A Statistical Model for Smoke Alarm Activation in Upholstered Furniture Fires

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Abstract

There are several determinstic smoke alarm/detector activation models of varying complexity based on the local environmental conditions. Their predictive capabilities vary significantly and uncertainty estimates are rarely reported. Here, a statistical smoke alarm activation model is proposed for a specific problem, upholstered furniture fires in residential settings. In the U.S., uphostered furniture fires are often identified as the first item ignited in structure fires with fatalities, and thus present a significant risk to occupants. A smoke alarm activation model for upholstered furniture fires will facilitate an evaluation of residential life safety impact from changes in codes, standards and products. The statistical approach reproduces the variation of smoke concentrations at alarm activation observed in full-scale fire tests and may better represent these variations than current deterministic models.

Keywords: Smoke alarms, fire models, upholstered furniture

Introduction

Smoke alarm/detector activation is an important event to capture in computer fire modeling to predict egress actions and occupant safety. There are a number of smoke alarm/detector activation models of varying complexity based on the predicted local environmental conditions which may include smoke concentration, smoke properties, temperature and velocity, and alarm/detector characteristics. Their predictive capabilities vary significantly and uncertainty estimates are rarely reported. Models based solely on thermal conditions are clearly not generally applicable, while even more sophisticated models may suffer significantly from estimated alarm and smoke properties, and fire model uncertainties [1]. While all smoke alarm activation models have their strengths and weaknesses, selecting the most appropriate model for a specific problem can be daunting.

Here, a statistical smoke alarm activation model is proposed for a specific problem, upholstered furniture fires in residential settings. In the U.S., upholstered furniture fires present a significant risk to occupants. Between 2007 and 2011, upholstered furniture and mattresses/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 [2]. 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. 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 was recently added to new smoldering and flaming fire test protocols of ANSI/UL 217-2015 [3].

The statistical approach captures the variation of smoke alarm activation observed in full-scale fire tests and may better represent observations than current deterministic models. Geiman and Gottuk presented alarm thresholds for a collection of flaming and smoldering fires where 20 %, 50 %, or 80 % of either photoelectric or ionization alarms activated [4]. They also proposed a fixed alarm threshold of 9.4 %/ft. obscuration (U.S. industry standard units) as a reasonable estimate when the majority of smoke alarms will have activated. The current version of the fire model CFAST [5] uses a default alarm threshold of 8.0 %/ft. obscuration based on an evaluation of smoke detector performance by Milke, Mowrer, and Gandhi [6].

Our implementation of a statistical approach envisions sampling the alarm threshold distribution for a particular alarm and fire source multiple times instead of picking a single value, then using the sampled thresholds for multiple fire model runs. Thus the output of the fire modeling exercise is probabilistic. This approach is amenable to hazard analysis estimates using zone models such as our conceptual system for evaluating the impact on residential life safety of new fire protection technology, the subject of another presentation at this conference [7].

Experimental Conditions

The data used to develop the statistical model comes from experiments recently conducted at the National Institute of Standards and Technology (NIST) on the response of a number of smoke alarms to the new smoldering and flaming polyurethane foam tests specified in ANSI/UL 217-2015 [8]. A total of 45 different alarm designs representing alarms currently available in the U.S. (23 containing ionization sensors and 22 containing photoelectric sensors) were examined in the study.

Six of each of the 45 different alarm designs were subject ANSI/UL 217-2015 smoke box exposures to determine baseline sensitivity to the cotton smolder smoke. Each alarm was tested in its worst-case orientation in the smoke box to establish a sensitivity level to the cotton smolder smoke. The worst-case orientation was defined by the angular position of the alarm where the smoke sensor was opposite from the incoming smoke direction.

The flaming polyurethane foam experiments were conducted in a fire test room in the manner described in ANSI/UL 217-2015. The smoke obscuration from a smoke meter located behind ceiling-installed alarms was tabulated for each alarm activation time.

The foam slabs were non-fire-retarded polyether urethane foam material 43.2 cm × 36.8 cm × 7.6 cm located on the test room floor. Just prior to ignition with a torch, 5 ml of ethanol was poured onto the corner top surface to aid ignition.

