Results from a Full-Scale Smoke Alarm Sensitivity Study

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Abstract

A series of 24 full-scale experiments was conducted during the summer of 2008 to examine the effects of alarm type (photoelectric, ionization, and dual sensor), alarm location, fabric type (100 % cotton and 100 % polyester), polyurethane foam density, ignition scenario, and room configuration, on smoke alarm performance. A two-level, fractional factorial design of eight experimental configurations was developed around the five factors: fabric type, foam density, fire location, ventilation, and ignition scenario. A structure, designed to represent a single-story home or apartment, was constructed inside the Large Fire Laboratory at the National Institute for Standards and Technology for the experiments. The fire source was a chair mockup consisting of a seat and back cushion of a specific cover fabric and foam density, weighing between 5.5 kg and 8.3 kg. It rested on a metal frame and was subjected to a small propane gas flame, or an electric cartridge heater to initiate smoldering. Each experimental configuration was conducted three times. Smoldering fires were allowed to progress until they naturally transitioned to flaming fires except for one test that was terminated early due to time constraints. The smoldering to flaming transition times ranged from (81 to 182) min. Each fire progressed for a time sufficient to produce multiple hazards (smoke, heat, and toxic gases). All alarms tested were purchased from retail outlets and activated at their preset levels. Photoelectric, ionization, and dual photoelectric/ionization alarms were co-located at multiple locations to facilitate comparisons of each alarm type, and different designs of the same type of alarm. For smoke alarms in the room of fire origin, it was observed that each of the five factors had an effect on the measured alarm times that was primarily a result of fire growth rate (fabric type, foam density, and ignition scenario), or smoke dilution (fire location and ventilation). The photoelectric alarm responded quicker on average than ionization alarm in two of four smoldering fire configurations, responding before the ionization alarm in all 6 trials, while the ionization alarm responded before the photoelectric alarm in two of three trials for the other two configurations. The ionization alarm responded quicker on average than photoelectric alarm in all four flaming fire configurations, and responded before the photoelectric alarm in all 12 flaming fire trials. One dual alarm had the fastest average alarm time for all four smoldering fire configurations, and responded first in 11 of the 12 trials. It also yielded faster average alarm times than the other dual alarm in seven of eight configurations, and was the first dual alarm to respond in 22 out of 23 trials where dual alarms were present.

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Introduction

The National Institute of Standards and Technology (NIST) has begun a multi-year program to develop sound performance measurements for smoke alarms that could be used to specify new detection requirements, would not be based on specific technologies, would not require prescriptive installation location mandates in addition to current requirements (every level plus bedrooms, plus interconnected alarms), and would provide better overall performance in residential settings (including hazards to occupants in the room of fire origin.) The work conducted in the NIST Home Smoke Alarm Project [1] laid a foundation to build a strong technical basis for smoke alarm performance assessment. The codes and standards organizations recognize the need for strong technically defensible requirements for smoke alarm performance. However, there is a lack of detailed data needed to objectively resolve current gaps in knowledge and, to more succinctly quantify fire hazard and nuisance alarm susceptibility. Smoke and nuisance source characteristics in any new standard test need to match real-scale test smoke characteristics (size distribution, concentration, rate of production, etc.) and the environmental conditions (air flow, temperature, humidity and gas species). Therefore, smoke alarm performance metrics must be tied to test results that reproduce realistic fire hazards and common nuisance sources. The work described in this paper focuses on full-scale fire tests conducted to generate data for improved smoke alarm performance metrics.

Experimental Design

Characterization of the performance of smoke alarms has historically relied on full-scale fire tests to assess the effectiveness of different types of smoke alarms, alarm locations, and number of alarms [1-3]. A requisite step in a smoke alarm test series is the selection of test fires to conduct as part of the experimental design. Previous extensive studies [1-3] focused on exploring a wide range of test fires to cover many potential fire scenarios and smoke sources. The Indiana Dunes tests [2] used old surplus furniture items that burned less vigorously than modern, primarily synthetic, cushioned furniture items. The NIST home smoke alarm project [1] used three distinct fuel packages for the furniture fire tests. The National Research Council Canada (NRC Canada) smoke alarm tests [3] used small amounts of natural materials (wood, paper, cotton flannel) or synthetic materials (polyurethane foam) to produce fire smokes. In this study, an experimental design was developed to examine the sensitivity of fabric flammability (a slow burning cotton or a fast burning polyester), polyurethane foam density (low density - 21kg/m^3 {1.3 lbs/ft^3} or high density - 29 kg/m^3 {1.8 lbs/ft^3}), fire location (living room or bedroom), ventilation (bedroom door open or closed), and ignition scenario (flaming or initially smoldering). A two-level, fractional factorial design of eight experimental configurations was developed around these five factors: fabric type, foam density, fire location, ventilation, and ignition scenario. Table 1 shows each configuration tested. Each test was replicated twice for a total of 24 tests.

