

# **TASK GROUP REPORT**

## **Minimum Performance Requirements for Smoke Alarm Detection Technology**

**February 22, 2008**

This report was prepared by the Task Group on Smoke Detection Technology, a task group of the NFPA 72 Technical Committee on Single- and Multiple-Station Alarms and Household Fire Alarm System (TC). The Task Group was chaired by Daniel O'Connor, P.E. of Schirmer Engineering Corporation.

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Steve Olenick – Combustion Science & Engineering, Inc.  
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Bob Bourke\* – International Fire Marshals Association  
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\* Comments and concerns raised are included in Appendix B of this report.

**Important Note about this Report:** The enclosed report was prepared by a task group of the NFPA Technical Committee on Single- and Multiple-Station Alarms and Household Fire Alarm Systems. This report presents the findings of the Task Group on Smoke Detection Technology, a task group formed to review the effectiveness of ionization and photoelectric smoke alarms. This report is advisory only, and the information and findings provided in this report do not necessarily reflect the official position of the Technical Committee on Single- and Multiple-Station Alarms and Household Fire Alarm Systems, nor do they automatically become adopted as a part of NFPA 72, the National Fire Alarm Code. Changes to NFPA 72 only occur as a result of being processed under NFPA Regulations Governing Committee Projects. The processing of revisions for the 2010 edition of NFPA 72 has already begun and will continue in accordance with NFPA regulations under the following schedule:

- Technical Committee Report on Proposals Meetings – January 14-18, 2008 [complete]
- Technical Correlating Committee Report on Proposals Meeting – April 22-25, 2008
- Report on Proposals Posted – June 20, 2008
- Comment Closing – August 29, 2008
- Technical Committee Report on Comments Meetings – October 20-24, 2008
- Technical Correlating Committee Report on Comments Meeting – January 6-8, 2009
- Report on Comments Posted – February 24, 2009
- Intent to Make Motion Closing Date – April 3, 2009
- World Safety Conference and Exposition – May 31- June 3, 2009
- Standard Council Issuance – July 31, 2009

It is also important to note that in some cases the report recommendations are made pending further evaluation in certain areas. It is expected that separate task groups will be organized to perform these evaluations. This separate task group work will then be considered by the full technical committee as a part of the remainder of the code development process for NFPA 72-2010.

# MINIMUM PERFORMANCE REQUIREMENTS FOR SMOKE ALARM DETECTION TECHNOLOGY

## INTRODUCTION

The Task Group on Smoke Detection Technology has been requested to review the issues of effectiveness of ionization and photoelectric smoke alarms used in the household or residential environment for life safety and escape. In recent years, there has been renewed interest and controversy (Fleming 1998, Fleming 2000, Fleming 2007, Massachusetts Board of Fire Prevention Regulations 2007) regarding the long known differences between ionization and photoelectric smoke alarms relative to smoldering and flaming fire scenarios. An important consideration for the Task Group is whether or not these differences in ionization and photoelectric smoke alarms support suggestions that ionization technology is failing to provide sufficient warning for escape under the assumptions of Chapter 11 of NFPA 72. It is recognized that there are scenarios that fall outside the assumptions of NFPA 72. Such situations include those where human behaviors are exhibited and/or occupant characteristics exist that clearly challenge the timeline for successful occupant evacuation. This review and the findings in this report are relevant to fire scenarios without fixed fire suppression systems and do not address the benefits of households protected by automatic fire suppression systems.

A number of informal demonstration tests ([www.smokealarminfo.org](http://www.smokealarminfo.org), [www.barrecityfire.org](http://www.barrecityfire.org)) have been produced to illustrate the differences in response for ionization and photoelectric smoke alarms in smoldering fire scenarios. It is apparent in some of these demonstrations using smoldering fires that the operation of ionization detectors lags significantly behind the operation of photoelectric detectors. However, these demonstrations have not been performed in a controlled or scientific manner that compares the time of smoke alarm operation to the time when occupants would be incapacitated. Consequently, any conclusions about escape effectiveness from these demonstrations can only be established if the smoke alarm responses are evaluated in context of appropriate evacuation scenarios (NFPA 72 assumptions) and corresponding times of occupant incapacitation.

The Task Group considers that appropriate scientific data is available and presented in the 2003 report, NIST TN 1455, of full scale residential experiments conducted by the National Institute of Standards and Technology (NIST) (Bukowski et.al. 2003). During the time of a Subtask Group review of the NIST TN 1455, several errors were identified. NIST has corrected these data errors and spreadsheet calculation errors and has issued an updated version of the report identified as NIST TN 1455-1 (2007). This analysis uses the corrected data and computations from NIST TN 1455-1. The report titled, *Performance of Home Smoke Alarms: Analysis of the Response of Several Available Technologies in Residential Fire Settings*, provides a detailed description of the tests, detectors, measurement devices, evacuation scenarios and smoke obscuration, heat and toxic gas levels developed during the tests. In reviewing the data provided by the NIST report, the Task Group considered it important to develop a firm understanding of the elements that constitute an ASET-RSET analysis.

The purpose of home smoke alarms as required by NFPA 72 is to allow for occupants of the home or residential occupancy to be notified of the presence of a threatening fire in order that they may escape safely. Arriving at a place of safety is embodied in the concept of Available Safe Egress Time or ASET. ASET is the time period between the sounding of the alarm and the onset of untenable conditions for one or more building areas, which is compared against RSET or Required Safe Evacuation Time. Prediction of RSET typically involves estimating the time that

it would take for people to be notified that there might be a fire, the time that people would take for pre-movement activities such as alerting others, checking on family members, etc. and the time it would take for people to egress to a safe location. During the course of the evacuation, there may be other behavior, action or inactions that extend the time for evacuations which are beyond the basic human response assumptions of NFPA 72.

The idea of comparing ASET to RSET as a methodology to evaluate the performance of smoke alarms requires an understanding of those major factors that constitute the analysis. The major factors are:

1. **Evacuation Scenarios** – These scenarios represent the RSET values for the analysis as based on the assumptions of NFPA 72.
2. **Tenability Criteria** – These criteria are the basis for determining when occupants are incapacitated which sets the ASET values. Incapacitation is defined as the inability to take effective action to accomplish one's own escape from a fire. This will occur when one has breathed too many toxic fire gases or been overcome by heat exposure. Additionally, loss of visibility or obscuration due to smoke can slow occupants escape sufficiently that toxic gases or heat exposure will result in incapacitation. However, reduced visibility alone is not a fatal or incapacitating condition.
3. **Detector Technology Response Characteristics** - The characteristic response of ionization and photoelectric detectors has long been recognized to differ and vary depending on the fire scenario – smoldering or flaming. Consequently the time at which an ionization or photoelectric detector will operate at a given location to provide warning to occupants must be integrated into the ASET/RSET analysis, so that the relative threat to occupants at any time can be compared with the time required for escape.

Both ionization and photoelectric detectors are subject to nuisance alarms that can impact the reliability of the smoke alarm installation. A discussion of the causes for nuisance alarms of both ionization and photoelectric detectors is provided along with suggestions to reduce the likelihood of occupants disabling their smoke alarms and assure that smoke alarms are powered and available to operate when a threatening fire occurs.

## **EVACUATION SCENARIOS**

The current assumptions of Chapter 11 of NFPA 72, “Single-and-Multiple-Station Alarms and Household Fire Alarm Systems”, are key to judging the performance of smoke detectors to serve their purpose, which is stated as follows:

*“Fire warning equipment for residential occupancies shall provide a reliable means to notify the occupants of the presence of a threatening fire (emphasis added) and the need to escape to a place of safety before such escape might be impeded by untenable conditions in the normal path of egress.”*

The current assumptions of Chapter 11 that establish the basis for evacuation scenarios are:

1. Occupants are not intimate with the ignition and are capable of self-rescue.
2. Occupants have an escape plan and ability to execute the plan.
3. An escape route is available to occupants, and the route is unobstructed prior to the event of the fire.
4. Smoke alarms are installed and maintained operable in accordance with Chapter 11 of NFPA 72.

Given these assumptions, appropriate estimates of the required time needed for evacuation must be compared to the time of development of untenable conditions. The original Indiana Dunes tests arbitrarily used two to five minutes as an estimate of required evacuation time. The University of Massachusetts (Nober et.al. 1983) reported on a field study involving three occupant groups - (1) a normal group [40 households including homes and apartments and children], (2) a geriatric group [20 households; 35 subjects age 63-75], (3) a mentally retarded group [three halfway houses; 35 subjects]. In this study, detector units were installed in the residences where they remained for 4 – 13 weeks in order to desensitize subject awareness. The detector alarms were activated remotely between 1:00 a.m. to 4:00 a.m. These three study groups fall within the basic assumptions of Chapter 11 of NFPA 72 given that occupants were given a briefing of an escape plan. The planned response for subjects upon waking was for any member of the household to turn on a light and alert the others present. Instructions stressed rapid and immediate evacuation of “all” occupants to street side of the front door. The resulting evacuation times observed by two observers with stopwatches are as indicated below.

- Normal Group (40 households) – 30 of 40 households evacuated in less than one minute; none of the remainder exceeded 120 seconds.
- Geriatric Group (20 households) – 8 of 20 households evacuated in less than one minute and exceeded 90 seconds in only one case.
- Mentally Retarded Group (three half-way houses) – Average evacuation time of 57.9 seconds, 18 of 22 males in less than one minute, 10 of 13 females in less than one minute. One male and two females took longer than two minutes.
- General – Overall, these results showed that occupants of varied age and capabilities could evacuate residential scenarios in one to two minutes’ time.

The 2003 NIST study (Bukowski et.al.2003) developed evacuation scenarios for direct comparison to tenability threat scenarios in the specified architecture of a two-story home and a manufactured home. Worst-case scenarios developed accounts for an arthritic elderly couple (reduced walking speed) with two children in separate bedrooms. Premovement activities are assumed, including time for occupants to dress, call the fire department, obtain personal items and awaken both children. Based on these occupant response considerations and the associated travel paths, a 135-second worst-case evacuation time is indicated for the manufactured home and 140 seconds for the two-story home.

The 1983 work by the University of Massachusetts and the 2003 work by NIST provide evacuation timelines for residential scenarios that considered several pessimistic factors - alarm during sleeping hours, slower moving occupants, premovement activities, & family dynamics. The noted evacuation time periods of 60 seconds to 140 seconds provide credible evacuation timelines for analysis that are consistent with the assumptions of Chapter 11 of NFPA 72, meaning the occupants are not intimate with the fire ignition, are capable of self-rescue and have an escape plan. This fundamental premise of NFPA 72 is important to any analysis that intends to

evaluate the performance of home smoke alarms. However, it should be recognized that there are scenarios that fall outside the assumptions of NFPA 72. Such situations include those where human behaviors are exhibited and/or occupant characteristics exist that clearly challenge the timeline for successful occupant evacuation. Some examples of these behaviors and occupant characteristics are as follows:

- Occupants difficult to awaken
- Alcohol or drug intoxicated individuals
- Behaviors that may be adverse to prompt escape – e.g. fire fighting, reentry
- Physically or cognitively impaired persons without others to assist
- Occupants committing suicide
- Other behaviors that increase harm from fire – e.g. falling asleep while smoking

### **TENABILITY CRITERIA**

There is significant available literature on tenability criteria and consequently there exists various methodologies, and levels of analysis that could be appropriate for estimating the effects of fire smoke and gases on occupants. However, only one document (ISO TC92 SC3 2007) is known to provide a comprehensive, peer reviewed, consensus methodology that address in total the following:

- Exposure to radiated and convected heat
- Inhalation of asphyxiant/narcotic gases
- Exposure to sensory/upper respiratory irritants
- Visual obscuration due to smoke

ISO TC92 SC3, Fire Threat to People and the Environment, has produced ISO 13571:2007, “Life Threatening Components of Fires — Guidelines on the Estimation of Time Available for Escape Using Fire Data.” This International Standard addresses the potential for smoke to incapacitate people as they move through the vicinity of a fire. Incapacitation is defined as the inability to take effective action to accomplish one's own escape from a fire. To make use of this document, one would first determine the time-dependent concentrations of the species in the fire effluent, as well as the time-varying thermal environment. In the Standard, incapacitation can result from the toxicity of the fire effluent, heat, and smoke obscuration. It is recognized that the susceptibility of people to these hazards varies. The following summarizes the key ISO methods of evaluation that are considered acceptable for use in a tenability analysis with the exception that the ISO criterion for visual obscuration is not considered for the purposes of this review by the Task Group to be sufficiently conservative.

#### **1. Inhalation of Narcotic Gases**

This includes CO and HCN. The equation for a Fractional Effective Dose (FED) that will incapacitate half of the exposed population is:

$$FED = \int_{t_1}^{t_2} \frac{CO}{35\,000} dt + \int_{t_1}^{t_2} \frac{\exp(-HCN/43)}{220} dt$$

where  $\phi$  is the average concentration, expressed in  $\mu\text{L}/\text{L}$  over the time increment,  $\Delta t$ .

If the concentration of CO<sub>2</sub> exceeds 2% by volume, the right hand side of the equation is multiplied by a factor to allow for the increased rate of asphyxiant uptake due to hyperventilation.

$$V_{CO_2} \exp \frac{CO_2}{5}$$

where CO<sub>2</sub> is the average concentration of CO<sub>2</sub>, expressed as a volume percent.

At present, the distribution of human responses to fire gases is not known. In the absence of information to the contrary, a log-normal distribution of human responses is a reasonable choice to represent a single peak distribution with a minimum value of zero and no upper limit. By definition, a FED threshold criterion of 1.0 corresponds to the median value of the distribution, with one-half of the population being more susceptible to an insult and one-half being less susceptible. It is recommended that a lower value of the threshold criterion, 0.3 FED, be used to address the more susceptible occupants of the population. At an FED or threshold criterion of 0.3, 11.4% of the population would be susceptible to less severe exposures (lower than 0.3) and, therefore, be unable to accomplish their own escape. A still lower threshold criterion would reduce the susceptible portion of the population further. However, there is no threshold criterion so low as to be statistically safe for every exposed occupant.

The estimated uncertainty in the FED equation is ± 35%, with an additional uncertainty from the hyperventilation term of ± 20%.

## 2. Exposure to Sensory Irritant Gases

Irritant gases have two effects on people. Sustained inhalation can lead to severe effects on the lungs and lower respiratory tract, leading to delayed trauma or death. There is also a nearly instantaneous irritation of the eyes, throat, etc. At some concentration, the latter effect is rapidly incapacitating.

The current state of knowledge is that this sensory effect is additive:

$$FEC = \frac{HCl}{F_{HCl}} + \frac{HBr}{F_{HBr}} + \frac{HF}{F_{HF}} + \frac{SO_2}{F_{SO_2}} + \frac{NO_2}{F_{NO_2}} + \frac{acrolein}{F_{acrolein}} + \frac{formaldehyde}{F_{formaldehyde}} + \frac{irritant}{F_{Ci}} + \dots$$

where *F* is the concentration, expressed in μL/L, of each irritant gas that is expected to seriously compromise an occupants' ability to take effective action to accomplish escape. Consensus values of *F* for some gases are provided in the Standard.

At present, the distribution of human responses to fire gases is not known. In the absence of information to the contrary, a log-normal distribution of human responses is a reasonable choice to represent a single peak distribution with a minimum value of zero and no upper limit. By definition, a FEC threshold criterion of 1.0 corresponds to the median value of the distribution, with one-half of the population being more susceptible to an insult and one-half being less susceptible. It is recommended that a lower value of the threshold criterion, 0.3 FEC, be used to address the more susceptible occupants of the population. At an FEC or threshold criterion of 0.3, 11.4% of the population would be susceptible to less severe exposures (lower than 0.3) and, therefore, be unable to accomplish their own escape. A still lower threshold criterion would

reduce the susceptible portion of the population further. However, there is no threshold criterion so low as to be statistically safe for every exposed occupant.

The estimated uncertainty in the FEC equation is  $\pm 35\%$ , with an additional uncertainty from the hyperventilation term of  $\pm 20\%$ .

The estimated uncertainty in the *FEC* for these gases is given as  $\pm 50\%$ . However, there is ongoing debate over the proper *F* values to be used, and this could result in a far higher uncertainty. The uncertainty could also be significantly larger if the combustibles involved in the fire generate toxicologically important quantities of additional irritants.

### 3. Exposure to Heat

#### a. Radiant Heat

The threshold for incapacitating pain from exposure of skin to radiant heat is about  $2.5 \text{ kW/m}^2$ . Below this incident heat flux level, exposure can be tolerated for 30 min or longer without significantly affecting the time available for escape. Above this threshold value, the time to 2<sup>nd</sup> degree burning of skin due to radiant heat decreases rapidly:

$$t_{\text{Irad}} = 4q^{-1.35}$$

where  $t_{\text{Irad}}$  is expressed in minutes and  $q$  is the radiant heat flux expressed in  $\text{kW/m}^2$ . As with toxic gases, an exposed occupant may be considered to accumulate a dose of radiant heat over a period of time. The FED of radiant heat accumulated per minute is the reciprocal of  $t_{\text{Irad}}$ . Radiant heat is directional and its effect is mitigated to some extent by clothing. The estimated uncertainty in this equation is  $\pm 25\%$ .

#### b. Convective Heat

The time to incapacitation due to accumulated convected heat depends on the humidity of the air and the extent and nature of the person's clothing. For a fully clothed person in dry (<10% R.H.) air, the time to incapacitation is:

$$t_{\text{Iconv}} = (4.1 \times 10^8) T^{-3.61}$$

Where  $t_{\text{Iconv}}$  is expressed in minutes and  $T$  is the temperature in  $^{\circ}\text{C}$ . For unclothed or lightly clothed subjects, the time to incapacitation is:

$$t_{\text{Iconv}} = (5 \times 10^7) T^{-3.4}$$

These equations are empirical fits to human data, with an estimated uncertainty of  $\pm 25\%$ .

