# Evaluation of Smoke Detector Response Estimation Methods: Optical Density, Temperature Rise, and Velocity at Alarm

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**ABSTRACT:** This work examines the optical density, temperature rise, and velocity conditions adjacent to smoke detectors at the time of alarm to provide guidance on estimating smoke detector response. Variables that affect the values of these measurements at the time of alarm are also discussed. Significant variations in the optical density, temperature rise, and velocity magnitude at the time of alarm are observed. Plots of the cumulative percentages of detector alarms are presented for optical density, temperature rise, and velocity at alarm values. These plots facilitate the consideration of uncertainty in smoke detector response estimates by allowing a range of alarm thresholds to be determined.

**KEY WORDS:** smoke detectors, detector response, alarm thresholds, optical density, temperature approximation, critical velocity, uncertainty.

## INTRODUCTION

THE GROWTH OF smoke detector usage in the 1970s was accompanied by several significant research efforts that were undertaken to understand the environments to which detectors were exposed and the response of detectors to such environments [1–4]. Many of the means to estimate the response of smoke detectors were formulated during this era, and they are still the only practical means for engineers to approximate the response of smoke detectors. To estimate detector response, threshold values of smoke

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optical density, temperature rise above ambient conditions, or gas velocity magnitude adjacent to the detectors were typically used [5,6]. However, the uncertainty in these thresholds, and the ensuing uncertainty in the response estimates using such thresholds, have generally been unknown. To address this shortcoming, over 400 spot-type ionization and photoelectric detector responses were analyzed from full-scale smoke detection tests. The optical density, temperature, and velocity measurements adjacent to these smoke detectors at the time of alarm were then examined and are presented in a manner that facilitates consideration of uncertainty in smoke detector response estimates. Additional details on this analysis are presented in [7].

## THRESHOLD VALUES ASSOCIATED WITH SMOKE DETECTOR ALARMS

As a basis of comparison for the experimentally determined threshold values of optical density, temperature rise, and velocity magnitude adjacent to the detector that will lead to alarm, various threshold values taken from the literature or used in practice were considered. The nominal sensitivity of detectors (the sensitivity value determined by the UL 217 [8] and UL 268 [9] smoke detector sensitivity tests) is often used in practice as an alarm threshold. Although the nominal sensitivity value is specific to the conditions of the tests and is not likely to extrapolate well to all scenarios, it does provide a benchmark to which all listed detectors are tested. Similarly, an optical density of $0.14\,m^{-1}$, the upper limit for optical density in the black smoke test formerly conducted as part of UL 268, has also been suggested as a worst-case estimate of the optical density at which detectors alarm [10]. Geiman and Gottuk [11] characterized a range of optical density values associated with detector alarms based on experimental data from full-scale detection tests. The 20, 50, and 80th percentile values of the population of optical density values at alarm provided a range of alarm thresholds.

Alarm thresholds based on temperature rise values have also been proposed [4]. This method has drawn a fair amount of criticism as numerous studies have questioned the validity of the assumptions made to use this method and provided data showing the variability of temperature rise values at detector alarm e.g., [12–15]. However, temperature rise thresholds are included here for completeness due to the prevalence and convenience of this method. Based on a recommendation in Appendix C of the 1984 edition of *NFPA 72E* (which has since been clarified [6] to more accurately portray the recommendations of Heskestad and Delichatsios [4]), a temperature rise of 13 K (23°F) is a commonly assumed value for detector activation to flaming fires, regardless of the material burning or the type of detector examined. This value comes from an example given in Evans and Stroup [16] for a particular ionization detector alarming to a wood crib fire (based on the optical density at alarm and optical density to temperature rise ratios from Heskestad and Delichatsios [4]). Using this single value as an alarm threshold for all materials and detectors was certainly not the original intent of the early proponents of this method [4,16], but it is still common in practice due to the scarcity of the data required to perform the analysis as recommended. More recently, a temperature rise of 4–5 K has been suggested as a more appropriate temperature rise threshold for modern detectors [17–19]. Other works have shown smoke detector alarms occurring at a temperature rise as low as 1–3 K [20–22].