The rationale for selecting these configurations was a desire to cover a wide range of scenarios and to have multiple pairs of configurations where only one factor was varied.

Cotton fabric was used exclusively for smoldering tests because small-scale tests showed the cotton fabric/foam combinations would continue to smolder when the heat source was removed, versus the polyester fabric/foam combinations, which would stop smoldering when the heat source was removed.

Test	Scenario	Foam sample	Fabric type	Fire location	Ventilation (Door)
1	Smoldering	Low density	Cotton	Bedroom	Open
2	Smoldering	Low density	Cotton	Bedroom	Closed
3	Smoldering	Low density	Cotton	Living room	Open
4	Smoldering	High density	Cotton	Living room	Open
5	Flaming	Low density	Polyester	Living room	Open
6	Flaming	Low density	Polyester	Bedroom	Closed
7	Flaming	Low density	Cotton	Living room	Open
8	Flaming	High density	Polyester	Bedroom	Open

Table 1. Experimental Configurations.

The fire tests were conducted in a building mock-up designed to represent a portion of an apartment or small home constructed inside the Large Fire Laboratory at NIST. Figure 1 is a schematic of the structure. It was wood-framed with interior walls and ceilings covered with gypsum wall board, which was spackled and painted.

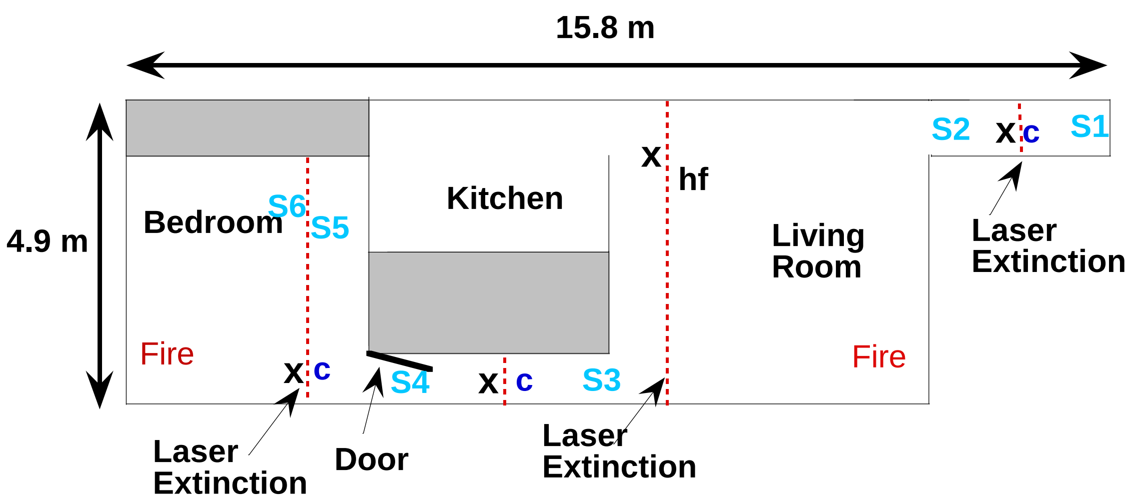

Figure 1. Schematic of the test structure. An X indicates a thermocouple tree. hf shows the location of the total heat flux gage, which was 1.5 m above the floor and pointing toward the fire source. S1…S6 indicate alarm set locations. c indicates gas sampling locations located 1.5 m above the floor. Hydrogen cyanide was sampled at the gas sampling location in the hallway between the bedroom and living room. The dashed lines represent laser beam paths for extinction measurements located 1.5 m above the floor.

The structure consisted of three contiguous spaces labeled, bedroom, kitchen, and living room with two hallways, and a floor to ceiling height of 2.4 m. In figure 1, shaded spaces were sealed off. The ceiling was continuous between the living room, hallways and kitchen (no headers). A door 0.9 m wide and 2.0 m tall connected the bedroom to the adjacent hallway. The hallway to the right of the living room is presumed to connect to additional rooms to complete the layout. No exterior doors or other means of egress were explicitly included. Access doors were built into the structure. Their location was dictated by testing requirements, including access to the fuel source for post-test fire suppression. Exterior doors or other means of egress could be specified at any locations deemed logical to conduct an egress analysis of the space.

