Conceptual System for Evaluating the Impact on Residential Life Safety of New Fire Protection Technology

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Abstract

There are a variety of fire protection technologies that have the potential to improve life safety in residences. This paper presents a plan for developing a standardized method to demonstrate what technologies are beneficial plus looks at a first step toward developing that method.

Keywords: Fire models, egress models, fire protection engineering, performance based codes

Introduction

There are a variety of fire protection technologies that have the potential to improve life safety in residences. Currently, there is no accepted methodology available to determine the absolute or even relative performance of different technologies. The Engineering Laboratory of the National Institute for Standards and Technology (NIST) is undertaking an effort to develop a method to quantify the relative improvements in fire safety that different technologies can make in a community. The idea is to provide a tool to evaluate the impact of changes in prescriptive or performance based requirements. While the system is primarily focused on community impact, it should also scale down for use on individual projects.

In order to understand the process NIST is applying the technique to a simplified problem of examining some of the benefits of the new detector standards due in 2020 with a long-term goal to develop a standard technique for such analyses. The structure of the rest of this paper will look at three main steps to developing a standardized method. After describing a step, we will describe how we are addressing that step in the simplified problem. Finally, a conclusion will present the long-term goals of this project.

Characterizing the Community

Step one is to develop a method to characterize the community being considered. The question is what constitutes a full characterization of a community and how is that accomplished. It is likely that there are holes in the available data so it is important to understand the kind of assumptions that would have to be made and the extra work that must be done, for example sensitivity testing of the assumptions, to have confidence in the result.

To characterize an average US community, the starting point is the American Housing Survey (AHS) the United States Census Bureau performs for the Department of Housing and Urban Development (HUD) [10]. The AHS has been around since 1973 in one form or another and is taken every odd number year with the purpose "to provide a current and continuous series of data on selected housing and demographic characteristics."[1]

Information from the AHS can be presented in a variety of tables. For this project, the base data started with the total square footage[1] of the homes. The data is sorted by a number of bins that divide up total area from 0 ft^2 to more than 4000 ft^2 (272 m^2) and gives the number of houses in each bin. For example, of the estimated 92 629 000 houses that have a total square footage 23 532 000 or 25.4 % had a foot print that was between 1000 ft^2 (93 m^2) and 1499 ft^2 (139 m^2). From this a cumulative density function (CDF) can be constructed as seen in Figure 1. As can be deduced from Figure 1, we cut off the total floor area at 5000 ft^2. The actual survey's final bin is total area of 4000 ft^2 (272 m^2) or more, however, since less than 3.3 % of houses were over 4000 ft^2 (272 m^2)and there was no real information on the distribution of larger houses the decision was made to cut the total floor area off at 5000 ft^2 (465 m^2).

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[1] The AHS provides data in square feet, while NIST's preferred units would be meters squared we use the squared feet to make it easier to go back to the original reference

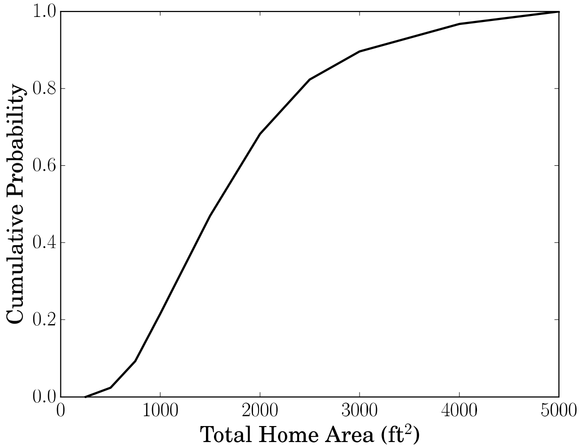

Figure 1. Cumulative Density Function (CDF) for the total home area.

The data is further broken down to give the number of bedrooms for each house in a particular bin. Continuing with the example of the homes between 1000 ft^2 (93 m^2) to 1499 ft^2 (139 m^2) there are only 20 000 or 0.08 % of the homes that do not have a bedroom while 53.1 % or 12 500 000 of the homes have three bedrooms. Finally, for a given number of bedrooms in any given square footage bin the table gives the distribution of the number of rooms the house has. For the 12 500 000 homes with square footage between 1000 ft^2 (93 m^2) and 1499 ft^2 (139 m^2) that have 3 bedrooms 5 905 000 or 47.2 % have 5 rooms total not counting bathrooms. From this table, a series of conditional CDFs can be created that allow a set of houses to be generated with a random total area, number of bedrooms and total rooms that are consistent with the housing data.

