Experimental Validation of Smoke Detector Spacing Requirements

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INTRODUCTION

A modeling study [1] performed in 2006 under a research grant from the Fire Protection Research Foundation used the program Fire Dynamics Simulator (FDS) to evaluate smoke detector spacing requirements with respect to level ceilings with deep-beam profiles. A subset of these model simulations was replicated with full-scale experimental testing to evaluate the findings of the modeling study. The primary focus of the experimental test program was to document the response times of smoke detectors installed in various beamed corridor configurations relative to the response of a detector on an open, smooth ceiling and to compare the relative responses with the results of the previous modeling study [1]. The experimental results were also used to provide a direct comparison of fire conditions (temperature, smoke, and velocity) as well as smoke detector responses with the output of the modeling study.

The previous modeling study [1] evaluated multiple corridor configurations consisting of corridor widths of 1.5 m (5 ft) and 3.7 m (12 ft); ceiling heights of 2.7 m (9 ft), 3.7 m (12 ft), and 5.5 m (18 ft); beam spacing of 0.9 m (3 ft) and 2.7 m (9 ft); and beam depths of 0.3 m (1 ft), 0.6 m (2 ft), and flat smooth ceilings. The beams were modeled as 0.15 m (6 in.) thick obstructions. A multi-block grid was utilized in which 38 mm (1.5 in.) cells were used around the fire plume and along the ceiling to capture the flow between and below beams. A courser grid of 152 mm (6 in.) cells was used for the rest of the domain. Fire Dynamics Simulator, version 4, was used [2,3] for all simulations. The modeling simulations used an instantaneous 100 kW fire centered between beams at one end of the corridor. The base of the fire was 0.31 x 0.31 m (1 x 1 ft) and was located on the floor. The exposure fire was prescribed with a soot yield of 2.2 percent. Instrumentation clusters were specified at various locations down the centerline of the corridor at the bottom of beams and centered in the beam bays on the ceiling.

The intent of this paper is to provide an overview of the experimental testing conducted, to present the findings of the experimental validation, and to address the impact of deep-beam profiles on level ceilings with respect to smoke detector response.

EXPERIMENTAL APPROACH

The corridor apparatus used in this work was designed such that a large subset of the configurations examined in the modeling study could be evaluated. Such configurations included corridor widths of 1.5 m (5 ft) and 3.7 m (12 ft); ceiling heights of 2.7 m (9 ft), 3.7 m (12 ft), and 5.5 m (18 ft); beam spacing of 0.9 m (3 ft) and 2.7 m (9 ft); and beam depths of 0.3 m (1 ft), 0.6 m (2 ft), and flat, smooth ceilings. The corridor apparatus was 14.6 m (48 ft) long, 3.7 m (12 ft) wide and consisted of a steel support structure and 6.35 mm (0.25 in.) gypsum wall board (GWB). The corridor had 6.35 mm (0.25 in.) GWB walls extending 1.2 m (4 ft) below the ceiling. The remainder of each wall extending to the floor was constructed of 0.1 mm (4 mil) polyethylene plastic sheeting. Corridor beams were constructed from steel stud framing and 6.35 mm (0.25 in.) GWB. The beams were 0.15 m (6 in.) thick and either 0.3 m (1 ft) or 0.6 m (2 ft) deep. The corridor ceiling was leveled to within $\pm$5.1 cm (2 in.) both laterally and longitudinally.

Figure 1 shows a diagram of the corridor apparatus with the beams in place. The figure presents the locations of spot smoke detectors, optical density meters and velocity probes. At every detector location, there was a 24 Ga, Type K, bare-bead thermocouple positioned 19 mm (0.75 in.) from the ceiling, beam, or wall surface that it was mounted on. Most devices were centered down the corridor on the ceiling or the bottom of a beam, except for a number of devices mounted to the wall, as shown by the symbols near the walls in Figure 1.