Several models have been proposed as a means to account for the phenomenon of smoke entry lag [2,23]. However, none of these models has gained widespread practical usage. This lack of usage is a symptom of the numerous tests required to characterize the necessary model parameters and the lack of incorporation of such testing into smoke detector approval regulations. Brozovski [24] introduced the idea that a critical velocity exists below which smoke detector response can become significantly delayed or nonexistent. Based on Brozovski's experimental study, a value of 0.15 m/s was suggested as a critical velocity. Coincidentally, this critical velocity corresponds to the velocity used in the approval standard for smoke detectors (UL 217 [8]). Schifiliti and Pucci [13] caution that the precise value for the critical velocity may vary with smoke detector design or that it is simply an artifact of the detectors, test parameters, or test apparatus used. Nevertheless, the *SFPE Handbook of Fire Protection Engineering* [5] and *Annex B of NFPA 72* [6] propose using the critical velocity approach as a means of estimating the response of smoke detectors.

## FULL-SCALE SMOKE DETECTION TESTS

The experimental data examined in this work consist of two independent series of full-scale smoke detection tests – the Navy [25,26] and Kemano [27] data sets. These data sets encompass a range of smoke sources, test conditions, smoke detector manufacturers, and models. Both flaming and smoldering fire sources are included in each series of tests. A brief summary of each test series is provided in the sections that follow.

### Navy Tests

Hughes Associates, Inc. and the Naval Research Laboratory conducted the first series of tests, referred to as the Navy test series [25,26]. Forty-one small flaming and smoldering fires from this test series were examined. The tests were conducted in both a small and medium-size test compartment. The overall dimensions of the small test compartment were approximately $6.1 \times 3.6 \times 3.0$ m ($20 \times 12 \times 10$ ft), while the medium test compartment measured approximately $5.9 \times 8.1 \times 3.0$ m ($19 \times 27 \times 10$ ft). There was a vestibule located in one corner of the medium test compartment, that measured $1.1 \times 2.2 \times 2.6$ m high, which was not part of the test space. Both compartments had 0.31 m deep beams spaced 1.2 m apart. In addition, a 0.5 m deep beam ran perpendicular to the smaller beams in the medium test compartment, bisecting the compartment into two distinct zones.

Four smoke detector models, two ionization and two photoelectric from different manufacturers, were studied during the Navy tests. Multiple smoke detectors of each model were installed in the test compartments, which provided a large number of alarm responses relative to the number of tests conducted. A total of 360 alarm responses were examined from the Navy tests. Only those detectors that alarmed during the course of a test were examined. Fire sources used in the Navy tests were generally small, in order to challenge the detection systems, and included wood cribs (12–125 kW), cardboard boxes, electrical cable, and a lactose/chlorate mixture that produced gray smoke (following the source described in British Standard BS 6266). The ignition source for the wood crib fires was 89 $cm^3$ (3 oz.) of methyl alcohol in a cup within shredded, fluffed wood excelsior placed under the crib; the methyl alcohol was ignited with a butane lighter. A butane lighter was also used to ignite the cardboard boxes and lactose/chlorate. Smoldering ignition of the electrical cable was initiated by a 500 W cartridge heater. Two ventilation scenarios of 0 and 12 air changes per hour (ACH) were used in these tests. Twelve ACH corresponds to a flow of approximately 0.22 $m^3/s$ (467 cfm) in the small test compartment and 0.45 $m^3/s$ (960 cfm) in the medium test compartment.

The smoke optical density at the detector was measured with an optical density meter (ODM), which utilized an 880 nm infrared (IR) light emitting diode (LED) and receptor arrangement over a 1.0 m path length. Temperature measurements in the Navy tests were made with Inconel-sheathed, type K thermocouples located adjacent to each smoke detector group. A sonic anemometer probe was used to measure the gas velocity in two orthogonal directions. The vertical (floor to ceiling) velocity component was not measured. The listed air speed measurement range for this probe was 0–50 m/s, with a resolution of $\pm 0.01$ m/s according to the manufacturer's specifications.

**Kemano Tests**

The National Research Council of Canada (NRC) recently conducted full-scale fire detection experiments in residential dwellings in Kemano, British Columbia [27]. A total of 13 fire detection tests were conducted as part of that study, 12 of which are examined here. (Test 12 from the Kemano test series was excluded from this analysis. This test involved smoldering cooking oil, but did not produce sufficient smoke with this original fuel to activate most of the detectors. A heptane/toluene mixture was then added to the cooking oil multiple times in the latter portion of the test to increase smoke production. Three separate periods of temporary flaming were also observed for this test.) Both dwellings used in the Kemano tests, a one-story bungalow and a two-story single-family home, were typical wood frame constructions with common residential interior furnishings and were unheated. The one-story bungalow had approximate internal dimensions of $7.7 \times 12.2 \times 2.4$ m ($25 \times 40 \times 8$ ft). Each story of the two-story single-family home had approximate internal dimensions of $6.9 \times 8.9 \times 2.4$ m ($23 \times 29 \times 8$ ft).