One problem that is not addressed with the data from the AHS is the floorplan of the house. This is, of course, a significant issue in that it controls both smoke movement and egress. An algorithm has been developed that starts by assuming all bedrooms are connected to the rest of the house via a hall. The other rooms are then connected by a random scheme that insures that there is a path from any room to any other room in the house. Going forward, the plan is to define a reduced set of floor plans as the layouts for the houses. While this will reduce the variability that the technique can capture, it should greatly simplify the analysis and eliminate completely unrealistic designs that the current method probably creates.

Develop Tools to Estimate Statistically Relevant Conditions

Step two is to develop tools and methods for specifying the numbers and types of runs with a fire model to provide statistically relevant conditions over time and an egress tool to quantify the impact of the conditions on occupants. One significant part is developing a performance model and the associated uncertainty for the fire protection technology being analyzed i.e., detection, suppression, reduced flammability of room contents, designs to improve egress, etc. An example is a statistical model for smoke alarm activation that could be used to evaluate new smoke alarm technologies, or to be used as a default detection routine for fire modeling.

To generate the kind of statistics that are desired, a Monte Carlo method using the conditional CDF's from the first step is used to generate a selection of homes. For example, Figure 2 shows the distribution of the total area of the houses for a given number of bedrooms. The thickness and shade of the line show the relative number of homes with that total area. As can be seen in the plot there are not that many houses without a dedicated bedroom and almost all of them are less than 1000 ft^2 (93 m^2). On the other extreme, the total area of houses with 4 bedrooms is relatively evenly distributed between 1500 ft^2 (139 m^2) to 4000 ft^2 (272 m^2)

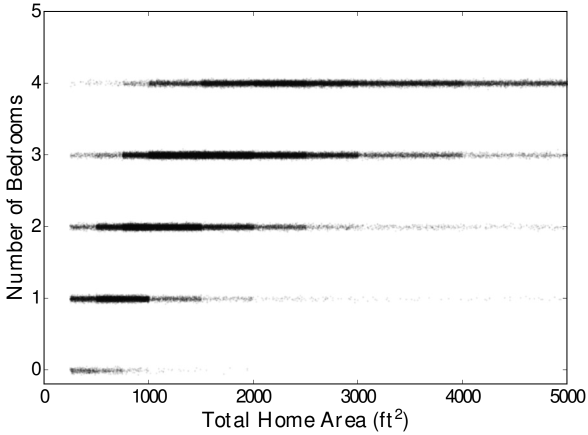

Figure 2. Distribution of total home area (ft^2) given the number of bedrooms.

Another place where there is variability is in the fire safety technology. In fire models, detectors are typically assumed to all have the same set point but in reality can have different set points for identical detector models from a single manufacturer [2]. In order to account for this variability, a statistical model of the response of detectors to flaming fires has been developed with the distribution shown in Figure 3 [2]. A second set of distributions would have to be used for smoldering fires. For each detector used in the model runs, the same Monte Carlo protocol is used to pick a set point from the appropriate distribution.

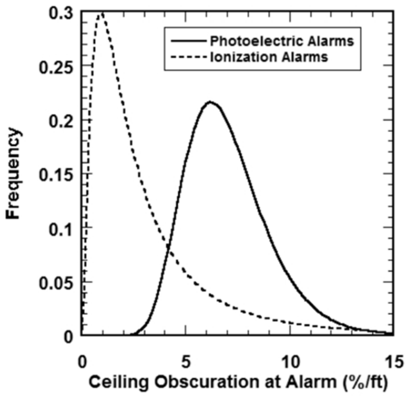

Figure 3. Model of ionization alarms and photoelectric alarms for flaming fires.

