



Smoke Detection Calculations – New Advances

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Need for Detection Prediction

- Performance-based design
- Forensic recreation
- Life saving potential of new designs
- Equivalency of performance
- Performance of detector in a fire event



Smoke Detector Modeling

- Limited research on this subject
- Two Types of Methods
 - Scientific Methods
 - Approximation Methods
- Scientific methods – principles of detection
- Approximation methods – Annex B of NFPA 72



Smoke Detector Modeling

- Approximation/Estimation Methods
 - Temperature Rise
 - Critical Velocity
 - Optical Density
- Methods do not address the operating principles of the detectors
- Uncertainty in approximation?

Estimation Alarm Thresholds

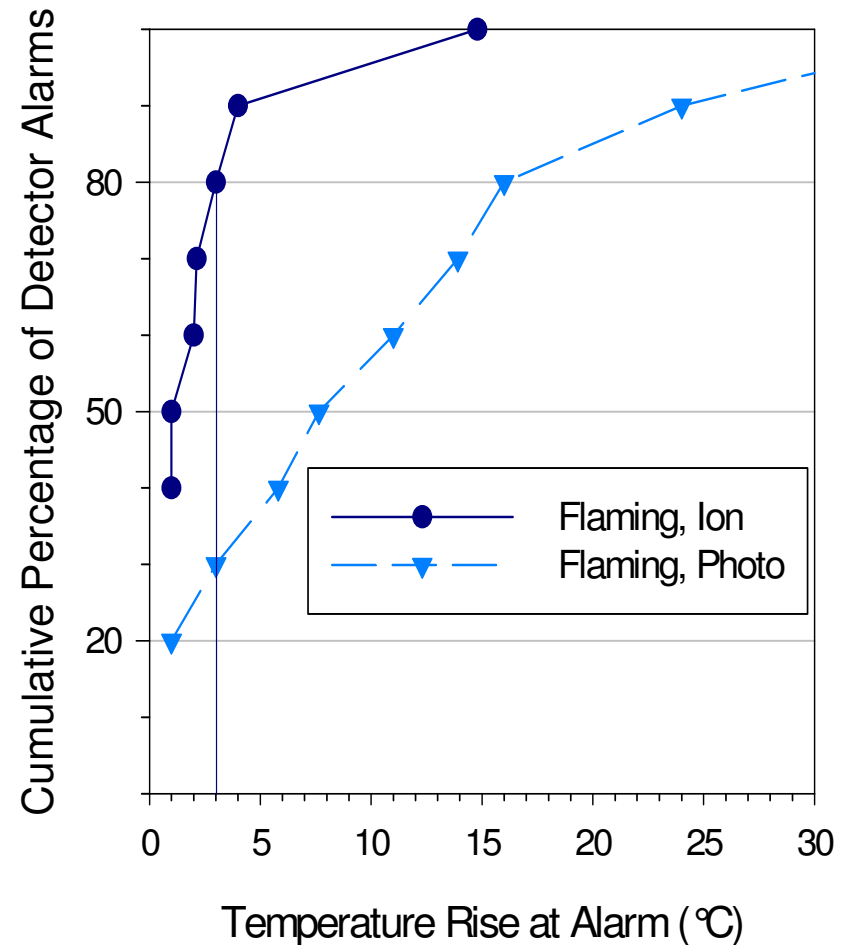
- Temperature Rise
 - OD \propto Temp Rise
 - 4 °C (Collier; Davis & Notarianni (5 °C))
 - 13 °C (Benjamin et al, Evans & Stroup)





Temperature Rise at Alarm

- Significant variables
 - Fire type
 - Detector type
- Flaming, ion lower than most report (80% < 3°C)
- Smoldering and smoldering-to-flaming fires not presented
 - Max values at alarm 1 to 3 °C



(Geiman 2006)