#### c. Total Heat

The body of an exposed occupant may be regarded as acquiring a "dose" of heat over a period of time. An estimation of the total fractional effective dose of heat acquired during an exposure is given by:

$$FED = \sum_{t_1}^{t_2} (1/t_{rad} + 1/t_{conv}) \Delta t$$

At present, the distribution of human responses to heat exposure is not known. In the absence of information to the contrary, a log-normal distribution of human responses is a reasonable choice to represent a single peak distribution with a minimum value of zero and no upper limit. By definition, an FED threshold criterion of 1.0 corresponds to the median value of the distribution, with one-half of the population being more susceptible to an insult and one-half being less susceptible. It is recommended that a lower value of the threshold criterion, 0.3 FED, be used to address the more susceptible occupants of the population. At an FED or threshold criterion of 0.3, 11.4% of the population would be susceptible to less severe exposures (lower than 0.3) and, therefore, be unable to accomplish their own escape. A still lower threshold criterion would reduce the susceptible portion of the population further. However, there is no threshold criterion so low as to be statistically safe for every exposed occupant.

#### 4. Visibility / Smoke Obscuration

A value of 0.5 m (1.6 ft) visibility is provided in ISO 13571:2007 for visual obscuration tenability criteria. For the purpose of this Task Group review the ISO value was not considered sufficiently conservative by the Task Group (explained further below). Therefore the task group reviewed the available research on this parameter and conducted a separate assessment. This review and assessment is presented in the following paragraphs.

The subject of visibility is an important consideration in the tenability analysis and a number of independent researchers and scientists (Jin 2002, Purser 2002) have put forth their own individual suggestions for visibility limits and/or associated extinction coefficient values/optical density values (extinction coefficient,  $m^{-1}$ ) can be converted to optical density (OD/m) by dividing by 2.303). These individual's suggestions range from visibility limits of 1.2 m to as high as 20 m. Jin (Jin 2002) conducted studies with a focus on the evacuation of people through fire smoke from public buildings. Jin notes that the wide variations in the visibility criterion suggested by several researchers are probably due to differences in the geometry of the test facilities and the composition of the group escaping from the fire (Jin 2002).

Simply selecting any one individual's suggested visibility value or associated extinction coefficient value does not afford an understanding of the relevance of the value selected. For example, Jin suggests the value of  $0.5 m^{-1}$  extinction coefficient (converts to 0.22 OD/m) as a reasonable visibility limit for evacuees exiting from a public building. This equates to a conservative visibility distance for light reflecting situations of 4 m (13 ft). Jin's suggestion (Jin 2002) stems from an experimental study using 49 subjects in a test chamber of 5 x 4 meters, with no windows and floor illumination of 30 lx. Half of the test subjects were Institute researchers who were introduced to the test chamber and briefed once on what to expect from the testing. Using white smoke from wood chips heated in a furnace, each subject was asked to thrust a metal stylus into holes of a device called a steadiness tester. Emotional variations were noted based on whether or not the stylus touched the hole edges and served as an indication of the effects of increasing smoke concentration in the room. From this experiment, Jin concluded that a value of 4 m (13 ft) visibility would be an appropriate limit that allows for safe escape for occupants familiar with a public building. The inference is that in a fire scenario occurring in a public building, when visibility declines to 4 m (13 ft), occupants will cease to move through a long corridor or abandon efforts to escape even without being overcome by heat or toxic gas exposure.

At present, the research concerning visibility of human subjects and its relationship to the ability to safely egress a structure has focused primarily on commercial and public buildings. No research has been conducted in a residential setting, where occupants are typically very familiar with their surroundings, which shows occupants will cease to move or abandon efforts to escape when not incapacitated. As such, using any of the above suggested values as a performance endpoint for tenability must be done with caution, since reduced visibility alone does not cause fatalities.

Even though none of the visibility studies completed to date have direct application to a residential environment, the suggested visibility criteria of the researchers noted above can be valuable if we understand the context and bases for their suggestions. However, such suggestions represent single viewpoint opinions at the time they were developed. Recently, the ISO TC92 SC3, Fire Threat to People and the Environment, Committee has produced ISO 13571:2007, “*Life Threatening Components of Fires — Guidelines on the Estimation of Time Available for Escape Using Fire Data.*” This consensus document’s approach to visibility is that a visibility endpoint occurs when occupants are no longer able to take effective action to accomplish their own escape. The ISO 13571:2007 document provides the following consensus viewpoint on smoke obscured visibility.

*As smoke accumulates in an enclosure, it becomes increasingly difficult for occupants to find their way. This results in a significant effect on the time required for their escape. Moreover, at some degree of smoke intensity, occupants can no longer discern boundaries and become unaware of their location relative to doors, walls, windows, etc., even if they are familiar with the premises. When this occurs, occupants can become so disoriented that they are unable to effect their own escape.*

The ISO 13571:2007 document equates the time that occupants can no longer affect their own escape to be the time when visibility is reduced so low that occupants cannot see their hands at arm’s length or approximately 0.5 m (1.6 ft.) Such a visibility value reflects a significantly reduced visibility condition and does not provide the conservatism for the analysis that is desired by the Task Group Smoke Detection Technology. This ISO value is considered not conservative enough as a performance tenability criterion, while other values previously noted are too unrealistic in assuming that occupants will abandon efforts to escape with visibility of 4 meters (13.1 ft.). Therefore, it was considered important to review Jin’s original work to develop reasonable criteria that provides 1) for the expectation that occupants can see sufficiently to move and 2) provides sufficient conservatism beyond arm’s length visibility as recognized by the ISO standard. The following represents the review of Jin’s work including his data related to visibility in irritant smoke.

The basis for our current knowledge on human subject visibility in smoke emanated from the work of Jin and Yamada in the 1970’s. Jin conducted and coauthored several studies that discuss the various effects of smoke on visibility. The relationship between Visibility and Smoke Density is described by Jin and Yamada, T., (Jin and Yamada 1985) as:

$$V = \frac{\text{Const.}}{C_s}$$

Where  $V$  is the visibility of signs at the obscuration threshold (m),  $C_s$  is the smoke density expressed by the extinction coefficient ( $m^{-1}$ ), and  $Const.$  is a constant that changes relative to whether the sign is light-emitting or reflective. The visibility expressed above is the distance where the sign just begins to become recognizable as an object. The extinction coefficient can be converted into optical density (OD/m) by dividing it by 2.303 (e.g. an extinction coefficient of 2.0 is equivalent to an optical density of 0.87).

Jin et al. found that for reflecting signs, the empirically determined constant was in a range of 2 to 4. In addition to the visibility of reflective signs, Jin et al. also suggest that this value is applicable for the visibility of other objects such as walls, floors, doors, and stairways (pg. 81 of Jin and Yamada 1985). Physical features of a space such as the walls, doors, floors are important markers that aid exiting.

Jin et al. originally plotted their data on a log-log graph of Visibility versus Extinction Coefficient. For ease of understanding, Jin's data can be expressed in a non-log manner as provide in Figure 1. The graph demonstrates that at higher values of the constant, higher values of the extinction coefficient result in higher values of visibility at the obscuration threshold. As the constant value is lowered, factors such as light-emitting versus reflective and non-irritant smoke versus irritant smoke are taken into account. Choosing the constant to be equal to 2 is a conservative choice that takes into account irritants that may obscure vision (e.g. through the watering of eyes) and takes into account the suggestion by Jin et al. that the lower  $Const.$  values are more applicable for the visibility of other objects. Thus, by using the  $Const.$  value of 2 and an extinction coefficient of 2 ( $0.87$  OD/m), the perceived visibility can be predicted to be approximately 1.0 m (3.3 ft) which is double the visibility limit of 0.5 m (1.6 ft.) set in the ISO 13571:2007 document.

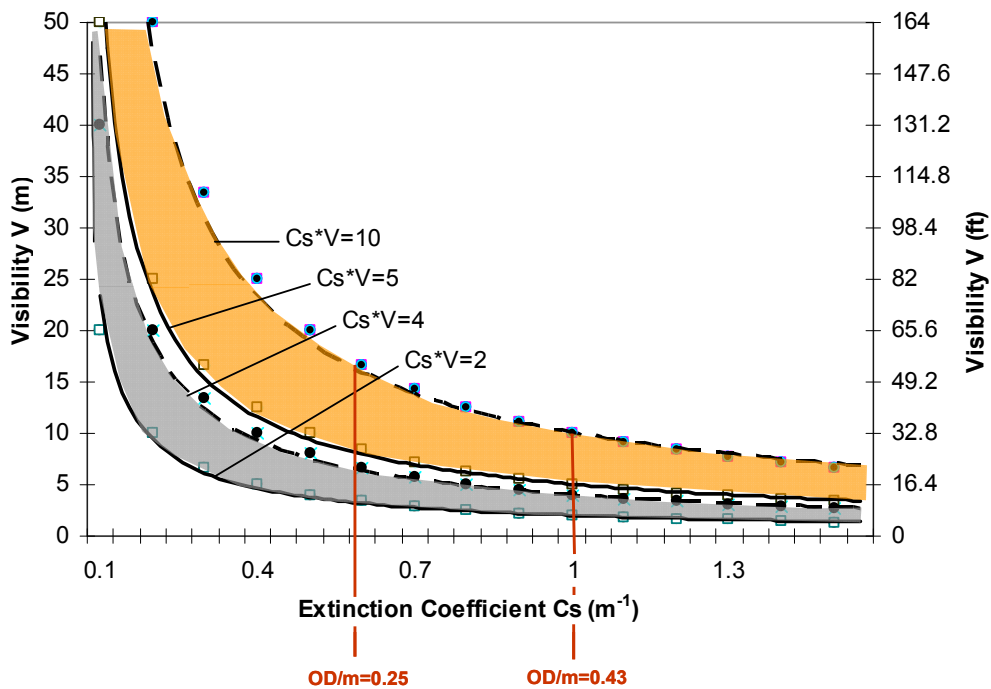


Figure 1 -Non-Log Plot of Jin's Visibility Relationship

Figure 2 below shows Jin's data and the effects of irritant and non-irritant smoke on human subjects. This data is based on asking the subjects to read the words on a lighted exit sign meaning a light emitting source was used. Given that the data applies for a light emitting source, a correction can be made by adjusting the data by a factor of 2.5 to result in values for a light reflecting source. Jin's visibility data points from Figure 2 for a light emitting source using an extinction coefficient of approximately  $0.5 \text{ m}^{-1}$  show visibility in the range of 5-7 m (16.4 -22.9 ft). Correcting for reduced visibility with light reflecting sources the visibility would be approximately 2.5 to 3.5 meters (8.2 to 11.5 ft.). The adjustment factor of 2.5 is resultant from the ratio of constant values as established by Jin for light emitting versus light reflecting signs.

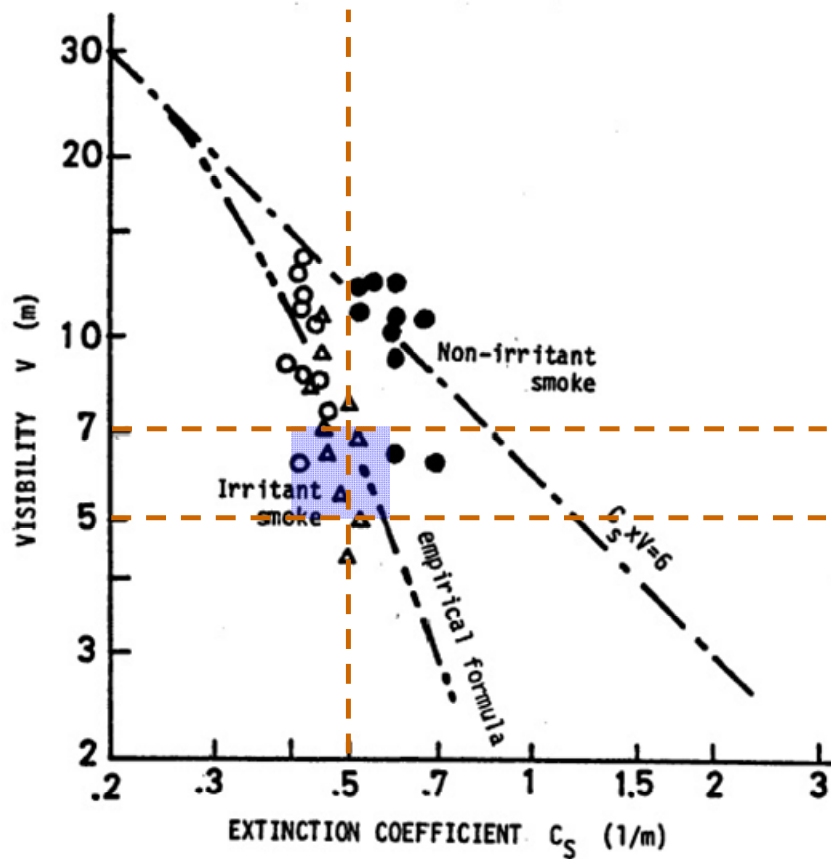


Figure 2 –Log-log Plot of Jin's Data: Effects of Irritant and Non Irritant Smoke

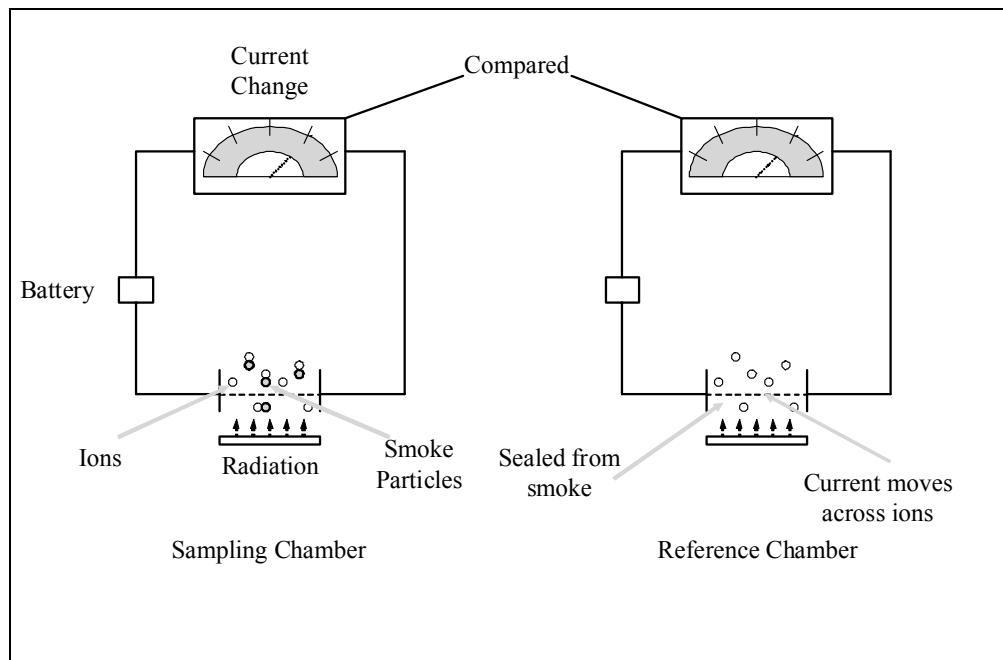
Maintaining the visibility above the conservatively derived visibility value of 1.0 m (3.3 ft) along the egress path should result in acceptable evacuation times from a residence and would be more conservative than the ISO 13571:2007 document value of 0.5 (1.6 ft) meters. However, based on uncertainties in the work by Jin et al. due to irritants and illumination levels within a residential structure, a safety factor was taken into account in order to assure that adequate time for egress is available. Thus, a further factor of safety of 2 was applied (the factor of safety is multiplied by the visibility and then related to optical density). This results in an optical density value of 0.43 OD/m (extinction coefficient of  $1.0 \text{ m}^{-1}$ ) as the minimum performance criterion for visibility. This optical density value equates to a visibility of 2 to 5 m (6.6 to 16.4 ft ), respectively, for light reflecting and light emitting sources and is consistent with values noted for visibility in irritant smoke (i.e. 2.5 to 3.5 meters (8.2 to 11.5 ft ).

## DETECTOR TECHNOLOGY RESPONSE CHARACTERISTICS

### Operating Principles

The characteristic response of ionization and photoelectric detectors has long been recognized to differ and vary depending on the fire scenario – smoldering or flaming. Consequently, the time at which an ionization or photoelectric detector will operate at a given location to provide warning to occupants must be integrated into the ASET/RSET analysis, so that the relative threat to occupants at any time can be compared with the time required for escape. The relative threat is paramount as in smoldering scenarios, smoky conditions with light to moderate levels of obscuration can result without any corresponding threat of incapacitation due to toxicity of the fire effluents and/or heat during the smoldering period. The following discussion explains the differences in smoke alarm technology response due to the detector operating principals.

