METHODS FOR PREDICTING SMOKE DETECTOR ACTIVATION

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Abstract
With the advent of performance-based codes in the United States, a reliable methodology for predicting the activation time of smoke detectors becomes crucial to the proper consideration of the value of detection systems to meeting performance objectives. This paper will review three approaches for predicting smoke detector activation time. The first method, and the one most frequently cited in the Fire Safety Engineering (FSE) literature is the temperature correlation method. The second approach uses a model comprising a measure of the ease of smoke entry into the detector (characteristic length, L) and a factor which accounts for the physics of the sensing method and aerosol characteristics (detector material response number, DMR). Finally, a rigorous approach involving modeling of physical phenomena will be discussed. The strengths and weaknesses of each approach will be explored in the context of FSE and recommendations for future research will be made.

Introduction
A practical and accurate method of predicting the activation time of a smoke detector is an important research issue facing the detector industry. While research into understanding the physical phenomena affecting smoke detector activation has been undertaken over the last few decades, the fruits of this research have not translated into a physical basis for the prediction of activation times. The focus of industry research has been driven by the desire to demonstrate speed of response to specific fire scenarios and this has resulted in improved products. These include improved sensor designs, analog sensors, detection algorithms, and most recently, multi-mode, multi-criteria detectors.

With the United States actively developing a performance-based code, however, an accurate method of predicting the activation time of detectors is needed by the fire protection community in order to assess the performance of detection systems against the performance objectives.

Current Requirements
Current standards such as NFPA 72[1] stipulate the spacing of smoke detectors based upon tests by nationally-recognized testing laboratories such as Underwriters Laboratories (UL 268[2]). An alternative, performance design method found in NFPA 72, Appendix B, is limited to flaming fires and does not consider ceilings higher than 8.5m (30ft). This method was developed from an experimental study conducted in the late 1970's for the Fire Detection Institute (FDI)[3], with the limitations related to the scope of the experiments conducted. However, this design method

introduces some important concepts, including design of a detection system to activate for a critical fire size (heat release rate) representing an acceptable threat level for the protected space. This is a departure from the earlier concept of detection "as quickly as possible" which often led to over sensitivity.

Temperature Correlations

The most commonly accepted engineering approach to predicting smoke detector activation is a temperature correlation. Specifically, activation for a 13 °C temperature rise at the detector location is cited in the SFPE Handbook of Fire Protection Engineering[4] and in the FSE guides published in the UK[5], Australia[6], and New Zealand[7]. A Nordic guide[8] cites smoke detector activation at a temperature rise of 20 °C. The approach was originally proposed by Heskestad and Delichatsios in 1977[9, 10] however, the 13 °C value was selected from a set of experimental results for different detectors and fuels for which the results varied over a wide range. A thorough discussion of this is found in a paper by Schifilitti and Pucci[11].

In Heskestad's discussion of the use of temperature correlations for predicting activation of smoke detectors, he observes that the process of heat being released by a burning fuel resulting in a rise in temperature at the ceiling is similar to smoke (soot) released by the fuel and carried in the buoyant plume. However, while heat losses occur through heat transfer to surroundings, smoke losses are minimal, so the temperature correlation used as a surrogate for smoke detector activation should be done for adiabatic conditions.

Since the original experiments used detectors employing older technology sensors and significant improvements have occurred in recent times, it is reasonable that lower temperature rise at activation values might be appropriate for more modern detectors. As discussed in the next section, recent literature has suggested that temperature rise at activation values of 4 °C or 5 °C provide good agreement with experiments in which current detectors were installed on ceilings of normal 2.4m (8 ft) heights.

High Ceilings

There is significant interest in understanding the quantitative relation between detector spacing and activation for high ceilings – above the 8.5m (30ft) height limit for the NFPA72 design method. The U.S. Navy and National Institute of Standards and Technology (NIST) conducted smoke detector activation experiments in an aircraft hangar in Barbers Point, Hawaii[12]. The selected fire was a 2.5m diameter pan of JP-5 producing a peak heat release rate of 7.7 MW and roughly corresponding to an ultra-fast fire*. The ceiling was 15m (50 ft) high and there were no draft curtains. The floor area of the hangar measured 97.8m by 73.8m. Commercial smoke detectors were installed on the ceiling at several radial distances from the plume axis.

