Four-Tier Array Rack Storage Fire Tests with Fast-Response Prototype Sprinklers

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ABSTRACT

A series of seven rack storage fire tests was conducted, using four pendent fast-response prototype sprinklers to determine the sprinkler discharge characteristics necessary for suppressing four-tier array rack storage fires under a 9.14-m high ceiling. The sprinklers had a nominal K-factor of either 11 or 14, and the sprinkler discharge pressure was maintained at 345 kPa. The commodities used as fuel consisted of polystyrene cups packaged in compartmented cartons. The commodities were arranged in double-row steel racks, two pallet-loads wide, two pallet-loads deep and four tiers high. Three different ignition locations with respect to sprinklers were employed. Sprinkler water distribution under a no-fire condition and spray center-core thrust force were identified as key parameters of sprinkler discharge characteristics pertaining to sprinkler fire-suppression ability. The relationships among the fire size at first sprinkler actuation, plume momentum flux, Required Delivered Density, sprinkler water distribution and spray center-core thrust force, with regard to suppression of the rack storage fires, were explored.

For fire tests with ignition directly under a sprinkler, it was highly desirable for the sprinkler spray to overpower the fire plume to achieve efficient delivery of sprinkler water to the fire source. In the fire tests when the spray center-core thrust force was greater than the plume momentum flux and the average water flux over the top surface of the fuel array under a no-fire condition was greater than the Required Delivered Density, fire suppression was achieved.

For fire tests with ignition centered below either two or four sprinklers, the fire plume was largely confined to the center flue of the fuel array, and most of the sprinkler water projected toward the top surface of the fuel array reached the top surface without passing through the fire plume. Therefore, the measured water flux over the top surface under a no-fire condition was expected to be close to that delivered during a fire. Fire suppression in these tests resulted from contributions of both the sprinkler water reaching the top surface and the side exposed surfaces of the fuel array. When the average water flux over the top surface under a no-fire condition was greater than the Required Delivered Density, fire suppression was achieved.

INTRODUCTION

Sprinkler protection against rack storage fires has been a major concern of the fire protection community for the past 20 years. Rack storage arrangements favor rapid and intense fire growth because combustible surfaces extend both horizontally between storage units on different levels and vertically between storage units placed back-to-back and side-to-side. Once initiated, fires spread through both vertical flues and along horizontal channels, rapidly growing faster and becoming more intense.

Protection against rack storage fires using ceiling sprinklers usually requires a large water demand and a correspondingly high cost sprinkler system. Further, the effectiveness of current sprinkler practice in protecting rack storage against fires is less than desirable. In numerous large-scale fire tests using conventional sprinkler systems, fire damage extended beyond the stack where the fire started and many sprinklers actuated, resulting in significant damage from both water and fire[(1)].

In this high-tech era, many warehouses are being used to store high-value commodities. In order to reduce large fire losses, it is critical to limit fire loss and water damage to a small portion of the storage array. A reasonable expectation is that the sprinkler system detect and suppress a fire quickly, while it is still small, so as to limit both fire damage and the number of operating sprinklers.

In the recent Factory Mutual Research Corporation (FMRC) Early Suppression Fast Response (ESFR) Sprinkler Research Program, a series of twenty-two reduced-scale rack storage fire tests was conducted, using five pendent prototype sprinklers to determine the sprinkler discharge characteristics necessary for suppressing rack storage fires under various test conditions[(2)]. Sprinkler discharges were characterized by their water distribution and center-core thrust force. This paper covers only the results of seven four-tier array fire tests, sprinkler water distribution and thrust force measurements for sprinklers used in these tests. An attempt has been made to relate fire test results with sprinkler discharge characteristics in order to provide recommendations for the sprinkler water distribution and center-core thrust force required for achieving early fire suppression. Full details of all fire tests are given in Reference 2.