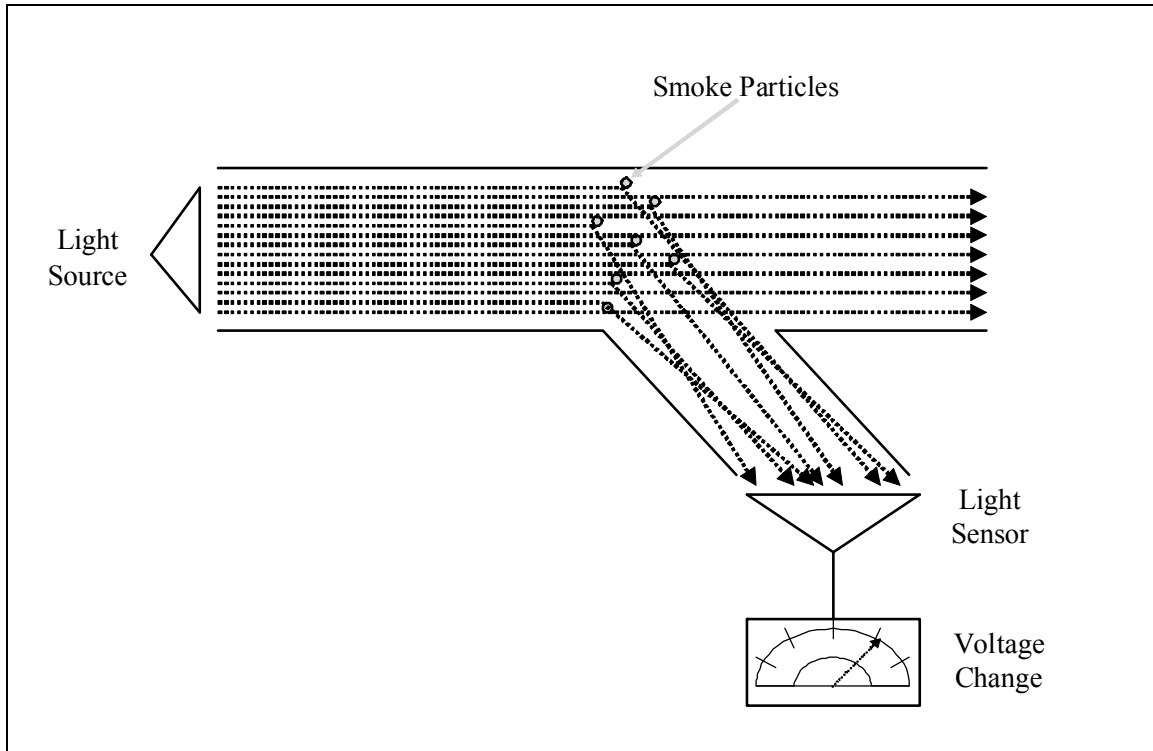
Ionization-type smoke detectors detect smoke by sensing the particulates created by combustion. Each detector contains two ionization chambers, a sampling chamber and a reference chamber. Inside each chamber, a radiation source (i.e. Americium 241) is used to create ions that flow between two plates. A battery or power source is used to flow current through a circuit, which includes flowing through the cloud of ions formed from the radiation source. When smoke enters the sampling ionization chamber, the smoke bonds to the ions causing less current to flow between the plates and limiting current flow in the circuit. This reduced current is then compared to the current in the reference ionization chamber where no smoke is present and when a sufficient difference in the currents of the two chambers occurs, the detector goes into alarm. Figure 3 shows a schematic of an ionization detector.



**Figure 3.** Ionization-type detector schematic.

Photoelectric-type smoke detectors detect smoke by sensing the visible particles of smoke that are able to scatter light. In a photoelectric-type detector, a light source is used to project a beam of

light through a chamber and a light sensor is used to sense light. Under normal conditions, the light does not significantly reach the light sensor. When visible smoke particles enter into the sensing chamber, they scatter some of the light, some of which inevitably is sensed by the light sensor in greater quantities than during normal operation. The sensing of this additional light by the light sensor causes the detector to go into alarm. A schematic of a photoelectric detector is shown as Figure 4.



**Figure 4.** Photoelectric-type detector schematic.

## Differences in Response

One-quarter of home fatal fires begin with open flame ignition and are presumably fires with no initial smoldering period, while at least one-third of home fatal fires begin under conditions that have been shown in laboratories to involve a significant initial smoldering period (Hall 2007). NIST TN1455-1 identified the top five fire scenarios ranked in terms of number of deaths during a time period from 1992 through 1996 considering NFIRS data as the fire scenarios to be studied. The rank order of scenarios implicated in descending number of deaths is: 1) smoldering upholstered furniture fires, 2) smoldering mattress fires, 3) flaming mattress fires, 4) flaming upholstered furniture fires, and 5) cooking fires. The specific fire scenarios were: 1) a smoldering chair in the living room, 2) a smoldering mattress in a bedroom, 3) a flaming mattress in a bedroom, 4) a flaming chair in the living room, and 5) a heated pot of cooking oil on the kitchen stove that bursts into a flaming fire.

The testing conducted by NIST (Bukowski, 2003) had many objectives, only one of which was to evaluate the differences in response times between currently available smoke detection technologies (i.e. ionization, photoelectric, dual, etc.). Since another of the test objectives was to provide data to detection experts for development of potentially more intelligent detector algorithms for future commercialization, the testing predominantly utilized detectors that were modified so their voltages could be monitored and recorded. The detectors did not sound audible alarms as typical detectors would. Instead, data acquisition connections were made to record the voltages of the sensing chambers as the detector was subjected to smoke. In order to know what voltage change a particular sensitivity corresponds to, calibration testing was conducted in NIST's Fire Emulator/Detector Evaluator (FE/DE) test apparatus. In these calibration tests, each modified detector was subjected to a standardized smoke curve and the voltages were recorded. After the calibration tests, a few unmodified detectors were subjected to the same standardized smoke curve and the time to alarm was recorded. The unmodified alarms were used to establish the sensitivity (i.e. amount of smoke) that would be required for alarm. From their testing with the unmodified detectors, NIST chose to use a sensitivity of 1.3 %/ft for ionization detectors and a sensitivity of 2.0 %/ft for photoelectric detectors. Since this task group utilized the alarm times reported by NIST, this task group likewise used these values. They then utilized the response of the modified detectors to the same standardized smoke curve to know what voltage change corresponds to that particular amount of smoke, and hence, calculated alarm times for the modified detectors in that fashion. But by actually reporting the calibration curve responses and the voltages from the actual fire tests for the modified detectors, an analysis conceivably could be done for any sensitivity.

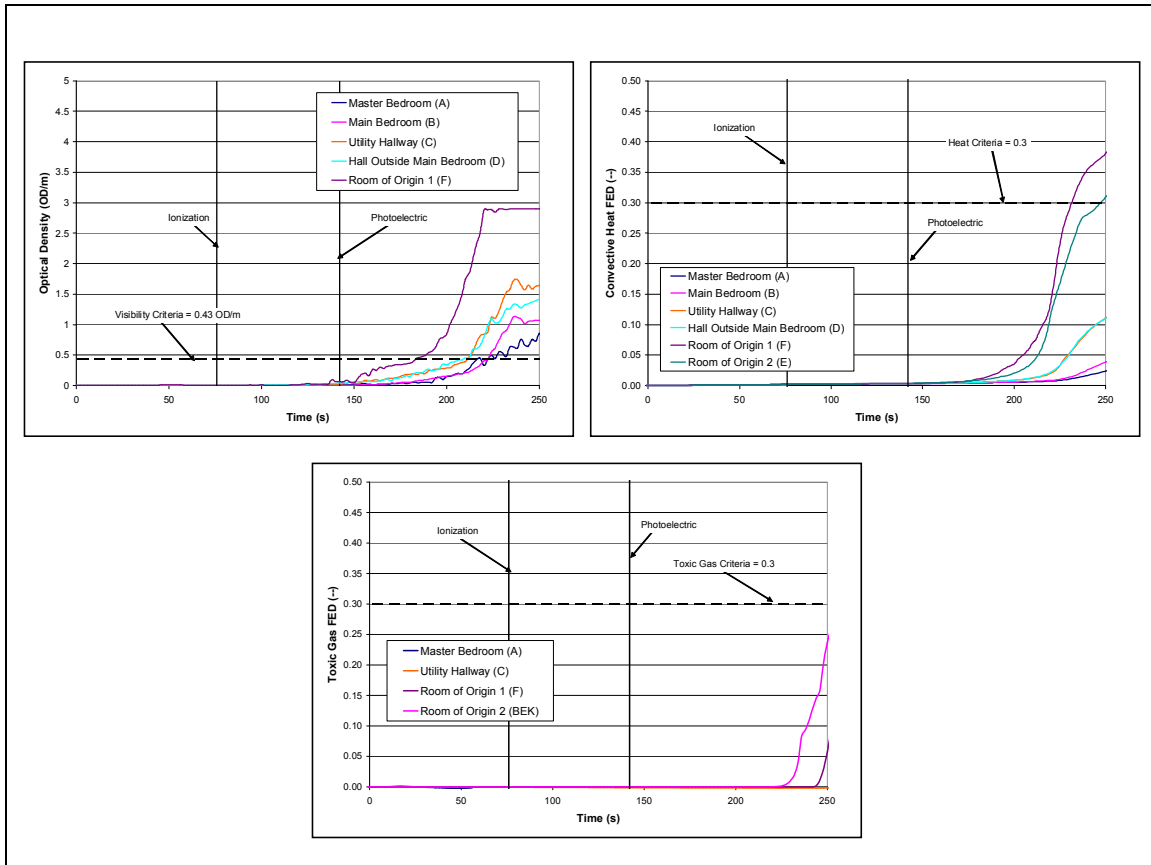
Fires initiated in either the flaming and smoldering mode of combustion present potentially hazardous conditions for occupants of a residence. During these fires, occupants can generally be categorized into three groups: intimate with ignition, in the room of origin, or remote from the room of origin. Persons that are intimate with ignition are subjected to unique effects of the fire such that a detector, regardless of the technology employed, potentially may not be able to provide adequate protection for that person. If the subject is in the room of origin but not intimate with ignition or is remote from the room of origin, it is expected that a detector, if located in the room or origin, will provide adequate protection for that occupant regardless of whether the fire is initiated in the smoldering or flaming mode of combustion. Based upon calculations outlined in the NIST study (Bukowski et al. 2003), in a worst case scenario, for the manufactured home, occupants of a residence could need as much as 135 seconds from notification of the fire by the detector to escape from the structure. Therefore, it is desired that smoke detectors will provide the requisite 135 seconds of warning, or if less than 135 seconds, as

much warning as is possible, to a fire before untenable conditions from smoke, including irritants, CO, or heat become present in the residence along the egress path at sufficient levels that could impair escape.

Technically, in calculating an individual's true FED values, it is necessary to take the time integrated values along the path traveled by an individual. The data presented in the graphs that follow represent FED values for a person fixed in the room based upon data collected during experiments (Bukowski et al., 2003). This approach is considered conservative as the worse-case scenario is an occupant being permanently fixed in a room. Additionally, the analysis below is conservative because it takes into account the visibility criterion defined above, however, reduced visibility alone does not result in incapacitation. It slows movement, but true incapacitation does not occur until the heat or toxic gas FED/FEC limits are reached.

In general, ionization detectors can be expected to give earlier warning than photoelectric detectors during a fire that is burning in the flaming mode of combustion. This is because some of the smoke produced by the flaming fire is composed of relatively small particles that are not readily able to scatter the light from the photoelectric light source, but can still easily bind to the ions in the ionization chamber. The additional warning provided by an ionization detector over a photoelectric detector is generally on the order of tens of seconds, depending on the growth rate of the fire. While this additional warning can seem small in absolute terms, the additional warning can be significant because of the fast growth nature of a flaming fire as opposed to a smoldering fire. Flaming fires can be expected to create conditions that are too smoky for easy escape, as well as, incapacitating levels of CO and heat, within a few minutes in a residence. Additionally, the levels of irritants in the smoke could be detrimental to escape efforts, although there is some research to suggest that irritants play little role in impeding escape (ISO, 2007).

The development of untenable conditions is graphed (Figure 5) for a flaming chair test originated in the living room of the test facility used by NIST (Bukowski et al., 2003). As can be seen below, the tenability limits as outlined above are achieved within approximately 4-5 minutes after initiation of the fire. Provided that the smoke alarms are installed as specified in Chapter 11 of NFPA 72 and interconnected as required (termed "every level and bedrooms" in NIST report), the ionization alarm provides the first warning to the fire for this particular test. The ionization warning was followed by the photoelectric warning, but both warnings occurred before the tenability limits were reached (NOTE: *both first alarms were in room D*). Additionally, it can be seen that very shortly after the conditions created visibility concerns, the heat and toxic gas limits were exceeded. This demonstrates the fast development of hazardous conditions during a flaming fire. Therefore, while the difference in detection times of the ionization and photoelectric technologies is small in absolute terms for flaming fires, the difference can be significant when these untenable conditions are evolving rapidly.

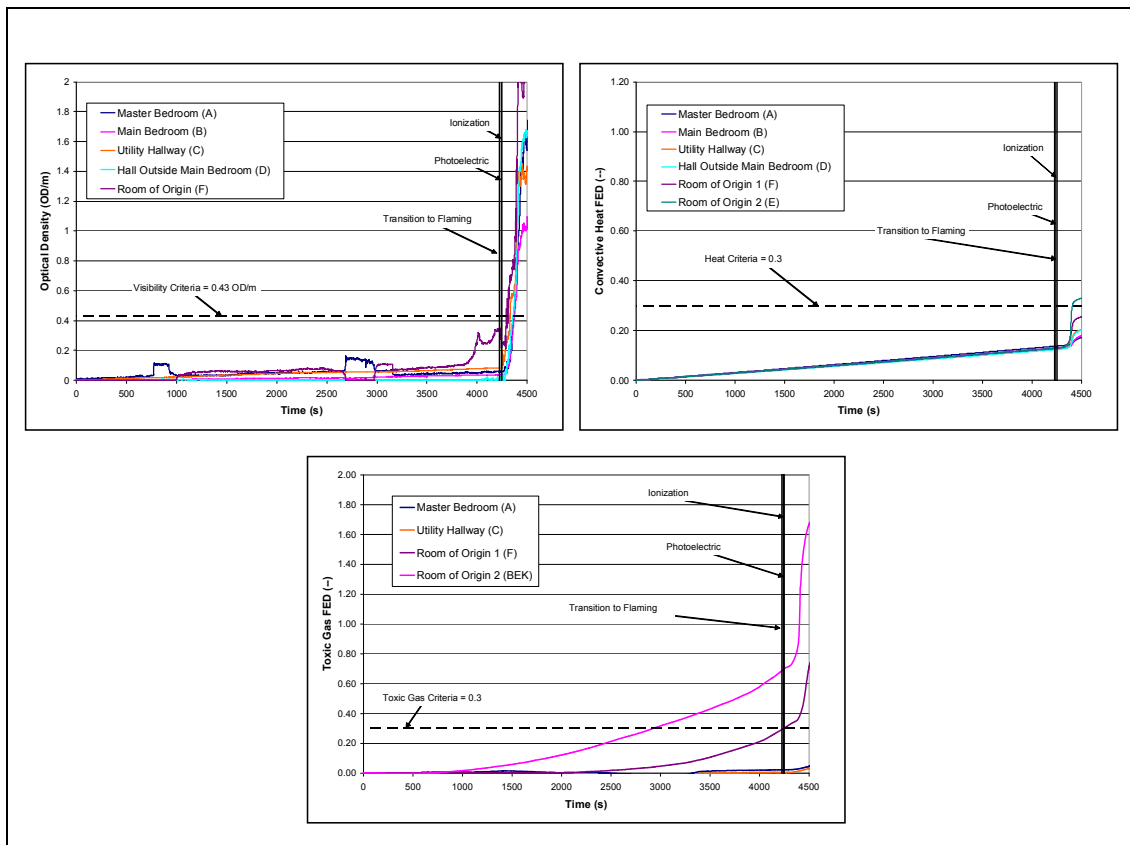


**Figure 5.** Development of hazardous conditions in NIST SDC10 flaming chair test originated in the living room. (See Appendix A for large scale graphs)

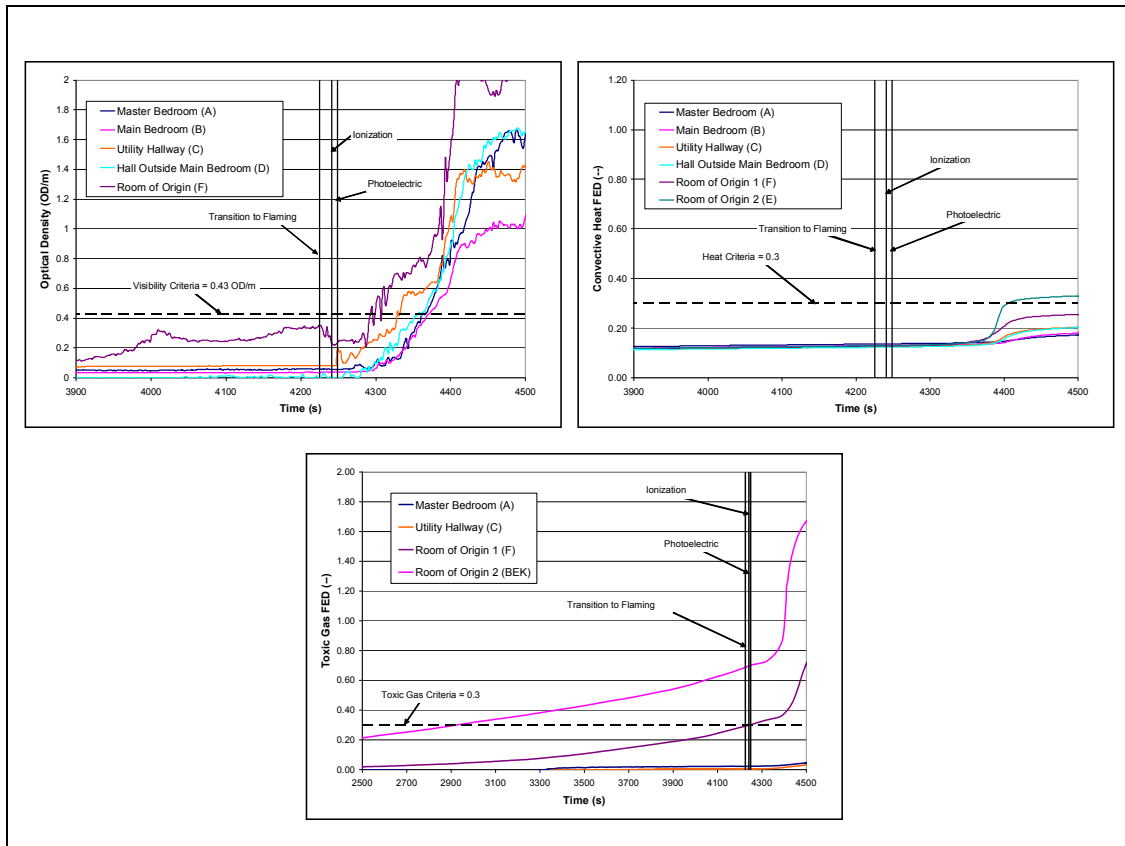
During a fire that is burning in the smoldering mode of combustion, in general, photoelectric detectors can be expected to give earlier warning than ionization detectors. This is because smoldering fires typically produce smoke that is in the visible range and hence is available to scatter the light in the photoelectric detector. Likewise, the smoke particles are able to bind to the ions in the ionization detector, but since in a slow growth smoldering fire there are less smoke particles being created, the photoelectric detector typically alarms first. The additional warning provided by a photoelectric detector over an ionization detector in a smoldering fire can be on the order of minutes to tens of minutes, depending on the characteristics of the fuel. While this additional warning can seem large in absolute terms, smoldering fires have such a slow growth rate that conditions that result in lack of egress potential for occupants in general do not occur until a timeframe on the order of hours. Often, threatening or untenable conditions are not present in the residence until after the fire has transitioned from a smoldering mode of combustion to a flaming mode of combustion. Figures 6 and 7 below depict results from a smoldering fire that originated in a chair in the living room in the NIST experimental facility. As can be seen, there is no significant impairment of visibility,

heat, or toxic gas remote from the room of origin, using the criteria outlined above, until after the transition to a flaming fire. The only tenability limit to be reached before the transition to flaming is that of the toxic gases in the living room (room of origin). This does not constitute a failure of either type of smoke alarm to detect this fire in an acceptable manner, as in the room of origin, the FED is calculated at a level of 5 feet off the floor. Had the occupant been at a level 5 feet off the floor in the room of origin, they would be expected to be standing and therefore have been aware of the fire without the need for a smoke alarm (bunk beds may be special scenario to consider). Additionally, recall that all of these curves are for a person remaining in a room and not for the time-averaged exposure to hazardous conditions along the path of travel. Therefore, the presentation below is generally of a conservative nature. In this particular test, the ionization alarm actually activated before the photoelectric and provided slightly more warning (*NOTE: First ion was in room D, first photo was in room C, as no photo was present in room D*) although both alarms activated at nearly the same time.

