Smoke Alarm Response: Estimation Guidelines and Tenability Issues – Part 2

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INTRODUCTION

The primary goal of a smoke alarm is to provide adequate warning to occupants before conditions within a space become untenable due to a fire event. In the past, researchers [e.g., 1-8] have investigated the performance of residential smoke alarms when exposed to various fire scenarios. These test programs have been conducted using various building geometries, fire scenarios, and detection technologies. In general, the conclusions of these programs were similar in that the performance of the tested devices was found to be satisfactory (i.e., the devices provided sufficient warning prior to conditions becoming untenable). There are currently three types of smoke detection technologies available in residential alarms; ionization, photoelectric, and dual sensor (combination ionization and photoelectric). At the time of this study, there were very limited tests that had evaluated all three smoke alarm technologies relative to realistic fire conditions that reached untenable conditions (i.e., incapacitating toxic gas or thermal exposure limits). The performance of these different technologies must be evaluated when exposed to various fire events that are capable of producing untenable conditions. The primary objective of this paper is to establish a basis for comparative analysis of the performance of commercially available residential smoke alarms with respect to the development of untenable conditions in the residential setting.

EXPERIMENTAL APPROACH

The foundation for the comparative analysis presented in this paper is a series of twenty full-scale enclosure fire tests conducted under a grant from the National Institute of Justice (NIJ) designed to investigate the impact of limited ventilation on compartment fire development. A detailed description of the entire NIJ test series is provided in Reference [9]. In seven of the twenty tests, smoke alarms were installed within the enclosure to investigate the performance of various commercially available devices with respect to the development of untenable conditions within the space. Of the seven tests conducted with smoke alarms in place, there were three flaming ignition scenarios and four smoldering ignition scenarios. A summary of the tests incorporating smoke alarms and smoke alarm cluster locations is presented in Table 1.

Table 1: Summary of Tests Conducted with Smoke Alarms.

Test ID	Fire Type	Fuel	Ignition Source	Fire Location	Ventilation Scheme	Alarm Cluster Locations
SM1	Smoldering	Cotton Batting	Cal Rod	Bedroom	Closed	2 / 3
SM2	Smoldering	Sofa A	Cal Rod	Living Room	Closed	1 / 2
SM3	Smoldering	Sofa A	Cal Rod	Living Room	Closed	1 / 2
SM4	Smoldering	Sofa B	Cal Rod	Living Room	Closed	1 / 2
S1	Flaming	Sofa A	Tissue Box	Living Room	Closed	1 / 2
CH1	Flaming	Wooden Cabinet	Tissue Box	Kitchen	Closed	1 / 3
CH2	Flaming	Wooden Cabinet	Tissue Box	Kitchen	Half-Open Window	1 / 3

The NIJ test series was conducted within a 41.8m^2 (450 ft^2) apartment-style enclosure comprised of four, inter-connected rooms. An overview of the test enclosure is provided in Figure 1. All rooms were open to each other through doorways with soffits and no doors. The full enclosure was closed to the outside in all tests except one in which the bottom pane of the window in the bedroom was half opened. The window vent area was 0.41 m^2 (1.33 ft^2). For the closed enclosure, the measured leakage area was 0.013 m^2 (0.14 ft^2). As indicated in Table 1, fire sources were located in three of the four rooms within the test enclosure. These locations are also shown in Figure 2.

A summary of the fuel packages used in these tests is provided in Table 2. The fire scenarios were designed to be realistic and representative of common residential fires; they consisted of upholstered furniture, wooden cabinets, and cotton bedding material folded like a large blanket. Both the flaming and smoldering ignition scenarios were designed to be both repeatable and realistic, that is representative of small class A flaming materials and various overheat/smoking material sources, respectively. Figures 3 to 5 show example photographs of fuels and ignition sources.

Except for sofa B, the batting, sofa, and kitchen cabinet fires consisted of using new products. In general, developing self-sustained smoldering of new commercial products can be very challenging, particularly with cigarettes which are more commonly required to meet new fire-safe test standards. For these smoldering tests, electric cartridge heaters were used as the ignition source. Initially, comforters purchased from a popular 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 medium for obtaining self-sustaining smolder 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 may bound many actual bedding products in ease of smolder, duration of smolder and CO production.

