Sprinkler, Vent, Draft Curtain Interaction - Experiments

Kevin McGrattan
National Institute of Standards and Technology
Gaithersburg, MD 20899, USA

David Sheppard
Underwriters Laboratories, Inc.
333 Pfingsten Road
Northbrook, IL 60062, USA

ABSTRACT

The International Fire Sprinkler, Smoke & Heat Vent, Draft Curtain Fire Test Project organized by the National Fire Protection Research Foundation (NFPRF) brought together a group of industrial sponsors to support and plan a series of large scale tests to study the interaction of sprinklers, roof vents and draft curtains of the type found in large warehouses, manufacturing facilities, and warehouse-like retail stores. Representatives from the sponsoring organizations, the National Institute of Standards and Technology (NIST), and other interested parties planned 39 large scale fire tests that were conducted in the Large Scale Fire Test Facility at Underwriters Laboratories (UL) in Northbrook, Illinois.

KEY WORDS: Draft Curtains, Sprinklers, Vents

INTRODUCTION

There has been a long-standing debate in the fire protection community about the combined use of roof vents, draft curtains (curtain boards) and sprinklers. Numerous studies have been conducted over the past few decades, yet many questions remain about the interaction of these devices. As a result, a coordinated public-private research effort was organized. A group of industrial sponsors was brought together by the National Fire Protection Research Foundation (NFPRF) to support and plan a series of large scale experiments using both a heptane spray burner and cartoned polystyrene cups (Group A plastic) as fire sources. A committee made up of representatives of the sponsoring organizations, the National Institute of Standards and Technology (NIST), and other invited participants was created by the NFPRF to guide the studies. The committee selected one sprinkler, roof vent, draft curtain design for installation in the test facility in order to simulate fire protection systems found in warehouses, warehouse retail stores and manufacturing facilities. The objective of the project was to investigate the effect of roof vents and draft curtains on the time, number, and location of sprinkler activations; and also the effect of sprinklers and draft curtains on the activation time, number, and discharge rates of roof vents.

In all, 39 tests were specified by the committee. All 39 tests were conducted in the Large Scale Fire Test Facility at Underwriters Laboratories (UL) in Northbrook, Illinois. The experiments were divided into three series: an initial set of 22 heptane spray burner tests (Heptane Series I) [1, 2], 12 additional heptane spray burner tests (Heptane Series II) [3, 2], and 5 cartoned plastic commodity tests (Plastic Series) [3, 2]. In addition, fire modeling and supporting laboratory experiments provided by NIST aided in the planning of large scale experiments and in the analysis of the data. This effort will be described in another paper.

TEST DESCRIPTION

The Large Scale Fire Test Facility at UL contains a 37 m by 37 m (120 ft by 120 ft) main fire test cell, equipped with a 30.5 m by 30.5 m (100 ft by 100 ft) adjustable height ceiling. The height of the ceiling may be adjusted by four hydraulic rams up to a maximum height of 14.6 m (48 ft). A flexible design sprinkler piping system was available at the ceiling to permit any arrangement of sprinkler spacing with minimum pressure losses. The exhaust flow rate in the test facility could be adjusted from a minimum rate of 11 m^3/s (24,000 ft^3/min) to a maximum of 28 m^3/s (60,000 ft^3/min). Four 1.5 m (5 ft) diameter inlet ducts provided make up air and were located at the walls 3 m (10 ft) above the test floor to minimize any induced drafts during the tests. The combustion products from the fire tests were exhausted through a regenerative smoke abatement system. During the heptane spray burner tests, the exhaust was maintained at the minimum operating rate; during the cartoned plastic commodity tests, the exhaust was maintained at the maximum to draw as much of the smoke from the plenum space as possible to delay the descent of the layer below the adjustable height ceiling.

The layout of the first series of heptane spray burner tests is shown in Fig. 1. One 1.2 m by 2.4 m (4 ft by 8 ft) vent (denoted by a rectangle) was installed among 49 upright sprinklers (small dots) with 3 m by 3 m (10 ft by 10 ft) spacing. The ceiling was raised to a height of 7.6 m (25 ft) and instrumented with thermocouples and other measurement devices. The ceiling was constructed of 0.6 m by 1.2 m by 1.6 cm (2 ft by 4 ft by 5/8 in) UL fire rated ceiling tiles, suspended from 3.8 cm (1.5 in) wide steel angle brackets. The layout for the second series of heptane burner tests and the cartoned plastic tests is shown in Fig. 2. For these tests, the ceiling height was 8.2 m (27 ft), and there were 5 vents.