FIRE TESTS

Fire tests were conducted at the FMRC Test Center in West Glocester, Rhode Island[(3)]. Overall dimensions of the test building are 61 m x 76 m with two floor-to-ceiling heights, 9.14 m and 18.29 m. The tests were conducted at the 9.14 m ceiling height site. During each test, no forced ventilation was provided, and all doors and windows of the test volume communicating to the outside were closed. The building was cleared of smoke between tests.

Fuel for fire tests consisted of pallet loads of the Factory Mutual Standard Plastic Test Commodity[(3)]. The commodity consisted of polystyrene cups packaged in compartmented, single-wall corrugated paper cartons; each measured 53.3 cm by 53.3 cm by 50.8 cm high and contained 125 compartments. Eight cartons of the Standard Plastic Commodity were placed on a wood pallet forming a stack two cartons wide by two cartons deep by two cartons high. The weight of the polystyrene cups per pallet load was 29.3 kg; the weight of empty cartons with compartment dividers per pallet load was 21.8 kg, while the weight of wood pallets ranged from 23.1 kg to 24.1 kg.

A double-row steel rack was used to hold pallets of the commodity. Fuel arrays were two-pallet-loads wide by two-pallet-loads deep by four-tiers high. Figure 1 shows the arrangement of the fuel array. The ceiling clearance to the top of the array was 2.9 m.

Ignition for the fuel array consisted of four cotton-cloth rolls (7.6 cm diameter, 7.6 cm long), each soaked with 118 mℓ of gasoline and wrapped in a plastic bag. The four ignition rolls were placed near the bottom of the center flue space of the fuel array, as shown in Figure 10 of Reference 3. A propane torch was used to ignite the rolls.

Prior to this test program, a sprinkler piping system already existed at the 9.14 m high test site for fire testing of upright sprinklers. The branch lines of the system were 5-cm (2-in.) nominal diameter with centerlines 33 cm below the ceiling to enable upright sprinkler links to be located 20 cm below the ceiling. Sprinkler fittings (sprinkler stations) and branch lines were arranged to achieve a 3.05 m x 3.05 m spacing of sprinklers. In this program, part of the original sprinkler piping was modified to accommodate pendent prototype sprinklers.

Fire tests for this program were conducted during two separate time periods. For Tests 1 through 12 conducted in the first time period, part of the original piping was removed and two new pipes (5 cm nominal diameter) installed along the north-south direction, as shown in Figure 2. Each pipe could accommodate two prototype sprinklers. The centerline of the two new pipes were 10.8 cm from the ceiling. The distance between the ceiling and sprinkler links was either 19 or 20 cm, depending on the prototype sprinklers used.

For Tests 13 to 22 conducted during the second time period, three 5-cm (2-in.) nominal diameter pipes were installed along the east-west direction. However, the centerlines of the three pipes were 26.7 cm below the ceiling. Two prototype sprinklers could be installed on each of the three pipes. The sprinkler links were either 34.3 or 36.8 cm below the ceiling, depending on the prototype sprinkler used.

Instrumentation consisted of thermocouples and brass disks installed at selected sprinkler stations surrounding the fuel array. At each of the

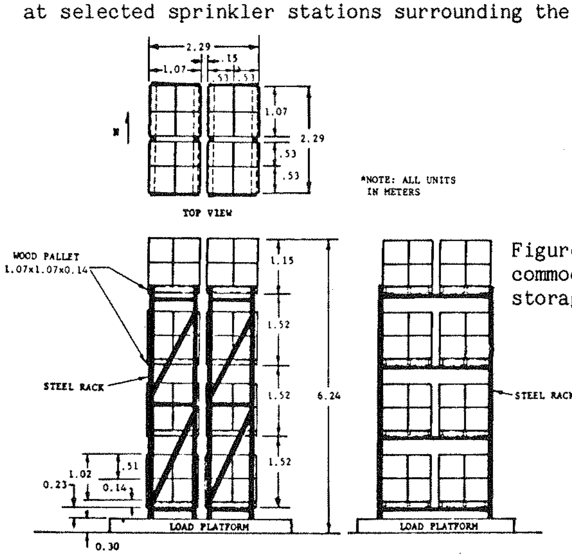
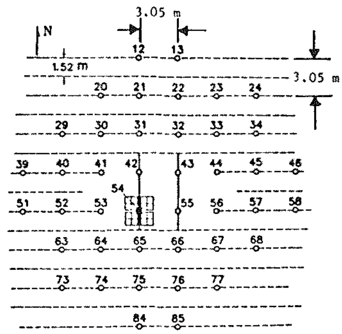


