An Investigation of the Causative Mechanism of Sprinkler Skipping

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ABSTRACT: The purpose of this work is to identify the cause of sprinkler skipping, a phenomenon whereby sprinklers operate out of the expected sequence. From a list of several mechanisms, three feasible ones are selected for investigation i.e., impingement of water droplets from previously activated sprinklers onto fusible elements, condensation of water vapor onto fusible elements, and entrainment of hot gases into the spray of operating sprinklers. New instrumentation is developed in order to make psychrometric and spray cooling measurements in the ceiling flow of a large-scale fire. A series of large-scale fire tests using these instruments and a controlled heptane spray fire source are conducted. The results indicate that droplet impingement is the causative mechanism of sprinkler skipping.

KEY WORDS: sprinkler skipping, sprinklered fire, fire–water spray interaction.

INTRODUCTION

'SPRINKLER SKIPPING' MAY be defined as a significantly irregular sprinkler operating sequence when compared to the expected sequence dictated by the ceiling flow behavior, assuming no sprinkler system malfunctions, e.g., hang-ups. More specifically, a skip occurs when a sprinkler head actuates significantly prior to a neighboring sprinkler that is closer to the fire plume. Skipped sprinklers may be subdivided into two – residual and temporary. A residual skip is one in which the sprinkler head does not operate for the duration of the fire, whereas a temporary skip is one in which the sprinkler eventually operates, but at a later time than a neighboring head farther from the plume. Both types of skips can be seen in an illustration in Figure 1, which shows the sprinkler operating sequence

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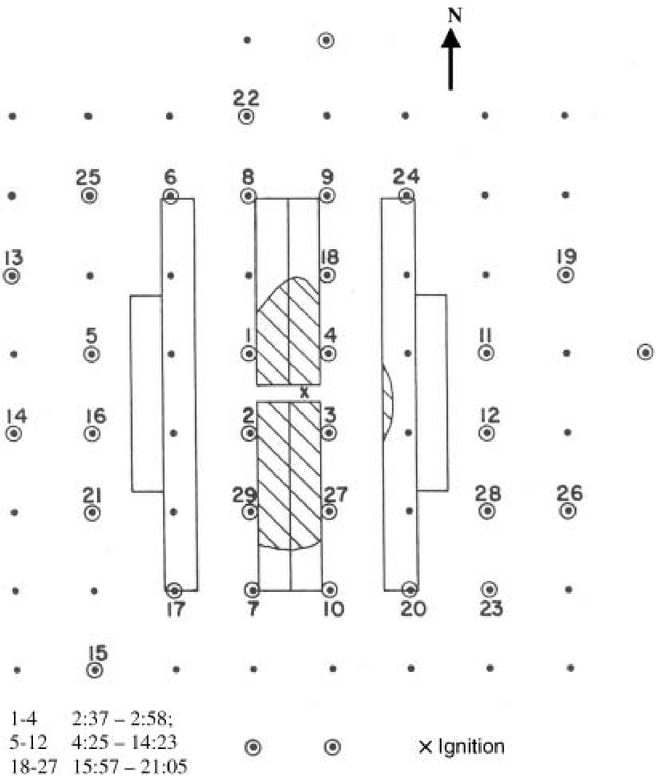

Figure 1. *An illustration of sprinkler shipping. The shaded area shows the extent of fire damage; circles indicate activated sprinklers; numbers indicate operating sequence.*

in a typical rack storage test. If there is no sprinkler skipping, the sprinklers are expected to operate in sequential rings, which are defined by rectangles in the sprinkler array concentric from the fire center. Residual skips are apparent in the east and west sides of the second sprinkler ring, and in the north and south sides of the fourth sprinkler ring, while temporary skips can be seen in the north and south sides of the second sprinkler ring.

The phenomenon of skipping has been observed many times following the analysis of data on sprinkler operating sequence obtained from fire tests with different rack storage arrangements and combustible materials [1–6; see Appendix for summaries]. On the other hand, very little information is available on the occurrence of skipping during fires in actual protected occupancies because the sprinkler operation sequence is usually not monitored. As a result, the significance and importance of skipping on the effectiveness of sprinkler protection have not been determined.

However, it is apparent that sprinkler skipping reduces the water discharge density over the flaming area in fire scenarios, and adversely affects fire suppression and control. Therefore, in the present work, an experimental study of sprinkler skipping is conducted to identify the causative mechanisms of the phenomenon. It is also expected that the testing results from this work can be utilized to assess the sprinkler models in fire simulation software [7–9].

POSSIBLE CAUSATIVE MECHANISMS

Before studying the skipping mechanisms, a careful investigation is conducted to evaluate the feasibility of various suspected mechanisms, using the existing data in [1–6,10–13; see Appendix for summaries]. It is found from these reports that skipping occurred mostly under conditions of high water discharge density and strong fire plumes. Water discharge density is defined as the volumetric water flow rate per unit plan area protected by a sprinkler. The above conditions are common to the high-challenge fire situation. In this work, the investigation focuses upon skips in the second sprinkler ring, because these skips occur earliest and most frequently, and are deemed the most crucial in terms of reducing the effective water discharge density applied to the base of a relatively small fire growing in its early stage.

From a survey of several plausible mechanisms, three appeared to be physically possible causes of skipping: (1) impingement of water droplets from the operating first ring sprinklers; (2) condensation of water vapor on sprinkler links; and (3) spray entrainment of hot ceiling layer gases by the operating first ring sprinklers.

Droplet Impingement

This mechanism requires that the amount of cooling resulting from droplet impingement upon a link is sufficient to prevent the link from fusing. Two quantities must, therefore, be determined in an a priori investigation: (1) the water droplet flux needed to cool a second ring sprinkler link sufficiently; and (2) the water droplet flux available to impinge upon a link.

Before estimation of the needed and the available water droplet flux, it is worth discussing briefly the heat transfer mechanism of droplet impingement, which may affect the way the water droplet flux should be calculated. When water droplets impinge on a sprinkler link, two heat transfer mechanisms may exist simultaneously: conduction and convection of heat from the link to the water droplets, and evaporation cooling on the water droplet surface. If the impinging water droplet flux is so low that a single droplet stays on the link for a period of time before the next droplet hits the link, then certainly evaporation cooling may dominate the heat transfer due to the high latent heat of evaporation compared to the sensible heat capacity. On the other hand, conduction and convection heat transfer plays a major role when the impinging droplet flux is so high that there is not sufficient time for evaporation as water droplets continuously impinge on the link. As a consequence, water dripping should occur and was indeed observed in the experiments conducted for this work. Therefore, the latter mechanism is adopted in estimating the water droplet flux.

The droplet flux needed can be estimated by calculating the minimum convective heating flux to a sprinkler link immersed in a ceiling flow and dividing by the sensible heat capacity of sprinkler water. For this estimate, as well as for many subsequent calculations, data and relationships were utilized from [10–13]. Since conditions in these tests are known, the only value that must be assumed is the sprinkler water temperature. Thus, for the test conditions and a sprinkler water temperature of 23°C, the minimum water flux necessary to prevent a link from fusing is in the range 50–130 g/m^2 s.

The droplet flux available was estimated by considering the interaction of the undisturbed spray pattern of first ring sprinklers with the plume and the ceiling flows [5]. By balancing the droplet weight with the drag forces, considering the droplet size distribution of the sprinkler discharge, and determining from the cooling data the amount of water evaporated, it was estimated that, for a sprinkler discharge flow of 1.9 L/s, the water flux available in the vicinity of a second ring sprinkler would be 80–125 g/m^2 s.

Although no data were available to indicate directly whether skipping did or did not occur under the test conditions in [10–13], the estimates for the amounts of the water spray required and the water spray available to cause skipping suggest that this mechanism of droplet impingement was both possible and reasonable.

Water Vapor Condensation

Condensation will occur on a sprinkler link whenever the link temperature is lower than the dew point of the surrounding gases. Since condensation is a heat releasing process, the possibility exists that condensation could, perhaps prematurely, raise a link temperature above its fusing point, if the dew point is higher than the link rating. On the other hand, if the condensate is formed on a link prior to, or during the early stages of a fire, this condensate would have to be heated and perhaps evaporated away before the link could be fused. Thus, it appears that condensation might conceivably cause a third ring sprinkler to fuse prematurely or a second ring sprinkler to be delayed, either of which could be the manifestation of skipping.