As will be discussed below, 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. This source was successful in developing self-sustaining smolder and is deemed to be representative of realistic incidents.

The flaming sofa and cabinet fires also 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 can be 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.

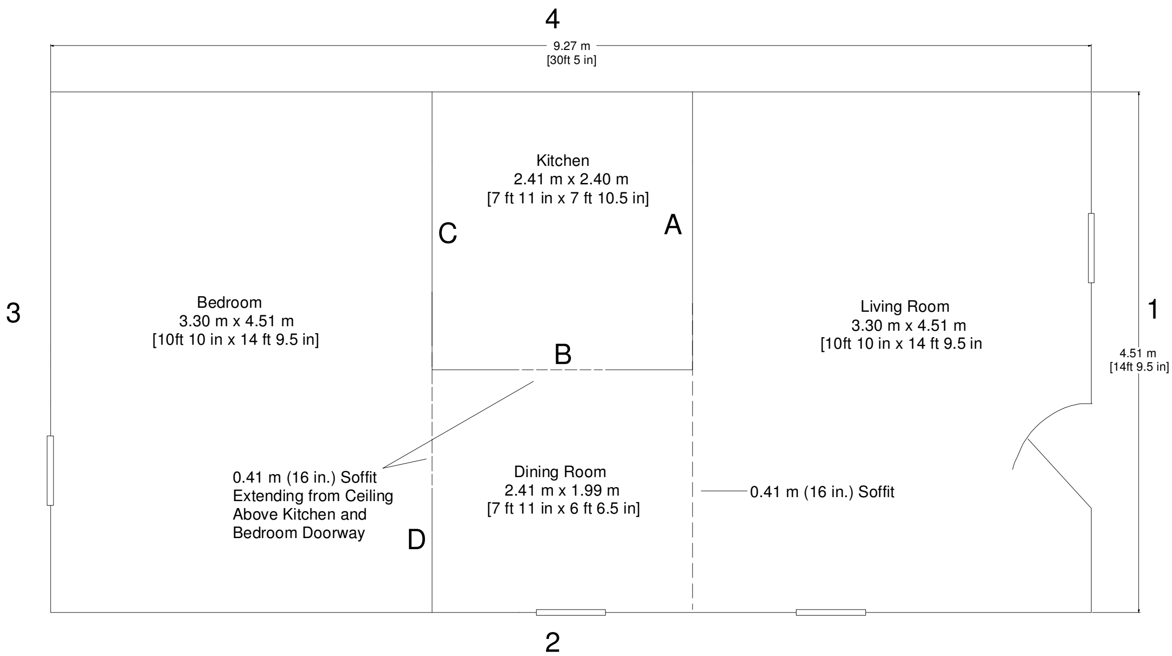

Figure 1. Overview of the Test Enclosure.

