# *Results and Analysis of the NIST Smoke Alarm Sensitivity Study*

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**Presentation to the California Office of the State Fire Marshal**
**Smoke Alarm Task Force**
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# Background

## Smoke Alarm Performance

- Information from US fire statistics
  - NFRIS; NFPA analysis
- Usage, functionality, installation studies
  - CPSC analysis, telephone surveys, random controlled trials, etc.
- Small-sample sensitivity tests
  - UL 217/268 room alarm/detector sensitivity tests
  - NRC Canada Kemano, BC tests
- Full-scale fire tests - comprehensive experiments
  - “Indiana Dunes” Project (1975, 1977)
  - NIST Home Smoke Alarm Project (2000-2002)
  - NIST Smoke Alarm Sensitivity Study (2008)

# Full-scale smoke alarm experiments

- **Fire scenarios should be representative of leading causes of fatalities and injuries**
- **Fires should progress to produce hazardous conditions, and hazardous conditions should be measured**
- **Analysis should be performed in terms of current standards or proposed changes**

# Outline

- Describe the Smoke Alarm Sensitivity Study
- Present smoke alarm response results
- Review standard ASET/RSET concepts
- Present ASET/RSET analysis using NIST Smoke Alarm Sensitivity Study data
- Detail new alternative analysis methodology
- Present new alternative analysis

# Results and Analyses Abstracted from the Following Papers

- Cleary, T.G., (2010) Results from a Full-Scale Smoke Alarm Sensitivity Study, Fire Technology, http://dx.doi.org/10.1007/s10694-010-0152-2
- Cleary, T.G., “Full-scale Residential Smoke Alarm Performance,” 14th International Conference on Automatic Fire Detection, University of Duisburg-Essen, Duisburg, Germany, 2009
- Cleary T.G., (2011) An Analysis of the Performance of Smoke Alarms, Accepted, 10th International Symposium on Fire Safety Science, University of Maryland, June 19-24, 2011

# Objective of Smoke Alarm Sensitivity Study

**To examine the effects of the following on smoke alarm performance:**

- Alarm type
  - Photoelectric
  - Ionization
  - Dual sensor
- Alarm location
- Fabric type
- Polyurethane foam density
- Ignition scenario
- Room configuration

# Experimental Design

A two-level, fractional factorial design of eight experimental configurations was developed around five factors:

Ignition scenario
Foam density
Fabric type
Fire location
Ventilation

| Test | Scenario | Foam sample | Fabric type | Fire location | Ventilation (Door) |
|---|---|---|---|---|---|
| 1 | Smoldering | Low density | Cotton | Bedroom | Open |
| 2 | Smoldering | Low density | Cotton | Bedroom | Closed |
| 3 | Smoldering | Low density | Cotton | Living room | Open |
| 4 | Smoldering | High density | Cotton | Living room | Open |
| 5 | Flaming | Low density | Polyester | Living room | Open |
| 6 | Flaming | Low density | Polyester | Bedroom | Closed |
| 7 | Flaming | Low density | Cotton | Living room | Open |
| 8 | Flaming | High density | Polyester | Bedroom | Open |

# Fire Source

The fire source configuration was seat and back cushions resting on a metal frame placed inside a pan. The pan rested on a load cell for mass loss measurement. Cushions were non-fire retarded flexible polyurethane foam slabs of either a low density - 21kg/$m^3$ {1.3 lbs/$ft^3$} or high density - 29 kg/$m^3$ {1.8 lbs/$ft^3$}, cut to fit the cushion covers. A fabric dust ruffle wrapped over the lower seat frame. The covered cushions and dust ruffle weighed approximately 5.5 kg to 8.3 kg, depending on the foam and fabric combination.

# Flaming Ignition Source

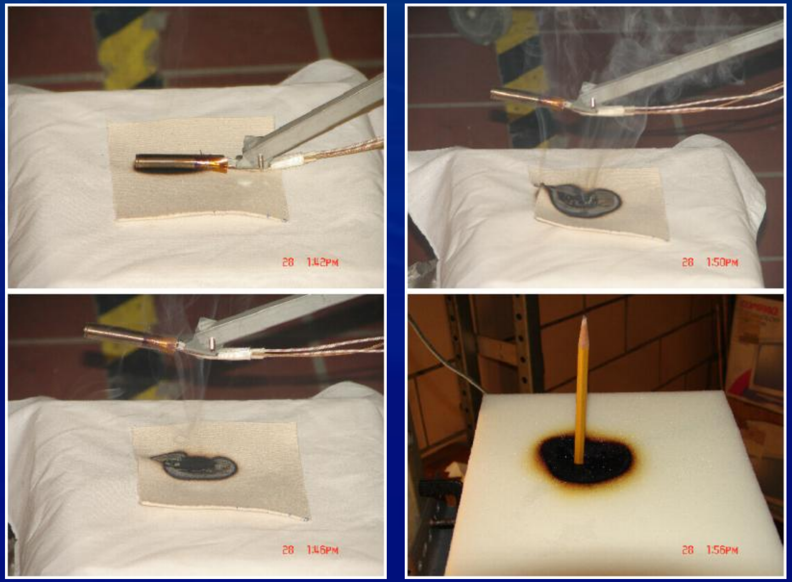
The flaming ignition source was a gas-flame ignition tube similar to British Standard 5852 with a propane fuel flow of 45 ml/min. At least two minutes of pre-burn before flame was positioned on edge of side seat cushion. After 40 seconds flame was removed.

# Smoldering Ignition Source

The smoldering ignition source was a 50 W electric cartridge heater, 50 mm long and 10 mm in diameter. The cartridge heater was placed on a 15 cm by 15 cm square of cotton duct fabric resting on the seat cushion to ensure a sustained smoldering fire.  Electrical power to the cartridge heater was applied in a controlled fashion to achieve an external temperature sufficient to produce sustained smoldering.  After about 6 minutes of total contact time, the cartridge heater was removed.

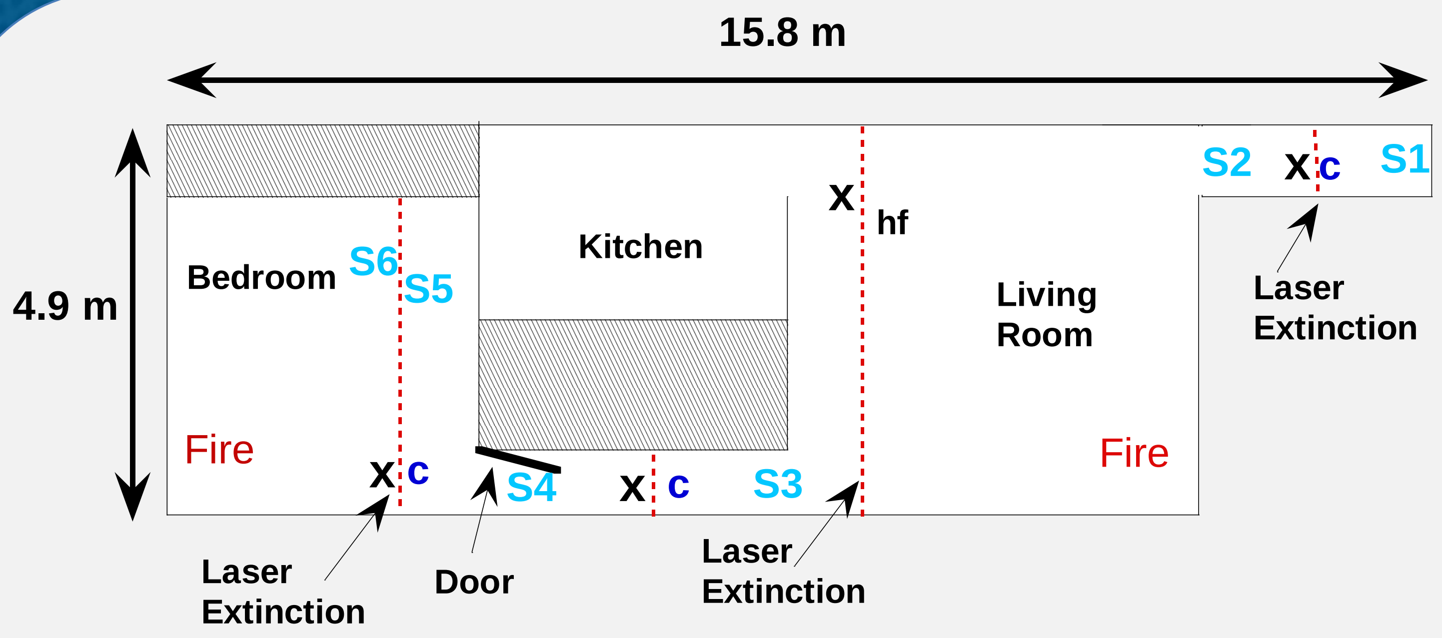
Smoldering to flaming transition times ranged from 81 to 182 minutes