Draft curtains (denoted by dashed lines in Figs. 1 and 2) 1.8 m (6 ft) deep were installed for 16 of the 22 tests in Heptane Series I, all of the tests in Heptane Series II, and 3 out of 5 tests in the Plastic Series. The curtains were constructed of 1.4 m (54 in) wide sheets of 18 gauge sheet metal. The seams in the draft curtains were connected with aluminum tape. The area of the largest quadrant in Fig. 2 was selected to provide a larger vent to floor ratio (1:42) than called for by the Uniform Fire Code (1:50 for up to 6.1 m (20 ft) of storage height and less then 560 m^2 (6000 ft^2) of curtained area) [4].

The sprinklers used in all the tests were Central ELO-231 (Extra Large Orifice) uprights. The orifice diameter of this sprinkler was reported by the manufacturer to be nominally 16 mm

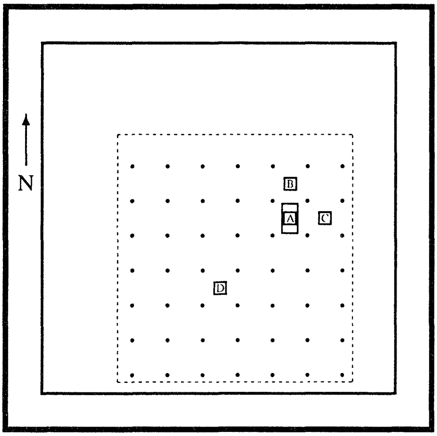

FIGURE 1: Plan view of heptane spray burner configuration, Series I.

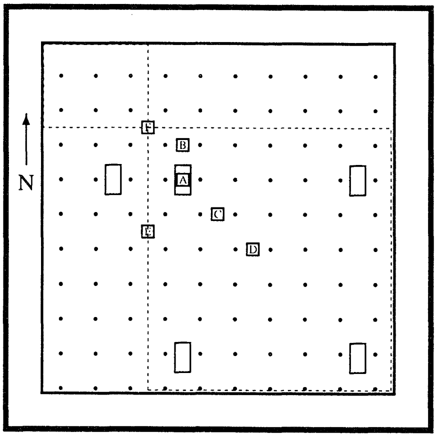

FIGURE 2: Plan view of heptane spray burner configuration, Series II.

(0.64 in), the reference actuation temperature was reported by the manufacturer to be 74°C (165°F). The RTI (Response Time Index) and C-factor (Conductivity factor)[1] were reported by UL to be 148 $(m{\cdot}s)^{\frac{1}{2}}$ (268 $(ft{\cdot}s)^{\frac{1}{2}}$) and 0.7 $(m/s)^{\frac{1}{2}}$ (1.3 $(ft/s)^{\frac{1}{2}}$), respectively [1]. When installed, the sprinkler deflector was located 8 cm (3 in) below the ceiling. The thermal element of the sprinkler was located 11 cm (4.25 in) below the ceiling. The sprinklers were installed with 3 m by 3 m (10 ft by 10 ft) spacing in a system designed to deliver a constant 0.34 $L/(s{\cdot}m^2)$ (0.50 gpm/ft^2) discharge density when supplied by a 131 kPa (19 psi) discharge pressure.

UL-listed double leaf fire vents with steel covers and steel curbs were installed in the adjustable height ceiling in the positions shown in Figs. 1 and 2. The vent design was selected in collaboration with the NFPRF Technical Advisory Committee who sponsored the large scale tests. The vent doors were recessed into the ceiling 0.3 m (1 ft). The vents were designed to open manually or automatically. In tests where automatic operation of the vents was desired, UL-listed fusible links rated at either 74°C (165°F) or 100°C (212°F) were installed. In most tests, the 74°C link was used. To determine the thermal response properties of the fusible link, a plunge tunnel test was performed at NIST on a representative link assembly that consisted of a fusible link rated at 74°C bolted to a steel tab that was welded to a steel support bar [6]. The interval between the time when the link reached its activation temperature and the time when it fused was significant, suggesting that a one parameter model of link activation may not suffice to fully characterize the thermal response of the link. However, for the present study, an effective RTI for the link assembly based on the fusing time was calculated to be between 167 and 180 $(m{\cdot}s)^{\frac{1}{2}}$ (302 and 326 $(ft{\cdot}s)^{\frac{1}{2}}$).

The heptane spray burner consisted of a 1 m by 1 m (40 in by 40 in) square of 12 mm (0.5 in) pipe supported by four cement blocks 0.6 m (2 ft) off the floor. Atomizing spray nozzles were used to provide a free spray of heptane that was then ignited. The total heat release rate from the fire was controlled manually following a the curve $\dot{Q} = \alpha t^2$ with $\alpha = 1.78$ kW/s^2. The

[1]See Ref. [5] for a description of RTI and C-factor.

fire growth rate was intended to approximate the estimated growth rate of the cartoned plastic commodity burns conducted at FMRC [7]. The fire growth curve was followed until a specified fire size was reached or the first sprinkler activated. After either of these events, the fire size was maintained at that level, consistent with a control-mode sprinkler system. The heat release rate from the burner was confirmed by placing it under the large product calorimeter at UL, ramping up the flow of heptane in the same manner as in the tests, and measuring the total and convective heat release rates. It was found that the convective heat release rate was 0.65 ± 0.02 of the total.

