NIST Technical Note 1837

Improving Smoke Alarm Performance – Justification for New Smoldering and Flaming Test Performance Criteria

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ABSTRACT

Although smoke alarms provide a substantial level of safety to households, reducing the risk of dying in reported fires by 50 % in homes with working smoke alarms, improved smoke alarm performance could further reduce fire risk. Earlier alarm activation by increasing the sensitivity of smoke alarms to risk-significant fire scenarios is one approach to improving performance. Flaming and smoldering upholstered furniture fires have been identified as risk-significant scenarios that are not adequately addressed in current standards. New polyurethane foam smoldering and flaming fire tests have been suggested to address this shortcoming, but need scientifically sound performance criteria to be complete.

An analysis methodology, based on the available safe egress time/required safe egress time (ASET/RSET) concept, is used to estimate the probability of escape given smoke alarm activation at specific smoke concentrations in flaming and smoldering polyurethane foam chair mock-up fire experiments to provide guidance in selecting new smoldering and flaming fire test performance criteria. The tenability limits were defined by a fractional effective dose value of 0.3 for toxic gas and heat exposure, and two smoke optical density limits used in previous studies, 0.25 m^{-1} and 0.43 m^{-1}, were considered. Analysis assumptions and limitations included:

- interconnected smoke alarms that alert occupants regardless of initial fire location,
- occupant pre-movement time treated as a distribution for distinct populations,
- travel speed as a function of smoke density,
- occupants traversing a range of equally frequent pre-determined egress routes,
- considering only one apartment-sized residential space,
- one location for the responsive smoke alarm, and
- three flaming and three smoldering scenarios, and a total of 18 full-scale tests.

Results are presented to provide guidance in selecting performance criteria for new smoldering and flaming polyurethane foam fire tests proposed for ANSI/UL 217 and ANSI/UL 268. This study provides a rationale for how to strengthen the requirements in a manner that considers commensurate improvement for flaming and smoldering alarm performance. Ultimately, the Standards Technical panel for ANSI/UL 217 and ANSI/UL 268, other regulatory bodies and/or standards development organizations need to make a judgment on the addition of any new tests or performance requirements.

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1 INTRODUCTION

In the United States, NFPA 72, The National Fire Alarm and Signaling Code [1] requires that all installed smoke alarms and detectors be assessed for compliance to the minimum performance requirements as specified in ANSI/UL 217, *Single and Multiple Station Smoke Alarms* [2] and ANSI/UL 268, *Smoke Detectors for Fire Alarm Systems* [3].

Analysis of US fire statistics for home structure fires from 2007-2011 shows the risk of dying in reported fires is less than 50 % lower in homes with working smoke alarms [4]. This indicates the benefits of working smoke alarms. Even with this benefit, the national fire statistics show that between 2007 and 2011, smoke alarms were deemed to have operated in 37 % of fatal home structure fires with installed working smoke alarms, and in those cases, analysis of victim activities showed that at the time of the fatal injury, one-third of victims were attempting to escape or rescue others [4]. This begs the question: ***what can be done to improve smoke alarm performance?***

Several factors influence the risk of dying in fires when working smoke alarms are present. Some examples include victims that do not respond to an operating smoke alarm while sleeping or incapacitated, and very rapid fire growth. Interconnected smoke alarms that activate all smoke alarms when any one smoke alarm senses fire conditions improves alerting, especially for sleeping occupants when interconnected alarms are located in all sleeping areas. Additionally, smoke alarms or notification devices with the low frequency 520 Hz alarm signal output provide improved alerting for occupants with mild to severe hearing loss. The current NFPA 72 Code requires interconnected alarms and alarm coverage on every level and in all sleeping areas for household fire alarms [1]. The number of homes protected at the level of the current Code, however, is uncertain. A 2010 survey found that approximately 40 % of households had smoke alarms in all bedrooms, but only 25 % of households had interconnected smoke alarms [4]. Some victims may be unable to respond due to alcohol or drug impairment, and other victims may be disabled and immobile, thus incapable of self-rescue. Between 2007 and 2011, in cases in which smoke alarms were present and operated, it was estimated that 11 % of fatal victims were possibly alcohol or drug impaired and 17 % were possibly physically or mentally disabled [4]. Finally, because of rapid fire growth and spread in contemporary furnishings containing flexible polyurethane foams, occupants may not have sufficient egress time even when alerted by a smoke alarm [5].

The National Institute of Standards and Technology (NIST) has conducted research on smoke alarm performance, including the Home Smoke Alarm Study [5] and the Smoke Alarm Sensitivity Study [6] that focused on fires involving modern upholstered furniture and mattress materials containing flexible polyurethane foams. Smoke alarm technologies examined included contemporary photoelectric, ionization, and dual-sensor combination photoelectric/ionization alarms. Both studies showed that properly installed ionization or photoelectric alarms provide enough time for most occupants to successfully egress for many fire scenarios. It was observed in both studies, however, that ionization alarms tended to react much slower to slowly growing extended smoldering fires than photoelectric alarms, and that photoelectric alarms tended to react somewhat slower to quickly growing flaming fires than ionization alarms. Analysis of initially flaming and initially smoldering fires in full-scale experiments revealed hypothetical situations involving both types of photoelectric and ionization alarms for which not all occupants would have sufficient time to escape before experiencing thick smoke and potentially succumbing to toxic gases and/or heat exposure. Thus, depending on the fire scenario, a particular sensing technology and/or increased detection sensitivity could provide additional time for escape, which may be necessary for some occupants, especially slower population groups (elderly or mobility impaired) and those with some level of cognitive impairment. Analysis of the performance of smoke alarms in full-scale experiments showed that dual sensor photoelectric/ionization alarms with equivalent or more sensitive settings than individual photoelectric or ionization alarms performed better over a range of flaming and smoldering fire scenarios [7, 8].

In an effort to increase available escape time, consideration of the national fire statistics and smoke alarm research [4-8] has led to the recommendation that consumers install both photoelectric and ionization alarms, or combination alarms by several fire safety and research organizations including the US Fire Administration, the US Consumer Products Safety Commission, the National Institute of Standards and Technology, the National Fire Protection Association, Underwriters Laboratories, Inc., the International Association of Fire Chiefs, and the National Association of State Fire Marshals. This recommendation is also made in the 2013 Edition of NFPA 72: "The use of both technologies generally offers the advantage of providing a faster response to both flaming and smoldering fires, and is recommended for those who desire a higher level of protection than the minimum requirements of this Code" [1]. The concern with this recommendation is the identification of specific technologies as surrogates for the desired performance level. The desired solution is to identify a minimum set of performance requirements for ANSI/UL 217 and ANSI/UL 268 that are technology-independent and increase escape times, yet enable innovation in smoke alarm design including use of new and emerging technologies.

It can be concluded prima facie that an improvement in smoke alarm fire test performance requirements necessitates earlier alarm activation and warning for both initially smoldering and initially flaming fires. Simply requiring smoke alarms to activate at a lower smoke concentration in only an initially smoldering test fire or an initially flaming test fire could bias the requirements to favor one stand-alone technology (photoelectric or ionization) over the other. The preferred situation, consistent with the recommendations of the organizations listed above, would be performance requirements that challenge the current generation of discrete photoelectric and discrete ionization alarms, leading to improved detection performance for both flaming and smoldering fires.

An increase in the sensitivity of smoke alarms designed to account for risk-significant fire scenarios (that is, fire scenarios for which the consequences of the fire are serious and most-likely life-threatening, and the likelihood is deemed high relative to other serious fires) not covered in the current ANSI/UL 217 and ANSI/UL 268 fire tests would provide earlier alarm activation and increased time to escape for those occupants alerted by such alarms. Additional fire tests tailored to replicate the early stages of risk-significant fire scenarios, in conjunction with detection sensitivity thresholds that increase egress time and therefore, the likelihood of escape, would refine the ANSI/UL 217 and ANSI/UL 268 Standard's requirements towards improved smoke alarm performance.

Fire loss statistics identify fires involving upholstered furniture and mattresses and bedding as risk-significant scenarios. Between 2007 and 2011, upholstered furniture and mattresses and bedding were the two leading categories of items first ignited in home structure fires with fatalities, totaling 31 % of the average 2570 deaths per year [9]. Upholstered furniture accounted for 2 % of the reported fires, but 18 % of the fire deaths, and mattresses and bedding accounted for 3 % of the reported fires, but 13 % of the fire deaths. Between 2005 and 2009, smoking materials were listed as the leading cause of upholstered furniture, and mattresses and bedding fire deaths, accounting for 58 % and 51 % respectively, while candles, matches and lighters accounted for about 12 % of both upholstered furniture, and mattresses and bedding fire deaths [10, 11].