Small-scale ignition tests



# Test Structure

The fire tests were conducted in a building mock-up designed to represent a portion of an apartment or small home




X - thermocouple tree location
hf - total heat flux gage (1.5 m above the floor and pointing toward the fire source)
S1…S6 - alarm set location
c - gas sampling location (1.5 m above the floor)
dashed line - beam path for extinction measurements (1.5 m above the floor)

# Smoke Alarms

Two sets of smoke alarms were mounted four across on panel boards in random order

- Set 1 Alarms
  - Photoelectric P1
  - Ionization I1
  - Dual sensor D1
  - Dual sensor D2
- Set 2 Alarms
  - Photoelectric P1
  - Ionization I1
  - Photoelectric P2
  - Ionization I2

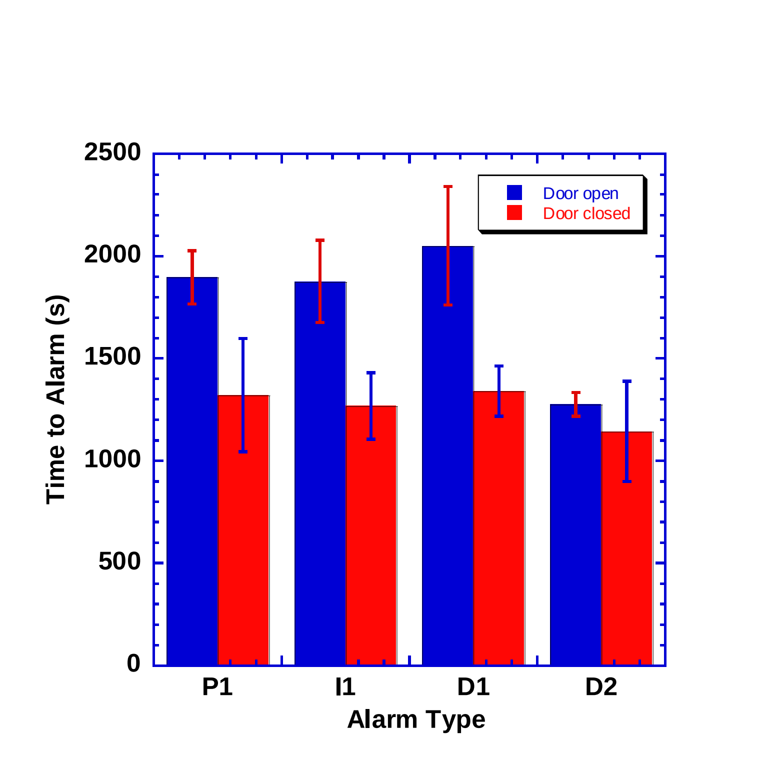
# Alarm Times – Smoldering Fires

## Locations 3 or 6 – per NFPA 72

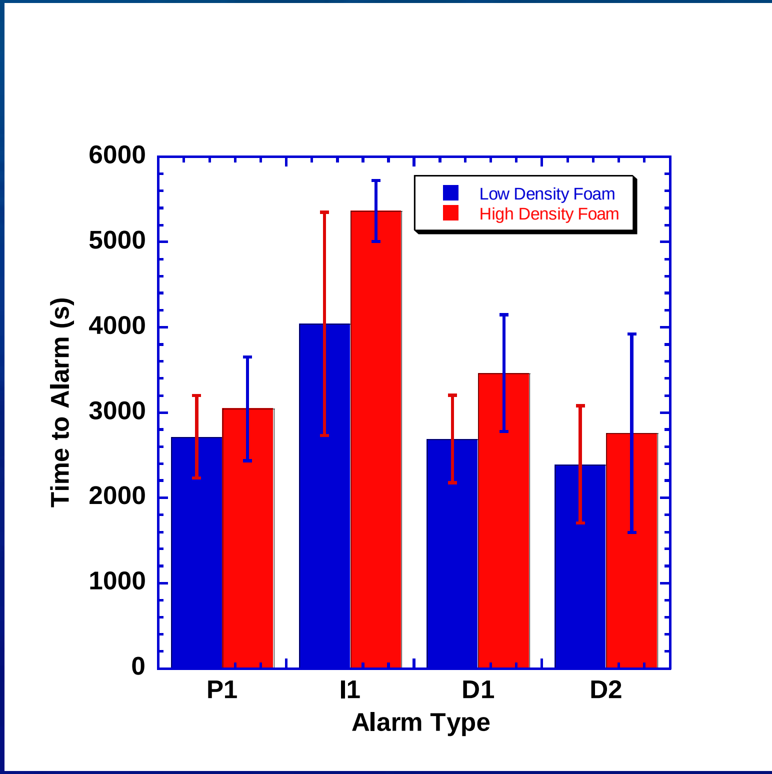
| Experimental Configuration | Time to Flaming (s, ± 1s) | Alarm Time (s, ± 1 s) | | | |
|---|---|---|---|---|---|
| | | P1 | I1 | D1 | D2 |
| (1) Smoldering Bedroom, Door Open Cotton, LD Foam | 4838 | 1775 | 1773 | 1775 | 1316 |
| | NA | 2033 | 1747 | 2025 | 1209 |
| | 10944 | 1884 | 2108 | 2354 | 1301 |
| (2) Smoldering Bedroom, Door Closed Cotton, LD Foam | 6000 | 1352 | 1222 | 1449 | 1256 |
| | 6845 | 1585 | 1448 | 1367 | 1311 |
| | 10392 | 1030 | 1134 | 1208 | 863 |
| (3) Smoldering Living room, Door Open Cotton, LD Foam | 6295 | 3266 | 5166 | 3284 | 3185 |
| | 9997 | 2356 | 2606 | 2404 | 1980 |
| | 5836 | 2524 | 4354 | 2386 | 2015 |
| (4) Smoldering Living room, Door Open Cotton, HD Foam | 5252 | 3143 | 5275 | 2939 | 4068 |
| | 4736 | 3596 | 5764 | 4237 | 1847 |
| | 5187 | 2397 | 5061 | 3210 | 2360 |