Small, slow-growing, flaming, and smoldering fire sources were used in the Kemano tests to challenge the smoke detectors. Most fires began as smoldering combustion and later transitioned to flaming. Representative household fire sources (e.g., wood, paper, and polyurethane foam) were used. Each fire source was placed on top of an electric heating element, which was used as an igniter. Battery-powered ionization and photoelectric smoke alarms compliant with the requirements of CAN/ULC-S531-M87 [28] were located throughout the dwellings in the Kemano tests. Note that in the Navy test series smoke *detectors* were used, while in the Kemano test series smoke *alarms* were used. For simplicity, both smoke alarms and smoke detectors are referred to as smoke detectors for the remainder of this work.

The optical density meters used in the Kemano tests were designed and constructed by NRC using a 940 nm, pulsed, near-IR LED light source separated by a distance of 0.6 m from a photodiode. Temperature was measured in the Kemano tests with 26 AWG, type K thermocouples. No instrumentation was provided in the Kemano tests to measure the gas velocity near the smoke detectors.

## METHODOLOGY

Three environmental measurements adjacent to detectors at the time of alarm are examined: smoke optical density, temperature rise above ambient conditions, and velocity magnitude. The values of the optical density and temperature measurements used in this study are the instantaneous values at the time of alarm. Initially, 5 and 10 s average values around the time of alarm were also examined, but were not found to differ significantly from the instantaneous values. Conversely, the temporal variation in the velocity data required that a 10 s average value around the time of alarm be used for all velocity at alarm values in this study.

### Variables Considered

For each of the experimental measurements, four parameters were considered as potentially having an influence on the value of the variable being measured at the time of detector alarm:

- Mode of combustion
- Smoke detector type
- Smoke detector model
- Compartment ventilation

The mode of combustion, in this context, refers to either smoldering or flaming combustion of the burning item (i.e., the type of fire). Flaming and smoldering fires produce smoke with significantly different characteristics. Smoldering fires are also less likely to produce a strong buoyant plume compared to flaming fires. Both these factors could result in variations of optical density, temperature, and velocity at alarm.

The type of smoke detector refers to the operating principle of the smoke detector (i.e., ionization (ion) or photoelectric (photo) for this investigation). Detectors with differing operating principles respond with varying degrees of sensitivity to smoke, depending on various characteristics of the smoke. As a result, differences in the optical density at alarm are likely between detector types.

Various aspects of the detector design that differ between manufacturers and/or models of smoke detectors may also affect the response of the detector and therefore the values of optical density, temperature, and velocity at alarm. In the data examined, the smoke detectors evaluated in the Navy tests are from two manufacturers, with each manufacturer's detector having a different nominal sensitivity. It may seem difficult to determine whether the detector model or the nominal sensitivity is the controlling variable. However, previous work done with optical density thresholds [11] indicates that there is little correlation between the nominal sensitivity of detectors and the optical density values at alarm (for identical detectors with varied sensitivity levels). Therefore, any variability in the values at alarm between detector models in the Navy tests is attributed to possible design differences between the models and not their varying nominal sensitivity levels. However, due to the limited number of detector models examined, it is unclear whether the conclusions regarding the significance of the detector model can be generalized to detectors other than the models studied.

The ventilation rate in a compartment is also likely to impact the optical density, temperature, and velocity at detector alarm. A functioning ventilation system may remove smoke and heat from a fire and would likely affect the air velocity adjacent to the detector. No ventilation was used in the Kemano tests, and therefore this variable was not examined for the Kemano data.

### Analytical Approach

Due to the variability seen in values of optical density at detector alarm [11], a novel approach was taken for the analysis of the values at alarm in the present study. To fully capture the variability of the data in a concise manner, the cumulative percentage of detector alarms, essentially a cumulative distribution function, is correlated with the values of optical density, temperature rise, and velocity at alarm. This approach avoids presenting only select percentages of the population. The desired percentage(s) of the population of data can then be selected from the plots for a given application. The cumulative distributions presented are determined in discrete ten-percentile intervals from the minimum to the maximum value, as shown by the markers on the plots.