A chair mock-up was used as the fire source for each test. The mock-up was constructed from non-fire-retarded, flexible polyurethane foam slabs and matching zippered seat cushion (90 cm by 70 cm by 20 cm) and seat back covers (90 cm by 50 cm by 20 cm) from commercial sources. The cushions rested on a steel frame sitting in a sheet metal pan which in turn was supported by a load cell for mass loss measurements (Photo 1, 2). For each flaming test, the chair seat cushion was ignited by a gas-flame ignition tube (similar to the flaming ignition source described in British Standard 5852 [4]) with a propane fuel flow of 0.75 cm^3/sec. The ignition tube flame was allowed to burn for two minutes before placing it in position next to the chair. To ignite the chair, the tube was placed near the front side of the seat cushion, approximately 1/3 of the way down from the top of the seat, and within 3 mm of the fabric surface (Photo 1). A pneumatic piston attached to a lever arm lowered the ignition tube into position. After 40 s (20 s for one test) of flame exposure, the arm was raised and the ignition flame extinguished. For each smoldering test, smoldering was initiated by a 50 W cylindrical electric cartridge heater 50 mm long and 10 mm in diameter. The cartridge heater rested on a 15 cm by 15 cm square of cotton duct fabric that was placed on the seat cushion to ensure a sustained smoldering fire (Photo2). Electrical power to the cartridge heater was applied in a controlled fashion to achieve an external temperature sufficient to produce sustained smoldering. After about 6 minutes of total contact time, the cartridge heater was removed. Smoldering fires were allowed to progress until they naturally transitioned to flaming fires except for one test that was stopped prior to the flaming transition.

Photoelectric, ionization, and dual photoelectric/ionization alarms were installed side by side at multiple locations to allow for relative performance characterizations. All alarms were purchased from retail outlets and activated at their manufactured preset levels. Each smoke alarm's battery voltage was monitored to determine if it was in alarm by observing a characteristic battery voltage drop signature when the horn was sounding. Figure 2 is a graph of a particular smoke alarm's battery voltage versus time for a period before, during, and after the test button was pressed and the horn sounding. The voltage drop is indicative of the current needed to drive the horn. The uncertainty of the alarm time obtained in this manner is estimated as 1 s, primarily due to the two second data acquisition time.

Groups of four smoke alarms were installed on the ceiling at various fixed locations shown in Figure 1. Smoke alarms were pre-mounted side-by-side on a 0.3 m by 0.6 m

Photo 1. Flaming ignition of a chair mockup. The ignitor was removed after 40 s.

Photo 2. Smoldering ignition of a chair mock-up. The heat source was removed after smoldering initiation (about 6 min).

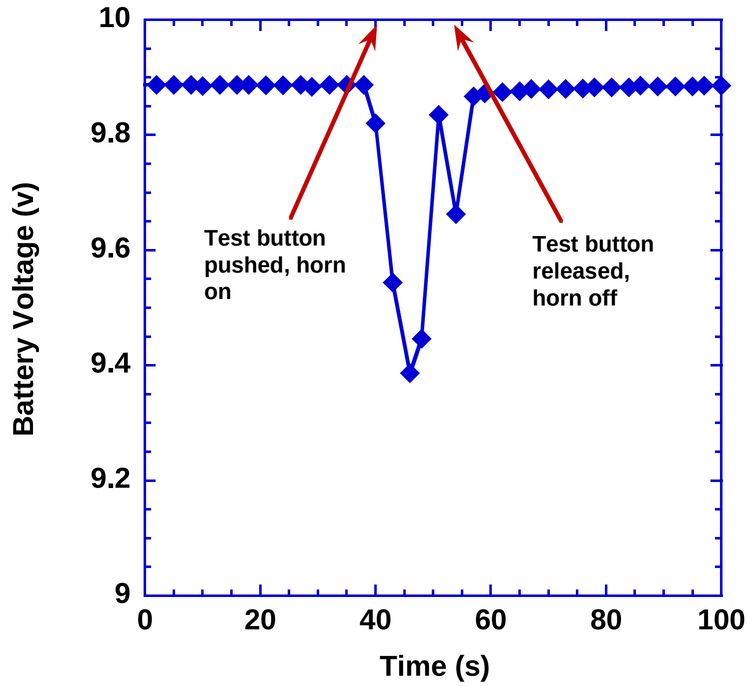

Figure 2. A representative plot of alarm battery voltage signal when the test button was depressed and released.

thin paneling sheet in random order. If smoke alarms in a particular location showed no signs of damage, they were tested and re-used for a following test. Two photoelectric alarms (P1 and P2), two ionization alarms (I1 and I2), and two dual alarms (D1 and D2) from different manufacturers were included in the tests. Smoke alarm groupings consisted of P1, I1, D1, and D2 in set 1 and P1, P2, I1, and I2 in set 2. There were six fixed locations for smoke alarms as indicated in Figure 1. The alarms in Set 1 were placed at locations 1, 3 and 6, and the alarms in Set 2 alarms were placed at locations 2, 4, and 5. Not all locations were populated with alarms during every test.