# Alarm Times – Smoldering Fires
## Locations 3 or 6

Experimental Configurations 1 & 2
Smoldering in Bedroom




Experimental Configurations 3 & 4
Smoldering in Living Room



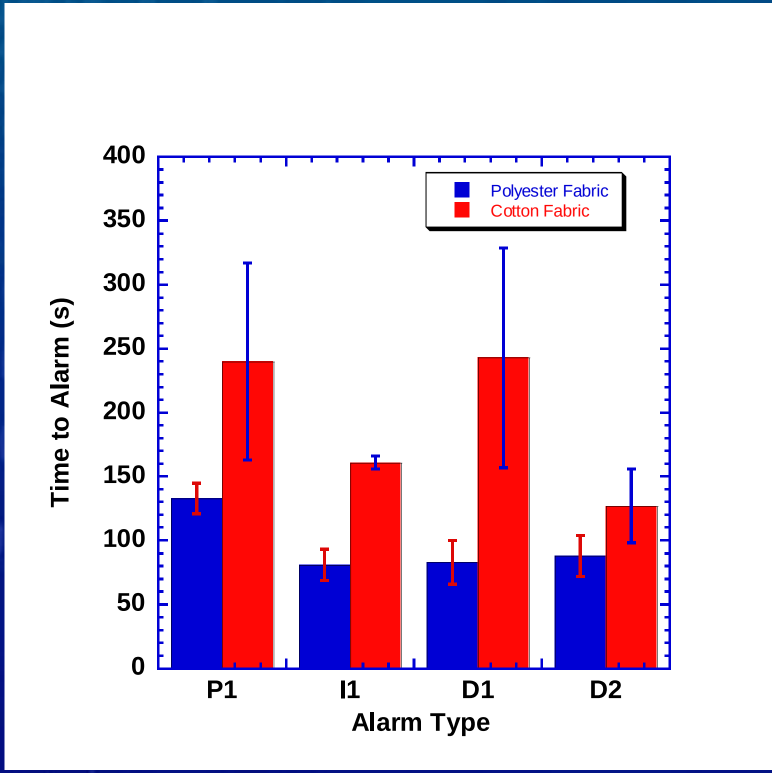
# Alarm Times – Flaming Fires

## Locations 3 or 6

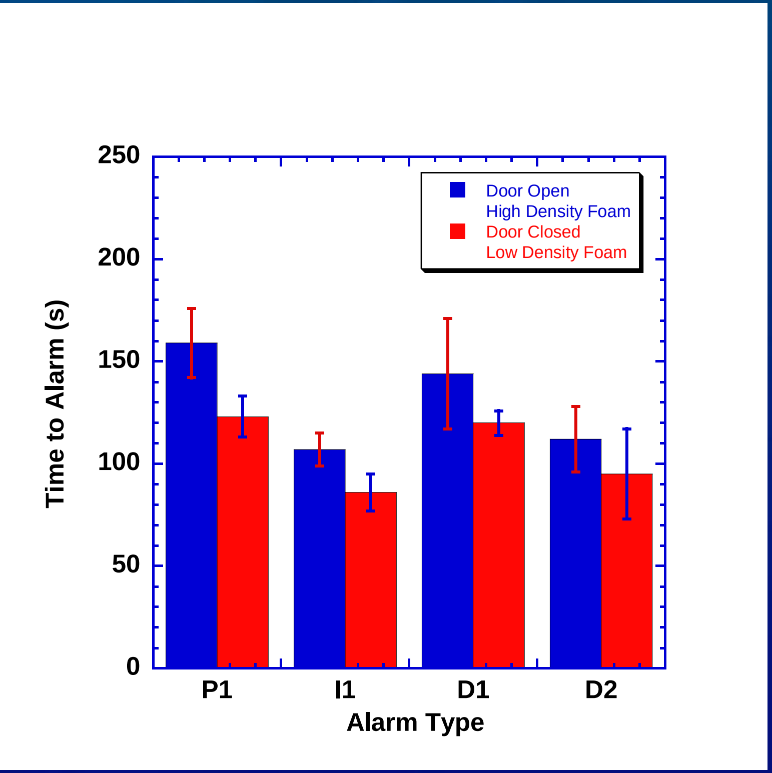
| Experimental Configuration | Time to Flaming (s, ± 1s) | Alarm Time (s, ± 1 s) | | | |
|---|---|---|---|---|---|
| | | P1 | I1 | D1 | D2 |
| (5) Flaming<br>Living room, Door Open<br>Polyester, LD Foam | 0 | 141 | 67 | 90 | 78 |
| | 0 | 120 | 89 | 96 | 106 |
| | 0 | 139 | 87 | 64 | 80 |
| (6) Flaming<br>Bedroom, Door Closed<br>Polyester, LD Foam | 0 | 125 | 94 | 117 | 86 |
| | 0 | 132 | 84 | 127 | 78 |
| | 0 | 108 | 81 | 117 | 120 |
| (7) Flaming<br>Living room, Door Open<br>Cotton, LD Foam | 0 | 1214 | 465 | 411 | 508 |
| | 0 | 295 | 157 | 182 | 147 |
| | 0 | 185 | 164 | 303 | 106 |
| (8) Flaming<br>Bedroom, Door Open<br>Polyester, HD Foam | 0 | 158 | 105 | - | - |
| | 0 | 142 | 100 | 125 | 123 |
| | 0 | 176 | 116 | 163 | 101 |

# Alarm Times – Flaming Fires
## Locations 3 or 6

Experimental Configurations 5 & 7
Flaming Fire in Living Room




Experimental Configurations 6 & 8
Flaming Fire in Bedroom



# Available Safe Egress Time - ASET

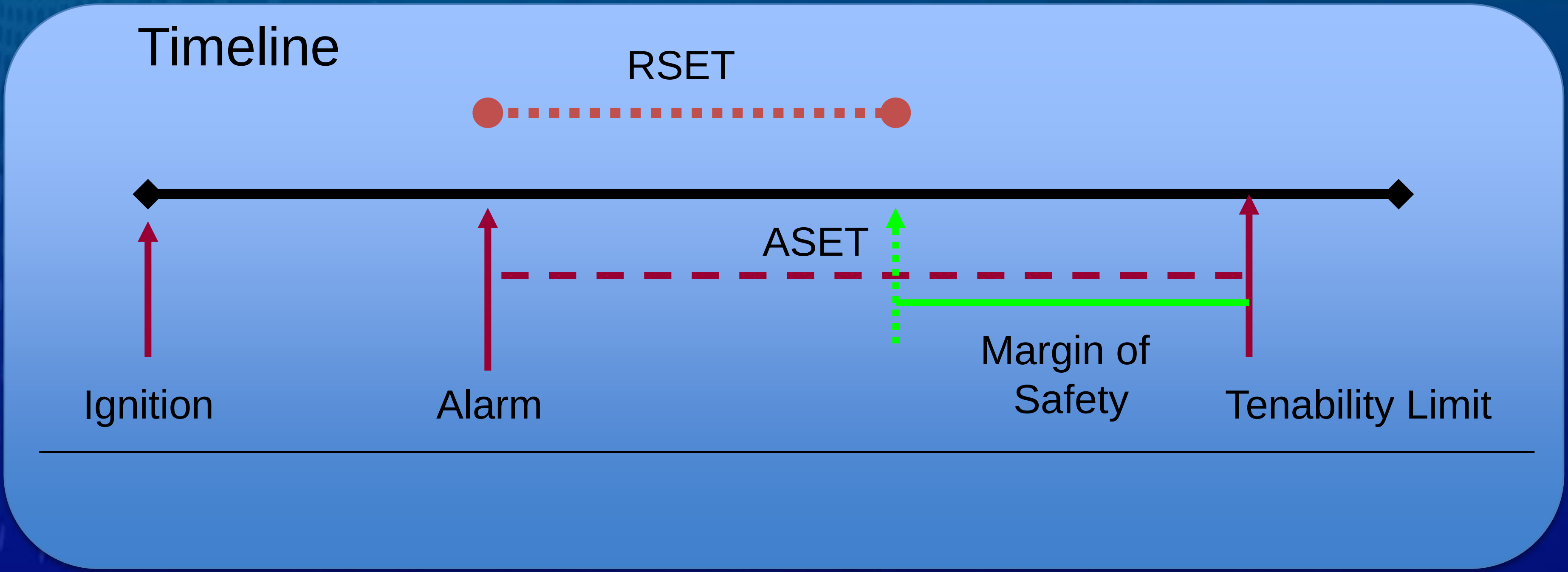
- ASET is the time to reach a threshold tenability limit on either:
  - Combustion gas exposure
  - Thermal exposure
  - Particulate smoke concentration