By utilizing the steady-state data from [10–13] and including moisture from ambient air, combustion, and evaporative cooling, it was estimated that dew point temperatures, for a variety of test conditions, would never be higher than 74°C; in fact, the absolute humidity was at least an order of magnitude below the level required to yield a dew point of 74°C. Thus, taken with the observation that skipping has occurred with 141°C-rated links, it did not appear likely that condensation could cause a third ring sprinkler to fuse prematurely.

Similar calculations also showed that it might be possible under certain conditions for the condensate to collect on a second ring sprinkler link. Accordingly, an estimate was made of the time required to evaporate the maximum amount of water that could collect on a link when exposed to a ceiling flow. The conditions in [10–13] yielded an evaporation time, or a delay time, of approximately 90 s. In view of the observation that residual skips have occurred under far more severe conditions, it seemed unlikely that condensation could cause a second ring sprinkler to be delayed to the extent observed in [1–6].

Spray Entrainment

Spray discharges entrain large volume flow rates of the surrounding gases [14]. As a cause for skipping, this mechanism assumes that the amount of air and combustion products entrained by the first ring sprinklers is sufficient to modify the ceiling flow conditions including temperature and velocity at the second ring, such that a sprinkler link in that ring will be delayed in fusing. The most probable manner in which this entrainment mechanism would act, for example, is to reduce the depth of the ceiling layer downstream of the operating sprinklers in the first ring, thus exposing the second ring links to cool gases below the hot layer. According to the data from Heskestad et al. [14], it is estimated that a standard sprinkler having a 12.7 mm (1/2 in.) diameter orifice entrains approximately 0.85 m^3/s from the ceiling layer flow when operating with a discharge rate of 1.9 L/s.

This entrained flow represents less than 8% of the flow through a quadrant of the first ring ceiling layer, and even a smaller fraction of the flow through the second ring. Accordingly, it appears unlikely that the ceiling layer could be thinned sufficiently to expose a second ring sprinkler to cool gases. This estimate does not take into account any direction effects (e.g., sufficient thinning in a narrow wake of a first ring sprinkler), nor does it preclude the possibility of this mechanism acting in another manner.

As a result of this preliminary study, it appeared that (1) droplet impingement was a likely candidate for the causative mechanism of skipping; (2) condensation, while a possible cause, was not very probable; and (3) spray entrainment, although not likely, remained a somewhat uncertain candidate.

EXPERIMENTAL METHOD

The objective of this work is to identify the causative mechanism for sprinkler skipping. As a consequence of the prior testing reports and the preliminary investigation described above, it was decided, in order to achieve the objective, that: (1) relevant measurements would have to be made in the ceiling layer flow of a full-scale fire; (2) these measurements should provide information on the spray cooling capability of water droplets, the humidity conditions, and the true gas temperature in the vicinity of skipped and nonskipped sprinklers. Since it appeared likely that the presence of water droplets in the ceiling flow might influence the sprinkler link response, it was felt that the response of exposed thermocouples might also be affected so that the true gas temperature must be measured using specially designed instrumentation; and (3) since instruments were not available commercially to make these measurements, instrumentation would have to be developed for this purpose.

Instrumentation

The hostile environment in which the necessary measurements were to be made presented a serious technical obstacle and the task of developing this instrumentation indeed proved to be difficult. The results of this developmental effort were the fabrication and testing of prototypes for (1) a droplet impingement, spray cooling meter (DISC); and (2) a fire environment psychrometric probe. Before this work could proceed, however, a facility was required in which to test these devices, i.e., a facility which could simulate the ceiling layer environment. A controllable, heated wind tunnel with a spray generating system was designed and constructed for this purpose. Brief descriptions of these instruments and facilities are presented here.

Heated Wind Tunnel and Spray Generating System

A wind tunnel facility was designed to produce uniform flows with temperatures up to 400°C and velocities up to 15 m/s in its test section (Figure 2). The facility incorporates a blower to produce the flow of air,

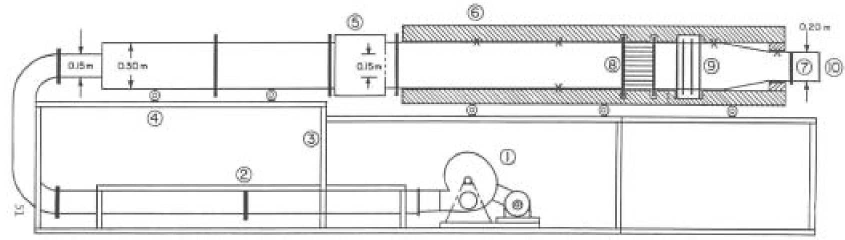

Figure 2. *Schematic of the heated wind tunnel. The numbered components are (1) fan; (2) orifice plate; (3) support frame; (4) roller; (6) burner chamber; (7) feedback TC; (8) flow straightener tube; (9) flow smoothing screens; (10) test area;* $\times$ *– thermocouples.*

a feedback-regulated gas burner to produce a controlled air temperature, flow smoothing techniques, flow monitoring instrumentation, and automatic safety and control devices. The tunnel terminates with a 0.2 m diameter open test section.

The spray generating system consists of a spray nozzle, a pressurized reservoir which supplies water to the spray nozzle located just upstream of the test section, and a delivery line with necessary control devices. Several nozzle sizes are available, resulting in water droplet mass fluxes up to 1.1 $\mathrm{kg/m^2\,s}$ that can be supplied to the test section (Part 10 in Figure 2). A variation in the mean droplet size at a constant mass flux is also available.

Droplet Impingement, Spray Cooling Meter (DISC)

In order to ascertain the spray cooling capability of the droplets in the ceiling flow, a device was fabricated which measures the temperature difference across a thin, but thermally finite disc of refractory material (see Figure 3) when exposed normally to a droplet-laden flow of hot gases. For such a device, the front side (facing the flow) is cooled by droplet impingement more than the rear side, resulting in a temperature difference across the disc. Accordingly, a spray cooling coefficient C_{sp} can be defined as

$$C_{\mathrm{sp}} = \frac{\Delta T}{T_g - T_w} \tag{1}$$

where $\Delta T = T_r - T_f$ is the difference between the rear and the front surface temperatures, T_g is the gas temperature and T_w is the water droplet temperature. For a given probe construction (geometry, materials), one would expect this temperature difference to be a function of T_g and T_w, the water droplet mass flux $\dot{m}''_w$, the gas velocity V, and possibly the mean

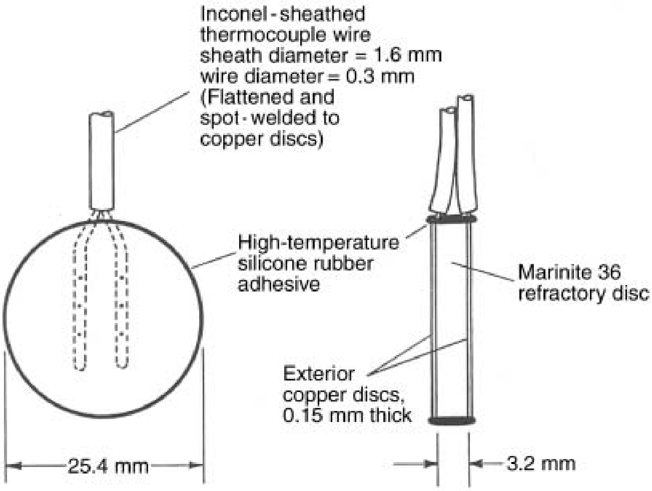

Figure 3. *Droplet impingement, spray cooling meter (DISC).*

droplet diameter d_m. A one-dimensional model balancing heat conduction, convection, and water cooling by conduction and evaporation across the DISC meter yields the following relationship for C_{sp}:

$$C_{sp} = \left\{ 1 + \frac{h_{avg}}{\dot{m}''_{wi} c_w} \left[\frac{\eta + 1}{Bi_{avg}} + \frac{2\eta}{\eta + 1} \right] + \frac{\eta + 1}{2Bi_{avg}} \right\}^{-1} \tag{2}$$