## OPTICAL DENSITY AT ALARM

Using an optical density threshold is perhaps the most obvious means of predicting smoke detector response; however, there are inherent pitfalls in this approach. The most notable pitfall is that the operating mechanisms for smoke detectors do not directly relate to optical density. For example, most photoelectric detectors operate based on light-scattering, which is not directly related to optical density. Light obscuration, which is directly related to optical density, is often mistakenly assumed to be the operating mechanism for photoelectric detectors. One further complication is that a significant variation has been observed in the values of optical density when smoke detectors alarm. Researchers have attempted to account for this variation by modeling smoke entry lag [2]. However, this approach is not practically useful as the characteristic lengths required to use this entry lag model are not readily available and require numerous tests to determine; and other researchers have shown this parameter to possibly be dependent on the flow velocity and smoke characteristics [13]. Therefore, in many

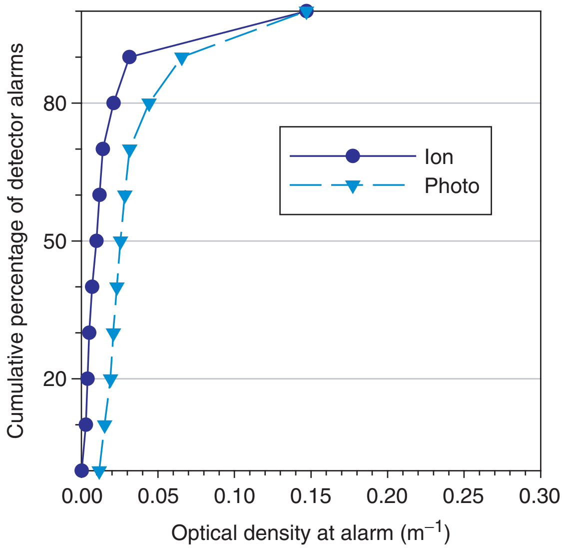


***Figure 1.*** *Cumulative distribution of optical density at alarm values for ion and photo detectors exposed to flaming fires in the Navy tests. (The color version of this figure is available on-line.)*

analyses, a range of optical density thresholds may be used to account for the variation in optical density at detector alarms.

Based on the results of this study for flaming fires, it can be stated that only the type of detector (i.e., ion or photo) significantly influenced the optical density at alarm; the differences in optical density at alarm for the ventilation conditions studied and for the two models of each detector type studied were not significant. However, due to the limited number of detector models examined, it is unclear whether this conclusion regarding the significance of the detector model can be generalized to detectors other than the models studied. Figure 1 shows the cumulative distribution of the optical density at alarm values for ionization and photoelectric detectors for flaming fires in the Navy test series. Since the fires in the Kemano tests were initially smoldering and later transitioned to flaming (i.e., the detectors were not exposed to products of flaming combustion throughout the test), they have been excluded from this figure. The distributions of ion and photo detector optical density at alarm values shown in Figure 1 are qualitatively similar, with the photo distribution shifted to slightly higher optical density values. Both distributions are fairly linear with a steep slope up to approximately the 80th percentile. The optical density at alarm for both ion and photo detectors increases significantly beyond the 80th percentile. The observation that the optical density at alarm for ion detectors is generally

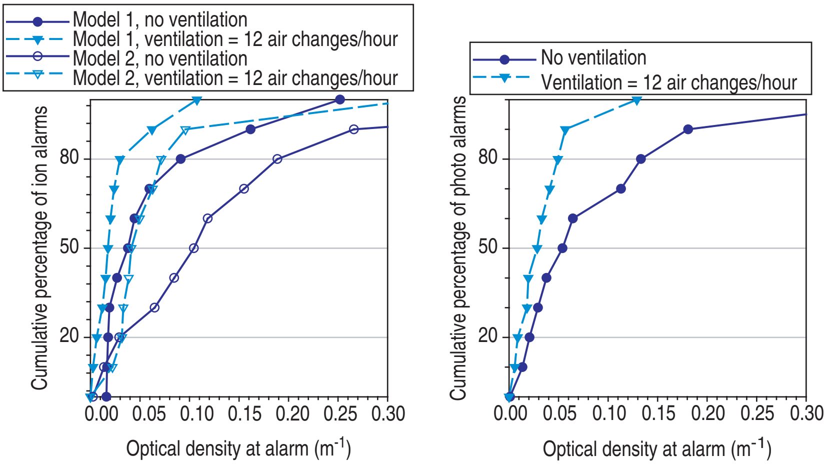


***Figure 2.*** *Cumulative distribution of optical density at alarm values for ion (left) and photo (right) detectors exposed to smoldering fires with ventilation of zero and 12 ACH in the Navy tests. (The color version of this figure is available on-line.)*

lower than that for photoelectric detectors for the flaming fires is consistent with previous experience with the response of these detector types for flaming fires.