The Factory Mutual Research Corporation (FMRC) Standard Plastic test commodity, a Cartoned Group A Unexpanded Plastic, served as the fuel for the cartoned plastic commodity series. This commodity has been used extensively for testing since 1971 [7]. It consisted of rigid crystalline polystyrene cups (empty, 0.47 L (16 fl oz) size) packaged in compartmented, single-wall, corrugated paper cartons. The cups were arranged open end down in five layers, 25 per layer for a total of 125 per carton. Each carton, or box, was a cube 0.53 m (21 in) on a side. Eight boxes comprised a pallet load. Two-way, 1.06 m by 1.06 m by 0.13 m (42 in by 42 in by 5 in) slatted deck hardwood pallets supported the loads. A pallet load weighed approximately 80 kg (170 lb), of which about 36% was plastic, 35% was wood and 29% was corrugated paper [7]. A Class II commodity was used in the target arrays beyond the expected area of the fire spread. This commodity consisted of double tri-wall corrugated paper cartons with five-sided steel stiffeners inserted for stability. The two cartons plus the liner formed a single 1.06 m (42 in) cube having a combined nominal wall thickness of 2.5 cm (1 in).

The layouts for the cartoned plastic commodity tests are shown in Figs. 3–6. Each storage array (denoted by gridded rectangles) consisted of a main (ignition) double-row rack at the center, flanked on two sides by single row target racks. The rows were separated by 2.4 m (8 ft) wide aisles. Each of the two rows of the main array consisted of four 2.4 m (8 ft) long bays; a 0.15 m (6 in) flue separated the rows. Longitudinal flues of 0.2 m (7.5 in) were used to separate the pallets within a row. The overall loaded area of the double-row rack measured approximately 2.3 m (7.5 ft) wide by 10 m (33 ft) long. The racks were divided vertically into 4 tiers; the overall loaded height was 5.8 m (19 ft). A similar configuration was used in a series of FMRC burns documented in Ref. [7]. The fire was ignited with 2 standard igniters which consisted of 8 cm (3 in) long by 8 cm diameter cylinders of rolled cotton material, each soaked in 120 mL (4 oz) of gasoline and enclosed in a polyethylene bag. The rolls were placed just above the pallet against the carton surfaces in the first tier of the main array, halfway down the transverse flue. The igniters were lit with a flaming propane torch at the start of each test.

Type K 1.6 mm (0.0625 in) diameter sheathed thermocouples were used to measure (i) temperatures near the sprinklers, (ii) temperatures of the ceiling jet, and (iii) temperatures near the vent. All thermocouple measurements were collected electronically at a 2 s scan rate. In the second series of heptane spray burner tests and in the cartoned plastic commodity tests, three calibrated brass disks with different thermal responses, plus a 1.6 mm (0.0625 in) sheathed type K thermocouple, were installed within the vent cavity near the fusible link. The RTI values of the disks were determined from plunge tests at UL [3]. The values were reported to be 32, 164 and 287 $(\mathrm{m{\cdot}s})^{\frac{1}{2}}$ (58, 297 and 519 $(\mathrm{ft{\cdot}s})^{\frac{1}{2}}$) for the "fast", "medium" and "slow" disks, respectively [3]. The measurements of each ranged between -10% and +10% of the reported

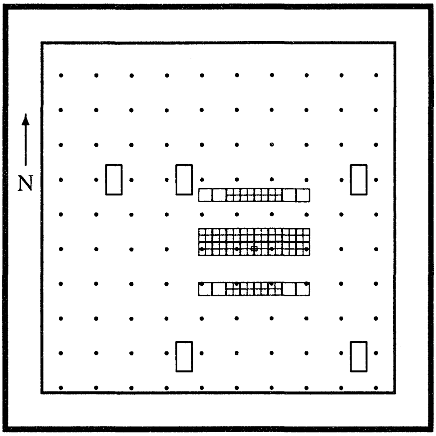

FIGURE 3: Layout of Plastic Test P-1.