A specific notable result indicated in Figure 6 is that the toxic gas FED is exceeded in the living room which is the room of origin before any NFPA 72 required ionization or photoelectric detector achieves alarm. In this case the living room is not a sleeping room; however, the result supports NFPA 72 requirements to have smoke alarms in the bedrooms.



**Figure 6.** Development of hazardous conditions in NIST SDC11 smoldering chair test originated in the living room. (See Appendix A for large scale graphs)



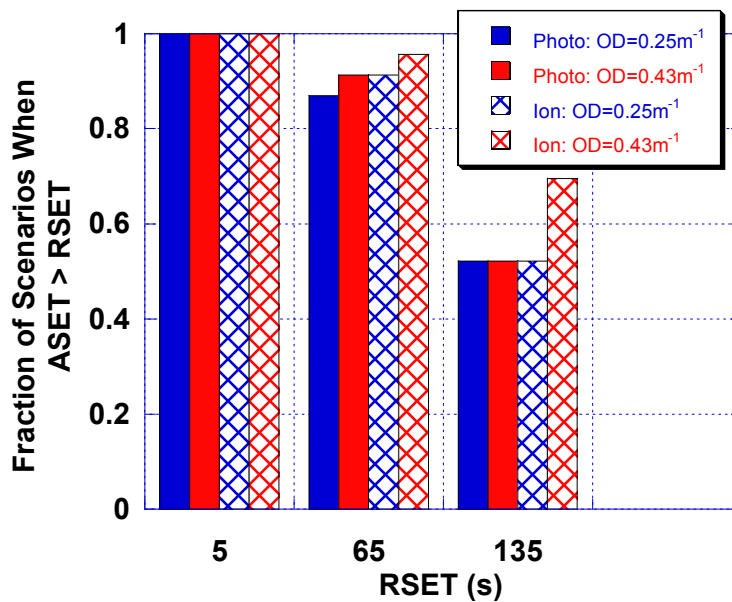
**Figure 7.** Development of hazardous conditions in NIST SDC11 smoldering chair test originated in the living room at the time to transition to flaming. (See Appendix A for large scale graphs)

While the presentation above was for a flaming and a smoldering chair fire in the living room, these are only two specific tests. The results are marginally dependent on the specific conditions of the particular test. Therefore, a multitude of tests were conducted by NIST to evaluate the average performance of ionization and photoelectric smoke alarms under many different fire conditions and locations. The NIST TN 1455 considered several scenarios including flaming and smoldering upholstered chairs, flaming and smoldering mattresses, and a cooking fire in both a single story and a two story residence. Considering all of the NIST single story fire scenarios where tenability limits were reached, either photoelectric or ionization smoke alarms installed on every level and in the bedrooms provided positive ASET values for each of 23 tests considered using the NIST tenability criteria for heat and combustion gas toxicity and a smoke visibility criterion of an optical density of  $0.25 \text{ m}^{-1}$ . Similar results were observed for the two-story residence.

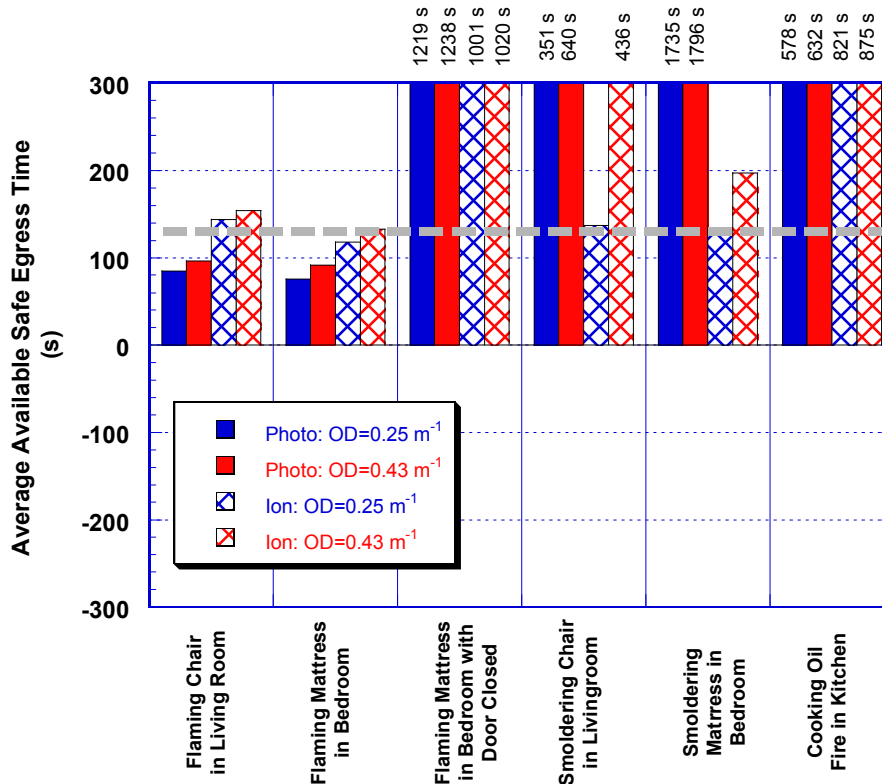
Considering the maximum RSET for the single-story home of 135 s, both the photoelectric and ionization alarms provide ASET values greater than  $RSET = 135 \text{ s}$  for 12 out of 23 scenarios. Re-computing ASET using only the smoke visibility criterion (generally the first tenability limit

reached) established above of  $0.43 \text{ m}^{-1}$  optical density, the ionization alarms provide ASET values greater than  $\text{RSET} = 135 \text{ s}$  in 16 out of 23 scenarios, while the number of photoelectric alarm scenarios remained at 12 out of 23. Figure 8 shows the fraction of scenarios where ASET is greater than a given RSET considering both photoelectric and ionization alarms and optical density values of  $0.25 \text{ m}^{-1}$  and  $0.43 \text{ m}^{-1}$ . By raising the optical density criterion to  $0.43 \text{ m}^{-1}$  the average increase in ASET for the 23 scenarios is 75 s for photoelectric alarms and 77 s for ionization alarms. Since reduced visibility alone is not a fatal or incapacitating condition it can be expected that additional time is available for escape based on toxic gas or heat tenability limits.

Figure 9 shows the average available safe egress time for each of the scenarios considering either photoelectric or ionization alarms on every level and in bedrooms. For the flaming fires with doors open ionization alarms provide 50 s of additional available safe egress time compared to photoelectric alarms, while for the smoldering fires photoelectric alarms provide 15 minutes of additional available safe egress time compared to ionization alarms.



**Figure 8.** NIST results - fraction of scenarios where ASET is greater than a given RSET considering both photoelectric and ionization alarms and optical density values of  $0.25 \text{ m}^{-1}$  and  $0.43 \text{ m}^{-1}$



**Figure 9.** NIST results - average available safe egress time for each of the scenarios considering either photoelectric or ionization alarms on every level and in bedrooms.

Figure 9 above indicates that when utilizing visibility criteria (i.e. no FEC/FED criteria), that ionization alarms (evaluated at optical density criterion of  $0.43 \text{ m}^{-1}$ ) are on average providing adequate response to most expected flaming residential fires, but that photoelectric alarms are not performing as well in flaming scenarios based on this visibility perspective. The data on photoelectric technology is showing potentially inadequate warning time for escape. Additionally, the charts show that for smoldering fires, the photoelectric detector is generally detecting the fire before the ionization, but that both are providing, on average, the requisite 135 seconds of alarm time before any of the tenability limits are reached.

The NIST report (TN1455-1, Dec. 2007) considers the following assumptions about occupant locations and the egress paths: (1) occupants are not located in the room of fire origin, and (2) egress paths through the room of fire origin are not considered. Therefore, for a living room or kitchen fire in the single-story manufactured home, the living room, dining area, and kitchen were treated as the room of fire origin, and connected hallways were not considered as egress paths. In those cases occupants were assumed to be in bedrooms and able to leave by alternate egress paths, i.e., bedroom windows. For the bedroom fire scenarios, egress paths included all other rooms and hallways.

The data makes available alternate analysis based on a different set of assumptions. The data was re-analyzed using two different sets of assumptions concerning available egress paths and occupant locations. The first case considered (alternate case A) assumes the hallways locations (utility hallway, front door hallway, and hallway outside back bedroom) are egress paths in

all fire scenarios, but occupants are not located in the room of fire origin. The second case considered (alternate case B) assumes the hallways locations (utility hallway, front door hallway, and hallway outside back burn bedroom) are egress paths in all fire scenarios, and that occupants are located in the room of fire origin.

The results for photoelectric and ionization alarms applying assumptions of alternate case A are shown below.

For alternate case A (Figures 10, 11), considering the maximum RSET for the single-story home of 135 s, the photoelectric and ionization alarms provide ASET values greater than RSET = 135 s for seven and 11 out of 23 scenarios for photoelectric and ionization alarms respectively. Re-computing ASET using only the smoke visibility criterion of 0.43 m<sup>-1</sup> optical density, the ionization alarms provide ASET values greater than RSET = 135 s in 14 out of 23 scenarios, while the number photoelectric alarm scenarios remained at 11 out of 23. Figure 10 shows the fraction of scenarios where ASET is greater than a given RSET considering both photoelectric and ionization alarms and optical density values of 0.25 m<sup>-1</sup> and 0.43 m<sup>-1</sup>. By raising the optical density criterion to 0.43 m<sup>-1</sup> the average increase in ASET for the 23 scenarios is 44 s for both photoelectric alarms and for ionization alarms (Figure 11).

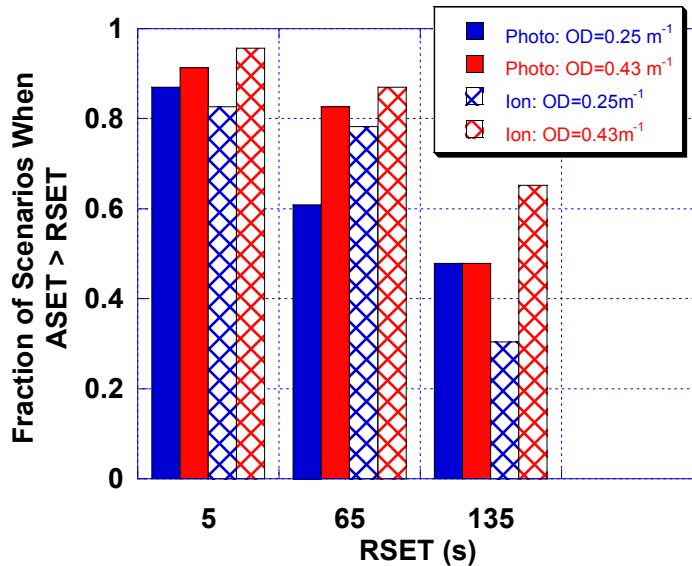


Figure 10. Alternate Case A

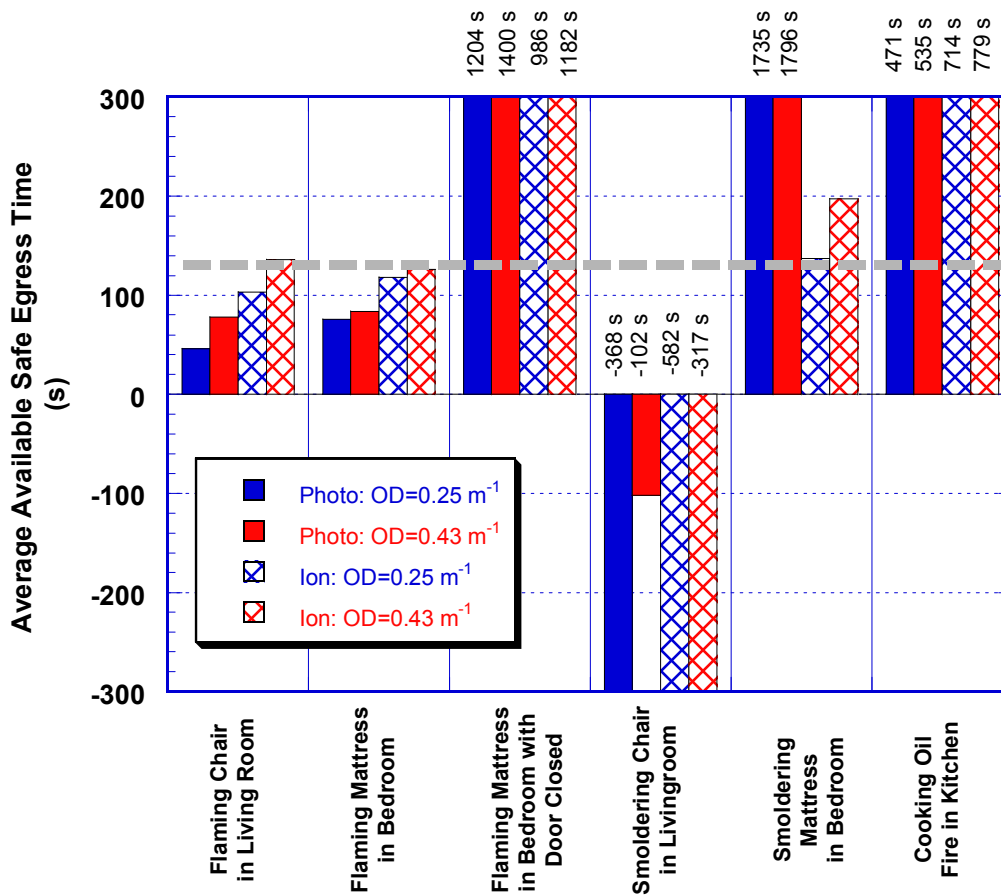


Figure 11. Alternate Case A

The results for photoelectric and ionization alarms applying assumptions of alternate case B are shown below.

For alternate case B (Figure 12,13), considering the maximum RSET for the single-story home of 135 s, the photoelectric and ionization alarms provide ASET values greater than RSET = 135 s for five and eight out of 23 scenarios for photoelectric and ionization alarms respectively. Re-computing ASET using only the smoke visibility criterion of 0.43 m<sup>-1</sup> optical density, the ionization alarms provide ASET values greater than RSET = 135 s in eight out of 23 scenarios, while the number photoelectric alarm scenarios remained at eight out of 23. Figure 12 shows the fraction of scenarios where ASET is greater than a given RSET considering both photoelectric and ionization alarms and optical density values of 0.25 m<sup>-1</sup> and 0.43 m<sup>-1</sup>. By raising the optical density criterion to 0.43 m<sup>-1</sup> the average increase in ASET for the 23 scenarios is 44 s for both photoelectric alarms and for ionization alarms (Figure 13).