In contrast to flaming fires, several variables were found to affect the optical density at alarm for the smoldering fires. The detector type and ventilation affected the optical density at alarm values for the smoldering fires in the Navy tests. In addition, differences in the optical density at alarm values and the total number of alarms were observed for two models of ion detectors exposed to smoldering fires in the Navy tests. However, the photo detectors showed little difference between the two models in the smoldering fire tests. Figure 2 shows the cumulative distribution of optical density at alarm values for the two ion detector models and the photo detectors exposed to smoldering fires under two ventilation conditions (no ventilation and a ventilation rate of 12 ACH) in the Navy tests. All three sets of distributions shown in Figure 2 illustrate deviations in the optical density at alarm between the two ventilation conditions studied. In some cases, such as the second model of ion detectors (shown on the left of Figure 2), the ventilation effect was more distinctive. For example, the optical density at alarm for these ion detectors was typically two to three times greater with no ventilation than with ventilation of 12 ACH. At the 80th percentile, the optical density at alarm was approximately 0.07 m$^{-1}$ with 12 ACH and 0.2 m$^{-1}$ with no ventilation. A similar trend, of lesser magnitude, was also observed for the other model of ion detector and the photo detectors.

Finally, notice the more moderate slope of the plots in Figure 2, especially when there was no ventilation, compared to those for flaming fires in Figure 1. The smaller slopes illustrate the large variation in optical density values at alarm for detectors exposed to smoldering fires, particularly when the detectors are located in compartments with no ventilation.

Figure 3 presents the optical density at alarm results for the flaming and smoldering portions of the Kemano tests. The Kemano tests did not include any fires with flaming combustion from the onset of the test; all of the fires evaluated from this test series were initially smoldering, some of which later transitioned to flaming combustion. The mode of combustion (i.e., flaming or smoldering) at the time the detector alarmed was used to categorize the alarms. The slope of the distribution in the plot on the left of Figure 3 is noticeably less than the slope of the distribution shown in Figure 1 for the Navy flaming fires. This discrepancy can be attributed to the period of smoldering combustion to which the detectors in the Kemano tests were exposed prior to flaming combustion. As expected from the results in Figure 2, the lack of ventilation in the Kemano tests resulted in optical density at alarm values that vary significantly across the distribution. The optical density at alarm values for the ion detectors that alarmed during the smoldering portion of the Kemano tests were significantly higher than those for the photo detectors; the minimum optical density at alarm value for the photo detectors was approximately one-fifth of the minimum optical density at alarm for the ion detectors. The distinction between the optical density at alarm value distributions for the ion and photo detectors in the

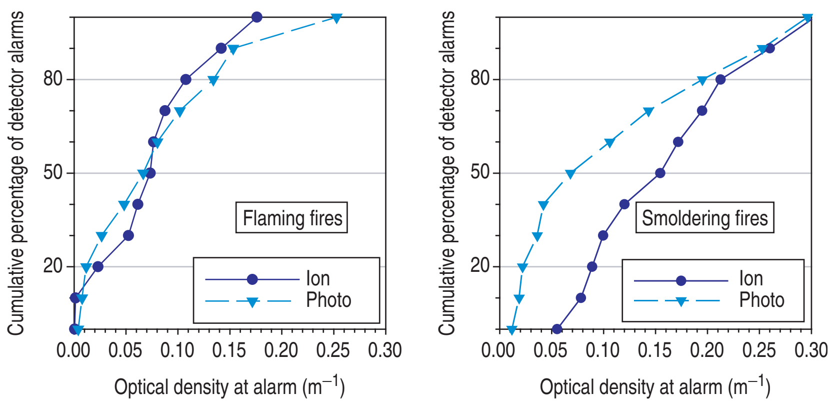


***Figure 3.*** *Cumulative distribution of optical density at alarm values for flaming (left) and smoldering (right) portions of the smoldering-to-flaming transitional fires in the Kemano tests. (The color version of this figure is available on-line.)*

smoldering Kemano tests gradually diminish up to the 80th percentile, where the distributions converge.