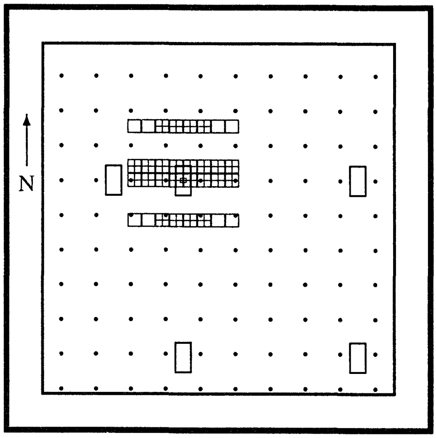

FIGURE 4: Layout of Plastic Test P-2.

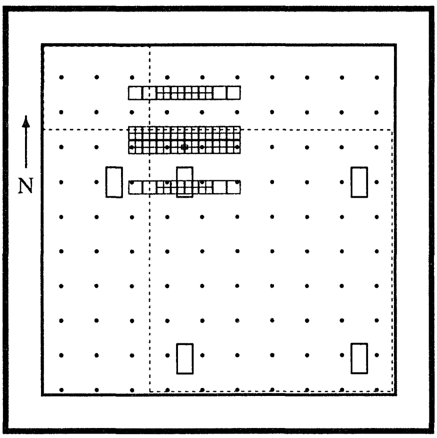

FIGURE 5: Layout of Plastic Test P-3.

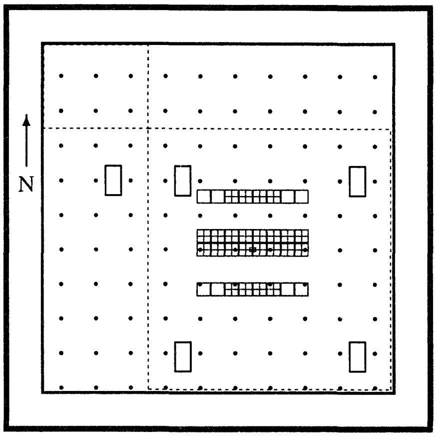

FIGURE 6: Layout of Plastic Tests P-4 and P-5.

value.

DISCUSSION OF EXPERIMENTAL RESULTS

In this section, the results of the experiments will be discussed with an emphasis on how roof vents and draft curtains affect the time, number and location of sprinkler activations; and how sprinklers and draft curtains affect the time, number and discharge rates of roof vents. To facilitate the discussion, a summary of the 39 large scale experiments is presented in Table 1.

Effect of Vents and Draft Curtains on Sprinkler Activation Times

When the fire was not ignited directly underneath a vent, the activation times of the nearest sprinklers to the fire were not affected by the opening of vents either prior to or after the first sprinkler activation. When the fire was ignited 3 m (10 ft) from the vent center, the only discernible affect of the vent opening on sprinkler activation was for those sprinklers immediately downstream of the vent.

In tests where the fire was ignited directly beneath a vent, vent openings prior to the activation of the nearest sprinklers had an effect on the sprinkler activation times. The earlier the vent opening, the more noticeable the effect. For example, in Tests I-12, I-13, I-14 and I-15 where the fire was positioned directly under the vent and the draft curtains were installed, the average sprinkler activation time of the nearest four sprinklers was 1:13 when the vent was held closed (Test I-12), 1:29 when the vent opened automatically at 1:04 (Test I-13), 1:58 when the vent was opened manually at 0:40 (Test I-14), and 1:08 when the vent was opened manually at 1:30 (Test I-15). This data suggests that the earlier the vent activation, the longer the delay in activation of the first ring of sprinklers.

Test I-16 was performed with a different fire growth curve, and cannot be directly compared with any other test. In that test, the first sprinkler activated at the same time that the vent opened (1:46), followed by the next two sprinklers at 2:06 and 2:08. One of the four sprinklers nearest the fire did not activate at all. The temperature near this sprinkler was 140°C (284°F) at the time of the vent opening, but it decreased to about 80°C (176°F) over the next few minutes.

During the second series of heptane spray burner tests, two tests were performed with the burner directly under a vent. In Test II-7, where the vent was held closed, the average activation times of the nearest two sprinklers was 1:14 and the nearest six 1:24. In Test II-3, where the vent opened automatically at 1:15, the average of the nearest two sprinklers was 1:17 and the nearest six 1:32.

