Smoke Movement and Detector Activation in High Bay Spaces

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ABSTRACT

A series of fire experiments were conducted in two aircraft hangars with ceiling heights of 15 m (50 ft) and 22 m (73 ft). The purpose of the experiments was to analyze the activation characteristics of smoke and heat detectors in response to JP-5 and JP-8 pool fires. The 15 m (50 ft) hangar was located in Hawaii, where ambient temperatures were approximately 30°C (86°F). The 15 m (50 ft) experiments used fire sizes that ranged from 100 kW (95 Btu/s) to 7.7 MW (7300 Btu/s). Experiments were conducted with and without draft curtains in the 15 m (50 ft) hangar. The 22 m (73 ft) hangar was located in Iceland, where ambient temperatures were approximately 12°C (54°F). The 22 m (73 ft) experiments used fire sizes that ranged from 100 kW (95 Btu/s) to 33 MW (31000 Btu/s). Draft curtains were present for all the 22 m (73 ft) experiments. Open- and closed-door fire experiments were conducted in both hangars.

Commercial detectors used in the series of experiments included spot smoke and heat detectors, bulb and fusible link elements, projected beam smoke detectors, UV/IR optical flame detectors, and a line-type heat detector. Other instrumentation included thermocouples, mass flow meters, and radiometers.

The analysis of these experiments has led to the following observations:

1. *Draft curtains improved the response time of heat detectors and sprinklers at these ceiling heights and reduced the size of the threshold fire needed for activation. Both the plume centerline temperature and the ceiling jet temperature increased in response to the growing smoke layer.*
2. *Standard response sprinklers were either activated substantially slower or not at all when compared to the activation of quick-response sprinklers at these heights.*
3. *Trouble windows used for beam-type smoke detectors gave false trouble signals in the presence of dense smoke from JP-5 fires.*
4. *Tests conducted in the presence of wind and open hangar doors showed that ceiling jet temperatures were substantially reduced but that downwind smoke detectors continued to activate for small fire sizes. Wind speeds inside the hangar ranged from 2 km/h to 32 km/h (1 mph to 20 mph).*

Based on the observed detector activation, spacing for both spot smoke and heat detectors at these heights was analyzed.

INTRODUCTION

Presently, installation standards for fire detection of buildings exist only for those buildings with ceiling heights of 9 m (30 ft) or less. Based on the results of experiments conducted in 15 m (50 ft) and 22 m (22 ft) high hangars (Gott et al. 1997), detector activation thresholds and detector spacing are analyzed for both smoke and heat detectors. The hangar experiments included small fires designed to investigate the operation of UV/IR detectors and ceiling-mounted spot and projected beam smoke detectors as well as large fires that were used to investigate the operation of ceiling-mounted heat detectors and sprinklers. This paper analyzes only ceiling-mounted detection devices. The hangar experiments were instrumented and included standard fire suppression or detection hardware such as bulb and link operated sprinklers, spot and line-type heat detectors, combination UV/IR detectors,

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and spot and projected beam smoke detectors. Smoke temperature measurements were accomplished using thermocouples.

EXPERIMENTS

Two sites were used to conduct the hangar experiments. The first site was a warm temperature site (≈ 30°C, 86°F) in Hawaii, and the second site was a cool temperature site (≈ 12°C, 54°F) in Iceland.

The hangar in Hawaii measured 97.8 m × 73.8 m (321 ft × 242 ft) in area and had a ceiling height at the center of 15.1 m (49.5 ft). A plan view of the hangar bay is shown in Figure 1. A total of 13 fire experiments were conducted (Table 1). Six of the experiments included a draft curtain 3.7 m (12 ft) deep, which enclosed an area of 18.3 m × 24.4 m (60.0 ft × 80.0 ft). The ceiling height at the center of the draft curtained area was 14.9 m (49 ft).

The hangar roof consists of built-up tar and gravel over a corrugated metal deck. The ceiling slopes from a height of 15.1 m (49.5 ft) at the center toward the east and west walls, which are 13.4 m (44.0 ft) high. The metal deck is directly supported by 0.25 m (10 in) I-beams that run the (N-S) width of the hangar and are spaced 4.1 m (13 ft) on center. The I-beams are supported by open steel trusses that run perpendicular to the beams (E-W) and are spaced 6.1 m (20 ft) on center. These trusses span the full length of the hangar.

Thermocouples were used to measure the ceiling jet temperature at radial distances from a plume center of 1.5 m (4.9 ft), 3.0 m (10 ft), 6.1 m (20 ft), 9.1 m (30 ft), and 11.6 m (38 ft) in the experimental east and west directions and at 1.5 m (4.9 ft), 3.0 m (10 ft), 6.1 m (20 ft), and 8.5 m (28 ft) in the experimental north and south directions. The thermocouples were located 0.31 m (1.0 ft) beneath the ceiling. The r/H value (r is the radial distance from the plume center and H is the height of the ceiling above the fire surface) for the 1.5 m (4.9 ft) thermocouples is 0.1, which means that these thermocouples are in the plume. All the other thermocouples were located outside the plume region.

Four thermocouple trees with thermocouples located at 0.15 m (0.5 ft), 0.3 m (1.0 ft), 0.46 m (1.5 ft), 0.61 m (2.0 ft), and 0.76 m (2.5 ft) beneath the ceiling were located 6.1 m (20 ft) from plume center in the north, south, east, and west directions, while a fifth tree with thermocouples located at 0.15 m (0.5 ft), 0.3 m (1.0 ft), 0.46 m (1.5 ft), 0.76 m (2.5 ft), 1.22 m (4.0 ft), and 3.0 m (10 ft) beneath the ceiling was located at 9.1 m (30. ft) toward experimental east. These thermocouple trees are used to investigate the temperature dependence of the ceiling jet as a function of distance beneath the ceiling.

In the 15 m (50 ft) high facility, nine types of standard spray, upright sprinklers with several different temperature ratings, fusible elements, and response-time indexes were installed and monitored to measure the activation time of each sprinkler when subject to a range of experimental fires. The pipe supplying the sprinkler was filled with water to simulate the heat sink associated with a wet-pipe sprinkler configuration. The water was not pressurized and, hence, only a negligible amount of water would be released when the sprinkler was activated. In addition, several sections of piping were used within the individual sprinkler trees to simulate a dry-pipe or pre-action sprinkler system. The sprinkler types and locations with respect to the fire plume are given in Table 2. The sprinkler deflectors were installed approximately 300 mm to 360 mm (1.0 ft to 1.2 ft) below the ceiling deck.