A common underlying component of contemporary upholstered furniture and mattresses is flexible polyurethane foam. It can rapidly burn from an initial flaming ignition source or smolder for long periods of time, and then transition to a flaming fire. This material is not currently represented in the smoldering or flaming fire test protocols of ANSI/UL 217 or ANSI/UL 268. Requiring detection of flaming and smoldering polyurethane foam materials representing the earliest stages of upholstered furniture fires may result in earlier alarm activations, which should provide additional time for escape or rescue. This might be achieved by revising the minimum smoke alarm/detector performance requirements to address flaming and smoldering polyurethane foam in ANSI/UL 217 and ANSI/UL 268. A task group was formed to make recommendations to the Standards Technical Panel of ANSI/UL 217 and ANSI/UL 268, regarding the addition of fire tests with the goal of increasing available egress time for non-specific fires (both flaming and smoldering fires) by "expanding alarm responsiveness". Previous research, detailed in the UL-Fire Protection Research Foundation's Smoke Characterization Project, identified differences in the smoke properties of flaming and smoldering fire smokes from polyurethane foam as compared to flaming and smoldering fire smokes from the current UL test fires [12]. Based on the fact that polyurethane foam is a major fuel component in risk-significant fire scenarios, and that smokes from polyurethane foam combustion differ from the smokes in the current UL fire tests, the task group chose to focus on developing flaming and smoldering polyurethane foam tests in the UL fire test room to complement the existing tests.

Suitable full-scale fire experiments can be used to guide scientifically sound selection of the performance criteria for new smoke sources. Such experiments include the Smoke Alarm Sensitivity Study, a series of 24 full-scale experiments NIST 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 [6]. The experimental results were used in an egress analysis to examine the effects of pre-movement time, reduced travel speeds through smoke, and smoke optical density limits on occupant survivability given different smoke alarm installations and multiple egress paths [8]. The data from those experiments is used here in a similar available safe egress time/required safe egress time (ASET/RSET) analysis to identify ceiling smoke concentration ranges, for which alarm activations would produce a high percentage of successful escape outcomes in some very challenging smoldering and flaming fire egress scenarios. The objective of this analysis is to develop a framework to guide the performance criteria specifications for new flaming and smoldering polyurethane foam fire test standards.

2 DESCRIPTION OF EXPERIMENTS

The fire experiments were conducted in a building mock-up, designed to represent a portion of an apartment or small home, constructed inside the National Fire Research Laboratory at NIST [see Reference 6 for more details]. 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. The structure consisted of three contiguous spaces labeled, master bedroom, kitchen, and living room with two hallways, and a floor to ceiling height of 2.4 m. 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. Access doors to the living room and the bedroom were built into the structure.

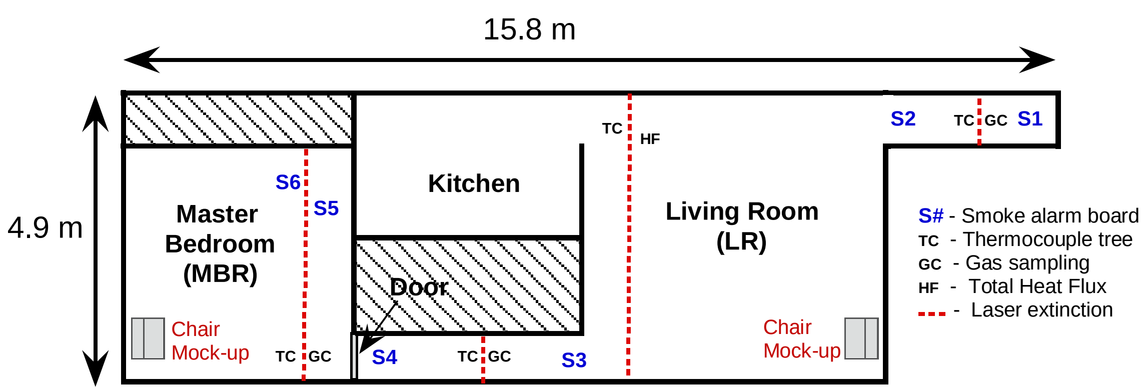

Figure 1. Schematic of the test structure. S1…S6 indicate the ceiling locations for sets of alarms. Gas samples were drawn at locations 1.5 m above the floor. The total heat flux gage was located 1.5 m above the floor and pointed toward the living room chair mock-up. The dashed lines represent laser beam paths located 1.5 m above the floor for extinction measurements. Shaded spaces were sealed off from the rest of the structure.

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 by 6 mm thick paneling sheet in random order. All smoke alarms were purchased from retail establishments and consisted of two photoelectric alarms (P1 and P2), two ionization alarms (I1 and I2), and two dual alarms (D1 and D2). 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 experiment.

The hallway between the master bedroom and living room contained additional light extinction, gas sampling, and particle sampling measurement locations near the ceiling. Figure 2 shows the measurement locations and the location of smoke alarm groups S3 (set 1) and S4 (set 2). In addition to smoke obscuration, CO and CO_2 concentrations, and temperature measurements were made at the ceiling height (where one would most-likely place a smoke alarm) to identify values of these fire signatures that could provide early warning times leading to an increase in successful escape outcomes compared to current alarm sensitivities.

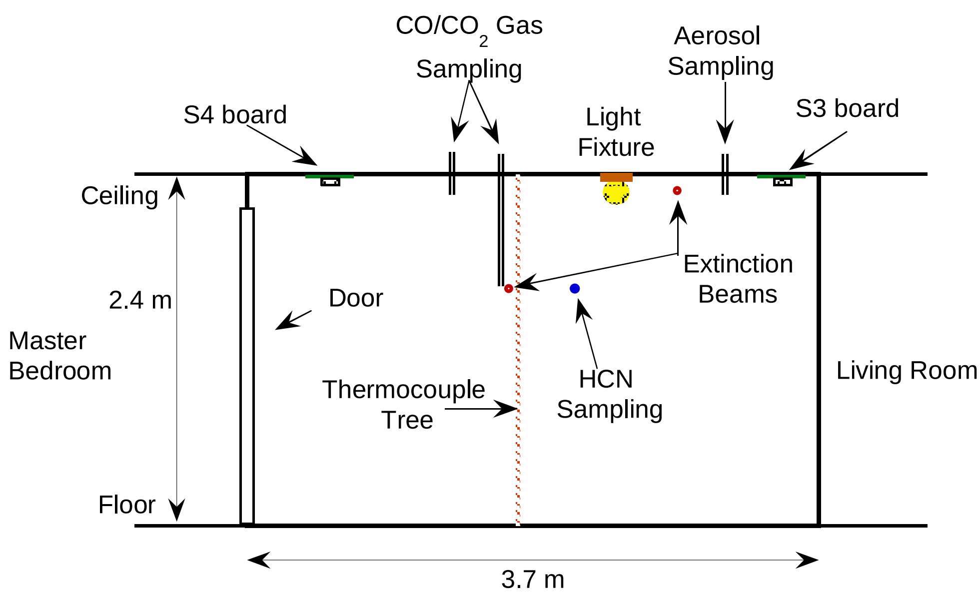

Figure 2. Location of hallway measurement positions. All sampling occurred along the centerline of the 0.91 m wide hallway. The thermocouple tree consisted of seven thermocouples, spaced 0.305 m apart from each other and the ceiling, with one thermocouple 2.5 cm below the ceiling. The measurement locations for the upper gas and aerosol sampling tube and the upper extinction beam was 10 cm below the ceiling, while the lower gas sampling tube, HCN sampling tube, and lower extinction beam was 1.5 m above the floor.

There were eight experimental configurations, each conducted three times for a total of 24 experiments. Here, the flaming and smoldering master bedroom fire configurations with the door to the master bedroom closed were not considered due to significant alarm activation delay for alarms located outside the master bedroom.

A chair mock-up was used as the fire source for each experiment. Each mock-up was constructed from non-fire-retarded, flexible polyurethane foam slabs of low or high density (low density – 21 kg/m^3 {1.3 lb/ft^3}, high density - 29 kg/m^3 {1.8 lb/ft^3}) covered by a matching zippered seat cushion (90 cm by 70 cm by 20 cm) and seat back covers (90 cm by 50 cm by 20 cm) of either cotton (CT) or polyester (PET) fabric. The foam cushions and fabric covers were obtained from retail sources. Mock-up cushion pairs weighed between 5.5 kg and 8.3 kg. 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.

One fabric type was selected that would smolder when subjected to a small ignition source like a cigarette. In his extensive study of cigarette ignition propensity of furniture fabrics, Hirschler examined smoldering ignition propensity of a set of 500 upholstery fabrics (chosen at random among typical upholstery fabrics) assumed to be a representative cross-section of the upholstery fabrics available in the early 1990s [13]. He found that of the 500 fabrics tested, only 145 fabrics were ignitable by cigarettes, all of them predominantly (or completely) cellulosic (cotton, or other plant-based cellulosic fibers). Therefore, a cotton covering fabric (CT) was selected, reflecting the upholstered furniture market and likely to exhibit smoldering ignition from cigarette-like sources.

The ignition sources in the Smoke Alarm Sensitivity Study were designed to be controlled and repeatable since it was important that variations in ignition strength be limited to reduce the uncertainty associated with the ignition process. Additionally, the sources were placed in a manner that could be considered representative of common ignition modes implicated in residential fires, which compared to the Home Smoke Alarm Study ignition sources [5] should produce slower growing flaming fires and longer duration smoldering before transition to flaming.

For each flaming experiment, the chair seat cushion was ignited by a gas-flame ignition tube (similar to the flaming ignition source described in British Standard 5852 [14]) with a propane fuel flow of 0.75 cm^3/sec. This burner tube flame is similar to a match-like small flame or candle flame, with a flame length of approximately 4 cm. The ignition tube flame was allowed to burn for two minutes before placing it next to the chair. To ignite the chair, the tube was placed near the front side of the seat cushion, approximately one-third down from the top of the seat and within 3 mm of the fabric surface. The rationale for positioning the burner tube flame near the upper edge of the seat cushion and away from the back cushion was to produce an initially slow fire growth rate. 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.