where Bi_{avg} is the average Biot number $(= h_{avg} t_m / k_m)$ and $\eta = h_f / h_r$. In these expressions, h_{avg} is the average overall convective heat transfer coefficient to the probe (a disc placed normal to the mean flow); h_f is the average convective heat transfer coefficient for the front side of the disc; h_r is the average convective heat transfer coefficient for the rear side of the disc; t_m is the thickness of the refractory material; k_m is the thermal conductivity of the refractory material; and $\dot{m}''_{wi}$ is the water droplet mass flux which impinges upon the front probe surface. It is important to note that η need not, and in fact, does not equal unity. If C_{sp} is known, Equation (2) permits a calculation of $\dot{m}''_{wi}$ to be made, since all other quantities are either known or calculable. One can then define a skipping coefficient C_{sk}, as the ratio of the amount of cooling available to the amount of cooling needed to prevent a sprinkler link from fusing; a simplified approach yields

$$C_{sk} = \frac{\dot{m}''_{wi} c_w (T_L - T_w)}{2 h_L (T_g - T_L)} \tag{3}$$

where c_w is the specific heat of water, T_L is the link temperature rating and h_L is the average heat transfer coefficient to the link. Intuitively, one would expect a skipped sprinkler to be associated with high values of C_{sk} and a nonskipped sprinkler to be associated with low values of C_{sk}, relative to a value of C_{sk} of order unity. In the present work, C_{sp} was obtained by measuring quantities on the right-hand side of Equation (1). Quantities $\dot{m}''_{wi}$ and C_{sk} were then calculated using Equations (2) and (3), respectively.

Fire Environment Psychrometric Probe

The requirement to measure the humidity conditions and the true gas temperature in the ceiling flow of a full-scale fire was satisfied with the development of a fire environment psychrometric probe. This probe consists of an aspirated sampling tube in which are mounted three thermocouples (Figure 4). One thermocouple is imbedded in a moistened wick and senses the wet-bulb temperature T_{wb}. The other two thermocouples, of different

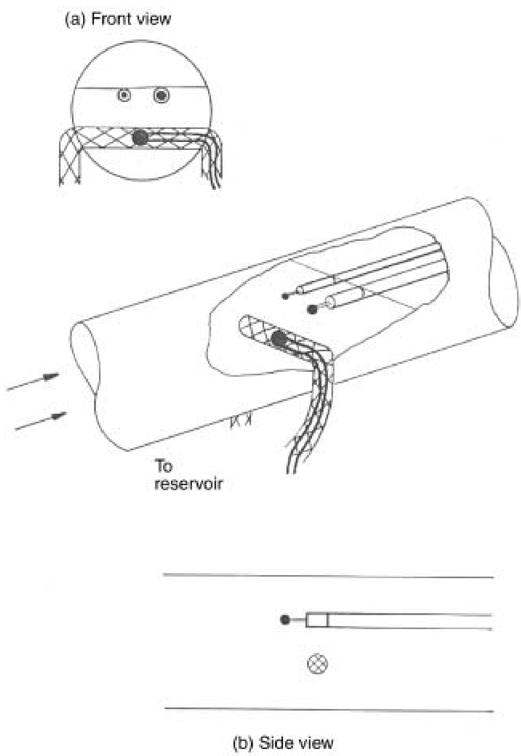

Figure 4. *Fire environment psychrometric probe.*

Table 1. Thermocouple bead sizes.

Measurement	Average bead diameter (mm)	Bead diameter range (mm)
Bare-bead	1.51	1.40–1.63
Large dry bulb	1.48	1.40–1.55
Small dry bulb	0.83	0.71–0.91
Wet bulb	1.80	1.65–1.96

bead sizes (Table 1), are used to obtain the dry-bulb (true gas) temperature T_{db}.

To obtain reasonably accurate readings of both the wet- and the dry-bulb temperatures in the hostile environment produced by a fire, a specially designed impaction filter was placed at the entrance of the aspirated tube. This filter is designed to strip the sampled flow of all, but the smallest particles and droplets (0.02 mm diameter) and, therefore, provides a reasonably clean flow for the measurements. The probe geometry is designed to yield a well mixed, uniform flow over the thermocouples. Two bead sizes of thermocouples were used in obtaining the true gas temperature. Additionally, a constant pressure drop aspirating system was incorporated to provide satisfactory probe performance as the temperature of the sampled gas varies during a fire test. In testing the prototype of the fire environment psychrometric probe, wet-bulb depressions ($T_{db} - T_{wb}$) as large as 295°C were measured satisfactorily in flows with dry-bulb temperatures as high as 375°C.

Full-scale Tests

In planning for the full-scale tests, the results of [1–6,10–13] were examined for the skipping behavior. It was then deemed that full-scale tests were required in this study in order to obtain definitive data relating to the causative mechanism of skipping. These tests had to ensure the occurrence of skipping yet provide adequate control of test conditions for analysis. A spray fire facility was selected for these tests to provide relatively good flexibility and control of important parameters in a full-scale fire. The facility was set up in a site having a 9.1-m (30 ft) high ceiling, using 12 heptane spray nozzles arranged as shown in Figure 5. The outer nozzles were at a height of 1.2 m from the floor, while the inner nozzles were at a height of 2.4 m, giving a ceiling clearance height of 6.7 m. The center of the nozzle arrangement was located 0.3 m west of the center of the 9.1-m (30 ft) site. Both the nozzle arrangement and the location of the nozzle array were selected on the basis of [10–13].

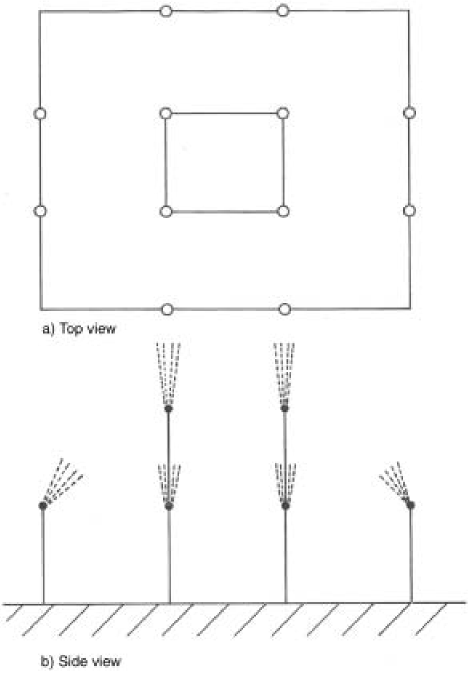

Figure 5. *Heptane spray nozzle arrangement for the spray fire facility.*

Standard 12.7-mm (1/2 in.) orifice upright sprinklers with 71°C links were used in a 7.4-m^2 spacing arrangement for all the sprinklered tests. Ninety-six sprinklers were timed. Links were not specially oriented, except for Test 10 which is discussed later (Table 2).

In order to facilitate effective placement and mounting, the instruments developed in the first part of this work were fabricated into compact packages, designed to face the center of the fire. The specific makeup of each package was dependent upon its planned location and the instrument availability. Figure 6 shows the makeup and location, relative to the fire center, of the seven probe packages used in all tests except the first (Table 2).

Aspirated thermocouples were identical to the pyschrometric probes except for the absence of the wet-bulb temperature measurement and its related paraphernalia. Twenty-five building thermocouples, located 150 mm below the ceiling at various positions from the center of the fire, were also monitored.

A total of 14 tests were conducted covering a range of fire strengths and sprinkler discharge densities. Table 2 lists all the test parameters. Test 1 (heptane flow = 0.88 L/s) was conducted as a precautionary measure without

Table 2. Test conditions.