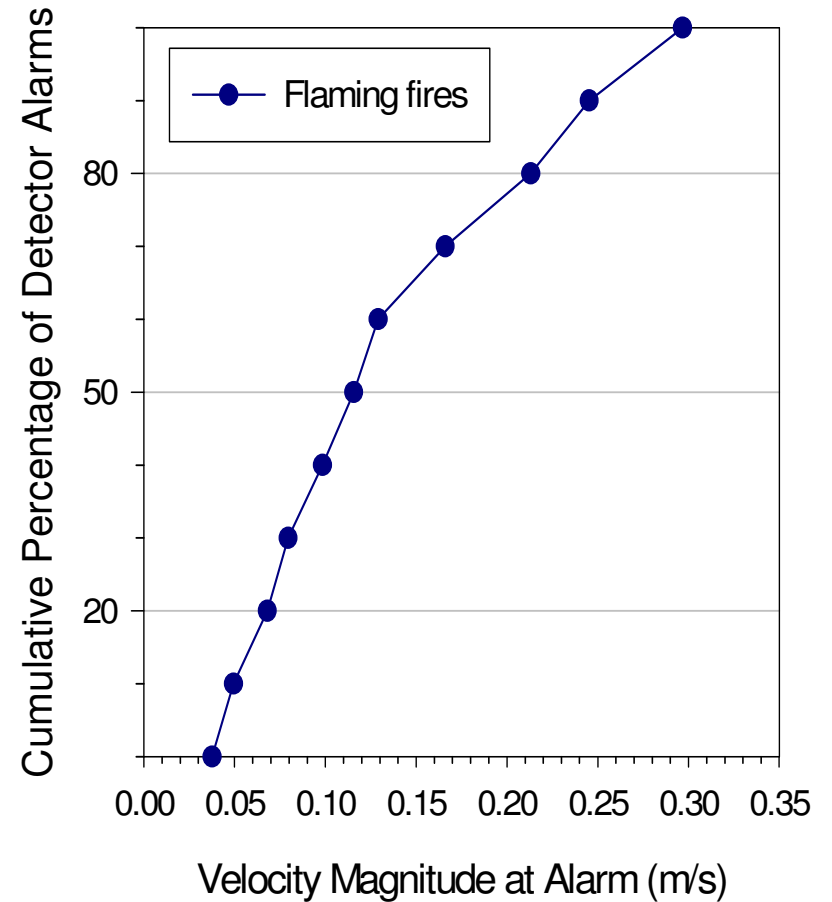
Estimation Alarm Thresholds

- Velocity (Brozovski)
 - Low velocity wind tunnel
 - Critical velocity ~ 0.15 m/s
 - Presence of sufficient smoke conc. assumed



Velocity at Alarm

- Fire type only significant variable
- Smoldering fires: No measurable velocity over ambient conditions
- Flaming fires: mean value consistent with previous reports
 - 0.13 ± 0.07 m/s



(Geiman 2006)



Velocity as Alarm Threshold?

- Limited applicability to smoldering fires
- Assumes sufficient smoke concentration for alarm
- Not correct to use as an independent threshold

Estimation Alarm Thresholds

- Optical Density
 - Nominal sensitivity (UL 217 / UL 268)
 - 0.14 m^{-1} (Max. black smoke OD from UL tests)
 - 20th, 50th, & 80th percentiles of optical density at alarm values from experiments (Geiman & Gottuk)



Optical Density at Alarm

Geiman Activation Thresholds

OD Alarm Threshold	Fire Type	Ionization Detectors	Photoelectric Detectors
20%	Flaming Fire	0.007 OD/m	0.031 OD/m
	Smoldering Fire	0.045 OD/m	0.032 OD/m
50%	Flaming Fire	0.021 OD/m	0.063 OD/m
	Smoldering Fire	0.113 OD/m	0.059 OD/m
80%	Flaming Fire	0.072 OD/m	0.106 OD/m
	Smoldering Fire	0.176 OD/m	0.110 OD/m