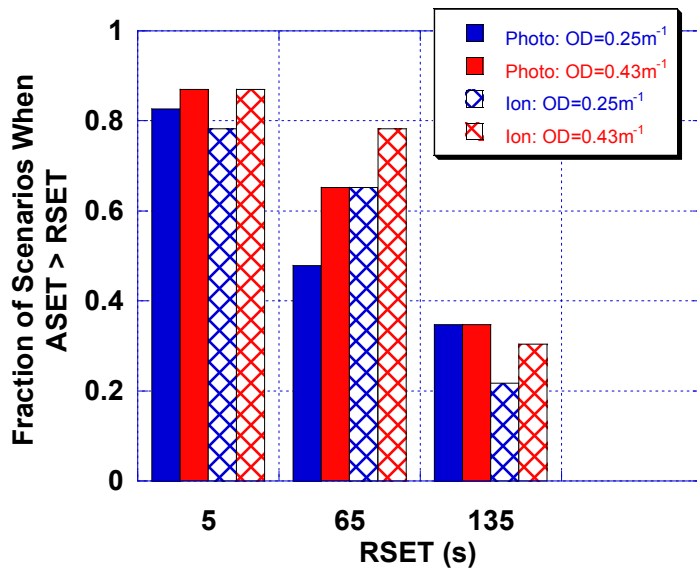


Figure 12. Alternate Case B

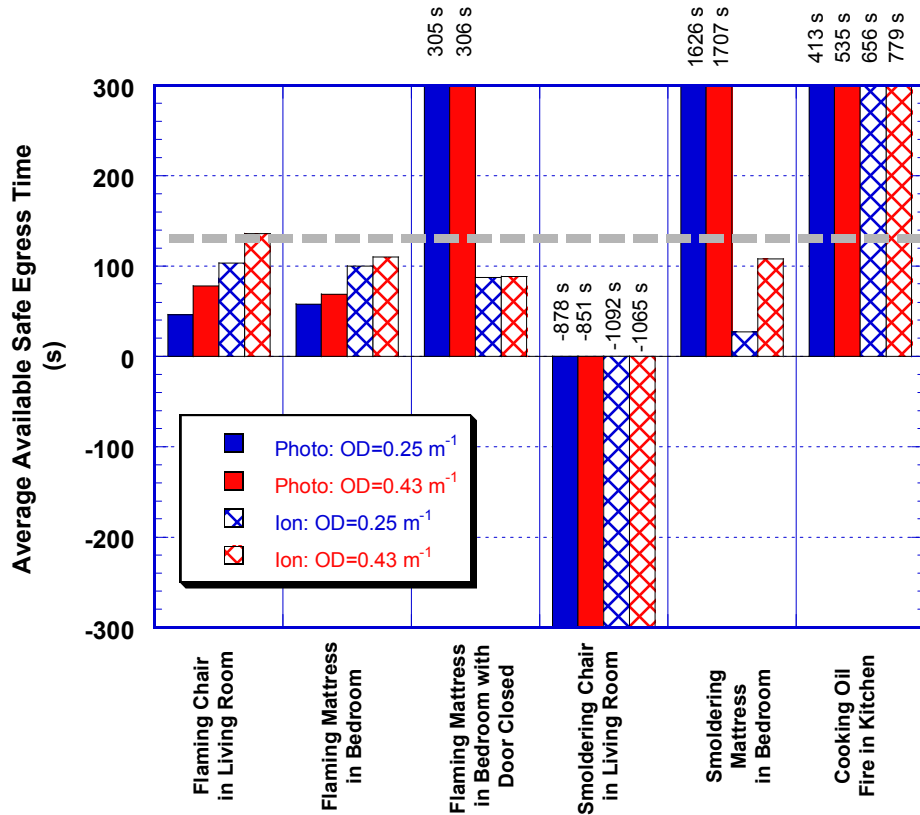


Figure 13. Alternate Case B

With regard to combination or dual photoelectric/ionization smoke alarms tested in the NIST study, it is important to note that functioning units were not placed in every location. In many cases individual photoelectric and ionization alarms were located closer to the fire and alarmed sooner. A direct comparison between individual sensor and combination sensor alarm is not possible unless one only compares collocated alarms. The dual photoelectric/alarms were calibrated to the same sensitivity as the individual photoelectric or ionization alarms. One can get a sense of the performance of a dual photoelectric/ionization alarm if the individual results above are considered.

Considering the NIST egress occupant assumptions, a dual photoelectric/ionization alarm that possesses the same individual sensor sensitivities as specified in the NIST analysis would increase the number of scenarios with ASET greater than RSET=135 s to 16 out of 23 using an optical density criterion of  $0.25 \text{ m}^{-1}$ , and to 19 out of 23 using an optical density criterion of  $0.43 \text{ m}^{-1}$ .

Considering alternate case A, a dual photoelectric/ionization alarm that possesses the same individual sensor sensitivities as specified in the NIST analysis would increase the number of scenarios with ASET greater than RSET=135 s to 12 out of 23 using an optical density criterion of  $0.25 \text{ m}^{-1}$ , and to 16 out of 23 using an optical density criterion of  $0.43 \text{ m}^{-1}$ .

Considering alternate case B, a dual photoelectric/ionization alarm that possesses the same individual sensor sensitivities as specified in the NIST analysis would increase the number of scenarios with ASET greater than RSET=135 s to 10 out of 23 using an optical density criterion of  $0.25 \text{ m}^{-1}$ , and to 12 out of 23 using an optical density criterion of  $0.43 \text{ m}^{-1}$ .

In current practice manufacturers may set alarm sensitivities in dual photoelectric/ionization alarms less sensitive than in individual sensor alarms with the intent to reduce nuisance alarms. Ideally the response of dual ionization/photoelectric units should not lag significantly behind the collective response of individual units, especially to flaming fires. Further evaluation of the dual ionization/photoelectric smoke alarms should be conducted to establish the set point characteristics that allow for effective alarm response comparable to individual units, while recognizing that set point changes may also be beneficial in the reduction of false alarms.

### **Nuisance Response Characteristics**

Nuisance alarms are the leading cause of occupants disabling their smoke alarms. Disabled smoke alarms account for roughly 20% of the smoke alarms installed in U.S. homes, and that number may be higher in high risk areas, such as inner cities and rural communities. (Ahrens 2004; DiGuseppi & el al 2002; DiGuseppi, Roberts & Speirs 1999; Fazzini, Perkins & Grossman 2000; Istre & Mallonee 2000; Kulinski, Berger & Weaver 1996; Ludington & Newsad 2000; Roberts & el al 2004; Rowland & el al 2002) Nearly all of the non-working smoke alarms are due to dead or missing batteries. (Ahrens 2004; DiGuseppi, Roberts & Speirs 1999; Istre & Mallonee 2000; Kulinski, Berger & Weaver 1996; Ludington & Newsad 2000; Rowland & el al 2002)

A nuisance alarm is an unwanted activation of a smoke alarm in response to a stimulus that is not the result of potentially hazardous fire. During a nuisance alarm, the smoke alarm sensor operates, and it is usually a true indication of the present state of the sensor. Even though the smoke alarm is alarming to a non-hazardous source, the smoke alarm is detecting particles that

may not be visible to the occupant, and therefore the occupant perceives the alarm activation as inconvenient, annoying, or vexatious.

Nuisance sources external to the smoke alarm are the leading cause for disabling smoke alarms. (Ahrens 2004) External nuisance sources can be cooking gases, steam, dust, insects, tobacco smoke, air circulated from heating equipment, and candle combustion products. Both types of smoke alarm detection technologies, ionization and photoelectric, are vulnerable to external nuisance sources. (Fazzini, Perkins & Grossman 2000; Kulinski, Berger & Weaver 1996; NIST 2003; Qiyuan, Hongyong & Yongming 2002-2003) Single station battery-only smoke alarms are more likely to be disabled than household 120 VAC-powered or 10-year-battery-powered smoke alarms. (Roberts & el al 2004; Rowland & el al 2002)

Cooking is the leading cause of nuisance alarms. (Ahrens 2004; Fazzini, Perkins & Grossman 2000; Kulinski, Berger & Weaver 1996) Factors that determine the rate of nuisance alarms are the type of cooking (frying causes a high rate of nuisance alarms), distance to the nuisance source, use of a cooking exhaust fan, air flow direction and rate in the occupancy, and type of smoke alarm. (Ahrens 2004; Kulinski, Berger & Weaver 1996; NIST 2003)

Ionization and photoelectric type detectors are sensitive to cooking gases, but several studies have shown that ionization type detectors installed too close to a cooking appliance have a higher frequency of nuisance alarms than photoelectric type detectors. The ionization type detectors are better at detecting smaller particles (less than one micron) that are typically generated during cooking. (Ahrens 2004; Fazzini, Perkins & Grossman 2000; Kulinski, Berger & Weaver 1996; NIST 2003)

The CPSC National Smoke Detector Project initiated in 1991 showed that ionization smoke alarms placed too close to a cooking source can cause a frequent number of nuisance alarms. The study found that ionization alarms accounted for 87% (769/880) of installed smoke alarms but for 96% (32/33) of nuisance alarms. (Shapiro, 1994) The main cause for the ionization smoke alarms to frequently nuisance alarm was being installed too close to a cooking appliance. Sixty-three percent (20/32) of the ionization smoke alarms were 10 feet or less to a cooking appliance. Eighteen of the 32 ionization smoke alarms collected for nuisance alarming in the study contained higher sensitivity values than the average sensitivity data for 125 ionization detectors measured. The single photoelectric smoke alarm that was collected in the study for frequent nuisance alarming was determined to contain excess dirt and dust in the unit. The unit was located more than 10 feet from a cooking appliance.

A survey of smoke detector nuisance alarms in a Native American community conducted in 1995 found that the majority of homes which had ionization smoke alarms had frequent nuisance alarms and only a few homes had photoelectric smoke alarms which did not have any nuisance alarms. (Kulinski, Berger & Weaver 1996) The study survey included 26 questions, as well as physical measurements and visual observations. The distances from smoke alarms to ceiling/wall junctions and to potential nuisance sources such as stoves, bathrooms, and fireplaces were recorded. The survey included visits to 173 households, of which 80 households had one or more smoke alarms. In the 80 households, there were 112 smoke alarms, including 106 ionization type, 3 photoelectric type, and 3 unidentified types. Forty-four of the 112 alarms were inoperable and in 86 percent of the 44 alarms, the power or batteries were disconnected because of frequent nuisance alarms. The study had only 3 photoelectric smoke alarms, none of which were reported as having nuisance alarms. Two of the photoelectric alarms were installed within 6 inches along side ionization smoke alarms. Even though the paired ionization smoke alarms had nuisance alarms from cooking, the photoelectric alarms did not sound from the same cooking source. The

third photoelectric smoke alarm was installed 6 feet closer to the stove than the ionization smoke alarm. Even though the photoelectric smoke alarm was closer, it did not have any reported nuisance alarms whereas the ionization alarm still sounded frequently during cooking. While there were a limited number of photoelectric smoke alarms in the survey, the three photoelectric smoke alarms experienced no nuisance alarms compared to the ionization smoke alarms in the same or closer distance to the cooking source. The study did not report the distance of the photoelectric smoke alarms relative to the cooking appliance.

The Native American community study includes an analysis on the ionization type smoke alarms because all the nuisance alarms resulted from the 106 [latter in the report incorrectly states 109 ionization smoke alarms] ionization smoke alarms. (Kulinski, Berger & Weaver 1996) The study showed that 77 percent of the respondents said that cooking was the cause for frequent nuisance alarms from their smoke alarms, and bathroom steam attributed for 18 percent of the nuisance alarms. Cooking related nuisance alarms for ionization smoke alarms were significantly related to the distance from the smoke alarm to the cooking source. The cooking related nuisance alarm rate was 68 percent for smoke alarms located less than 20 feet from the cooking appliance and 58 percent for smoke alarms located between 20 and 25 feet. If the smoke alarm was located more than 25 feet from the cooking appliance, the nuisance alarm rate dropped to only 36 percent. Ionization smoke alarms placed farther than 25 feet to a cooking appliance can result in a significant reduction of nuisance alarms. Steam from a bathroom caused 19 percent of the nuisance alarms if the smoke alarm was installed within 10 feet of a bathroom door. Smoke alarms that were more than 10 feet of the bathroom door had no reported nuisance alarms. (Note: The current NFPA 72 uses a 20 foot distance requirement for cooking appliances and 3 feet for separation distance from a bathroom door).

A study of Alaskan Eskimo villages, published in 2000, found that ionization smoke alarms had a significantly higher number of nuisance alarms than photoelectric smoke alarms when installed 10 to 15 feet from a nuisance source. (Fazzini, Perkins & Grossman 2000) For the study, the researchers installed both ionization and photoelectric type smoke alarms in homes with less than 1,000 square feet of living space. The smoke alarms were installed on the ceiling between 10 to 15 feet from a cooking and the heating sources. The study found 92% of homes with ionization smoke alarms experienced nuisance alarms compared with only 11% of homes with photoelectric smoke alarms, a ratio of more than 8 to 1. After six months, 19% of the installed ionization smoke alarms had been disconnected compared to only 4% of the installed photoelectric smoke alarms, which had batteries removed. The authors report that even though the ionization smoke alarms had silencing or hush buttons that allowed quieting the unit for 10 minutes, the batteries were still removed from the unit because of frequent nuisance alarming.

The Native American community study shows that the frequency of nuisance alarms for ionization type alarms increases as the distance to the cooking source decreases. The study by Fazzini at an Alaskan Eskimo community shows that ionization smoke alarms have more frequent nuisance alarms than photoelectric smoke alarms placed the same distance, 10 to 15 feet, from the nuisance source. The ionization smoke alarms had a 92% nuisance rate, whereas the photoelectric smoke alarms had only 11% nuisance rate. Smoke alarms placed less than 10 feet will increase the nuisance alarm rate for both the ionization and photoelectric type smoke alarms, but ionization smoke alarms will have a proportionally higher nuisance alarms than photoelectric smoke alarms. To achieve the same nuisance rate for both detection type smoke alarms, the minimum distance from a cooking source for ionization smoke alarm would be greater than a photoelectric smoke alarm. The Native American community study shows that for distances greater than 25 feet, the rate of nuisance alarms for ionization smoke alarms is 36%, but additional data to determine the minimum distance for photoelectric smoke alarms to a cooking

source to achieve the same 36% rate would be needed. The nuisance rate for photoelectric smoke alarms in the Fazzini study was 11% when installed 10 to 15 feet from nuisance source.

Some smoke alarms include a hush or silencing button intended to reduce the likelihood that a user will disable an alarm during a nuisance alarm condition. However, this feature may not be completely effective in reducing the likelihood of occupants disabling their smoke alarms. A lack of understanding or awareness in the hush or silencing feature on the smoke alarms is a contributing factor for occupants disabling, rather silencing their smoke alarms from a nuisance source. (Campbell 2003; DiGuseppi & el al 2002). The study by Fazzini of Alaskan Eskimo villages found that despite the ionization smoke alarms having the hush or silencing feature, the smoke alarms were still disabled because of frequent nuisance alarming.

Even though a smoke alarm is warning the occupants that the battery is low and should be replaced, occupants may perceive the low battery chirping as a nuisance. A lack of understanding or awareness of the meaning of the low battery chirp from the smoke alarms is a contributing factor for occupants disabling, rather than replacing the battery on their smoke alarms. (Campbell 2003; DiGuseppi & el al 2002) Both ionization and photoelectric types of smoke alarm are vulnerable to low battery chirping-related alarm disabling. The inherent higher power consumption for photoelectric type smoke alarms could cause a higher rate of low battery chirping than ionization type smoke alarms and increase the chance for occupants to disable their smoke alarms. Installing smoke alarms that are powered by household 120 VAC or 10 year batteries reduces the frequency of low battery chirping and lessens the likelihood of occupants disabling their smoke alarms because of it.

### **CONCERNS REGARDING NFPA 72 INSTALLATION ASSUMPTIONS**

While the Task Group's primary interest was evaluating performance differences in smoke detection technology, the following observations may be of equal or perhaps more importance in understanding reasons for perceived inadequate smoke alarm performance.

- The National Smoke Detector Project found that 26% of the households surveyed had fewer than one alarm per floor. Additional households may have had too few smoke alarms to protect widely separated sleeping areas on the same floor. Researchers estimated that 43% of the households had fewer than one *working* smoke alarm per floor (Hall 2007)
- A 2000 study of 691 homes in rural Iowa found that 86% had at least one smoke alarm. The study also found that smoke alarms were not installed according to NFPA requirements in 57% of the homes with smoke alarms. In 85% of these cases (48% of the homes with at least one smoke alarm), a smoke alarm had not been installed on every level. Basements were the least likely level to have smoke alarms. Overall, only 22% of the homes were fully protected by smoke alarms according to these requirements (Peek-Asa et al 2005)

The underlying assumptions in the Task Group's work include the assumption that smoke alarms have been installed in accordance with the requirements of NFPA 72-2007. This means that interconnected smoke alarms are installed on every level of the home and in each bedroom. Given the variety of fire scenarios possible in the household environment, too few operating smoke alarms, regardless of the technology, will generally not provide the needed coverage and sufficiently audible warning signal necessary to alert occupants before threatening heat and toxic gases levels develop.

## **SUMMARY & CONCLUSIONS**

The Task Group on Smoke Detection Technology has been requested to review the issues of effectiveness of ionization and photoelectric smoke alarms used in the household or residential environment for life safety and escape. In recent years, there has been renewed interest and controversy regarding the long known differences between ionization and photoelectric smoke alarms relative to smoldering and flaming fire scenarios. An important consideration for the Task Group is whether or not these differences in ionization and photoelectric smoke alarms support suggestions that ionization technology is failing to provide sufficient warning for escape under the assumptions of Chapter 11 of NFPA 72. It is recognized that there are scenarios that fall outside the assumptions of NFPA 72. Such situations include those where human behaviors are exhibited and/or occupant characteristics exist that clearly challenge the timeline for successful occupant evacuation. This review and the findings in this report are relevant to fire scenarios without fixed fire suppression systems and do not address the benefits of households protected by automatic fire suppression systems.

A number of informal demonstration tests have been produced to illustrate the differences in response for ionization and photoelectric smoke alarms in smoldering fire scenarios. It is apparent in some of these demonstrations using smoldering fires that the operation of ionization detectors lags significantly behind the operation of photoelectric detectors. However, these demonstrations have not been performed in a controlled or scientific manner that compares the time of smoke alarm operation to the time when occupants would be incapacitated. Consequently, any conclusions about escape effectiveness from these demonstrations can only be established if the smoke alarm responses are evaluated in context of appropriate evacuation scenarios (NFPA 72 assumptions) and corresponding times of occupant incapacitation due to heat and/or toxic gas exposure.

The Task Group considers that appropriate scientific data is available and presented in the 2003 report of full scale residential experiments conducted by the National Institute of Standards and Technology (NIST). The report titled, *Performance of Home Smoke Alarms: Analysis of the Response of Several Available Technologies in Residential Fire Settings*, provides a detailed description of the tests, detectors, measurement devices, evacuation scenarios and smoke obscuration, heat and toxic gas levels developed during the tests. In reviewing the data provide by the NIST report, the Task Group considered it important to develop a firm understanding of the elements that constitute an ASET-RSET analysis. ASET being the time period between the sounding of the alarm and the onset of untenable conditions for one or more building areas, which is compared against RSET time after alarm required for people to mobilize and egress to a safe location. The Task Group identified and reviewed three major factors that constitute the ASET-RSET analysis.