A comparison of results from the two NIST studies shows that the flaming fires in the Smoke Alarm Sensitivity Study [15] were characterized by generally slower fire growth relative to the Home Smoke Alarm Study [5] experiments as indicated by the times to reach the optical density limit of 0.25 m^{-1} in the room of fire origin for similar fire scenarios. For example, the average time to reach the optical density limit in the Home Smoke Alarm Study flaming chair experiments (single-story home tests 2, 10, 15, 33, and 35) was 164 s, while the average time to reach the optical density limit in the Smoke Alarm Sensitivity Study's flaming chair in the living room experiments (polyester-covered cushion tests 4, 17, 19) was 217 s, a difference of 53 s (or about 30 %) on average.

The smoldering initiation source was developed to provide a controlled low-temperature heat source, to induce a smolder process that looks and behaves close to a cigarette-type ignition event (a cigarette sized heat source inducing smoldering of a fabric capable of initiating smoldering and propagating the smolder front down into the polyurethane foam). For each experiment, 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 duck fabric that was placed on the seat cushion to ensure a sustained smoldering fire. Electrical power to the cartridge heater was applied in a controlled fashion to achieve an external temperature sufficient to produce sustained smoldering. A thermocouple was attached to the exterior of the cartridge heater and the temperature controller set point was fixed at 425 ^{o}C. After about 6 min of total contact time, the cartridge heater was removed. The cotton cushion covers were used during the smoldering tests. (Cushion covers made from polyester, the other fabric cover used in the Smoke Alarm Sensitivity Study, melts when exposed to a heat source like a cigarette or small power cartridge heater, instead of charring and propagating the smolder front into the foam (like a cotton cover fabric will allow.) Others have used cartridge heaters to initiate foam smoldering [16] and as a potential replacement for a standardized cigarette in smoldering tests [17]. Smoldering was initiated in the front corner of the seat cushion, so that the smolder front had to travel the length of the seat cushion to reach the back cushion and develop conditions favorable for transition to flaming. The intent was to maximize the in-depth polyurethane foam smoldering phase to the extent possible. The bulk of the smoke produced during smoldering was from the smoldering polyurethane foam. Smoldering fires were allowed to progress until they naturally transitioned to flaming fires except for one experiment that was stopped prior to the flaming transition.

A comparison of the living room fire alarm activation times to the bedroom fire alarm activation times (with identical smoldering sources) showed that the difference between photoelectric and ionization alarms was much greater for the living room tests than the bedroom tests. This observation re-emphasizes the fact that smoke alarm activation depends on a number of factors and not just what is burning. For instance, the room size and the distance of the smoke alarms from the fire source affect smoke aerosol aging as it reaches and enters the smoke alarm. This is relevant because smoke aging affects smoke particle sizes which in turn influences smoke alarm activation. Additionally, the local air flows induced from a smoldering source are usually low velocity, and it is well established that smoke alarms, when exposed to smoke in low velocity flows, can experience long activation delay times even when the smoke concentration in the surroundings is well above the alarm point [18].

The fire growth rate of the burning chair mock-up determined, to a great extent, the hazard development in the test enclosure [6]. Due to differences in foam density and cover fabric, variation in the burning rate of different chair mock-up configurations was expected. One chair mock-up constructed from high-density foam and polyester cushion covers was burned in the NIST furniture calorimeter to determine the average heat of combustion of the mock-up. The mock-up was ignited with the flame tube in the same manner as the full-scale tests. A peak heat release rate of approximately 700 kW was achieved, with a test-average heat of combustion (obtained by dividing the total heat released by the total mass loss) of 25 MJ/kg.[1] The combined standard uncertainty of the average heat of combustion was estimated as ± 3 MJ/kg.

A heat release rate estimate of most chair mock-ups was determined by differentiating the mass loss curve for each test to obtain the mass loss rate, and multiplying that curve by the test-average heat of combustion. In order to characterize the heat release rate results for each chair mock-up, the heat release rate curve was fitted to a "t-squared" power law fire growth curve, following an initial linear growth phase. This functional form fits the heat release rate of many common materials, and is used extensively for design fires in fire hazard analysis [19]. Annex B, Engineering Design Guide for Automatic Fire Detector Spacing, in the 13 ed. of NFPA 72 specifies a design fire range as *slow* being a time to reach 1055 kW in a period greater than or equal to 400 s, *medium* for growth times between 150 s to 400 s, and *fast* for growth times less than 150 s [1]. Figure 3 shows two fitted heat release rate curves for an initially flaming and an initially smoldering chair mock-up fire. The linear portion spanned from ignition to the time to reach a fixed value (typically 25 kW for initially flaming fires, and 10 kW for initially smoldering fires). Table 1 shows the linear time span for each fit, the fitting parameter, the expected fire growth time to reach 1055 kW (after the linear growth phase), and the fire growth category. All but one of the chair mock-up fires fall within the medium "t-squared" fire category after the linear growth phase, and the linear growth phase was estimated to be at least 150 s for initially flaming fires and 4840 s or greater for initially smoldering fires. The combination of the linear growth phase and the "t-squared" fire growth rate suggests that these fire sources were not so fast developing as to render smoke detection inconsequential, but that alarm activation during the linear growth phase could provide substantial available safe egress times.

[1] The heat of combustion for the smoldering phase is expected to be lower than the specified 25 MJ/kg, but the transition to flaming occurred before significant mass loss rate was measured.

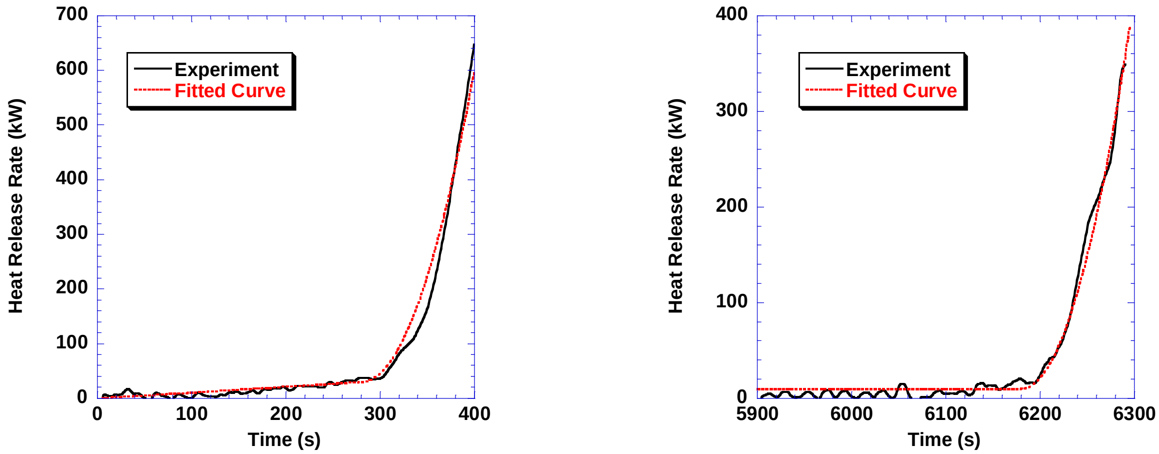

Figure 3. Experimental heat release rate curves for an initially flaming fire (Exp. 10, left figure) and initially smoldering fire (Exp. 5, right figure). Dashed lines are fitted curves consisting of a linear segment and a “t-squared” segment. Fitting parameters are listed in Table 1.

Data on hydrogen cyanide (HCN) was not included in previous analysis of the Smoke Alarm Sensitivity Study [6, 8 and 15], but is included here with conservative HCN estimates used in the following tenability calculations. The HCN sampling in the hallway was accomplished by drawing a fixed flow of hallway air through soda lime HCN sorbent tubes for a fixed time. The sorbent tubes were located inside the hallway at the centerline. A rigid metal pipe terminating at the center of the hallway supported the sorbent tube, and the flow tube attached to it. The flow tube led from the structure connecting to a mass flow controller and then to a vacuum pump. Multiple sorbent tubes could be switched out during individual tests. The samples were analyzed for adsorbed HCN mass using the NIOSH 6010 method [20]. The HCN mass was converted to a mean volume fraction (at room conditions) over the sampling time (sampling times restricted to smoldering phase or flaming phase) and scaled by the volume fraction of carbon monoxide. HCN has been shown to correlate with CO in combustion gas yields of furnishing materials [21]. Figure 4 shows the HCN yield values for samples taken during flaming and smoldering phases of combustion. The combined relative uncertainty is estimated as ± 15 %. Also shown are best fit lines through all of the flaming mode and smoldering mode data points. In order to compute toxic gas tenability limits using HCN along with CO in a conservative manner, fixed values of HCN yields of 0.075 and 0.025 (approximately double the best fit lines) were specified for flaming and smoldering phases of combustion.

Table 1. Fire growth rate fitting parameters[2] for chair mock-up fires based on mass loss rate and an average effective heat of combustion.

