Full-Scale Residential Smoke Alarm Performance[1]

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Abstract

A series of 24 full-scale fire experiments were conducted in a multi-room structure to examine the effects of alarm type (photoelectric, ionization, and dual sensor), alarm location, fabric type (cotton and polyester), polyurethane foam density, ignition scenario (smoldering or flaming), and room configuration on smoke alarm performance. The fire source was a chair mock-up consisting of a seat and back cushion of a specific fabric and foam density, resting on a metal frame. Each fire progressed for a time sufficient to produce multiple hazards (smoke, heat, toxic gases) throughout the compartment. Photoelectric, ionization, and dual photoelectric/ionization alarms were co-located at multiple locations to facilitate comparisons of each type of alarm. In the room of fire origin, a smoke optical density of 0.25 m^{-1} was reached before a fractional effective dose of 0.3 for either toxic gases or heat exposure. The available safe egress time (ASET) for both flaming and smoldering fires was sensitive to the imposed optical density limit. Further study is needed to deduce the impact of visibility-limiting smoke levels on the time needed to egress residential fires to justify any particular optical density limit value.

Introduction

Historically, in the US the performance assessment of residential smoke alarms has been based on results from full-scale fire tests [1, 2]. The NIST home smoke alarm project laid a foundation to build a strong technical basis for smoke alarm performance assessment [2]. By allowing fires to grow until conditions that threaten life safety are surpassed, the time available for escape, termed the available safe egress time (ASET), can be estimated from the difference between the time it takes to develop hazardous conditions and an alarm's activation time. The standard ISO/TS 13571 *Life Threat from Fires – Guidance on the Estimation of Time Available for Escape Using Fire Data* [3] provides a methodology for estimating available safe egress time from smoke, heat,

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and toxic gase exposure. Smoke exposure is a threshold concentration or optical density where visibility along escape routes is significantly reduced. The smoke optical density limit specified in the NIST home smoke alarm tests was an optical density (OD) value of 0.25 m^{-1} [1], while ISO/TC 13571 proposes an OD of 1.7 m^{-1} [3], a value where it was estimated that one could not see more than an arms length (0.5 m) distance. At an OD of 0.25 m^{-1}, the research of Jin and Yamada [4] suggests a visibility distance of 5 m for reflective surfaces (walls, doors, objects), while at an OD of 0.5 m^{-1}, the visibility distance drops to 2.5 m which retains egress capabililty, albeit at a slower pace. Heat and toxic gas exposure effects are cummulative with threshold values of incapacitiation for exposed persons. The toxic gas model, and the heat and radiative energy model specified in the ISO standard [3] use equations that integrate doses of relavent gases or heat exposure into a value termed the fractional effective dose (FED). The equations are available in the standard, or in the NIST Home Smoke Alarm report [2]. A fractional effective dose of 0.3 corresponds to an incapacitation threshold for more susceptible people (this value was used in the NIST study [2]), and a value of 1.0 corresponds to the dose where one half of the population would be incapacitated. Becoming incapacitated or unable to escape due to limited visibility is considered the end point for ASET evaluation. Typically, the ASET is compared to the time required for occupants to escape, the required safe egress time (RSET). Unfortunately, there is no single value of RSET since it depends on variables such as travel distances, age and mobility of occupants, actions taken, and whether occupants assist or rescue others. A bounding value of about 2 minutes has been estimated to encompass a large fraction of the RSET distribution in typical residences [2]. An increase in the RSET bounding value accounts for an additional fraction of occupants that require more time to escape.

Experimental Design

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 – 21 kg/m^3 or high density - 29 kg/m^3), fire location (living room or bedroom), ventilation (bedroom door open or closed), and ignition scenario (flaming or initially smoldering) on smoke alarm performance. 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.

Experiments 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. It consisted of three contiguous spaces and a floor to ceiling height of 2.4 m. The ceiling was continuous

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

Table 1. Experimental Configurations

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, and shaded spaces were sealed. The hallway to the right of the living room was presumed to connect to additional rooms to complete the layout.