The smoldering polyurethane foam experiments were conducted in the same room as the flaming foam experiments in manner similar to that described in ANSI/UL 217-2015. A radiant heater arrangement consisting of two rectangular 46 cm × 15 cm, 1080 W radiant panels was configured to irradiate the horizontal foam surface somewhat uniformly. The foam samples were non-fire-retarded polyether urethane foam material 43.2 cm × 36.8 cm × 10.2 cm (the same material as the flaming foam samples, only thicker). Each foam slab had a 17.8 cm diameter cotton duct fabric disk placed in the center. An aluminum shutter plate was placed between the foam surface and the radiant panels while the panels were allowed to heat up to a fixed set point of 300 °C. The shutter was subsequently removed to expose the foam to low level radiant heat flux of about 4 kW/m^2 over the central portion of the horizontal surface. A lit cigarette was immediately placed on the fabric to induce smoldering. While the smoke obscuration profile was within the specifications of the Standard, the smoke's measuring ionization chamber profile differed from the Standard's specification.

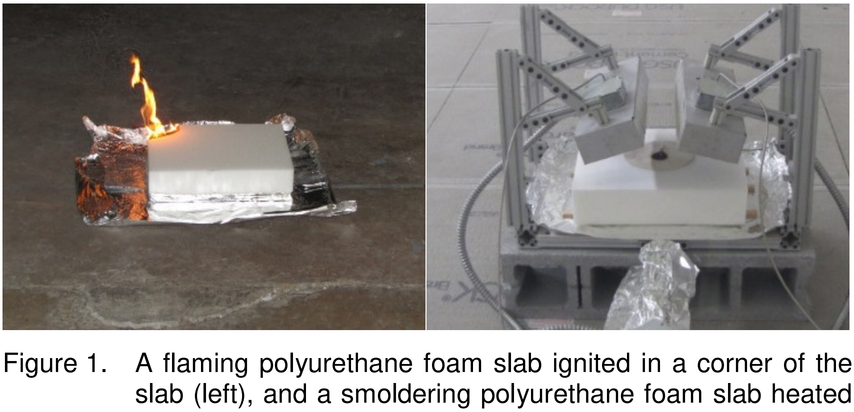

Figure 1. A flaming polyurethane foam slab ignited in a corner of the slab (left), and a smoldering polyurethane foam slab heated by radiant panels with a lit cigarette on a cotton fabric disk to initiate smoldering (right).

Distribution of Smoke Alarm Activations

Results are presented in the industry-standard units of %/ft. osbcuration. First, the results from the ANSI/UL 217-2015 smoke box are presented for photoelectric and ionization alarms studied. Figure 2 shows histograms for the beam obscuration at alarm versus the frequency of alarms aggregated for the photoelectric and ionization alarms. The histograms were fitted to log-normal distributions yielding geometric means (μ_g) of 1.03 %/ft. obsc. and 2.48 %/ft. obsc. and geometric standard deviations (σ_g) of 1.47 and 1.28 for ionization and photoelectric alarms respectively. All smoke alarms responded within the limits of ANSI/UL 217 (between 0.5 %/ft. obsc. to 4.0 %/ft. obsc.), with the exception of one photoelectric model which was excluded from the following analysis.

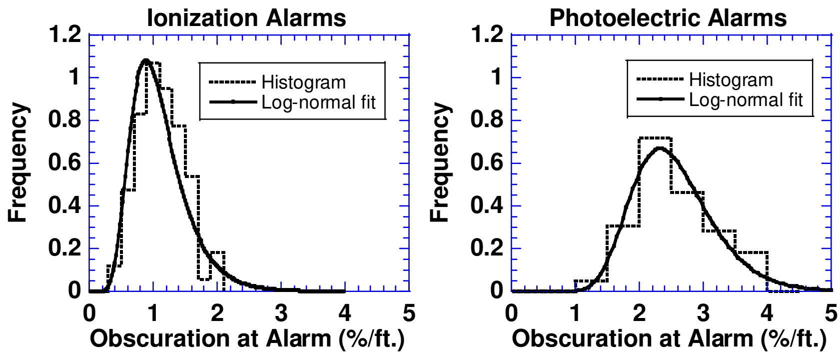

Figure 2. Histograms for ionization and photoelectric alarm response to ANSI/UL 217-2015 smoke box experiments.

The results for the flaming and smoldering room fire experiments are shown below. The results were aggregated for each of the fire sources and alarms containing photoelectric sensors or ionization sensors. Dual photoelectric/ionization alarm results were partitioned such that for flaming fires results were aggregated with ionization alarms, and for smoldering fires results were aggregated with photoelectric alarms.

