Modeling Expected Performance of Smoke Alarms Meeting the Requirements of ANSI/UL 217-2015

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Abstract

There are new fire and cooking nuisance test requirements that smoke alarm manufacturers for the US market will need to meet soon. The recently developed CFAST Fire Data Generator (CData) method to assess residential fire safety designs was used to quantify the relative impact on safe egress given the expected performance of smoke alarms meeting the new requirements compared to current photoelectric and ionization alarms. The computer fire model CFAST was used to determine hazard development for selected egress scenarios and the expected successful escape outcome for a range of fires, room configurations and specified smoke alarm activations. The overall expected performance of smoke alarms meeting the new standard appears better than either photoelectric or ionization alarms in terms of successful escape outcomes over the range of scenarios considered.

Keywords: Fire detection, smoke alarms, hazard analysis, Monte-Carlo method

Introduction

With the changes to ANSI/UL 217-2015 [1], the added performance requirements for new fire tests and a cooking nuisance test, manufacturers in the US market need to meet those requirements soon. Experiments conducted with smoke alarms meeting the previous edition of the standard showed that no current smoke alarms come close to meeting the new performance requirements [2]. The performance metrics of the new fire tests were developed in part from full-scale fire research conducted by the National Institute of Standards and Technology (NIST) using an analysis methodology based on the Available Safe Egress Time (ASET) / Required Safe Egress Time (RSET) concept to estimate the relative performance of smoke alarms in flaming and smoldering polyurethane foam mattresses, chairs and chair mock-up fires [3-5]. The recently developed NIST CFAST Fire Data Generator (CData) to assess residential fire safety designs [6] is used to quantify the relative impact on safe egress given the expected performance of smoke alarms meeting the new requirements compared to current photoelectric and ionization alarms.

Modelling Residential Fire Scenarios

Descriptions of the Monte-Carlo method, building characteristics, fire scenarios, smoke alarm sensitivities and the assumed occupant characteristics are detailed in NIST Tech Note 2041 [6] and reference [7]. The deterministic zone fire model CFAST [8] is used to compute the fire hazard development from individual fire scenarios. Given a configuration of rooms, the fire heat release rate, heat of combustion and yields of smoke and toxic gases, CFAST can predict the smoke obscuration, toxic gas and thermal effects as a function of time in any room location at a specified height from the floor; thus, ASET can be determined. ASET is based on exposure limits to toxic gases, heat and smoke obscuration. Toxic gases and heat exposure limits are defined by a fractional effective dose (FED) of both gases and heat at a conservative limit of 0.3 as evaluated 1.5 m from the floor and computed using equations from ISO 13571:2012 [9]. A smoke obscuration limit of an optical density of 0.25 m^{-1} was specified, consistent with a value used in previous analyses [3-5]. A simple smoke alarm sub-model which specifies the smoke concentration (optical density) at alarm for a device located some small distance from the ceiling yields the smoke alarm activation time. RSET can be determined from the smoke alarm notification time and an estimate of occupant egress characteristics.

To determine building configurations, results from the US housing survey were used to gather the statistics on the number of rooms and the size of the US housing stock [4]. Room height is assumed to be 2.44 m. After sampling the building size, number of bedrooms, total number of rooms, and specifying room sizes (minimum room size 1.9 m^2), connections between rooms are randomly assigned with a 50 % probability that any two rooms are connected. A check is then made to verify the configuration thus selected is feasible (i.e. a planar graph). The process is repeated until the desired number of floor plans is generated.

Fire scenarios include both flaming and smoldering upholstered furniture and flaming mattress fires. Experimental data were used to develop the distribution of fire growth rate and linear growth phase of items. Smoldering or flaming fire yields of smoke and toxic gases were constant for each burning mode. Details are provided in NIST Tech Note 2041 [4]. The room of fire origin (RFO) is randomly selected from the rooms in each configuration.