Material*, Exp. No.	Ignition Mode, Location#	Linear Phase t_L (s), $\dot{Q}_L$(kW)	a (kW/s^2)	R%	Time to 1055 kW (s)	Category+
PET fabric, LD foam, 4	Flaming, LR	150, 10	0.0142	0.995	271	Medium
PET fabric, LD foam, 17	Flaming, LR	200, 25	0.0229	0.983	212	Medium
PET fabric, LD foam, 19	Flaming, LR	175, 25	0.0256	0.970	201	Medium
PET fabric, HD foam, 8	Flaming, BR	260, 30	0.0207	0.977	223	Medium
PET fabric, HD foam, 10	Flaming, BR	280, 30	0.0397	0.986	161	Medium
PET fabric, HD foam, 24	Flaming, BR	240, 25	0.0241	0.972	207	Medium
PET fabric, LD foam, 7	Flaming, BR	180, 25	0.0246	0.990	205	Medium
PET fabric, LD foam, 11	Flaming, BR	160, 10	0.0315	0.973	182	Medium
CT fabric, LD foam, 1	Flaming, LR	1200, 25	0.0106	0.987	312	Medium
CT fabric, LD foam, 6	Flaming, LR	220, 25	0.0127	0.975	285	Medium
CT fabric, LD foam, 18	Flaming, LR	800, 25	0.0284	0.954	190	Medium
CT fabric, LD foam, 5	Smoldering, LR	6180, 10	0.0285	0.991	191	Medium
CT fabric, LD foam, 22	Smoldering, LR	5790, 10	0.0333	0.980	177	Medium
CT fabric, HD foam, 16	Smoldering, LR	5240, 10	0.0334	0.976	177	Medium
CT fabric, HD foam, 21	Smoldering, LR	6210, 10	0.0401	0.995	160	Medium
CT fabric, HD foam, 23	Smoldering, LR	5180, 10	0.0395	0.980	163	Medium
CT fabric, LD foam, 12	Smoldering, BR	4840, 10	0.0344	0.983	174	Medium
CT fabric, LD foam, 15	Smoldering, BR	10910, 20	0.0579	0.986	131	Fast
CT fabric, LD foam, 2	Smoldering, BR	6125, 10	0.0118	0.963	298	Medium
CT fabric, LD foam, 9	Smoldering, BR	6790, 10	0.0201	0.986	228	Medium

*PET – Polyester, CT – Cotton, LD – low density, HD – high density

#LR – living room, BR – bedroom

% Correlation coefficient R

+NFPA 72 Annex B definition

[2] Fitting equations given below, where $\dot{Q}$(t) is the heat release rate at time t, $\dot{Q}_L$is the heat release rate maximum during the linear growth phase, t_l is the linear growth phase time and a is the pre-exponential.

$$\dot{Q}(t) = \frac{\dot{Q}_L}{t_L}\, t \qquad\qquad t < t_l$$

$$\dot{Q}(t) = a\,(t - t_L)^2 + \dot{Q}_L \qquad\qquad t \geq t_L$$

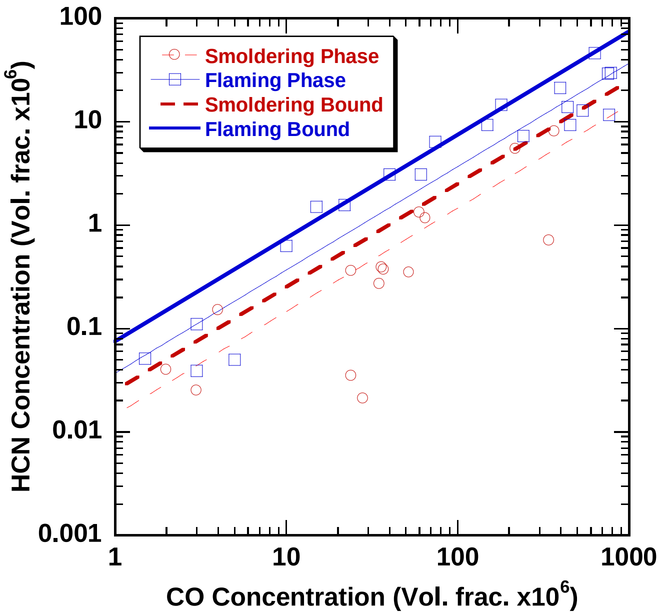

Figure 4. Mean HCN concentration as a function of mean CO concentration for samples taken at a height of 1.5 m above the floor in the center of the hallway leading to the master bedroom. Symbols are experimental time-averaged values, and thin lines are linear fits through the data (combined relative uncertainty is estimated as ± 15 %.) The thick lines define upper bounds of HCN yields for flaming and smoldering phases used in the fractional effective dose (FED) calculations.

Toxic gas and thermal exposure tenability criteria were computed using the fractional effective dose (FED) concept and equations ISO 13571 [22]. Figure 5 shows two examples of toxic gas FED and thermal exposure FED in initially flaming and initially smoldering fires. The location of the fire in each case was the living room, and the FEDs were calculated using the average of the hallway toxic gas concentrations and living room temperature and heat flux values. Two FED toxic gas calculations were performed using either, CO and CO_2, or CO, CO_2 and HCN. The FED calculations that included HCN rose faster than the calculations that excluded HCN. Only in the initially smoldering fire does the more rapid HCN rise significantly impact the calculated hazard. When HCN was considered, the toxic gas FED reached a value of 0.3 approximately 400 s sooner compared to the toxic gas FED computed without HCN. Additionally, the toxic gas FED (including HCN) reached a limit of 0.3 more than 400 s sooner than the thermal FED.

3 ASET/RSET MODEL

An ASET/RSET analysis was performed using the model presented in Reference 7 where scenario-averaged outcomes were computed for specific alarm activation times to provide a comparison between the performance of photoelectric, ionization, and dual sensor alarms.

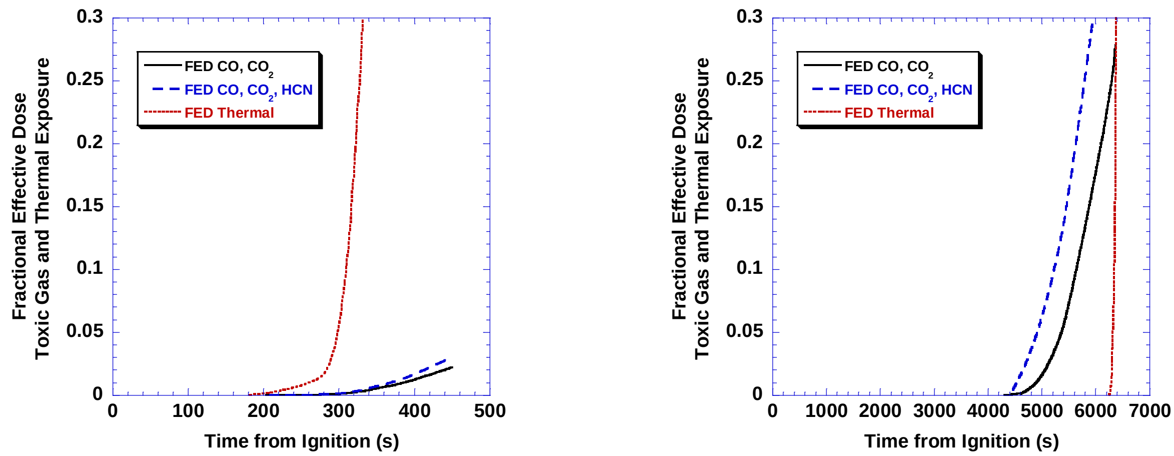

Figure 5. Comparison of FED calculations in living room fires with and without HCN. Left figure flaming fire, right figure initially smoldering fire that transitioned to flaming.

Here, the results are presented in terms of activation time. The time to reach a specific smoke obscuration value provided by the ceiling extinction meter was compared to the fraction of successful escape outcomes assuming that an alarm activates at that smoke obscuration level. The basis for the analysis assumed that smoke alarms were interconnected and alerted occupants, regardless of their initial location, and occupants started to move after a pre-determined, pre-movement delay time.

3.1 Egress Scenarios

The space considered was the residential test structure with a fictitious attached space representing a second bedroom and an entrance/exit door off the living room, as shown in Figure 6. Again, it was sized to represent a small, single-floor apartment space. The shaded spaces were closed-off from the rest of the structure. The second bedroom is assumed to have an interconnected smoke alarm.

Table 2 shows 13 specified occupant travel paths. These routes were selected to include direct egress paths, investigational and rescue activity paths, and include initially locating the occupant in the room of fire origin in some cases. All 13 scenarios were included in the analysis of every experiment, and equally weighted to provide a basis for calculation of ASET and RSET.