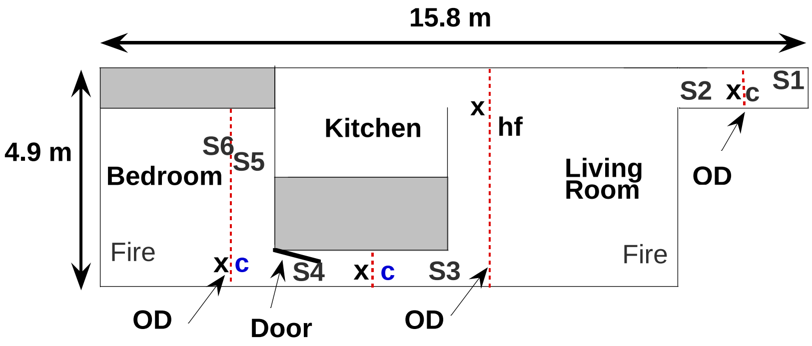

Figure 1. Schematic of the test structure.

An “x“ indicates the position of a type-K bare bead thermocouple, located 1.5 m above the floor. “hf“ indicates the position of a Schmidt-Boelter-type total heat flux gage located 1.5 m above the floor and pointing toward the fire source. S1…S6 indicate alarm set locations. A “c“ indicates a gas sampling tube position located 1.5 m above the floor, where carbon monoxide and carbon dioxide concentrations were measured with non-dispersive infrared gas analyzers. Temperature, heat flux, and gas concentration relative expanded uncertainties were estimated as ± 5%, ± 6% and ± 12%, respectively, following a previous uncertainty analysis [5]. The dashed lines represent beam paths for laser transmission measurements located 1.5 m above the floor. Optical densities were estimated from light transmission measurements across each hallway, living room, and bedroom. The relative expanded uncertainty for optical density was estimated as ± 10% [2].

Commercially available photoelectric, ionization, and two dual photoelectric/ionization alarms were installed side by side at multiple locations to allow for relative performance characterizations. A characteristic battery voltage drop signature indicating when the alarm horn was sounding was used to estimate each alarm time. The expanded uncertainty of the alarm time obtained in this manner is estimated as ±1 s.

A chair mock-up constructed from non-fire-retarded, flexible polyurethane foam slabs and matching zippered seat cushion and seat back cover, weighing between 5.5 kg and 8.3 kg, and resting on a steel frame was used as the fire source for each test. Flaming was initiated by a gas-flame ignition tube (similar to the flaming ignition source described in British Standard 5852 [6]) with a propane flow of 0.75 cm^3/s and 40 s of flame contact. Smoldering was initiated by a 50 W cylindrical electric cartridge heater 50 mm long and 10 mm in diameter resting on a 15 cm by 15 cm square of cotton duct fabric that was placed on the seat cushion. The cartridge heater was removed after 6 minutes.

Experimental Results

Alarm times for alarms (photoelectric – P1, ionization – I1, and two dual alarms – D1 and D2) located nearest to the fire source, in the bedroom (S6) or hallway (S3), are given in Table 2 for each test. The results presented include alarm locations for installations that meet the National Fire Alarm Code (NFPA 72) requirements [7]. A previous paper discusses the alarm time trends observed with these smoke alarms [8]. Smoldering chairs were allowed to transition to flaming in 11 of 12 smoldering tests with the time to flaming indicated in the table. One smoldering test (No. 14) was terminated 142 min after the start of the test, prior to a transition to flaming, due to time constraints.

Figures 1 and 2 show FED calculations and OD values for a flaming fire test (No. 19) and smoldering fire test (No. 22) respectively. Table 3 shows the times to reach FED and smoke limits in the room of fire origin or adjacent hallways (whichever location reaches the threshold first). FED heat calculations for living room fires account for heat flux exposure. Smoke limits include OD values of 0.25 m^{-1}, 0.50 m^{-1}, and 1.7 m^{-1}. Temperature, heat flux and gas concentrations at a height 1.5 m from the floor were used to calculate FED [3]. The total expanded uncertainty for the FED of toxic gases (carbon monoxide and carbon dioxide) is $\pm$ 0.01, and for heat exposure is $\pm$ 0.02 for the computations performed.