Figure 1. Arrangement of plastic commodity in a four-tier rack storage configuration.



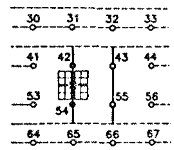


Figure 2(b)

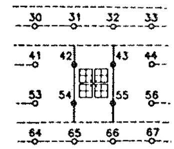


Figure 2(c)

Figure 2(a). Fuel Array Positioned Directly Under a Single Prototype Sprinkler (Sprinkler Location 54); (b) Centered Below Two Prototype Sprinklers (Sprinkler Locations 42 and 54); (c) Centered Below Four Prototype Sprinklers (Sprinkler Locations 42, 43, 54 and 55).

selected sprinkler stations, a brass disk was installed to simulate the thermal response of a fast-response sprinkler link. Brass disks were located 20 cm below the ceiling for Tests 1 to 12; 33 cm below the ceiling for Tests 13 to 22. All brass disks were 2.5 cm diameter with a thickness of 0.4 mm, corresponding to an RTI[4] value of 24 $m^{1/2}s^{1/2}$. Adjacent to each brass disk, a thermocouple was installed to measure gas temperature in the vicinity of the disk.

Seven fire tests were conducted to determine the sprinkler discharge characteristics required for suppressing a four-tier rack storage fire under a 9.14 m high ceiling. Four different prototype sprinklers, designated as B/PA, M/PA, F/PA and B/PB, were used in the test program. Sprinklers B/PA, M/PA, F/PA and B/PB had K* factors of 11.1, 11.0, 10.0 and 13.6, respectively. All had a temperature rating of 73°C with RTI values of 27 $m^{1/2}s^{1/2}$ for prototypes B/PA, M/PA and B/PB and 22 $m^{1/2}s^{1/2}$** for prototype F/PA. In each test, the point of ignition was located in one of the following three positions: 1) directly under a sprinkler, 2) centered below four sprinklers, or 3) centered below two sprinklers. The locations (plan view) of prototype sprinklers in relation to fuel array positions are shown in Figure 2. At sprinkler locations other than those at which prototype sprinklers are indicated in Figure 2, uncharged fast-response upright sprinklers were installed for some of the tests to evaluate the potential of sprinkler operations at these locations. In all tests, 3.05 m x 3.05 m sprinkler spacing was used, and water was discharged through prototype sprinklers located over the fuel array with discharge pressure maintained at 345 kPa.

SPRINKLER THRUST FORCE AND WATER DISTRIBUTION

To measure the center-core thrust force, a 34.3 cm diameter circular plate was positioned directly under the sprinkler 1.83 m from the

*K factor, a number indicating the sprinkler discharge capacity, is defined as the discharge rate, Q, divided by the square root of the discharge pressure, Δp, i.e., $K = Q\ (gpm)/\Delta P(psig))^{1/2}$.

**The RTI for sprinkler F/PA was also measured with the sprinkler deflector orientated toward the air flow; the measured RTI value was 81 $m^{1/2}s^{1/2}$ in this case.

deflector. Before each thrust-force measurement, water was poured slowly on the plate to form a film, and the total weight of the water film and the plate was recorded as the baseline weight. Then, water flow to the sprinkler at 345 kPa pressure was actuated and the thrust force impinging on the plate monitored by a force transducer (GSE Model 4850, 4.5 Kg capacity), placed under the plate. The actual weight of water film on the plate during sprinkler discharge was not obtained.

