J. of Fire Prot. Engr., **3** (3), 1991, pp 95-107

PREDICTING THE SUPPRESSION CAPABILITY OF QUICK RESPONSE SPRINKLERS IN A LIGHT HAZARD SCENARIO PART 2: Actual Delivered Density (ADD) Measurements and Full-Scale Fire Tests

by

Robert G. Bill, Jr., Hsiang-Cheng Kung, Bennie G. Vincent, William R. Brown, and Edward E. Hill, Jr.
Factory Mutual Research Corporation*

SUMMARY

An apparatus to determine the Actual Delivered Density (ADD) of quick response and residential sprinklers under light hazard conditions was constructed and calibrated. The plume of a burning chair at different stages of fire development was simulated by the apparatus using five convective heat release rates: 110, 160, 250, 300 and 390 kW (6300, 9100, 14,200, 17,100, and 22,200 Btu/min). The ADD as a function of the convective heat release rate was determined for a residential sprinkler at ceiling heights ranging from 2.4 m to 4.6 m (8 ft to 15 ft). ADDs were obtained for single and multiple sprinklers installed using a 3.6 m x 3.6 m (12 ft x 12 ft) spacing. The ADD of a 12.7 mm (1/2 in.) orifice, quick response sprinkler was determined for a single sprinkler directly over the ADD apparatus at a ceiling height of 3 m (10 ft). Previously reported Required Delivered Density (RDD) measurements for the reclining chair allowed suppression predictions to be made. Seven full-scale fire tests were conducted to evaluate the ADD/RDD approach to suppression prediction. Predictions were verified in five tests; suppression, however, occurred in two tests with ADD < RDD. The results of the seven tests indicate that the ADD/RDD approach used provided a conservative means for predicting suppression.

INTRODUCTION

The Actual Delivered Density (ADD) concept was developed at Factory Mutual Research Corporation (FMRC) as a means of predicting sprinkler performance in its Early Suppression Fast Response (ESFR) Program.[1] The ADD of a sprinkler is "the density of water actually penetrating the fire plume and delivered onto the top of the burning array."[1] In order to predict the performance of a sprinkler from ADD tests, it is necessary to compare the ADD results with the Required Delivered Density (RDD) for a particular commodity at the convective heat release rate for which first sprinkler actuation occurs. The RDD is the water application density delivered to the top surface of the burning commodity which will cause suppression. A discussion of the ADD/RDD approach to predicting suppression and its development in the ESFR Program is given in Part 1 of this study.[2]

In the ESFR program, a series of full-scale fire tests indicated that when the ADD provided by all the operating sprinklers was larger than the RDD value, early suppression was achieved.[1] It is interesting to note that in some tests in which the commodity was between two or four sprinklers, suppression occurred even though ADD was less than RDD. Presumably the existence of other suppression mechanisms (e.g., droplet impingement on the side) not simulated by the RDD tests was responsible for this outcome.

The objective of the present study is to evaluate the ADD/RDD approach to suppression prediction in a light hazard scenario by determining the ADDs of a residential and a quick response (QR) sprinkler, and by verifying the ADD/RDD relationship in full-scale fire tests. The commodity used in this study is a vinyl-covered reclining chair similar to that used in the Los Angeles Test Program[3] sponsored by the United States Fire Administration (USFA). Fire growth and RDD measurements were reported for this commodity in Part 1[2] of this study.

**Address for correspondence: Factory Mutual Research Corporation, 1151 Boston-Providence Turnpike, Norwood, Massachusetts 02602.*

ADD MEASUREMENTS

The ADD Apparatus

An ADD apparatus was designed and fabricated to simulate the plume of the vinyl-covered reclining chair and to measure the water density penetrating the simulated plume. A schematic of the apparatus showing an elevation and plan view is presented in Figure 1. The plan view indicates the twenty-five, 25 cm x 25 cm (10 in. x 10 in.), galvanized collecting pans which were welded together along their sides. The total collection area (127 cm x 127 cm; 50 in. x 50 in.) of the ADD apparatus was more than sufficient to cover the base area of the chair being simulated (66 cm x 75 cm; 26 in. x 29.5 in.). In the center of each collecting pan, a tube was inserted in order to allow the collected water to continuously flow to 5ℓ graduated beakers below the apparatus. These tubes are shown schematically in both the plan and elevation views.

The elevation view in Figure 1 indicates schematically the location of the heptane spray nozzles, the pitch of the collecting pan sides, the water cooling system for the pans, and the tubes carrying the collected water to the measurement beakers. Nozzles of various capacities were used to provide the selected convective heat release rates. Nominal operating conditions of the nozzles are shown in Table 1. All the nozzles had a cone angle of 80°.

The heptane spray nozzles were placed at the corners of a 61 cm. x 61 cm (2 ft x 2 ft) square centered in the collection pans. A plan view of the spray nozzle array is shown in Figure 2. The nozzles were directed radially toward the center of the ADD apparatus at an angle to the horizontal plane of 53°, except in the case of the 110 kW (6300 Btu/min) plume for which the angle was 23°. Heptane under a regulated pressure was delivered in a symmetrical manner to the nozzles in 6 mm (1/4 in.) stainless steel tubing. The heptane was supplied as in Reference 4 from a fuel tank pressurized by a regulated tank of nitrogen. The stainless steel tubing used to supply the heptane was cooled by a 2.5 cm (1 in.) outer water jacket as the heptane flowed across the ADD apparatus to the center of the heptane spray array; the supply lines from that point on towards the nozzles were not cooled.

As shown in Figure 1, water spray nozzles were used to cool the underside of the collecting pans. An inspection of the collecting pans after ADD tests at the highest convective heat release rate (390 kW; 22,200 Btu/min) indicated that the

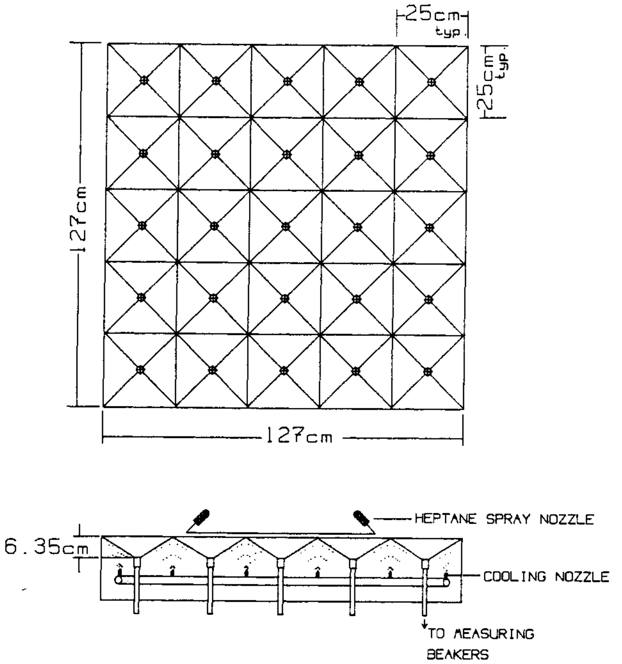

Figure 1. Schematic of the ADD Apparatus.