Figure 1 compares the activation times of commercial smoke detectors installed at several radial distances from the plume axis to activation times predicted (using BFRL's CFAST model) by temperature rise at activation criteria of 13, 8, and 4 °C (adiabatic) and 4 °C with heat transfer to

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*An ultra-fast fire is a t-squared fire that grows to1055 kW in 75 seconds.

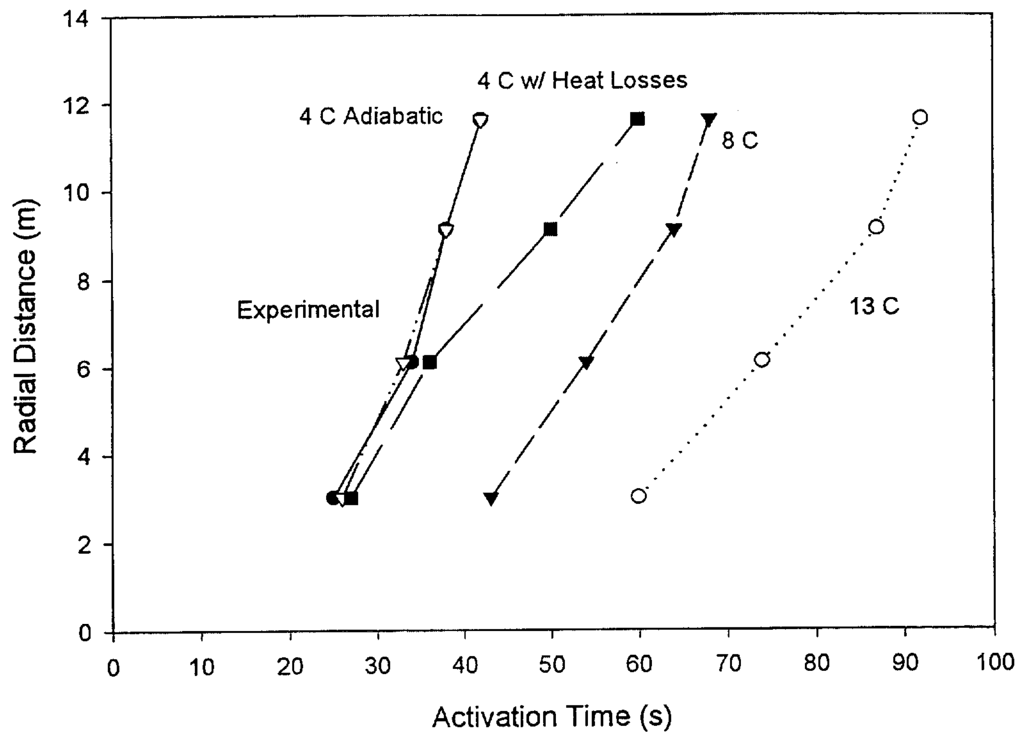

Figure 1: Comparison of Experimental and Predicted Activation Times Using Different Temperature Correlations for JP5 fuel fires.

the ceiling at the same radial distances. The 4°C correlation (adiabatic) matches the experimental data closely. A similar result was obtained in residential fire tests by Collier[13] who found that when using CFAST, 4°C provided the best match to experimentally observed smoke detector activation times in a typical residence. Additionally, Davis and Notarianni recommended a temperature rise at the detector of 5°C for ionization detectors alarming at 2.5% m^{-1} in high bay spaces using a commercial CFD code to model the fire flows.[14] While limitations of any temperature correlation preclude the likelihood of consistently predicting activation times as closely matched to the experimental data as that shown in Figure 1, there is substantial evidence for the appropriate use of a value well below the traditional 13°C criteria.