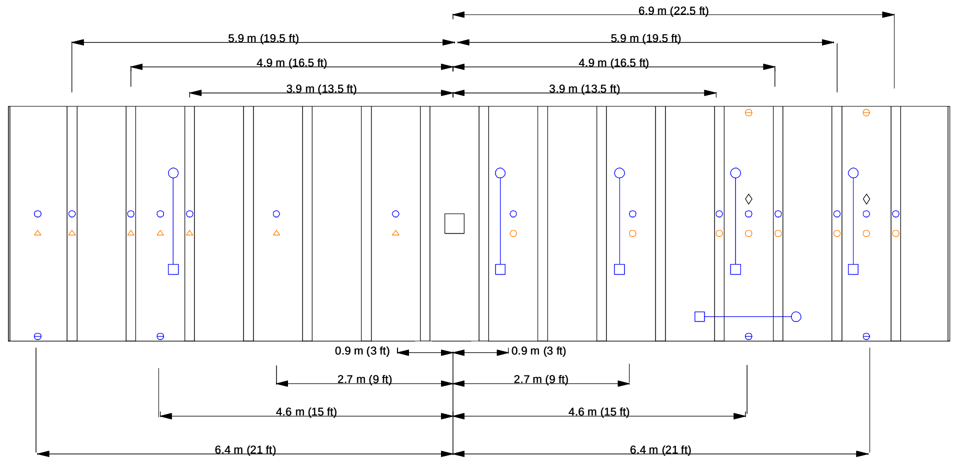

Figure 1: Diagram of Corridor Test Apparatus with Instrumentation.

Optical density meters were constructed in general accordance with the specifications of UL 268. [4] The optical density meters used were comprised of a 6V General Electric sealed beam light source, and a Huygen Model 856 RRV, photovoltaic cell. The path length for all ceiling mounted ODM's was 1.52 m (5 ft). In order to accommodate the installation of beams within the corridor, it was necessary to decrease the path length of the wall-mounted ODM. This ODM had a path length of 0.6 m (2 ft).

Velocity measurements were collected at two locations using Applied Technologies Sonic Anemometer/Thermometer *Model SPA5/2Y* (courtesy of NIST BFRL). The velocity probes were located in the 4.6 m (15 ft) and 6.4 m (21 ft) beam bays on the right side of the corridor. The probes were able to measure velocities in both the longitudinal and lateral directions. They were installed such that velocities were measured approximately 19 mm (0.75 in.) from the ceiling of the corridor. The velocity probes were capable of measuring velocities ranging from 0 – 10 m/s with a resolution of 0.01 m/s.

Two different spot detection technologies (i.e., ionization, photoelectric) from two different manufacturers were installed within the corridor. Smoke detector clusters were installed on the ceiling of the corridor, on beam bottoms, and at various elevations along the walls of the corridor. Detector clusters were installed at the locations illustrated in Figure 1. Wall-mounted detectors were installed at locations of 0.07 m (3 in.) and 0.3 m (1 ft) to center below the corridor ceiling at each of the locations presented in Figure 1.

Photoelectric detectors from the same manufacturer (Mfg A) were installed at all locations along the length of the corridor as well as on the walls of the corridor. The installation of the same technology from the same manufacturer on both sides of the fire source provided a means of verifying corridor symmetry. Photoelectric detectors from Manufacturer B were installed on the right hand side (RHS) of the corridor and ionization detectors from Manufacturer B were installed on the left hand side (LHS). The installation of the same detector technology (i.e., photoelectric) from two different manufacturers on the same side of the corridor (i.e., RHS) provided a means of assessing whether the results of the study were independent of manufacturer. Furthermore, the installation of different detector technologies (ion and photo) on the same side of the corridor (i.e., LHS) provided a means of evaluating the different detector technologies when subjected to comparable exposures.

The photoelectric detectors provided by both Manufacturers A and B were set to an alarm threshold of 2.5 percent obscuration per foot and the ionization smoke detectors provided by Manufacturer B were set to an alarm threshold of 1.2 percent obscuration per foot. Detector activation for Manufacturer B devices was via panel activated I/O modules that were monitored as normally-open relays by the data acquisition system which recorded a step change in voltage for each individual detector activation. Detector outputs for Manufacturer A devices were collected using an independent data logger and a post-processing routine. This system allowed post-test evaluation of alarms at any user-selected sensitivity setting.

The fire source used in this test series was a 0.31 x 0.31 m (1x1 ft) sand burner constructed in general accordance with Annex A of ISO 9705 [5]. The burner was designed to replicate the prescribed fire source in the 2006 modeling study. An instantaneous, constant 100 kW fire was centrally located beneath the corridor as shown in Figure 1. The burner was laterally centered beneath the corridor ceiling and located beneath the central most beam bay of the corridor. The burner was not geometrically centered in the longitudinal direction due to the fact that in the previous modeling research [1], the burner was centered beneath a beam bay, whereas the geometric center of the test corridor falls directly on a beam.

Prior to the start of each test, the corridor environment was permitted to return to ambient air conditions. Once these criteria were verified, a two minute baseline was collected for all instrumentation. The exposure fire was initiated immediately following the two minute baseline and permitted to burn for 90 – 300s depending upon the exposure fire size and corridor ceiling elevation. Tests were conducted until quasi-steady state conditions (i.e., temperature and optical density) along the length of the corridor were achieved.