To measure water flux of the spray center core, a 34.3 cm diameter circular funnel was placed directly underneath the sprinkler also at a distance of 1.83 m from the deflector. Water collected by the funnel was fed into a drum and weighed. Center core water flux measurements were also made at sprinkler water pressure of 345 kPa.

The sprinkler water distribution over the top surface of a simulated fuel array was measured for the sprinkler operating patterns observed in the fire tests. An array of 72 collection pans was used to measure sprinkler water distribution over a surface corresponding to the top of a two-pallet-load wide by two-pallet-load deep fuel array. Water distribution to the flue space of the fuel array was measured using eight pans; distribution to top surfaces of the commodities was measured with 64 pans. The top surface of the collection pans was maintained at 2.9 m below the ceiling. The distance between the sprinkler deflectors and the water collection surface in water distribution measurements was approximately the same as the clearance between the sprinkler deflectors and the fuel array in actual fire tests. Water distribution for the sprinkler operating patterns observed in the fire tests were measured under no-fire conditions.

FIRE TEST RESULTS AND DISCUSSION

Convective Heat Release Rate at First Sprinkler Actuation

Fire size, as indicated by the convective heat release rate, at first sprinkler actuation plays a very important role in the outcome of fire suppression operations by sprinklers. It has been shown that for rack storage fires, as the fire size at the start of water application increases, so does the Required Delivered Density (RDD) necessary for suppressing the fire[5,6]. Furthermore, the amount of sprinkler water actually delivered to the fuel array decreases as the fire size increases. Therefore, to determine sprinkler discharge characteristics needed to suppress a given fire, knowledge of the convective heat release rate of the fire at first sprinkler actuation is required.

To determine the convective heat release rate at sprinkler actuation for fuel arrays tested in this program, the results from a study by Lee[6] were used. In Lee's study, convective heat release rates were measured for a similar four-tier fuel array during freeburn under the FMRC Fire Products Collector[7]. The fire growth behavior for tests conducted in the current program was assumed to be basically the same as the comparable freeburn test performed by Lee, except for differences in the incipient stages of fire growth.

For fuel arrangements of the types used in this program, the incipient growth period was taken to be the time interval from ignition to the point at which flames in a vertical flue reached the top of the four-tier array. Incipient growth periods for fire tests were determined from the video tapes of fires.

After the incipient growth period, fires initiated in identical fuel arrays are expected to grow approximately in the same manner, both in magnitude and behavior. This basic characteristic of fire development in this type fuel arrays was used as the rationale for approximating convective heat release rates at the time of first sprinkler actuation.

To determine convective heat release rates at the time of first sprinkler actuation for tests in this program, time intervals between completion of the incipient time period and first sprinkler actuation were determined. These time intervals, commencing with the completion of the incipient time period, were then referenced on a freeburn fire growth curve generated by Lee for this type fuel array, and the associated convective heat release rate determined. The convective heat release rates were 850 to 970 kW for fire tests in which the ignition and fuel array were located directly under a sprinkler; 1150 and 1340 kW for the tests in which the ignition and fuel array were centered below four sprinklers; and 1380 kW for the test in which the ignition and fuel array were centered below two sprinklers.

With knowledge of the fire size at first sprinkler actuation it becomes possible, for a given sprinkler protection arrangement, to use RDD data previously generated by Lee[6] to determine the water density required for suppressing the fire in the fuel array. It also becomes possible through the use of plume laws[3] to determine relevant fire plume characteristics, such as plume diameter and plume upward momentum fluxes, for the fire. Sprinkler spray/plume interactions play an important role in certain fire source/sprinkler configurations and an assessment of the impact of these interactions is necessary for designing a sprinkler spray of sufficient force to penetrate the plume and deliver the required water to the burning fuel array.

Once the desired sprinkler characteristics, i.e., sprinkler water distribution and the spray center core thrust force and water flux are determined, attempts were made to relate measured values of these parameters for a given prototype sprinkler to its performance in actual fire tests.