# Required Safe Egress Time - RSET

- Occupant characteristics
  - Pre-movement time
  - Travel speed
- Scenario dependent characteristics
  - Travel distance
    - Direct escape path
    - Indirect path (alert/assist others, investigate)
- Other

# ASET/RSET Concepts

Available Safe Egress Time (ASET) – Required Safe Egress Time (RSET)




Installed smoke alarms should provide early enough warning such that ASET > RSET

# ASET - Combustion Gas Toxicity

- FED – *fractional effective dose*
  - Time weighted average of asphyxiant gases (carbon monoxide and hydrogen cyanide) with a synergistic effect from carbon dioxide.
  - Value of 1.0 associated with effects that would render occupants of average susceptibility incapable of self escape.
  - Value of 0.3 selected as reasonable criterion  to provide the ability to escape for more sensitive populations.
  - Gas sampled at 1.5 m height from floor.

# ASET - Thermal Exposure

- FED - *fractional effective dose*
  - a time weighted average of convected and/or radiated exposures.
  - Value of 1.0 associated with effects that would render occupants of average susceptibility incapable of self escape.
  - Value of 0.3 selected as reasonable criterion to provide the ability to escape for more sensitive populations.
  - The Home Smoke Alarm Project only considered convected heat along the egress path. Temperature measured at a height of 1.5 m.

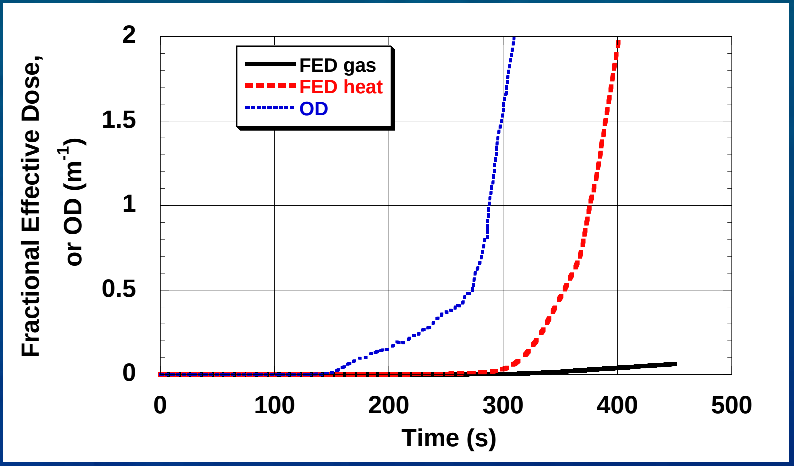
# ASET - Particulate Smoke

- Smoke optical density (OD)
  - is a function of the amount of smoke and optical properties of the smoke and measuring instrument.
  - correlates with visibility distance.
  - correlates with travel speed.
  - a limiting threshold value is equated to untenable conditions (Home Smoke Alarm Project used a value of 0.25 $m^{-1}$, ISO 13571 suggests a value as high as 3.4 $m^{-1}$).
  - evaluated at a height of 1.5 m above the floor.

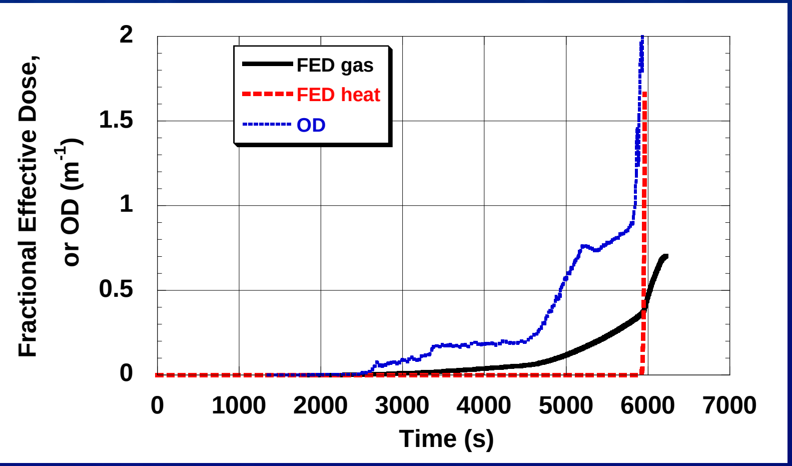
# ASET - Tenability Times - Examples

- "Worst Case" Examples
  - Assume occupant in room of fire origin
  - Tenability conditions evaluated in room of fire origin

Flaming Fire




**Smoldering Fire**



# Conservative Maximum RSET Values for Residential Settings

| Reference | Pre-movement time (s) (from alarm time) | RSET (s) (pre-movement time plus travel time) |
|---|---|---|
| NIST[1] estimate (dressing, calling FD, gathering personal items, awakening others) | 55 - 80 | 90 - 134 |
| NRC[2] estimate (investigate, fight fire, awaken others, dress for winter conditions, gather belongings) | 480 | 550 |
| NRC[2] estimate (not including dressing for winter conditions or fighting fire – save 330 s) | 150 | 220 |

1 Bukowski, R. W., Peacock, R. D., Averill, J. D., Cleary, T. G., Bryner, N. P., Walton W.D., Reneke, P. A., and Kuligowski, E. D. Performance of Home Smoke Alarms, Analysis of the Response of Several Available Technologies in Residential Fire Settings, Natl. Inst. Stand. Technol., Tech. Note 1455-1 (2008)

2 Proulx, G., Cavan, N., Tonikian, R., “Egress Times from Single Family Houses,” Institute for Research in Construction, National Research Council Canada Research Report: IRC-RR-209, July 2006

# ASET/RSET Analysis

Tenability limits - FED of 0.3 and optical density of 0.25 $m^{-1}$ in the room of fire origin

RSET = 120 s

| Alarm Type | Fraction of tests with positive Margin of Safety (ASET – RSET) | Average value of Margin of Safety (s) | Range in Margin of Safety (s) |
|---|---|---|---|
| Photoelectric | 14/24 | 740 | -57, 3140 |
| Ionization | 18/24 | 349 | -484, 2916 |
| Dual 1 | 18/23 | 742 | -100, 2670 |
| Dual 2 | 20/23 | 1011 | -22, 3816 |

RSET = 220 s

| Alarm Type | Fraction of tests with positive Margin of Safety (ASET – RSET) | Average value of Margin of Safety (s) | Range in Margin of Safety (s) |
|---|---|---|---|
| Photoelectric | 12/24 | 640 | -157, 3040 |
| Ionization | 9/24 | 249 | -584, 2816 |
| Dual 1 | 13/23 | 642 | -200, 2570 |
| Dual 2 | 15/23 | 911 | -122, 3716 |