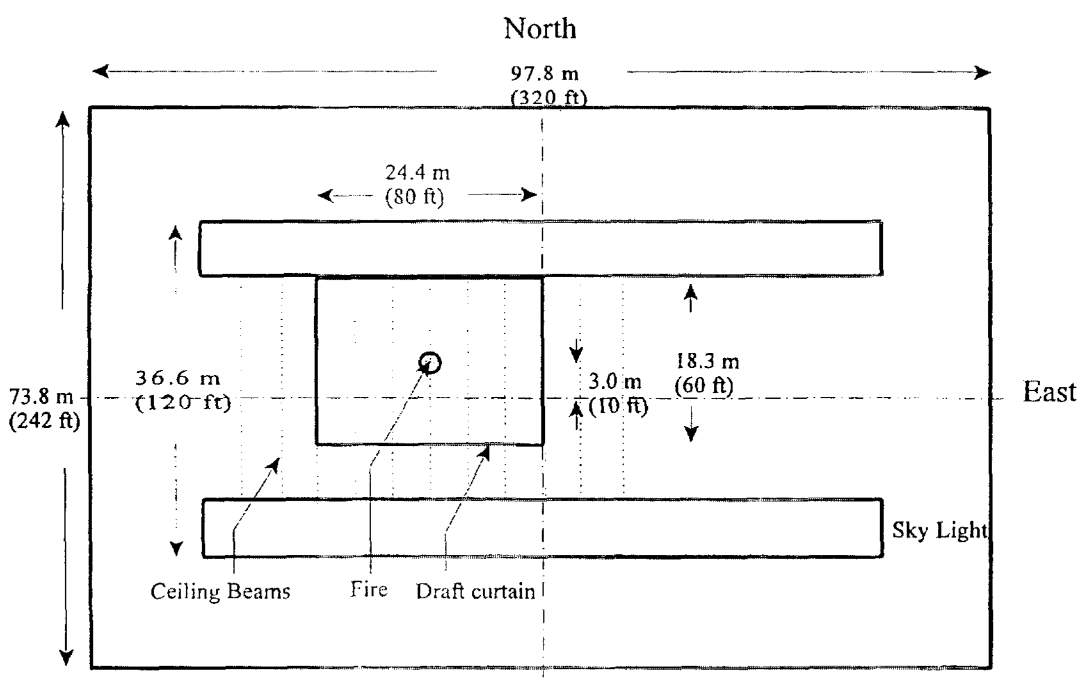

Figure 1 Plan view of 15 m (50 ft) hangar bay.

TABLE 1
Test Summary for 15 m (50 ft) Facility

Test Number	Pan/Crib Size m (ft)	Fire Size (1 ± 10%) MW (1000 Btu/s)	Fuel Type	Sprinkler* Act.†s (Wet Pipe) (QR 79°C)(175 °F)	Smoke Det. Act.†s (P.B.‡/ S.P.**)± 10. s
1	0.3 × 0.3 (1 × 1)	0.1(95)	JP-5	No	75/382.
2	0.6 × 0.6 (2 × 2)	0.5 (470)	JP-5	No	T††/28
3	0.9 × 0.9 (3 × 3)	1.1 (1000)	JP-5	No	T††/37
4	1.5 (4.9) Dia.	3.1 (2900)	JP-5	No	T††/22
5	2.0 (6.6) Dia.	6.8 (6400)	JP-5	192 ±10	T††/29
6	2.5 (8.2) Dia.	7.7 (7300)	JP-5	104 ±10	T††/28
7‡‡	2.0 (6.6) Dia.	5.6 (5300)	JP-5	403 ±10	T††/26
8‡‡	2.5 (8.2) Dia.	7.7 (7300)	JP-5	359 ±10	T††/26
9‡‡	0.6 × 0.6 × 0.6 (2 × 2 × 2)	0.4 (380)	Wood Crib Fir	No	66/52
10‡‡	0.6 × 0.6 × 1.2 (2 × 2 × 4)	0.6 (570)	Wood Crib Fir	No	67/58
11‡‡	0.3 × 0.3 (1 × 1)	0.1 (95)	JP-5	No	73/504
12‡‡	0.6 × 0.6 (2 × 2)	n/a	JP-5	No	T††/50
13***	2.0 (6.6) Dia.	n/a	JP-5	No	T††/38

* The sprinklers were located 3.1 m (10 ft) from plume center.
† Activation times represent the first time that a detector activated at that distance from plume center.
‡ Denotes a projected beam detector with the beam located 0.3 m (1 ft) beneath the ceiling and passing through plume center.
** Denotes a single-point smoke detector located 3.1 m (10 ft) from plume center.
†† Trouble signal.
‡‡ These numbers did not have a draft curtain.
***An open door test.
The term "n/a" stands for not available.

TABLE 2
Sprinkler Locations (x) for the 15 m (50 ft) Hangar*

Distance m (ft) E-W/N-S	79°C (175°F) QR	79°C (175°F) QR dry	79°C (175°F) STD	93°C (200°F) QR	141°C (286°F) QR	141°C (286°F) QR dry	141°C (286°F) STD	141°C (286°F) Link†	182°C (360°F) STD
0.0	x	x	x	x	x	x	x	x	x
3.1(10)	x	x			x	x	x	x	
6.1 (20)	x				x		x	x	
9.1/8.5 (30/28)	x				x				
11.6/OD‡ (38/OD)	x				x				

* All the sprinklers have bulbs.
† No bulb.
‡ Due to the rectangular shape of the draft curtain, 24.4 m × 18.3 m (80 ft × 60 ft), the 11.6 m (38 ft) location in the N-S direction was outside the draft curtain.

Photoelectric smoke detectors and electronic heat detectors were connected to an addressable fire alarm control panel via signaling line circuits wired in the Style 4 configuration (NFPA 1993). The photoelectric smoke detectors were analog addressable, spot type detectors that operate according to the light-scattering principle. These detectors contain a pulsed LED and silicon photodiode receiver arranged so that light does not fall on the receiver. When smoke particles enter the light path, light strikes the particles and is scattered onto the photosensitive receiver, causing the detector to respond. The smoke detector sensitivity threshold was 8.2% per meter (2.5% per foot) of smoke obscuration.

The electronic heat detectors were analog addressable, spot type detectors that were programmed to operate as fixed-temperature heat detectors with an alarm threshold of 57.2°C (135°F). This type of detector employs a nonmetallic thermistor and experiences little thermal lag in its response to changing temperatures.

There were 18 detector stations, each consisting of a smoke detector and a heat detector mounted to a plywood board. The plywood board was suspended from conduit, which was clamped to the underside of the I-beams supporting the metal roof deck. The detectors were installed at the same elevation as the bottom of the beams, 0.25 m (10 in) below the ceiling deck. The detector stations within the draft curtained area were located at distances from the plume center of 3.0 m (10 ft), 6.1 m (20 ft), 9.1 m (30 ft), and 11.6 m (38 ft) in the E-W direction and 3.0 m (10 ft), 6.1 m (20 ft), and 8.5 m (28 ft) in the N-S direction.

Projected beam smoke detection systems are photoelectric smoke detectors that consist of separate transmitters and receivers. The light source in the transmitter produces an infrared beam that is measured by the receiver to determine obscuration caused by smoke. If the beam intensity falls below an alarm threshold and remains there for a preset length of time, a fire alarm is initiated. If complete beam blockage occurs, a trouble output is generated rather than a fire alarm. The receiver will wait a preset length of time after the beam is blocked before giving a trouble signal. Gradual loss of signal due to dust/dirt buildup and other long-term effects is automatically compensated for by the receiver up to a point where the signal has been reduced by 50%. When 50% of the signal is lost, the receiver will give a trouble signal (DSI 1994).