Effect of Vents and Draft Curtains on Number of Sprinkler Activations

In general, draft curtains increased the number of sprinkler activations. Inspection of Table 1 indicates that in Tests I-1 and I-8 there were 11 activations when the draft curtains were installed and the vent was closed, and in Test I-17 there were 4 activations when the curtains were not installed and the vent was closed. Tests I-4 and I-7 both had 10 activations with the curtains installed and the vent closed, Tests I-18 and I-21 had 4 and 10 activations with the curtains removed. Tests I-9 and I-10 had 12 and 13 activations with curtains installed, Test

Summary of Sprinkler, Smoke&Heat Vent, Draft Curtain Project Experiments

Test	Fire Location		Fire Size	Draft	Vent	Sprinklers			Avg. Peak Temp.		# Boxes
No.	Pos.	Rel. to Vent	MW @ s	Curtains	Operation	First	Last	Tot.	°C	°F	Consumed
I-12	A	Under	4.4 @ 50	Yes	Closed	1:08	7:24	14	111.0	231.8	
I-13	A	Under	6.0 @ 60	Yes	74°C link (1:04)	1:09	2:53	5	96.2	205.2	
I-14	A	Under	5.8 @ 60	Yes	Manual (0:40)	1:14	7:48	7	95.2	203.4	
I-15	A	Under	5.8 @ 60	Yes	Manual (1:30)	1:04	2:08	5	113.8	236.9	
I-16	A	Under	5.0 @ 110	Yes	74°C link (1:46)	1:46	2:16	4	87.7	189.9	
I-19	A	Under	4.6 @ 50	No	100°C link (10:00)	0:56	9:43	10	84.4	183.8	
I-20	A	Under	4.2 @ 50	No	74°C link (1:20)	0:54	3:16	4	75.8	168.5	
II-3	A	Under	10 @ 75	Yes	74°C link (1:15)	1:08	4:00	12	101.8	215.2	
II-7	A	Under	10 @ 75	Yes	Closed	1:09	4:11	18	117.2	243.0	
P-2	A	Under	Plastic	No	74°C link (DNO)	1:40	5:37	23	85.8	185.9	127
I-1	B	3.05 m (10 ft) N	4.4 @ 50	Yes	Closed	1:05	3:29	11	110.9	231.6	
I-8	B	3.05 m (10 ft) N	4.4 @ 50	Yes	74°C link (9:26)	1:00	6:01	11	99.7	211.4	
I-2	B	3.05 m (10 ft) N	4.4 @ 50	Yes	Manual (0:40)	1:06	4:08	12	105.9	222.7	
I-3	B	3.05 m (10 ft) N	4.4 @ 50	Yes	Manual (1:30)	1:04	6:02	12	109.2	228.5	
I-17	B	3.05 m (10 ft) N	4.6 @ 50	No	100°C link (DNO)	0:58	1:20	4	81.2	178.1	
II-4	B	3.05 m (10 ft) N	10 @ 75	Yes	74°C link (1:48)	1:03	5:54	16	108.8	227.8	
II-8	B	3.05 m (10 ft) N	10 @ 75	Yes	74°C link (1:12)	1:10	3:34	13	107.7	225.9	
P-3	B	3.05 m (10 ft) N	Plastic	Yes	74°C link (4:11)	1:07	16:06	19	90.5	194.9	184
I-4	C	3.05 m (10 ft) E	4.4 @ 50	Yes	Closed	1:00	3:44	10	109.6	229.3	
I-7	C	3.05 m (10 ft) E	4.4 @ 50	Yes	74°C link (DNO)	1:10	3:52	10	107.3	225.1	
I-5	C	3.05 m (10 ft) E	4.4 @ 50	Yes	Manual (0:40)	1:12	6:47	9	98.9	210.0	
I-6	C	3.05 m (10 ft) E	4.4 @ 50	Yes	Manual (1:30)	1:02	2:50	8	105.2	221.4	
I-18	C	3.05 m (10 ft) E	3.7 @ 50	No	100°C link (DNO)	0:58	1:18	4	70.9	159.7	
I-21	C	3.05 m (10 ft) E	4.6 @ 50	No	74°C link (7:00)	0:58	4:06	10	85.6	186.1	
II-11	C	3.05 m (10 ft) E, 3.05 m (10 ft) S	10 @ 75	Yes	74°C link (DNO)	1:02	3:56	23	123.4	254.1	
II-12	C	3.05 m (10 ft) E, 3.05 m (10 ft) S	10 @ 75	Yes	Manual (0:00)	0:58	4:55	23	119.0	246.2	
I-9	D	6.10 m (20 ft) W, 6.10 m (20 ft) S	4.4 @ 50	Yes	74°C link (DNO)	1:10	11:15	12	108.7	227.7	
I-10	D	6.10 m (20 ft) W, 6.10 m (20 ft) S	4.4 @ 50	Yes	Manual (0:40)	1:12	6:52	13	107.5	225.5	
I-11	D	6.10 m (20 ft) W, 6.10 m (20 ft) S	4.4 @ 50	Yes	74°C link (4:48)	N/A	N/A	N/A	184.9	364.9	
I-22	D	6.10 m (20 ft) W, 6.10 m (20 ft) S	4.6 @ 50	No	100°C link (DNO)	1:00	4:25	6	88.7	191.7	
II-1	D	6.10 m (20 ft) E, 6.10 m (20 ft) S	10 @ 75	Yes	74°C link (DNO)	1:15	6:13	27	129.4	264.9	
II-5	D	6.10 m (20 ft) E, 6.10 m (20 ft) S	10 @ 75	Yes	74°C link (DNO)	1:10	7:07	28 .	130.0	266.0	
II-2	D	6.10 m (20 ft) E, 6.10 m (20 ft) S	10 @ 75	Yes	Manual (0:00)	1:05	5:53	28	128.8	263.8	
II-6	D	6.10 m (20 ft) E, 6.10 m (20 ft) S	10 @ 75	Yes	Manual (0:00)	1:10	5:21	27	127.5	261.5	
P-1	D	6.10 m (20 ft) E, 6.10 m (20 ft) S	Plastic	No	74°C link (DNO)	1:16	13:41	20	93.8	200.8	117
P-4	D	6.10 m (20 ft) E, 6.10 m (20 ft) S	Plastic	Yes	74°C link (DNO)	1:33	2:40	5	82.6	180.7	103
P-5	D	6.10 m (20 ft) E, 6.10 m (20 ft) S	Plastic	Yes	Manual (1:14)	1:14	5:04	7	83.3	181.9	81
II-9	E	3.05 m (10 ft) W, 4.57 m (15 ft) S	10 @ 75	Yes	74°C link (DNO)	1:07	3:28	23	115.8	240.4	
II-10	F	3.05 m (10 ft) W, 4.57 m (15 ft) N	10 @ 75	Yes	74°C link (3:20)	1:14	3:01	19	108.4	227.1	