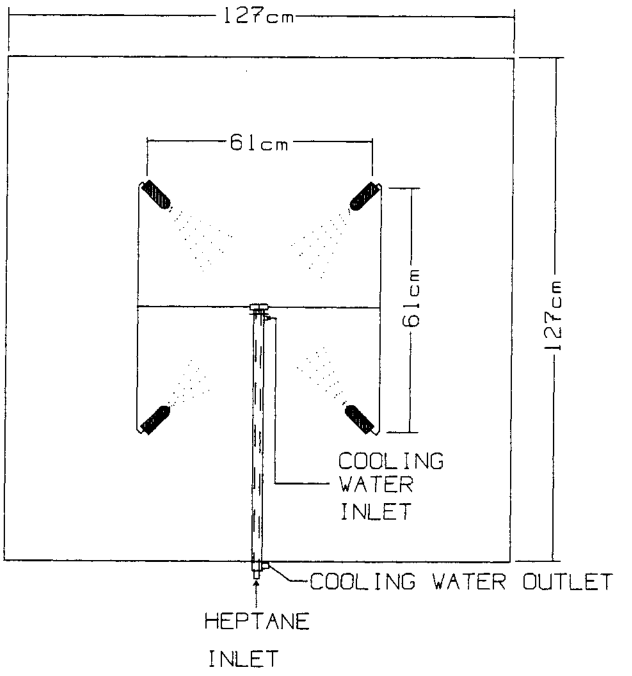

Figure 2. Plan View of the Heptane Spray Nozzles and Tubing.

TABLE 1

NOMINAL OPERATING CONDITIONS FOR THE HEPTANE SPRAY NOZZLES

Convective Heat Release Rate (kW)	Model*	Rated** Nozzle Capacity (Q/hr.)	Supply Pressure (kPa)
110	R	5.1	690
160	R	6.6	790
250	PLP	11.4	600
300	PLP	11.4	790
400	PLP	17.0	500

*Monarch Manufacturing Work, Inc. Philadelphia, PA 19134

**Conditions for Rating: 34 to 36 S.S.U. viscosity at 100°F, gravity 32 to 38 A.P.I. at 60°F and test temperatures 75°F to 80F. Note these are the manufacturer's conditions for rating capacity and do not apply to actual test conditions for heptane in this study.

flow from the cooling nozzles was sufficient to have kept the pan surface temperatures from significantly increasing due to flame radiation. The tubing leading from the collection pans to the beakers below was carefully installed and sealed to avoid any leakage of cooling water into the measuring beakers.

PLUME SIMULATION

In Part 1 of this study, the heat release rate histories (chemical, convective and radiative) were reported above a burning chair. Using these measurements and gas temperature and velocity measurements discussed below, Yu[5] estimated the convective heat release rates at the time of sprinkler actuation for ceiling heights of 2.4, 3.0 and 4.6 m (8, 10, and 15 ft) and for three sprinkler configurations (fire under one, between two, and between four sprinklers) for a quick response sprinkler installed with a 3.6 m (12 ft) spacing. The heat release rate estimates, summarized in Part 1[2] of this study, indicated that first sprinkler actuation would occur in a convective heat release range of 100 to 400 kW (5700 to 22,700 Btu/min) for the conditions noted above. The following convective heat release rates were generated by the heptane-spray fires of the ADD apparatus: 110, 160, 250, 300 and 390 kW (6300, 9100, 14,200, 17,100 and 22,200 Btu/min). As established in Part 1, the convective heat release rate was 56% of the chemical heat release rate of the chair.

At each of the selected heat release rates, temperatures and velocities in the plume of the burning chair were approximated by the heptane spray fire of the ADD apparatus. This was accomplished using gas temperatures at four elevations measured simultaneously with the heat release rate measurements of the burning chair, as reported in Part 1. Centerline gas velocities were also measured at the same elevations using bi-directional probes. The same instrumentation array was then used to measure the plume characteristics above the ADD apparatus under the FPC. Details of the measurements are given in Reference 5.

In preliminary tests to determine appropriate operating conditions for the ADD apparatus, the top collecting pans and heptane spray nozzles were placed to reproduce the location of the top of the chair. A number of different heptane nozzle configurations were tried in order to reproduce the gas temperature profiles of the burning chair. The configurations included variations in the number of nozzles (1, 2, or 4), the angle of the nozzles with respect to the horizontal plane, and the spacing of the nozzles. A 0.6 m (2 ft) spacing provided the best simulation of the plume width; however, the gas temperatures were still unacceptably high compared to plume temperatures. In order to lower the gas temperatures, the ADD apparatus was lowered 0.28 m (0.9 ft) to bring the top of the collecting pans to an elevation of 0.71 m (2.3 ft). This corresponds to a position halfway between the seat and top of the chair.

In Part 1[2] of this study, the RDD was determined by applying a uniform density of water in a horizontal plane at the top of the chair. In order to be consistent with these RDD measurements, the ADD should be measured at the same position. Thus, the lowering of the ADD apparatus represents a compromise between the need to accurately simulate the plume of the burning chair and the need to measure the ADD at the same location where water was applied to the RDD tests. Since combustion occurs over the entire height of the chair, this compromise seemed reasonable. In Figure 3, gas temperatures at four elevations in the plume of the heptane spray fire are compared with the gas temperature profiles fitted to the data from the plume of the burning chair. The agreement is moderate and typical of that obtained at all conditions. In general, the simulated plume widths were narrower than the plume of the burning chair. The centerline gas temperatures at the 2.1, 2.7 and 3.3 m (7, 9 and 11 ft) elevations were typically higher in the simulated plume than in the plume of the burning chair. Comparisons between gas temperatures of the heptane spray fire and the fitted temperature profiles at other heat release rates are given in Reference 5.