Additional data was collected which will be used to conduct a thorough analysis of tenability conditions, and to provide information on smoke properties in a subsequent studies. Measurements included gas concentrations of carbon dioxide, carbon monoxide, oxygen, total hydrocarbons, and hydrogen cyanide 1.5 m from the floor at locations indicated in Figure 1. Temperature profiles were collected from 4 thermocouple trees at locations marked by an “X” in Figure. One total heat flux gage was located 1.5 m from the floor with the sensing surface perpendicular to the floor, facing the living room chair mock up. Its location is marked by an “hf” in Figure 1. Laser light extinction measurements were made from diode laser beams (635 nm wavelength) aimed at a photo detectors on opposing walls. The dashed red lines in Figure 1 indicate the path length of the measurements. Lasers and detectors were located outside the test structure to reduce any temperature effects on the extinction measurement. Glass windows allowed the beam to pass through the walls. Two residential CO alarms with LED readouts were placed in hallways and monitored during the tests. Aerosol size distribution and concentration measurements were made with and electrical low pressure impactor in the center hallway. Video cameras recorded scenes in each room during the tests.

Results

Smoldering chairs were allowed to transition to flaming with no artificial inducement in 11 out of 12 smoldering tests. One smoldering test was terminated 142 min after the start of the test, prior to the transition to flaming, due to time constraints. The range for smoldering to flaming transitions for the other 11 tests was between 81 min to 182 min. Average alarm time and the standard deviation for Set 1 alarms (photoelectric, ionization, and two dual alarms) located nearest to the fire source, in the bedroom (S6) or hallway (S3), are given in Table 2 for each configuration. The individual alarm times are given in the appendix. The Set 1 alarm results presented include alarm locations that are required for installations that meet the National Fire Alarm Code (NFPA 72) requirements [5].

Test	Scenario	P1 (s)	I1 (s)	D1 (s)	D2 (s)
1	Smoldering, low density foam, cotton, bedroom, door open	1897 (130)	1876 (201)	2051 (290)	1275 (58)
2	Smoldering, low density foam, cotton, bedroom, door closed	1322 (279)	1268 (162)	1341 (123)	1143 (244)
3	Smoldering, low density foam, cotton, living room, door open	2715 (484)	4042 (1308)	2691 (513)	2393 (686)
4	Smoldering, high density foam, cotton, living room, door open	3045 (605)	5367 (360)	3462 (685)	2758 (1163)
5	Flaming, low density foam, polyester, living room door open	133 (12)	81 (12)	83 (17)	88 (16)
6	Flaming, low density foam, polyester, bedroom, door closed	122 (12)	86 (7)	120 (6)	95 (22)
7*	Flaming, low density foam, cotton, living room, door open	240 (77)	161 (5)	243 (86)	127 (29)
8	Flaming, high density foam polyester, bedroom, door open	159 (17)	107 (8)	144 (27)	112 (16)

*** Average of two tests.**

Table 2. Average alarm times for each configuration for Set 1 alarms located at position S3 for living room tests, and position S6 for bedroom tests. The number in parenthesis is the standard deviation.

Alarm times for only two of the three configuration 7 trials were averaged in Table 1. The very first flaming fire test was a configuration 7 trial where only 20 s of ignition tube flame contact was provided, which resulted in very slow initial fire growth. Subsequent flaming fire tests were conducted with 40 s of ignition tube flame contact to assure sustained flaming ignition of the chair mock-up.

Results from similar configurations were compared to explore the effects of a single or dominant factor. Configurations 1 and 2, smoldering fires, differ only in the position of the bedroom door, either open or closed. Figure 3 is a bar chart that compares the average alarm time values for each alarm type for configurations 1 and 2. From this chart it is obvious that the average alarm time was slower when the bedroom door was open for each alarm type. For configuration 1, the average alarm time for D2 was faster than P1, I1 and D1, which as a group had about the same average alarm times and overlapping standard deviations. D2 also alarmed quicker on average for configuration 2. Interestingly, the ionization alarm responded faster on average than the photoelectric alarm, and responded quicker in two of three trials for both configurations.