“Scientific Method”

- Cleary Detector Model (2000)
 - Calculates transient evolution of smoke within a smoke detector
 - Evolution based upon characteristic lag or dwell/mixing times
 - Detector specific constants required as input
 - Activation threshold required as input

Mass Concentration of Smoke within Smoke Detector

$$\frac{dY_c}{dt} = \frac{Y_e(t + \delta t_e) - Y_c(t)}{\delta t_c}$$

Characteristic Filling Time of Sensing Chamber Detector

$$\delta t_e = \alpha_e u^{\beta_e}$$





Methodologies to Predicting Activation

- Calculate smoke concentration outside of detector
- Determine alarm via
 - Geiman thresholds
 - Cleary model



Calculate Smoke Concentration

- Fire Size (mass burning rate)
- Soot yield
- Transport smoke from fire to detector

- Computer fire models
- Issues
 - Smoldering fires ill defined
 - Soot yields (source and deposition)

Soot Yields

- Measured smoke yields found to be significantly less than that provided in the literature

- Propane

- 2.4% [Tewarson]
- 0.4% from 1ft² burner

- Ethylene

- 4.3% [Tewarson]
- 2.0% from 1ft² burner

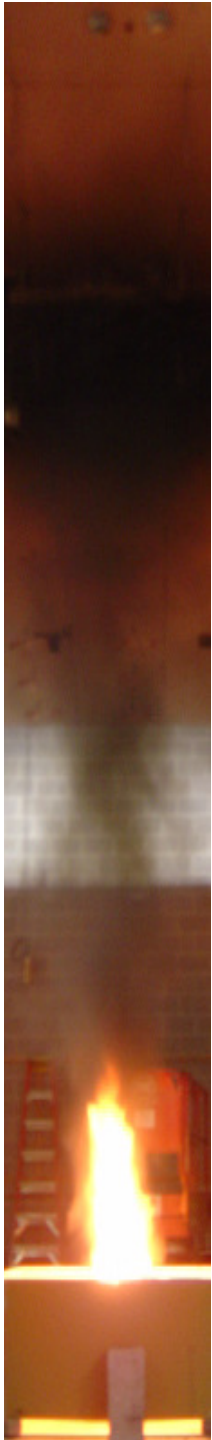
- Propylene

- 9.5% [Tewarson]
- 4.8% from 1ft² burner

Propane



Propylene



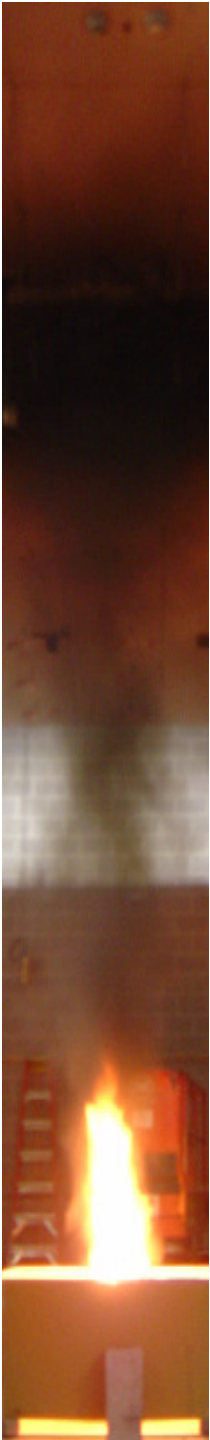


Soot Yields

- Difference between soot yields for the 100kW fires in FPRF test series and those reported in the literature ranged from a factor of 2 to 5.
- Expected to be an artifact of the differences in scale between the fires developed in the ASTM E2058 test apparatus and the 100kW fires.
- Findings consistent to these have been reported using similar fuels (i.e., Pitts & Mullholland – Propane)
- Disparity between measured soot yields for varying fire sizes deserves renewed attention