The projected beam smoke detectors were configured to view paths through plume center and 7.0 m (23 ft) on either side of plume center for distances beneath the ceiling of 0.3 m (1 ft), 2.7 m (9 ft), and 5.8 m (19 ft) for tests 1 through 8. The beam lengths were 24.4 m (80.0 ft) with the beams directed perpendicular to the 0.25 m (10 in) deep ceiling I-beams. Tests 1 through 6 had a 3.7 m (12 ft) deep draft curtain in place, which meant that the 5.8 m (19 ft) paths were substantially below the bottom of the draft curtain. Tests 9 through 13 substituted the 5.8 m (19 ft) paths with a single path located 1.8 m (6 ft) beneath the ceiling and passing through plume center.

A total of 21 pan fire experiments were conducted in Iceland. See Table 3 for tests with heat release rate (HRR) less than 3.0 MW (2,800 Btu/s) and Table 4 for tests with HRR greater than 3.0 MW (2,800 Btu/s). The Iceland hangar measured 73.8 m × 45.7 m (242 ft × 150 ft) and had a barrel roof that was 22.3 m (73.1 ft) high at the center and 12.2 m (40.0 ft) high at the walls. Corrugated steel draft curtains were used to divide the ceiling into five equal bays approximately 14.8 m × 45.7 m (48.5 ft × 150 ft), with the fire experiments conducted in the middle bay and centered under the 22.3 m (73 ft) high ceiling. A plan view of the hangar is shown in Figure 2.

TABLE 3
Test Summary for Fire Sizes Smaller than 3 MW (2800 Btu/s) for the 22 m (73 ft) Facility*

Test Number	Pan Size m (ft)	Fire Size (1 ± 10%) MW(1000 Btu/s)	Fuel Type	Sprinkler Act.† s (Wet Pipe) (QR 79°C)(175°F)	Smoke Det. Act.† S (P.B.‡/S.P.**) ± 10. s
1	0.3 × 0.3 (1 × 1)	0.1 (95)	JP-5	No	53/ No
2	0.3 × 0.3 (1 × 1)	0.1 (95)	JP-5	No	60/No
3	0.6 × 0.6 (2 × 2)	0.9 (850)	JP-5	No	36/53.
4	0.6 × 0.6 (2 × 2)	0.8 (760)	JP-5	No	19/51.
5	0.9 × 0.9 (3 × 3)	1.7 (1600)	JP-5	No	25/28.
6	0.9 × 0.9 (3 × 3)	1.4 (1300)	JP-5	No	31/32.
7	1.2 × 1.2 (4 × 4)	2.8 (2700)	JP-5	No	31/36.
8	1.2 × 1.2 (4 × 4)	2.5 (2400)	JP-5	No	27/33.
9	0.3 × 0.3 (1 × 1)	0.1 (95)	JP-8	No	108/No
10	0.6 × 0.6 (2 × 2)	0.6 (570)	JP-8	No	47/150.
11	0.6 × 0.6 (2 × 2)	0.8 (760)	JP-8	No	35/90.
12	0.9 × 0.9 (3 × 3)	1.6 (1500)	JP-8	No	34/45.
13	1.2 × 1.2 (4 × 4)	2.7 (2600)	JP-8	No	37/37.

* The sprinklers were located 3.1 m (10 ft) from plume center.
† Activation times represent the first time that a detector activated at that distance from the fire.
‡ Denotes a projected beam detector with the beam located 1.3 m (4.2 ft) beneath the ceiling and passing through plume center.
** Denotes a single-point smoke detector that was located 3.1 m (10 ft) from plume center.

TABLE 4
Test Summary for Fire Sizes Larger than 3 MW (2800 Btu/s) for the 22 m (73 ft) Facility*

Test Number	Pan Size m (ft)	Fire Size (1 ± 10%) MW (Btu/s)	Fuel Type	Sprinkler Act.† s (Wet Pipe) (QR 79°C)(175°F)	Smoke Det.Act.†s (P.B.‡/S.P.**) ± 10 s
14	2.5 (8.2) Dia	7.9 (7500)	JP-5	361.±10.	38/65.
15	3.0 × 3.0 (10 × 10)	15.7 (14900)	JP-5	119.±10.	33/46.
16‡‡	2.5 (8.2) Dia	7.0 (6600)	JP-5	No	T††/51.
17	3.0 × 3.0 (10 × 10)	14.3 (13600	JP-8	100.±10.	27/30.
18	2.0 (6.6) Dia	4.9 (4600)	JP-5	No	42/49.
19‡‡	2.5 (8.2) Dia	9.1 (8600)	JP-5	No	39/56.
20	3.0 × 3.0 (10 × 10)	14.6 (13800)	JP-5	101.±10.	31/38.
21	4.6 × 4.6 (15 × 15)	33 (31000)	JP-5	87.±10.	30/37.

* The sprinklers were located 3.1 m (10 ft) from plume center.
† Activation times represent the first time that a detector activated at that distance from the fire. Activation times for detectors should include a ±10 s uncertainty in establishing the start time of the experiment.
‡ Denotes a projected beam detector with the beam located 1.3 m (4.3 ft) below the ceiling and passing through plume center.
** Denotes a single-point smoke detector located 3.1 m (10 ft) from plume center.
†† Trouble signal.
‡‡ Open door test.

The primary roof support consisted of a series of steel trusses that form arches spanning the width of the hangar bay, running parallel to the hangar doors. These primary trusses are approximately 1.0 m (3.3 ft) deep and are spaced 7.4 m (23 ft) on center. The primary trusses are interconnected with a series of secondary trusses that are perpendicular to them and run the length of the hangar bay. The secondary trusses are spaced at intervals ranging from 5.8 m (19 ft) to 6.4 m (21 ft) on center. The metal deck roof is directly attached to a series of steel beams that sit on top of the primary and secondary trusses. These steel beams are perpendicular to the primary trusses, are spaced 1.5 m (5 ft) to 2.1 m (7 ft) on center, and vary in height from 0.2 m (8 in) to 0.3 m (12 in).

The roof was insulated via a barrel-shaped suspended tile ceiling that was supported by a conventional suspended tile ceiling grid located at the same elevation as the bottom of the steel beams. The ceiling tiles were removed in the middle bay and the adjacent bays prior to testing.

Experimental east and west were designated to be the directions parallel to the 13.4 m (44.0 ft) draft curtain and pointed along the direction of the barrel roof. Experimental north and south directions ran perpendicular to the draft curtain. Thermocouples located 0.31 m (1.0 ft) beneath the ceiling were at radial distances from the fire center of 3.0 m (10 ft), 4.6 m (15 ft), 6.1 m (20 ft), and 6.7 m (22 ft) in the south direction and 3.0 m (10 ft) and 6.1 m (20 ft) in the north direction. Thermocouples located 0.31 m (1.0 ft) beneath the ceiling were at radial distances from the fire center of 3.0 m (10 ft), 6.1 m (20 ft), 9.1 m (30 ft), 12.2 m (40 ft), 15.2 m (50 ft), and 18.3 m (60 ft). Additional thermocouples were positioned at many of these locations and are represented in Figure 3.