Test Results For Ignition Directly Under a Sprinkler

For Tests 8, 9, 14 and 15 with ignition directly under a prototype sprinkler, it was highly desirable for the sprinkler spray to overpower the fire plume in order to achieve efficient delivery of sprinkler water to the top surface of the fuel array. For a given ceiling clearance, the ability of the sprinkler spray to overpower the fire plume depended upon the thrust force, water flux and drop size distribution of the sprinkler spray, and the convective heat release rate and plume width of the fire at first sprinkler actuation. If the fire was overpowered by the sprinkler discharge, and if sufficient amount of sprinkler water was applied to the top surface of the fuel array, the fire was expected to be suppressed.

A fire was considered to be successfully suppressed if the major fire damage was limited to the center flues of the ignition stack and damages outside the center flues involved only minor charring of carton surfaces and wood pallets. Table I presents the fire suppression results and convective heat release rates at first sprinkler actuation for the fire tests with the four-tier fuel array and with ignition directly under a prototype sprinkler.

For prototype sprinklers used in tests, the center-core thrust force of the sprinkler discharge was measured over a circular area with diameter of 34.3 cm at 1.83 m below the sprinkler deflector (0.86 m above the top surface of the fuel array for Tests 8 and 9). The measured center-core thrust force was used to evaluate the ability of the spray to overpower the plume in these tests. Table I presents the center-core thrust force, F_c, and water flux, W_c, over a 34.3 cm diameter area 1.83 m below the sprinkler deflector for the prototype sprinklers used in the tests. The average water flux, W_f, over the flue space and the average water flux, W_a, over the top surface of the fuel array are also shown in this table.

In Test 8, fire suppression was not achieved. The upward momentum flux of the fire plume over a 34.3 cm diameter area 1.07 m above the fuel array top surface was estimated to be 0.98 N for a 850 kW rack-storage fire, using the plume temperature and velocity profiles measured in a separate study by You and Kung[3,8]. The detailed calculation of plume momentum flux and the measured plume temperature and velocity profiles are presented in Appendix C of Reference 2. The estimated plume momentum flux at 1.07 m above the fuel-array top surface was expected to be close to the plume momentum flux at 0.86 m above the top surface (1.83 m below the sprinkler deflector), which was used for comparison with the spray center-core thrust force. The measured thrust force of the B/PA prototype sprinkler used in this test, over a 34.3-cm diameter area 1.83 m below the sprinkler deflector was only 0.44 N. Consequently, the sprinkler spray could not overpower the plume. After sprinkler operation, the fire plume was still visible at the top of the fuel array and the sprinkler spray appeared to be opened up by the plume. Therefore, the water flux over the

Table 1. Fire Test Results and Sprinkler Discharge Characteristics

Fire Test No.	Sprinkler	Convective Heat Release Rate, Q_c[1] (kW)	Fire Suppressed	Center-Core Thrust Force, F_c[2] (N)	Center-Core Water Flux W_c[3] (ℓ/min/m^2)	Water Flux Over Fuel-Array Top, W_a (ℓ/min/m^2)	Water Flux Over Flue Space, W_f (ℓ/min)m^2)
Ignition Directly Under One Sprinkler							
8	B/PA	850	No	0.44	17.9	14.7	10.6
9	M/PA	850	Yes	1.07	40.7	25.3	39.5
14	F/PA	970	Yes	3.01	55.4	28.5	42.0
15	B/PA	920	Yes	9.51	297.0	30.6	75.0
Ignition Centered Under Four Sprinklers							
3	B/PA	1150	Yes	-	-	39.1	50.1
4	M/PA	1340	Yes	-	-	27.3	21.2
Ignition Centered Between Two Sprinklers							
6	B/PA	1380	Yes	-	-	17.5	12.2

Notes: [1]Q_c - Convective heat release rate at sprinkler actuation.