The centerline gas temperatures and velocities of the simulated plume are compared in Figures 4 and 5 with the corresponding plume correlations for the burning chair as derived by Yu[5]. In Figure 4, $T_c - T_o$ is the centerline gas temperature rise above the ambient temperature, T_o. The elevation is denoted by H, and Q_c is the convective heat release rate. The virtual origin of the plume, Z_0 derived by Yu[5] is used in these figures. The nomenclature in Figure 5 is the same with the centerline gas velocity indicated by U_c.

As anticipated from an inspection of Figure 3, the normalized gas temperatures and velocities are above the established plume correlations; however, the dependence upon the convective heat release rate and elevation are consistent with the turbulent plume relationship. Thus the heptane-spray fire appears to be a reasonable simulation of the plume of the burning chair. Figure 6 shows a photograph of the ADD apparatus with a convective heat release rate of 300 kW (17,100 Btu/min).

Description of the Test Facility

ADD tests were conducted under a 10.4 m x 11.6 m (34 ft x 38 ft) suspended ceiling within a test facility at FMRC with dimensions 18 m (L) x 12 m (W) x 10 m (H) (60 ft x 40 ft x 33 ft). The height of the ceiling was maintained at 4.6 m (15 ft) above the floor for all the ADD tests reported here.

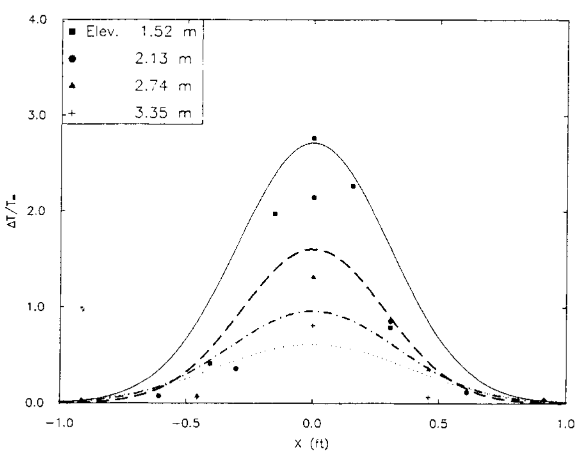

Figure 3. Comparison of Gas Temperatures in the Plume Above the ADD Apparatus (Symbols) with Profiles of Gas Temperature in the Plume of the Burning Chair at 300 kW (17,000 Btu/min): Elevations —— 1.52 m (5 ft); - - - 2.13 m (7 ft); - . - 2.74 m (9 ft); . . . 3.35 m (11 ft).

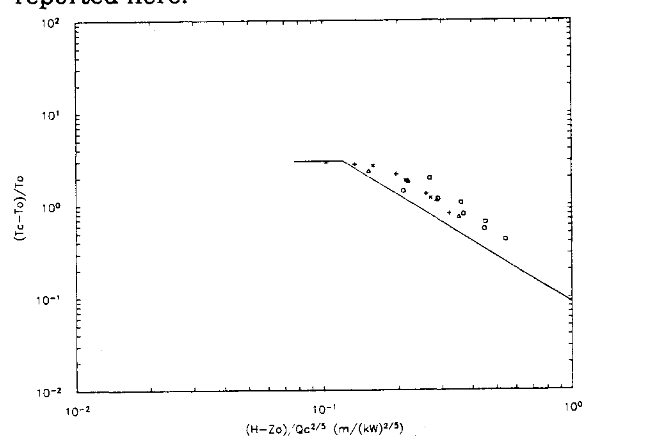

Figure 4. Comparison of the Normalized Centerline Excess Temperature of the Heptane Spray Fire with a Plume Correlation for the Burning Chair (Yu[5]); —— Correlation; Heptane Spray Fire: 110 kW (6300 Btu/min); o 160 kW (9100 Btu/min); Δ 250 kW (14,200 Btu/min); + 300 kW (17,000 Btu/min; x 390 kW (22,200 Btu/min).

The ADD apparatus was positioned on a platform whose height was adjusted to provide the appropriate clearance between the top of the ADD apparatus and the ceiling. Since the top of the collecting pans was to simulate a position 0.71 m (2.3 ft) above the floor and the ceiling heights to be tested were 2.4, 3.1 and 4.6 m (8, 10 and 15 ft), the ceiling clearances were respectively 1.7, 2.3 and 3.9 m (5.7, 7.7 and 12.7 ft). The ADD apparatus was centered below the suspended ceiling.

Two pendent sprinklers were tested in this investigation: a residential sprinkler and a 12.7 mm (1/2 in.) orifice, quick-response sprinkler. (These sprinklers are designated, respectively, as Sprinkler A and B in Reference 5). The flow rate to the residential sprinkler was established at 68 ℓ/min (18 gpm) at 283 kPa (41 psig) for the case of a single actuated sprinkler, and at a rate of 49 ℓ/min (13 gpm) sprinkler at 145 kPa (21 psig) when two or four sprinklers were actuated. The spacing of the sprinklers in multiple sprinkler tests was 3.6 m x 3.6 m (12 ft x 12 ft).

The QR sprinkler was only tested with the ADD apparatus below a single sprinkler. The flow rate for the 12.7 mm (1/2 in.) orifice sprinkler was 95 ℓ/min (25 gpm) at 145 kPa (21 psig). Details of the hydraulic system for establishing flow rates are given in Reference 5.

Test Conditions and Procedures

The test conditions for this study are listed in Table 2. The residential sprinkler was selected for extensive investigation since the Local Applied Densities (LAD or water density in the absence of fire) were close to the nominal RDD reported in Part 1,[2] 5 mm/min (0.12 gpm/ft^2). (The RDD was bracketed between 3.7 and 6.6 mm/min (0.09 and 0.15 gpm/ft^2).) The LADs of the other sprinklers considered were significantly higher or lower than this range.