TABLE 1: Summary of Experiments. Test Nos. I-*n* and II-*n* refer to the heptane spray burner tests, P-*n* to the Plastic tests.

I-22 had 6 activations with the curtains removed. This data indicates that in tests performed with draft curtains where the fire was not directly beneath a vent, there were up to twice as many sprinkler activations compared to tests performed without draft curtains.

The reason for the increased number of activations is that draft curtains lead to an increase of the near-ceiling gas temperatures. Consider, for example, the peak gas temperatures near the second ring sprinklers in Test I-1 compared to those of Test I-17. The temperatures were between 20°C and 30°C (36°F and 54°F) lower in Test I-17. Similar differences can be seen when comparing temperatures in Tests I-1 through I-16 with those in Tests I-17 through I-22. The difference between temperatures in the curtained and uncurtained tests can be explained by considering a fire plume impinging on a well-developed, 1.8 m (6 ft) deep smoke layer as opposed to a thinner layer. In the latter case, the plume can entrain more cool air before it reaches the ceiling layer, and therefore the smoke is cooler by the time it reaches the ceiling. Plus, the deeper smoke layer formed by the draft curtains insulates the sprinklers from cooler air below the layer, leading to more activations.

What effect did the vents have on the number of activations? When the fire was ignited directly under a vent (Position A), the number of activations was reduced. Consider Test I-12 versus Tests I-13, I-14, I-15 and I-16. The number of activations was roughly halved due to the opening of the vent directly above the fire. Tests II-3 and II-7 show the number of activations reduced from 18 to 12. However, when the fire was not ignited under a vent, there was either a small decrease or no decrease at all in the number of sprinkler activations. Tests I-1 and I-8 compared with Tests I-2 and I-3 showed no reduction in the number of activations when the fire was ignited 3 m (10 ft) north of the vent. Tests I-4 and I-7 compared to Tests I-5 and I-6 showed a reduction of 1 and 2 sprinklers from 10. Tests II-11 and II-12 showed no reduction at all. Tests I-9 and I-10, as well as Tests II-1, II-5, II-2 and II-6 showed no reduction either. Thus, unless the ignition took place under or very near a vent, there was no evidence in this data set that venting reduced the number of sprinkler activations.

To see why vents had little effect on the number of sprinkler activations, consider the average peak temperatures in the curtained area in Tests II-1, II-2, II-5, II-6, II-11 and II-12. In Tests II-1 and II-5 where the fire was located at Position D and no vents operated, the average peak temperatures were 129.4°C and 130.0°C, respectively. In Tests II-2 and II-6 where the fires were at Position D but all the vents were opened at the start of the tests, the average peak temperatures were 128.8°C and 127.5°C, respectively. Similarly, in Test II-11 where the fire was at Position C and the vent did not operate, the average peak temperature was 123.4°C, whereas in Test II-12, where all the vents were opened at the start, the temperature was 119.0°C.