## TEMPERATURE RISE AT ALARM

An analysis similar to that used for the optical density at alarm values was performed to characterize the temperature rise values at alarm and to identify the significant variables. The fire type (flaming or smoldering) and detector type, both affected the temperature rise at alarm, whereas the detector model and compartment ventilation did not affect the detectors and ventilation conditions studied. Figure 4 shows the cumulative distribution of temperature rise at alarm values for flaming fires in the Navy tests. The values of temperature rise at detector alarm presented in Figure 4, particularly for ionization detectors, are lower than those typically presented. Eighty percent of the ionization detectors alarmed at temperature rise values less than or equal to 3 K in the Navy flaming fire tests. For comparison, the 80th percentile value of temperature rise at alarm for photoelectric detectors was approximately 16 K. The variation in the temperature rise at alarm values was much larger for photoelectric detectors than ionization detectors to flaming fires. The significant difference in the

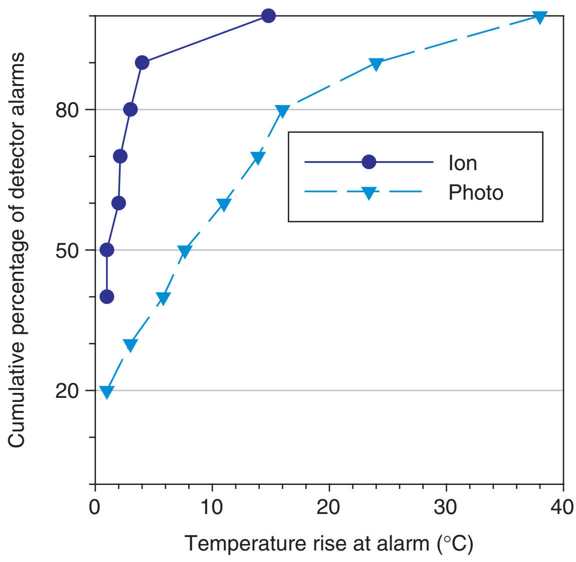


***Figure 4.*** *Cumulative distribution of temperature rise at alarm values for flaming fires in the Navy tests. (The color version of this figure is available on-line.)*

slopes of the curves in Figure 4 demonstrates this. The temperature rise at alarm values from the smoldering Navy tests and smoldering-to-flaming transition fires from the Kemano test series were not presented because the majority of alarms occurred at barely measurable temperature rise values (i.e., the maximum values of the populations of temperature rise at alarm values for these cases were 1–3 K). However, this result is instructive in that it illustrates that temperature rise values should not be used to predict alarms to smoldering fires. The original proponents of using an increase in temperature to estimate smoke detector response specifically stated that it only applied to flaming fires [4,16] and the results from this study clearly support that restriction.

## VELOCITY AT ALARM

The population of data on velocity magnitude at alarm is small compared to those of optical density and temperature data, which have respective populations of 375 and 424 measurements. A total of 53 measurements of velocity magnitudes at detector alarm, 30 values from flaming fires and 23 values from smoldering fires, were examined. The limited population of data was a result of the velocity being measured only in a few of the Navy tests. In the Navy tests for which velocity was measured, there was only one anemometer available to take measurements and multiple groupings of detectors, so the number of possible alarms at which velocity readings were available for a given test was also limited. Despite the more limited data set examined for the value of velocity magnitude at alarm, the results were consistent enough to draw useful conclusions. Interestingly, only the fire type (flaming or smoldering) was a significant variable for the velocity at alarm, for the detectors and conditions studied. The type of detector was not significant, which may indicate that the smoke entry characteristics of the detectors examined were similar.