Prior to the start of a series of tests with a given sprinkler configuration and heat release rate, the LAD was determined by actuating the appropriate sprinkler(s) at the predetermined pressure and then collecting for 4 minutes the sprinkler spray in the measurement beakers below the ADD apparatus. Then two ADD tests were conducted at the selected heat release rates. In these tests the heptane spray was ignited and allowed to burn for 2 minutes before sprinkler actuation. At that time the appropri-

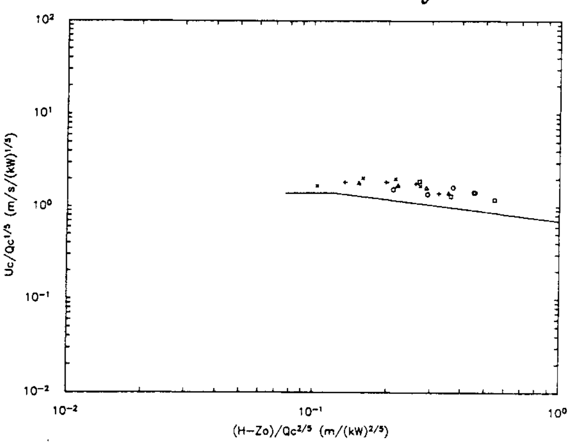

Figure 5. Comparison of the Normalized Centerline Gas Velocity of the Heptane Spray Fire with a Plume Correlation for the Burning Chair (Yu[5]); —— Correlation; Heptane Spray Fire: 110 kW (6300 Btu/min); o 160 kW (9100 Btu/min); Δ 250 kW (14,200 Btu/min); + 300 kW (17,000 Btu/min; x 390 kW (22,200 Btu/min).

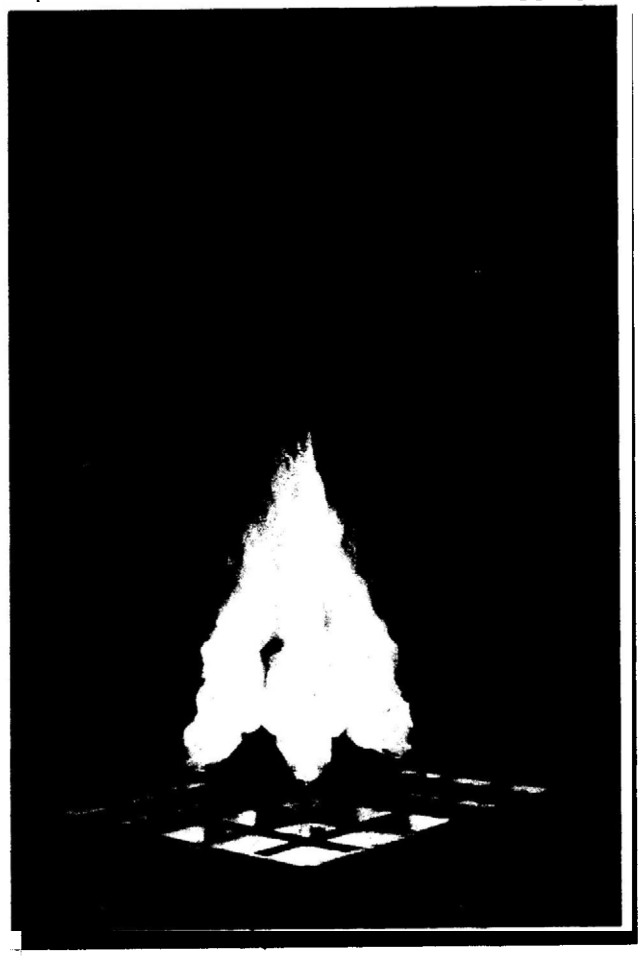

Figure 6. The Heptane Spray Fire of the ADD Apparatus at a Convective Heat Release Rate of 300 kW (17,100 Btu/min).

TABLE 2

ADD TEST CONDITIONS

Sprinkler Tvpe	Configuration*	Flow Per Sprinkler (ℓ/min)	Ceiling Height (m)	Convective Heat Release Rates (kW)
Residential	1	68	2.4	0-300
Residential	2	49	2.4	0-300
Residential	4	49	2.4	0-300
Residential	1	68	3.0	0-390
Residential	2	49	3.0	0-390
Residential	1	68	4.6	0,160,300
QR (12.7 mm)	1	95	4.6	0,160,250

* 1: ADD apparatus under one sprinkler
2: ADD apparatus between two sprinklers
4: ADD apparatus between four sprinklers

ate sprinklers were actuated using the solenoid valves. The test continued for an additional 4 minutes after which the water flow to the sprinklers was stopped. After the second ADD test, another LAD test was conducted.

The ADD and LAD results reported below represent the average results for the ADD and LAD tests in a given sprinkler configuration, ceiling height and heat release rate.

ADD Results

In Table 3, results are shown of the LAD and ADD tests using the residential sprinkler. The table includes the ceiling height, number of sprinklers actuated, the convective heat release rate of the simulated plume, and mean water application densities for the central nine pan, 0.76 m x 0.76 m (2.5 ft x 2.5 ft) collection area. In Figures 7 and 8, the ADD as a function of convective heat release rates is shown for the case of a single sprinkler over the ADD apparatus and for the case of ADD apparatus between two sprinklers. The ceiling height in both cases is 3 m (10 ft). Application densities are shown for three sets of collection pans. The result designated as Den. 1 corresponds to the mean water density for the entire 1.27 m x 1.27 m (4.2 ft x 4.2 ft) collection area. Den. 2 corresponds to the central nine pan 0.76 m x 0.76 m (2.5 ft x 2.5 ft) collection area, and Den. 3 is the center 0.25 m x 0.25 m (10 in. x 10 in.) single pan. The results are typical of the ADD tests.

It is noteworthy that as shown in Figure 7 and as indicated in Table 2, a substantial decrease in spray penetration occurs for the case of a single residential sprinkler even at the relatively low ceiling heights investigated here. In contrast, as shown in Figure 8, the effect of heat release rate on spray penetration is considerably reduced in the case of multiple sprinkler ADD tests. This is to be expected since droplets enter the plume from the sides rather than travel through the entire plume.

The ADD results shown in Figure 8 are not monotonically decreasing with heat release rate as expected. The unexpected variations in the ADD are possibly due to sampling errors caused by the short duration of the individual tests (4 minutes) and the small number of tests for a given heat release rate (two).

Predictions of sprinkler performance can be made based upon the ADD results reported here, the RDD results reported in Part 1, and the convective heat release rates at first sprinkler actuation predicted by Yu.[5] These results are listed in Table 4.