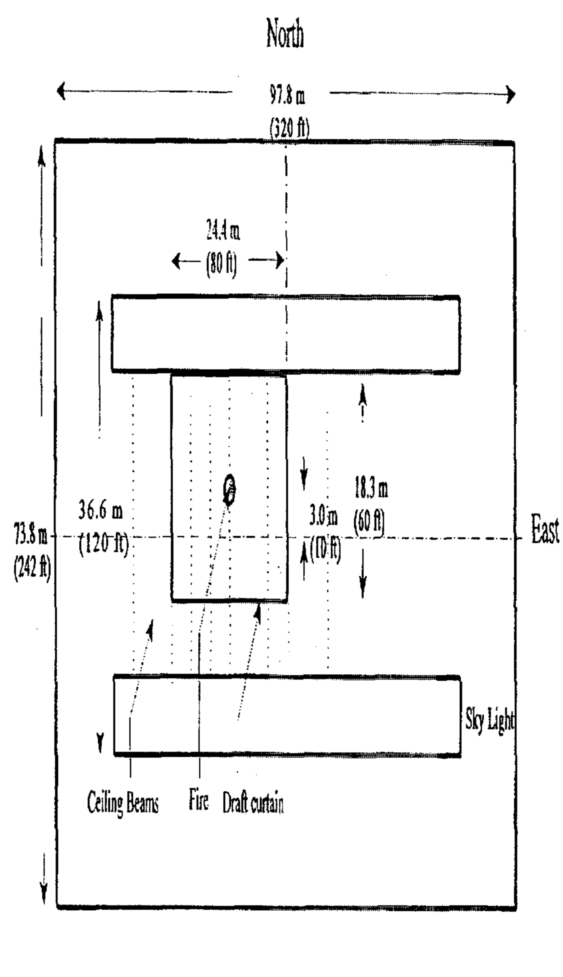

Figure 2 Plan view of 22 m (73 ft) hangar.

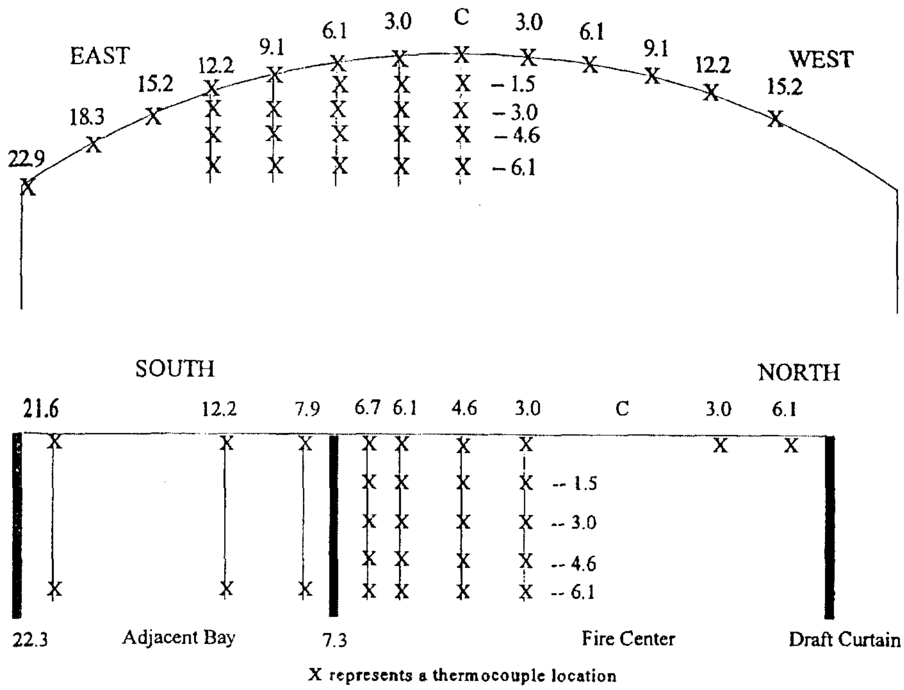

Figure 3 Thermocouple locations (m) for the 22 m (73 ft) hangar.

The same kinds of sprinklers, spot heat and smoke detectors, and projected beam smoke detectors that were used in the 15 m (50 ft) hangar tests were used in the 22 m (73 ft) tests. In addition, conventional hard-wired heat detectors using a thermistor-type sensing element with an alarm threshold of 93.3°C (200°F) were included. The 18 detector stations consisted of a smoke detector and the two types of heat detectors (57°C [135°F] and 93°C [200°F]). These detector stations were located at distances of 3.0 m (10 ft) and 6.1 m (20 ft) from plume center in the north and south directions and 3.0 m (10 ft), 6.1 m (20 ft), 9.1 m (30 ft), 12.2 m (40 ft), 15.2 m (50 ft), and 18.3 m (60 ft) from plume center in the east and west directions along the curved ceiling. The detector stations were located at approximately the same elevation as the sprinklers, which ranged from 0.3 m (1 ft) to 0.6 m (2 ft) below the ceiling deck. The sprinkler locations with respect to plume center are listed in Table 5. Additional details concerning the installation of these detectors are available in Gott et al. (1997).

DETECTION EXPERIMENTS

Heat detectors tested in the hangar experiments included analog addressable spot-type detectors operating as fixed-temperature heat detectors with an alarm threshold of 57.2°C (135°F), a line type heat detector with a response time index (RTI) of 58 $(m/s)^{1/2}$ (105 $[ft/s]^{1/2}$), and fusible elements with activation temperatures of 79°C (175°F), 93°C (200°F),

TABLE 5
Sprinkler Locations (x) for the 22 m (73 ft) Hangar*

Distance m (ft) E-W/N-S	79°C (175°F) QR	79°C 175°F QR dry	79°C 175°F STD	93°C 200°F QR	141°C 286°F QR	141°C 286°F QR dry	141°C 286°F STD	141°C 286°F STD Link	182°C 360°F STD
0.	x	x	x	x	x	x	x	x	x
3.1 (10)	x	x			x	x	x	x	
6.1 (20)	x				x		x	x	
9.1 (30)/OD†	x				x				
12.2 (40)/OD†	x				x				
15.2 (50)/OD†	x				x				

* Each bay had dimensions of 45.7 m × 14.8 m (150 ft × 49 ft).
† Locations outside the draft curtained area.

141°C (286°F), and 182°C (360°F). The fusible elements used were either quick response, 35 $(m/s)^{½}$ (105 $[ft/s]^{½}$), or standard response, 95 $(m/s)^{½}$ (172 $[ft/s]^{½}$) and 188 $(m/s)^{½}$ (340 $[ft/s]^{½}$), links.

Fusible Elements

Threshold fire sizes for the activation of 79°C (175°F) links can be determined using the data presented in Tables 1 and 4. For the 15 m (50 ft) hangar, a fire size of 5.6 MW (5,300 Btu/s) was required to activate a 79°C (175°F) link located 3.0 m (10 ft) from plume center. While this experiment did not have a draft curtain in place, the activation time for the sprinkler was so late that a hot upper layer was beginning to develop in the entire hangar. For the 22 m (73 ft) hangar, a fire size of 7.9 MW (7,500 Btu/s) was required to activate a 79°C (175°F) link located 3.0 m (10 ft) from plume center. In this case, a draft curtain was in place, which caused a hot upper layer to form early in the experiment.

The presence of draft curtains produces a more uniform and higher temperature region within the draft curtain volume (Davis and Notarianni 1998). This results in both the activation of fusible elements with smaller fire sizes and the earlier activation of fusible elements located away from plume center but within the draft curtains. These effects are readily seen in Figure 4 for two 7.7 MW (7,300 Btu/s) fires in the 15 m (50 ft) facility. The fire with draft curtains (3.7 m deep [12 ft]) caused 79°C (175°F) fusible elements to activate several minutes earlier than the fire without draft curtains for distances from the fire center out to 6.1 m (20 ft) and produced activations at 8.5 m (28 ft) and 9.1 m (30 ft), which did not occur for the fire without draft curtains. It should be noted that the fusible links activated in the hangar fire without draft curtains at a time so late that an upper layer was beginning to develop in the entire hangar.