Test no.	Heptane flow rate (L/s)	Theoretical heat release rate (MW)	Sprinkler discharge density (mm/s)
1	0.88	28	freeburn, no sprinklers
2	0.76	24	0.24
3	0.57	18	0.24
4	0.57	18	0.20
5	0.57	18	0.20
6	0.38	12	0.20
7	0.57	18	0.31
8	0.76	24	0.20
9	0.57	18	0.10
10	0.57	18	0.24 w/links oriented
11	0.57	18	freeburn, timed sprinklers
12	0.38	12	freeburn, no sprinklers
13	0.57	18	freeburn, no sprinklers
14	0.76	24	freeburn, no sprinklers

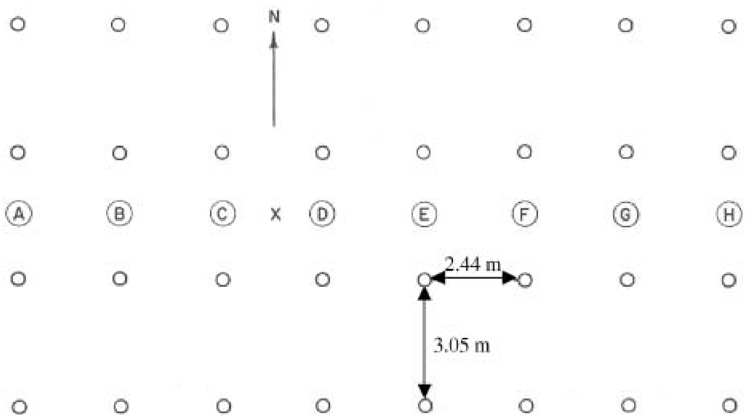

Figure 6. *Components and locations of instrument packages. A and H – aspirated TC, DISC, and bare-bead TC; B and E–G psychrometric probe, DISC and bare-bead TC; C – none; D – aspirated and bare-bead TC;* $\times$ *– fire center.*

the instrument packages mounted on the ceiling in order to determine maximum temperature levels that could be expected at the various data stations. Results of this test showed that temperatures at the second sprinkler ring locations were slightly in excess of the maximum allowable operating temperatures for the psychrometric probe and the droplet meter. Accordingly, heptane flow rates of 0.76, 0.57, and 0.38 L/s were selected for the test conditions. In all the tests, the heptane flow rate was increased every 15 s from time zero in increments of 1/4 total flow, so that the test condition flow was achieved 1 min after ignition. The heptane flow rate was then held constant for an additional 7 min in the sprinklered tests and 4–6 min in the unsprinklered tests. The range of sprinkler discharge densities was selected to be 0.0–0.31 mm/s. The variation of this parameter was achieved by adjusting the sprinkler discharge pressure.

RESULTS AND DISCUSSION

Evaluation of Experimental Uncertainties

True Gas Temperature

An accurate determination of the true gas (dry-bulb) temperature in a fire test environment depends strongly upon either (1) making a measurement that is free of significant errors, or (2) adjusting measured values to compensate for significant errors. In the current work, as in most large-scale, sprinklered fire tests, radiation and moisture can introduce serious uncertainties in the measurement of gas temperatures. If radiation were the only significant source of error, satisfactory values of true gas temperatures can be determined either directly from highly aspirated, uncooled thermocouple probes [15], or by the adjustment of measured values from thermocouples whose radiation environment, i.e., ambient temperature for radiation and bead emissivity, is adequately known. The presence of moisture, however, can complicate these determinations either (1) indirectly by dramatically altering the radiation environment of a bead, or (2) directly by impinging upon a bead, additionally cooling sampled gases or electrically attenuating the thermocouple signal.

It is important to note that, when the radiative environment is at a lower temperature than the gas temperature, all of these effects tend to cause a bead to register a temperature below the true gas temperature. In addition, if radiation is the only cause of serious error, the small bead should register a higher value than the large bead, i.e., a value closer to the true gas temperature. However, if moisture is causing significant errors, either by impingement or by electrical attenuation, it is no longer definite which bead will register the higher value.

Table 3 shows average readings from bare-bead thermocouples T_{BB} and both large- and small-bead thermocouples (T_{BL} and T_{BS}) in aspirated probes at various stations during the steady intervals of the tests. At Station E, gas temperature was also obtained from the small-bead thermocouple assuming radiation to be the only effect. This computation is performed only for Station E, since it is the only station for which the ambient temperature for radiation is known.

Table 3. Readings of bare-bead and aspirated thermocouples during steady interval (°C).

Test no.	Station D (first ring)			Station E (second ring)			Station F/A (third ring)			Station H (fifth ring)		
	T_{BB}	T_{BL}	T_{BS}	T_{BB}	T_{BL}	T_{BS}	T_{BB}	T_{BL}	T_{BS}	T_{BB}	T_{BL}	T_{BS}
2	764	696	716	358	248	242	$72_w/63_w$	142/121	148/122	56_w	88	94
3	68_w	221	225	65_w	163	164	$55_w/89_{pw}$	101/101	109/100	63_w	70	69
4	434	416	426	167	162	154	123/126	131/121	136/120	49_w	74	79
6	53_w	116	123	53_w	83	86	$43_w/43_w$	69/57	76/62	82	81	81
7	68_w	232	242	58_w	128	128	$50_w/102_{pw}$	81/110	72/112	45_w	71	72
8	572	541	556	337	183	217	155/208	136/159	117/158	53_w	90	91
9	446	459	463	298	237	261	208/169	172/164	154/164	119_{pw}	121	123
10	156_{pw}	239	246	61_w	144	166	$52_w/53_w$	86/98	79/99	48_w	74	74
12	234	242	241	177	151	163	139/141	114/138	102/138	116	117	117
13	476	491	489	307	248	275	231/208	213/202	218/202	191	188	189
14	605	608	611	372	302	297	269/322	237/309	250/310	211	208	210

Note: BB – bare-bead; BL – aspirated large-bead; BS – aspirated small-bead; w – wetted during entire interval; pw – wetted during part of the interval.

Immediately evident in Table 3 are the noticeable differences between the bare-bead and the aspirated thermocouple values. The bare-bead values that are significantly higher than the aspirated values are attributed to a high radiative input to the bare bead or to a low-aspirated reading due to moisture (see discussion below) or a combination of both. The bare-bead values that are significantly lower than the aspirated values are attributed primarily to the water droplets wetting the bare-bead thermocouple. The cases of wetted bare-bead values have been indicated in Table 3. It is noticed that wetted values show good agreement with measured wet-bulb temperatures.

Moisture also appears to have influenced some of the aspirated-bead values. Evident in Table 3 are a number of instances where the large-bead value is significantly higher than the small-bead value, e.g., Station E in Test 4 and Station F in Test 8, and an additional number of instances where the large-bead value is not significantly lower than the small-bead value when it should be if moisture were not having a significant effect, e.g., Stations E in Tests 3 and 7 and Station A in Test 2. In addition, it was also observed in some cases that a large-bead thermocouple within an aspirated probe was apparently being wetted during portions of a test.

It appears, therefore, that, although precautions were taken to prevent moisture from influencing the dry-bulb measurements and although these precautionary measures worked well during the prototype testing, some dry-bulb measurements were unfortunately influenced significantly by the presence of moisture within these probes. The examination of the data reveals that the presence of moisture may have affected the dry-bulb measurements by altering the ambient temperatures for radiation (to an unknown degree in the uncooled aspirated thermocouple probes) as well as by direct impingement or attenuation. As a result, an accurate determination of true gas temperatures during large-scale, sprinklered fire tests has not been fully achieved.

Despite the limited success in obtaining true gas temperatures in this work, the following statements can be made regarding this measurement.

Although an accurate determination of true gas temperatures has not been fully achieved, the technique of using aspiration with impaction filtration is superior to the bare-bead measurements. Further improvement of the true gas measurements is possible by (1) using an uncooled, highly aspirated probe with perhaps a second shield to keep droplets off the aspirating tube, and (2) modifying the impaction filter to be more effective. However, the accuracy of the measured gas temperatures was deemed sufficient to characterize the skipping mechanisms qualitatively for the present work.

Wet-bulb Temperature

The measurement of wet-bulb temperatures in this work is considered successful, i.e., the measurements were achieved directly in the ceiling layer flow with a sufficient accuracy for evaluating feasible skipping mechanisms. The examination of the wet-bulb temperature data and the probes during and after the test program indicates no reason to expect larger uncertainties than $\pm 5\%$. Even the presence of water droplets within the probe, as evidenced from the observations on the dry-bulb temperature measurements, should not strongly affect the wet-bulb temperature measurement since these droplets will be at or close to the wet-bulb temperatures. A key factor in the success of this measurement is the cooling of the walls of the aspirating tube in the vicinity of the wick, a measure which is not desirable for accurate dry-bulb measurements.

