Smoke Alarm Response and Tenability

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Abstract

A set of apartment fires with flaming and smoldering fire scenarios were used to assess the performance of various smoke alarm technologies relative to available escape time before untenable conditions.

Introduction

The primary goal of a smoke alarm is to provide adequate warning to occupants before conditions become untenable in a fire. There are currently three types of smoke detection technologies available in residential alarms; ionization, photoelectric, and combination ion and photo. There has been very limited testing of all three smoke alarm technologies relative to realistic fire conditions that reach untenable conditions (i.e., incapacitating toxic gas or thermal exposure limits). The primary objective of this work was to evaluate the performance of commercially available residential smoke alarms with respect to the development of untenable conditions in the residential setting.

Experimental Setup and Procedure

Smoke alarms were installed in seven tests of a larger series of full-scale, limited ventilation enclosure fire tests. A detailed description of the entire test series is provided in Reference [1]. A summary of the four smoldering and three flaming tests with alarms is presented in Table 1. The test series was conducted within a 41.8 m^2 (450 ft^2) apartment-style enclosure of four, inter-connected rooms. An overview of the test enclosure is provided in Fig. 1. All rooms were open to each other through doorways with soffits and no doors. The enclosure was fully closed in all tests except one where the bottom pane of the bedroom window was half open with a vent area of 0.41 m^2 (1.33 ft^2).

A summary of the fuel packages used in these tests is provided in Table 2. For the smoldering tests, electric cartridge heaters were used as the

ignition source. Initially, comforters purchased from a retail store were evaluated for a smoldering bedding scenario. However, sustained smoldering was not achievable. Therefore, the use of cotton batting was used as a bounding source for bedding, since it has been established in prior works as a reliable self-sustaining smolder source with significant carbon monoxide production. In order to have a test that would last multiple hours, a large quantity of cotton batting (36 m^2 (384 ft^2)) was used and folded into a thick pile. It is expected that this source material and configuration bounds many bedding products in ease of smolder, duration of smolder and CO production. Sustained smoldering with the new Sofa A products was not achievable, even with various ignition scenarios, such as that used in SM4. Consequently, an older sofa from a thrift store (Sofa B) was obtained and used in test SM4 to successfully develop self-sustaining smolder.

Table 1. Summary of Tests Conducted with Smoke Alarms**.**

Test ID	Fire Type	Fuel	Ignition Source	Fire Loc.	Vent. Scheme	Alarm Cluster Locations
SM1	S	Cotton Batting	Heater	BR	Closed	2 & 3
SM2	S	Sofa A	Heater	LR	Closed	1 & 2
SM3	S	Sofa A	Heater	LR	Closed	1 & 2
SM4	S	Sofa B	Heater	LR	Closed	1 & 2
S1	F	Sofa A	Tissue Box	LR	Closed	1 & 2
CH1	F	Wooden Cabinet	Tissue Box	K	Closed	1 & 3
CH2	F	Wooden Cabinet	Tissue Box	K	Half-window	1 & 3

The flaming sofa and cabinet fires represent realistic fire scenarios in which a small combustible source is ignited and grows to ultimately impinge on and ignite the primary fuel source. A set of tissue boxes ignited with a small flame served as the small combustible ignition source. This source is representative of many combustibles ranging from clothing to paper to toys to other miscellaneous items, in which the object is ignited with a small flame or represents a combustible ignited from a smoldering to flaming transition.

Smoke alarm clusters (shown in Fig. 2) consisted of 3 ionization, 3 photoelectric, and 2 dual sensor alarms from three manufacturers. Individual alarm activations were monitored with the data acquisition system. Thermocouples, gas sampling, and optical density meters (in general accordance with UL 217) were used to characterize conditions at

locations applicable to occupant tenability (i.e., at 0.6 m (2 ft) and 1.5 m (5 ft) heights along the path of egress). These instrument locations are also shown in Fig. 2 as the points of tenability locations.