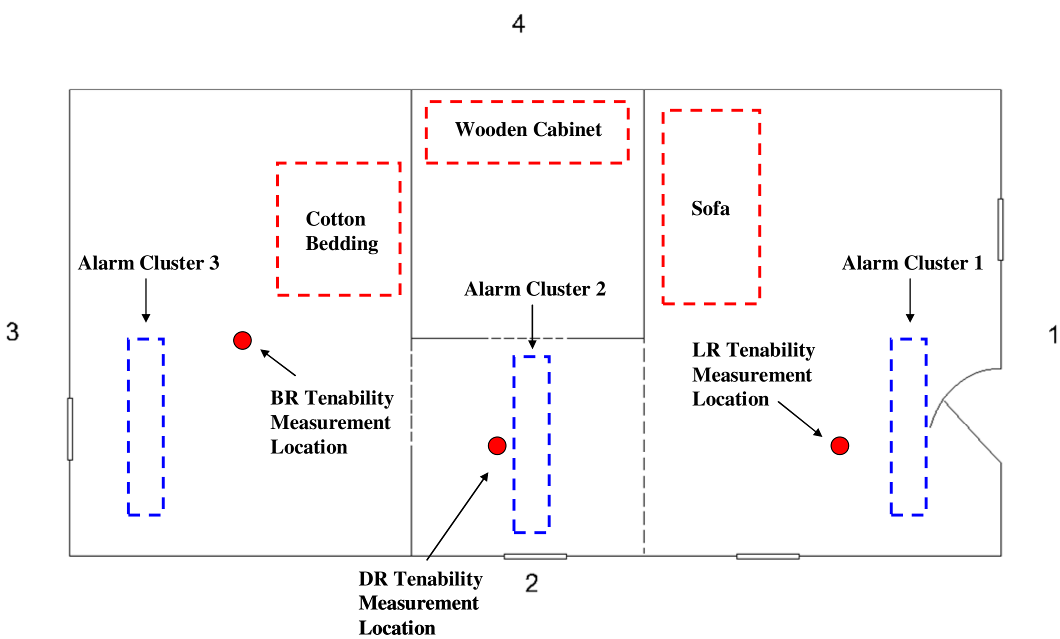

Figure 2. Overview of the NIJ test enclosure set-up showing the locations of fire sources and instrumentation.

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 material 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 simulate typical cabinet stock. The remaining cabients remained empty.
Cotton Bedding	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.

Figure 3. Sofa B used for smoldering fire test SM4 (left) and sofa A with tissue box ignition source used in flaming fire test S1 (right).

Figure 4. Kitchen cabinet with tissue box ignition source and view inside a loaded cabinet.

Figure 5. Cotton batting and cartridge heater used for smoldering source.

Smoke alarm cluster locations are presented in Figure 2. It is important to note that only two clusters were installed for each test and that the cluster locations were dependent upon the fire source location as noted in Table 1. For each fire scenario, two clusters of eight alarms each were installed along the path of egress within the enclosure. Each cluster was comprised of 3 ionization, 3 photoelectric, and 2 dual sensor alarms from three manufacturers. All alarms were installed 0.31 m (12 in.) center to center, except the dining room devices that were spaced 0.23 m (9 in.) on center due to the limited ceiling space. With the exception of one, all smoke alarms tested were installed such that individual alarm activation could be monitored via the interconnect feature of the device. Activation of the single unit without the interconnect feature was captured using an acoustic monitoring device.

Figure 6 shows a schematic of the smoke alarm and instrument layout within a cluster. Each alarm cluster was instrumented with three, 24Ga, bare-bead, Type K thermocouples installed approximately 0.05 m (2 in.) beneath the ceiling. The thermocouples were installed over the width of the cluster in order to establish that uniform exposure conditions were achieved during testing. Similarly, each cluster was instrumented with optical density meters intended to serve the same purpose (i.e., demonstrate that a relatively uniform smoke exposure was achieved over the width of the alarm cluster). The optical density meters were constructed in general accordance with UL 217 and consisted of a General Electric 6V light source directed at a Huygen Model 856 RRV Photocell over a path length of 1.5 m (5 ft). In addition to the instrumentation used to characterize the exposure conditions at the alarm clusters, thermocouples, gas sampling, and optical density meters 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 Figure 2.