All the experiments conducted in the 22 m (73 ft) hangar had draft curtains present in the direction perpendicular to the curved ceiling. Figure 5 gives the first activation time at each radial position in the direction of the curved ceiling for 79°C (175°F) fusible links. For the threshold fire at 7.9 MW (7,500 Btu/s), fusible links activated only in the plume region ($r/H < 0.2$). Fires of size 14 MW (13,000 Btu/s) to 16 MW (15,000 Btu/s) produced activations requiring less than 200 s for distances up to 6.1 m (20 ft) from plume center, while a 33 MW (31,000 Btu/s) fire activated all the elements out to 12.2 m (40 ft) in less than 200 s. Activation times for fires 14 MW (13,000 Btu/s) or larger were within 60 s of each other for sprinklers, at distances out to 6.1 m (20 ft). The impact of the curved ceiling on detector activation for these fire sizes was unimportant for distances up to 6.1 m (20 ft) from plume center.

The effect of using quick response (QR) sprinklers compared to standard sprinklers (STD) is shown in Figure 6 for four fire tests in the 22 m hangar. Here, three different configurations, a quick response sprinkler with an RTI of 35 $(m\ s)^{1/2}$ (63 $(ft\ s)^{1/2}$) connected to a dry pipe (dry), a second quick response sprinkler with identical RTI connected to a water-filled pipe (wet), and a standard response sprinkler with an RTI of 188 $(m/s)^{½}$ (340 $[ft/s]^{½}$)

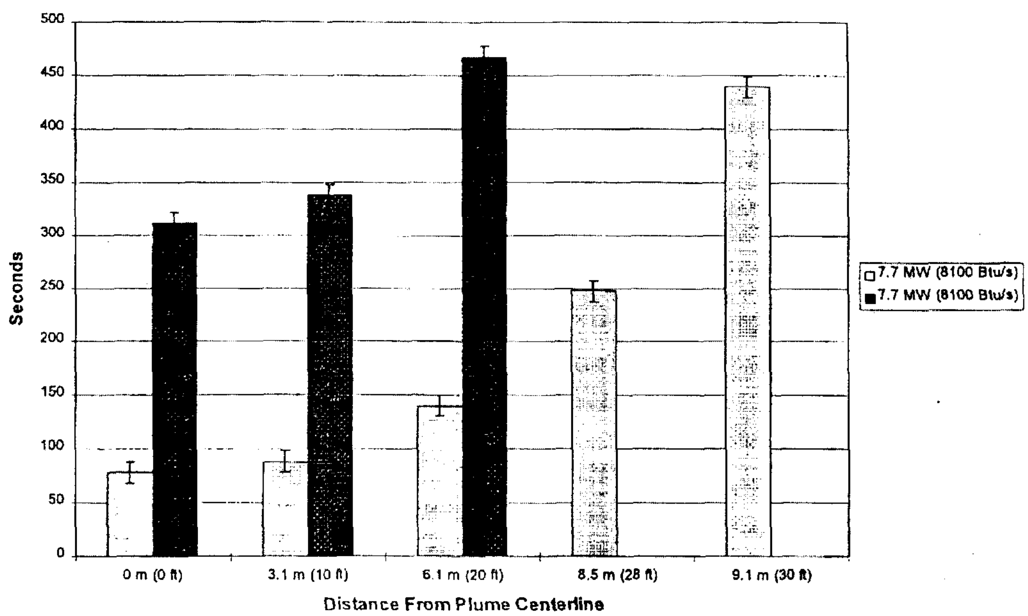

Figure 4 Earliest activation time for a 79°C (175°F) sprinkler bulb at each of the distances shown. The first bar gives the activation in the presence of a draft curtain, while the second bar gives the activation when no draft curtain is present. Both tests were 2.5 m diameter JP-5 pan fires in the 15 m (50 ft) hangar. The ±10 s uncertainty interval represents the uncertainty in the timing for the start of the experiment.

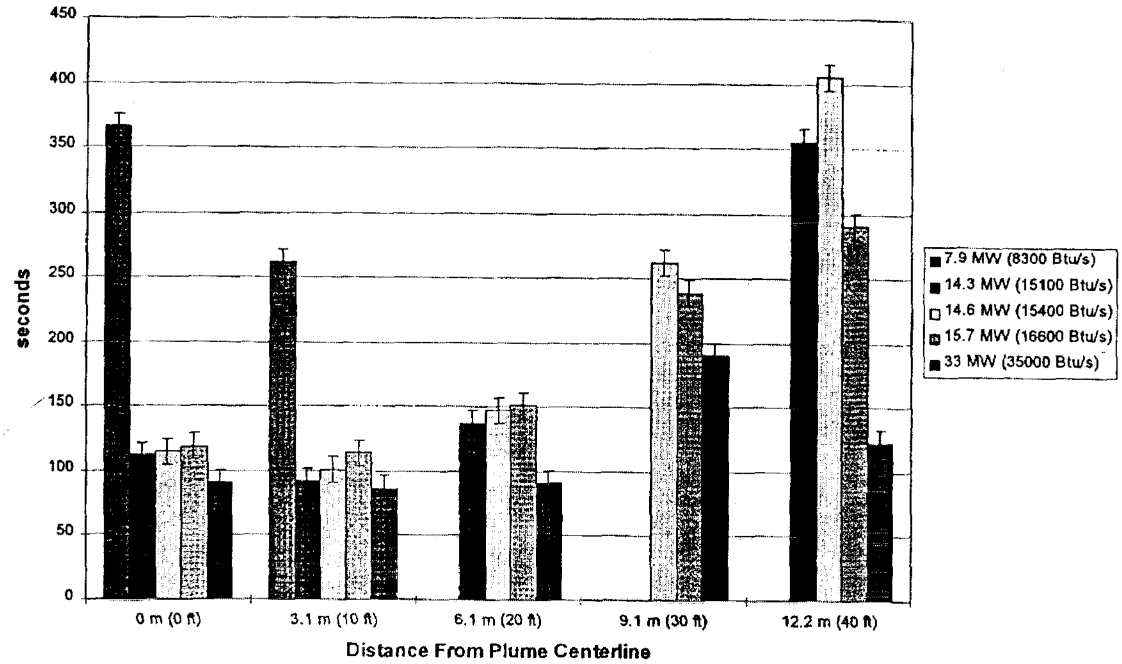

Figure 5 *Earliest activation time of 79°C (175°F) sprinkler bulbs in the 22 m (73 ft) hangar as a function of distance and fire size. The fires are identified by total heat release rate. Uncertainties in these heat release rates are given in Table 4.*