The ADDs listed in Table 4 correspond to the central 0.76 m x 0.76 m (2.5 ft x 2.5 ft) nine pan

TABLE 3

ADD RESULTS FOR THE RESIDENTIAL SPRINKLER

Ceiling Height (m)	No. of Sprinklers	Convective Heat Release Rate (kW)*	ADD (mm/min)**
2.4	1	0	3.5
2.4	1	110	2.4
2.4	1	160	2.3
2.4	1	250	1.7
2.4	1	300	1.5
2.4	2	0	3.3
2.4	2	110	2.5
2.4	2	160	2.6
2.4	2	250	2.3
2.4	2	300	2.4
2.4	4	0	3.9
2.4	4	110	3.7
2.4	4	160	3.5
2.4	4	250	3.1
2.4	4	300	3.2
3.0	1	0	4.0
3.0	1	160	2.3
3.0	1	250	2.0
3.0	1	300	1.8
3.0	1	390	1.5
3.0	2	0	3.3
3.0	2	160	2.9
3.0	2	250	2.8
3.0	2	300	2.6
3.0	2	390	2.1
4.6	1	0	3.4
4.6	1	160	2.1
4.6	1	300	1.7

* 1 mm/min = 0.0245 gpm/ft^2
** 1 kW = 56.87 Btu/min

area (Den. 2) that covers the area of the chair. Comparing the RDDs from Part 1[2] with the ADDs, it is clear that suppression is not expected for any of the sprinkler configurations investigated here.

Quick-Response, 12.7 mm (1/2 in.) Orifice Sprinkler Tests

In the previous section, it was predicted that the residential sprinkler would not act as a suppression sprinkler in realistic fire tests for the conditions shown in Table 4. In order to obtain a case in which the ADD would be greater than the RDD, a 12.7 mm (1/2 in.) orifice pendent sprinkler was used with the ADD apparatus under a single sprinkler. In contrast to the residential sprinkler, the deflector design of this sprinkler is such that the water application density is highest in the center.

The convective heat release rate at which a single sprinkler directly above the fire is predicted to actuate under a 3 m (10 ft) high ceiling is 150 kW (8500 Btu/min). The ADD at that heat release rate was measured to be 5.5 mm/min (0.135 gpm/ft^2) in the central 0.76 m x 0.76 m area of the ADD apparatus. The nominal RDD is 5 mm/min (0.12 gpm/ft^2); thus suppression is expected to occur.

TABLE 4

RESIDENTIAL SPRINKLER PERFORMANCE PREDICTION

Ceiling Height (m)	No. of Sprinklers	Predicted Convective Heat Release Rate (kW)	RDD* (mm/min)	ADD (mm/min) Den.2
2.4	1	110	5	2.4
2.4	2	240	5	2.3
2.4	4	310	5	3.2
3.0	1	150	5	2.3
3.0	2	300	5	2.6
4.6	1	260	5	1.8

* References 2,5

Full-Scale Fire Tests

Test Conditions

A test series consisting of seven full-scale fire tests was conducted to validate the suppression predictions for the residential sprinkler and the 12.7 mm (1/2 in.) orifice QR sprinkler. The tests conducted were designed so that the sprinklers would actuate in direct response to the chair fire. Due to the many unknowns and complexities of fire suppression, the validity of the ADD/RDD approach can only be established by fire testing.

A summary of conditions for the fire tests is presented in Table 5. The ceiling height/sprinkler locations were the same as those investigated in the ADD tests.

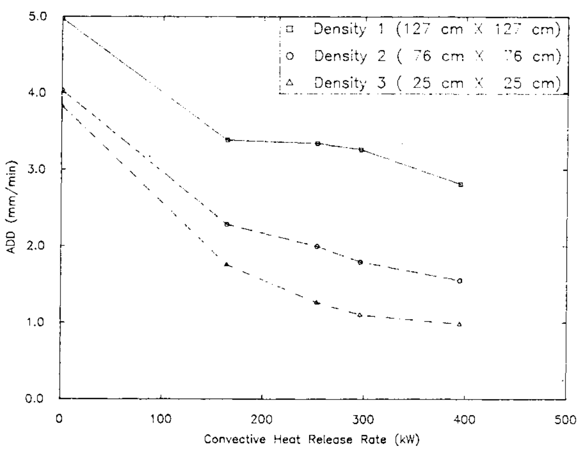

Figure 7. ADD Test with a Residential Sprinkler at a Ceiling Height of 3 m (10 ft); Mean Densities of Three Central Collection Areas: —— 127 cm x 127 cm (50 in. x 50 in.); - - - 76 cm x 76 cm (30 in. x 30 in.); - . - 25 cm x 25 cm (10 in. x 10 in.).

The residential sprinkler was tested at three ceiling heights, 2.4, 3.0 and 4.6 m (8, 10 and 15 ft). At the 2.4 m (8 ft) ceiling height, the sprinkler performance was investigated using each of the three selected ignition configurations, i.e., with the chair centered directly under one sprinkler, between two sprinklers or between four sprinklers. At the 3 m (10 ft) ceiling height, the residential sprinkler was tested with the chair under one sprinkler and with ignition between two sprinklers. The residential sprinkler was also evaluated at a ceiling height of 4.6 m (15 ft) with the chair centered directly under a sprinkler. The residential sprinkler was tested using discharge rates of 68 ℓ/min (18 gpm) for one discharging sprinkler, and 49 ℓ/min (13 gpm) each for two or four operating sprinklers. Recall that measurements of the ADD of the residential sprinkler were less than the

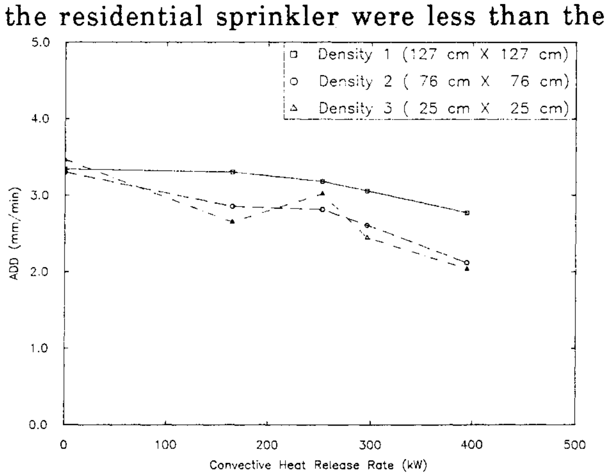

Figure 8. ADD Tests Between Two Residential Sprinklers at a Ceiling Height of 3 m (10 ft); Mean Densities of Three Central Collection Areas: —— 127 cm x 127 cm (50 in. x 50 in.); - - - 76 cm x 76 cm (30 in. x 30 in.); - . - 25 cm x 25 cm (10 in. x 10 in.).