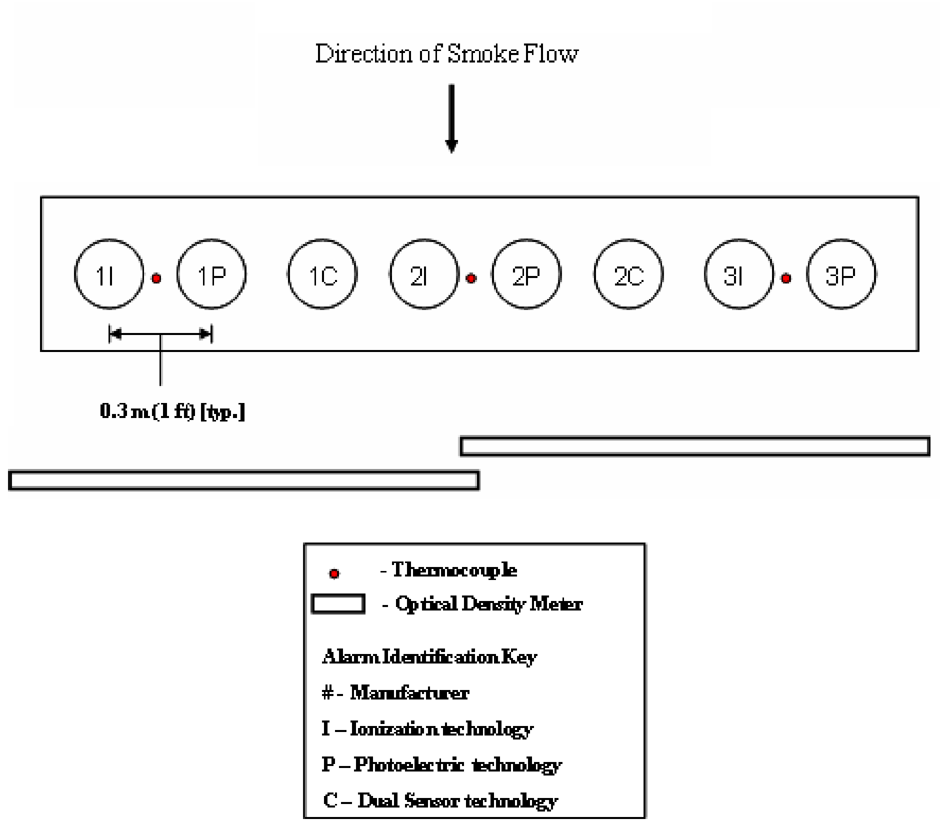

Figure 6. Graphical representation of typical alarm cluster. Note: Alarms in the dining room cluster were spaced at 0.23m (9 in.) on center.

EXPERIMENTAL PROCEDURE

Prior to each test, alarm activation was verified using the *Test* button provided on each device. Testing began with the initiation of the source (i.e., flaming tissue box or heating element on), but background data was saved for two minutes prior to source initiation. During the test the fire was permitted to develop naturally during which time alarm activation times were collected and conditions within the test enclosure were monitored. 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 in an occupancy. The performance of a smoke alarm to allow occupants sufficient time to escape from a fire cannot be fully evaluated if conditions never become untenable. Tenability within a space was assessed based upon the development of thermal and toxic gas conditions at elevations relevant to occupant egress. These elevations are 1.5 m (5 ft) and 0.6 m (2 ft) which generally correspond to 'head level' and 'crawl level', respectively. These parameters directly correlate to life threatening conditions. The development of visible smoke within a space has been considered in tenability analyses, however, visibility through smoke (and even irritancy) is not actually a measure of a life threatening tenability criteria. Reduced visibility is often considered as a mechanism that slows occupant egress as opposed to directly contributing to the incapacitation of occupants.

Thermally untenable conditions are generally considered to be reached when temperatures measured at either the 1.5 m (5 ft) or 0.6 m (2 ft) exceed the threshold of 120°C [10,11]. 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 seven minutes [11].

Untenable toxic gas conditions, particularly with respect to the presence of carbon monoxide (CO), 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 [10,12]. The equation used to calculate FED values in this paper is presented below in Equation 1.

$$FED_{CO} = \sum_{t_2}^{t_1} \frac{[CO_{ppm}]}{35{,}000\, ppm \cdot \min} \Delta t \qquad \text{(Eq. 1)}$$

ISO 13571, an international standard on life-threatening conditions, suggest the use of an FED threshold criteria 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 [10]. Many studies have used FED thresholds of 1 as the incapacitating dose.

Many studies have used the measurement of smoke concentration (or visibility) as a criteria 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 discussed 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 [2, 10, 13].

DISCUSSION OF RESULTS

A summary of fire conditions obtained within the test enclosure during each test is presented in Table 3. The data presented includes test duration, mass of fuel consumed during each scenario, maximum temperature reached, maximum fractional effective dose with respect to carbon monoxide, and smoke concentration. The thermal, gas, and smoke data presented in Table 3 are based upon data collected at elevations relevant to occupant tenability at locations along the expected path of egress. The data shows that 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.