3.2 Tenability Criteria

The tenability criteria for toxic gas and heat exposure followed the criteria used in other studies [5, 8, 15 and 23], specifically, an FED limit of 0.3 for both toxic gases and heat exposure. These limits are conservative in that only the most vulnerable population would potentially become

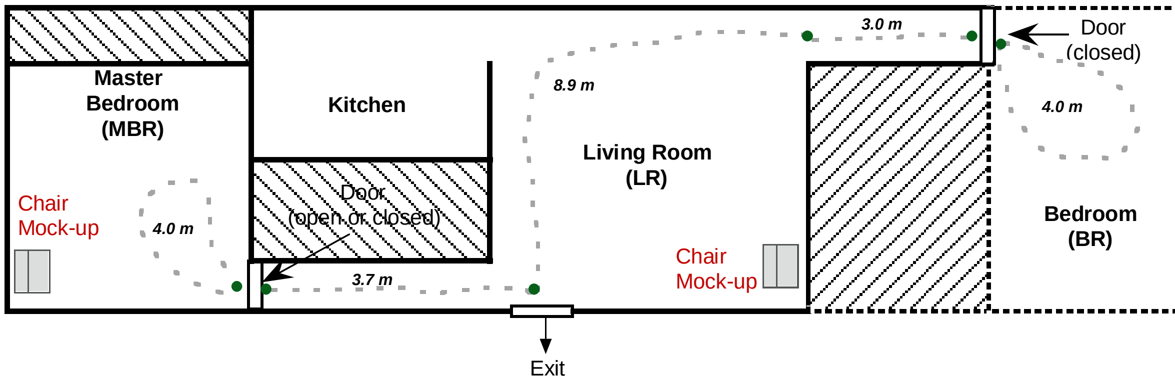

Figure 6. Layout of the residential structure as defined for egress analysis. Dashed lines represent travel path segments with their respective distances indicated.

Table 2. Travel paths indicating order of rooms visited, number of segments and total distance traveled for each egress scenario considered (Figure 6).

Scenario	Travel Path	Travel Segments	Travel Distance (m)
1	MBR – Exit	2	7.7
2	LR – Exit	1	8.9
3	BR – Exit	3	15.9
4	MBR – BR – Exit	7	35.5
5	BR – MBR – Exit	6	27.3
6	LR – BR – Exit	5	27.8
7	LR – MBR – Exit	4	20.3
8	LR – BR – MBR – Exit	8	39.2
9	LR – MBR – BR – Exit	9	48.1
10	MBR – LR – MBR – Exit	6	28.0
11	BR – LR – BR – Exit	7	34.8
12	MBR – BR – MBR – Exit	10	46.9
13	BR – MBR – BR – Exit	11	55.1

MBR – master bedroom
LR – living room
BR – Bedroom

incapacitated at these levels. The smoke obscuration limit, while not a tenability criteria, was nevertheless used as a limiting smoke value, as an occupant's escape can be significantly affected in a negative manner. Studies have shown that increasing smoke obscuration decreases visibility distance and reduces travel speed. A limiting value of smoke optical density of 0.25 m^{-1} was used in the NIST Home Smoke Alarm Study, whereas a value of 0.43 m^{-1} was used in an NFPA task group report that performed a re-analysis of the NIST data [23]. Neither analysis considered the effect of smoke on occupant travel speed. Analysis of the NIST Smoke Alarm Sensitivity Study results, that did consider the effect of smoke on travel speed, showed that the assumed smoke obscuration limit had a significant effect on the escape outcomes for flaming and smoldering fire scenarios over a range of 0.25 m^{-1} to 1.0 m^{-1} [8]. In the analysis below, the results are presented for four smoke limits (0.20 m^{-1}, 0.25 m^{-1}, 0.30 m^{-1}, and 0.43 m^{-1}) and when the smoke limit is not enforced ("no smoke" limit). The 0.20 m^{-1} and 0.30 m^{-1} limits represent ± 20 % differences from the 0.25 m^{-1} value and are included to show the sensitivity of the results about the nominal uncertainty of the optical density measurement at 0.25 m^{-1}. The "no smoke" limit results force either the heat or toxic gas tenability limits to become the limiting condition. The "no smoke" limit conveys a relative urgency for a given scenario, whereas a small time difference between a smoke limit and "no smoke" limit implies little time for alternate outcomes like being rescued.

3.3 Occupant Characteristics

In each egress simulation, the occupant is alerted at some time from an interconnected smoke alarm. Since the ceiling smoke obscuration was only measured in the south hallway (leading from the master bedroom, and next to the exit door), it was defined as the location of the initiating alarm; the actual recorded alarm times throughout the structure were ignored. After receiving the alarm, the occupant remained at their initial location for a specified time before moving, designated as the pre-movement time. Pre-movement times are represented as a probability distribution in the model. In previous work, three probability distributions were proposed to characterize a fast reacting, "primed" group, a more measured normal-reacting group, and a slower-to-react group characteristic of elderly or mobility-impaired occupants [8]. Here, these distributions are postulated from discrete pre-movement activities tied to similar activities considered in the NIST Home Smoke Alarm Report [5].

The Home Smoke Alarm Report considered the following pre-movement activities: calling the fire department, getting dressed, gathering belongings, and waking/rescuing two individuals. Waking to the alarm was not included. This omission is contradicted by research that showed waking to an alarm is not instantaneous, but may take 30 s or longer in some cases [24]. The action of calling the fire department was included in human response studies conducted in the 1980's. However, here, it is speculated that with the prevalence of cell phones presently, an individual would not make a call to the fire department from inside the home. Therefore, in this analysis, calling fire department was dropped and waking/arising was added as pre-movement activities. The Home Smoke Alarm Study used estimated mean values for the pre-movement times obtained from previous research [25]. Here, a distribution was associated with each pre-movement activity. The "awaken and arise" pre-movement distribution was postulated given the experimental results of Duncan [26] and Ashley [27]. The fast-responding "primed" occupants are described as responding sooner and with less spread in their responses. This group represents the response of test subjects who were expecting an alarm, i.e. "primed", as part of a study. This group does not alert others as defined to represent the quickest expected individual occupant response and this group is not included in the following analysis. Both the normal-responding mobile occupants and the slower-to-react occupants take somewhat longer to arise, awaken, and accomplish pre-movement activities on average.

As described in [8], the total pre-movement time was characterized by a median time and a geometric standard deviation (σ_g) with a log-normal distribution. The Fenton-Wilkinson method was used to estimate a single log-normal distribution that approximates the sum of the individual pre-movement activity distributions [28]. Table 3 details the individual contributions and the final distribution for three separate populations which, as it turns out, are the same as those considered previously [8]. Response times for 84.1 % of a group to complete individual tasks are presented to show how long it would take a large portion of the population to complete each task (for a log-normal distribution, the median time multiplied by the geometric standard deviation defines the 84.1 % response time, thus, it is a convenient way to compare different distributions). For the normal-responding occupants group (median = 35 s, σ_g = 1.6), 84.1 % accomplished all pre-movement tasks in 56 s. Whereas for slower-to-react occupants group (median = 55 s, σ_g = 1.6), 84.1 % accomplished all pre-movement tasks in 88 s. This compares with the cumulative worst-case pre-movement times of 55 s for the young family at night and 80 s for the elderly family at night estimated in the NIST Home Smoke Alarm Study [5].

Table 3. Pre-movement activities and the corresponding log-normal distribution that approximates the sum of the individual pre-movement activities for three populations.

Population	Pre-movement Activity	Mean Time (s)	Median Time (s)	Geometric Standard Deviation (σ_g)	Time for 84.1 % of Population to complete task(s)
Fast-responding, primed occupants	Awaken and arise	8.0	6.1	2.1	12.8
	Dress or don robe	5.0	3.8	2.1	8.0
	Gather belongings	5.0	3.8	2.1	8.0
	Distribution representing the sum	**18**	**16**	**1.6**	**26**
Normal-responding, mobile occupants	Awaken and arise	12	8.2	2.4	17.2
	Dress or don robe	8	5.5	2.4	11.5
	Gather belongings	8	5.5	2.4	11.5
	Awaken occupant 1	6	4.1	2.4	8.6
	Awaken occupant 2	6	4.1	2.4	8.6
	Distribution representing the sum	**40**	**35**	**1.6**	**56**
Elderly, mobility impaired, slower-to-react occupants	Awaken and arise	15	10.2	2.4	21.5
	Dress or don robe	15	10.2	2.4	21.5
	Gather belongings	12	8.2	2.4	17.2
	Awaken occupant 1	10	6.8	2.4	14.3
	Awaken occupant 2	10	6.8	2.4	14.3
	Distribution representing the sum	**62**	**55**	**1.6**	**88**

Travel speed was treated as a function of the smoke optical density along the travel path in the model. The NIST Home Smoke Alarm Study analysis used fixed floor travel speeds of 1.2 m/s for young occupants and 0.75 m/s for elderly occupants [5]. Here, the initial travel speed for all occupants was an intermediate value of 1.05 m/s and, as the smoke optical density increased, the occupant travel speed was assumed to decrease from 1.05 m/s to a limiting speed of 0.1 m/s [8]. Figure 7 shows the travel speed along with an estimated visibility range for various reflective surfaces (walls, doors, furniture objects, etc. under normal lighting conditions) as a function of optical density. The visibility was estimated by a dimensionless constant divided by the optical density. Here, the constants were 0.9 and 1.7 for the lower and upper range of visibility for reflective surfaces [29]. For an optical density of 0.5 m^{-1} in Figure 7, the travel speed drops by about 85 %, whereas the visibility is estimated to be between 3.5 m and 7.0 m.