TABLE 5

FIRE TEST CONDITIONS AND RESULTS

Test No.	Ceiling Height (m)	Ignition Location	Sprinkler Discharge (ℓ/min)	Sprinkler Sprinkler Type	ADD (mm/min)	Actuation Time (s)	Fire Suppressed
1	3.0	Under one	68	Residential	2.3	88	No
2	3.0	Under one	95	12.7 mm - QR	5.5	121	Yes
3	3.0	Between two	49	Residential	2.6	177	No
4	2.4	Between two	49	Residential	2.3	149	Yes
5	2.4	Under one	68	Residential	2.4	89	No
6	2.4	Between fou	49	Residential	3.2	181	Yes
7	4.6	Under one	68	Residential	1.8	153	No

RDD for the reclining chair; thus suppression was not expected in any of the tests.

The 12.7 mm (1/2 in.) orifice QR sprinkler was tested under a 3.0 m (10 ft) ceiling with the recliner located under one sprinkler. The nominal discharge rate was 95 ℓ/min (25 gpm).

Test Setup

Fire tests were conducted in the same FMRC testing where the ADD tests were conducted.

A schematic drawing of the test setup for a simulated ceiling height of 2.44 m (8 ft) is presented as Figure 9. The recliner chair was centered below a 10.4 m x 11.6 m (34 ft x 38 ft) ceiling which remained fixed at a height of 4.6 m (15 ft) for all tests in this program. The ceiling was constructed of ceiling panels suspended in a steel I-beam and truss support framework. The chair used in the validation test series was slightly different from that used in Part 1 of the study due to changes in design by the manufacturer and the unavailability of the chair from stock. The chair used in Part 1 was a 28.6 Kg vinyl-covered upholstered recliner with a wood frame. The padding was nominally 30% polyurethane foam, 63% shredded polyurethane foam and 7% cotton.

The new chair used in this study, weighing 33.9 Kg, had the same exterior design, frame, and covering; however, the padding was 31% polyurethane foam, 59% shredded polyurethane foam and 10% cotton. The major difference between the chair used in this study and that used in Part 1 was the additional weight of polyurethane. Therefore, it is believed that the chair used in the fire tests reasonably represented the results of previous tests.

Sprinkler spacing in all tests was set at 3.6 m x 3.6 m (12 ft x 12 ft). All sprinklers in a given configuration were open sprinklers and water discharge was controlled by solenoid valves installed in the length of pipe between the sprinkler and the branch line above the ceiling. In each ignition configuration a linked sprinkler, uncharged with water, was integrated into an electrical circuit which, when the sprinkler link fused, would electrically actuate the solenoid valves and allow water to flow to all open heads simultaneously. The actuating sprinkler for each ignition configuration was 15 cm (6 in.) from one of the open sprinklers. This open head/solenoid valve control procedure was followed to insure proper replication of the ADD test procedure for the multiple-sprinkler arrangements, i.e., for ignition below two or four sprinklers, all sprinklers commenced water dis-

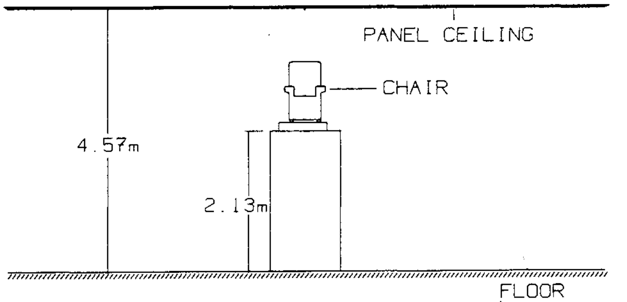

Figure 9. Schematic of Full-Scale Test Setup with a Simulated Ceiling Height of 2.44 m (8 ft).

charge at the same time. Details of the hydraulic and actuating systems are given in Reference 5.

The recliner chair was placed upon an adjustable support for tests in which simulated ceiling heights of 2.4 and 3.0 m (8 and 10 ft) were required. For the 4.6 m (15 ft) high ceiling tests, the chair was placed directly on the floor of the test facility.

Test Procedure

Tests commenced with ignition of a cotton wick placed on the floor along the side of the chair, as in Part 1. The wick had been soaked in approximately 25 ml of methanol.

After operation of the sprinkler system, tests were allowed to continue for a minimum 10 minute period. This period was extended if residual burning was observed in the chair past this time.

Full-Scale Test Results

Fire suppression was achieved in three of the seven tests conducted. Suppression was defined in this study as in the RDD measurements of Part 1[2] as occurring when water application resulted in an immediate and significant reduction of flame height and fire size with no subsequent regrowth of the fire. In this study, as in Part 1, complete extinguishment of the fire was not achieved; however the flames were reduced to the point where only flamelets less than 0.3 m (1 ft) high remained.

The primary method of determining if suppression occurred during the fire tests was visual observation. A visual record of each test was made on videotape. Data from other instrumentation provided supporting evidence for evaluating sprinkler performance; however, due to the large unconfined nature of the test facility and cooling of the ceiling gas layer by the sprinkler spray, gas temperatures and carbon monoxide were not dramatically high. Examination of the fire test results revealed that gas temperatures from two thermocouples, 8 cm (3 in.) below the ceiling and 3.6 m (12 ft) from the center of the chair on either side, correlated well with visual

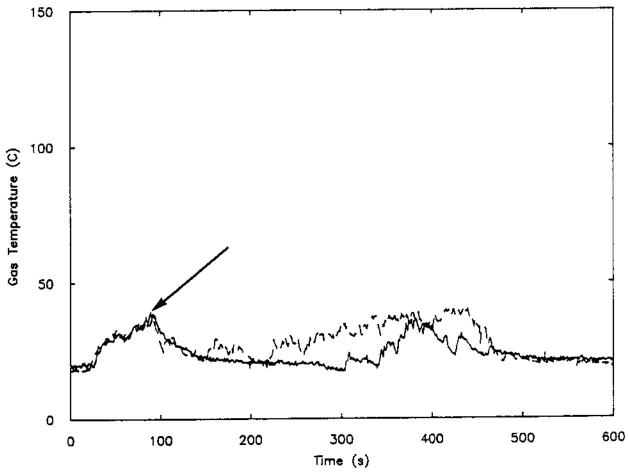

Figure10a. Test 1, Fire Under One Residential Sprinkler, 3 m Ceiling.