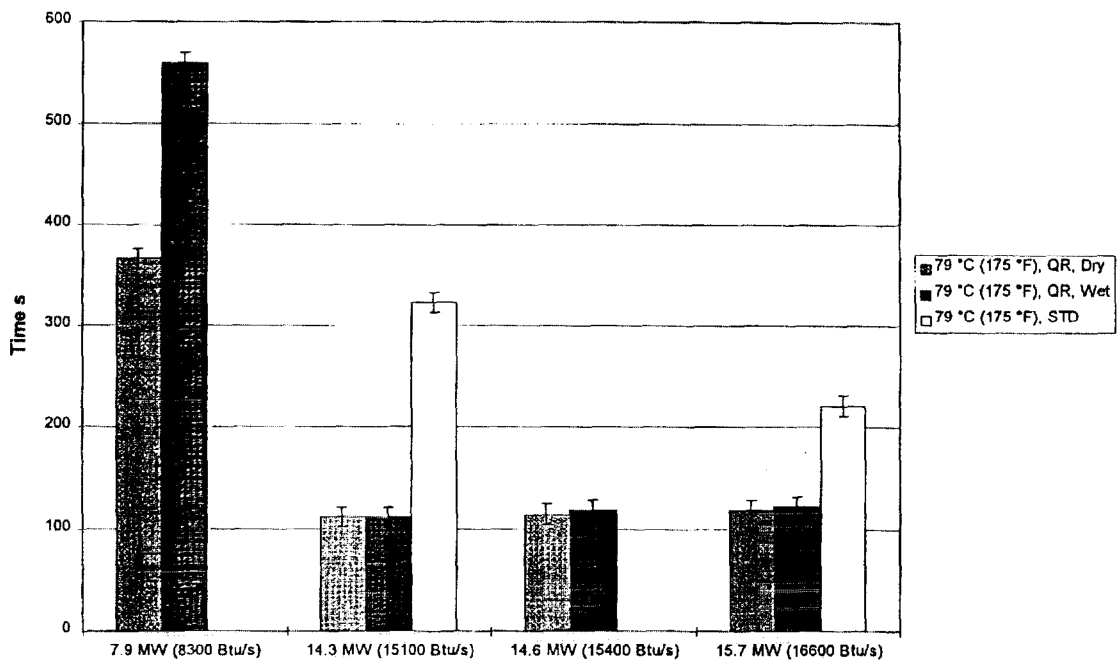

Figure 6 *Activation times of 79°C (175°F) sprinkler bulbs for quick response, dry pipe, quick response, wet pipe, and standard response sprinklers. The sprinklers are located on the plume centerline. The quick response sprinklers had an RTI rating of 35 (m/s)$^{1/2}$ (63 [ft/s]$^{1/2}$), while the standard response sprinkler had an RTI rating of 188 (m/s)$^{1/2}$ (340 [ft/s]$^{1/2}$).*

connected to a dry pipe. The standard response sprinkler either did not activate or activated 100 s or more after the quick response sprinklers. The quick response wet and dry pipe configurations exhibited the same activation times for the larger fires, but for the smaller fire the dry pipe configuration responded substantially earlier than the wet pipe configuration. While this response would be expected for a threshold fire, additional experiments are required to verify that the water-filled pipe impacted the response time of the sprinkler.

Heat Detectors

The heat detector responses to the fires in the two facilities were similar to the sprinkler element responses. Differences between the two types of detectors were primarily due to the activation temperatures of the heat detectors being lower at 57°C (135°F). The impact of the presence of the draft curtain is clearly shown in Figure 7. All heat detectors in the draft curtained area activated at essentially the same time, while for the fire with no draft curtains, substantial delays occurred once the distance from plume centerline reached 8.5 m (28 ft).

The impact of threshold fires on detector spacing is shown in Figure 8. Here a 2.8 MW (2,700 Btu/s) fire produces activation out to 9.1 m (30 ft), but activation times increase substantially with distance. A 7.7 MW (7300 Btu/s) fire produces nearly identical activation times across the draft curtained area. Hence, in a draft curtained area, if detection is designed for a threshold or smallest detectable fire, detector spacing should approximate the expected plume width. Where initial detector activation is designed to occur for fire sizes substantially above the threshold fire size, detectors would be expected to activate almost simultaneously anywhere inside draft curtained space.

For the tests in the 22 m (73 ft) facility, a 4.9 MW (4,600 Btu/s) fire was just able to activate one heat detector at 6.1 m (20 ft), as shown in Figure 9, which would represent a fire at threshold. As the fire size was increased to 7.9 MW (7,500 Btu/s), activation times varied substantially with distance from plume center. For fires larger than 14 MW (13,000 Btu/s), activation times showed a reduced dependence on the distance from plume center.

Smoke Detectors

The activation of photoelectric smoke detectors in the 15 m (50 ft) and 22 m (73 ft) experiments were typically quicker and were sensitive to smaller fire sizes than the heat detectors (see Tables 1 and 3). For the photoelectric smoke detectors, no activation was observed for the 100 kW (95 Btu/s) fire size. Smoke detectors activated between 23 s and 61 s for fire sizes of 500 kW (470 Btu/s) and larger. The activation times for these larger fires will not correlate with fire size since the smoke detectors were activating during the growing phase of the fire. The presence of draft curtains did not affect activation times. The reason for this is that the smoke detectors were located in the ceiling jet and would only be marginally affected by a developing layer. Based on the 15 m (50 ft) experiments, spacing for the ceiling-mounted smoke detectors could be as

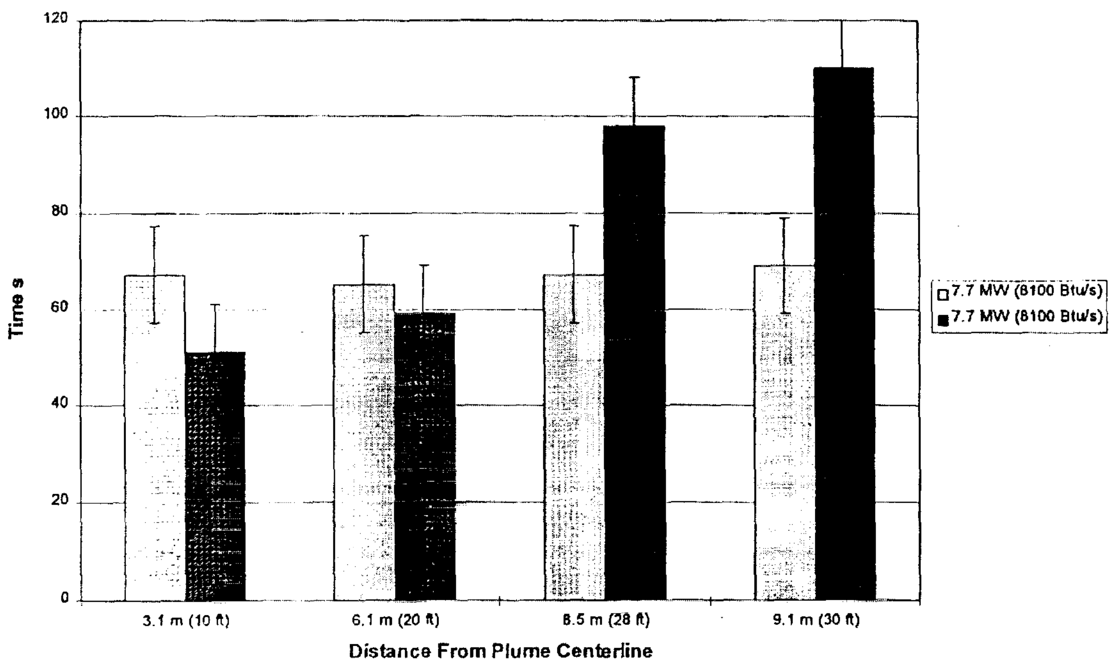

Figure 7 *Earliest activation time for 57°C (135°F) heat detectors as a function of distance for the 2.5 m diameter JP-5 pan fires with and without a draft curtain in the 15 m hangar. The draft curtain tests are represented by the first bar at each position.*