[2,3]F_c and W_c - Center-core thrust force and water flux measured over a 34.3 cm diameter area 1.83 m below the sprinkler deflector.

top surface of the fuel array in this test was expected to be less than that measured under a no-fire condition. The measured average water flux, W_a of Sprinkler B/PA over the entire collection surface under a no-fire condition was 14.7 ℓ/min/m^2 whereas the measured average water flux, W_f, over the flue space was 10.6 ℓ/min/m^2. In Lee's study[6] on fire suppression of rack storage fires, it was shown that a four-tier rack storage fire of Standard Plastic Commodity could not be suppressed with an application flux* of 14.3 (ℓ/min)/m^2 over the top surface of the fuel array when water application commenced at a fire size of 600 kW. Since the sprinkler spray seemed to be opened up by the fire plume, the sprinkler water flux over the fuel-array top surface was expected to be less than 14.3 (ℓ/min)/m^2. Consequently, the fire in Test 8 was not suppressed.

For Tests 9, 14 and 15, the fire was suppressed. As indicated in Table I, the center-core thrust forces of the prototype sprinklers used in these tests upon a 34.3 cm diameter area located 1.83 m beneath the sprinkler deflector were all greater than the estimated plume momentum flux. Shortly after sprinkler operation, the fire plume was overpowered by the sprinkler spray. The average water fluxes (1) over the top surface of the fuel array, W_a, and (2) over the flue space, W_f, measured under no-fire condition were expected to be close to those in the fire tests. Both values of W_a and W_f for the three prototype sprinklers used in the three tests were considerably higher than the Required Delivered Density (RDD) values determined in Lee's study.[6] The Required Delivered Density for a four-tier array of Standard Plastic Commodity at a heat release rate of 1400 kW was determined to be 16 (ℓ/min)m^2. Therefore, the fires in Tests 9, 14 and 15 were all suppressed.

Fire Test Results for Ignition Centered Below Two or Four Sprinklers

For Tests 3, 4 and 6 in which ignition and the fuel array were centered below four or two sprinklers, fire gases rose only through the center flue of the fuel array at the time of first sprinkler actuation. Most of the sprinkler water projected toward the fuel array therefore reached the fuel array without passing through the plume, and che water flux over the top surface of the fuel array measured under a no-fire condition was expected to be close to that in the actual fire tests.

With large ceiling clearances, sprinkler water drops, as they approach the fuel array, tend to have increasingly vertical trajectories. The amount of sprinkler water impinging on the exterior vertical surfaces of the fuel array therefore decreases as ceiling clearance increases. For the tests with 2.93-m ceiling clearance (to the fuel-array top), the major contribution toward suppression of the fire was expected to come from water applied to the top surface of the fuel array. After a sufficient quantity of water was delivered to the top surface, it began to cascade down vertical surfaces of the center flue and starts to suppress the fire. The water drops impinging on exterior surfaces acted to prevent fire spread beyond the center flue.

Table I also presents fire suppression results and convective heat release rates at first sprinkler actuation for Tests 3, 4 and 6. In all

*In Lee's study, water was applied uniformly over the top surface of the fuel array using 64 nozzles. Each nozzle covered a 30 cm x 30 cm area with the nozzles placed within 30 cm from the fuel surface.

three tests, the fire was suppressed by the operating sprinklers. In Tests 3 and 4, ignition was centered below four sprinklers. All four prototype sprinklers actuated within 1.2 s of each other. The average water fluxes, W_a, over the top surface of the fuel array, measured under a no-fire condition, were 39 and 27 $\ell/min/m^2$ for Tests 3 and 4, respectively. In Lee's study[6], a four-tier rack-storage fire of Standard Plastic Commodity with a heat release rate of 1400 kW at the beginning of water application was suppressed with a 16 $(\ell/min)/m^2$ application rate. As expected, the fires in Tests 3 and 4 were suppressed, and dummy sprinklers at remote sprinkler stations did not actuate. In Test 6, ignition was centered beneath two prototype sprinklers. The time difference between the two sprinkler actuations was 2 s. Since the average water flux, W_a, over the fuel-array top surface delivered by the two prototype sprinklers under no-fire condition was 17.5 $\ell/min/m^2$ (greater than 16 $\ell/min/m^2$), the fire was suppressed and no dummy sprinkler actuated.

