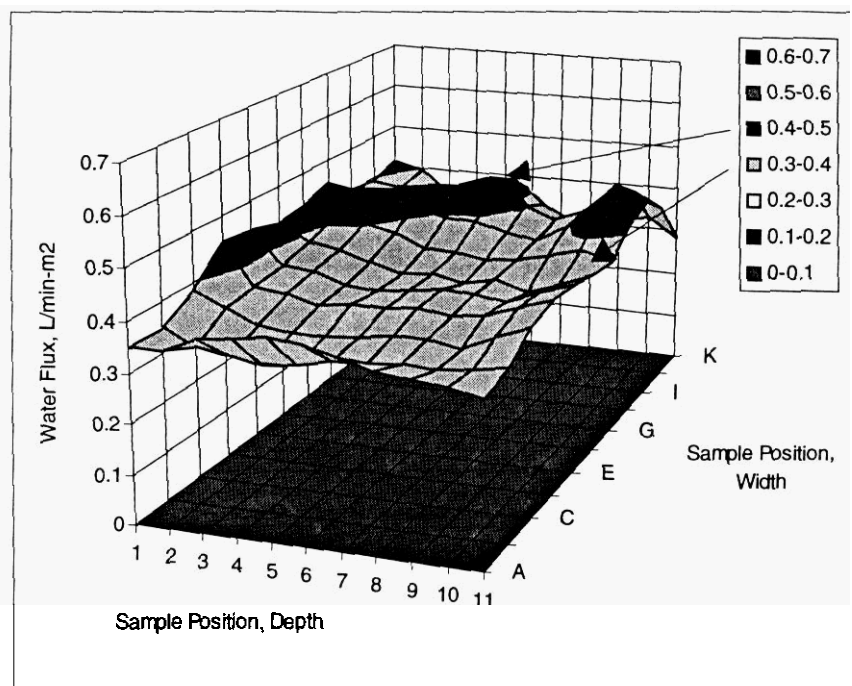


Figure 5. Water flux for a 7-nozzle array at 40.6 cm spacing.

Room-Scale Results

An unobstructed 32 kW heptane pool fire was extinguished in 100 ± 34 s using an average 5.7 ± 1.9 L of water. Partially obstructing the same fire (Figure 2) increased the extinguishment time to 315 s, requiring the use of 17.9 L of water (Figure 7). This three-fold increase in time indicates the relative importance of getting the water mist into the flame/fuel interface from the sides of the fire, since penetration and cooling of the fire from above is inefficient as demonstrated by these data. This was again demonstrated for the single test of a closed cabinet for which the top was covered and there was only 10 to 15% open area (slits) along three sides. This fire extinguishment took 512 s and required the use of 29.1 L of water.

One of the goals of any fire suppression system is the inertion of the protected space or the prevention from reignition after the fire has been extinguished. A single reignition test was run after the water was turned off. The initial spark, at 10s after the water mist system was turned off, reignited the heptane pool fire in the presence of the water mist. Subsequent reignition testing with the water mist system operating showed that, at a water flux rate of 0.46 L/min- m^2 , the system cannot protect the space from reignition (Figure 6). Although the water mist was unable to inert the space, it was able to repeatedly extinguish the fire averaging 41 ± 25 s for five repeat extinguishments. Additionally, the temperature immediately above the flame was reduced

by the water mist **for** an unobstructed fire (Figure 6). This is in contrast to the partially obstructed fire which showed a recovery to near initial temperature conditions (Figure 7).