Prior to each test, alarm activation was verified using the test button on each device. Testing began with the initiation of the source (i.e., flaming tissue box or heating element on). The fire was permitted to develop naturally, and tests were concluded once the fire source was consumed or conditions within the space began returning to ambient conditions.

Tenability Analysis

Evaluating the fire detection performance of smoke alarms is primarily dependent on the development of untenable conditions along the path of egress. Tenability within a space was assessed based upon the development of thermal and toxic gas conditions at elevations relevant to occupant egress. The development of visible smoke within a space has been considered in tenability analyses; however, visibility through smoke is not actually a measure of a life threatening tenability criterion. Reduced visibility is often considered as a mechanism that slows occupant egress as opposed to directly contributing to the incapacitation of occupants. The path of egress was considered to be from the bedroom, through the dining room, and into the living room prior to exiting out the front door.

Thermally untenable conditions are generally considered to be reached when temperatures measured at 1.5 m (5 ft) exceed the threshold of 120°C [2,3]. At this temperature, a relatively short duration exposure can result in skin burn and the potential incapacitation of an occupant. Purser reports the tolerance time for exposure to 120°C as being 7 minutes [3].

Untenable carbon monoxide (CO) conditions can be determined using the product of transient gas concentrations and exposure duration, also known as a dose. A fractional effective dose (FED) can be calculated by normalizing the measured dose of CO with an empirical value of 35,000 ppm-min, determined to be lethal in experimental studies [2,4]. ISO 13571 suggests the use of an FED threshold criterion for tenability of 0.3. This value is considered to be a conservative tenability limit given that statistics indicate 11 percent of the population is sensitive to a lesser toxic gas exposure [2]. Many studies have used FED thresholds of 1 as the incapacitating dose. The CO FED calculation assumes that an occupant is in the room for which the calculation is performed for the entire duration.

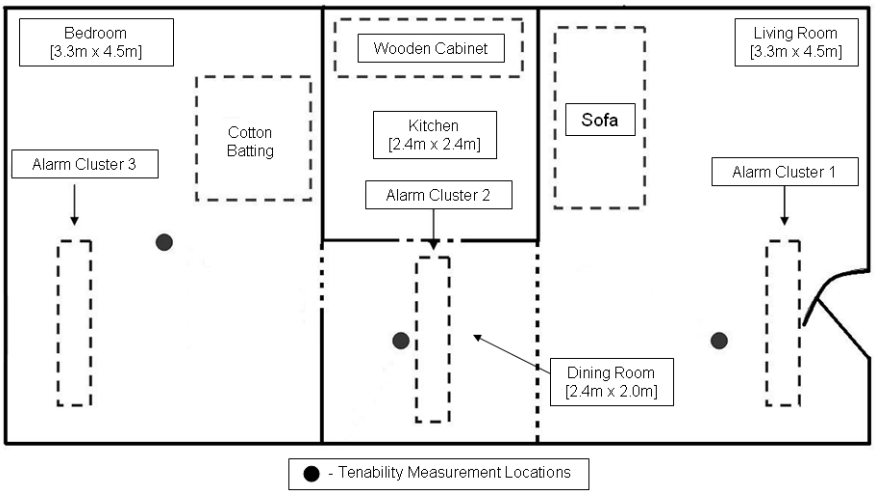

Fig. 1. Overview of the test enclosure.

Many studies have used smoke concentration (or visibility) as a criterion for which an occupant may stop attempting to egress. However, a specific value for the critical smoke level has not been fully agreed upon by the fire protection community. Threshold values currently being cited include, but are not limited to, 0.25 OD/m, 0.43 OD/m, and 0.87 OD/m which correlate to visibilities of approximately 4-5.2 m (13–17 ft), 2.3–3.0 m (7.5–10 ft), and 1.1–1.5 m (3.6–5 ft), respectively [5,6,2].