DISC Meter Measurements

The temperature differences across the DISC meter were of the order expected, and the probes survived the entire test series, including free burns, although some were beginning to fail under the severe exposures. It is important to realize that, although these meters were designed to register temperature differences under the conditions of convective heating and spray cooling, the effects of radiation must also be considered. A significant radiative input to the front side will induce a measurable negative temperature difference, $\Delta T = T_r - T_f$. If it is assumed that the radiation effects in a sprinklered fire test are similar to those in a free burn test, corrections to the sprinklered test results could be achieved by subtracting the usually negative ΔT-values measured in the free burn tests at corresponding times. Unfortunately, it appears that the control of heptane and water flow rate was not sufficiently fine to allow this type of adjustment to be made without introducing greater variations into the data.

Another method for making the radiation adjustment is to subtract the usually negative ΔT just prior to the sprinkler activation from the value for this skipping interval. Unfortunately, this approach is useful only for the first ring skipping interval, i.e., for the second ring skipping. If this correction is made, the spray cooling coefficient, C_{sp}, can be calculated using the adjusted ΔT and assuming $T_{\mathrm{db}} = T_{\mathrm{wb}}$ and $T_{\mathrm{wb}} = T_{\mathrm{w}}$.

Skipping Behavior

The range of test conditions, although limited in parameters to fire intensity and sprinkler discharge pressure, was sufficiently broad to include the nonskipping behavior, the temporary skipping behavior, and the residual skipping behavior. A summary presentation of the occurrence of skipping as a function of the theoretical heat release rate $\dot{Q}_{\mathrm{TH}}$ and the sprinkler discharge density is given in Figure 7. In this figure, four relevant data points from [16; see Appendix for summary] with $\dot{Q}_{\mathrm{TH}} = 12\,\mathrm{MW}$ have been included. The sprinkler operations were timed in Tests 2–11 (see Table 2). An example of the detailed sprinkler operating times and patterns is given in Figure 8 for Test 2. It is significant to note that, with the continuously fed, stationary, fairly symmetrical source fire used in these tests, skipping always occurred first in the second ring and then in increasingly farther rings from the fire center. Figures 9 and 10 show the skipping patterns for the two tested parameters.

Causative Mechanisms of Sprinkler Skipping

Figures 11–13 present a typical example (Test 8, $\dot{Q}_{\mathrm{TH}} = 24\,\mathrm{MW}$, water discharge density $= 0.2\,\mathrm{mm/s}$) of certain instrument package data for Tests 2–4, 6–10, and 12–14. In Figures 11–13, the averaged dry-bulb temperature, the wet-bulb temperature, and the temperature difference registered across the DISC are plotted. The average value is the arithmetic average over the entire interval shown in the legend as t01, t13, t35, and tss. These time intervals are based upon the activation of certain key sprinklers. The information in Figures 11–13 focuses on the sprinklers located just north and south of the east-west centerline of the test setup, i.e., those sprinklers adjacent to the instrument packages (see Figure 6). More specifically,

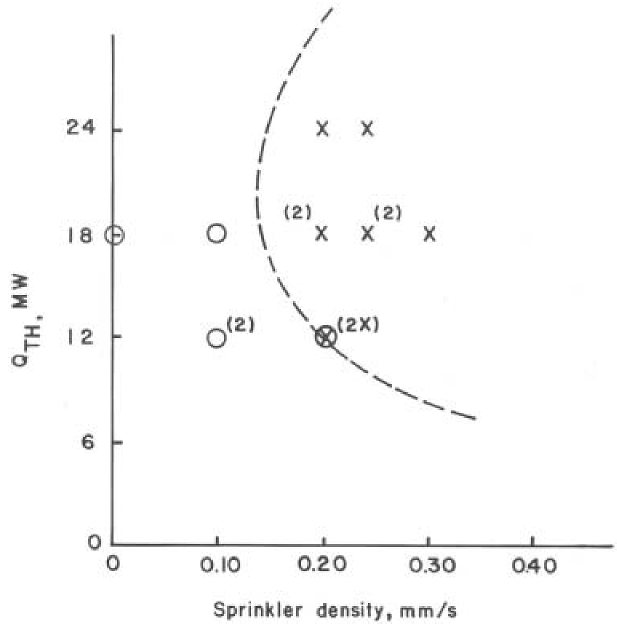

Figure 7. *The occurrence of skipping as a function of fire intensity and water discharge density. The dashed line stands for a possible boundary between skipping and nonskipping behavior.* × *– skipping; o – non-skipping.*

the measured values are given for those stations located in the first, second, third, fourth, and fifth sprinkler rings east of the fire center in Stations D–H. The first interval t01 represents the time from ignition to activation of the first ring sprinklers. The second interval t13 represents the time between the activation of the first ring sprinklers and activation of the third ring sprinklers. The third interval t35 represents the time between the activation of the third ring sprinklers and the fifth ring sprinklers. The fourth interval tss represents 1 min time period (5 : 00–6 : 00) of steady state during the test.

It should be noted that the values of T_{db} given in Figure 11 are the highest of the two dry-bulb measuring thermocouple values. The highest of the two values was chosen because it represents the closer unadjusted value to true gas temperature as discussed in the 'Evaluation of Experimental Uncertainties'.

Some very clear observations can be made from these results. In Figure 11, the only case in which the measured dry-bulb temperature is lower than the link temperature occurs at the second ring before the first sprinkler opened. Therefore, all dry-bulb temperatures exceed the rated link temperature in the vicinity of skipped sprinklers during the skipping intervals. In Figure 12,

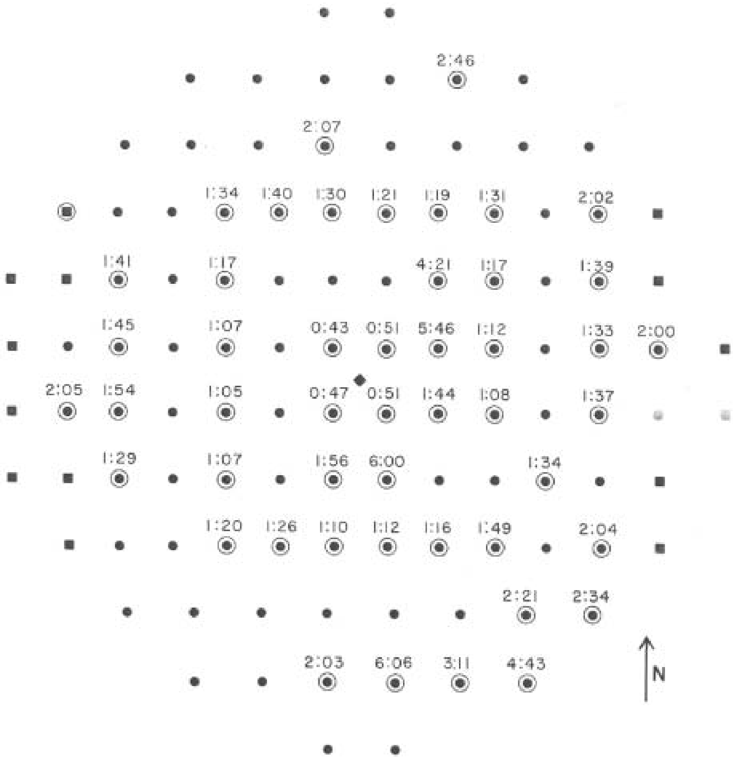

Figure 8. *Sprinkler operating sequence of Test 2. • – timed sprinklers; ■ – nontimed sprinklers; ⦿ – operated sprinklers; ◆ – fire center.*

wet-bulb temperatures, which are always greater than or equal to dew points, always lag the dry-bulb temperature and never reach the rated link temperature. In Figure 13, the temperature differences $\Delta T = T_r - T_f$ registered across the DISC meter are always greatly positive in the vicinity of skipped sprinklers during skipping intervals and not so in the vicinity of normally-activated sprinklers prior to activation. For example, $\Delta T = T_r - T_f$ at the second ring, is much higher than that at the third ring during the time (t13) between activation of first ring sprinklers and third ring sprinklers.