In the vicinity of each dummy sprinkler, at least one simulated sprinkler link, i.e., brass disk, was installed. In Tests 3 and 4, there were eight brass disks installed at 4.82 m from the center line of the fuel array and 20 cm below the ceiling. For each brass disk, the difference between the maximum disk temperature and the disk temperature at first sprinkler actuation was obtained. The largest value of the disk temperature difference among the eight disks, (ΔT_L) max, was 9°C for Test 3; 22°C for Test 4. The largest value of the disk temperature difference, (ΔT_L) max, was used as an indicator on the sprinkler effectiveness in fire suppression. Since the average water flux, W_a, in Test 3 was greater than that in Test 4, the value of (ΔT_L) max for Test 3 was expected to be smaller than the (ΔT_L) max for Test 4.

CONCLUSIONS

ESFR sprinkler protection is intended to achieve suppression of rack-storage fires in warehouses. The suppression of rack-storage fires depends on: 1) fire size and upward momentum flux of the fire plume at first sprinkler actuation; 2) Required Delivered Density of the fuel array; 3) sprinkler discharge characteristics related to delivery of sprinkler water to the fire source. As the fire source at the start of water application increases, so does the Required Delivered Density necessary for suppressing the fire. Furthermore, the amount of sprinkler water actually delivered to the fire source depends on the fire size, sprinkler discharge characteristics, sprinkler location relative to the fire source and the clearance between sprinkler deflector and the top surface of the fuel array. Sprinkler water distribution under a no-fire condition and spray center-core thrust force were identified as key parameters of sprinkler discharge characteristics pertaining to sprinkler ability to deliver water to the fire source. Through analysis of the fire test results, the relationships among the fire size, plume momentum flux, Required Delivered Density, and sprinkler discharge characteristics, with regard to suppression of rack storage fires were explored.

For the case with ignition directly under a sprinkler, it was highly desirable for the sprinkler spray to overpower the fire plume in order to achieve efficient delivery of sprinkler water to the top surface of the fuel array. To evaluate the ability of the sprinkler spray to overpower the plume in the fire tests with a four-tier fuel array and a ceiling clearance of 2.93 m to the fuel array top, the spray center-core thrust force measured over a 34.3-cm diameter area 1.83 m below the sprinkler deflector was compared with the plume momentum flux measured over a 34.3-cm diameter area 1.63 m below the deflector. In one of the tests, the spray thrust force was significantly less than the plume momentum flux, the sprinkler spray appeared to be opened up by the plume, and the water flux over the top surface of the fuel array was expected to be less than that measured under a no-fire condition. Furthermore, the measured average water flux over the top surface under a no-fire condition for this test was even less than the Required Delivered Density. Therefore, the fire in the test was not suppressed. In other tests, the spray thrust force was greater than the plume momentum flux and the sprinkler spray overpowered the plume. The sprinkler water flux over the top surface of the fuel array under a no-fire condition was expected to be close to that under the fire condition. In each of those tests, the average water flux under a no-fire condition was greater than the Required Delivered Density and the fire was suppressed.

For the case with ignition centered below two or four sprinklers, fire gases rose only through the center flue of the fuel array at the time of first sprinkler actuation. Most of the sprinkler water projected toward the fuel array reached the fuel array without passing through the plume, and the water flux over the top surface of the fuel array measured under a no-fire condition was expected to be close to that under the fire condition. For the three four-tier fuel array fire tests having 2.93-m ceiling clearance and ignition centered below two or four sprinklers, the average water flux over the top surface under a no-fire condition was greater than the Required Delivered Density, and the fire was suppressed.

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