Soot Deposition

- Measured smoke yield at detector significantly less than model predicted ($\sim 1/2$)
- Measurements indicate $\sim 40\%$ soot deposit at plume impact
- Models do not account for soot deposition



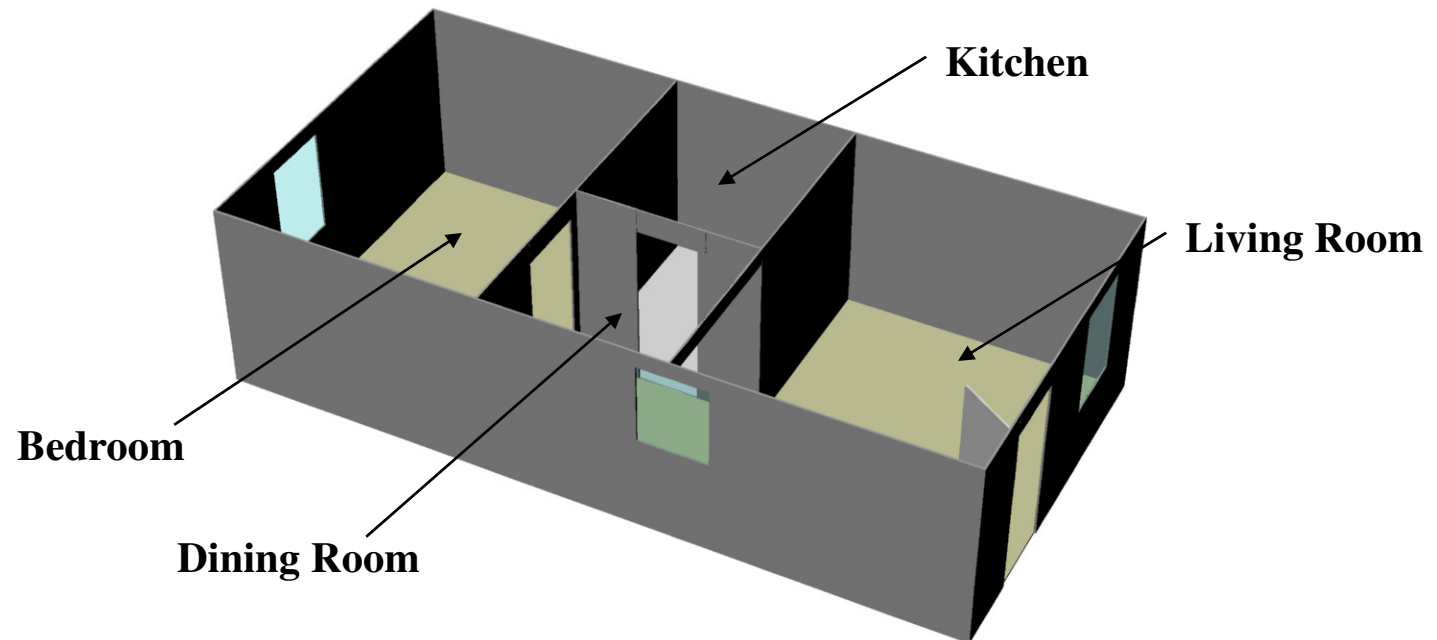


Evaluation of Prediction Methods

- Methods
 - Geiman
 - Cleary model implemented in FDS
- FDS simulations conducted on selected tests
 - Enclosure fire scenario
 - Corridor fire scenario
- Compared predicted and empirical results