- 1. Evacuation Scenarios**
- 2. Tenability Criteria**
- 3. Detector Technology Response Characteristics**

**Several key findings of this review are as follows:**

**1. Evacuation Scenarios** - The 1983 work by the University of Massachusetts and the 2003 work by NIST provide evacuation timelines for residential scenarios that considered several pessimistic factors - alarm during sleeping hours, slower moving occupants, premovement activities, & family dynamics. The noted evacuation time periods of 60 seconds to 140 seconds

provide credible evacuation timelines for analysis that are consistent with the assumptions of Chapter 11 of NFPA 72 meaning the occupants are not intimate with the fire ignition, are capable of self-rescue and have an escape plan. This fundamental premise of NFPA 72 is important to any analysis that intends to evaluate the performance of home smoke alarms. However, it should be recognized that there are scenarios that fall outside the assumptions of NFPA 72. Such situations include those where human behaviors are exhibited and/or occupant characteristics exist that clearly challenge the timeline for successful occupant evacuation. Some examples of these behaviors and occupant characteristics are as follows:

- Occupants difficult to awaken
- Alcohol or drug intoxicated individuals
- Behaviors that may be adverse to prompt escape – e.g. fire fighting, reentry
- Physically or cognitively impaired persons without others to assist
- Occupants committing suicide
- Other behaviors that increase harm from fire – e.g. falling to sleep while smoking

**2. Tenability Criteria** - There is significant available literature on tenability criteria and consequently there exists various methodologies, and levels of analysis that could be appropriated for estimating the effects of fire smoke and gases on occupants. However, only one document is known to provide a comprehensive, peer reviewed, consensus methodology that address in total the following:

- Exposure to radiated and convected heat
- Inhalation of asphyxiant/narcotic gases
- Exposure to sensory/upper respiratory irritants
- Visual obscuration due to smoke

ISO TC92 SC3, Fire Threat to People and the Environment, has produced ISO 13571:2007, “Life Threatening Components of Fires — Guidelines on the Estimation of Time Available for Escape Using Fire Data.” This International Standard addresses the potential for smoke to incapacitate people as they move through the vicinity of a fire. Incapacitation is defined as the inability to take effective action to accomplish one's own escape from a fire. The following summarizes the key ISO methods of evaluation that are considered acceptable for use in a tenability analysis with the exception that the ISO criterion for visual obscuration is not considered sufficiently conservative.

For human exposure to narcotic gases, irritant gases and total heat exposure the respective values recommended to be used are 0.3 FED, 0.3 FEC and 0.3 FED. By definition, FED/FEC threshold criteria of 1.0 correspond to the median value of the distribution, with one-half of the population being more susceptible to an insult and one-half being less susceptible. It is recommended that a lower value of the threshold criterion, 0.3 FEC, be used to address the more susceptible occupants of the population. At an FED/FEC or threshold criterion of 0.3, 11.4% of the population would be susceptible to less severe exposures (lower than 0.3) and, therefore, be unable to accomplish their own escape. A still lower threshold criterion would reduce the susceptible portion of the population further. However, there is no threshold criterion so low as to be statistically safe for every exposed occupant.

With Regard the to visibility and smoke obscuration the Task Group on Smoke Detection Technology has carefully considered the criterion set in the ISO 13571 document. The ISO 13571:2007 document equates the time that occupants can no longer affect their own escape to be the time when visibility is reduced so low that occupants cannot see their hands at arm's length or

approximately 0.5 m (1.6 ft.) Such a visibility value reflects a significantly reduced visibility condition and does not provide the conservatism for the analysis that is desired by the Task Group on Smoke Detection Technology. This ISO value is considered not conservative enough as a performance tenability criterion, while other values previously noted are too unrealistic in assuming that occupants will abandon efforts to escape with visibility of 4 meters (13.1 ft.). Therefore, it was considered important to review Jin's original work on visibility in public buildings to develop reasonable criteria that provides 1) for the expectation that occupants can see sufficiently to move and 2) provides sufficient conservatism beyond arm's length visibility as recognized by the ISO standard. Based on uncertainties in the work by Jin et al. due to irritants and illumination levels within a residential structure, a safety factor was taken into account in order to assure that adequate time for egress is available. A factor of safety of 2 was applied (the factor of safety is multiplied by the visibility and then related to optical density). This results in an optical density value of 0.43 (OD/m) (extinction coefficient of 1.0 1/m) as the minimum performance criterion for visibility. This optical density value equates to a visibility of 2 to 5 m (6.6 - 16.4 ft.), respectively, for light reflecting and light emitting sources and is consistent with values for visibility in irritant smoke.

The intent of the tenability criteria being recommended is to evaluate and measure a time when occupants are incapacitated. Incapacitation being defined as the inability to take effective action to accomplish one's own escape from a fire. This will occur when one has breathed too many toxic fire gases or been overcome by heat exposure. Additionally, loss of visibility or obscuration due to smoke can slow occupants' escape sufficiently that toxic gases or heat exposure will result in incapacitation. However, it is important to note that reduced visibility alone is not a fatal or incapacitating condition. True incapacitation does not occur until the heat or toxic gas tenability criterion is exceeded.

**3. Detector Technology Response Characteristics** - The data provided by the revised NIST report shows that either detection technology installed per NFPA 72 requirements provides positive available safe egress times for all but one of the tested fire scenarios. Based on the Task Group on Smoke Detection Technology's review of NIST TN 1455-1, using the escape scenarios considered in the NIST report, the Task Group concludes that stand-alone ionization and photoelectric smoke detection technologies are generally providing acceptable response to smoldering fires, but additional study is needed regarding photoelectric alarm response in flaming fires. The escape scenarios considered in the NIST report assume that occupants are not located in the room of fire origin and that egress paths do not go through the room of fire origin. For these scenarios occupants are assumed to use alternate egress paths. For scenarios where occupants are in the room of fire origin or the egress path is through the room of fire origin, average available safe egress times are reduced for both technologies but with positive available safe egress times provided for all but one of the tested fire scenarios. The Task Group's conclusion considers that NIST TN 1455-1 generally used conservative methods of analysis including 1) conservative tenability criteria based on incapacitation of the most vulnerable occupants, 2) visibility as a tenability limit although true incapacitation does not occur until the heat or toxic gas tenability limits are exceeded, and 3) FED values were calculated for a person fixed in the room rather than using the time integrated values along the path traveled by an individual. Further analysis will be required to fully assess results for escape scenarios where occupants are located in the room of fire origin or egress through the room of fire origin.

The task group acknowledges that there are some additional scenarios where performance may be challenged. Included are situations where scenarios fall outside the current assumptions of NFPA 72. Also, it is noted in the NIST study that the window of escape time in flaming fires has been

reduced from 17 minutes to 3 minutes attributable in large part to faster fire growth rates observed today compared to the 1970's tests (Bukowski et. al. 1975, Harp et. al. 1977)

It has long been known that ionization detection typically responds more quickly to flaming fires and photoelectric detection typically responds more quickly to smoldering fires. The data provided by the NIST study reaffirms this previously established fact. For flaming fires, the additional warning provided by ionization detection over a photoelectric detection is generally on the order of tens of seconds, depending on the fire growth rate. For smoldering fires the additional warning provided by a photoelectric detection over ionization detection is generally on the order of minutes to tens of minutes, depending on the characteristics of the fuel. While this additional warning can seem large in absolute terms, smoldering fires have such a slow growth rate that conditions that result in lack of egress potential for occupants in general do not occur until threatening conditions develop. This generally occurs within minutes after the smoldering event transitions to flaming combustion with a rapid increase in toxic gas and heat levels. However, while both detection technologies generally provide adequate safe egress time for smoldering fires, the data on photoelectric technology is showing potentially inadequate warning time for escape from flaming fires. Additional study is needed regarding photoelectric alarm response in flaming scenarios. Because of the rapid development of flaming fires, ionization detection provides a clear advantage over photoelectric detection providing an additional 30 to 60 seconds average warning time for these fast moving fires which can result in incapacitating conditions within 3 to 4 minutes. It is evident that ionization technology provides a time advantage for flaming fire scenarios, while photoelectric technology provides a time advantage in smoldering situations.

**4. Nuisance Response Characteristics – Nuisance Response Characteristics** – Sources of nuisance alarms vary widely and include cooking vapors, steam, dust, insects, tobacco products, heating equipment and candles. Cooking is the leading cause for frequent nuisance alarms resulting in disabled smoke alarms. Both types of detection technology are vulnerable to nuisance sources, but ionization technology is particularly susceptible to cooking gases generated during frying especially if the smoke alarm is installed less than 25 feet of a cooking appliance as shown in a study of a Native American community. Installing ionization smoke alarms at least 20 feet from a cooking appliance will reduce the chances for frequent nuisance alarms to 68%, installing them at least 25 feet from a cooking appliance reduces the frequency of nuisance alarms to 58% and installing them more the 25 feet from a cooking appliance reduces the frequency of nuisance alarms to less than 36%. For an ionization type smoke alarm with a silence or hush feature that is installed less than 20 feet to a cooking appliance (as is currently permitted by NFPA 72), the silence or hush feature on the ionization smoke alarm does not reduce the frequency of nuisance alarms and still potentially result in disabled smoke alarms by the occupants. Although photoelectric smoke alarms appear to be less susceptible to nuisance alarms than ionization type alarms, more investigation is needed to establish a clear minimum distance from cooking appliances. Installing a smoke alarm at least 10 feet from a bathroom door will reduce the chances for frequent nuisance alarming due to steam for either detector type.

Location, regardless of detection technology, appears to be the single most important consideration in trying to minimize nuisance alarms. In small living spaces, the option to place an ionization type smoke alarm 20 feet or more from the cooking appliance and 10 feet from the bathroom door may not be feasible or possible. In these instances, the use of a photoelectric type detector can significantly reduce the frequency of nuisance alarms from cooking sources and therefore reduce the chances of a disabled smoke alarm. However a clear minimum distance for photoelectric alarms still needs to be established. Other factors that may contribute to smoke alarms being disabled are: lack of understanding of the operation of alarm silencing features

(where provided), and confusion over the operation of the low battery signal versus the alarm signal.

**5. Comments Regarding NFPA 72 Installation Assumptions** - The findings of two studies may be of equal or perhaps more importance in understanding reasons for perceived inadequate smoke alarm performance. The National Smoke Detector Project found that 26% of the households surveyed had fewer than one alarm per floor. A 2000 study of 691 homes in rural Iowa found that smoke alarms were not installed according to NFPA requirements in 57% of the homes with smoke alarms. The underlying assumptions in the Task Group's work include the assumption that smoke alarms have been installed in accordance with the requirements of NFPA 72-2007. This means that interconnected smoke alarms are installed on every level of the home and in each bedroom. Given the variety of fire scenarios possible in the household environment, too few operating smoke alarms, regardless of the technology, will generally not provide the needed coverage and sufficiently audible warning signal necessary to alert occupants before threatening heat and toxic gases levels develop.

## RECOMMENDATIONS

1. Based on the Task Group on Smoke Detection Technology's review of NIST TN 1455-1, using the escape scenarios considered in the NIST report, the Task Group concludes that smoke alarms using either ionization or photoelectric smoke detection technologies, installed per NFPA 72-2007, are generally providing acceptable response to smoldering fires. Additional study is needed regard photoelectric alarm response in flaming scenarios. The Task Group's conclusion considers that NIST TN 1455-1 used conservative methods of analysis including 1) conservative tenability criteria based on incapacitation of the most vulnerable occupants, 2) visibility as a tenability limit although true incapacitation does not occur until the heat or toxic gas tenability limits are exceeded, 3) FED values were calculated for a person fixed in the room rather than using the time integrated values along the path traveled by an individual. Further analysis will also be required to fully assess results for escape scenarios where occupants are located in the room of fire origin or egress through the room of fire origin. Given this information (pending further evaluation of photoelectric response data to flaming scenarios and the alternate escape scenarios) the TC HOU should reaffirm the minimum requirements of Chapter 11, NFPA 72 allowing either ionization or photoelectric smoke alarm technology, provided it is listed in accordance with NFPA 72.
2. The NFPA Technical Committee on Single- and Multiple-Station Alarms and Household Fire Alarm Systems (TC HOU) should review the assumptions of NFPA 72, Chapter 11 to determine if any changes should be made to address one or more of the identified challenging evacuation scenarios. If additional scenarios are to be addressed the TG HOU should reevaluate how ionization and photoelectric smoke alarm technology will serve any new scenarios and develop code/annex language that addresses any additional scenarios.
3. The TC HOU should review and consider the data of NIST TN 1455-1 demonstrating that ionization technology provides a time advantage for flaming fire scenarios, while photoelectric technology provides an advantage in smoldering situations. The recommended outcome would be that Chapter 11 and/or the Annex would formally recognize in future editions of Chapter 11 code provisions and/or explanatory material the benefits of using both ionization and photoelectric smoke alarms in the household. Although the NFPA 72 Code establishes minimum required levels of performance, it is evident that the simultaneous use of both technologies would assure to a higher level, than currently required, that adequate escape time can be provided for occupants in household environments regardless of the fire scenario development (smoldering or flaming). Such consideration is important in view of the fact that the window of escape time in flaming fires has been reduced from 17 minutes to 3 minutes attributable in large part to faster fire growth rates observed today compared to the 1970's tests.
4. In current practice manufacturers can set alarm sensitivities in dual photoelectric/ionization alarms less sensitive than in individual sensor alarms with the intent to reduce nuisance alarms while passing the UL 217 performance requirements. Ideally the response of dual ionization/photoelectric units should not lag significantly behind the collective response of individual units, especially to flaming fires. Further evaluation of the dual ionization/photoelectric smoke alarms should be conducted to establish the set point characteristics that allow for effective alarm response comparable to individual units, while recognizing that set point changes may also be beneficial in the reduction of false alarms.

5. The TC HOU should develop guidance or provisions to further address the nuisance alarm issues attributable to the installation of smoke alarms near a cooking appliance.
  - Restrict the use of ionization type detector smoke alarms or detectors within 25 feet of a cooking appliance, unless listed for this application.
  - Restrict the use of any smoke alarm to a clear minimum distance from cooking appliances. Further investigation will be needed to establish this minimum distance.

The TC HOU should develop ANNEX material to further address the nuisance alarm issues attributable to the installation of smoke alarm near bathrooms.

- Include information in the Annex that the frequency of nuisance alarms from bathroom steam can be reduced if the smoke alarm is located more than 3 feet from the bathroom door. Locating the smoke alarm more than 10 feet from the bathroom door most likely will not provide any additional benefits in reducing nuisance alarms from bathroom steam.
6. Contingent upon the outcome of the TC HOU efforts during the development of the 2010 edition of NFPA 72 it is recommended that NFPA develop and implement new public education campaign strategies that address the following:
    - a. Benefits of using both ionization and photoelectric smoke alarms in the household.
    - b. Avoidance of nuisance alarms by locating alarms at appropriate distances from cooking areas and bathroom doorways
  7. It is recommended that NFPA update public education campaign strategies to emphasize the following:
    - a. The importance of installing interconnected smoke alarms on every level of the home and in each bedroom in accordance with NFPA 72-2007.
    - b. The importance of having escape plans and of properly testing and maintaining their smoke alarms. (Required egress time depends on effective escape planning and implementation. Battery maintenance is essential to reliable smoke alarm performance.)
    - c. The importance of maintaining backup batteries in AC/DC powered smoke alarms.
  8. Further analysis of the NIST TN 1455-1 data should be conducted to identify and better define realistic FED values. The NIST tabulated FED values were calculated for a person fixed in the room rather than using the time integrated values along the path traveled by an individual. The time integrated values would provide more appropriate values for comparison in the ASET/RSET analysis. This additional analysis is important to resolving questions regarding the observation that data on photoelectric technology is showing potentially inadequate warning time for escape.
  9. The smoke alarm/detection industry should support or conduct research pursuing technological advances to help eliminate or reduce nuisance alarms encountered in the household environment.