EXPERIMENTAL RESULTS

Exposure Fires

In the previous modeling study [1], the simulated exposure fire was prescribed using a soot yield of 2.2 percent. Based upon this input parameter and data provided in the literature [6], propane was selected as the initial experimental fuel source. However, during hood calorimetry testing, it was determined that at the prescribed fire size (i.e., 100 kW) a soot yield of 0.4 percent was produced by the propane fuel. Consequently, additional hood calorimetry tests were performed in an effort to identify a fuel with a soot yield, at 100kW, that was comparable to that prescribed in the modeling. The second fuel evaluated, ethylene, was found to have a soot yield of 2.0 percent, a value comparable to that specified in the modeling study. However, after initial ethylene detection tests were conducted for the baseline smooth ceiling scenario, it was found that these exposure fires were not sufficient to cause alarm conditions at a distance of 4.6 m (15 ft) from the source (i.e., 30 x 30 ft coverage) for several ceiling elevations. As a result of this finding and the need for detection at the 4.6 m (15 ft) location for baseline comparison purposes, a third fuel, propylene, was selected and tested in both hood calorimetry and initial detection tests. From these tests, it was determined that while the propylene fuel produced a soot yield of 4.8 percent, a value more than double that specified in the modeling study, the smoke obscuration conditions at locations remote from the source (i.e., 4.6 m [15 ft] down the corridor) were comparable to those predicted in the modeling study.

The occurrence of these conditions along with visual observations suggested that a non-trivial quantity of soot was being deposited onto the corridor ceiling. Based upon a series of exploratory experiments designed to quantify this loss, it was determined that as much as 37 percent of the soot being produced by the exposure fire was deposited onto the ceiling, thereby not being transported to locations downstream in the ceiling jet. The impact of this deposition phenomenon is illustrated by the plots in Figure 2.

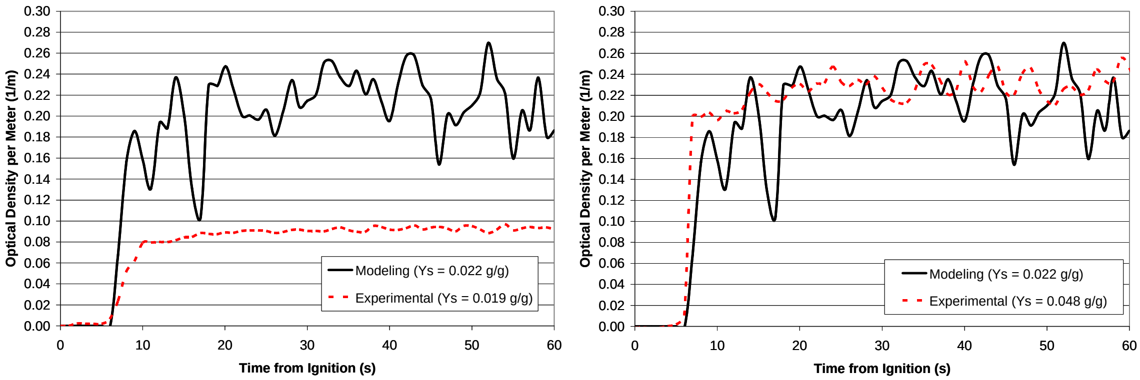

Figure 2: Optical Density Measurements at the 4.6 m (15 ft) Location for Ethylene (left) and Propylene (right) Compared to Predicted Optical Density Data from the Modeling Study. The Trends Presented are for the Open, Smooth Ceiling Configuration at an Elevation of 2.7 m (9 ft).

As shown in Figure 2, corridor conditions resulting from an exposure fire with a prescribed soot yield of 2.2 percent do not agree with experimental data measured during an exposure to a fire source with a 2.0 percent soot yield. Furthermore, it is shown that in order to achieve the conditions predicted for a source with a 2.2 percent soot yield, an experimental fire source having a soot yield of 4.8 percent was needed. Consequently, the sootier fuel was adopted as the source fuel for the experimental test program in order to be able to evaluate relative detector response times in a manner similar to that used in the previous modeling study.

Corridor Conditions

The 2006 modeling study [1] did not directly simulate smoke detectors but rather determined when conditions were reached that would likely result in detection. Thus it becomes critically important to understand the degree to which the predicted conditions are representative of actual conditions expected within a similarly configured corridor. The corridor apparatus was designed and instrumented such that direct comparisons of temperature, smoke obscuration, and velocity could be evaluated between the modeling and experimental results. A summary of the average quasi- steady-state conditions measured during each of the corridor ceiling configurations tested is provided in Table 1. Also provided in Table 1 are the conditions predicted by the model for the same corridor configurations.