Disadvantages of Temperature Correlations

As previously mentioned, the test data from which the 13°C value was derived showed a wide variation in correlated values for specific detector types and for different fuels -- values range from 2°C to over 20°C. Several distinctions exist between the assumptions used in the analysis of experimental data and the application of temperature correlations in a performance-based code environment. There are four basic assumptions inherent in the 13°C activation correlation:

1. The Lewis number=1*; the ratio of species mass concentration to temperature is constant in space and time.
2. Species are carried passively by turbulent convective motion without significant effects of gravity, molecular motion, or particle-fluid inertial effects.
3. Insignificant heat transfer occurs by radiation between elements of the fluid.
4. Heat transfer between the fluid and confining material surfaces is negligible.

An additional assumption implicit in temperature correlations is that there is no HVAC interaction with the room. Such forced ventilation may significantly increase or decrease the activation time of a detector. CFAST is essentially consistent with these basic assumptions. First, the CFAST default assumes that 30% of the fire energy is emitted by radiation from a point source, while the remaining 70% is convection energy carried by the plume to the ceiling jet and upper layer. There are no additional radiative losses from either the plume or the ceiling jet. Second, by turning off heat transfer to the ceiling and wall materials (an option in CFAST), there is no heat loss to the room boundaries. Additionally, there is no particulate deposition to surfaces, therefore, the ratio of mass concentration to temperature is constant within model space and time. Thus, using temperature correlations within CFAST or other similar models is consistent with other assumptions.

In reality these assumptions are not always justified. Considering the assumption that the ratio of mass concentration to temperature is constant, mass concentration is affected by several physical phenomena. As air is entrained into the plume from the lower layer, mass concentration is decreased by dilution. Along the ceiling jet, air is entrained from the upper layer, assuming that an upper layer has formed and that the interface height is below the bottom of the ceiling jet. This may or may not dilute the species mass concentration in the ceiling jet as it progresses towards the detector since the entrained air may itself contain smoke from the upper layer. Additionally, species may be deposited on the ceiling or other bounding surfaces encountered en route to the detector.

As particulates age, they coagulate, decreasing the number of particles while increasing the average particulate size. This has a significant effect on the activation of both ionization and light-scattering detectors. In work published in 1978, Waterman *et al*[15] tested the response of ionization and photoelectric (scattering) detectors to the UL217/268 test fires while installed side-by-side at increasing distances down a long corridor (the G series tests discussed in the reference). For a flaming source, the ionization detector responded first at 7.6 m(25 feet), they responded together at 15.2 m (50 ft) and the photoelectric responding first at 22.8 m (75 ft). This clearly demonstrated the effect of smoke ageing on the two types of detector.

Temperature rise at the detector is a function of several variables. The most important is the entrainment of air into the plume and ceiling jet. The fire plume may entrain cool, clean air, or may entrain cool, but slightly warmer, smoky air that accumulates in the compartment. The ceiling jet may entrain hot or cool gases as well as smoky or particulate-free gases depending on

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** Lewis number = $k/\rho c_p D$, where k = conductivity, ρ = density of air, c_p = specific heat capacity of ambient air, D = effective binary diffusion coefficient.

the height of the layer interface, the depth of the ceiling jet, and the output of the fire. A secondary consideration is the radiative losses and absorption from the plume, ceiling jet fluid, and soot. The greater travel time and the greater the temperature gradient between the gases and the surrounding environment, the more significant this effect becomes. These mechanisms may have a significant effect on the ratio of species concentration to temperature. In summary, the assumptions inherent in the derivation of the original 13 °C smoke detector activation correlation must be taken into account, particularly for high ceiling or large area spaces, unconventional geometry, or other unique applications.

Ionization, photoelectric light scattering and projected beam detectors are known to exhibit significant differences in response to different fuels and to smoke that has been "aged" as it travels from the source. Temperature correlations do not capture any of these known differences and are thus not necessarily capable of supporting the selection of the most appropriate smoke detection principle for a specific hazard.