A significant issue is with egress. Residential egress is a statistical process. Occupants do not necessarily respond to the first indications of a fire, for example the smoke alarm going off, by evacuating. The difficulty is that in residential fires, the first action is often to investigate the alarm and even fight any fire that was discovered [3]. Another common action of parents is to find children and make sure they escape. Also in residential fires it is not uncommon for people to reenter the residence [3]. These activities can result in very large pre-movement time and must be accounted for in the analysis. Currently, there are no egress models that do the type of egress modeling needed for residential evacuations [4].

Develop Performance Measures

The last step is to develop performance measures that represent the results accurately, are easily interpreted, and allow the user to set performance standards. The importance of the performance measures being understandable cannot be over stressed. For this method to become a standard tool for addressing issues of performance and regulation, the authorities having jurisdiction must be able to understand the measure in order to have confidence in it and use it.

If there was an egress model that could accurately represent residential evacuation, the measurement to look at would be the probability of one or more people being killed in a fire scenario. This would have a Bernoulli distribution with an uncertainty for the probability that someone will die. It would be easy to compare probabilities and determine if the difference was statistically significant.

To find a measurement that is similar, we will look at the fractional effective dose (FED) level a fixed amount of time after the alarm sounds in each room other than the room of fire origin. This information can be used to answer the question “What is the probability that the FED in any room in the house will exceed the FED level being considered?", for example, an FED of 1 50 % incapacitation or 0.3 for more sensitive occupants such as the elderly [5] in 1 min after the alarm sounds. Analyzing the same set of scenarios one with the new technology and one with current technology, we can get the rate of FED exceeding a critical set point for both sets and treat these as Bernoulli distributed variables, say $\hat{p}_0$ for the probability of a house exceeding the critical FED point without the new technology and $\hat{p}_n$ for houses with the new technology. Each estimate has an uncertainty, $\sqrt{\hat{p}(1-\hat{p})/_n}$ where n is the total number of scenarios run, which can be used to determine the number of runs needed to achieve a prescribed relative tolerance such as 5 %.

As an example of the system envisioned, a probabilistic methodology is presented for estimating building fire hazard applied to the specific case of evaluating residential upholstered furniture fires employing different barrier fabric technologies [6]. As a model of the fire scenario, a three room home section is modeled in the Consolidated Model of Fire and Smoke Transport (CFAST) [7]. A visualization of a typical scenario is provided in Figure 4. The furniture fire takes place in the living room and hot gases are transported to the adjoining bedroom either down a hallway or through a connecting open door.

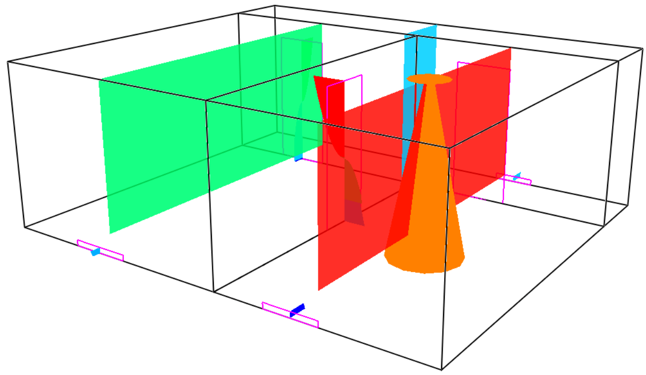

Figure 4. Visualization of a typical CFAST simulation. The orange cone represents the plume of the furniture fire occurring in the living room.

Various parameters of this scenario (such as the ceiling height and floor area) are uncertain and are modeled probabilistically based on statistics from such sources as the U.S. Census Bureau's American Housing Survey and data from the National Association of Home Builders. Hazard is characterized in terms of the hot gas layer (HGL) temperature in the living room, which is a predictor of flashover, as well as the thermal fractional effective dose (FED) in the bedroom.

Six different furniture fires, representing the fire performance of different barrier fabrics, were assumed as inputs to Monte Carlo simulations of 10 000 different building scenarios, and the hazard parameters are shown in the scatter plot of Figure 5. Such data allows for predictions of the probability of lethal conditions for each of the six fires, and thus a quantitative prediction of barrier fabric performance in residential settings. This probability is computed by dividing the number of cases in which the FED exceeds one by the total number of Monte Carlo simulations for a given barrier fabric. The barrier fabric that resulted in the highest risk of a bedroom fatality is BF 6 with a probability of FED exceeding one equal to 22 % ± 0.3 %. The least hazardous barrier fabric is BF 2 with a probability of FED exceeding one equal to 6 % ± 0.2 %. Similar calculations may be used to compare the effectiveness of smoke detectors in reducing fire hazard by considering the time at which the FED exceeds one for each of the cases and comparing it with the time of smoke detector activation.