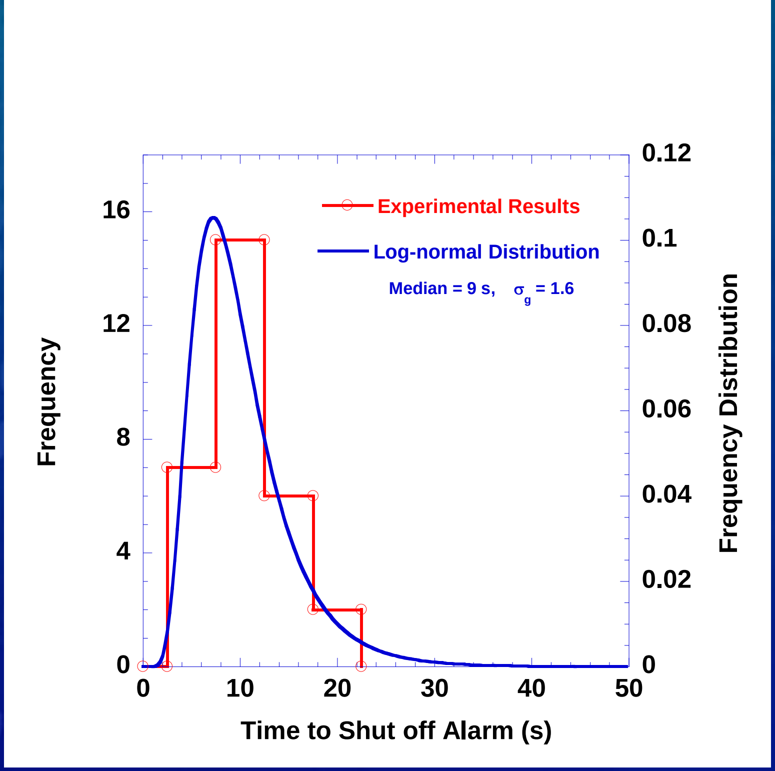
# New Alternative Analysis
# Relative Smoke Alarm Effectiveness

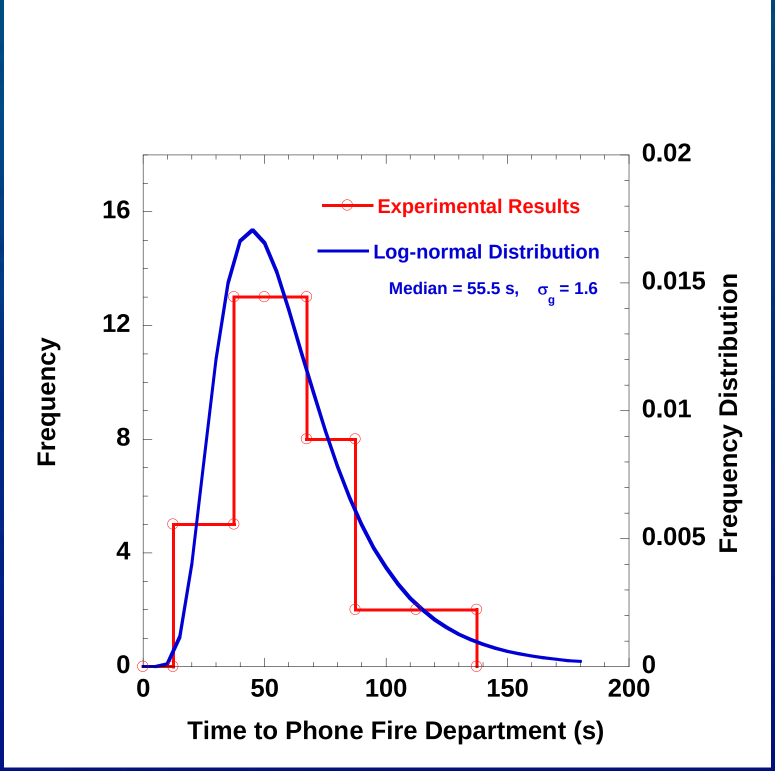
- Treat pre-movement time as a frequency distribution
- Evacuation speed depends on smoke density
- Consider multiple direct and indirect evacuation paths
- Aggregate results to assess performance

# Treating Pre-movement Time as a Distribution

- **Why treat pre-movement time as a frequency distribution?**
  - RSET "worst case" value is subjective
  - Experimental data suggests pre-movement time can be characterized by a log-normal distribution
  - More vulnerable populations can be addressed by changing the frequency distribution
  - Results can be meaningfully averaged over evacuation scenarios and fire scenarios unlike individual margin of safety values

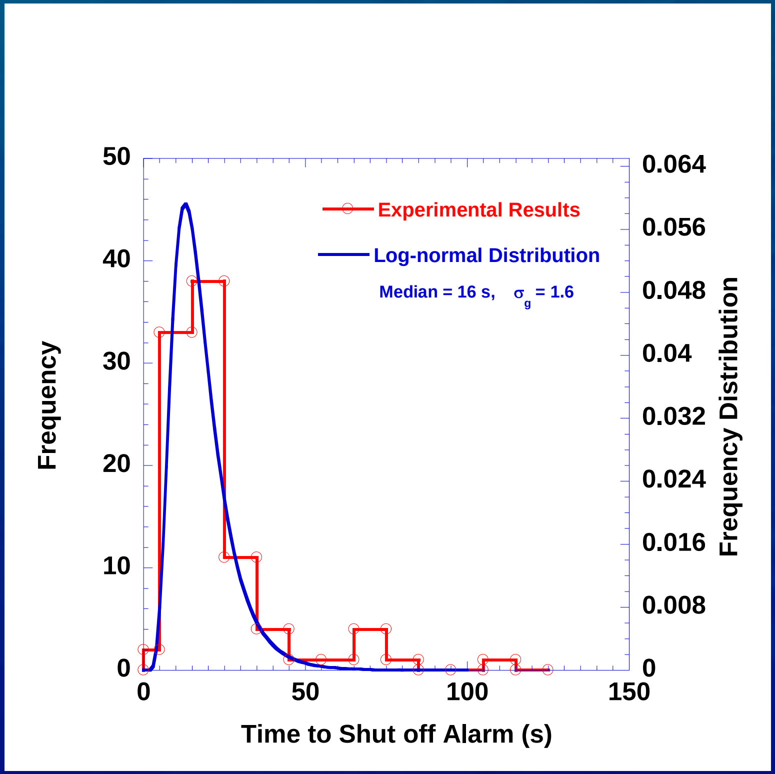
# Pre-movement Distributions
## (college-aged students – residential setting)




Nober, E. H., H. Peirce & A. Well, 1983, Waking Effectiveness of Household Smoke and Fire Detection Devices, NBS-GCR 83-439.