Table 1: Comparison of Quasi- Steady-State Conditions Measured within the Corridor at the 4.6 m (15 ft) Location and the Conditions Predicted in the Modeling Study at the Same Location.

Corridor Configuration			Average Steady-State Conditions					
			Temperature Rise (°C)			Optical Density (OD/m)		
Corridor Width	**Corridor Height**	**Beam Depth**	**Experimental**	**Modeling**	**Difference**	**Experimental***	**Modeling**	**Difference**
12	9	Smooth	31	30	**1**	0.23	0.26	**-0.03**
		1	27	26	**1**	0.36	0.34	**0.02**
		2	18	22	**-4**	0.32	0.35	**-0.03**
	12	Smooth	21	21	**0**	0.15	0.17	**-0.02**
		1	19	23	**-4**	0.23	0.23	**0.00**
		2	15	21	**-6**	0.20	0.22	**-0.03**
	18	Smooth	12	11	**1**	0.09	0.08	**0.01**
		1	10	11	**-1**	0.11	0.10	**0.01**
		2	10	11	**-1**	0.12	0.09	**0.03**
5	9	Smooth	35	39	**-4**	0.31	0.31	**0.00**
		1	38	43	**-5**	0.41	0.40	**0.01**
		2	35	41	**-6**	0.37	0.47	**-0.10**
	12	Smooth	23	26	**-3**	0.17	0.20	**-0.03**
		1	24	30	**-6**	0.27	0.28	**-0.01**
		2	30	28	**2**	0.22	0.29	**-0.07**
	18	Smooth	14	17	**-3**	0.13	0.12	**0.01**
		1	14	16	**-2**	0.17	0.14	**0.03**
		2	15	16	**-1**	0.11	0.14	**-0.03**

*** It is important to note that experimental optical densities were achieved using a fuel with a soot yield of 4.8 percent whereas the data presented in the modeling is the result of a fuel source with a prescribed soot yield of 2.2 percent.**

Although in most cases the predicted thermal conditions were slightly higher than those measured experimentally, in general the thermal conditions within the corridor for all ceiling configurations were comparable to those predicted in the modeling simulations. The uncertainty in the temperature comparisons was estimated to be 3°C based on the uncertainties in thermocouple measurements, the heat release rate and the subsequent effect on plume ceiling temperature calculations. The optical densities measured experimentally were found to agree fairly well with those predicted in the modeling study. However, as noted in Table 1, these experimental values were achieved using a significantly sootier (i.e., a soot yield 2.2 times larger) fuel than that prescribed for the source fire in the modeling study. Therefore, the similarities in the optical density values presented in Table 1 indicate that the model is over-predicting the transport of smoke along the length of the corridor. However, this data comparison demonstrates that the conditions in which the experimental smoke detectors were exposed were similar to those used to evaluate detection in the previous modeling study. Although not presented, velocity measurements collected at the 4.6 m (15 ft) and 6.4 m (21 ft) location were comparable to the values predicted in the previous modeling study.

ANALYSIS & VALIDATION

Smoke Detector Performance Metric

Smoke detector performance was evaluated based upon the response time of a device at a certain location with respect to the response of a baseline detector. For the purposes of this evaluation, the baseline detector was taken to be a detector at the 4.6 m (15 ft) location at the corresponding ceiling height on an open, smooth ceiling (i.e., the typical detector location for a smooth ceiling spacing of 900 ft^2 per detector). This relative response time was the metric adopted in the previous modeling study; thus it was necessary that the same metric be used to evaluate smoke detector performance for all corridor ceiling configurations evaluated experimentally. Furthermore, it is important to note that the metric for comparable performance, as prescribed in the modeling study, was a difference in response times of less than 60 seconds. The asymmetry of the corridor used in the modeling study [1] resulted in a relative response time based upon a single detector response at a certain distance from the fire. Conversely, the symmetry of the experimental corridor apparatus and the installation of detector pairs at each location resulted in relative response times based upon the responses of multiple devices (i.e., six events from three detectors per test and two tests per configuration). The average of these six response times was used to develop the relative response time for each detector technology at each detector location.

Validation

The experimental results obtained for the various corridor configurations were used to assess a series of conclusions put forth in the modeling study [1]. A summary of the conclusions evaluated from the modeling study is provided below;

1. *"Deep-Beam Configurations do not Negatively Affect the Expected Performance of Smoke Detectors when the Ceiling Height is less than 24ft"*
2. *"No Significant Difference in Temperature Rise or Optical Density Conditions between Detectors located on the Bottom of a Beam or on the Ceiling in the Adjacent Beam Bay"*
3. *"Conditions within a Beam Bay are relatively uniform and Well-Mixed throughout the Volume of the Beam Pocket thus keeping Detectors 12 in. Below the Ceiling in Wall-Mounted Configurations is Unsubstantiated"*

The affect of the deep-beam configurations (Conclusion 1) was evaluated using the relative detector response data from each of the corridor configurations tested. A summary of these relative responses is presented in Table 2.