In order to determine the expected performance impact of some change in a variable that could influence safe egress, many scenarios need to be explored. For instance, hazard development is a function of the room size(s) and the fire growth rate. Given the range of building configurations and fire growth rates possible, the expected performance is inherently probabilistic. In CData, samples are drawn from the various known probability distributions of relevant variables to generate the input conditions and the CFAST simulation is run using those input conditions. The process is repeated numerous times and the results aggregated to provide a probabilistic data set for analysis. Here and in NIST Tech Note 2041 [6], approximately 50,000 CFAST simulations were run and analyzed. The relevant variables include building size, number and configuration of rooms, fire scenario (here included both flaming and smoldering upholstered furniture and flaming mattress fires) and smoke alarm properties. Occupant characteristics are represented as a distribution of pre-movement time and egress time, but they are not part of the sampled input variables for CFAST runs; rather, the output results were integrated over the entire RSET distribution.

To perform the ASET/RSET analysis, the responsive occupant will have a specific RSET distribution for the particular CFAST run computed by summing the first alerting alarm time, and the RSET probability distribution. This resultant probability distribution is integrated from the minimum RSET time up to the time where ASET = RSET and the normalized fraction equals the fraction of successful escapes.

Smoke Alarm Sensitivities

A statistical smoke alarm activation model for photoelectric and ionization alarms was developed for upholstered furniture containing polyurethane foam [10]. The statistical model is represented as a log-normal distribution with a geometric mean and geometric standard deviation. The specific distribution depends on the smoke alarm type, and the mode of combustion prior to alarm activation. The data used to develop the statistical model comes from NIST experiments measuring the response of a sample of smoke alarms to the new smoldering and flaming polyurethane foam tests specified in ANSI/UL 217-2015. Estimates were made for the geometric mean and geometric standard deviation of the obscuration at alarm for flaming and smoldering upholstered furniture fires for theorectical smoke alarms that would meet the ANSI/UL 217-2015 Standard, with consideration of the necessary performance in the cooking fire test. Note, the distributions are meant to represent the performance variation of many alarms designed to meet the Standard for a particular fire scenario (flaming or smoldering).

Table 1 gives the geometric mean and geometric standard deviation for ionization, photoelectric and new smoke alarms, denoted A, B and C for flaming and smoldering upholstered furniture fires. For each CFAST run, an alarm obscuration is sampled from the (smoldering and/or flaming) probability distribution function. Thus, for a CFAST run, all smoke alarms would have the same obscuration limit. If a smoldering fire was to transition to a flaming fire, the alarm obscuration limit would change from the smoldering to flaming value for the alarms.

Alarms A and B represent possible distributions of alarm sensitivities with A having a lower geometeric mean value and a larger spread (standard deviation) in obscruation for flaming fires. Alarm B sensitivity was proposed after consultation with testing labs. Alarm C is a fictious, ideal alarm with a single sensitivity at the limit of the Standard for flaming polyurethane foam.

Table 1. Log-normal distribution parameters for alarm statistical models

Alarm	Flaming Fire Obscuration		Smoldering Fire Obscuration	
	Geometric Mean (%/ft)	Geometric Std. Dev.	Geometric Mean (%/ft)	Geometric Std. Dev.
Ionization	2.1	1.3	10.0	1.2
Photoelectric	6.7	1.3	3.5	1.7
A	3.0	1.3	5.0	1.3
B	4.0	1.15	5.0	1.3
C	5.0	1	5.0	1.3

Occupant Characteristics

In NIST Tech Note 2041 [4] a fixed time was used to characterize the RSET for the scenarios. Here, the occupant characteristics include a responsive occupant capable of self-rescue and an RSET drawn from a distribution representing a range in pre-movement activities and travel distances modeled after the distributions in NIST Tech Note 1837 [3]. The pre-movement activities distribution here represents individual activities aggregated into a log-normal distribution (the same as the normal-responding, mobile occupants described in Tech Note 1837) with a median pre-movement time of 35 s and a geometric standard deviation of 1.6. Added to the pre-movement time distribution is a fixed time of 30 s representing a mean travel time during egress. ASET is computed at a fixed location where the occupant is initially located. For occupants initially located in the RFO, ASET is computed from conditions in that room until the required time to exit, a worst-case scenario.