Effect of Vents and Draft Curtains on Sprinkler Discharge Pattern

In the cartoned plastic commodity Test P-3, the draft curtain to the north of the ignition point delayed the operation of sprinklers further north and blocked the spray of sprinklers on either side of it. In this test, the fuel array extended beneath the north and west curtains. The fire spread to the north side of the main array because the commodity there was unwetted due to a delay in sprinkler activation on the north side of the curtain and blockage of the sprinkler spray from the south side. The results of Test P-3 reinforced evidence provided by two similar[2]

[2]The tests performed at FMRC involved slatted wood shelving, a slightly different rack configuration, and

tests performed by Factory Mutual [7]. In the FMRC tests, the fires spread underneath the curtains, resulting in the development of a more severe fire, a greater number of sprinkler operations, an atypical sprinkler opening pattern, distorted sprinkler discharge patterns which affected prewetting of commodity, and more smoke production. Although the fire damage and number of sprinkler activations in Test P-3 were not as great as that seen in the tests performed at FMRC, the fire damage was substantially higher in this test than in any other test performed in the series, even though the first two sprinkler activations were relatively early (67 and 72 s). This early activation was most likely due to the close proximity of the fire to the intersection of the draft curtains. However, the early jump on the fire did not lead to a rapid decrease in temperatures or sprinkler activations as was the case in Tests P-4 and P-5, the other two tests performed with draft curtains installed. Instead, the fire spread to the unprotected north face of the central array; and even though it was eventually controlled by sprinklers on the north side of the east-west curtain, it ultimately consumed approximately 184 boxes, nearly twice as much as Tests P-4 and P-5. A vent did automatically activate at 4:11, but by that time the two sprinklers on each side of it had already activated. Based on an examination of the the sprinkler activation pattern and the thermocouple data, the opening of the vent had no influence on the test results.

Effect of Sprinklers on the Number and Time of Vent Activations

Based on the test data collected in this study, it is difficult to assess how, in general, sprinklers affect the activation of vents because (1) there is little information about how the vents would have operated in an unsprinklered facility because only one test was performed without sprinklers, and (2) only one vent design was used in the test program. However, it appears from the data below that the sprinkler spray influenced the thermal response characteristics of this particular vent, and it is believed that sprinklers could have a similar influence on comparable vent designs.

In the one unsprinklered test of the study (Test I-11), the vent opened at 4:48. The heptane spray burner was 8.6 m (28 ft) from the vent center. Six other sprinklered tests were performed with the fire at this distance from the vent when the vent was equipped with a fusible link, and in none of these tests did the vent open. In the unsprinklered Test I-11, the temperature near the vent was about 170°C (338°F), whereas in Test I-10, with the fire at the same location, the temperature near the vent was about 90°C (194°F) after the sprinklers had activated around the fire. Examination of the near-ceiling temperatures from all the tests indicates that sprinklers of this type have a significant cooling effect that alters the response of the thermally-responsive, independently-controlled vents.

To better understand the thermal environment in the vicinity of the vent's fusible link, a thermocouple and three calibrated brass disks were placed near the link of the vent located at the northwest corner of the curtained area during the second series of heptane spray burner tests. In Tests II-3 and II-4, when the vent opened automatically, the temperature of the "medium" and "slow" disks rose above the rated temperature of the link (74°C, 165°F) at about the same time that the vent opened. In Test II-8, the vent opened about 10 s before the "medium" disk temperature reached 74°C, and 30 s before the "slow" disk temperature reached 74°C. In Tests II-9 and II-11, where the vent did not open, the temperatures recorded by the "medium" and

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different sprinkler spacing and flow rate.

"slow" disks were comparable to those recorded by the disks in Tests II-3, II-4 and II-8.

In Plastic Test P-2, the fire was ignited directly under a vent. In the experiment, flames reached the top of the central array at about 65 s and the vent cavity at about 70 s. The first sprinkler activated at 100 s. The vent did not open at any time during the 30 min test even though another vent 6 m (20 ft) to the west of the unopened vent opened at 6:04. The temperature histories of the brass disks within the cavity of the unopened vent are given by Fig. 7. After the test, the

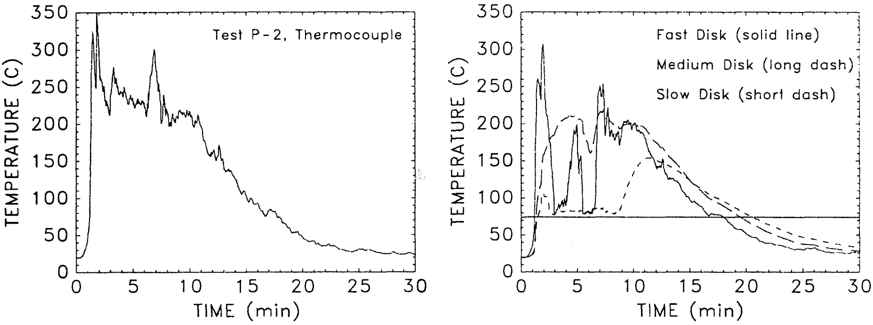

FIGURE 7: Temperatures inside the instrumented vent cavity during Plastic Test P-2. The curve on the left displays the temperature of the thermocouple near the fusible link. The curve on the right displays the temperature of the brass disks. The horizontal line on the right plot indicates the rated temperature of the fusible link.

fusible link was examined, and it was observed that the solder holding the two strips of metal together had begun to melt. This observation had been made when examining the links after several of the heptane spray burner tests, as well.