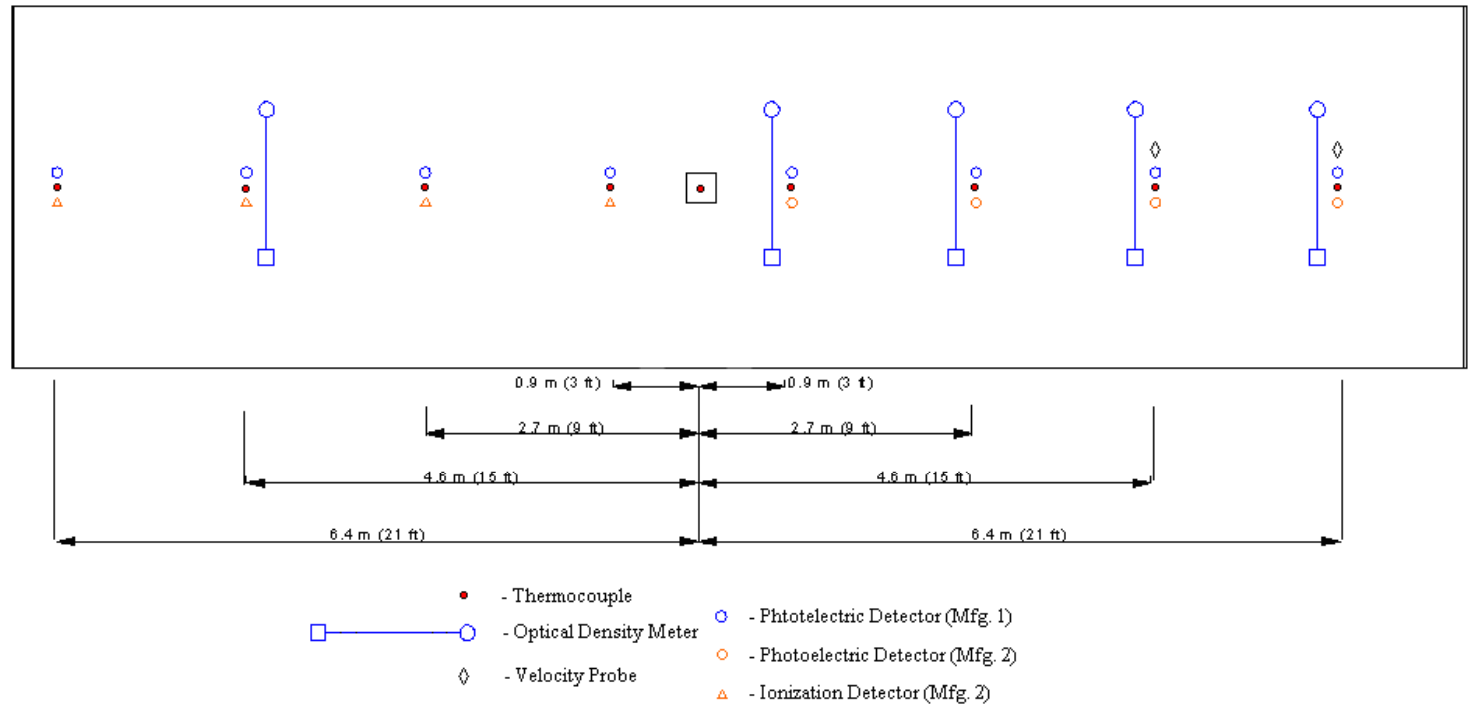
Overview of Experimental Test Series

- **National Institute of Justice (NIJ) Enclosure**
 - 41.8 m² (450 ft²) apartment-style enclosure
 - Four, inter-connected rooms
 - Flaming upholstered sofa exposure fire
 - Two detector clusters located outside room of origin





FPRF Experimental Set-Up



- Smooth Ceiling
- Elevation of 3.7m (12ft)
- 100kW Exposure Fire
- Detector clusters at 0.9m (3ft), 2.7m (9ft), 4.6m (15ft), and 6.4m (21ft)



Modeling Simulation Overview

- All simulations executed using FDS v5 [2/3/09 release]
- Grid Resolution
 - NIJ: ~350,000 grid cells (5 – 10 cm resolution)
 - FPRF: ~234,000 grid cells (3 – 6 cm resolution at ceiling)
- 2-parameter Cleary smoke detector algorithm