Figure 3 shows the results for photoelectric and ionization alarms subjected to the flaming polyurethane foam smoke exposure. For these experiments, a log-normal fit for ionization alarms yielded a μ_g of 2.07 %/ft. obsc. with a σ_g of 1.34, and for photoelectric alarms yielded a μ_g of 6.74 %/ft. obsc. with a σ_g of 1.33.

Figure 4 shows the results for photoelectric and ionization alarms subjected to the smoldering polyurethane foam smoke exposure. For these experiments, the log-normal fit for ionization alarms yielded a μ_g of 9.71 %/ft. obsc. with a σ_g of 1.15, and for photoelectric alarms yielded a μ_g of 3.19 %/ft. obsc. with a σ_g of 1.72.

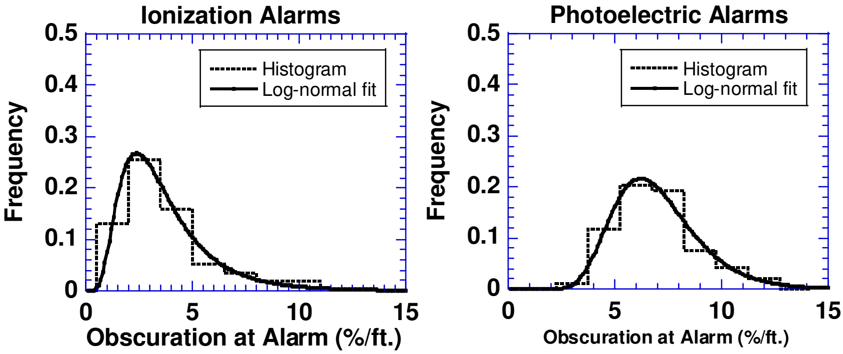

Figure 3. Histograms for ionization and photoelectric alarm response to ANSI/UL 217-2015 flaming polyurethane foam experiments.

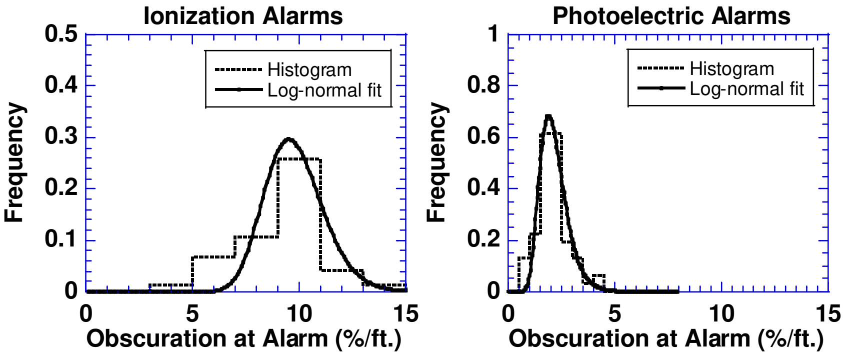

Figure 4. Histograms for ionization and photoelectric alarm response to ANSI/UL 217-2015 smoldering polyurethane foam experiments.

A comparison of these distributions to results from the NIST smoke alarm sensitivity study [9] is illustrative. In that study, chair mockups consisting of non-fire retared polyurethane foam covered with cotton or polyester cushion covers were ignited by a small flame or induced to smolder in full-scale fire experiments in a bedroom or living room attached to each other by a common hallway. Ceiling beam obscurations in the hallway were tabulated for activations of photoelectric and ionization alarms located in the hallway.

Figure 5 shows the cumulative distributions from fitted histograms for both the ANSI/UL 217 flaming foam experiments and the flaming chair mockup experiments. For ionization alarms, the geometric means for the chair mockup results were nearly the same as the ANSI/UL 217-2015 foam results 2.05 %/ft. obsc. versus 2.07 %/ft. obsc. respectively, but the distribution was broader for the chair mockup experiments.

For photoelectric alarms, the geometric mean for chair mockup results was lower, 5.35 %/ft. obsc. versus 6.74 %/ft. obsc., and the chair mockup distribution was again broader.