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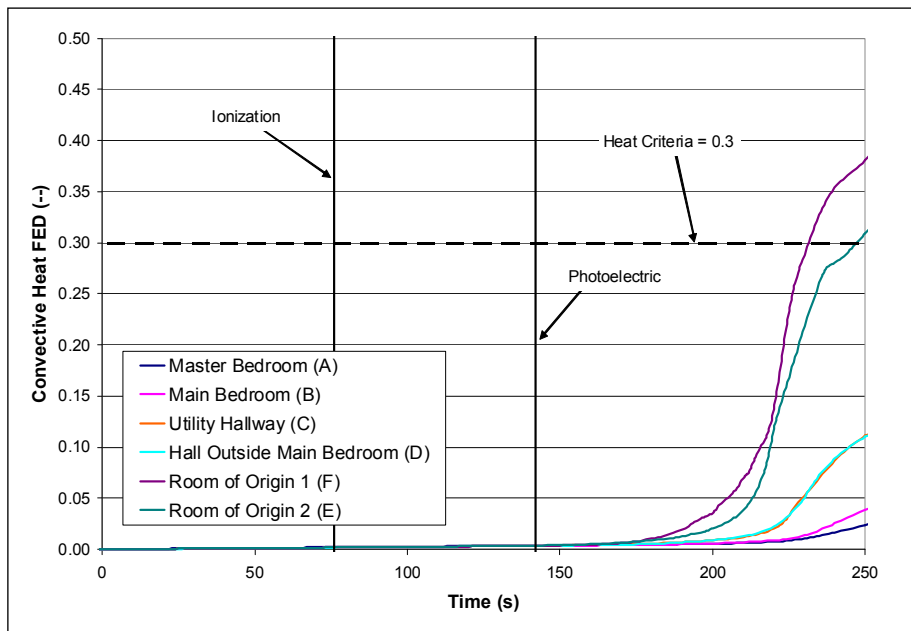
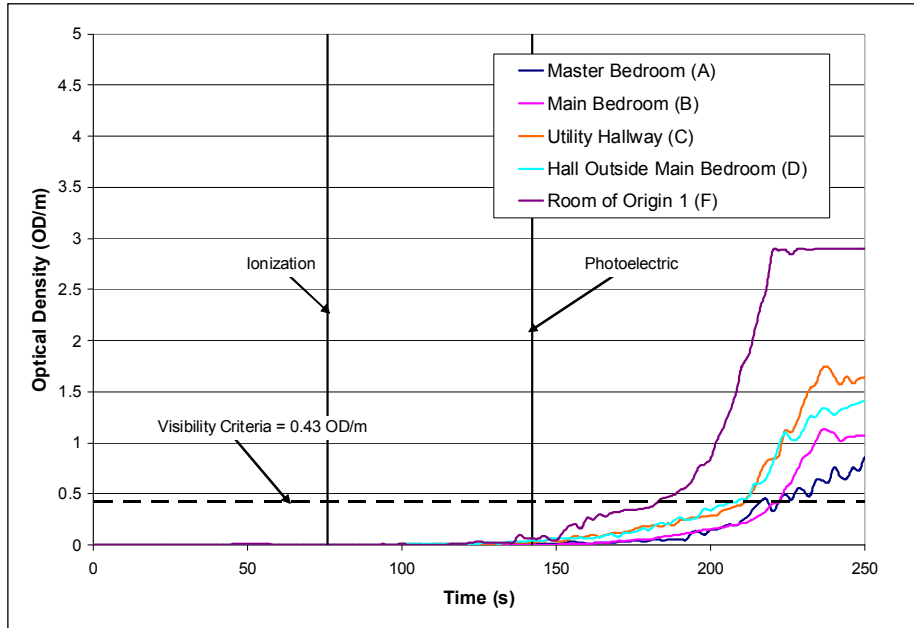
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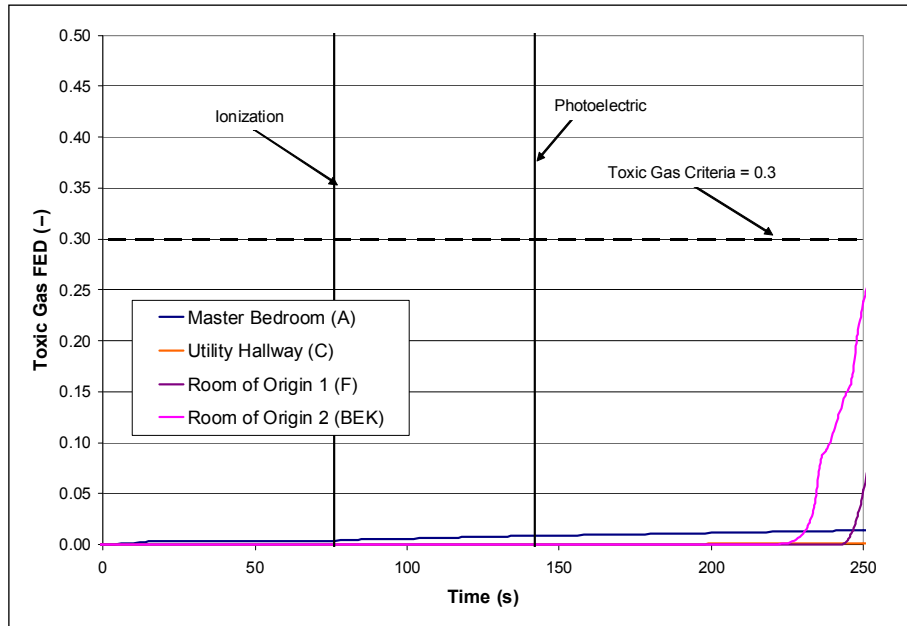
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## APPENDIX A

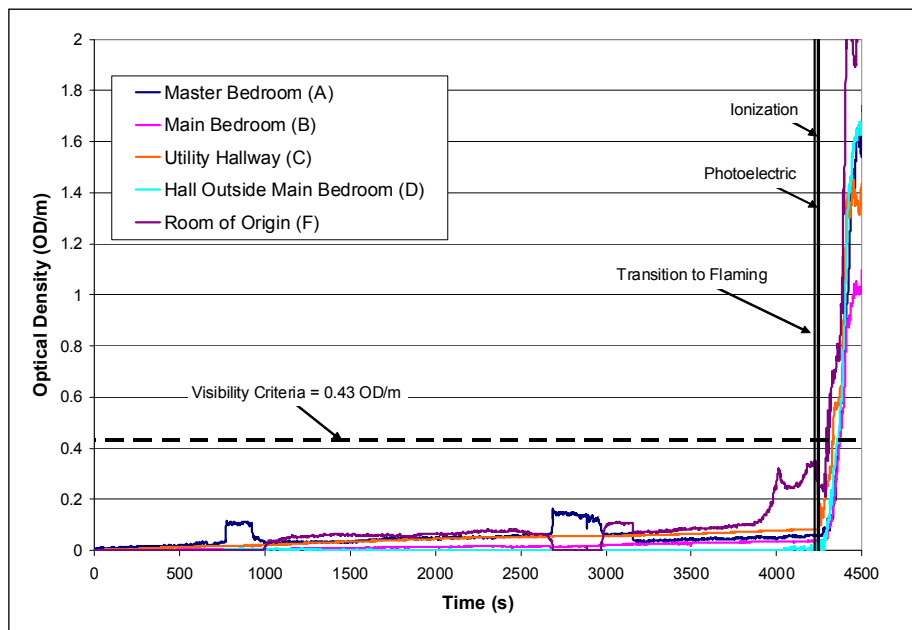
**Large scale graphs - Figure 5.** Development of hazardous conditions in NIST SDC10 flaming chair test originated in the living room.



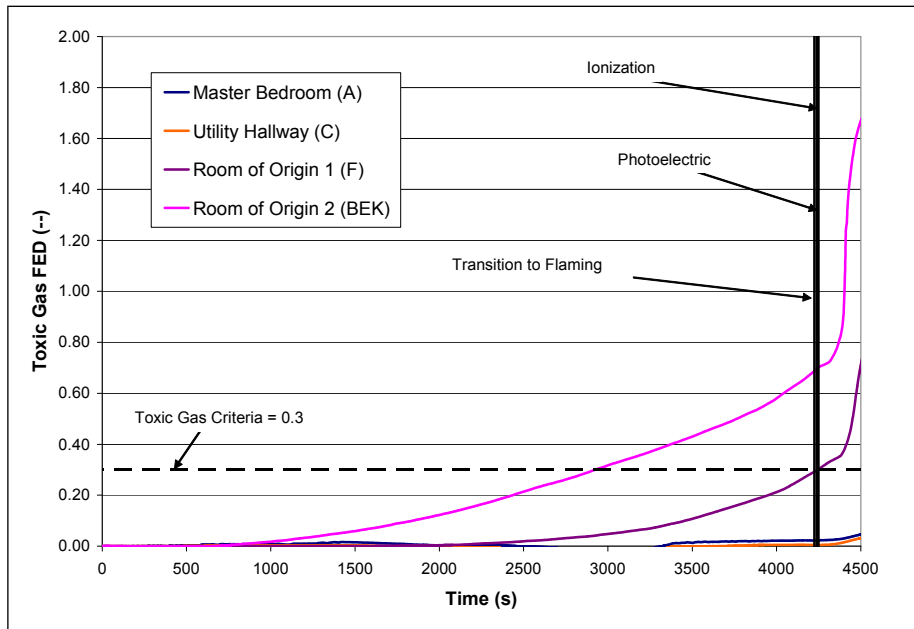
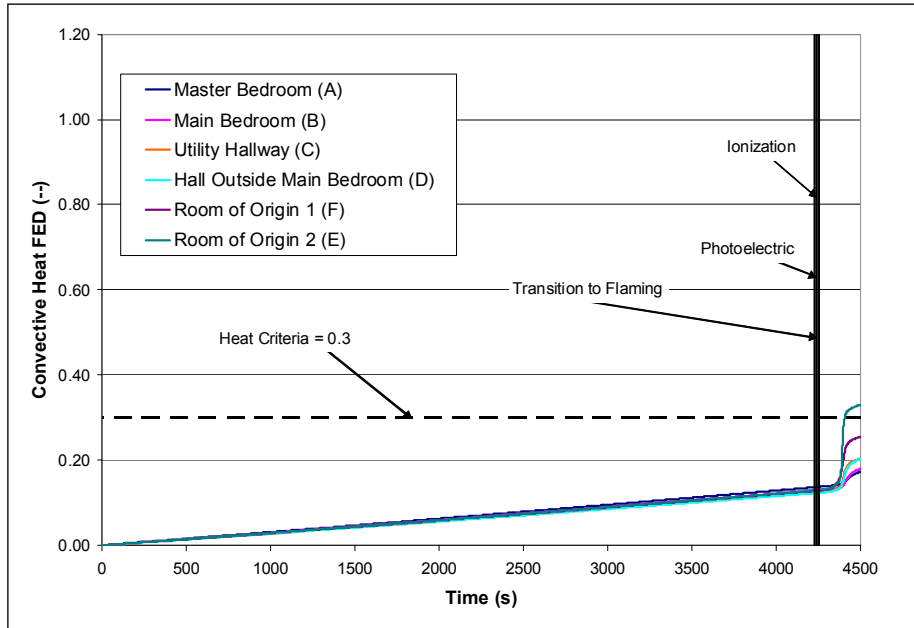
**Large scale graphs - Figure 5.** Development of hazardous conditions in NIST SDC10 flaming chair test originated in the living room.



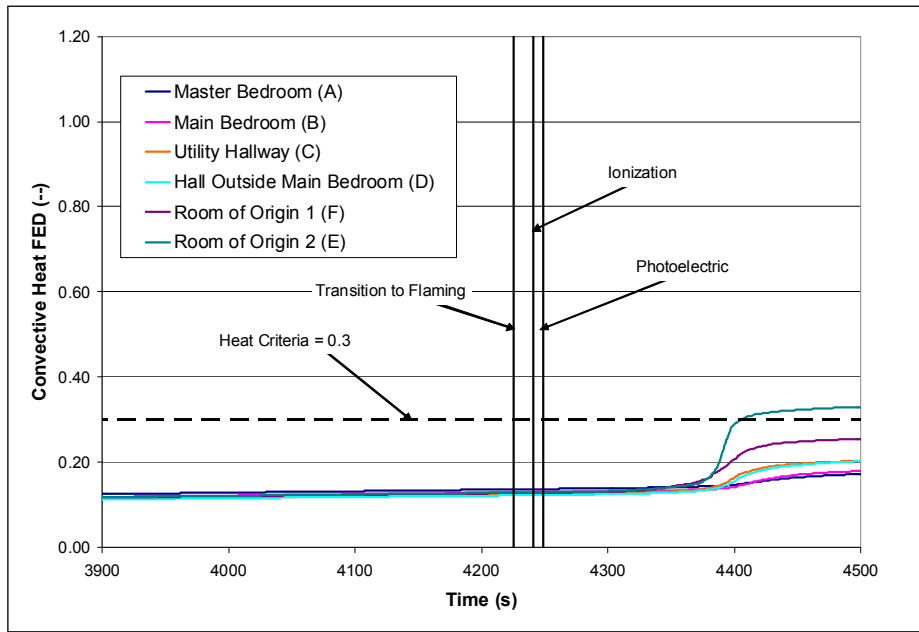
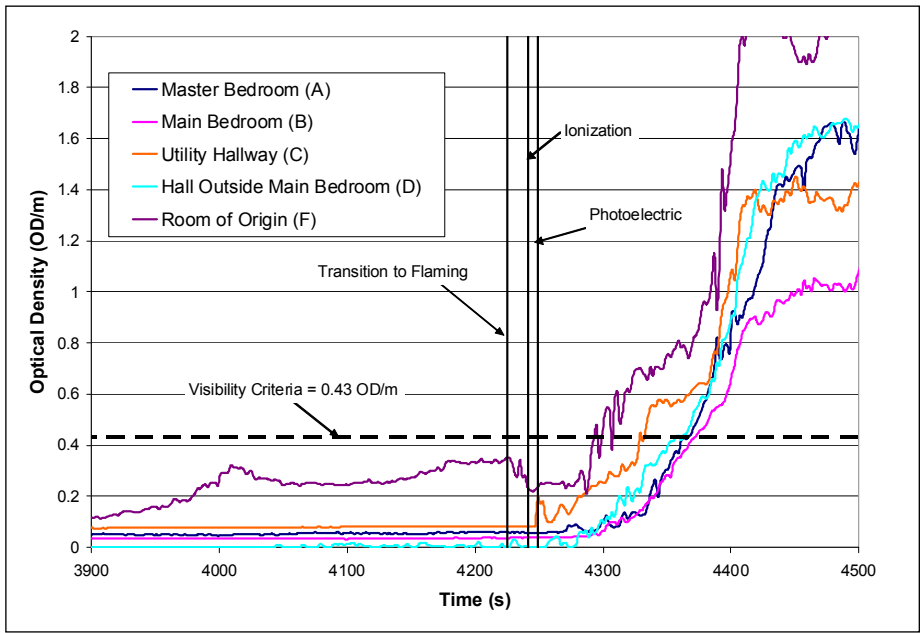
**Large scale graphs - Figure 6.** Development of hazardous conditions in NIST SDC11 smoldering chair test originated in the living room.



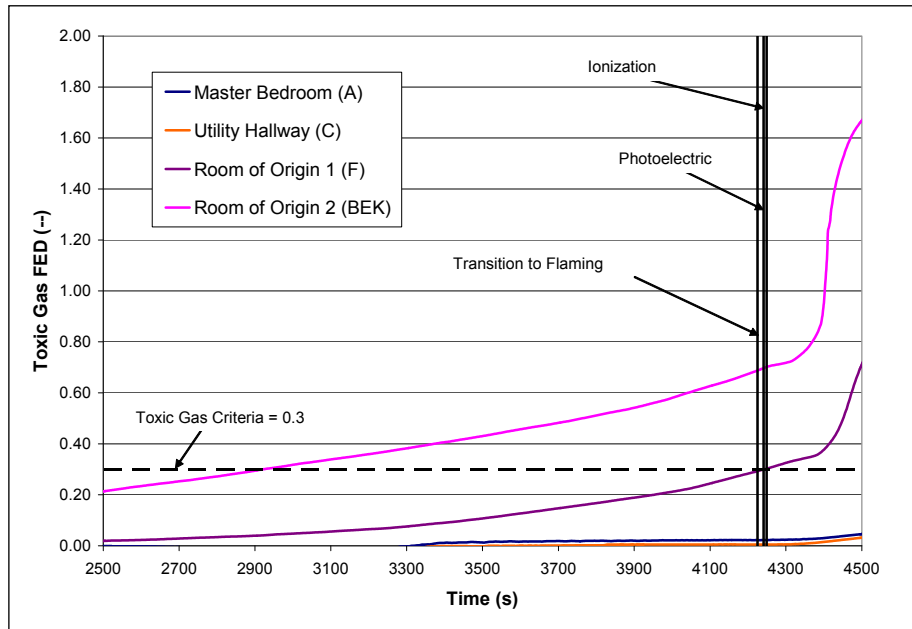
**Large scale graphs - Figure 6.** Development of hazardous conditions in NIST SDC11 smoldering chair test originated in the living room.



**Large scale graphs -Figure 7.** Development of hazardous conditions in NIST SDC11 smoldering chair test originated in the living room at the time to transition to flaming.



**Large scale graphs -Figure 7.** Development of hazardous conditions in NIST SDC11 smoldering chair test originated in the living room at the time to transition to flaming.



## **APPENDIX B**

### **ATTACHMENTS**

The following documents include comments and concerns expressed by Jay Fleming of the Boston Fire Department, B. Don Russell of Texas A&M University, and Bob Bourke of the International Fire Marshals Association.

**Richardson, Lee**


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**From:** Joseph Fleming [jfireeng@gmail.com]  
**Sent:** Thursday, January 10, 2008 2:58 PM  
**To:** Richardson, Lee  
**Cc:** Aron, Oded; Lee, Arthur; daveo@gentex.com; john.l.parssinen@us.ul.com; Larry.Ratzlaff@kiddeus.com; lbrown@nahb.com; Lynn.Nielson@cityofhenderson.com; mikesavagemoo@aol.com; ribourke@verizon.net; Stephen M. Olenick; Sorlowski@nahb.com; thomas.cleary@nist.gov; usse@jps.net; W B Gifford; B. Don Russell; jsutula@csefire.com; Dan\_OConnor@schirmereng.com; Robert Schifiliti; ljd@codeconsultants.com  
**Subject:** Re: FW: Firehouse.Com Suggestion from RFD  
**Attachments:** Response to Marshal's Comment on Combination Alarms..doc; 4-14-05 Miami of Ohio Complaint.doc; Newport News 10-25-06.doc; 4-25-06 Barre complaint.doc; Manhattan Mom 4-25-06.doc; Lincoln NE 11-15-06.doc

Lee,

Here is the reference that I promised.

*"Photoelectric vs. Ionization Detectors - A Review of the Literature, Revisited"*  
 (This presentation included analyses of: 1) 30 years of smoke detector studies, 2) the National Institute of Standards Smoke Detector Project, 3) statistic regarding the effectiveness of smoke detectors, and 4) the effectiveness of Underwriter's Labs Smoke Detector Approval Standard, UL217.)

- NFPRF Fire Suppression and Detection Research Symposium, Orlando, FL, 01/05.
- Annual meeting of Underwriter's Laboratories, Chicago, IL 05/05.
- National Association of State Fire Marshal's, Annual Meeting, Reno, NV, 07/05.
- Fire Marshal's Annual Training Seminar, Barre, VT 06/06.

In addition,

**I would appreciate it if you could remove my name from a list of people who agree with the task group report. I would also appreciate it if my name wasn't presented as a participant when presenting the results to other groups. In my opinion, it gives the impression that I agree with the report, which for the most part I do not. (This was done at the Summit in Massachusetts.) I will provide more specific reasons when I have time but here are some.**

- 1) At several meetings I have objected to the task groups opinion that the intent of NFPA72 is to allow occupants to escape out of windows, yet this gets brought up at every meeting and I am the only one who objects.
- 2) I have asked for NIST to put some videos on the website yet this has never happened.
- 3) I think it is inappropriate to categorize the tenability criteria as "conservative" when it is twice as high as any other researcher has used. In addition the Task Group is using numbers that are based on criteria measured in non-conservative locations.
- 4) The Task group continues to claim fires are growing faster without putting this in proper context.
- 5) See attached document.