Discussion of Results

Specific times to untenable conditions and various smoke levels are presented in Ref [1] along with individual smoke alarm response times. Untenable thermal and toxic gas levels (and high smoke levels) were reached much faster in the flaming fires compared to the smoldering fires. There was negligible temperature rise and negligible reduction in oxygen in the smoldering tests (SM1 to SM4). In the smoldering cotton batting (SM1) and the smoldering sofa (SM4) tests, there was a notable increase in CO and smoke. However, in contrast to the smoldering fires, the flaming fires (S1, CH1 and CH2) produced the most hazardous fire conditions. These flaming fires produced elevated temperatures, with two of them exceeding the tenable threshold of 120°C. Oxygen concentrations were reduced to about 14 to 15 percent along the path of egress and CO levels exceeded FED values of one, indicating lethal exposures. In addition, smoke density levels exceeded 2.1 OD/m, representing loss of visibility down below the 0.6 m (2 ft) height.

Table 2. Summary of Fuels used in Fire Scenarios

Fire Source	Description
Upholstered Sofa A	IKEA Klippan style sofa measuring 1.8 m (5.9 ft) wide by 0.9 m (2.9 ft) deep by 0.7 m (2.3 ft) high. Constructed from PU foam with polyester wadding in the cushions, seat back, and armrest. The upholstery fabric is 100% cotton.
Upholstered Sofa B	Upholstered sofa comparable in size to Sofa A purchased from a thrift store. Constructed from PU foam with cotton upholstery fabric and wood frame.
Wooden Cabinet	Kitchen Kompact Chadwood 2 oak cabinets measuring 0.5 m (18 in. wide by 0.3 m (12 in.) deep by 0.8 m (30 in.) high. An array consisted of 4 cabinets placed side by side. Two of the four cabinets contain a combination of cellulosic and plastic fuel load to simulated typical cabinet stock. The remaining cabinets remained empty.
Cotton Batting	100% cotton batting folded to a dimension of 0.5 m (21 in.) wide by 0.4 m (17 in.) deep by 0.2 m (8 in.) high.

With the exception of two devices in test SM2, all alarms activated in all tests. In test SM2 (as in SM3), the sofa did not develop a self-sustaining smoldering fire; the foam only pyrolized to a small diameter around the cartridge heater. Consequently, the conditions within the enclosure were quite benign. There was visible smoke throughout the whole apartment but only sufficient to reach the lowest smoke criteria of 0.25 OD/m (~5 m visibility) at the 1.5 m (5 ft) elevation in about a half an hour.

In general, for the smoldering fires, the combination alarms responded the earliest, with photoelectric alarms providing a slightly slower response (~4.5 min. later), and ionization alarms responding the slowest (~13.7 min.). For flaming fires, the ionization alarms were generally the quickest to respond with the combination alarms lagging only slightly behind (~13 s) and the photoelectric alarms responding the slowest (67 s later).

It is necessary to evaluate these temporal differences in alarm response with respect to the tenability data calculated along the path of egress. The comparison of the smoke alarm time relative to the time to untenable conditions provides a metric by which the life saving capability of individual smoke alarms and/or generic smoke alarm technologies can be evaluated.

This metric is generally referred to as the Available Safe Egress Time (ASET = Time to untenable condition – Time of alarm). Recent studies have utilized a time of required safe egress (RSET) of 135 s (2.25 min.), which was developed for a manufactured home with a larger floor area than the apartment layout used in this test series [5, 6]. Therefore, a minimum ASET value of 2.25 minutes was used to assess whether an alarm provided adequate time to escape. A summary of the ASET values for the first and last device to activate from each alarm technology for each test conducted is presented in Table 3.

As shown in Table 3, generally all alarms in these tests provided ASET values greater than 2.25 minutes for each of the tenability criteria considered. The one exception was the photoelectric alarms in the flaming sofa test S1. In this test, all of the photoelectric alarms responded with less than 2.25 minutes before thermal untenability was reached. For flaming fires, other than the photoelectric alarms in test S1, ASET values ranged from 3.3 to 19.3 minutes. For smoldering fires, ASET values ranged from 5 to 93 minutes. In most cases, the alarms provided 60 to 90 minutes of warning prior to reaching untenable conditions.