Table 2: Comparison of Relative Response Times from Experimental and Modeling Data Sets for All Corridor Ceiling Configurations Tested.

Ceiling Geometry			12' Width / Smooth			12' Width / 1' Beam Depth			12' Width / 2' Beam Depth			5' Width / Smooth			5' Width / 1' Beam Depth			5' Width / 2' Beam Depth		
Ceiling Height (ft)			**9**	**12**	**18**	**9**	**12**	**18**	**9**	**12**	**18**	**9**	**12**	**18**	**9**	**12**	**18**	**9**	**12**	**18**
Experimental	**Detector Location**	**15'**	4	0	5	-8	-9	-13	-19	-15	-16	9	2	-1	-7	-6	-4	-9	-12	-16
		21'	-2	-5	0	-13	-9	-17	-34	-32	-33	0	2	-5	-13	-11	-13	-25	-24	-29
Modeling		**15'**	5	5	N/D	-10	2	N/D	-18	-15	N/D	9	9	N/D	1	4	N/D	-1	-1	N/D
		21'	3	3	N/D	-21	-15	N/D	-30	-23	N/D	6	7	N/D	-3	0	N/D	-4	-4	N/D

N/D – No Detector Activation was achieved in the Modeling Study [1].

The values presented in Table 2 are in terms of the relative response times for photoelectric alarms from both spot-type detector manufacturers. In this table, negative values are indicative of detector response times slower than baseline detector responses (i.e., detectors located at 900 ft^2 spacing on a smooth, open ceiling). Similarly, positive values are indicative of detector response times faster than baseline detector responses. In general, the relative detector responses for the smooth, corridor ceiling were found to be faster or no slower than 5 seconds when compared to baseline detector responses. Furthermore, the addition of 0.3 m (1 ft) and 0.6 m (2 ft) deep-beams was found to slow detector response times in all configurations for both corridor widths. The presence of a 0.3 m (1 ft) deep beam resulted in delays of 9 and 12 s or more for corridor widths of 1.5 m (5 ft) and 3.2 m (12 ft), respectively. Delays for the 0.6 m (2 ft) deep beam profile were calculated to be 19 and 25 s or more for corridor widths of 1.5 m (5 ft) and 3.2 m (12 ft), respectively. A maximum delay in the response of 34 s was measured for the 3.2 m (12 ft) wide corridor with a 0.6 m (2 ft) deep beam profile. Based upon the data presented in Table 2, it was determined that the addition of deep beams to corridor ceilings can delay the response of smoke detectors for as much as 34 seconds compared to the response of detectors on an open, smooth ceiling.

The performance of the ceiling-mounted smoke detectors compared to detectors mounted on the bottoms of beams (Conclusion 2) was evaluated using the relative response data collected from detectors in these locations as well as thermal data collected from the 4.6 m (15 ft) location and the two adjacent bottom-of-beam locations. In general, the relative response times for detectors located on the ceiling of the corridor when compared to the relative response times of detectors mounted on adjacent beam bottoms were found to be similar for both corridor widths considered. The average differences in relative response times for the 1.5 m (5 ft) and 3.2 (12 ft) corridor widths were calculated to be $7s \pm 5s$ and $10s \pm 6s$, respectively. When considering the 3.2 m (12 ft) wide corridor, it was determined that 80 percent of the time detectors mounted at the bottom-of-beam locations were the first to activate with respect to adjacent ceiling mounted detectors. This percentage decreased to 50 percent for the 1.5 m (5 ft) wide corridor configurations. A comparison of temperature trends measured at these locations is presented in Figure 3. Generally, as shown, temperatures at the bottom of beams were higher than on the ceiling of the beam bay. In general, based upon the thermal and detector response data collected for various corridor configurations, the results of the experimental test program were found to be consistent with Conclusion 2 of the modeling study.