Although these observations have definite importance in establishing the cause of sprinkler skipping, the measurements made with newly developed instruments need evaluation before conclusions are drawn. The values of C_{sp}, corrected for radiation, can be calculated as discussed in ''Evaluation of Experimental Uncertainties''. This quantity should vary from zero, for no impinging droplets, to a value that approaches unity for very high impingement rates. It is recalled that the DISC meter probes were

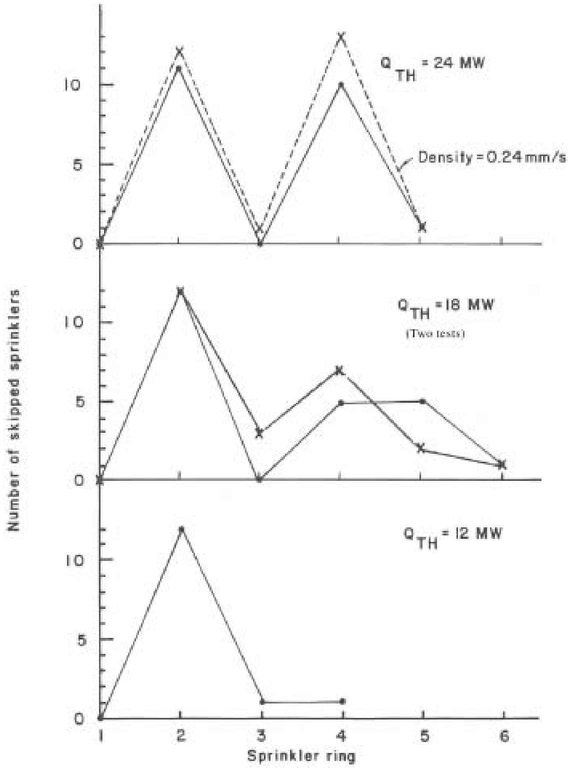

Figure 9. *Skipping patterns for water discharge density 0.2 mm/s except where indicated.*

constructed so as to register a significant ΔT for impingement rates that were estimated to be necessary to cause skipping. Table 4 presents values of C_{sp} in both the second and third sprinkler rings for all the sprinklered tests except Test 5 in comparison with the observed skipping behavior. Clearly, high values of C_{sp} are associated with skipped sprinklers and low values with nonskipped ones, as one would expect if droplet impingement were the cause of skipping. The measured spray cooling coefficients, therefore, yield sufficient evidence of the capability of water droplets carried by the flow to impinge upon and cool a fusible element, potentially preventing activation. From the results given in Figures 11–13 and the discussion in "Evaluation of Experimental Uncertainties", it becomes apparent that neither condensation nor sprinkler spray entrainment is the cause of sprinkler skipping. The results in Figures 11–13 also indicate that droplet impingement, with the resultant spray cooling of sprinkler links, may indeed be the causative mechanism.

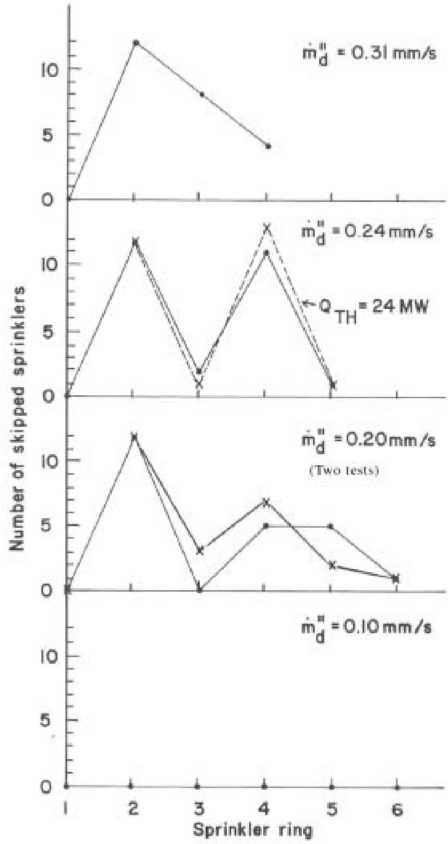

Figure 10. *Skipping patterns for $\dot{Q}_{TH} = 18$ MW except where indicated.*

Table 5 presents statistical results on the skipping behavior. Included in this table for each test are the total number of both temporary and residual skipped sprinklers, the total number of operated sprinklers, the total number of operated plus residual skipped sprinklers and a quantity called the skipping ratio – defined as the number of temporary and residual skips divided by the sum of the total operated plus the residual skips. With droplet impingement causing skipping, a skipped sprinkler represents an anomalous result, i.e., an abnormal delay or prevention of activation, due to the spray cooling of skipped sprinkler elements. Thus, if this spray cooling capability were not present or somehow negated, the total number of sprinklers that would have operated in these tests can be argued to be approximately the sum of the operated plus the residual skipped sprinklers. The tendency for skipping to occur with a given set of conditions, therefore, can be reflected

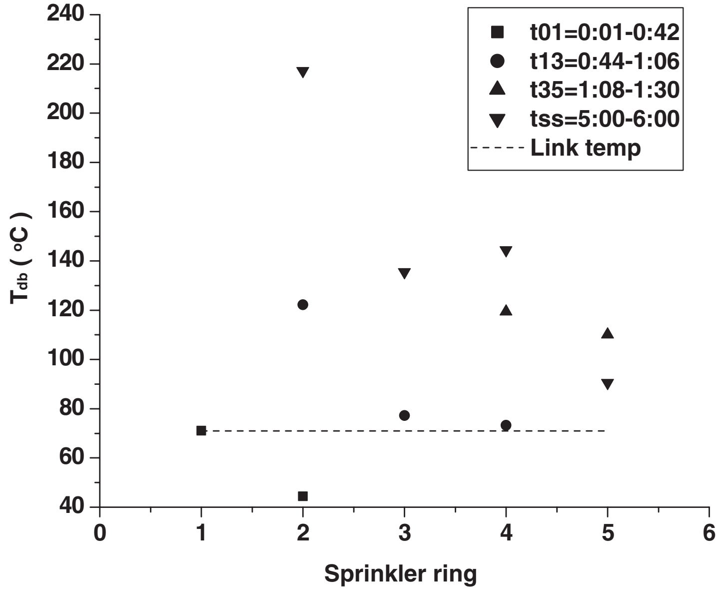

Figure 11. *Dry-bulb temperature in Test 8.*

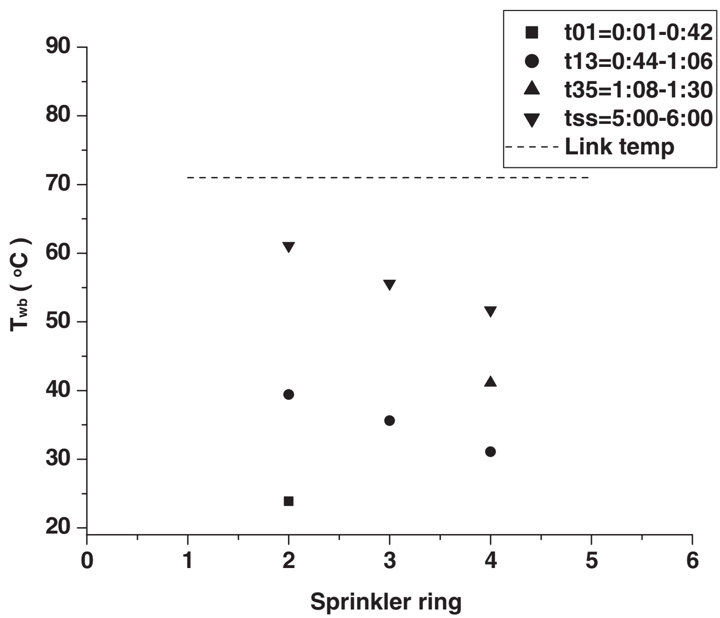

Figure 12. *Wet-bulb temperature in Test 8.*

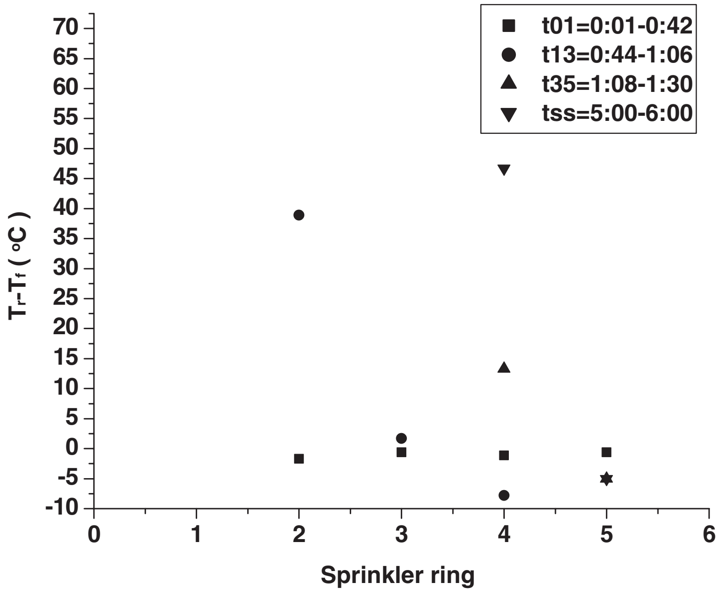

Figure 13. *Wet-bulb temperature in Test 8.*

Table 4. ***C_{sp} and skipping behavior for the second and third ring sprinklers*.***