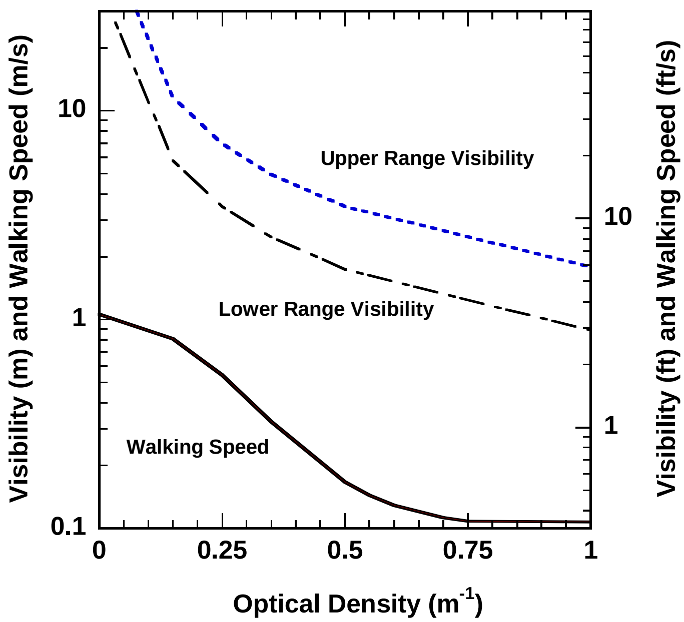

Figure 7. The walking speed as a function of the optical density correlation used in the model [8], and the estimated upper and low reflective surface visibility range as a function of optical density [29].

4 MODEL IMPLEMENTATION

The start of each experiment (application of heat source or flame to the seat cushion) was considered time zero. At some time well before non-tenable conditions, a fictitious hallway alarm was assumed to activate. From this alarm activation time, egress calculations were conducted for 41 pre-movement times from 0 s to 200 s in 5 s intervals, which covered more than 99 % and 97 % of the normal-responding occupants and the slower-to-react occupants distributions, respectively. If egress was deemed unsuccessful, because a tenability or smoke limit was reached for a given pre-movement time, then the fraction of the population deemed to successfully escape was estimated by the integral of the pre-movement frequency distribution from zero to the last successful pre-movement time step (and normalized by 0.99 or 0.97, depending on the occupancy group.) The fraction of successful escapes was calculated for each of the 13 egress scenarios, and those values were averaged to represent a single fraction of successful escapes for the presumed alarm time of a given fire experiment. The initial alarm time was then increased by 10 s in the case of initially flaming fires and 30 s in the case of initially smoldering fires and the fraction of successful escapes re-calculated. The alarm time was increased and the calculations repeated until essentially all egress attempts were unsuccessful. This process was conducted for the two characteristic occupant groups considered here, the normal-responding occupants and the slower-to-react occupants.

5 SIMULATION RESULTS

There were a total of six fire scenarios considered: two flaming fires located in the living room (with different cover fabrics, either cotton or polyester) and one located in the master bedroom, and two initially smoldering fires located in the living room (with different foam densities) and one located in the master bedroom. Each fire scenario experiment was conducted three times, to quantify the variability in the ignition, fire growth, and time to alarm, for a total of 18 individual experimental fires used for the simulations considered in this analysis.

Figures 8-11 are sample plots showing the results for flaming and smoldering fire experiments in the living room and master bedroom, respectively. For each experiment, the fraction of successful escapes is plotted versus the presumed alarm time. In addition, the smoke obscuration at the ceiling is plotted. In the analysis presented, results are given for four hypothetical smoke limit criteria (0.20 m^{-1}, 0.25 m^{-1}, 0.30 m^{-1}, and 0.43 m^{-1}) and when "no smoke" limit is enforced. Figures 8 and 9 show the results of a flaming fire in the living room with occupant pre-movement distributions representing the normal-responding occupant group and the slower-to-react occupant group, respectively. Figures 10 and 11 show the results for a smoldering fire in the master bedroom with occupant pre-movement distributions representing the normal-responding occupant group, and the slower-to-react occupant group, respectively. There are significant differences in egress outcomes for the various smoke limit criteria that define smoke alarm performance. For the smoldering cases, there were long time differences for different smoke limits in the slowly developing smoldering fire, whereas in the flaming fire case, the egress outcomes for the different smoke limits were relatively close together, indicating rapid smoke development. The flat portion of some curves at approximately 31 % in Figures 10 and 11 was due to the fact that 4 of the 13 egress scenarios that did not include traversing the south hallway nor the master bedroom, and combined with the relatively long time for the smolder smoke to fill the living room as it traveled from the master bedroom, led to extended safe egress time for those scenarios.

The surrogate for smoke alarm performance is the ceiling smoke obscuration measurement at the desired smoke alarm activation time which would be considered as the target alarm criterion for new polyurethane foam smoldering and flaming fire sensitivity tests in ANSI/UL 217 and ANSI/UL 268. A performance level of 100 % successful escapes may be a target that is too challenging to achieve given that the continuous pre-movement frequency distributions for which 99 % or 97 % of a population's pre-movement time is longer than 200 s, and that three egress scenario travel distances were greater than 45 m, requiring significant travel time. Likewise, a performance level of 50 % successful escapes or less may be too lax. Therefore, three performance levels were examined, with 95 %, 85 % and 75 % success rates.

The results for the three performance levels, with values of 95 %, 85 % and 75 % egress success for two target populations (normal-responding occupants, and slower-to-react occupants) are given in Tables 4 - 6 to provide a comparison between the levels of performance and the smoke obscuration values at which alarms would need to respond to attain different levels of performance. Results are also tabulated for two different optical density limits, namely a more conservative 0.25 m^{-1} and a less conservative value, 0.43 m^{-1}. The tabulated values include the average smoke obscuration[3] and standard deviation (std dev) for the nine smoldering and nine flaming experiments, along with the singular values that would produce the desired egress success rate (95 %, 85 % and 75 %) across all 9 flaming or smoldering experiments. Obviously, the smoke alarm sensitivity, as indicated by the smoke obscuration value, needed to achieve a given performance level decreased (indicated by an increase in smoke obscuration) as the desired egress success rate decreased. The sensitivity required for the most conservative assumptions versus the least conservative assumptions (optical density limit of 0.25 m^{-1} for the slower-to-react occupant group versus optical density limit of 0.43 m^{-1} for the normal-responding occupant group) varied by 4 %/ft -6 %/ft obscuration for flaming fire scenarios to 6 %/ft -8 %/ft obscuration for smoldering fire scenarios for each of the three performance levels.

To provide some context to the three performance levels chosen, the performance of actual smoke alarms used in the experiments were assessed. Table 7 shows the corresponding egress success rate for the experimentally determined hallway-mounted ionization or photoelectric alarm times used as model inputs. For fires located in the living room or bedroom, alarm activations at the S3 or S4 locations were used, respectively. The alarm locations and the ceiling smoke measurements were not at the same locations in the hallway, with the alarms are located closer to the fire source, so a direct correlation is not expected. However, the alarm time results are suggestive of the level of relative performance current photoelectric and ionization alarms achieve for the tenability criteria and occupant characteristics investigated. The lowest average egress success rates for the most conservative assumptions (optical density limit of 0.25 m^{-1} for the slower-to-react occupant group) were 55 % for ionization alarms in smoldering fire scenarios and 66 % for photoelectric alarms in flaming fire scenarios. These values are below the lowest performance level of 75 % success rate specified above. This contrasts with the lowest average egress success rates for the least conservative assumptions (optical density limit of 0.43 m^{-1} for the normal-responding mobile occupant group) of 95 % for ionization alarms in smoldering fire scenarios and 94 % for photoelectric alarms in flaming fire scenarios.

[3] Smoke obscuration is reported throughout this paper in terms of percent obscuration per foot (%/ft obscuration) as specified in ANSI/UL 217 and ANSI/UL 268 and per US fire detection industry norms.

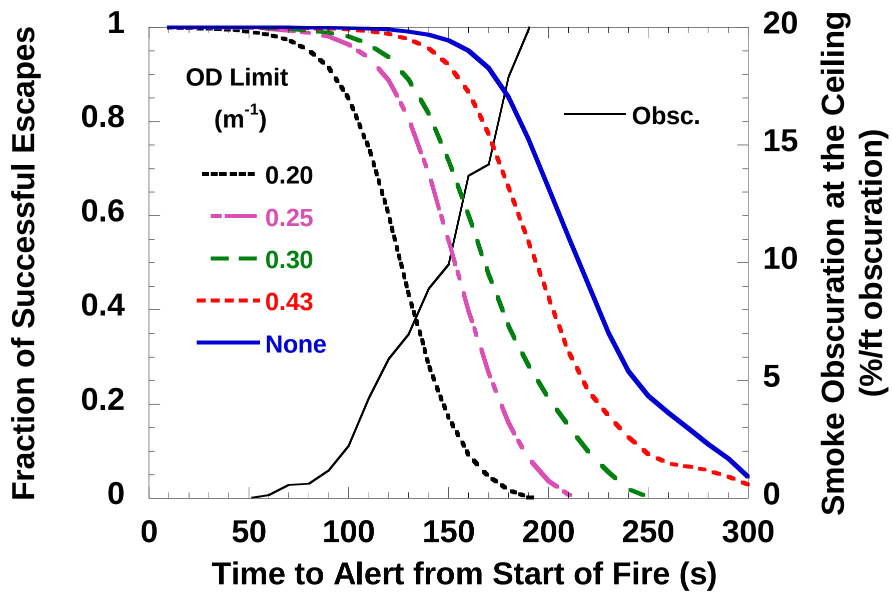

Figure 8. Calculated fraction of successful escapes as a function of the time to alarm for a flaming fire originating in the living room for the normal-responding mobile occupant group. Also shown is the measured smoke obscuration at the ceiling.