The times to reach untenable conditions based on the transient fire conditions are presented in Table 4 for each test relative to elevation and location within the test compartment. These times are based upon data collected along the expected path of egress from the test enclosure. The expected 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. The FED for CO calculation assumes that an occupant is in the room for which the calculation is performed for the entire duration. A summary of the times at which various smoke density thresholds were reached is presented in Table 5. Untenable thermal and toxic gas levels were reached much faster in the flaming fires compared to the smoldering fires. The same trend is also observed for smoke production.

ALARM ACTIVATION

Individual smoke alarm response times are presented in Table 6 for each test and location within the enclosure. With the exception of two devices in test SM2, all alarms activated as a result of the fire scenarios that were evaluated. In test SM2 (as in SM3), the sofa did not develop a self-sustaining smoldering fire. Instead, the polyurethane foam in the sofa only pyrolized to a small diameter around the cartridge heater where the radiant heat was sufficient to affect it. Consequently, the conditions within the enclosure were quite benign as indicated in Tables 3 to 5. Though the environment was not hazardous in tests SM2 and SM3, there was visible smoke throughout the whole apartment and the sofas produced sufficient smoke to reach the lowest smoke criteria of 0.25 OD/m at the 1.5 m (5 ft) elevation in about a half an hour.

Table 3. Summary of Conditions Achieved during Testing

Test ID	Test Duration [min.]	Mass Consumed [kg]	TMAX. @ 1.5 m (5 ft) [°C]	TMAX. @ 0.6 m (2 ft) [°C]	$FED_{CO,MAX.}$ @ 1.5 m (5 ft)	$FED_{CO,MAX.}$ @ 0.6m (2 ft)	Max. Smoke Density @ 1.5 m (5 ft) [OD/m]	Max. Smoke Density @ 0.6m (2 ft) [OD/m]
SM1	220	4.2	37.8	33.3	>1.0	>1.0	1.14	1
SM2	89	Negligible	26.8	25.3	0	0	0.41	0.08
SM3	126	Negligible	28.3	27.5	0	0	0.39	0.2
SM4	117	1.1	27.7	25.1	0.47	0.28	1.02	0.83
S1	205	5.8	195.4	59.9	>1.0	>1.0	>2.1	>2.1
CH1	260	28.8	129.1	69.1	>1.0	>1.0	>2.1	>2.1
CH2	242	40.9	92.8	65.4	>1.0	>1.0	>2.1	>2.1

Table 4. Times (min.) from Source Initiation to Untenable Conditions

Criteria	Location	Elevation (m [ft])	SM1	SM2	SM3	SM4	S1	CH1	CH2
Temperature (> 120° C)	Living Room	0.6 m (2 ft)	N	N	N	N	N	N	N
	Living Room	1.5 m (5 ft)	N	N	N	N	14.0	N	N
	Dining Room	0.6 m (2 ft)	N	N	N	N	N	N	N
	Dining Room	1.5 m (5 ft)	N	N	N	N	15.1	15.8	N
	Bedroom	0.6 m (2 ft)	N	N	N	N	N	N	N
	Bedroom	1.5 m (5 ft)	N	N	N	N	N	N	N
FED = 0.3	Living Room	0.6 m (2 ft)	97.5	N	N	N	22.7	15.0	21.1
	Living Room	1.5 m (5 ft)	95.8	N	N	103.7	19.4	11.6	17.7
	Dining Room	1.5 m (5 ft)	82.5	N	N	N/A	22.5	N/A	N/A
	Bedroom	0.6 m (2 ft)	85.1	N	N	N	21.3	15.5	21.0
	Bedroom	1.5 m (5 ft)	79.2	N	N	N	22.0	13.4	19.7
FED = 1.0	Living Room	0.6 m (2 ft)	126.3	N	N	N	35.1	17.3	23.6
	Living Room	1.5 m (5 ft)	115.5	N	N	N	27.6	13.1	19.3
	Dining Room	1.5 m (5 ft)	116.3	N	N	N/A	34.8	N/A	N/A
	Bedroom	0.6 m (2 ft)	109.0	N	N	N	30.3	18.2	23.7
	Bedroom	1.5 m (5 ft)	113.5	N	N	N	36.5	15.9	22.4