Test no.	Second ring		Third ring	
	C_{sp}	Behavior	C_{sp}	Behavior
2	0.57	ST	0.07	N
3	0.66	SR	0.17	N
4	0.65	SRT	0.04	N
6	0.66	SR	0.02	N
7	0.81	SR	0.39	N
8	0.52	SRT	0.05	N
9	0.0	N	0.0	N
10	0.73	SR	0.09	N

*The C_{sp} and skipping behavior are during the first skipping interval.
Legend to skipping behavior:
ST – Both sprinklers skipped temporarily; SR – Both sprinklers skipped residually;
SRT – One residual skip and one temporary skip; and N – Neither sprinkler skipped.

by the skipping ratio. Figure 14 shows the skipping ratio as a function of heat release rate for constant water discharge density (or constant Δp), and as a function of water discharge density (Δp) for constant heat release rate. The parametric trends become clear with the tendency to skip increasing with the discharge density above some threshold value; increasing and then

Table 5. Skipping behavior.

Test no.	No. of skips (temp + residuals)	Total operated	Total operated + residuals	Skipping ratio
2	27	49	71	0.38
3	26	44	66	0.39
4	29	62	76	0.38
5	25	64	80	0.31
6	14	27	37	0.38
7	24	29	49	0.49
8	22	76	89	0.25
9	0	110	110	0.00
10	25	38	60	0.42

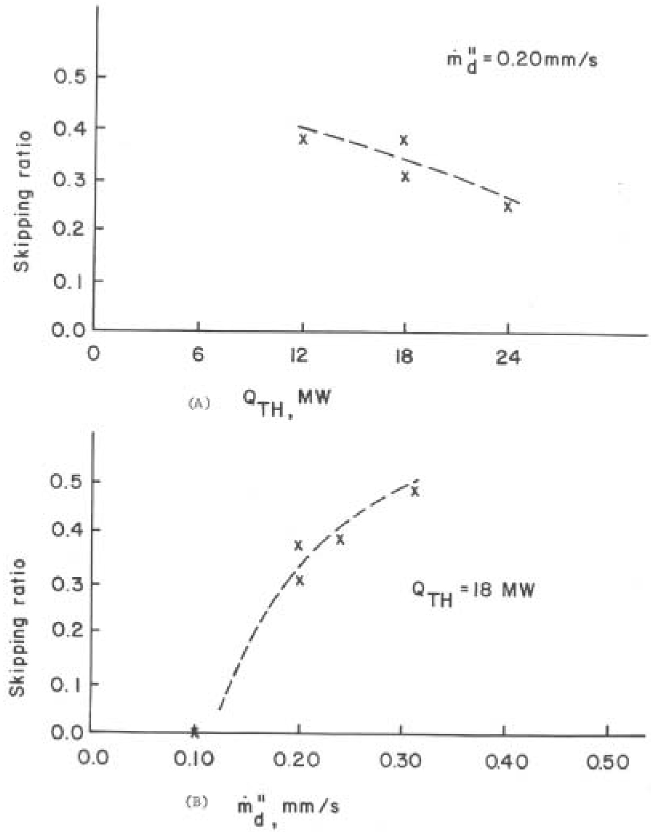

Figure 14. *Skipping ratio as a function of (A) heat release rate and (B) water discharge density.*

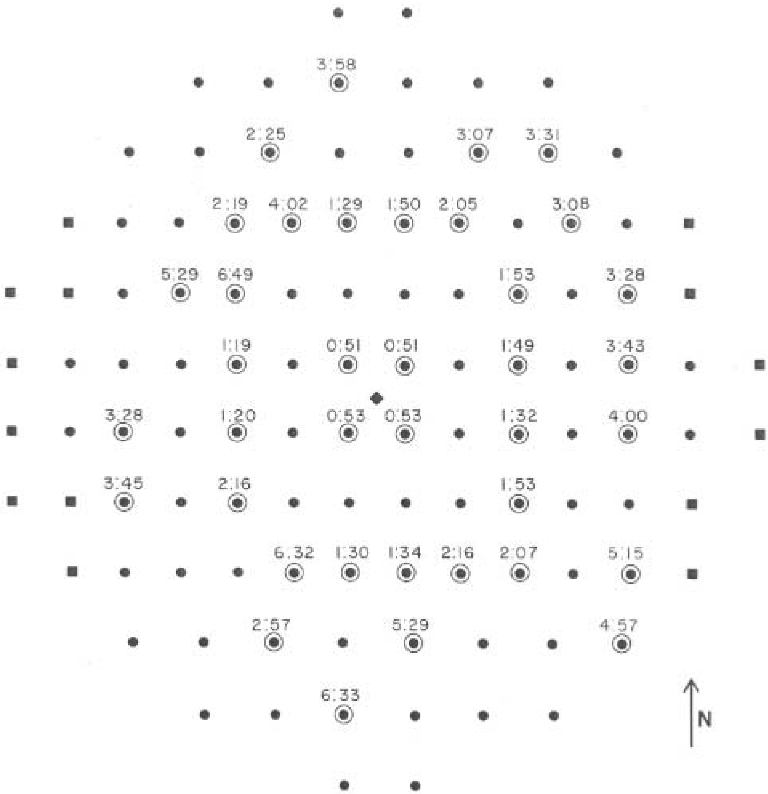

Figure 15. *Sprinkler operating sequence of Test 10. • – timed sprinklers; ■ – nontimed sprinklers; ⦿ – operated sprinklers; ◆ – fire center.*

decreasing with heat release rate. Accordingly, the skipping boundary in Figure 7 is shown qualitatively as an envelope, with an upper as well as a lower limit because one would not expect skipping to occur at a sufficiently small heat release rate for a given discharge density.

With droplet impingement as the causative mechanism, the important parameters controlling the skipping phenomenon for a given sprinkler geometry are convective heat release rate, $\dot{Q}$; clearance height, H; sprinkler discharge pressure, Δp; sprinkler spacing, s; rated link temperature, T_L; and link sensitivity, RTI. The quantification of the effect of each of these parameters is beyond the scope of this work. However, observations from the tests indicate that very small or large values of these parameters will unlikely cause skipping because the skipping phenomenon is essentially the competition between the fire plume and the sprinkler spray.

Finally, with droplet impingement as the cause of skipping, the possibility exists for reducing the number of skips by minimizing the fusible link area projected to the flow. Accordingly, a single test (No. 10) was performed in the large-scale test series with all the timed fusible links oriented normal to the ceiling flow direction on one side of the fire (east of the fire center in Figure 15) and parallel to the flow direction on the other side. The only difference between Tests 3 and 10 is the sprinkler orientation. As can be seen from Figure 15, no significant difference in sprinkler operating sequence between the two regions is apparent. This result is not too surprising considering the large turbulent fluctuations in flow direction within the ceiling layer flow; however, it does point out that eliminating or reducing the occurrence of skipping may not be easily achievable.