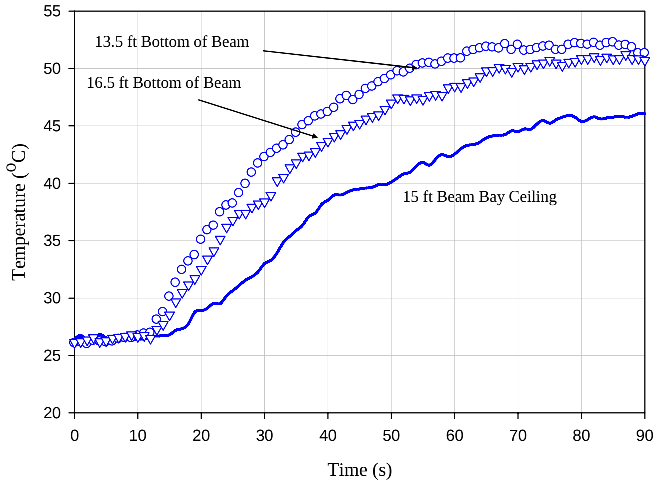

Figure 3: Comparison of Temperature Data Collected at the 4.6 m (15 ft) Ceiling Location, 4.1 m (13.5 ft) Bottom of Beam Location, and the 5.0 m (16.5 ft) Bottom of Beam Location.

The positioning of smoke detectors with respect to wall-mounted installations (Conclusion 3) was also evaluated using both thermal measurements collected at various wall-locations as well as relative detector response data. In order to fully-evaluate the assertion that the 0.3 m (1 ft) offset requirement is unsubstantiated, it was necessary to evaluate data from all three corridor ceiling configurations considered (i.e., smooth ceiling profiles, 0.3 m (1 ft) deep beam profiles, and 0.6 m (2 ft) deep beam profiles). A comparison of temperature trends measured at the ceiling, 0.07 m (3 in.) below the ceiling on the wall, and 0.3 m (12 in.) below the ceiling on the wall is presented in Figure 4. These data were collected from the 3.2 m (12 ft) wide corridor with a ceiling height of 3.2 m (12 ft) for each of the three ceiling configurations considered.

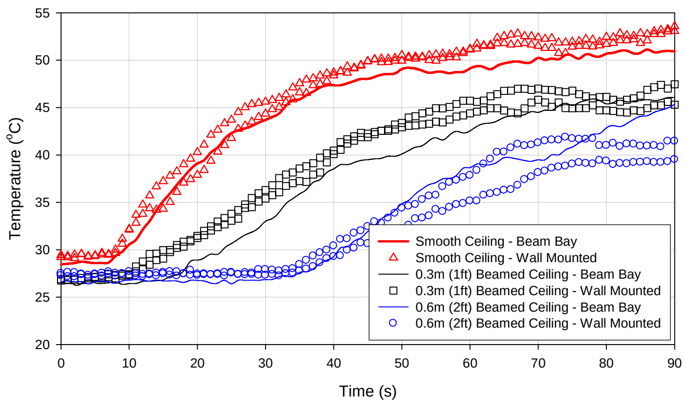

Figure 4: Comparison of Temperatures Measured at the Ceiling of the Corridor, at a distance 0.07 m (3 in.) below the Ceiling on the Wall, and at a distance 0.3 m (12 in.) below the Ceiling on the Wall. Note: The Two Wall-Mounted Temperature Measurements are presented using the same symbols for each beam configuration.

As shown in Figure 4, for all three ceiling configurations, there was little (i.e., less than 3^{o}C) difference between the temperature measured at the ceiling and at both wall-mounted locations. This was also true with respect to the relative detector response times recorded for all configurations evaluated. In total, 72 wall-mounted detector clusters were tested under various corridor ceiling configurations. From this data set it was determined that in 40 percent of the clusters, the wall-mounted detector located proximate to the ceiling (i.e., located 0.07 m [3 in.] below the ceiling) responded before the detector located 0.3 m (12 in.) below the ceiling. The maximum difference in response times for detectors in the same cluster was found to be 14 seconds and the average difference in response times between wall-mounted detector pairs was calculated to be $5s \pm 3s$.

Detector Siting Impacts

As a result of the findings of the 2006 modeling study [1], several changes were adopted into the 2007 edition of NFPA 72 – *National Fire Alarm Code* [7]. The changes, as related to this work, addressed the placement of spot-type smoke detection in corridors 4.5 m (15 ft) or less in width with deep beams or joists perpendicular to the length of the corridor. The latest version of the code prescribes a smooth ceiling spacing for all configurations fitting the aforementioned criteria.

Given that the intent of this work was to validate the conclusions of the 2006 modeling study it was important to understand the implications of the changes made to the code based upon the conclusions of the modeling. A comparison of the maximum allowable siting requirements for spot-type smoke detectors installed on corridor ceilings with deep beam profiles is provided in Table 3. The table outlines configuration specific changes to detector siting requirements based upon the prescriptive requirements of the 2002 [8] and 2007 editions of NFPA 72.

Table 3: Summary of Maximum Allowable Siting Requirements for 2002 and 2007 Editions of NFPA 72 for the Corridor Configurations Tested.