N - Untenable conditions not reached

N/A - Data not collected at this location in this test

Table 5. Times (min.) from Source Initiation to Specified Smoke Levels

Criteria	Location	Elevation (m [ft])	SM1	SM2	SM3	SM4	S1	CH1	CH2
0.25 OD/m [16.1 %/ft]	Living Room	0.6 m [2 ft]	85.1	N	N	91.9	14.2	12.0	17.7
	Living Room	1.5 m [5 ft]	78.7	28.2	36.9	87.5	12.3	8.6	15.3
	Bedroom	0.6 m [2 ft]	78.7	N	N	90.7	13.6	10.4	17.4
	Bedroom	1.5 m [5 ft]	70.1	N	N	89.1	13.0	9.9	16.7
0.43 OD/m [26.1 %/ft]	Living Room	0.6 m [2 ft]	101.9	N	N	98.1	14.4	12.2	18.8
	Living Room	1.5 m [5 ft]	95.3	N	N	91.1	12.5	8.9	15.8
	Bedroom	0.6 m [2 ft]	96.5	N	N	96.2	13.8	12.2	17.9
	Bedroom	1.5 m [5 ft]	86.1	N	N	93.1	13.2	11.1	17.0
0.87 OD/m [45.7 %/ft]	Living Room	0.6 m [2 ft]	152.8	N	N	N	14.7	13.2	19.2
	Living Room	1.5 m [5 ft]	144.1	N	N	103.8	12.7	9.3	16.2
	Bedroom	0.6 m [2 ft]	147.7	N	N	111.4	14.2	13.1	18.7
	Bedroom	1.5 m [5 ft]	128.3	N	N	106.9	13.5	12.3	17.8

N/R - Crieteria not reached

Table 6. Smoke Alarm Activation Times (min.) from Source Initiation

Smoldering Batting (SM1)																
Cluster Location	Dining Room								Living Room							
Alarm ID	1I	2I	3I	1P	2P	3P	1C	2C	1I	2I	3I	1P	2P	3P	1C	2C
Time to Activation (min.)	26.3	30.6	30.4	24.6	28.4	25.5	22.0	29.0	62.6	68.0	73.9	47.8	46.6	67.6	42.8	42.0
Smoldering Sofa (SM2)																
Cluster Location	Dining Room								Bedroom							
Alarm ID	1I	2I	3I	1P	2P	3P	1C	2C	1I	2I	3I	1P	2P	3P	1C	2C
Time to Activation (min.)	38.7	25.3	DNA	15.7	18.1	19.2	15.5	15.9	45.0	21.9	DNA	17.0	23.5	61.6	17.0	19.0
Smoldering Sofa (SM3)																
Cluster Location	Dining Room								Bedroom							
Alarm ID	1I	2I	3I	1P	2P	3P	1C	2C	1I	2I	3I	1P	2P	3P	1C	2C
Time to Activation (min.)	25.7	16.0	38.7	15.4	16.0	15.9	14.6	15.3	29.1	14.3	42.0	15.4	16.7	21.4	15.7	12.4
Smoldering Sofa (SM4)																
Cluster Location	Dining Room								Bedroom							
Alarm ID	1I	2I	3I	1P	2P	3P	1C	2C	1I	2I	3I	1P	2P	3P	1C	2C
Time to Activation (min.)	14.2	N/P	20.3	12.3	12.5	13.1	13.8	11.0	25.9	N/P	36.4	14.4	17.6	15.1	14.1	N/D
Flaming Sofa (S1)																
Cluster Location	Dining Room								Bedroom							
Alarm ID	1I	2I	3I	1P	2P	3P	1C	2C	1I	2I	3I	1P	2P	3P	1C	2C
Time to Activation (min.)	8.3	8.3	9.2	11.8	11.8	12.0	8.8	9.2	9.7	9.5	10.4	12.3	12.1	12.2	10.7	9.6
Flaming Cabinet (CH1)																
Cluster Location	Living Room								Bedroom							
Alarm ID	1I	2I	3I	1P	2P	3P	1C	2C	1I	2I	3I	1P	2P	3P	1C	2C
Time to Activation (min.)	6.3	5.1	6.3	6.8	5.4	6.1	6.8	5.4	7.4	6.2	6.5	6.5	6.6	7.2	6.7	6.4
Flaming Cabinet (CH2)																
Cluster Location	Living Room								Bedroom							
Alarm ID	1I	2I	3I	1P	2P	3P	1C	2C	1I	2I	3I	1P	2P	3P	1C	2C
Time to Activation (min.)	13.0	12.9	13.1	13.8	12.7	13.0	14.2	N/D	13.8	13.1	13.3	14.3	N/P	13.7	12.8	N/D