Figure 5 presents the cumulative distribution of velocity magnitudes at alarm for flaming fires in the Navy tests. For flaming fires, the mean velocity magnitude at the time of alarm was 0.13 m/s with a standard deviation of 0.07 m/s. The median value of the velocity at alarm for flaming fires (0.12 m/s) was consistent with the mean value. Both of these measures of central tendency of the population of data are consistent with previously recommended threshold values of velocity magnitude in the range of 0.15 m/s. However, this consistency does not necessarily support the claim that this value is a *critical* value below which detectors may not alarm. In this study, detectors alarmed at lower velocities. Figure 5 shows velocity magnitudes at alarm as low as 0.04 m/s. A similar conclusion can be made for the smoldering fires given that there was no measurable velocity

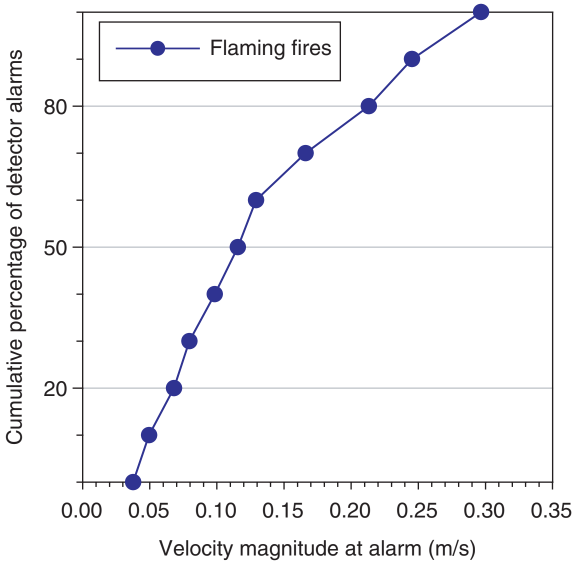


***Figure 5.*** *Cumulative distribution of velocity magnitude at alarm values for flaming fires in the Navy tests. (The color version of this figure is available on-line.)*

over ambient conditions for a majority of tests and alarms still occurred in these experiments.

## RELATIONSHIP BETWEEN OPTICAL DENSITY AND TEMPERATURE

Since values of optical density and temperature rise at alarm were determined as part of this project, the ratio of these two values could be calculated. A constant ratio of optical density to temperature rise for a particular material and combustion mode is a fundamental assumption of the temperature rise method of estimating detector response. However, the original data by Heskestad and Delichatsios [4] did not fully support this claim [12].

The ratio of optical density to temperature rise at alarm for the Navy flaming wood crib fires is shown in Figure 6. A logarithmic scale is used for the abscissa of Figure 6 due to the fact that distribution of values spans almost two orders of magnitude. However, the middle 60% of the distribution (i.e., values between the 20 and 80th percentiles) is within one order of magnitude. The vertical dashed line shown in Figure 6 is the ratio of optical density to temperature rise suggested by Heskestad

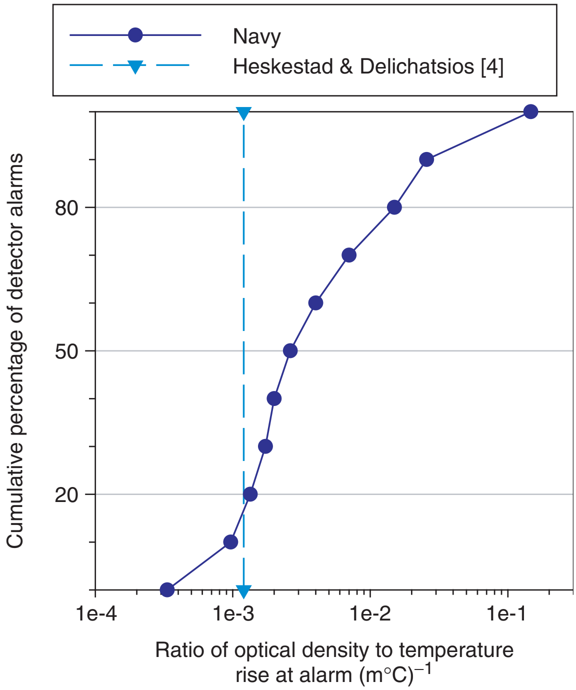


***Figure 6.*** *Cumulative distribution of the ratio of optical density to temperature rise at alarm values for flaming fires in the navy tests. (The color version of this figure is available on-line.)*

and Delichatsios [4] for a flaming wood fire. If this value were representative of conditions at the time of detector alarms, one would expect a narrow band around the representative value, not values differing by two orders of magnitude. Heskestad and Delichatsios did not examine the optical density and temperature rise at the time of alarm; they examined obscuration and temperature measurements at various ceiling locations averaged over a period of time, independent of detector activation. However, the comparison between this analysis and that of Heskestad and Delichatsios is still appropriate given that they claimed that the ratio of optical density to temperature rise does not 'vary appreciably' in time and space for a given combustible [4].