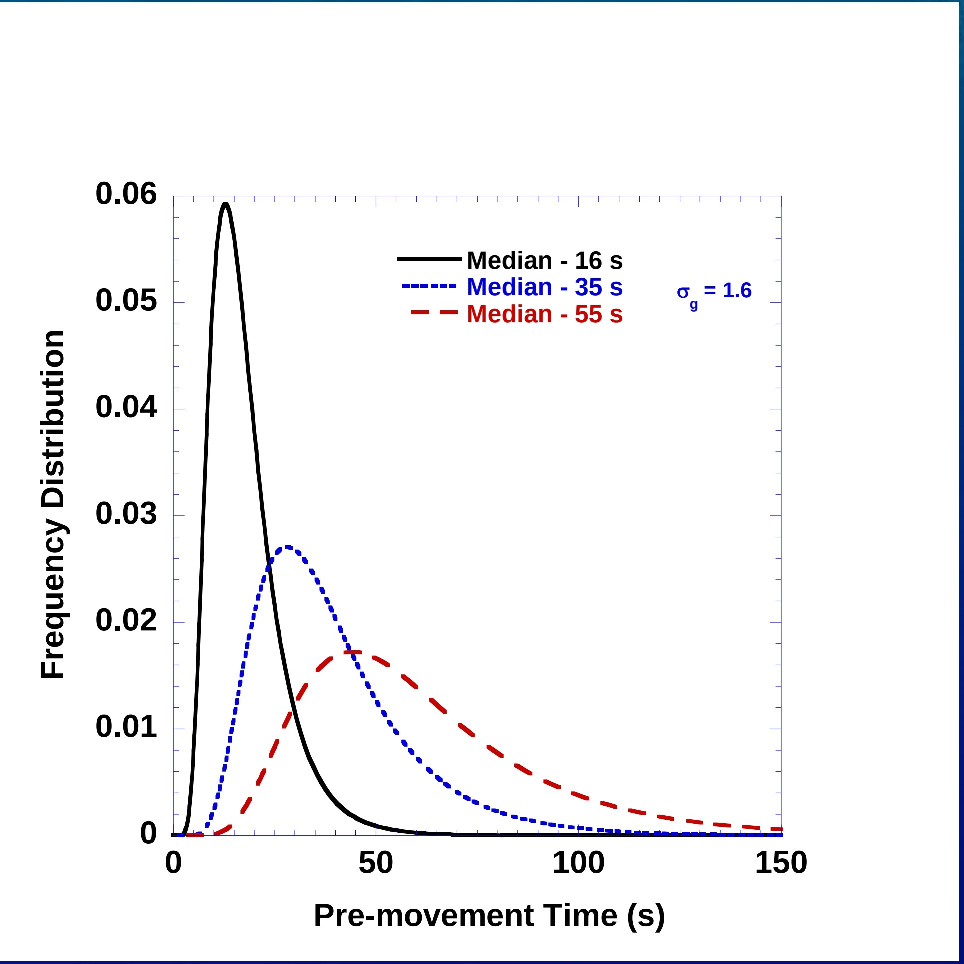
# Pre-movement Distributions
## (65 % college-aged students, 25 % elderly, 10% unfamiliar with alarms – residential settings)




Duncan, C., “The Effectiveness of the Domestic Smoke Alarm Signal,” Fire Engineering Research Report 99/5, School of Engineering, University of Canterbury, Christchurch, New Zealand, March 1999.

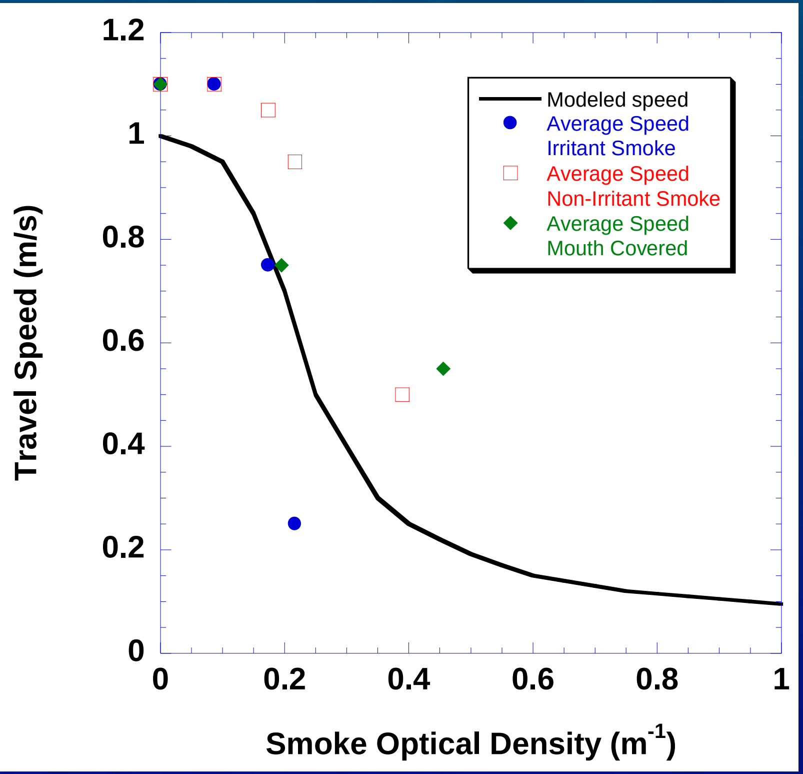
# Sample Residential Pre-movement Distributions

- Distribution can represent a distinct population
- Example distributions shown in graph
  - Easily alerted, mobile
  - Somewhat slower to respond
  - More vulnerable, elderly or impaired



# Evacuation Speed a Function of Smoke Concentration

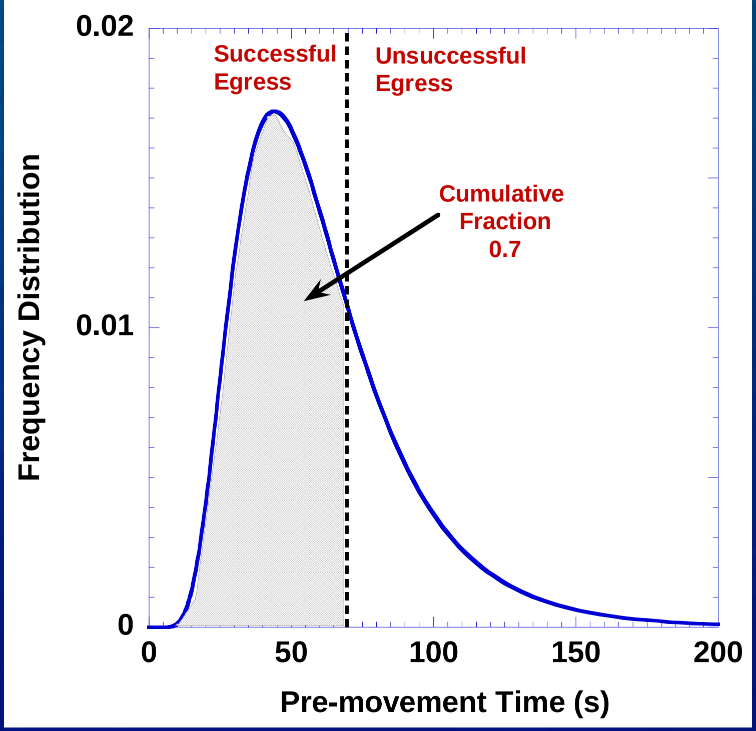
- RSET normally computed using mean travel speed in normal lighting and no smoke obscuration
- Here, the travel speed is a function of the optical density an occupant is traversing through.
  - The assignment of a reduced travel speed through smoke accounts for some of the negative impact of reduced visibility.
  - Furthermore, since smoke obscuration tends to increase as a fire progresses, an increase in pre-movement time will cause an increase in travel time for a particular scenario.