DNA - Did not Alarm
N/P - Alarm not present at this location during test
N/D - Activation could not be determined due instrument malfunction

In general, for the smoldering fire scenarios, the combination alarms responded the earliest, with photoelectric alarms providing a slightly slower response, and ionization alarms responding the slowest. On average, combination alarms responded 4.5 minutes sooner than photoelectric alarms and 13.7 minutes faster than ionization alarms for the smoldering fire scenarios. In the flaming fires, the ionization alarms were generally the quickest to respond with the combination alarms lagging only slightly behind and the photoelectric alarms responding the slowest. In these scenarios, the ionization alarm responded on average 13 s sooner than combination alarms and 67 s faster than photoelectric alarms.

SMOKE ALARM PERFORMANCE

Although the differences in alarm activation times presented above are in some cases on the order of tens of minutes it is important to note that the performance of a smoke alarm with respect to life safety cannot be assessed upon this comparison. It is necessary to evaluate these temporal differences 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). It is generally accepted that an ASET threshold of about 2 minutes is required to provide adequate life safety performance. This is the time from alarm that is required to escape. 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 [2, 13]. Therefore, a minimum RSET value of 2.25 minutes suggests that a device must activate at least 2.25 minutes prior to any of the tenability criteria being reached at either the 1.5 m (5 ft) or 0.6 m (2 ft) elevation. 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 7.

As shown in Table 7, generally all alarms evaluated 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.

The ASET values based on specified smoke levels are reported for each fire test in Table 8. 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 are 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. The majority of these incidents occurred for test SM2 and SM3, the smoldering Ikea sofa tests. As noted earlier, these tests did not actually result in self-sustaining smolder and did not produce a hazard relative to thermal or toxic gas conditions. The maximum level of smoke in SM2 and SM3 were 0.41 and 0.39 OD/m, indicating that visibility at 1.5 m (5 ft) did not fall below about 3 m (10 ft). An interesting observation is that for test SM2 and SM3 that were primarily pyrolizing polyurethane foam sources, the ASET values for all alarms, were lower than those for test SM4 with the self-sustaining smoldering foam sofa. The mass of fuel consumed in SM2 and SM3 was not measurable in the tests with the load cell, compared to 1.09 kg for the SM4 sofa. Though less foam was consumed in SM2 and SM3, the 0.25 OD/m smoke level was reached approximately 1 hour earlier than in the smoldering sofa test SM4.

For the flaming fire scenarios ASET values for 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.

Table 7: ASET Values (min.) for Thermal and Toxic Gas Tenability Criteria

Test ID	Alarm Scenario	Tenability Criteria		
		120°C	FED_{CO} = 0.3	FED_{CO} = 1.0
SM1	1st Ion	N/R	52.9	82.7
	Last Ion	N/R	5.3	35.1
	1st Photo	N/R	54.5	84.4
	Last Photo	N/R	11.5	41.4
	1st Combo	N/R	57.2	87.0
	Last Combo	N/R	36.3	66.2
SM2	1st Ion	N/R	N/R	N/R
	Last Ion	N/R	N/R	N/R
	1st Photo	N/R	N/R	N/R
	Last Photo	N/R	N/R	N/R
	1st Combo	N/R	N/R	N/R
	Last Combo	N/R	N/R	N/R
SM3	1st Ion	N/R	N/R	N/R
	Last Ion	N/R	N/R	N/R
	1st Photo	N/R	N/R	N/R
	Last Photo	N/R	N/R	N/R
	1st Combo	N/R	N/R	N/R
	Last Combo	N/R	N/R	N/R
SM4	1st Ion	N/R	89.5	N/R
	Last Ion	N/R	67.3	N/R
	1st Photo	N/R	91.4	N/R
	Last Photo	N/R	86.1	N/R
	1st Combo	N/R	92.7	N/R
	Last Combo	N/R	89.6	N/R
S1	1st Ion	5.7	11.1	19.3
	Last Ion	3.6	9.0	17.3
	1st Photo	2.2	7.6	15.8
	Last Photo	1.7	7.2	15.4
	1st Combo	5.2	10.6	18.8
	Last Combo	3.3	8.7	16.9
CH1	1st Ion	10.7	6.5	8.0
	Last Ion	8.4	4.2	5.7
	1st Photo	10.3	6.2	7.7
	Last Photo	8.5	4.4	5.9
	1st Combo	10.4	6.2	7.7
	Last Combo	9.0	4.8	6.3
CH2	1st Ion	N/R	4.8	6.4
	Last Ion	N/R	3.9	5.5
	1st Photo	N/R	5.0	6.6
	Last Photo	N/R	3.4	5.0
	1st Combo	N/R	4.9	6.5
	Last Combo	N/R	3.5	5.1