Heskestad's Smoke Detector Model

In 1975 Heskestad suggested a "simple model for (smoke) detector response" which included a way of characterizing the difficulty that smoke had in getting into some smoke detectors of the day[16]. The aerodynamic entry characteristics of a detector were measured in a sensitivity test tunnel by measuring alarm points at several test velocities. The entry was described by a value, L; called a "characteristic length" because it has the units of length. This parameter is characteristic of a particular detector geometry but is independent of the properties of the smoke to which the detector is responding. It represents a transport delay for smoke to move from the outside to the sensor at the local convective flow rate. A detector's characteristic length could be measured by the manufacturer or as part of the listing investigation and provided along with its nominal sensitivity setting.

The characteristic length was used in a response delay term in the equation

$$D_{ur} = D_{uo} + L\left[d(D_{uo}) / dt\right] / V$$

where: D_{ur} is the optical density per unit length at alarm inside the detector sensor given a linear increase in smoke density (dD_{uo}/dt),

D_{uo} is the optical density per unit length at alarm immediately outside the detector, and V is the convective flow velocity at the detector.

For the model to be used in practice, L values would need to be supplied and D_{uo} would need to be tabulated for each detector model by testing its response to a set of specified fuels and combustion conditions. Unfortunately, this was never done and L values for specific smoke detectors are more difficult to obtain than are RTI values for specific sprinklers.

In later work for the FDI, the optical density terms were replaced by temperature rise and D_{uo} became the Detector Material Response number (DMR); or the observed temperature rise at the detector at response, T_{uo}.-- the 13 °C value cited in so many engineering documents. DMR still varied with fuel, combustion conditions, sensor physics and alarm threshold, but it was more practical to predict (smoke) detector response by temperature rise since there are a number of correlations and models available which predict upper layer temperatures, with or without ceiling jets. Since L was not being measured or tabulated, this delay term was neglected and the temperature correlation method became accepted without accounting for entry delays.

Today there are models, both zone and CFD, that predict soot (mass) density and optical density. It is no longer necessary to use temperature as a surrogate for smoke and the Heskestad model should be revisited. Such is being done at VTT in Finland.[17] They are measuring L in a new test tunnel that does not recirculate the test aerosol and thus avoids uncertainties from smoke ageing. They found that the range of L for all detector models tested range between 1 and 2 meters. Further, they are testing smoke detectors in a room, measuring the temperature rise and optical density at the detector for different fuels, tabulating DMR values as both temperature rise and smoke density at response. A default L-value of 2m (6ft) could be used in the absence of actual data, but such measurements could be added to the approval laboratory testing regime and the results included among the manufacturer's catalog data.

First Principles Approach

Finally, the most technically satisfying approach to modeling smoke detector response time is one where the actual physics of the sensor and aerosol dynamics are the basis for the prediction of activation. Such a first principles approach could be used to predict smoke detector activation under actual fire conditions within a compartment or building using computational fluid dynamics (CFD), or a well-constructed zone model that incorporates enough of the relevant physics. A zone model divides the space into two or three control volumes while a CFD model, or field model, divides a compartment into a grid of hundreds or thousands of such volumes. For each control volume at each time step, the computer solves the predictive equations; ordinary differential equations for the zone model or the Navier-Stokes and energy equations for CFD.[18]

The first principles approach involves modeling the dynamics of the smoke aerosol as particulates are generated by the fire and transported to the detector, and some of the physics of the specific sensor. For the aerosol, the number density and mass density of particulates at the detector will probably suffice. Optical properties such as refractive index are not needed unless detailed scattering and absorption processes are included. But here, theory is only defined for spherical particles.

For the sensor, Mulholland discusses a first-principles approach to detector activation time modeling in The SFPE Handbook of Fire Protection Engineering.[19] His discussion illustrates the complexity and uncertainty associated with a first-principles analysis. The Mulholland approach to detector modeling has several limitations. First, the detector response function must be determined experimentally or from the detector design. For photoelectric (scattering) this detector response function depends on the wavelength of the light source in the smoke detector, the scattering angle, the scattering volume, and the distribution of smoke particle diameters relative to three theoretical scattering regimes. Methods for determining such functions are not available.