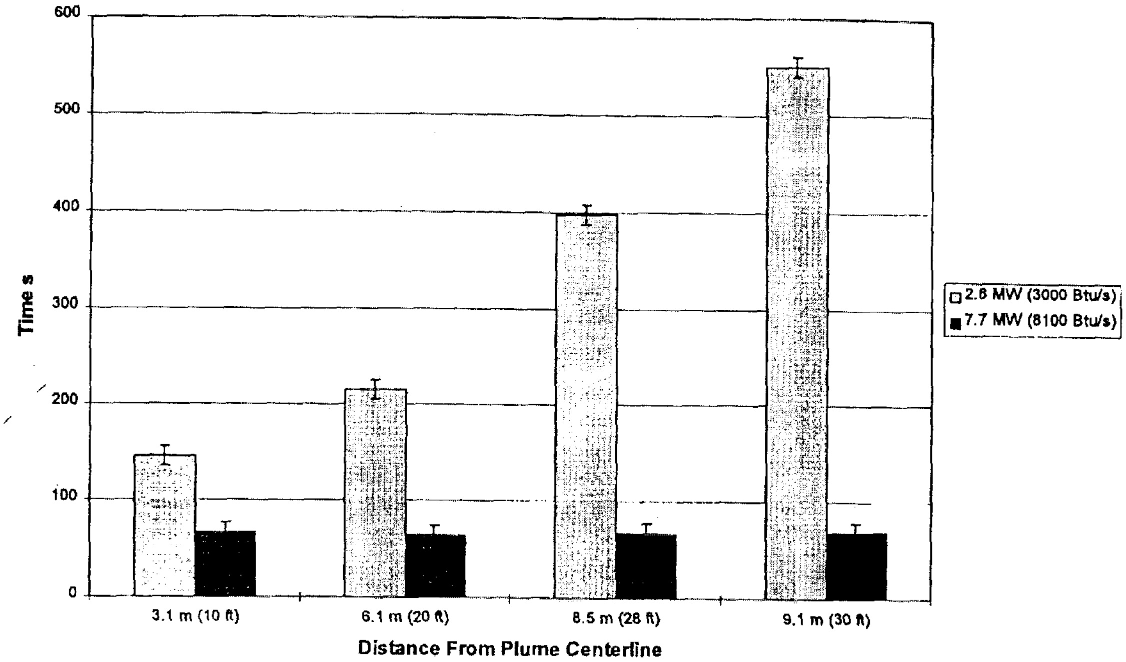

Figure 8 Earliest activation times as a function of distance for 57°C (135°F) heat detectors in the 15 m (50 ft) hangar for two tests that have draft curtains.

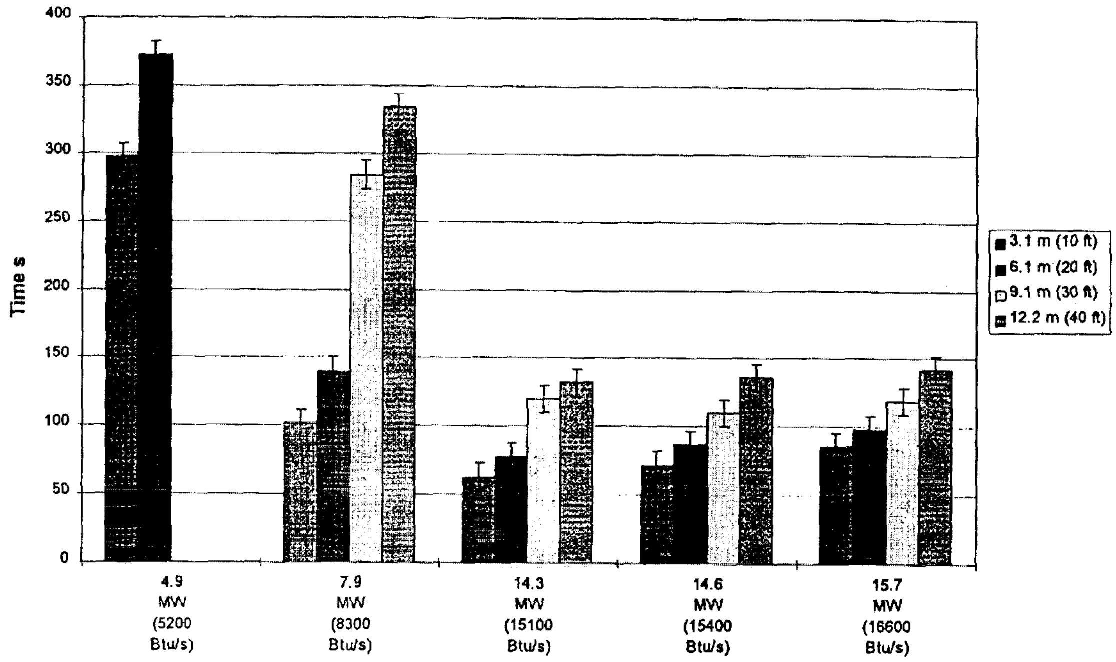

Figure 9 Earliest activation times as a function of distance for 57°C (135°F) heat detectors in the 22 m (73 ft) hangar. Distances from fire center are given in the side box in meters (feet).

large as 12 m (40 ft), based on the activation observed for the JP-5 fires. Similar results were observed for wood crib fires, where a 600 kW (570 Btu/s) fire produced activation of smoke detectors to 6 m (20 ft) on either side of plume center without substantial loss in detection time.

The responses of projected beam detectors to the fires were as expected (see Tables 1 and 3). Activation occurred in less than a minute for beams located near the ceiling, which sampled the ceiling jet. For beams located below the ceiling jet and outside of the plume region, activation occurred at acceptable times only when the beam sampled the smokey layer created by the draft curtains. These detectors were able to detect the 100 kW (95 Btu/s) test fires in less than two minutes after the start of the fire. One problem that was observed with these detectors was that many times, trouble signals rather than alarms were registered due to the very dense smoke produced by the JP-5 fires, which completely obscured the beam. The alarm window was reduced from 30 s to 5 s for the 22 m (73 ft) experiments, which eliminated the trouble signals for all but one of the open door tests. Trouble signals were not a problem for the wood crib fires due to the less dense smoke produced by this type of fire.

Impact of Beams on Detection

The impact of the presence of beams could be analyzed with the 15 m (50 ft) data since the roof was supported by 0.25 m (10 in) I-beams that ran in the N-S direction and would, therefore, impede the flow of smoke in the E-W direction. Table 6 gives the activation times in the north, south, east, and west directions for spot smoke detectors operating at a radial distance of 6.1 m from plume center for the two 500 kW (470 Btu/s) fires, which were the smallest fires to activate the smoke detectors. The smoke detectors activate at roughly the same time in all directions except for in the east direction in Test 2, which activated at a substantially earlier time. The reason for this activation is that the plume leaned to the east early in this test, which would favor the activation of smoke detectors in this direction. Ceiling beams of this size seem to have little impact on smoke detector activation for high ceiling fires, probably due to the increased thickness of the ceiling jet with height. The beams in this study supported a corrugated roof, and the seal between the beams and the roof was not perfect.