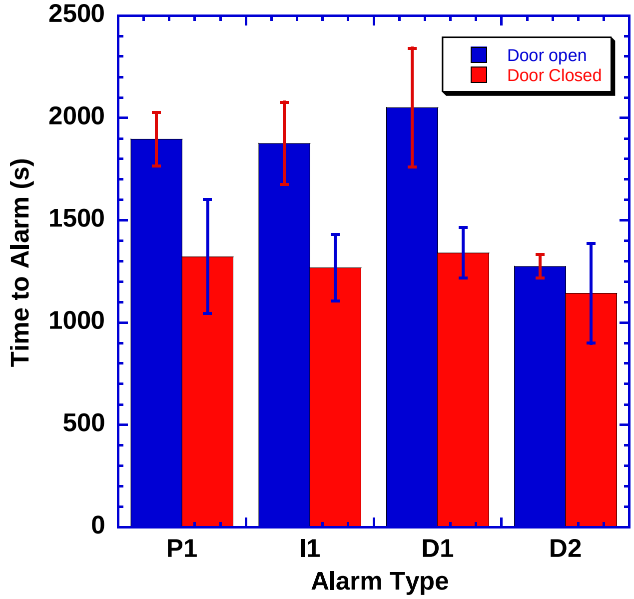

Figure 3. Average alarm time for smoldering, low density foam, cotton fabric tests. Comparison between the bedroom fire with the door opened (configuration 1) or closed (configuration 2). Error bars are one standard deviation.

A possible explanation for the faster alarm times with the door closed is that smoke can build up relatively quicker when the door is closed since it can't spill out into the hallway from under the door header. The smoke thus reached alarm threshold concentrations earlier with the increased rate of smoke build up.

Configurations 1 and 3, smoldering fires, differ in the location of the fire. This factor can be considered as a room size factor. The floor space for the bedroom was 15.7 m^2 (169 ft^2) while the living room, kitchen and two connected hallways had a combined floor space of 39.9 m^2 (429 ft^2), some two and half times greater than the bedroom. Figure 4 is a bar chart that compares the average values for configurations 1 and 3. The average time to alarm for fires located in the living room were slower than fires located in the bedroom with the average difference ranging from 640 s for D1 and 2166 s for I1. For the living room fire configuration, D2 responded first and the ionization alarm responded last in all three trials.

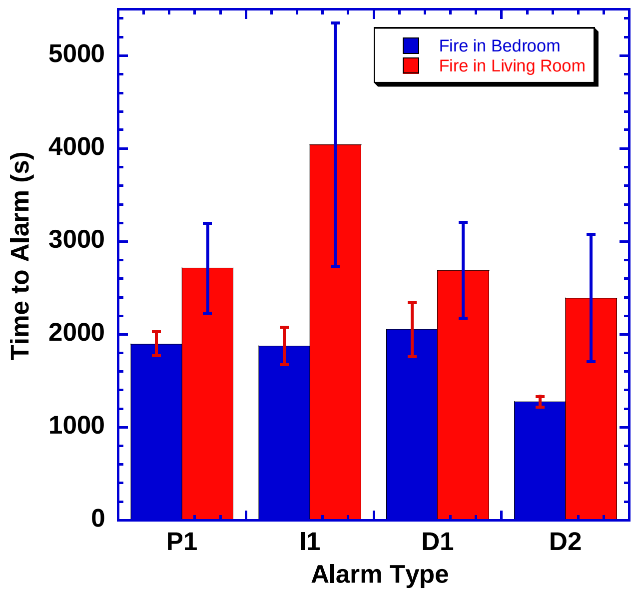

Figure 4. Average alarm time for smoldering, low density foam, cotton fabric tests. Comparison between the fire located in bedroom (configuration 1) versus the living room (configuration 3). Error bars are one standard deviation.

The effect of room size is most likely a dilution effect. The living room and connected spaces provide 2.5 times more volume than the bedroom, thus the smolder smoke can mix in a much larger space yielding slower smoke concentration build up and slower alarm times. The observation that the ionization alarm was slower to respond in the living room fires suggests that dynamic effects beyond the dilution rate like smoke entry delay, or coagulation were impacting the ionization sensor response.

Configurations 3 and 4, smoldering fires, differ in the foam density used in the chair mockups. Figure 5 shows that the high density foam smoldering fires yielded slower

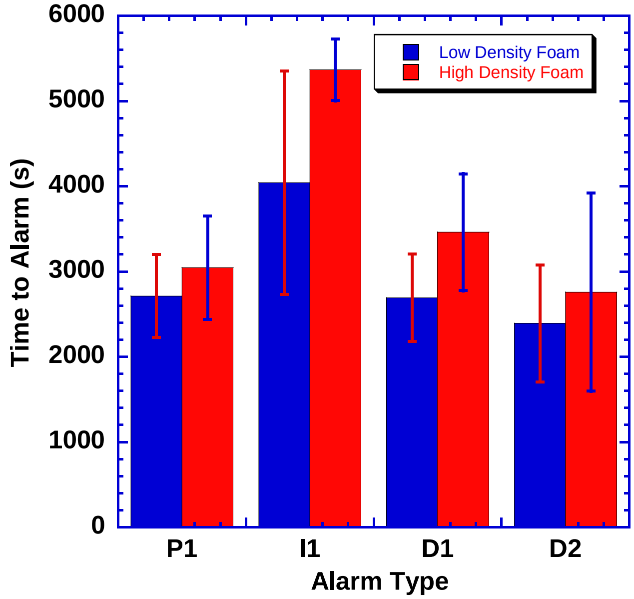

Figure 5. Average alarm time for living room smoldering fire, cotton fabric tests. Comparison between foam density, low (configuration 3) and high (configuration 4). Error bars are one standard deviation.

average alarm times than the low density foam smoldering fires. The photoelectric alarm responded before the ionization alarm in all six trials. D2 had the fastest average alarm time for both configurations, and responded first in five of six trials.