Second, the approach assumes uniform distribution of all smoke particles throughout the volume of the room. In reality, this assumption may be violated in the presence of a strong fire plume, ceiling jet, or the simple formation of an upper layer. Smoke particulates are often transported by convective forces to the ceiling of the compartment, where they spread radially from the point of plume impingement. The concentration of smoke particulates at or near the ceiling can be orders of magnitude greater than the concentration near the floor. Therefore, the concentration at the detector and subsequently, the voltage level in the detector, will be higher than predicted by this approach.

Additionally, the presence of a ceiling jet will increase the velocity of the particulates as they enter the detector, which generally reduces the activation time. The approach does not account for delays associated with low-energy fires, where particles may have difficulty entering the detector due to a lack of momentum.

Finally, the approach does not account for coagulation of the particulates as a function of time. Smoke particles collide and stick together, with larger particles scavenging numerous smaller ones. Thus, depending upon the location within the volume, the assumption of log-normal distribution of smoke particles is violated, as the distribution becomes more skewed towards the larger particle end of the spectrum. Therefore, the number concentration will decrease significantly over time, while the mass concentration remains constant.

Future Research in First Principles Approach

The use of CFD models to study detector activation under conditions of complex ceiling geometries,[20] large volume spaces,[21] and long hallways[22] has been demonstrated using correlations to temperature rise or mass density but these are not as rigorous as the first principles technique discussed above. Mulholland's approach clearly accounts for some, but not all, of the physical phenomena associated with smoke detector activation. Presently, numerical techniques exist to predict most phenomena independently, so it should be possible to assemble these components into a soluble numerical model.

The Mulholland approach neglects transport of smoke particles from the source to the detector, and smoke aging effects. Soot mass density can be predicted now in both zone and CFD models, but number density predictions which account for coagulation effects are yet to be done. Baum used a simple a numerical technique to account for smoke coagulation (they assumed proportionality to concentration and time squared) but this is not presently incorporated into any commercial CFD code.[23] For smoke detectors, the response of optical types should correlate well with mass density and ionization types with number density.

Hand calculations, such as those provided in the SFPE Handbook, can provide engineering estimates of activation time. But the first principles approach that is needed to show response differences among various smoke detection principles will require use of advanced numerical techniques and modern computing power.

Conclusions

With the advent of performance-based codes it is important that reliable methods for predicting the activation of smoke detectors be developed so that they can be given appropriate credit for their role in achieving the objectives of the design. The 13 °C temperature correlation is widely accepted for engineering analysis in the absence of something better. Properly documented, the Heskestad model using L and DMR could fill this role. Characteristic length (L) can be neglected in the room of origin if the detector is in the ceiling jet; conditions generally met where complete systems are used. Elsewhere, a default value of 2m (6ft) could be used in the absence of actual data, but such measurements could be added to the approval laboratory testing regime and the results included among the manufacturer's catalog data.

DMR values are being tabulated by some researchers (i.e., VTT) and more such work could be done. If there is significant variability of these data among fuels it may be necessary to agree on some rules for selecting the DMR value for non-homogeneous materials, but for modern detectors values of 4-5 °C may be sufficient. In any case, a series of large-scale tests on ceilings 10-30m (30-100ft) in height will be needed to quantify uncertainties and designate an appropriate safety factor.

The first principles approach could be pursued for use as a subroutine in fire models. This is the only method powerful enough to differentiate the performance of the different types of smoke detection currently in use, and the only way to approach the multi-mode, multi-criteria detectors of the future. If the first principles subroutine were designed to incorporate the actual detector's algorithm as a "black box" (to protect its proprietary nature), such models could provide an accurate representation of a specific detector's performance, allowing the manufacturer to receive proper credit for his design.

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