One significant difference between this plot and their work is that temperature rise values less than 3 K (5°F) are included here, whereas Heskestad and Delichatsios excluded them. The rationale given by Heskestad and Delichatsios behind the exclusion of these small temperature rise values is to prevent interference from ambient temperature variations and contributions of the igniter fuels. While these are both reasonable considerations, for the Navy flaming fires, 80 percent of ionization detectors and 40 percent of photoelectric detectors alarm at a temperature rise less than or equal to 3 K. Ignoring this substantial portion of the dataset seems overly restrictive and a poor representation of the data; therefore, temperature rise values less than 3 K are not excluded from the determination of the optical density to temperature rise ratio in this study. Note that the portion of the distribution in the vicinity of the ratio of optical density to temperature rise recommended by Heskestad and Delichatsios primarily consists of alarms that occur at a larger temperature rise.

Based on the results for the optical density to temperature rise ratio at alarm presented in this study, the ratio at the time of detector alarm is not constant for wood crib fires and in fact can vary over several orders of magnitude. In the wood crib fires they conducted, Heskestad and Delichatsios [4] observed variations in the ratio of optical density to temperature rise over time and with respect to radial distance from the fire location; however, they claimed that the variation was over a sufficiently narrow range to be treated as invariant in time and space for wood crib fires. The representative ratio of optical density to temperature rise suggested by Heskestad and Delichatsios [4] is based on the period of active fire spread. However, the goal of smoke detection systems is to provide early warning of a fire, hopefully in the incipient stages of the fire. By excluding temperature rise values less than 3 K (5°F), the representative ratios of optical density to temperature rise reported by Heskestad and Delichatios [4] may not be able to capture the value of the ratio during the incipient stage of the fire, where smoke detectors are expected to alarm. In addition, heat losses to the ceiling may also have contributed to the larger ratios of optical density to temperature rise at alarm shown in Figure 6, given that the detectors were located at various distances from the fire and the ceiling construction in the Navy tests differed from that in the study by Heskestad and Delichatsios [4].

## CONCLUSIONS

This work examines the optical density, temperature rise, and velocity conditions adjacent to smoke detectors when they alarm to provide guidance on estimating smoke detector response. Significant variations in these measurements at the time of alarm are observed. In some cases, the observed variation may preclude the use of a single threshold value to estimate detector response, and instead require a range of conditions to be considered.

The optical density, temperature rise, and velocity at detector alarm were affected by different variables. The velocity at alarm was only a function of the type of fire, whereas the temperature rise at alarm was also dependent on the type of detector (ionization or photoelectric). The optical density at alarm was also a function of the fire type and detector type. However, for smoldering fires, the optical density at alarm was also dependent on ventilation conditions in the space. Furthermore, a dependence on the detector model was also observed in these smoldering fires for ionization detectors.

There was less variation in the optical density at alarm for the flaming fire tests than for the smoldering fire tests. For smoldering fires, the effect of ventilation was often pronounced, with the optical density at alarm typically two to three times greater when there was no ventilation as compared to tests with a ventilation rate of 12 air changes per hour. The values of temperature rise at alarm presented here are lower than those reported previously, with 80% of ionization detectors alarming to flaming fires at temperature rise values less than or equal to 3 K. For smoldering fires, the maximum temperature rise values at alarm for all detectors are in the range of 1–3 K. An examination of the ratio of optical density to temperature rise values at alarm for flaming wood crib fires demonstrate a variation of almost two orders of magnitude. The lack of constancy of this ratio at the time of alarm may result from the incipient and transient nature of fires at the time of smoke detection and heat losses to the ceiling.

The population of velocity at alarm data considered here is significantly less than that of optical density and temperature rise. Despite the lack of a noticeable increase in velocity over ambient conditions for most of the smoldering fires, detectors did alarm. The mean and median values of velocity magnitude at alarm for flaming fires are consistent with previously proposed threshold values in the range of 0.15 m/s. However, detectors did alarm at lower velocities in some cases.

Great care must be taken when applying smoke detector response estimation methods, including careful selection of threshold values and consideration of the sensitivity of results to the selected threshold values.

## ACKNOWLEDGMENTS

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