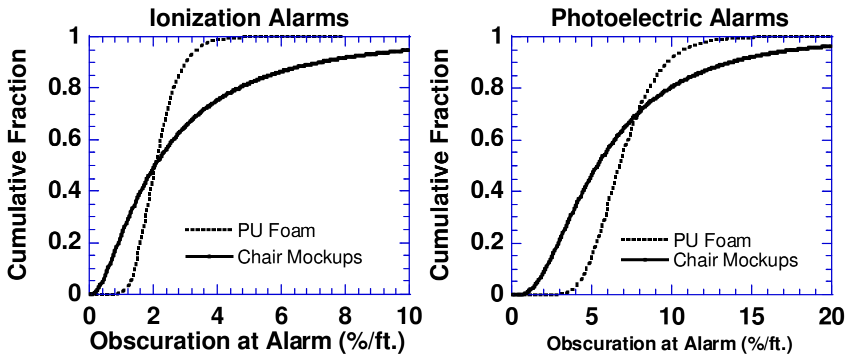

Figure 5. Cumulative distributions of the ANSI/UL 217-2015 flaming foam experiments and the flaming chair mockup experiments.

Figure 6 shows the cumulative distribution from the fitted histograms for the ANSI/UL 217-2015 smoldering foam experiments and point-to-point cumulative distributions from the smoldering chair mockup experiments. The median alarm threshold values for smoldering chair mockups show the same trend for ionization and photoelectric alarms, but were higher than the geometric means of the ANSI/UL 217-2015 smoldering foam results.

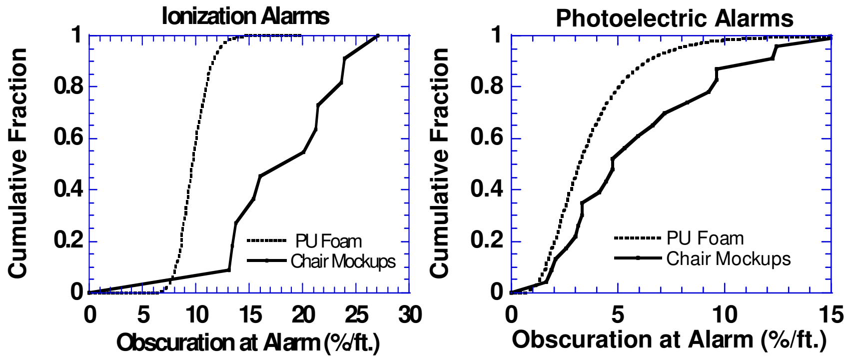

Figure 6. Cumulative distributions of the ANSI/UL 217-2015 smoldering foam experiments and the smoldering chair mockup experiments.

Table 1 summarizes the results. Note, the median value of a cummulative distribution is equivalent to the geometric mean.

The geometric mean beam obscuration from the flaming foam and flaming chair mockups compare favorably for both ionization and photoelectric alarms. The chair mockup distributions were wider, which may be related to the room configuration and the location of the alarms relative to the source. The smoldering results also appear sensitive to the alarm distance from the source and room configuration which warrants closer study.

Table 1. Summary of alarm concentration distribution results.

Alarm Type	Flaming Fires				Smoldering Fires		
	Foam slab		Mockup		Foam slab		Mockup
	μ_g (%/ft.)	σ_g	μ_g (%/ft.)	σ_g	μ_g (%/ft.)	σ_g	Median (%/ft.)
Ionization	2.07	1.34	2.05	2.64	9.71	1.15	18.0
Photoelectric	6.74	1.33	5.35	2.07	3.19	1.72	4.74

Conclusions

A statistical smoke alarm activation model was developed for upholstered furniture containing polyurethane foam. The specific distribution depends on the smoke alarm type, and the mode of combustion prior to alarm activation. The distributions are more refined than the current default value in the computer fire model CFAST. Comparison of the statistical model results to real-scale furniture mockup experiments shows good agreement with flaming scenarios and the correct trend in smoldering scenarios. These distributions can be used as initial estimates for simulations regarding photoelectric and ionization alarm activation, though it appears that further examination of the smoldering scenario with ionization alarms needs to be conducted.

An additional benefit to using the results from the ANSI/UL 217-2015 test configuration is that the performance of new alarms meeting the standard can be directly translated into statistical models for those alarms to allow for direct comparisons between newer smoke alarms and pre-2015 edition smoke alarms.

Acknowledgements and Disclaimer

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