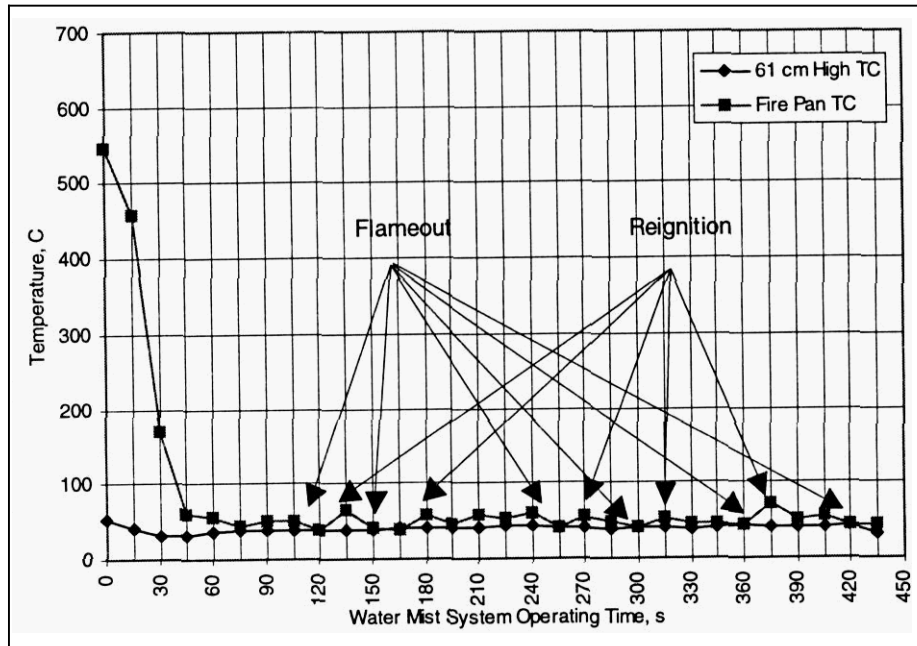


Figure 6. Fire pan temperature trace during multiple reignitions for a 32-kW heptane pool fire.

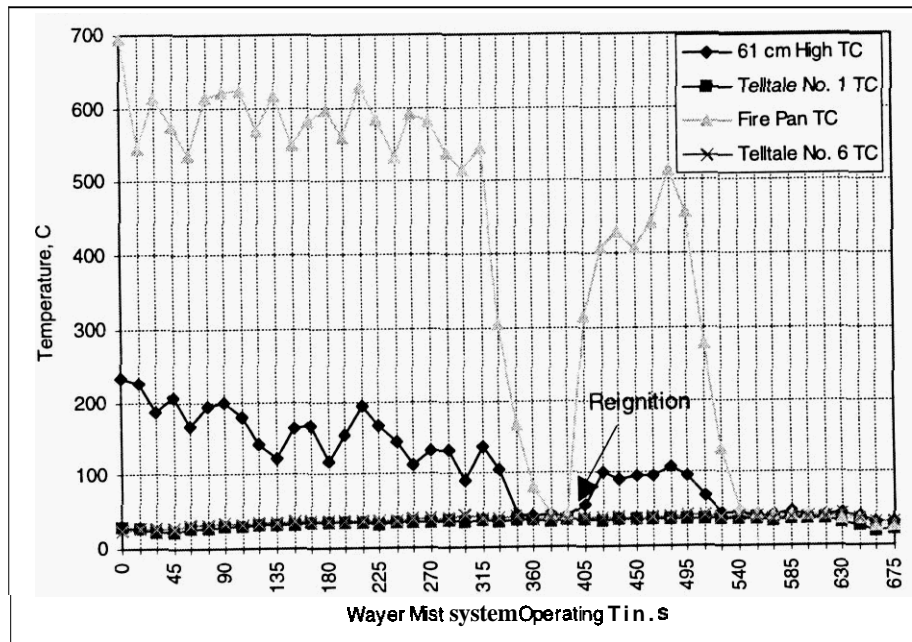


Figure 7. Temperature trace for a partially obstructed 32-kW heptane pool fire.

Eight 7.6-cm diameter telltales were placed in the corners of the room with the upper telltales 15 cm below the nozzles array and 11 cm behind the nearest nozzle during the pan fire

testing. Since not all telltales could be monitored with thermocouples, operating times of the water mist system prior to shutting down to check the telltales were arbitrary. Testing indicated that 2 to 3 min were required to extinguish the majority of the telltales. The inability to consistently extinguish some of the upper telltales appeared to be due to their position relative to the wall and nozzles. These telltales were outside any water mist spray coming from any nozzle. Only recycled mist would have reached these telltales and the 2.5-cm recess between the top of the telltale and the heptane made it extremely difficult for sufficient water mist to get to the flame/fuel interface from below with such a small diameter cylinder. Moving the ceiling telltales 3 cm away from the wall allowed the water mist to extinguish all the telltales, thereby showing the three-dimensional character of water mists and the importance of entraining water mist from all sides in extinguishing the fires.

For the Class A shredded-paper extinguishment tests, the thermocouple was placed in the geometric center of the wastepaper basket and the fire was not considered fully extinguished until the thermocouple temperature returned to $40 \pm 5 \text{ }^\circ\text{C}$ or below (Figure 8). During the extinguishment test at 6.90 MPa, the nozzles on both sides of the nearest overhead nozzle plugged-up. In spite of this plugging, the water mist system easily extinguished the fire. Temperature traces for the shredded paper fires showed that water mist has difficulty penetrating deep-seated fires at an application rate of $0.46 \text{ L}/\text{min}\cdot\text{m}^2$. As an example, the fire in Test 9 was not extinguished until the fire consumed greater than 50 percent of the paper, thereby opening a path for the water to enter.