Occupant and Smoke Alarm Locations

The fire, alarm, and occupant locations for any individual model simulation will impact whether an occupant is predicted to escape successfully. A conservative assumption is that occupants are only alerted to smoke alarms located in the room they occupy. Several cases examined to cover a range of possible configurations are listed below. Smoke alarms may or may not be interconnected. If interconnected, occupants may be alerted sooner than the alert from the local alarm responding to smoke.

For multiple rooms connected to the RFO, the occupant is placed in the room which reaches a tenability or smoke limit first, representing the worst-case location.

Case 1: All smoke alarms were interconnected. A smoke alarm was located in the RFO. Occupants were located in any room with an interconnected smoke alarm.

Case 2: All smoke alarms were interconnected, but no smoke alarm was located in the RFO, but there was a smoke alarm adjacent to the RFO. Occupants were located outside the RFO and were alerted by an interconnected smoke alarm.

Case 3: All smoke alarms were interconnected. A smoke alarm and an occupant not capable of self-rescue were located in the RFO. A smoke alarm located in the RFO provided the initial notification signal. The smoke alarm in the room where the responsive occupant was located can respond either to smoke or from an interconnected smoke alarm. RSET was computed for the responsive occupant, but ASET was computed for the occupant in the RFO that needs rescue (answering the question: Does the responsive occupant have sufficient time to rescue the occupant in the RFO?)

Case 3 NI: All smoke alarms were not interconnected. A smoke alarm and an occupant not capable of self-rescue were located in the RFO, but a smoke alarm located outside the RFO provides the initial notification signal to the responsive occupant. The smoke alarm in the room where the responsive occupant was located responds to smoke. RSET was computed for the responsive occupant, but ASET was computed for the occupant in the RFO that needs rescue.

Case 3 NSL: Same scenario as Case 3 where all smoke alarms were interconnected, but with a variation in the smoke limits. The smoke limit was relaxed and not enforced on the occupant in the RFO (no smoke limit, NSL), but was still enforced for the responding occupant outside the RFO.

Case 3 NSL NI: Same scenario as Case 3 NI where all smoke alarms were not interconnected and the smoke limit was relaxed. The smoke limit was not enforced on the occupant in the RFO, but was still enforced for the responding occupant outside the RFO.

Results

Results are presented as a percentage of successful escapes as function of initially flaming or smoldering fires for each scenario. Fig. 1 shows the results for Case 1 and Case 2. For both Case 1 and Case 2 the smoldering fire ionization alarm results are similar to the flaming fire photoelectric results with successful escape percentages of about 98 % and 96 % respectively. The results for alarms A, B and C show successful escape percentages of about 99 % or higher. While a combination of photoelectric and ionization alarms, or dual photoelectric/ionization alarms would most likely perform better than alarms A, B and C, and would presumably also experience more frequent nuisance alarms.

Fig. 2 shows the results for Case 3 and Case 3 NI. For Case 3, the benefits of the new alarms A and B over photoelectric or ionization alarms are apparent. For Case 3 NI the results for the new alarms are less impressive, re-enforcing the importance of interconnecting smoke alarms.

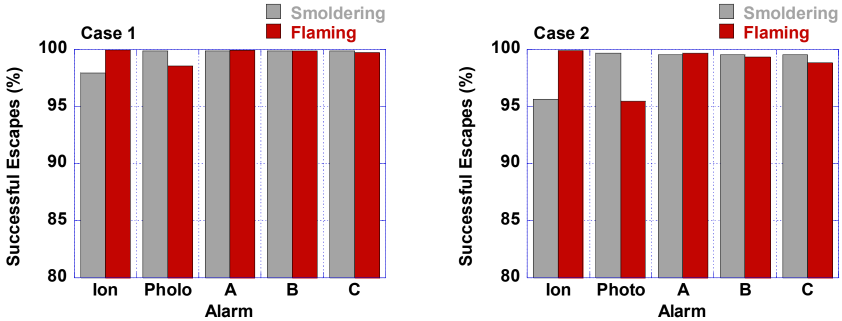

Fig. 1. Case 1) Smoke alarm in RFO and occupant in the RFO or any other room. Case 2) Smoke alarm and occupants located outside the RFO.