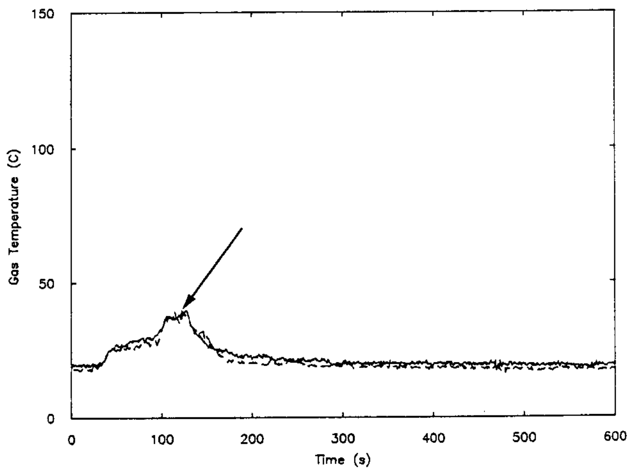

Figure 10b. Test 2, Fire Under One QR Sprinkler, 3 m Ceiling.

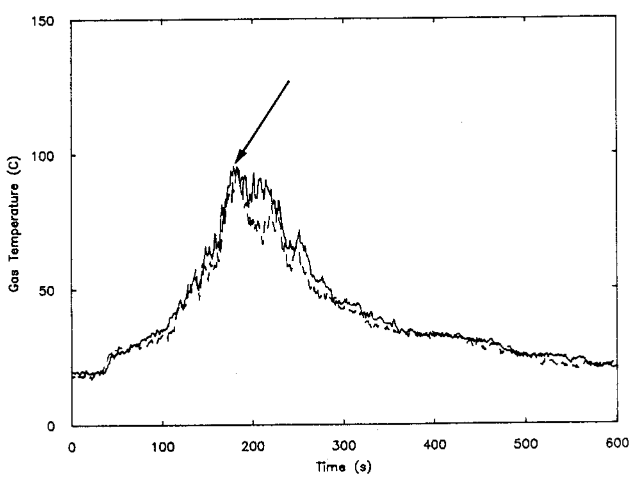

Figure 10c. Test 3, Fire Between Two Residential Sprinklers, 3 m Ceiling.

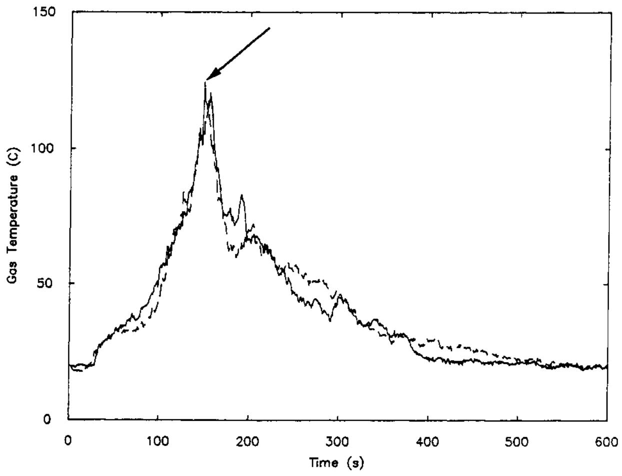

Figure 10d. Test 4, Fire Between Two Residential Sprinklers, 2.4 m Ceiling.

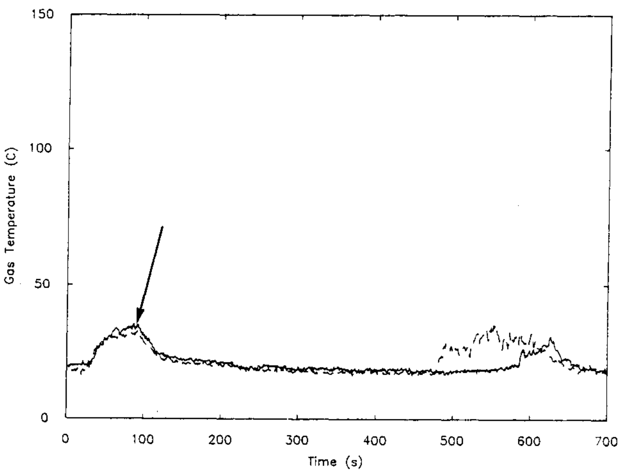

Figure 10e. Test 5, Fire Under One Residential Sprinkler, 2.4 m Ceiling.

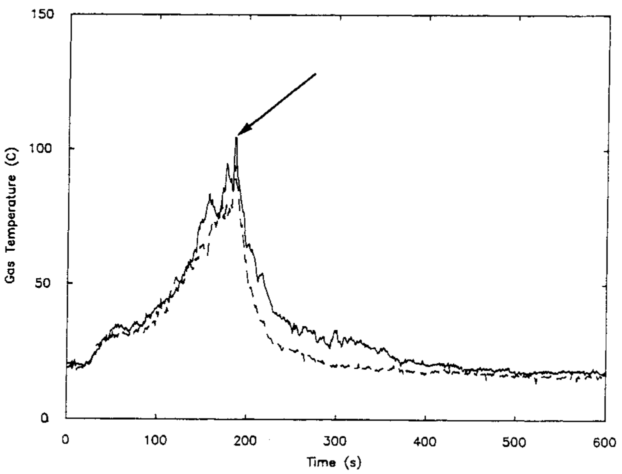

Figure 10f. Test 6, Fire Between Four Residential Sprinklers, 2.4 m Ceiling.

observations. These results for Tests 1 through 7 are shown in Figures 10a through 10g, respectively.

Three types of fire behavior were observed in the fire tests: (1) a reduction in fire size after sprinkler actuation followed by fire regrowth; (2) no significant immediate reduction in fire size after sprinkler actuation with fire size maintained; and (3) suppression of the fire.

Suppression did not occur in four tests (Tests 1, 3, 5 and 7; Figures 10a,c,e, and g). Ignition was directly under one sprinkler in all tests, except Test 3, in which ignition was between two sprinklers. In all of the tests in which suppression did not occur, ADD < RDD.