Exp. Conf.	**Test No., Alarm Location**	**Time to Flaming (s, $\pm$ 1s)**	**Alarm Time (s, $\pm$ 1 s)**			
			P1	**I1**	**D1**	**D2**
1	12, S6	4838	1775	1773	1775	1316
1	14, S6	NA	2033	1747	2025	1209
1	15, S6	10944	1884	2108	2354	1301
2	2, S6	6000	1352	1222	1449	1256
2	9, S6	6845	1585	1448	1367	1311
2	13, S6	10392	1030	1134	1208	863
3	5, S3	6295	3266	5166	3284	3185
3	20, S3	9997	2356	2606	2404	1980
3	22, S3	5836	2524	4354	2386	2015
4	16, S3	5252	3143	5275	2939	4068
4	21, S3	4736	3596	5764	4237	1847
4	23, S3	5187	2397	5061	3210	2360
5	4, S3	0	141	67	90	78
5	17, S3	0	120	89	96	106
5	19, S3	0	139	87	64	80
6	3, S6	0	125	94	117	86
6	7, S6	0	132	84	127	78
6	11, S6	0	108	81	117	120
7	1, S3	0	1214	465	411	508
7	6, S3	0	295	157	182	147
7	18, S3	0	185	164	303	106
8#	8, S6	0	158	105	-	-
8	10, S6	0	142	100	125	123
8	24, S6	0	176	116	163	101

No dual alarms at location S6

Table 2. Alarm times for alarms located at S3 and S6.

An OD of 0.25 m^{-1} was reached first in all tests where smoke was measured in the room of fire origin, followed by the OD of 0.5 m^{-1} in all but one test where a toxic gas FED of 0.3 was reached. Nine out of twelve smoldering fire tests reached a toxic gas FED of 0.3 before a heat FED of 0.3. For all flaming fire scenarios, a toxic gas FED of 0.3 was never reached before the end of a test. These trends are similar to those observed in the previous NIST study [2].

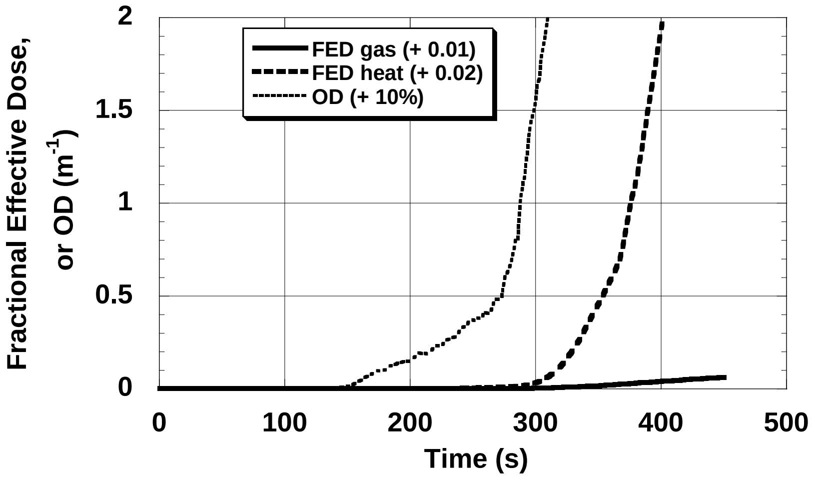

Fig 1. Evolution of toxic gas and heat FED, and OD for a flaming fire.