Relative to the smoke criteria, for the four smoldering scenarios, sufficient warning was provided by all devices when evaluated against smoke levels of 0.43 OD/m and 0.87 OD/m, with ASET values ranging from 12 to 106 minutes. Even for the lowest smoke criteria, ASET values were generally greater than 2.25 minutes with the exception of several of the later ion and photo alarms which did not respond before the 0.25 OD/m level was reached. For the flaming fire scenarios, ASET values for the smoke criteria ranged from 0 to 6.1 minutes. In general for all three smoke criteria, the devices identified as first to activate for all detection technologies provided ASET values greater than 2.25 minutes with the exception of the photoelectric device in the flaming sofa fire scenario (S1). In test S1, the ASET values were 0.5 and 0.7 minutes for the specified smoke values of 0.25 and 0.43 OD/m, respectively. The devices identified as last to activate generally had ASET values less than 2.25 minutes for all cases except for the 0.87 OD/m smoke criterion.

Conclusions

The analysis demonstrates that the most hazardous conditions developed during flaming fire scenarios with untenable conditions occurring in minutes. Smoldering fires only posed threats under specific conditions and after hours. In general, all of the smoke alarm technologies provided sufficient time to escape the fires before untenable conditions.

Table 3. ASET Values (min.) for Thermal and Toxic Gas Tenability Criteria

Test ID	Alarm Scenario	Tenability Criteria			Smoke Criteria	
		120° C	FED_{CO} = 0.3	FED_{CO} = 1.0	0.25 OD/m	0.43 OD/m
SM1	1st Ion	N/R	52.9	82.7	43.8	59.8
	Last Ion	N/R	5.3	35.1	-3.8	12.2
	1st Photo	N/R	54.5	84.4	45.5	61.5
	Last Photo	N/R	11.5	41.4	2.5	18.5
	1st Combo	N/R	57.2	87.0	48.1	64.1
	Last Combo	N/R	36.3	66.2	27.3	43.3
SM2	All Alarms	N/R	N/R	N/R	-61 to 13	N/R
SM2	All Alarms	N/R	N/R	N/R	-5 to 25	N/R
SM4	1st Ion	N/R	89.5	N/R	73.4	76.9
	Last Ion	N/R	67.3	N/R	51.2	54.7
	1st Photo	N/R	91.4	N/R	75.3	78.8
	Last Photo	N/R	86.1	N/R	69.9	73.5
	1st Combo	N/R	92.7	N/R	76.5	80.0
	Last Combo	N/R	89.6	N/R	73.5	77.0
S1	1st Ion	5.7	11.1	19.3	4.0	4.2
	Last Ion	3.6	9.0	17.3	1.9	2.1
	1st Photo	2.2	7.6	15.8	0.5	0.7
	Last Photo	1.7	7.2	15.4	0.0	0.3
	1st Combo	5.2	10.6	18.8	3.5	3.7
	Last Combo	3.3	8.7	16.9	1.6	1.8
CH1	1st Ion	10.7	6.5	8.0	3.5	3.9
	Last Ion	8.4	4.2	5.7	1.2	1.6
	1st Photo	10.3	6.2	7.7	3.2	3.5
	Last Photo	8.5	4.4	5.9	1.4	1.7
	1st Combo	10.4	6.2	7.7	3.2	3.6
	Last Combo	9.0	4.8	6.3	1.8	2.2
CH2	1st Ion	N/R	4.8	6.4	2.4	2.9
	Last Ion	N/R	3.9	5.5	1.5	2.0
	1st Photo	N/R	5.0	6.6	2.6	3.1
	Last Photo	N/R	3.4	5.0	1.0	1.5
	1st Combo	N/R	4.9	6.5	2.5	3.0
	Last Combo	N/R	3.5	5.1	1.1	1.6

N/R - Tenability criteria not reached.

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