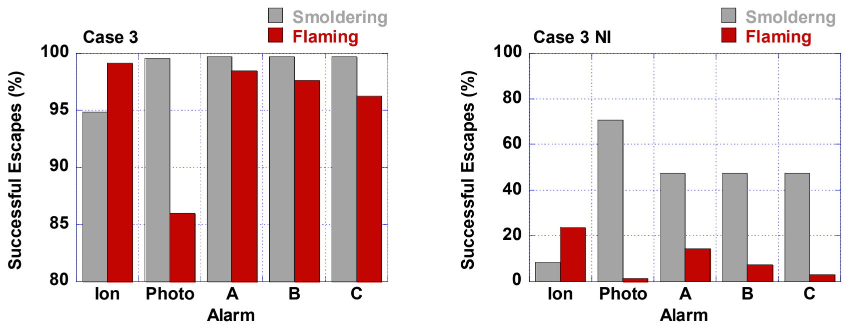

Fig. 2. Case 3) Smoke Alarm and occupant needing rescue located in RFO. Case 3 NI) Case 3 configuration without smoke alarm interconnection.

Fig. 3 shows the results for modified Case 3 and Case 3 NI with the relaxation of the smoke limit in the RFO where the responding occupant needs to travel to rescue the occupant in the RFO (or more generally to travel through the RFO for escape). The rationale for relaxing the smoke limit in the RFO is that the responding occupant while not succumbing to toxic gases or heat could dash in and out or through the RFO at a smoke optical density exceeding 0.25 m^{-1}. For both interconnected and non-interconnected alarms the overall performance of alarms A, B and C exceed ionization and photoelectric alarms.

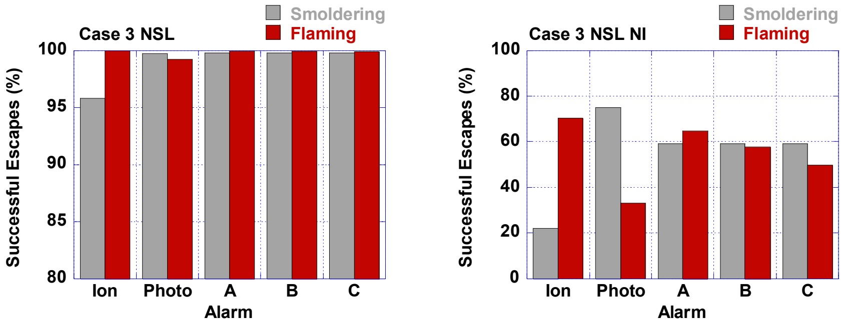

Fig. 3. Case 3 NSL) Smoke Alarm and occupant needing rescue located in RFO with smoke limit not enforced. Case 3 NSL NI) Case 3 configuration with smoke limit not enforced and without smoke alarm interconnection.

Conclusions

The CFAST Fire Data Generator simulation method, CData, was used to assess relative impact on safe egress given the expected performance of smoke alarms meeting the new ANSI/UL 217-2015 requirements compared to current photoelectric and ionization alarms. This analysis is a prospective attempt to assess the future performance improvement as new smoke alarms are installed in new construction and the slow replacement of current alarms in existing homes.

From estimated expected alarm sensitivities, the overall performance of interconnected new smoke alarms is better than current photoelectric or ionization alarms. For non-interconnected alarms, the new alarms should outperform current ionization alarms in the initially smoldering fires and current photoelectric alarms in the flaming fires, but the overall benefit is not apparent. In scenarios where the occupant of interest was traveling back to the RFO, relaxing the smoke limit in the RFO suggests that the new alarms should exhibit better overall performance than current ionization and photoelectric alarms.

The analysis presented here does not consider the benefits of the nuisance resistance properties of alarms meeting the new standard. The enhanced nuisance resistance is expected to reduce alarm disabling and removal in homes.

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