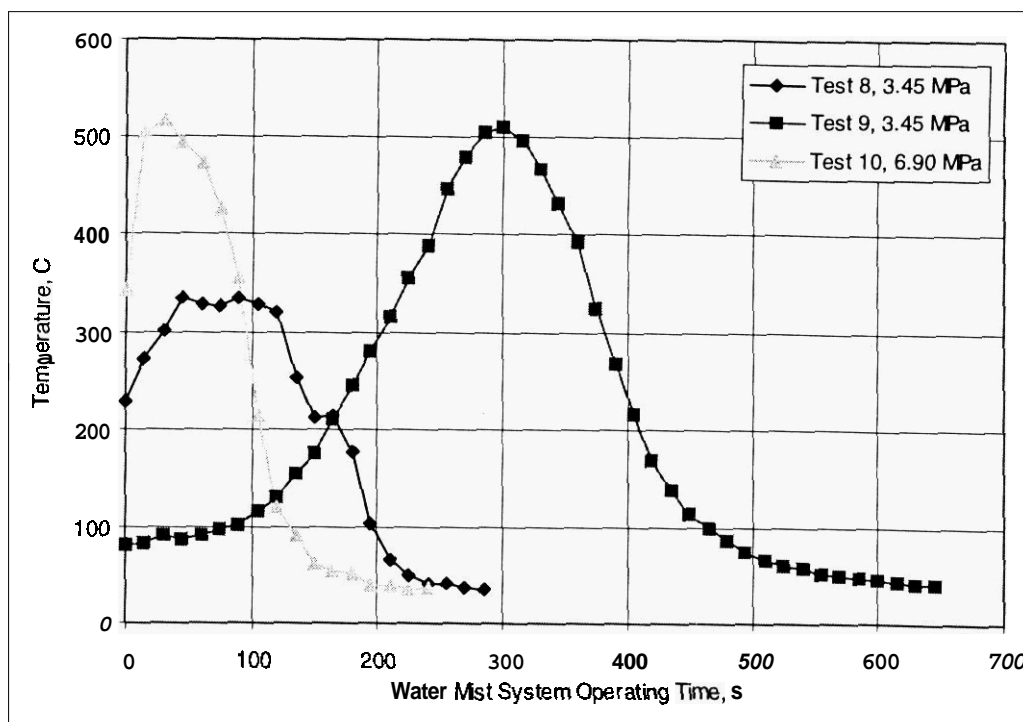


Figure 8. Temperature trace of the internal thermocouple for deep-seated paper fires.

Extinguishment tests were run on both partially obstructed and unobstructed wood crib fires. The partially obstructed fire used the same feature as the partially obstructed pan fires

except that the crib was placed 46 cm above the base of the feature (Figure 2). The unobstructed wood crib fires were run with an operating PC and a shelf of books and newspapers across the room from the fire during the extinguishment, 1.14 m and 1.42 m away respectively. Most of the damage to the PC was caused by smoke and heat, with the water mist forming only a thin film on the computer. The film evaporated quickly after the water mist system was shut down. The computer operated throughout the extinguishment test. No noticeable film of water was detected on the books; the only effect from the fire was soot, which was easily cleaned off the book covers.

CONCLUSIONS

While very small amounts of water can extinguish a heptane fire (0.02 to 0.03 L/min-m²) the project showed the optimum water flux rate for heptane telltale fires to be 0.6 L/min-m² and the DNT to be 0.3 L/m². It is at this point that fires are extinguished quickly without excessive amounts of water.

Room-scale experiments demonstrated that scale-up from the laboratory experimental results is straight forward. At the water flux rates tested (0.46 L/min-m²) the water mist was able to suppress and extinguish all unobstructed, partially obstructed, and fully obstructed Class A and Class B fires. Increasing the water flux to 0.76 L/min-m² showed a significant greater water usage (44%) in comparison to a minimal decrease in extinguishment time (7 %). Other findings from the room-scale testing are (1) at a water flux of 0.46 L/min-m², the water mist cannot inert the space nor stop reignition of the hydrocarbon pool fire, (2) upon reignition, the water mist can repeatedly extinguish the fire, and (3) fires can be extinguished without collateral water damage to books, papers, and energized electrical (computer) systems present in the room.

Possible follow-up projects may answer the question of droplet size and size distribution effects on fire extinguishment now that a testing range (0.02 to 0.6 L/min-m²) has been determined. Further study appears merited in this water flux range with regard to changes in drop size, size distribution, and water mist interactions with the flame for heptane fires.

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