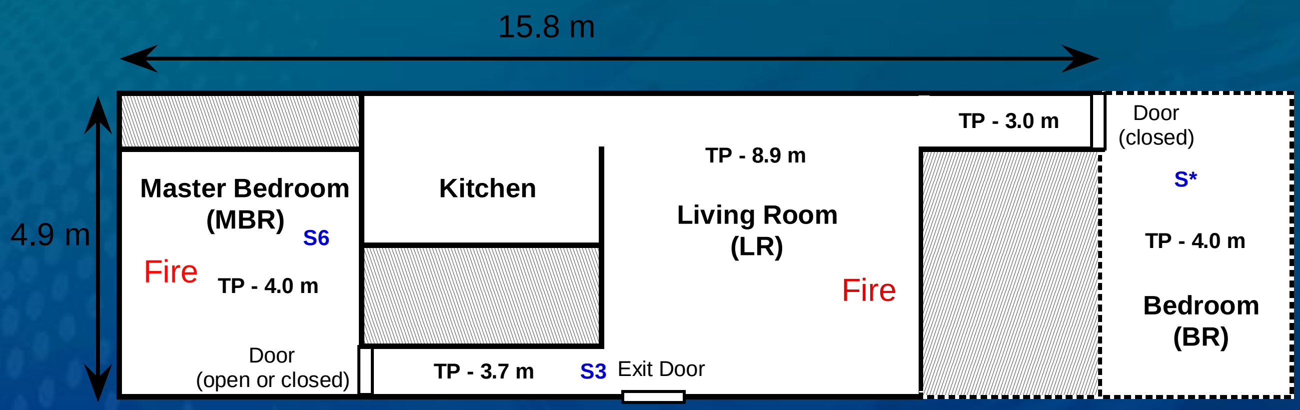

Data points from:
Jin, T., Yamada, T., “Irritating Effects on Fire Smoke on Visibility,” Fire Science and Technology, Vol. 5, No. 1, 1985.

# Computing Cumulative Fractions of Successful Outcomes

- Given an alarm configuration (type and location of alarms)
  - For a given fire and egress scenario
    - Compute evacuation times (RSET) and tenability times (ASET) for incremented pre-movement times
    - Determine the pre-movement time where ASET<RSET (unsuccessful egress)
    - Compute the cumulative fraction of the frequency distribution where ASET≥RSET
  - Average the cumulative fractions over all egress scenarios and representative fire scenarios for the total fraction of successful egress outcomes
- Assess the performance of different alarm configurations by comparing the total fraction of successful egress outcomes



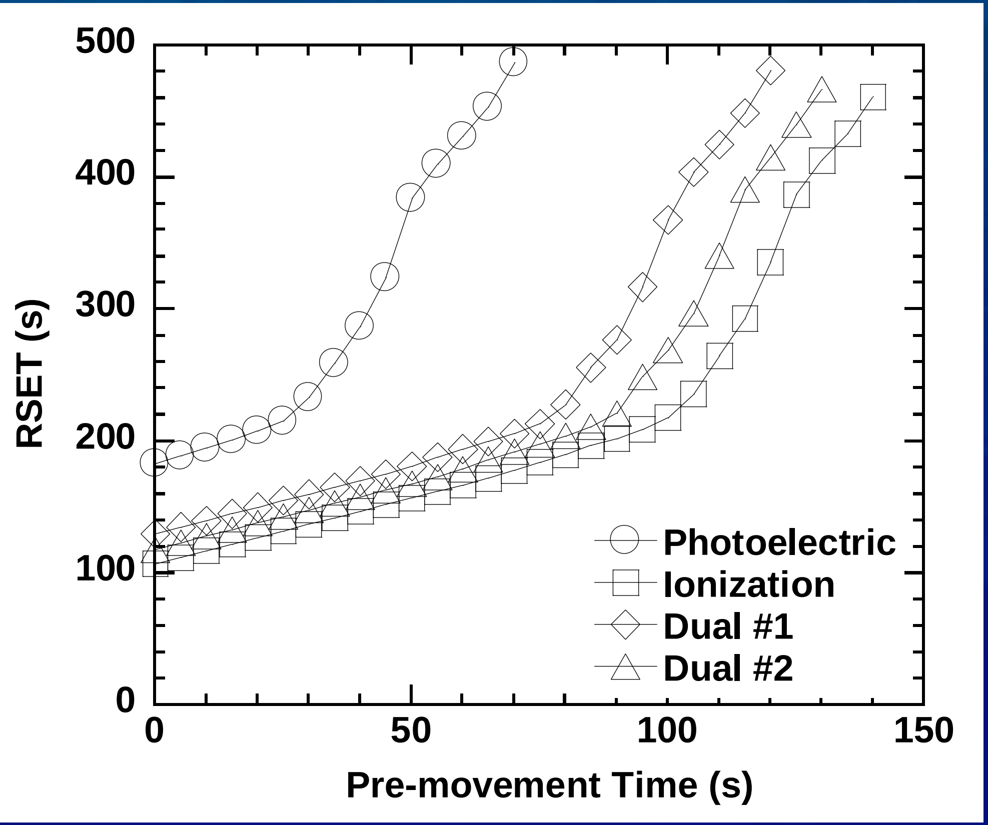
# Egress Scenarios




| Egress Scenario | Travel Path | Travel Segments | Travel Distance (m) |
|---|---|---|---|
| 1 | MBR – Exit | 2 | 7.7 |
| 2 | LR – Exit | 1 | 8.9 |
| 3 | BR – Exit | 3 | 15.9 |
| 4 | MBR – BR – Exit | 7 | 35.5 |
| 5 | BR – MBR – Exit | 6 | 27.3 |
| 6 | LR – BR – Exit | 5 | 27.8 |
| 7 | LR – MBR – Exit | 4 | 20.3 |
| 8 | LR – BR – MBR – Exit | 8 | 39.2 |
| 9 | LR – MBR – BR – Exit | 9 | 48.1 |
| 10 | MBR – LR – MBR – Exit | 6 | 28 |
| 11 | BR – LR – BR – Exit | 7 | 34.8 |
| 12 | MBR – BR – MBR – Exit | 10 | 46.9 |
| 13 | BR – MBR – BR – Exit | 11 | 55.1 |

# RSET Computed for Different Pre-Movement Times

Flaming fire in the living room and egress scenario 8 (LR- BR-MBR-Exit)



# Maximum Pre-movement Time That Allows for Successful Escape

Flaming fire in the living room and egress scenario 8 (LR- BR-MBR-Exit)

| Optical density limit ($m^{-1}$) | Photoelectric alarm P1 (s) | Ionization alarm I1 (s) | Dual alarm D1 (s) | Dual alarm D2 (s) |
|---|---|---|---|---|
| **0.25** | 20 | 95 | 75 | 85 |
| **0.50** | 30 | 105 | 80 | 95 |
| **1.00** | 35 | 110 | 85 | 95 |
| **1.70** | 40 | 115 | 90 | 100 |