Foam density appeared to have an effect on the rate of smoldering, with the high density foam smoldering slower with a lower smoke production rate than the low density foam.

Configurations 3 and 7 differ in the ignition mode of the chair mockups. The obvious effect of disparate rates of fire growth on the alarm times is shown in Figure 6. The average alarm times for the four alarm types ranged from about 40 min to 67 min for smoldering fires, and about 2 min to 4 min for flaming fires. D2 responded first in all three trials of configuration 3 and both trials of configuration 7 considered in Table 2.

Configurations 5 and 7, flaming fires, differ in the covering fabric used in the chair mockups. Figure 7 shows that the average alarm times for the polyester fabric tests were faster than the cotton fabric tests. In configuration 7 (cotton fabric), D2 had the fastest average alarm time, while D1 had the slowest average alarm time. In configuration 5 (polyester fabric), I1 had the fastest average alarm time, responding first in two of three trials, while P1 had the slowest average alarm time, responding last in all three trials.

The polyester covering fabric produced a faster growing fire than the cotton fabric. These fabrics were selected since they represent a range of fire growth rates.

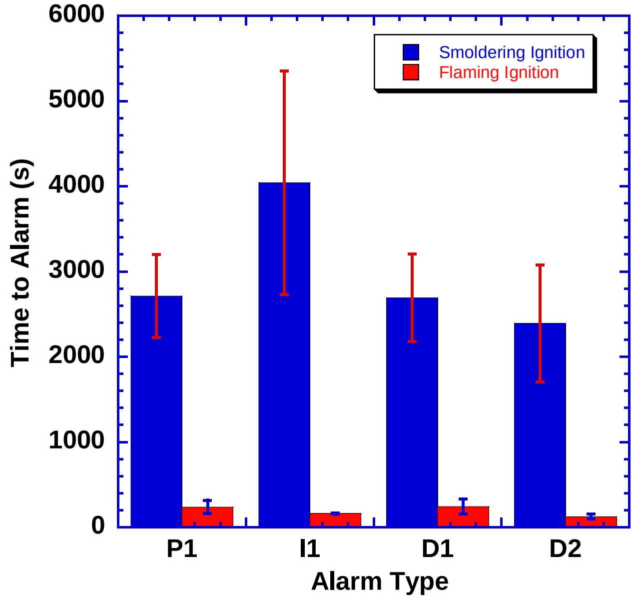

Figure 6. Average alarm time for living room, low density foam, cotton fabric tests. Comparison between smoldering (configuration 3) and flaming (configuration 7) fires. Error bars are one standard deviation.

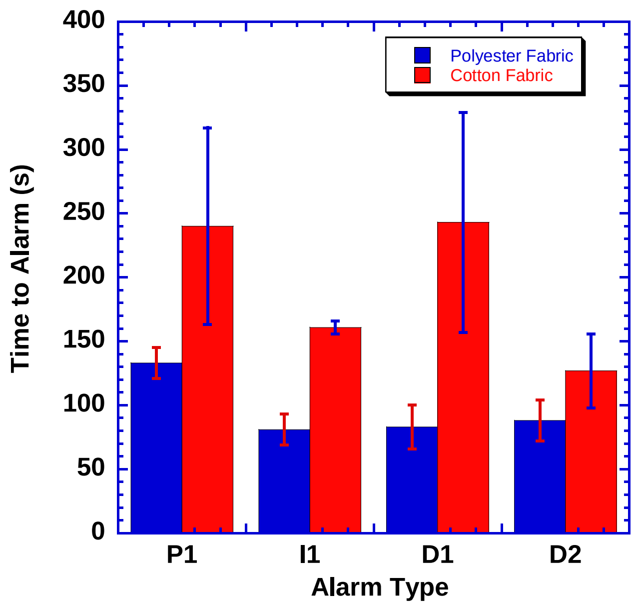

Figure 7. Average alarm time for flaming, low density foam, living room fires. Comparison between the polyester (configuration 5) and cotton (configuration 7) fabrics. Error bars are one standard deviation.

Configurations 6 and 8 differed in two factors: foam density, and door position. Figure 8 shows that configuration 8, (door open, high density foam) yielded slower average alarm times than configuration 6, (door closed, low density foam) for each alarm type. I1 had the fastest average alarm time, while P1 had the slowest average alarm time for both configurations.