In Tests 1 and 5, observations indicated that the fire size was reduced when water was applied, but fire regrowth occurred. Figure 10a shows the ceiling gas temperature for Test 1. Sprinkler actuation occurred at 88 s (see Table 4), and the fire size was substantially reduced. However, at approximately 200 s the fire began to regrow and achieved a flame height of approximately 1.2 m (4 ft) at 384 s. Figure 11 shows a photograph from the videotape of the test at that time (6 min 23.67 s). The top of the chair seat is approximately 0.4 m (1.4 ft) above the floor. Flames are visible beneath the chair on the floor. The fire history and gas temperature results were similar in Test 5 (see Figure 10e).

In Tests 3 and 7, water application was

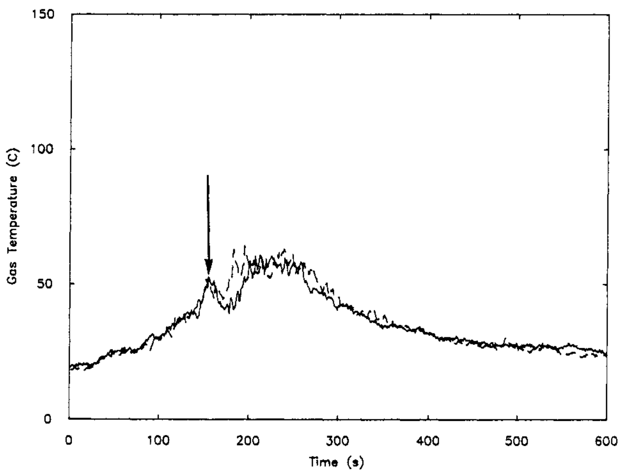

Figure 10g. Test 7, Fire Under One Residential Sprinkler, 4.6 m Ceiling.

observed to have little impact on the fire. In Test 3, the fire size remained approximately constant after sprinkler actuation, while in Test 7 the fire size increased. Figure 10c indicates the gas temperature in Test 3. The gas temperature remained approximately constant for approximately 45 s after sprinkler actuation at 177 s. Figure 10g shows the gas temperature in Test 7.

Suppression was observed to occur in Tests 2, 4, and 6. In Test 2, in which the sprinkler was directly over ignition, the ADD was within the bracketed range of RDD. Figure 10b shows the decrease in gas temperature at the time of sprinkler actuation. In Tests 4 and 6, suppression occurred even though ADD < RDD. Ignition in these two tests was between two and four sprinklers, respectively. Gas temperatures for Tests 4 and 6 are shown in Figures 10d and 10f. In both tests there is a sharp decrease in gas temperature after sprinkler actuation without a subsequent systematic increase.

Suppression in Tests 4 and 6 indicates that side wetting of the reclining chair, not accounted for in the RDD apparatus, is an important factor contributing to suppression. It is important, however, to recall that in Test 3, in which ignition was between two sprinklers, suppression did not occur even though the ADD was comparable to that of Test 4. Tests 3 and 4 differed only in the ceiling heights, which were, respectively, 3.0 m and 2.4 m (10 and 8 ft). It appears that the increased ceiling height decreased the degree of side wetting, as might be expected.

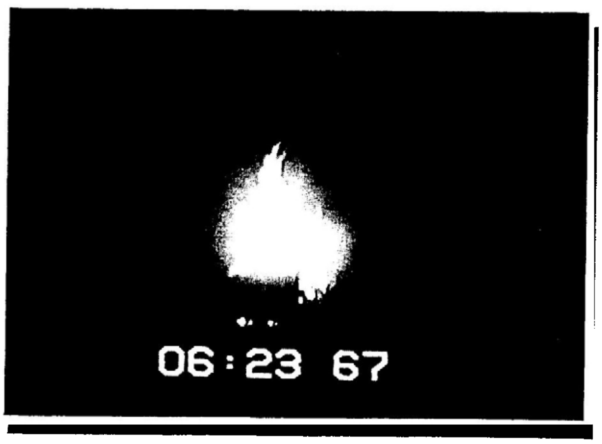

Figure 11. Photograph (from Videotape) of Fire in Test 1, 6 min 23.67 s (383.67 s) after Ignition.

Conclusions

In four full-scale fire tests, the ADD was less than the RDD and suppression did not occur. Suppression occurred in three tests. In one test, the ADD was within the bracketed range of the RDD, while in the two tests in which ignition occurred between two and four sprinklers, suppression occurred even though the ADD was less than the RDD.

The latter test results indicate that side wetting of the recliner may be an important factor contributing to fire suppression for this type of fire. Note, however, that in another test at a higher ceiling height in which ignition was between two sprinklers, suppression did not occur although the ADD was comparable. Thus, further work is needed to quantify the impact that side wetting has upon the RDD for the fuel package. The results of the full scale test indicate that the techniques used in this study and in Part 1[2] provide a conservative means for predicting fire suppression.

Acknowledgements

We wish to acknowledge the support of the United States Fire Administration (USFA) under Contract No. EMW-88-2769 and the support of Factory Mutual Research Corporation (FMRC) under its Long Range Sprinkler Technology Program. The guidance and encouragement of Mr. Tom Smith of USFA and Mr. Cheng Yao of FMRC are gratefully acknowledged.

References

1. Yao, C., "The Development of the ESFR Sprinkler System," *Fire Safety J.*, **14**, pp. 65-73, 1988.
2. Bill, R.G., Jr., Kung, H-C., Brown, W.R., Hill, E.E., Jr., and Spaulding, R.D., "Predicting the Suppression Capability of Quick Response Sprinklers in a Light Hazard Scenario, Part 1: Fire Growth and Required Delivered Density (RDD) Measurements," *J. Fire Protection Engineering*, **3**, pp. 81-93, 1991.
3. Kung, H-C., Spaulding, R.D., Hill, E.E., Jr., and Symonds, A.P., "Field Evaluation of Residential Prototype Sprinkler - Los Angeles Fire Test Program," Factory Mutual

Research Corporation Technical Report, J.I. OEOR3.RA(l), September 1981.

4. Yu, H-Z., Kung, H-C., and Han, Z., "Spray Cooling in Room Fires," *Twenty-First Symposium (International) on Combustion*, The Combustion Institute, pp. 129-136, 1986.
5. Bill, R.G., Jr., Kung, H-C., Brown, W.R., Hill, E.E., Jr., Spaulding, R.D., Stavrianidis, P., Vincent, B.G., and Yu, H-Z., "Evaluation of the Suppression Capability of Residential and Quick Response Sprinklers, Technical Report J.I. OQ5N0-8.RA, December 1990.