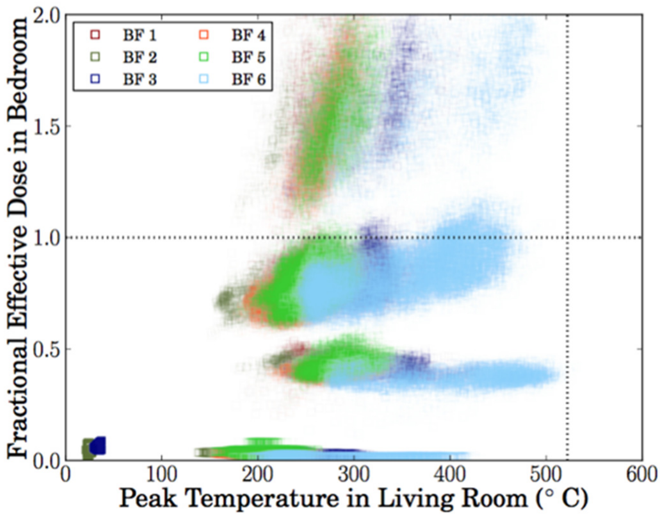

Figure 5. Scatter plot of bedroom fraction effective dose versus living room hot gas layer temperature computed using CFAST with 10 000 samples for each barrier fabric.

Summary

A plan has been presented for developing a standardized framework for performing an analysis of the impact of different fire technologies on a community. An initial three steps were identified and discussed as well as how they were being addressed in an analysis of the impact of new fire alarm requirements. The biggest problem identified when discussing this analysis is the lack of an egress model for residential evacuations. The first response to an alarm by an occupant is often to investigate the reason for the alarm and even fight any fire that is discovered.

These behaviors are statistical in nature meaning that any residential evacuation model would also need to be a statistical model.

Finally, the results of some previous work following the same general model was presented to give an understanding of the kind of results the project is looking to generate.

The intermediate goal of this project is to develop a set of tools that can be used together to do this kind of community analysis of a variety of fire technology, both current and yet to be realized. The ultimate goal is to work with the fire research and safety community to develop a standardized method of addressing these issues – one that is sufficiently normalized that separate groups doing the same analysis would come to the same conclusion if not the exact same probabilities. This would give authorities having jurisdiction and others using the results of such analysis confidence in the results and should make it easier to show technologies are effective.

References

[1] *American Housing Survey 2015*. American Housing Survey 2015 [cited 2017; Available from: https://www.census.gov/programs-surveys/ahs.html.

[2] T. Cleary and R. Peacock, *A Statistical Model for Smoke Alarm Activation in upholstered Furniture Fires*, in *Suppression, Detection and Signaling Research and Applications Conference SUPDET 2017*. 2017: Hyattsville, MD.

[3] J. Bryan, *Smoke as a Determinant of Human Behavior in Fire Situations (Project People)*, in *GCR-77-94*. 1977, National Bureau of Standards.

[4] E. Kuligowski, R. Peacock, and B. Hoskins, *Review of Building Evacuation Models*. In NIST Technical Note 1471. 2010, National Institute of Standards and Technology: Gaithersburg, MD.

[5] ISO 13571:2007, Life-threatening components of fire – Guidelines for the estimation of time available for escape using fire data.

[6] M. Bruns, *Predicting the Effects of Barrier Fabrics on Residential Upholstered Furniture Fire Hazard*, in *NIST Technical Note 1920*. 2016, National Institute of Standards and Technology: Gaithersburg MD.

[7] R. Peacock, G. Forney, and P. Reneke, *CFAST, Consolidated Model of FIre Growth and Smoke Transport (Version 7), Volume 3: Verification and Validation Guide*, in *Technical Note 1889v3*. 2015, National Institute of Standards and Technology: Gaithersburg, MD.