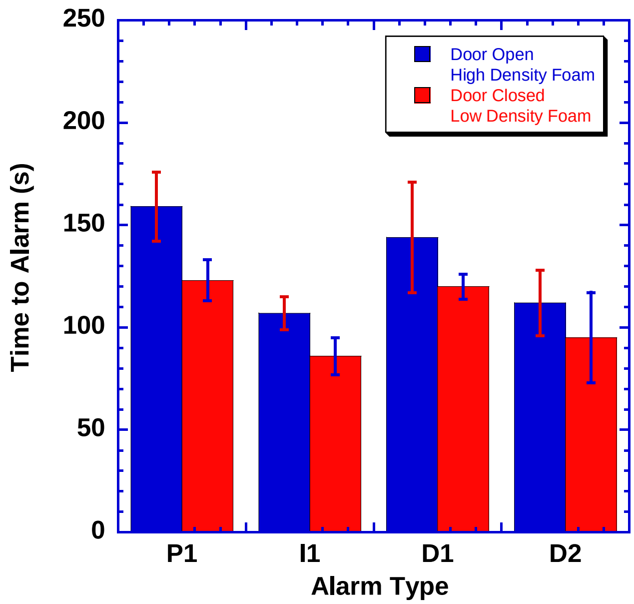

Figure 8. Average alarm time for flaming, polyester fabric, bedroom fires. Comparison between configuration 8 (door open, high density foam) and configuration 6 (door closed, low density foam. Error bars are one standard deviation.

The door position was a significant factor in the smoldering fire tests. It is not clear if the foam density had a positive or negative effect with respect to door position. However, as suggested below, a slower mass loss rate of the high density foam chair fires would shift alarm times to slower values, which is the same expected direction of time shift for an open door versus a closed door configuration. Thus the observed increase in alarm times between configurations 6 and 8 is most likely split between the effects of high density foam, and an open door position.

Configurations 5 and 8 differed in two factors, foam density and fire location. Figure 9 shows configuration 8 (bedroom, high density foam) yielded slower average alarm times than configuration 5 (living room, low density foam) for each alarm type. I1 had the fastest average alarm time and P1 had the slowest average alarm time for both configurations.

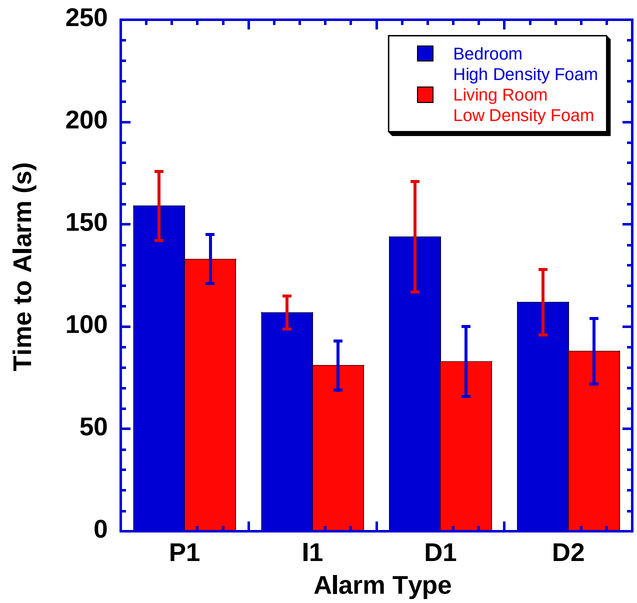

Figure 9. Average alarm time for flaming, polyester fabric fires. Comparison between configuration 8 (bedroom, high density foam fire) and configuration 5 (living room, low density foam fire). Error bars are one standard deviation.

Since the high density foam burning in the bedroom yielded slower average alarm times than the low density foam burning in the bedroom, this result suggests that the high density foam fires had a slower fire growth rate. Figure 10 shows two mass loss rate curves for representative tests of these two configurations. The mass loss rate uncertainty is estimated as 0.001 kg/s. The slower initial mass loss rate of the high density chair mockup most likely delayed the smoke concentration build up and the time to reach alarm concentrations.

Conclusions

From the examination of the alarm times of the smoke alarms near the fire source, and considering the five factors that make up the configurations, the following conclusions were drawn.

It was observed that each of the five factors had an effect on the measured alarm times that was primarily a result of fire growth rate (fabric type, foam density, and ignition scenario), or smoke dilution (fire location and ventilation).

1. The mode of ignition had a significant effect. Alarm times for smoldering fires were a factor of about 10 to 25 times slower than flaming fires.