Ceiling Height (ft)	Beam Depth (ft)	Corridor Width (ft)	Maximum Detector Spacing	
			NPFA 72 - 2002 (Parallel / Perpendicular)	NFPA 72 - 2007
9	0	5	42ft	42ft
		12	40ft	42ft
	1	5	42ft / 21ft	42ft
		12	40ft / 20ft	42ft
	2	5	Every Pocket	42ft
		12	Every Pocket	42ft
12	0	5	42ft	42ft
		12	40ft	42ft
	1	5	42ft / 21ft	42ft
		12	40ft / 20ft	42ft
	2	5	Every Pocket	42ft
		12	Every Pocket	42ft
18	0	5	42ft	42ft
		12	40ft	42ft
	1	5	Every Pocket	42ft
		12	Every Pocket	42ft
	2	5	Every Pocket	42ft
		12	Every Pocket	42ft

As shown in Table 3, the siting locations required by the 2002 ed. were dependent upon the configuration of the ceiling (i.e., beam depth, ceiling height, etc.). Furthermore, the earlier version of the code also prescribed siting locations dependent upon the orientation of the beam with respect to the length of the corridor (e.g., perpendicular or parallel). The most current version of NFPA 72 (i.e., 2007) does not differentiate between neither ceiling configurations nor beam orientations and simply applies a smooth ceiling spacing to all scenarios with the only caveat being that the corridor be less than 4.6 m (15 ft) in width. Comparing the performance of the detectors with respect to the 2002 and 2007 requirements provides a means assessing the findings of the modeling study.

Based upon the smoke detector siting locations prescribed in Table 3, relative response times for detectors installed at these locations were calculated. A summary of these calculated times are presented in Table 4.

Table 4: Summary of Relative Smoke Detector Response Times at the Locations Prescribed in both the 2002 Ed. and 2007 Ed. of NFPA 72 – National Fire Alarm Code for 100-kW fire exposures.

Ceiling Configuration			Prescribed Alarm Spacing (ft) per NFPA 72		Response Time at Prescribed Location (s)		Impact of Change in Siting Requirements [2007ed. v. 2002ed.] (s)
Ceiling Height (ft)	Beam Depth (ft)	Corridor Width (ft)	2002 Ed.	2007 Ed.	2002 Ed.	2007 Ed.	
9	0	5	42	42	29	29	0
		12	40	42	31	31	0
9	1	5	21	42	29	42	13
		12	20	42	28	42	14
9	2	5	every pocket[1]	42	23	54	31
		12	every pocket[1]	42	24	63	39
12	0	5	42	42	32	32	0
		12	40	42	38	38	0
12	1	5	21	42	36	44	8
		12	20	42	33	42	9
12	2	5	every pocket[1]	42	26	57	31
		12	every pocket[1]	42	31	65	34
18	0	5	42	42	45	45	0
		12	40	42	42	42	0
18	1	5	every pocket[1]	42	35	53	18
		12	every pocket[1]	42	24	57	33
18	2	5	every pocket[1]	42	36	69	34
		12	every pocket[1]	42	35	73	38

1 – Detectors were not located in the beam bay directly above the fire source therefore response times are reported for the detector located in the adjacent beam bay (i.e., 3 ft away).

The requirements for smooth ceiling spacing for spot-type smoke detectors did not change from the 2002 ed. to the 2007 ed. of the code; thus there was no impact to the performance of the detectors in these configurations. With the addition of a 0.3 m (1 ft) deep beams to ceiling heights of 2.7 m (9 ft) and 3.2 m (12 ft), the prescribed requirements changed from a 20 or 21 ft spacing to a smooth ceiling spacing (i.e., a 40 or 42 ft spacing). These changes resulted in delays of the relative response times ranging from 8 – 14 seconds. With the addition of 0.6 m (2 ft) deep beams at all ceiling heights as well as a 0.3 m (1 ft) deep beam profile on the 5.5 m (18 ft) high ceiling, the prescribed requirements changed from detectors located in every pocket to a spacing of 42 ft. The impact of these changes on relative response times were delays ranging from 31 – 39 seconds.

In addition to the results from 100-kW exposure fires presented above, the results from a subset of tests conducted using a 15-kW exposure fire were also used to evaluate the impacts of the changes made to the siting requirements in the code. Results similar to those presented in Table 4 were observed. A summary of these results is presented in Table 5.

Table 5: Summary of Relative Smoke Detector Response Times at the Locations Prescribed in both the 2002 Ed. and 2007 Ed. of NFPA 72 – National Fire Alarm Code for 15-kW fire exposures.