Table 7 gives the activation times in the north, south, east, and west directions for the 57°C (135°F) spot heat detectors for all distances inside the draft curtain. If the 0.25 m (0.82 ft) I-beams impacted the flow of hot smoke across the ceiling, the detectors in the east-west direction should activate at later times than the detectors in the north-south direction. As can be seen from the table, activation times did not appear to be dependent on direction, which again suggests that these detectors were not impacted by the presence of the beams.

Impact of Wind

The impact of wind on the activation of detectors can be analyzed by comparing the activation history of the open-door tests (#13 at Barbers Point and #16 and #19 at Keflavik, see Tables 1 and 4) with the corresponding closed-door tests (#7 at Barbers Point and #14 at Keflavik). In both closed-door tests, 79°C (175°F) sprinklers activated. For the open-door tests, none of the 79°C (175°F) sprinklers activated. The temperatures measured at the ceiling for the open-door tests were substantially less than for the closed-door tests. With two doors open in the 15 m (50 ft) hangar, the temperature measured at the ceiling reached only 58°C ±2°C (136°F ±4°F) compared with 90°C ±2°C (194°F ± 4°F) for a similar fire size with both doors closed. For the 22 m (73 ft) hangar, with two doors open, the ceiling temperature reached 66°C ±2°C (151°F ±4°F); with one door open, the ceiling temperature reached 77°C ±2°C (171°F ±4°F); with both doors closed, it reached 93°C ±2°C (199°F ±4°F). Wind speeds were measured to range from 14 km/h to 32 km/h (9 mph to 20 mph) 10.4 m north of the fire center and 3 m above the floor in the

TABLE 6
Photoelectric Smoke Detector Response Times (s) for the 15 m (50 ft) Hangar

Location	3.0 m (10 ft)	6.1 m (20 ft)	8.5 m (28 ft)	9.1 m (30 ft)
Test 2: 500 kW (470 Btu/s) with Draft Curtain				
North	27 ± 10	44 ± 10	40 ± 10	nd*
East	23 ± 10	35 ± 10	nd*	73 ± 10
South	32 ± 10	53 ± 10	48 ± 10	nd*
West	31 ± 10	60 ± 10	nd*	81 ± 10
Test 12: 500 kW (470 Btu/s) without Draft Curtain				
North	58 ± 10	53 ± 10	58 ± 10	nd*
East	61 ± 10	49 ± 10	nd*	153 ± 10
South	41 ± 10	49 ± 10	58 ± 10	nd*
West	40 ± 10	57 ± 10	nd*	115 ± 10

* nd = no detector present at that location.

TABLE 7
57°C (135°F) Heat Detector Response Times (s) in 15 m (50 ft) High Hangar

Location	3.0 m (10 ft)	6.1 m (20 ft)	8.5 m (28 ft)	9.1 m (30 ft)
Test 5: 6.8 MW (6400 Btu/s) with Draft Curtain				
North	92 ± 10	96 ± 10	154 ± 10	nd*
East	71 ± 10	88 ± 10	nd*	121 ± 10
South	80 ± 10	92 ± 10	113 ± 10	nd*
West	71 ± 10	100 ± 10	nd*	175 ± 10
Test 6b: 7.7 MW (7300 Btu/s) with Draft Curtain				
North	65 ± 10	65 ± 10	69 ± 10	nd*
East	69 ± 10	27 ± 10	nd*	69 ± 10
South	19 ± 10	65 ± 10	65 ± 10	nd*
West	85 ± 10	69 ± 10	nd*	32 ± 10
Test 7: 5.6 MW (5300 Btu/s) without Draft Curtain				
North	188 ± 10	92 ± 10	200 ± 10	nd*
East	75 ± 10	138 ± 10	nd*	274 ± 10
South	84 ± 10	101 ± 10	138 ± 10	nd*
West	63 ± 10	113 ± 10	nd*	167 ± 10
Test 8: 7.7 MW (730 Btu/s) without Draft Curtain				
North	59 ± 10	59 ± 10	105 ± 10	nd*
East	51 ± 10	59 ± 10	nd*	96 ± 10
South	51 ± 10	67 ± 10	92 ± 10	nd*
West	51 ± 10	75 ± 10	nd*	125 ± 10

* nd = no detector was installed at that position.

15 m (50 ft) hangar. In the 22 m (73 ft) hangar, the two-doors-open test had wind speeds that ranged from 4 km/h to 7 km/h (2 mph to 4 mph) 7 m south of the fire center and 0.8 m above the floor, while the one-door-open test had wind speeds that ranged from 2 km/h to 6 km/h (1 mph to 4 mph) 5.7 m south of the fire center and 0.8 m above the floor. Wind-speed measurements have an uncertainty of ±1 km/h (±0.6 mph).

From a smoke obscuration standpoint, the one-door-open experiment produced substantially more mixing of smoke into the lower layer than the two-doors-open experiments. In the one-door-open experiment, the smoke near the ceiling was observed to flow to the back of the hangar, deflect downward, and flow back toward the fire near the floor. By 240 s into the fire, the floor area was very smoky, and by 330 s, all personnel without breathing apparatus had to be evacuated from the building. In both two-doors-open experiments, the smoke mixing into the lower layer did not become severe enough to require an evacuation.

Smoke detector activation times were unaffected by the wind for all three open-door tests. The smoke detectors downwind from the fire typically were the first detectors to activate with the upwind detector activating at later times.

CONCLUSIONS

The following conclusions can be made concerning the application of detectors at these ceiling heights.

1. The presence of draft curtains decreased the response time of heat detectors and sprinklers tested in these experiments. Detectors respond to smaller fires when draft curtains are present. The impact of the fire plume located at the intersection of two adjacent curtained areas was not studied in these experiments as the test fires were always located in the geometric center of the curtained space.
2. When located near the center of the curtained area, the presence of draft curtains effectively contained the fire plume and resulted in a relatively flat temperature distribution within the curtained area with no significant temperature increase in adjacent areas. Thus, it should be possible for automatic sprinkler systems to activate and control or extinguish fires under a single curtained area without the need for deluge systems that apply agent over the entire hangar area.
3. For ceiling heights of 9 m (30 ft), NFPA 72 recommends that the linear spacing of heat detectors be reduced to 3.0 m (10 ft). The experiments in this study demonstrated that the

spacing between heat detectors may be increased to as much as 12 m (40 ft) at a ceiling height of 15 m (50 ft) without affecting activation times.

4. Ceiling beams 0.25 m (10 in) deep had no effect on the activation of smoke and heat detectors.

5. Beam-type smoke detectors proved to be the most sensitive to small fires of the smoke detector types tested, but also registered a number of trouble signals in response to the dense smoke produced by JP-5 pool fires.

6. Quick response sprinklers responded substantially faster than standard response sprinklers at these heights.

7. In the presence of windy conditions (wind speeds in excess of 2 km/h [1 mph]), heat detectors and sprinklers would not be expected to activate at the same fire sizes predicted to activate these detectors when no wind is present. Smoke detector activation will be affected by the wind in that only the downwind detectors will activate for small fire sizes.

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