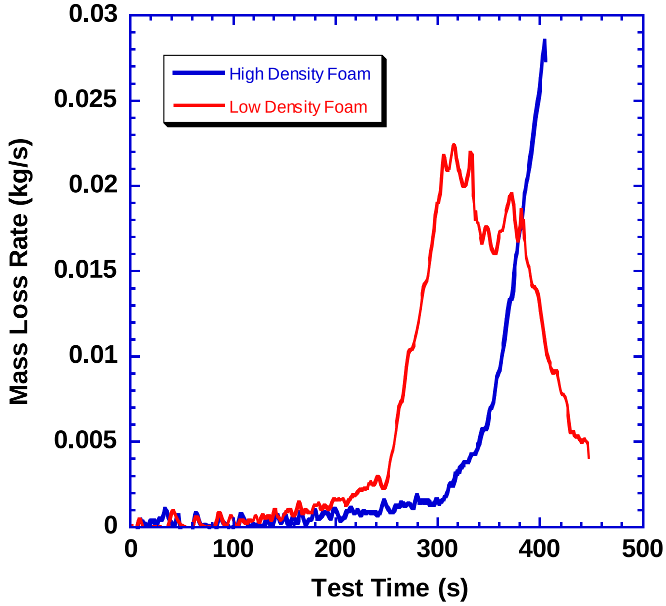

Figure 10. The mass loss rate for a configuration 8 flaming fire test (bedroom, high density foam) and a configuration 5 flaming fire test (living room, low density foam).

2. The effect of density of the polyurethane foams tested in this study was faster alarm times for both flaming and smoldering fires with the low density foam. It appears that both the smoldering rate and the flaming-fire burning rate were slower with the high density polyurethane foam.

3. The cushion covering fabric had an effect on alarm time for flaming fires. Polyester fabric was observed to yield faster average alarm times than the cotton fabric. This is consistent with a slower fire growth rate of cotton-covered cushions.

4. Placing the smoldering fire in the living room had the effect of increasing alarm times compared to bedroom smoldering fires, with an average time increase of about 40% to over 200% depending on the alarm type. This was primarily a room volume dilution effect.

5. Having the bedroom door open rather than closed for bedroom fires had the effect of increasing the average alarm times for both flaming and smoldering fires. For alarms located in the bedroom, this was primarily a room volume dilution effect.

6. Photoelectric alarm P1 responded quicker on average than ionization alarm I1 in two of four smoldering fire configurations. It responded before I1 in all 6 trials. For the two

other smoldering fire configurations I1 responded quicker on average than P1. It responded before P1 in four of six trials.

7. Ionization alarm I1 responded quicker on average than photoelectric alarm P1 in all four flaming fire configurations. It responded before P1 in all 12 trials.

8. Dual alarm D2 had the fastest average alarm time for all four smoldering fire configurations, and responded first in 11 of the 12 trials.

9. Dual alarm D2 yielded faster average alarm times than dual alarm D1 in seven of eight configurations, and was the first dual alarm to respond in 22 out of 23 trials where dual alarms were present.

Future Research

This preliminary analysis presents key results from the smoke alarm sensitivity study. Additional analysis is being conducted to assess the available safe egress times based on tenability criteria and alarm times, and time needed for occupants to escape threatening fires. Detailed analysis of the sensitivity of individual sensors in the photoelectric, ionization, and dual alarms will be conducted to shed light on individual alarm performance observed in the full-scale tests. In addition analysis of the particle size statistics and concentration measurements will be performed to better quantify the smoke evolution and smoke size properties of these fires.

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Appendix

Test Configuration	Experiment Number	Alarm Location	Alarm Time (s)			
			P1	I1	D1	D2
1	12	S6	1775	1773	1775	1316
1	14	S6	2033	1747	2025	1209
1	15	S6	1884	2108	2354	1301
2	2	S6	1352	1222	1449	1256
2	9	S6	1585	1448	1367	1311
2	13	S6	1030	1134	1208	863
3	5	S3	3266	5166	3284	3185
3	20	S3	2356	2606	2404	1980
3	22	S3	2524	4354	2386	2015
4	16	S3	3143	5275	2939	4068
4	21	S3	3596	5764	4237	1847
4	23	S3	2397	5061	3210	2360
5	4	S3	141	67	90	78
5	17	S3	120	89	96	106
5	19	S3	139	87	64	80
6	3	S6	125	94	117	86
6	7	S6	132	84	127	78
6	11	S6	108	81	117	120
7*	1	S3	1214	465	411	508
7	6	S3	295	157	182	147
7	18	S3	185	164	303	106
8#	8	S6	158	105	-	-
8	10	S6	142	100	125	123
8	24	S6	176	116	163	101

*** Not averaged in Table 2**
 # No dual alarms at location S6

Table A1. Alarm times for Set one alarms located at S3 and S6