N/R - Tenability criteria not reached.

Table 8. ASET Values (min.) based on Specified Smoke Level

Test ID	Alarm Scenario	Smoke Criteria		
		0.25 OD/m	0.43 OD/m	0.87 OD/m
SM1	1st Ion	43.8	59.8	102.0
	Last Ion	-3.8	12.2	54.4
	1st Photo	45.5	61.5	103.7
	Last Photo	2.5	18.5	60.7
	1st Combo	48.1	64.1	106.3
	Last Combo	27.3	43.3	85.5
SM2	1st Ion	6.3	N/R	N/R
	Last Ion[1]	-60.8	N/R	N/R
	1st Photo	12.5	N/R	N/R
	Last Photo	-33.4	N/R	N/R
	1st Combo	12.7	N/R	N/R
	Last Combo	9.2	N/R	N/R
SM3	1st Ion	22.5	N/R	N/R
	Last Ion	-5.1	N/R	N/R
	1st Photo	21.5	N/R	N/R
	Last Photo	15.5	N/R	N/R
	1st Combo	24.5	N/R	N/R
	Last Combo	21.2	N/R	N/R
SM4	1st Ion	73.4	76.9	N/R
	Last Ion	51.2	54.7	N/R
	1st Photo	75.3	78.8	N/R
	Last Photo	69.9	73.5	N/R
	1st Combo	76.5	80.0	N/R
	Last Combo	73.5	77.0	N/R
S1	1st Ion	4.0	4.2	6.1
	Last Ion	1.9	2.1	4.0
	1st Photo	0.5	0.7	2.6
	Last Photo	0.0	0.3	2.1
	1st Combo	3.5	3.7	5.6
	Last Combo	1.6	1.8	3.7
CH1	1st Ion	3.5	3.9	4.6
	Last Ion	1.2	1.6	2.3
	1st Photo	3.2	3.5	4.3
	Last Photo	1.4	1.7	2.5
	1st Combo	3.2	3.6	4.3
	Last Combo	1.8	2.2	2.9
CH2	1st Ion	2.4	2.9	4.3
	Last Ion	1.5	2.0	3.3
	1st Photo	2.6	3.1	4.4
	Last Photo	1.0	1.5	2.8
	1st Combo	2.5	3.0	4.4
	Last Combo	1.1	1.6	2.9

N/R - Criteria not reached.
[1] Ion alarm did not activate thus time is based upon test duration.

CONCLUSIONS

A set of full-scale apartment fires with flaming and smoldering fire scenarios were used to assess the performance of various smoke alarm technologies. Ionization, photoelectric and combination ion-photo alarms were evaluated. The fires were allowed to develop and reach untenable conditions, although some did not produce hazardous thermal or toxic gas levels. Available safe egress times were calculated for each smoke alarm by comparing the time to alarm to the time to reach a range of life-threatening conditions as well as specified smoke density levels. The tests demonstrate that the most hazardous conditions developed during the flaming fire scenarios. In general, all of the smoke alarm technologies provided sufficient time to escape the fires before untenable conditions.

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