2/14/2008

6) In Orlando the NFPA72 Committee asked me to provide actual fires were people died because of the late response of ion smoke alarms. I spend hundreds of hours collecting this information and when it is provided it is ignored.

Every one of these "errors" favors the ion or combination alarm relative to the photo.

I have several proposals before the NFPA Committee and the logic supporting them differs from the Task Group report. **Nothing brought up in the meetings has changed my opinion from my proposals.**

Jay Fleming  
Boston Fire Dept.

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**From:** [rduval@nfpa.org](mailto:rduval@nfpa.org) [mailto:[rduval@nfpa.org](mailto:rduval@nfpa.org)]  
**Sent:** Friday, December 21, 2007 1:36 PM  
**To:** Richardson, Lee  
**Subject:** Firehouse.Com Suggestion from RFD

Hi Lee Richardson,

RFD stopped by Firehouse.Com and thought the following article might be of interest to you:

[The Fire That Changed Everything - And What is Being Done](#)

In Barre City, we are advocating dual sensor smoke alarms, those with both ionization and photoelectric sensors built in.

To view the entire article go to <http://cms.firehouse.com/content/article/article.jsp?sectionId=9&id=57586>

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Firehouse.Com  
The Online Leader for Fire, Rescue and Ems  
<http://www.firehouse.com>

2/14/2008

**Jay Fleming's Comments**  
**on**  
**NFPA Task Group Final Report on Smoke Detection Technology**

1. Page One - It appears to me that many people who participated in this effort are not listed is left of the list: Professor Don Russell, Texas AM, Dave Christian, Gentex, UL Staff etc. Why were some people names left off?
2. Page Two – This report describes the “publicized” tests as unscientific, and subsequently ignores them. But why does the report fails to discuss the many scientific tests that I discuss in my papers (California 1979, England 1979, Norway 1991, England 1997). All of which noted the inadequate response of ionization alarms to smoldering fires.
3. The Task Group uses the 2007 NIST Report as opposed to the original NIST Report. Here are a couple of changes.

**ORIGINAL NIST DATA**  
**TABLE 1 - AVAILABLE SAFE EGRESS TIME (PAGE 242)**  
**(Manufactured Home)**

	Photo	Ion	Dual
<b>Flaming</b>			
Living Room	85	142	138
Bedroom	58	93	-10
Bedroom (Door Closed)	451	898	440
<b>Smoldering</b>			
Living Room	172	-43	513
Bedroom	1091	82	339
<b>Cooking</b>			
Kitchen	575	821	429

**NEW (2007) NIST DATA**  
**TABLE 1 - AVAILABLE SAFE EGRESS TIME (PAGE 242)**  
**(Manufactured Home)**

	Photo	Ion	Dual
<b>Flaming</b>			
Living Room	89	147	142
Bedroom	58	93	39
Bedroom (Door Closed)	876	898	1808
<b>Smoldering</b>			
Living Room	351	137	361
Bedroom	1382	120	362
<b>Cooking</b>			
Kitchen	592	838	899

NIST never explains how the ion “magically” changes from failing to passing. Of course this is not obvious since NIST has removed the earlier versions from the website. The 2007 Report should not be used until NIST explains the specific changes that took place and describes the impact of those

changes on the results of **each test**. (I have requested that this be done since the meeting this summer.)

4. Even with the magical changes that allowed some ion that formerly failed to now pass the 2007 NIST Report still had some average smoldering scenarios where the ion was provided inadequate escape time. Of course, by deciding to re-analyze the NIST Report using a different tenability criterion for visibility this “problem” also disappeared. The report ignores 3 different references from the SFPE Handbook, that recommend or suggest a tenability criteria similar to the one used by NIST in 1975 and in 2004, by describing them as “individual opinions.” Then proceeds to describe their own approach as “conservative” even though it is 50-100% higher, and therefore less conservative than the choice of almost every other research. (Refer to attachment and earlier e-mails. This new criteria solves the problem of late responding ions by providing extra time for the ions to operate.

But in the real world, like the fire that occurred at the University of Miami in Ohio, (information on this fire was provided by me to the Task Group) this doesn't happen. If the ion alarm, in this fire, operated at about 17% obs/ft, like the ion alarms in the NIST Tests, as well as the UL Smoke Characterization Report, the Norwegian tests in 1991 and as reported in Fire Journal in 1979, did, then the amount of smoke that prevented those kids from escaping at the time of smoke alarm operation would have been about 15-20% obs/ft. All of the survivors had to escape out of windows. (Note: this fact did not bother at least 3 members of the Group who believed that to be an acceptable response since windows constitute an escape route.) This level of smoke is far lower than the one used in this report for untenability.

5. On page 14 the Task group tries to justify a RSET (Required Safe Egress Time) of 135 seconds. In the same fashion that the Task Group's selection of tenability guaranteed the ion would pass the smoldering test, the selection of this RSET guarantees the photo will fail the “ultra fast” flaming tests. First of all the assumption that occupants are sleeping during flaming fires is generally not true (refer to my e-mails) so the application of “sleeping” RET is inappropriate for most flaming scenarios. Secondly, on page 4 of this report it points out studies which showed that for geriatric occupants that 40% evacuated in less than 60 seconds and 95% evacuated in less than 90 seconds. So why would 135 seconds be used?

Note: Changing the “tenability criteria” buys the ion a few extra minutes (-43 seconds ASET to 137 seconds ASET) in the smoldering tests but buys the photo only a few seconds in the “ultra fast” flaming tests (85 seconds ASET to 89 seconds ASET). This favors the ion relative to the photo. As a consequence, using an “extra long” RSET that assumes occupants are sleeping doesn't change the new outcome for the ions but guarantees the photo will fail the flaming tests since they are providing less than 120 seconds ASET in the original NIST results.

6. In figure 7 on page 18 (Test SDC11) the ion is responding before the photo in a smoldering living room fire. This fact is highlighted in the Report. What the Report fails to mention is that in this test the “unmodified detectors in the same

room, i.e. the living room responded very differently. Here is a passage from a letter I sent to NIST, which has never been adequately addressed.

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***In any case, where in the report does NIST present this comparison in a manner that justifies their analysis of “modified” detector response?***

*NIST calibrated the “modified detectors” using smoke similar to smoke used in the UL and European Approval tests, i.e. flaming hydrocarbon and smoldering cotton. But neither of the tests simulates smoldering plastic. As a consequence it is possible that NIST could mischaracterize detector response. In particular they might overestimate an ion’s response and underestimate a photo’s response. NIST could have validated their approach by putting real detectors in the same room as modified detectors so that a comparison could be made but IN MOST CASES THEY DID NOT. This oversight is hard to explain. I would like to illustrate my concern by looking at SDC011 – Smoldering Chair in Living Room of Manufactured Home.*

NIST considers all of these detectors to be in the “room of origin.”

DETECTOR TYPE	LOCATION	IONIZATION	PHOTO-ELECTRIC	ADVANTAGE OF PHOTO (Ave Ion – Ave Photo)
Un-Modified (Real)	Living Room	3961-3971	882	3,100 Sacs
Modified	Hall Outside Bedroom	4241-4245	2463-4241	850 Sacs
Modified	Utility Hall	4256-4415	3503-4251	450 Sacs
Data from Table 23		4829	4615	200 Sacs

*Why is NIST so confident that the manner in which they model the response of their “modified detectors is valid? Unfortunately, I could not find any scenarios where unmodified and modified were in the same area to allow for comparison.*

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**I do not think that this task group should use the data from “modified alarms until NIST can explain this discrepancy.**

7. On page 24 The Report states that it assumes that the ion & photo elements of a dual alarm are calibrated to the same sensitivity as individual ion or photo, even though the Report acknowledges that this isn’t necessarily true. This means that the report will make the dual alarm appear better than they really are.
8. On page 4, the Report claims that victims intimate with ignition cannot be saved by smoke alarms. However **isn’t this only true for flaming scenarios?** If the victim sleeping on the chair in scenario 11 (SDC11) was alerted 2,000 – 3,000 seconds before the transition to flaming, as they would be with a real photo detector, wouldn’t they be saved?

9. In John Hall's Report for the CPSC (available at the Task group web site), which was incorporated into the NIST Report, the following data is reported. For the Period of 1992-1996:
- 973 died in smoldering fires,
  - 2292 died in flaming fires (including 142 from cooking fires)
  - 423 died in fast flaming fires

What is left unstated by NIST, and left as a footnote in the CPSC Report, is that Dr. Hall assumed that only smoking materials could cause smoldering fires, that only flammable liquids could cause fast flaming fires and all others were flaming. These assumptions are, in my opinion, highly dubious. Perhaps that is why, after I supplied my data to the Group and Dr. Hall that he stated in a report for the Committee, "*Many, perhaps most, fatal fires involve an initial smoldering period followed by an open-flaming period*".

I agree with Dr. Halls more recent comment. I would also like to know why for the purposes of highlighting the "flaming" problem that NIST and this Task group consider cooking fires to be part of the flaming problem. But when looking at the response of smoke alarms to "flaming" fires, cooking is excluded. Is it possible that this was done because the photos are providing several minutes warning in cooking fires, essentially equivalent to the ion, and that this would undercut a finding of this report that photos were inadequate for flaming fires?

Finally,

I only received this report on 2/19 in the afternoon. I am sure that in time I will find more flaws with this report. The ones I have identified are enough for me to vote against the issuance of this report with my approval.

Jay Fleming



Deputy Chief  
Boston Fire Dept.  
02/21/2007

**From:** B. Don Russell [mailto:bdrussell@tamu.edu]  
**Sent:** Wednesday, February 20, 2008 6:22 PM  
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**Cc:** Robert Schifiliti; ljd@codeconsultants.com  
**Subject:** Comments on Draft Report

As requested, I have the following comments on the draft report. Let me say that it is my assumption that the entire task group has a desire to improve the safety of the public by improving fire detection within technical and practical bounds. It is with this assumption that the following suggestions are made.

While interconnection of smoke detectors is an appropriate goal and reasonable objective for the future, this will not be the majority practice for a long time. Interconnection of smoke alarms in residences should never be assumed in any way in the evaluation of performance data of individual smoke detectors. Given the state of application of residential smoke detectors in the United States, we should make every attempt to optimize the performance of each individual stand-alone detector as to both detection sensitivity and reliability. I am not sure these are the assumptions we have used in the draft report.

We most certainly should not use only the NIST experiments to define the performance of ionization and photoelectric smoke detectors. Those of us who have tested a significant number of smoke detectors in full-scale experiments realize that we often get substantially worse performance of ionization smoke detectors than is demonstrated by the NIST experiments. I am on record from before the NIST experiments were conducted that I disagree with the protocol used by NIST and the methodology of some of the experiments. Specifically, the number of side by side smoke detectors tested by NIST was too small and the number of overall smoke detectors was too small to draw the conclusions we seem to be drawing from their data. While the NIST data is certainly instructive, it by no means shows the performance limitations of residential smoke detectors that have been documented in other tests. The performance problems identified by other researchers have not been adequately taken into account in our draft report.

I am concerned about apparent contradictions in our draft report with respect to recommendations. If we believe that the best possible protection can be obtained by co-locating independent ionization and photoelectric detectors in a residence in multiple locations, then I do not understand any recommendation that we apply combination smoke detectors with the sensing chambers desensitized. This seems inherently contradictory. If the fastest possible detection of the next fire that will occur can be achieved by having smoke products seen by both ionization and photoelectric detectors set at a sensitivity that one would find them in stand alone implementation, than this is the same sensitivity we should use in a combination detector. There are other ways to

address the nuisance alarm issue and there are other technologies that can be incorporated if we really want to address the best possible fire detection in a residence. We should not solve the problem by desensitizing combination detectors with respect to single detection method detectors.

We have completely ignored the substantial problem of sample-to-sample variation of performance of smoke detectors of the same type, particularly noted in ionization detectors. Those researchers that have tested large numbers of smoke detectors in side-by-side tests can affirm that any given unit will sound very late in a fire as compared to other samples. They will also affirm that some samples of smoke detectors will not sound at all to a given fire, while other samples of the same detector will sound at a reasonable time in the fire. This problem may actual be a greater problem for the industry than the issue of the sensitivity setting of a specific detector.

As I read the report, I disagree with the presumed criteria we are using for acceptable performance of detectors. When I read the analysis of the NIST data it appears to state that it is acceptable to stay in a residence that is on fire for a longer time than necessary because we are establishing the criteria of success as adequate time to escape before conditions become untenable. I disagree with this philosophy when establishing performance objectives for fire detection.

Our criteria should be that we provide the fastest possible warning of the presence of a fire in a residence within the constraints of the technologies available to us for application. All residents should be warned of a fire as fast as possible. The combination of types of detectors, location of detectors, sensitivity of detectors, etc. should be optimized for the sole purpose of the fastest possible warning. Our draft report understates the impact of visibility and smoke obscuration on tenability and understates the combined impact of smoke and toxic gases on the behavior of residents.

Those researchers who have conducted a significant number of full-scale tests have demonstrated the following scenario. I have stated the scenario in laymen terms.

A low energy ignition source (e.g. cigarette) is located on a fabric covered polyurethane furniture cushion creating a very slow developing fire. The fire develops over a period of one to two hours producing copious levels of smoke with toxic gases. Technically, the spaces are "tenable" for much of the development period. However, substantial smoke is present with obscuration levels exceeding 25% with no smoke alarm sounding.

Once this smoldering fire has developed a substantial cavity in the polyurethane cushion, a small change in the environment, particularly air flow, will result in an immediate and substantial flame condition that will consume the entire furniture structure in a matter of minutes. At this point the temperature rise is most significant and the smoke levels have increased markedly. The result is that conditions go from "tenable" to totally untenable, by any measure, in a matter of tens of seconds with the entire house environment preconditioned to the edge of untenable based on the levels of smoke and toxic gases that have been generated by the smoldering fire.

When the above scenario occurs, any delay in the smoke detectors in sounding the presence of the smoldering fire condition represents a very dangerous delay. The sounding of the detectors, once the flame has begun, is too late, since the entire environment already has substantial smoke, loss of visibility, and relatively high levels of toxic gases. In other words, we need a much more advanced notice of the presence of this smoldering fire before it becomes technically "untenable" by the measures used in our draft report.

Given all of the above and much more, I cannot support the conclusions of the draft report as they are currently stated. In my opinion, all of the relevant data on the performance of ionization and photoelectric smoke detectors has not been properly considered and does not support the conclusions drawn by this draft report.

This draft report should be tabled until further discussion and investigation can be made. The draft report does not fully address the findings of various researchers that contradict the NIST performance data. The draft report relies far too heavily on just the NIST data and does not take into account the substantial problem of sample-to-sample variation in performance of smoke detectors from a given manufacturer when exposed to the same fire. All of these issues need additional time and discussion before the report is submitted or used.

If possible, I would like to discuss this matter with the task group chair. If the task group decides to move forward with the draft report, I respectfully request the opportunity to include an objection to the conclusions of the report and to file a minority position.

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To: Task Group  
From: Bob Bourke  
Re: Draft Report

Dear Task Group Members,

I wish to enter my strong objection to the issuance of the task group report as published as of February 19, 2008.

While I am not an engineer (FPE or otherwise) with 31 years in the fire service and over 25 years devoted to fire prevention I feel that the task group draft report has little to do with the resolution of the issue at hand.

While the reason, as I understood it, that the task group was formed was to address the perception (in the fire service community) and claims by some individuals, that ionization technology smoke detectors were somehow deficient in performing adequately in smoldering fire scenarios.

This report, in my opinion, concludes that photo electric technology detectors need to be evaluated for their inadequacy in detecting flaming fires and that ionization technology detectors perform acceptably. As I understood the original question to be the exact opposite of that conclusion, I don't understand how we got here.

As a layman I cannot speak to the volumes of formulas and calculations that have been included in this report to support the conclusions however I can offer the following.

1. Perhaps the assumptions in NFPA 72 should be revised by deleting the word "threatening" from the performance objective. What type of home fire that is not intentionally ignited is not ultimately threatening? Does NFPA 72 want to take a position that an ignited fire that does not develop into a life threatening fire should go unnoticed until the charred debris is discovered the next day?
2. The assumption that the occupants of the home have an escape plan is not at all realistic. In reality the only occupancies that have a true escape plan and in fact practice it are primarily health care and educational use groups. How many TG members can truthfully say that they have an escape plan for their home? And don't forget when your child has a sleepover you should go over the plan and practice it with your house guest.
3. The evacuation scenarios that are referenced in the report are also of concern to me. The U Mass study had normal group members take up to 120 seconds in clear air. (Notice I maximized that number rather than minimize it as the draft report does). Why does this report only recommend an additional 15 seconds to escape under nearly untenable conditions?
4. The report strongly relies on the NIST TN 1455-1 for many of its conclusions but then summarily dismisses the obscuration factor without adequate "scientific" support. Even though the report supports a more conservative obscuration level, I feel this is a disingenuous attempt to appease those who believe an even more conservative obscuration level should be used. The report time and again mentions that "reduced visibility alone does not cause fatalities". While this statement is true, there are no studies that I know of that can measure the effect of reduced visibility and the resultant

- panic that sets in, but as a human being I am fairly certain that this is a factor that is very real and has not been considered. Some studies indicate that as many as 5% of the population suffer from claustrophobia, a psychological disorder that places a person in a total state of panic when they feel confined and cannot readily exit a room or space. The obscuration levels in the report could render these people helpless in a smoldering fire situation until it was too late for escape. That equates to a possible 129 persons that died in fires in the US in 2006.
5. While there are three and one half pages of comments on nuisance alarms the report passes the problem back to the TC HOU. I thought that that was one of the major issues that this Task Group was formed to resolve. From the thousands of pages of reports and the 250 plus emails I have read over the past 11 months I am convinced that the nuisance alarm problems and the disabling of smoke detectors can be best addressed by eliminating Ionization type smoke detectors from residential occupancies. I know that it is not a 100% solution but look at the numbers in this report. The text of the report supports this position but the recommendations ignore it.

Please log me as a NO on issuing this report as written.

Bob Bourke

# End of TG Report