This data, along with the plunge tunnel measurements reported above suggests that the fusible link reached its activation temperature before or at about the same time as the the first sprinkler activated, but the link did not fuse. It is not clear whether the link did not fuse because it was cooled directly by water drawn upwards into the vent cavity, or whether the sprinkler spray simply cooled the rising smoke plume enough to prevent the link from fusing. In any event, this phenomenon requires further study.

Effect of Sprinklers on the Discharge Rate of Vents

The cooling of the near-ceiling gases due to the operation of sprinklers will affect the rate of discharge through a vent. To measure the flow of gases through a vent, a velocity probe and thermocouples were positioned in the vent nearest the fire location in the second series of heptane burner tests and the cartoned plastic commodity tests. Unfortunately, the velocity data was deemed unreliable, thus there was no means to directly measure the discharge rate. Instead, the numerical model was used to examine the effect of sprinklers on the discharge rate of vents, and this issue will be taken up in a separate paper.

An indirect effect of sprinklers on vent performance is that sprinkler sprays entrain smoke and hot gases, cool them, and transport them towards the floor. No measurements were made during the tests to quantify this phenomenon, but visual observations were made by the authors to determine what areas of the test space filled with smoke during the first 5 or 10 minutes of the cartoned plastic commodity tests. In Test P-1, earlier and more frequent sprinkler activation occurred to the north of the ignition point, leading to heavier observed smoke logging in the north aisle. In Test P-2 it was less obvious which aisle was more heavily smoke logged. In Test P-3, the south aisle was more smoke logged because sprinklers to the north of the ignition point were delayed by the draft curtains. The curtains also blocked the smoke from the north aisle, at least initially. In Test P-4, the south aisle was more heavily smoke logged; in Test P-5, the north aisle. The sprinkler activation pattern in Tests P-4 and P-5 was consistent with these observations.

CONCLUSIONS

Thirty-four large scale fire tests were conducted at the Underwriters Laboratories Large Scale Fire Test Facility in Northbrook, Illinois, to investigate what effect roof vents and draft curtains have on the time, number and location of sprinkler activations; and what effect sprinklers and draft curtains have on the time, number and discharge rates of roof vents in a warehouse or warehouse-like retail store. The test site and experimental test parameters were chosen by an industry-led Technical Advisory Committee to address relatively large, open-area buildings with smooth, unobstructed (except for draft curtains) horizontal ceilings, adequate sprinkler systems and independently-controlled (*i.e.* not grouped) automatic roof vents. Because the smoke was vented into a large plenum space and not the atmosphere, wind effects were not considered and the effect of venting on smoke obscuration could not be quantified.

The major findings relative to the interaction of sprinklers, draft curtains and vents based on an analysis of the UL experiments in this study were:

- In tests where the fire was not ignited directly under a roof vent, venting had no significant effect on the sprinkler activation times, the number of activated sprinklers, the near-ceiling gas temperatures, or the quantity of combustibles consumed.
- In tests where the fire was ignited directly under a roof vent, automatic vent activation usually occurred at about the same time as the first sprinkler activation, but the average activation time of the first ring of sprinklers was delayed. The length of the delay depended on the difference in activation times between the vent and the first sprinkler.
- In tests where the fire was ignited directly under a roof vent that activated either before or at about the same time as the first sprinkler, the number of sprinkler activations decreased by as much as 50% compared to tests performed with the vent closed.
- In tests where draft curtains were installed, up to twice as many sprinklers activated compared to tests performed without curtains.
- In one rack storage test where the ignition of the fire took place near a draft curtain and the fuel array extended underneath the curtain, disruption of the sprinkler spray and delay in sprinkler operation caused by the draft curtain led to a fire that consumed more commodity compared to the other tests where the fires were ignited away from the draft curtains. This result was demonstrated by the model simulation, as well.

- The significant cooling effect of sprinkler sprays on the near-ceiling gas flow often prevented the automatic operation of the vents. This conclusion is based on thermocouple measurements within the vent cavity, the presence of drips of solder on the fusible links recovered from unopened vents, and several tests where vents remote from the fire and the sprinkler spray activated. In one cartoned plastic commodity experiment, a vent did not open when the fire was ignited directly beneath it.

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