Ceiling Configuration			Prescribed Alarm Spacing (ft) per NFPA 72		Response Time at Prescribed Spacing (s)		Impact of Change in Siting Requirements [2007ed. v. 2002ed.] (s)
Ceiling Height (ft)	Beam Depth (ft)	Corridor Width (ft)	2002 Ed.[1]	2007 Ed.	2002 Ed.	2007 Ed.	
9	0	5	42	42	153	153	0
9	1	5	21	42	145	178	33
9	2	5	every pocket	42	132	193	62
12	0	5	42	42	DNA	DNA	None
12	1	5	21	42	137	190	53
12	2	5	every pocket	42	DNC		
18	0	5	42	42	DNA	DNA	None
18	1	5	every pocket	42	237	DNA	No Detection v. Detection
18	2	5	every pocket	42	DNC		

1 - Detectors were not located in beam bay directly above source therefore response times were reported for the detector located in the adjacent beam bay (i.e., 3 ft away)
DNA - Detector at this location did not alarm
DNC - Alarm data not collected for this ceiling configuration

As shown in Table 5, the delays in relative response times were greater than those measured during the 100-kW fire exposures. Furthermore, for the 5.5 m (18 ft) high, 1.5 m (5 ft) wide corridor configuration with 0.3 m (1 ft) beams, the detector spacing prescribed by the 2002 ed. of the code was able to detect fires that the spacing prescribed by the current version (i.e., 2007 ed.) was not able to detect. The data presented in Table 5 is strictly for a corridor width of 1.5 m (5 ft); the 3.2 m (12 ft) width was not evaluated using the 15-kW exposure. However, it can be assumed that the delays in relative response times for the wider corridor will be larger than those calculated for the narrower corridor.

CONCLUSIONS

The intent of this experimental test program was to evaluate the performance of various smoke detector spacing layouts on beamed ceiling configurations and in doing so to develop an empirical, technical basis to validate the findings of the earlier modeling research [1]. This was achieved through the comparison of detector response times for various corridor ceiling configurations to baseline (i.e., 30 x 30 ft spacing on an infinite smooth ceiling) detector responses as well as through the direct comparison of fire conditions within the corridor. During initial testing, it was discovered that in order to achieve comparable detector responses it was necessary to use a fuel source with a soot yield 2.2 times greater than that prescribed in the modeling study. This source was needed due to the fact that the version of the FDS model used does not account for soot deposition, which was demonstrated to have a significant impact on the composition of the ceiling jet in the experimental tests.

In general, temperature and velocity measurements collected during experimental testing were comparable to the conditions predicted in the modeling simulations. Furthermore, with adoption of a sootier fuel source, the measured optical densities were also found to be comparable to those predicted in the modeling simulations. For the 100-kW fire exposures, the inclusion of 0.3 m (1 ft) and 0.6 m (2 ft) deep beams resulted in average delays in relative response times for the detectors spaced at 30 and 42 ft of at most 34 seconds when compared to baseline detector responses. The results from the experimental testing were found to be consistent with the conclusions made in the modeling study with respect to exposure conditions and detector response for devices mounted on the bottoms of beams as opposed to on the ceiling of the beam bay. Furthermore, these results were also consistent with the conclusions of the modeling study regarding the uniformity of exposure conditions within a specific beam bay, suggesting little difference in detector performance for devices mounted on the wall or the ceiling.

To understand the implications of the changes made to the code based upon the conclusions of the modeling study, a comparison was made of the experimental detection time differences between detectors sited per the maximum allowable siting requirements in the 2002 and the 2007 editions of NFPA 72. In general, the 2007 edition allowed fewer detectors per a length of hallway with beams than the 2002 edition. Based upon a 100-kW exposure fire, delays of 8 to 39 seconds were incurred with detectors spaced per the 2007 requirements compared to the 2002 ed. Based upon data from 15-kW exposures, these delays range from 33 seconds to no detection with detectors sited per 2007 requirements. In general, it was found that the changes made to NFPA 72 (2007 ed.) resulted in slower detector response times when compared to the requirements of the previous version (2002 ed.).

Ultimately, the experimental data set collected (i.e., temperatures, optical densities, velocities and detector response times) was generally similar to the modeling data set; however, it was determined that direct use of the fuel source parameters adopted in the modeling study (i.e., a soot yield 2.2 percent) was found to be inadequate for the corridor configurations evaluated. Based upon experimental testing, a soot yield of 2.2 percent was not sufficient to activate the alarms predicted by the model to have activated. It is important to note that in order to obtain comparable detector activation in the experimental data set, it was necessary to use a fuel source with a soot yield of 4.8 percent, over twice that prescribed in the model simulations. This dichotomy between experimental and modeling results can be attributed to FDS v4 not accounting for soot deposition when modeling the transport of smoke.

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