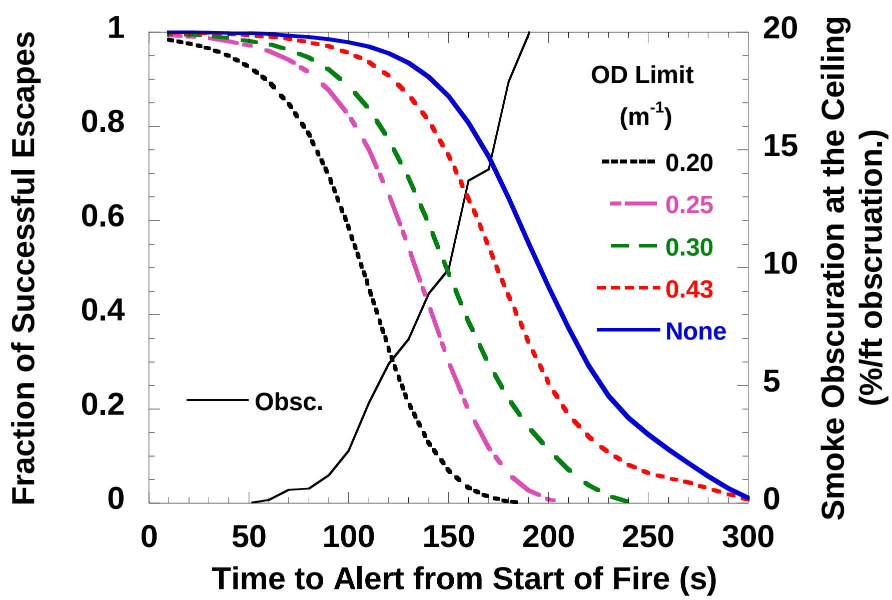

Figure 9. Calculated fraction of successful escapes as a function of the time to alarm for a flaming fire originating in the living room for the slower-to-react occupant group. Also shown is the measured smoke obscuration at the ceiling.

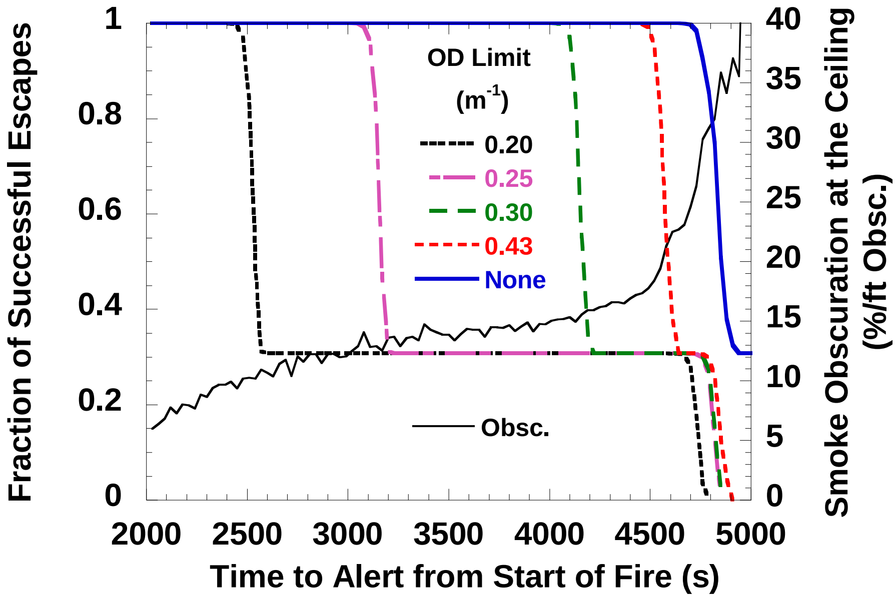

Figure 10. Calculated fraction of successful escapes as a function of the time to alarm for a smoldering fire originating in the master bedroom for the normal-responding mobile occupant group. Also shown is the measured smoke obscuration at the ceiling.

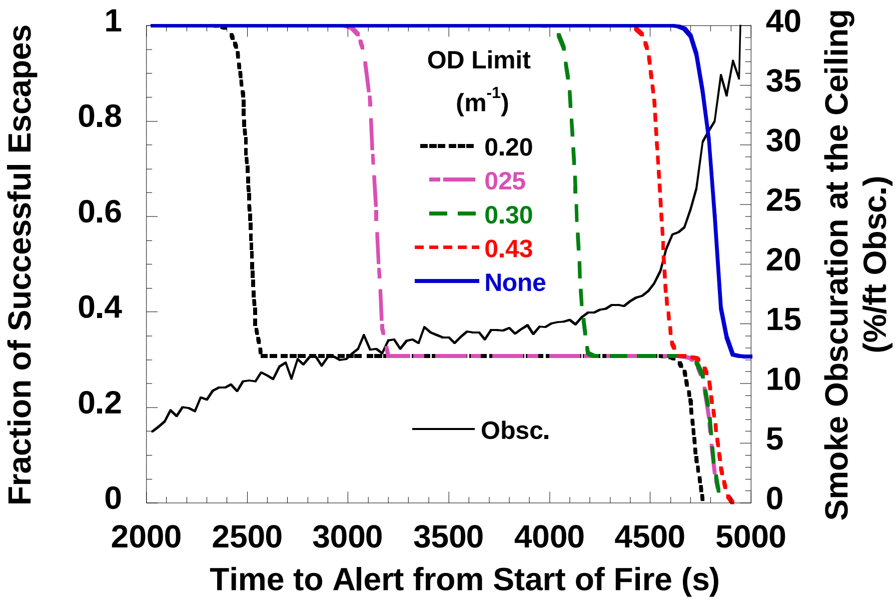

Figure 11. Calculated fraction of successful escapes as a function of the time to alarm for a smoldering fire originating in the master bedroom for the slower-to-react occupant group. Also shown is the measured smoke obscuration at the ceiling.

Table 4. Ceiling smoke obscuration required to achieve a calculated 95 % egress success rate for the target populations and optical density limits.

Optical Density Limit (m^{-1})	Pre-movement Distribution (median (s) /σ_g)	Initially smoldering fire scenario ceiling smoke obscuration to achieve 95 % egress success rate (%/ft obsc.)		Flaming fire scenario ceiling smoke obscuration to achieve 95 % egress success rate (%/ft obsc.)	
		Average of 9 experiments ± std dev	Value to achieve 95 % success rate across all 9 experiments	Average of 9 experiments ± std dev	Value to achieve 95 % success rate across all 9 experiments
0.25	35/1.6	17.2 ± 5.2	11.3	3.1 ± 1.7	2.5
	55/1.6	16.7 ± 5.1	10.7	0.9 ± 0.8	0.4
0.43	35/1.6	23.3 ± 7.6	18.3	5.6 ± 2.2	4.7
	55/1.6	22.3 ± 7.2	13.3	2.5 ± 1.7	2.0

Table 5. Ceiling smoke obscuration required to achieve a calculated 85 % egress success rate for the target populations and optical density limits.

Optical Density Limit (m^{-1})	Pre-movement Distribution (median (s) /σ_g)	Initially smoldering fire scenario ceiling smoke obscuration to achieve 85 % egress success rate (%/ft obsc.)		Flaming fire scenario ceiling smoke obscuration to achieve 85 % egress success rate (%/ft obsc.)	
		Average of 9 experiments ± std dev	Value to achieve 85 % success rate across all 9 experiments	Average of 9 experiments ± std dev	Value to achieve 85 % success rate across all 9 experiments
0.25	35/1.6	17.5 ± 5.3	12.7	5.0 ± 1.6	4.5
	55/1.6	17.1 ± 5.2	12.5	2.3 ± 1.5	2.1
0.43	35/1.6	24.6 ± 8.9	19.9	8.6 ± 3.2	7.5
	55/1.6	23.3 ± 7.8	18.9	5.5 ± 2.1	4.5

Table 6. Ceiling smoke obscuration required to achieve a calculated 75 % egress success rate for the target populations and optical density limits.

Optical Density Limit (m^{-1})	Pre-movement Distribution (median (s) /σ_g)	Initially smoldering fire scenario ceiling smoke obscuration to achieve 75 % egress success rate (%/ft obsc.)		Flaming fire scenario ceiling smoke obscuration to (%/ft obsc.)achieve 75 % egress success rate	
		Average of 9 experiments ± std dev	Value to achieve 75 % success rate across all 9 experiments	Average of 9 experiments ± std dev	Value to achieve 75 % success rate across all 9 experiments
0.25	35/1.6	17.7 ± 5.3	14.0	5.9 ± 1.7	5.5
	55/1.6	17.4 ± 5.3	13.9	3.7 ± 1.6	3.4
0.43	35/1.6	25.3 ± 9.0	22.4	9.9 ± 3.2	9.7
	55/1.6	24.3 ± 8.6	21.5	7.1 ± 2.5	6.2

Table 7. Calculated relative egress performance using experimental activation times for photoelectric and ionization alarms in the hallway where the ceiling smoke obscuration was measured.