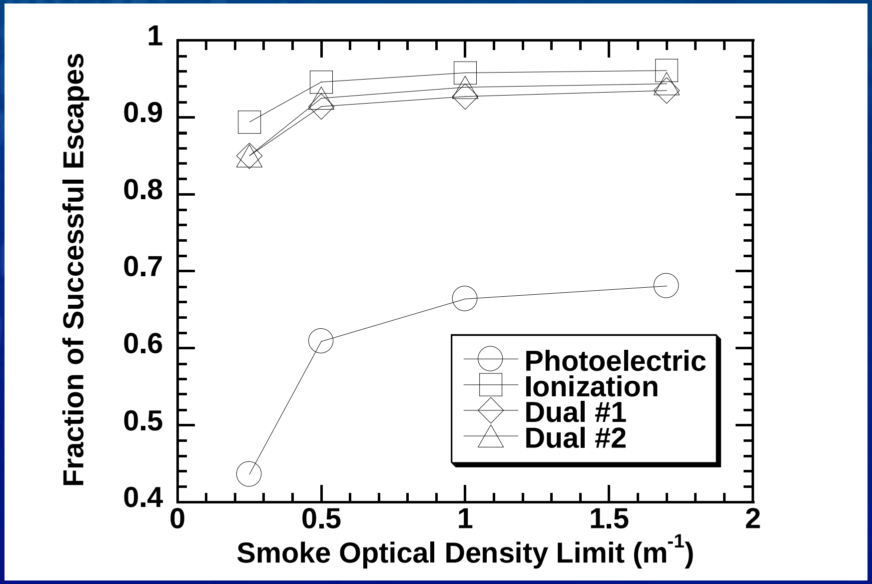
# Cumulative Fraction of Successful Escapes for the Most Vulnerable Population

Flaming fire in the living room and egress scenario 8 (LR- BR-MBR-Exit)

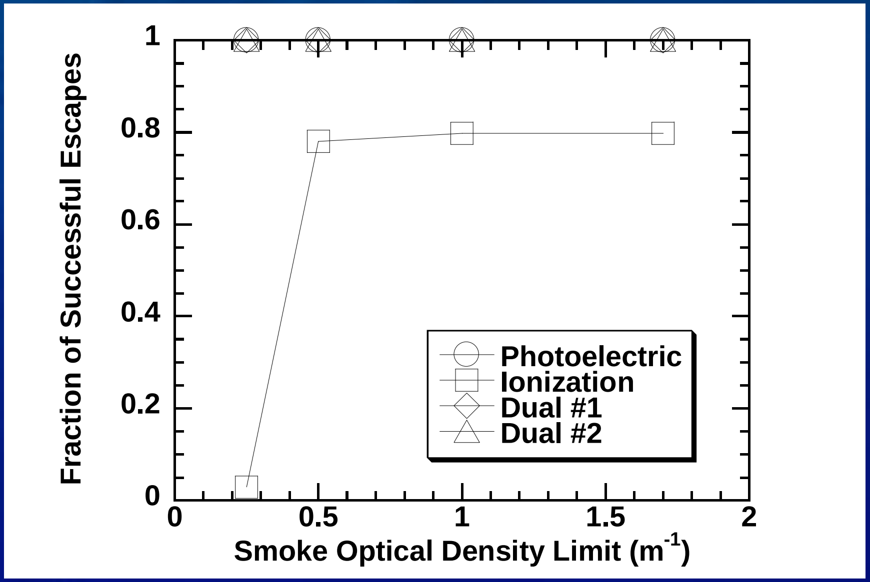
| Optical density limit ($m^{-1}$) | Photoelectric alarm P1 (s) | Ionization alarm I1 (s) | Dual alarm D1 (s) | Dual alarm D2 (s) |
|---|---|---|---|---|
| **0.25** | 0.02 | 0.88 | 0.75 | 0.83 |
| **1.70** | 0.26 | 0.95 | 0.86 | 0.90 |

# Relative Smoke Alarm Effectiveness Considering the More Vulnerable Group

A living room flaming fire chair scenario and all egress scenarios

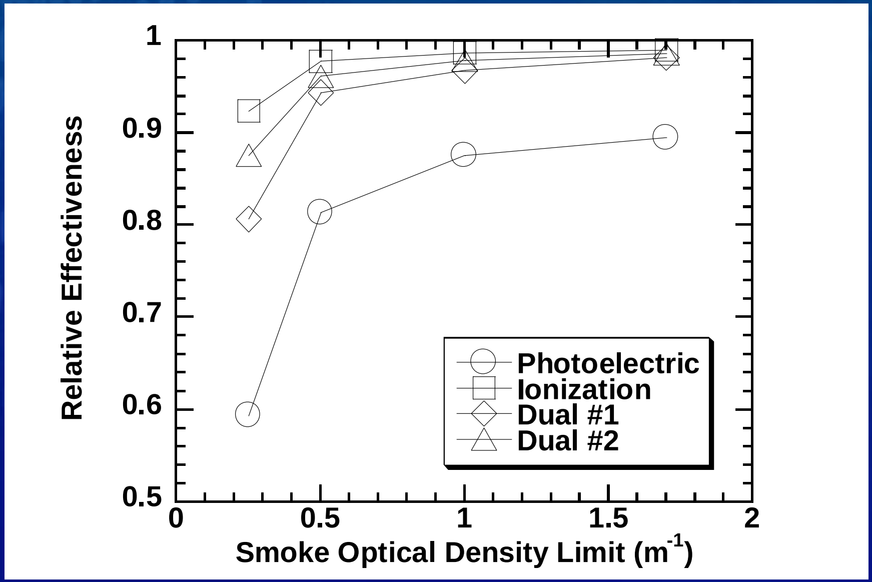



A living room smoldering fire chair scenario and all egress scenarios

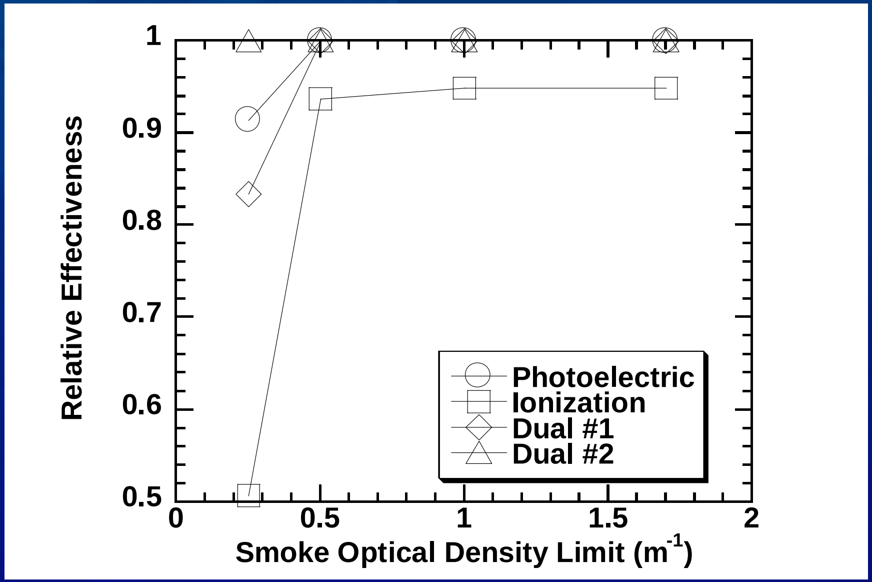


# Relative Smoke Alarm Effectiveness Considering the More Vulnerable Group

12 flaming fire chair tests and all 13 egress scenarios




12 smoldering chair tests and all 13 egress scenarios



# Relative Smoke Alarm Effectiveness Observations

- Observed a steep increase in relative effectiveness from a smoke optical density limit of 0.25 $m^{-1}$ to 0.50 $m^{-1}$. However, the ranking of smoke alarms tend to remain the same.
- Relative effectiveness is less sensitive to changes in the optical density limit above 0.50 $m^{-1}$.
- Photoelectric alarms had the lowest relative effectiveness values for flaming fires, while ionization alarms had the lowest relative effectiveness values for smoldering fires.
- Vulnerable populations who may require significantly more time to escape than more mobile populations would benefit the most from dual alarm technology or side-by-side photoelectric and ionization alarms with alarm placement following current NFPA 72 requirements.