CONCLUSIONS

Skipped sprinklers are sprinklers which are delayed or prohibited in their activation anomalously when compared to the designed and expected sequence of operation. The following conclusions can be stated with regard to the sprinkler skipping behavior:

(1) Sprinkler skipping is caused by the impingement of entrained and diverted water droplets from previously activated sprinklers onto the fusible element of the skipped sprinkler. Skipping occurs when the cooling of a fusible element by droplet impingement exceeds the heating of the element, thus preventing activation.
(2) The results of the large-scale spray fire tests, limited to high heat release rates, showed that the tendency to skip decreases slowly as the heat release rate increases.
(3) The large-scale sprayfire test results also indicated that the tendency to skip increases as water discharge density (pressure drop) increases.
(4) With droplet impingement as the causative mechanism, other parameters that may be important to the skipping phenomenon for a given sprinkler geometry are: clearance height, sprinkler spacing, rated link temperature, and link sensitivity. The sprinkler geometry should also be an important factor, especially with regard to effects on the distribution pattern and the droplet size distribution.

ACKNOWLEDGMENTS

We would like to express our gratitude to Dr. Gunnar Heskestad for making us aware of this problem and subsequently providing us with unselfish support and helpful discussion. Also, the help of our former

FMRC and current FM Global Research colleagues regarding the experiment, data acquisition, and processing is acknowledged.

APPENDIX

Summaries of References [1–6,10,12,13,16] Not in the Open Literature.

[1]:

Observations of skipping in the sprinkler operating patterns in eighteen rack storage fire tests were reported. The general comments on skipping are (1) the ignition was located in the center among four sprinklers in each test except one; (2) the four sprinklers in the first ring did not skip in each test except one; (3) skipping propensity increases with water discharge density; (4) skipping beyond the second ring was not observed. Possible conclusions are that skipping tends to happen with a strong fire plume and a higher water discharge density, and is affected by the fire plume position and the sprinkler type and spacing.

[2]:

A study on the final opened sprinkler locations in four groups of fire tests (idle pallets, auto part rack storage, polyurethane foam, and plastic commodities evaluation) was completed for evidence of frequency of sprinkler 'skipping.' The tests were $2 \times 2 \times 3$ high or 4 high pallet loads of various plastic goods. The pile dimensions were all limited to $2.44 \times 2.44 \times 4.575\,m^3$ high ($8 \times 8 \times 15\ ft^3$ high) so there were no differences in fire travel. The six most severe fires shared the characteristic that four sprinklers directly over the pile were actuated first and that most or all of the twelve sprinklers in the next surrounding ring were skipped. In these tests, the skipping phenomenon is common and occurs with both 12.7 and 13.5 mm (1/2 and 17/32 in.) sprinklers.

[3]:

A detailed analysis of the results of two rack storage fire tests was reported. Both the tests were conducted using $3.05 \times 3.05\,m^2$ ($10 \times 10\,ft^2$) spacing, 74°C (165°F) sprinklers and a 0.305 mm/s (0.45 gpm/ft^2) water discharge density. But in one test (No. 68), 12.7 mm (1/2 in.) sprinklers were used under 431 kPa (62.5 psi) and seven heads opened while in the other test (No. 88), 13.5 mm (17/32 in.) sprinklers were used under 221 kPa (32 psi) and 33 heads opened. The analysis shows that the different testing results were caused by sprinkler skipping instead of sprinkler type. A series of calculations were also performed to identify the parametric effects on skipping and the conditions under which skipping would occur for 13.5 mm (17/32 in.) sprinklers with a 74°C (165°F) temperature rating.

[4]:

Further discussions on sprinkler skipping and analysis of a series of fire tests were reported. Numerous parameters affecting the skipping phenomenon, including sprinkler spacing and rating, water discharge density, type of fuel/commodity, fuel arrangement, and ignition location, were identified. It was pointed out that (1) skipping phenomenon may exist since the development of standard sprinkler; (2) loss information on skipping from the field has not been reported; and (3) there are some factors other than the direct water discharge from one sprinkler onto the link of another causing skipping based on the calculations in [3].

[5]:

An analysis of the skipping problem was provided together with its impact on Approval Standard and the necessity of developing a research program to resolve the issue. It was pointed out in the report that the importance, impact, and possible solutions of the skipping problem need to be studied. There are very few field reports on the problem and laboratory testing results still leave some unknowns. Assuming that the direct discharge of water from an opened sprinkler to its adjacent sprinklers is the causative reason of skipping, it is necessary to develop an Approval Standard to evaluation sprinklers. Further research program is suggested if the problem cannot be solved easily through an approval testing procedure.

[6]:

This report provides further discussions about sprinkler skipping based on current knowledge and assessed the possible impact of skipping on fire protection system performance. It was identified that the only consistent prerequisite for skipping thus far was a persistent, high-challenging fire, and both residual and permanent skipping might occur. It was also noted that head skipping had not been identified as a factor in loss experience. The impact of reducing and eliminating skipping might include control of a fire, minimization of water demand, and increase of area demand. Due to skipping, sprinkler spray pattern, close spacing, drop size distribution, and deflector have to be considered in the design of sprinkler systems. Several examples of the fire test experience were given with comments. Finally, it was suggested that (1) sprinkler operating sequence should be a major design consideration; (2) threshold skipping parameters need to be determined; (3) field experience of skipping need to be checked; and

(4) a test program would be valuable to investigate skipping on the sprinkler system performance and water demand.

[10]:

A research facility, termed as 'fire plume simulator,' has been constructed for simulating the convective flow generated by a fire and is described in this report. The simulator consists of six natural gas burners discharging hot gases horizontally toward a common center near the floor of the laboratory; the hot gases rise to form a convective plume and subsequent ceiling jet under the 4.72 m (15.5 ft) high, flat ceiling. It is found that, provided the individual burners are operated at rated capacity, the ensuing plume flow simulates the near-source region of an actual fire reasonably well. In a six-burner mode, a 4572 kW (260,000 Btu/min) fire is simulated while in a three-burner mode, a 2286 kW (130,000 Btu/min) fire is simulated. The ceiling flow resembles the flow generated by a source fuel extending to some 4 m (13 ft) from the ceiling. The facility includes provision for collecting and continuously measuring the flux of sprinkler water penetrating the fire plume to the fire base. Thermocouple instrumentation for the measurement of the ceiling gas temperatures is being continuously expanded.

[12]:

The cooling of the ceiling produced by a sprinkler is an important part of its function. Of equal importance is its ability to deliver water through a buoyant fire plume to the seat of the fire. The relationship between these two parameters is explored both in theory and experiment. For each sprinkler device tested, a unique relationship has been found, which allows both cooling and plume penetration to be predicted for any operating pressure. An increase in ceiling cooling is generally accompanied by a decrease in plume penetration. The report focuses on a comparison of a 16.26 mm (0.64 in.) diameter prototype sprinkler with standard sprinklers having orifices of 9.5, 12.7, and 13.5 mm (3/8, 1/2, and 17/32 in.) diameter.

[13]:

An experimental study of the scaling of drop size with respect to the sprinkler size was conducted. The results show that under typical conditions for sprinklers, the drop size of the spray can be scaled provided the sprinklers are geometrically similar. When these conditions are met, it is found that the drop size in ratio to the sprinkler size varies as the $-1/3$ power of the Weber number. This implies that the median drop size is inversely proportional to the $-1/3$ power of the pressure and directly proportional to the $2/3$ power of the orifice diameter.

[16]:

Ninety-three fire tests were conducted to determine the number of sprinklers operating in the sprinkler systems using 100°C (212°F) sprinklers relative to the number of sprinklers operating in the systems using 74°C (165°F) and 141°C (286°F) sprinklers. Three makes of sprinklers were employed. The fire size, the sprinkler spacing, and the water discharge density were varied to investigate their effect. The test results indicate that for continuously fueled, stationary flammable liquid fires: (1) the number of sprinklers operating in the systems using 100°C (212°F) sprinklers is midway between the number of sprinklers operating in systems using 74°C (165°F) and 141°C (286°F) sprinklers, and (2) the number of sprinklers operating in the sprinkler systems using sprinklers with solder melting points nominally rated at 100°C (212°F), whether the solder melts above or below 100°C (212°F), should be taken to be the same for the purpose of specifying water demands. Five more tests are needed to determine whether conclusion number (1) above holds true for fires on which the sprinkler water has an effect.

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