Optical Density Limit (m^{-1})	Pre-movement Distribution (median (s) /σ_g)	Initially smoldering fire scenario egress success rate percentage using local (hallway) alarm times		Flaming fire scenario egress success rate percentage using local (hallway) alarm times	
		Ionization Alarms (average of 9 experiments ± std dev)	Photoelectric Alarms (average of 9 experiments ± std dev)	Ionization Alarms (average of 9 experiments ± std dev)	Photoelectric Alarms (average of 9 experiments ± std dev)
0.25	35/1.6	59 ± 40	100 ± 0	95 ± 13	83 ± 18
	55/1.6	55 ± 44	100 ± 0	89 ± 18	66 ± 23
0.43	35/1.6	95 ± 16	100 ± 0	100 ± 1	94 ± 13
	55/1.6	94 ± 21	100 ± 0	97 ± 4	85 ± 20

Another way to examine the results is to tabulate the egress success rate as a function of alarm activation at a given smoke obscuration. Table 8 shows the corresponding egress success rate for flaming fire scenarios with smoke obscuration ranging from 2 %/ft obscuration to 10 %/ft obscuration. Table 9 shows the corresponding success rate for smoldering fire scenarios with smoke obscuration ranging from 8 %/ft obscuration to 24 %/ft obscuration. Additional columns are shown for the egress success rate for a given smoke obscuration plus a 30 s delay (dwell time, which has been suggested by some manufacturers as part of the fire test performance criteria).

Table 8. Calculated relative egress performance for an alarm activated at a prescribed ceiling smoke obscuration for flaming fires.

Smoke Obscuration (%/ft obsc.)	Success Rate (%) Normal-responding occupants (Pre-movement distribution – 35 s, σ_g 1.6)				Success Rate (%) Slower-to-react occupants (Pre-movement distribution – 55 s, σ_g 1.6)			
	Optical density limit 0.25 m^{-1}		Optical density limit 0.43 m^{-1}		Optical density limit 0.25 m^{-1}		Optical density limit 0.43 m^{-1}	
	Delay 0 s	Delay 30s	Delay 0 s	Delay 30s	Delay 0 s	Delay 30s	Delay 0 s	Delay 30s
2	97	85	99	97	86	65	95	86
3	94	73	98	91	78	55	91	78
4	89	63	97	87	70	43	88	71
5	80	50	94	80	60	33	82	62
6	70	40	91	71	50	26	76	52
7	62	32	87	63	42	20	70	44
8	55	28	83	56	37	17	64	38
9	49	23	79	49	32	13	59	33
10	44	19	73	42	27	11	52	27

Table 9. Calculated relative egress performance for an alarm activated at a prescribed ceiling smoke obscuration for smoldering fires.

Smoke Obscuration (%/ft obsc.)	Success Rate (%) Normal-responding occupants (Pre-movement distribution – 35 s, σ_g 1.6)				Success Rate (%) Slower-to-react occupants (Pre-movement distribution – 55 s, σ_g 1.6)			
	Optical density limit 0.25 m^{-1}		Optical density limit 0.43 m^{-1}		Optical density limit 0.25 m^{-1}		Optical density limit 0.43 m^{-1}	
	Delay 0 s	Delay 30s	Delay 0 s	Delay 30s	Delay 0 s	Delay 30s	Delay 0 s	Delay 30s
8	100	100	100	100	100	100	100	100
10	100	100	100	100	100	99	100	100
12	91	88	98	94	88	85	95	92
14	77	74	97	94	75	72	95	92
16	67	66	96	93	66	66	94	92
18	67	65	96	92	66	64	93	88
20	59	52	84	77	54	47	79	74
22	43	39	78	73	40	37	74	70
24	27	25	66	60	26	24	62	56

For the flaming fire scenarios and smoke obscuration values from 2 %/ft to 10 %/ft, the success rate ranged from 99 % to 27 %, and 87 % to 11 % for the no delay and 30 s delays cases, respectively. The 30 s delay is equivalent to about a 3 %/ft to 6 %/ft obscuration increase to achieve the same egress success rate. For the smoldering fire scenarios and smoke obscuration values from 8 %/ft to 24 %/ft, the success rate ranged from 100 % to 26 %, and 100 % to 24 % for the no delay and 30 s delays cases, respectively. In the smoldering scenarios, the 30 s delay has very little impact on the smoke obscuration increase needed to achieve the same egress success rate. This is due to the relatively slow smoke concentration build-up in the smoldering fires

Since the simulated egress success rates are a function of egress scenarios (Table 2), occupant characteristics (Table 3), optical density limits (Tables 4 - 6) and the experimental results, a success rate averaged over the four occupant characteristic/optical density limit results was used to characterize an averaged relative success rate for a given smoke obscuration performance criterion. Averaging the normal-responding occupant group results and the slower-to-react occupant group results yields an equal weighting of both groups in lieu of a specific combined population distribution. An average of the results from the two optical density limits (0.25 m^{-1} and 0.43 m^{-1}) is an approximation of the mean smoke concentration limit that starts to inhibit egress of more and less susceptible occupants, given their psychophysical response to smoke.

It is asserted here that the performance criterion for flaming and smoldering fire test scenarios should lead to nominally equal relative egress success rates to provide commensurate improvement in flaming and smoldering fire detection performance. Table 10 gives matched pairs of flaming and smoldering fire performance criteria based on the averaged simulated egress success rates. The first tabulated performance criteria representing an average egress success rate of about 94 % yielded a flaming fire performance criterion (2 %/ft obscuration) that would significantly challenge photoelectric alarms, whereas the smoldering fire performance criterion (12 %/ft obscuration) would significantly challenge ionization alarms. Most-likely, a combination of sensors would be needed to meet these performance criteria. The last tabulated performance criteria representing an average egress success rate of about 47 % yielded flaming and smoldering fire performance criteria (10 %/ft obscuration and 24 %/ft obscuration, respectively) that most-likely would not challenge current existing standalone photoelectric or ionization alarms and detectors. Intermediate levels of performance are also presented in the table.

The selection of performance criteria for new fire tests ought to consider factors other than just the relative alarm performance in a series of full-scale fire experiments. The smoke production rate and the smoke concentration build up in the fire test room should be similar to the full-scale fire experiments to assure alarms in the fire test room respond in a similar fashion. In fact, tests should be conducted in the fire test room using the flaming and smoldering smoke sources and current smoke alarm technologies to assess baseline performance. This would provide a reality check on the performance criteria developed from the analysis here, similar to the relative performance of smoke alarms placed in the hallway of the NIST Smoke Alarm Sensitivity Study (Table 7). In addition, nuisance alarm resistance needs to be considered in lieu of specific nuisance resistance tests.

Table 10. Matched pairs of flaming and smoldering fire performance criteria where the average success rate is nominally equal for smoke obscuration target values on the same row.

Flaming fire test alarm criterion		Smoldering fire test alarm criterion	
Smoke Obscuration (%/ft obsc.)	Averaged success rate and standard deviation (%/%)	Smoke Obscuration (%/ft obsc.)	Averaged success rate and standard deviation (%/%)
2*	94.3/5.7	**12***	93.0/4.4
4	86.0/11.4	**14**	86.0/11.6
5	79.0/14.1	**16**	80.8/16.5
6	71.8/17.0	**20**	69.0/19.7
8	59.8/19.1	**22**	58.8/20.0
10**	49.0/19.1	**24****	45.3/21.7

* Matched performance achievable with combination photoelectric/Ionization alarm

**Current standalone photoelectric and ionization alarms would most likely pass with these criteria [4].

6 CONCLUSIONS

An analysis methodology based on the ASET/RSET concept was used to estimate the relative performance of smoke alarms designed to alarm at specific smoke concentrations in flaming and smoldering polyurethane foam chair mock-up fires. The tenability limits were defined by a fractional effective dose value of 0.3 for toxic gas and heat exposure, and two smoke optical density limits used in previous studies, 0.25 m^{-1} and 0.43 m^{-1}, were considered. Analysis limitations and modeling assumptions included:

- interconnected smoke alarms that alert occupants regardless of initial fire location,
- occupant pre-movement time treated as a distribution for distinct populations,
- travel speed as a function of smoke density,
- occupants traversing a range of equally frequent pre-determined egress routes,
- considering only one apartment-sized residential space,
- one location for the responsive smoke alarm, and
- three flaming and three smoldering scenarios, and a total of 18 full-scale tests.

Results were presented to provide guidance in selecting performance criteria for new polyurethane foam fire tests proposed for ANSI/UL 217 and ANSI/UL 268. Averaged performance criteria for flaming and smoldering fire tests were specified in matched pairs of smoke concentrations representing commensurate relative performance improvements. The matched pairs ranged from an egress success rate of about 47 % with little to no expected improvement achieved by adding tests with these criteria to an egress success rate of about 94 %, representing the potential performance of combination photoelectric/ionization sensor alarms. Other considerations including the smoke production rate of the smoldering and flaming test samples and smoke transport in the fire test room may also likely affect the final performance criteria for the new proposed tests. In addition, some level of resistance to sources of nuisance alarms needs to be factored into the fire performance criteria.

Ultimately, the ANSI/UL 217 Standards Technical Panel or other regulatory bodies or standards development organizations needs to make a judgment on the performance it would like to achieve with the addition of the new tests.

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