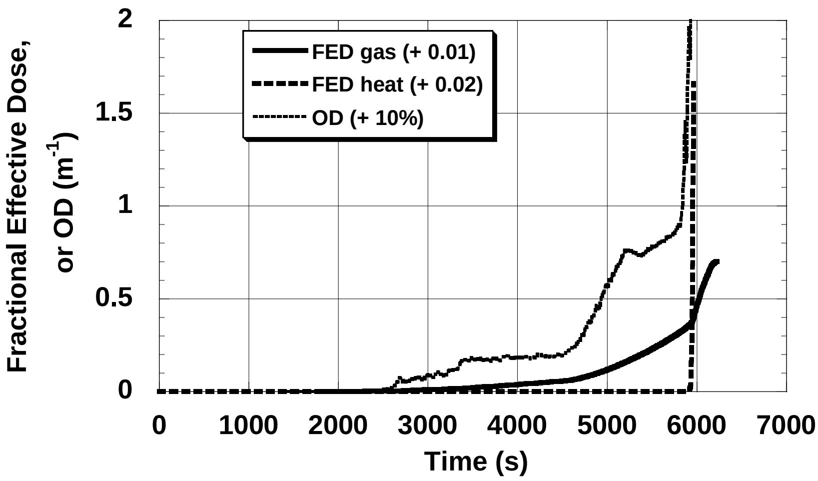

Fig 2. Evolution of toxic gas and heat FED and OD for a smoldering fire.

The difference between a limiting time in Table 3 and a corresponding alarm time in Table 2 can be used to estimate an ASET provided by a particular alarm for a given test. The limiting time chosen from Table 3 depends on a set of assumptions regarding tenability. Using the most conservative limits (FED of 0.3 and OD of 0.25 m^{-1}), P1, D1, and D2 provided positive ASET values for all tests, while I1 provided positive ASET values in 20 of 24 tests. The fraction of tests that provided ASET values of 120 s or greater was 10/24, 6/24, 3/23, and 2/23 for P1, I1, D1, and D2 respectively. At an OD limit of 0.5 m^{-1}, all alarms provide positive ASET values for all tests, and the fraction of tests with ASET values of 120 s or greater was 22/24 for P1 and 100% for I1, D1, and D2. This observed ASET sensitivity to the smoke OD value, and the wide range of OD limits require additional study to assess the impact of reduced egress time due to smoke obscuration and the resultant impact on the RSET distribution for residential settings.

Exp. Conf., Test	**FED toxic gas ($\pm$ 0.01)**		**FED heat ($\pm$ 0.02)**		**Optical Density (m^{-1}, $\pm$ 10%)**		
	0.3	**1.0**	**0.3**	**1.0**	**0.25**	**0.5**	**1.7**
1, 12	5060	--	4977	4995	3228	4738	--
1, 14	6141	--	--	--	2335	--	--
1, 15	7574	10376	--	--	5144	7047	11011
2, 2	4737	6287	6296	6321	1822	2532	NA
2, 9	5877	--	--	--	3654	4757	NA
2, 13	4469	6527	--	--	1801	2590	NA
3, 5	6360	--	--	--	5199	5352	6297
3, 20	6120	8690	10060	10070	2424	6366	10046
3, 22	5749	--	5945	5958	3990	4931	5902
4, 16	--	--	5406	5412	5279	5347	5353
4, 21	6163	--	6351	6366	5783	6049	6373
4, 23	--	--	5323	5338	5160	5243	5269
5, 4	--	--	286	305	206	224	265
5, 17	--	--	361	383	216	293	333
5, 19	--	--	332	376	228	274	305
6, 3	--	--	308	332	245	279	NA
6, 7	--	--	294	317	210	250	NA
6, 11			269	292	218	253	NA
7, 1	--	--	1404	1433	1347	1359	--
7, 6	--	--	500	518	397	456	518
7, 18	--	--	967	980	905	914	974
8, 8	--	--	407	427	273	355	433
8, 10	--	--	391	--	230	337	--
8, 24	--	--	379	399	239	321	--

Table 3. Time to reach optical density or FED limits, -- limit not reached

Summary

Considering the room of fire origin, a smoke OD of 0.25 m^{-1} was reached before a toxic gas or heat FED of 0.3. An OD of 0.5 m^{-1} was the second limit reached in all but one test, in which a toxic gas FED of 0.3 was reached first. Nine of twelve smoldering fire tests reached a toxic gas FED of 0.3 before a heat FED of 0.3 was reached. For all flaming fire tests a toxic gas FED of 0.3 was never reached before the end of a test. For both flaming and smoldering fires, ASET estimates were sensitive to the OD limit. Further study is needed to deduce the impact of visibility-limiting smoke levels on the time needed to egress residential fires.

References

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