Detection Technology	External Housing	
	Alpha	Beta
Ionization	2.5	-0.7
Photoelectric	1.8	-1.0
Detection Technology	Sensing Chamber	
	Alpha	Beta
Ionization	0.8	-0.9
Photoelectric	1.0	-0.8

- FDS/Cleary model used mid-point value from UL listed device sensitivity used as alarm threshold
- Geiman 20%, 50%, and 80% thresholds used

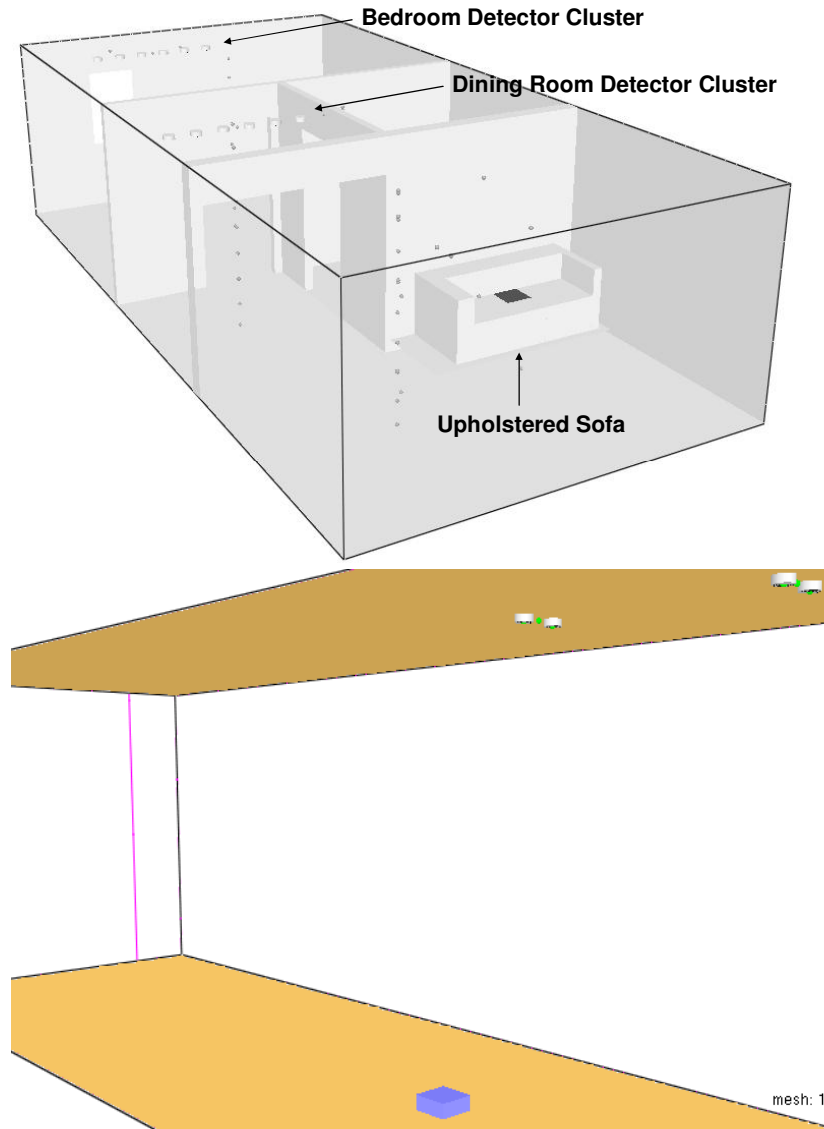
Modeling Simulation Fire Input

- **NIJ Sofa Fire**

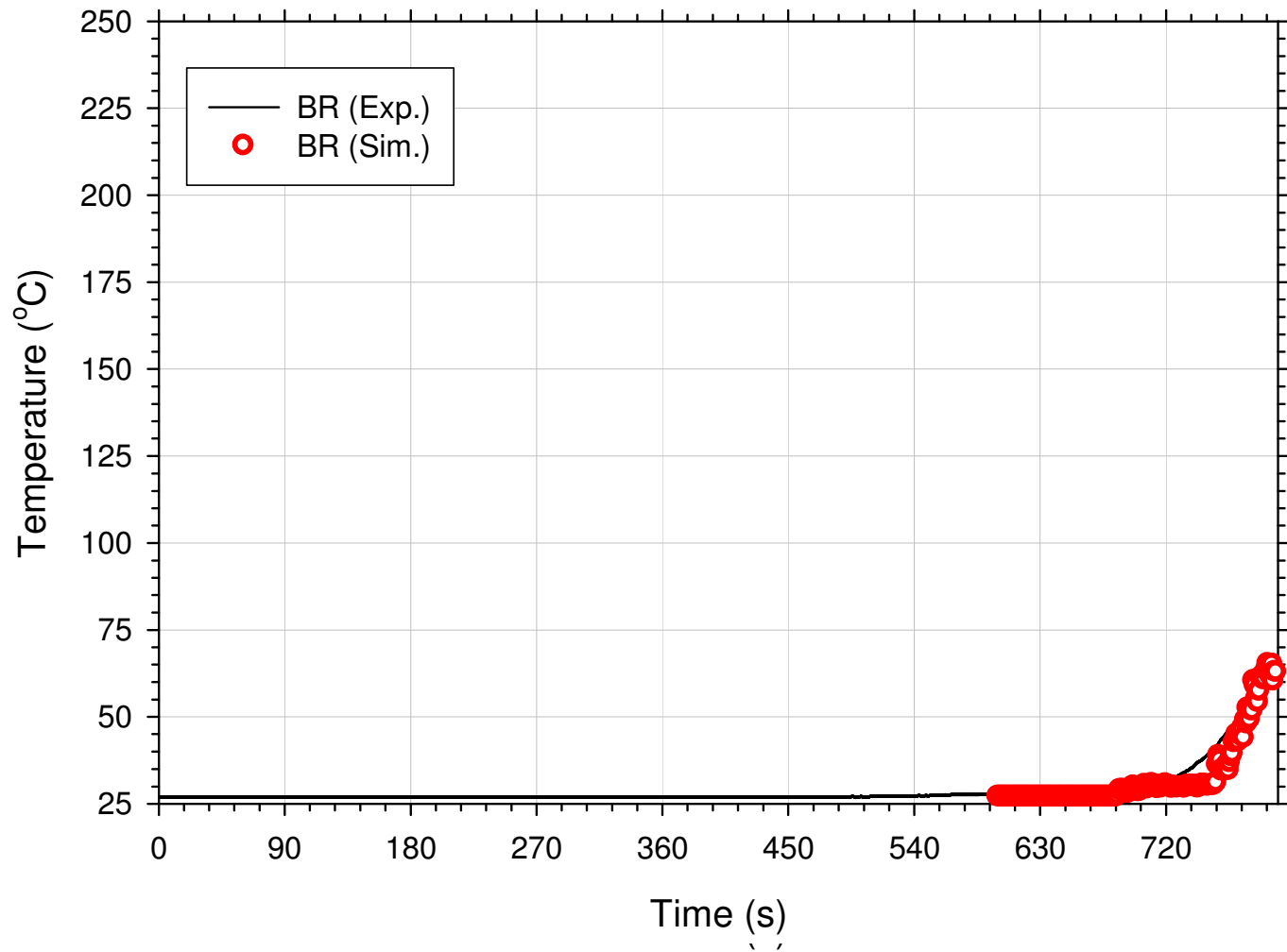
- Polyurethane Reaction
- Time-dependent HRR ramp
- Soot Yield = 0.213

- **FPRF Corridor Fire**

- MMA Reaction
- Constant 100kW Fire
- Soot Yield = 0.022

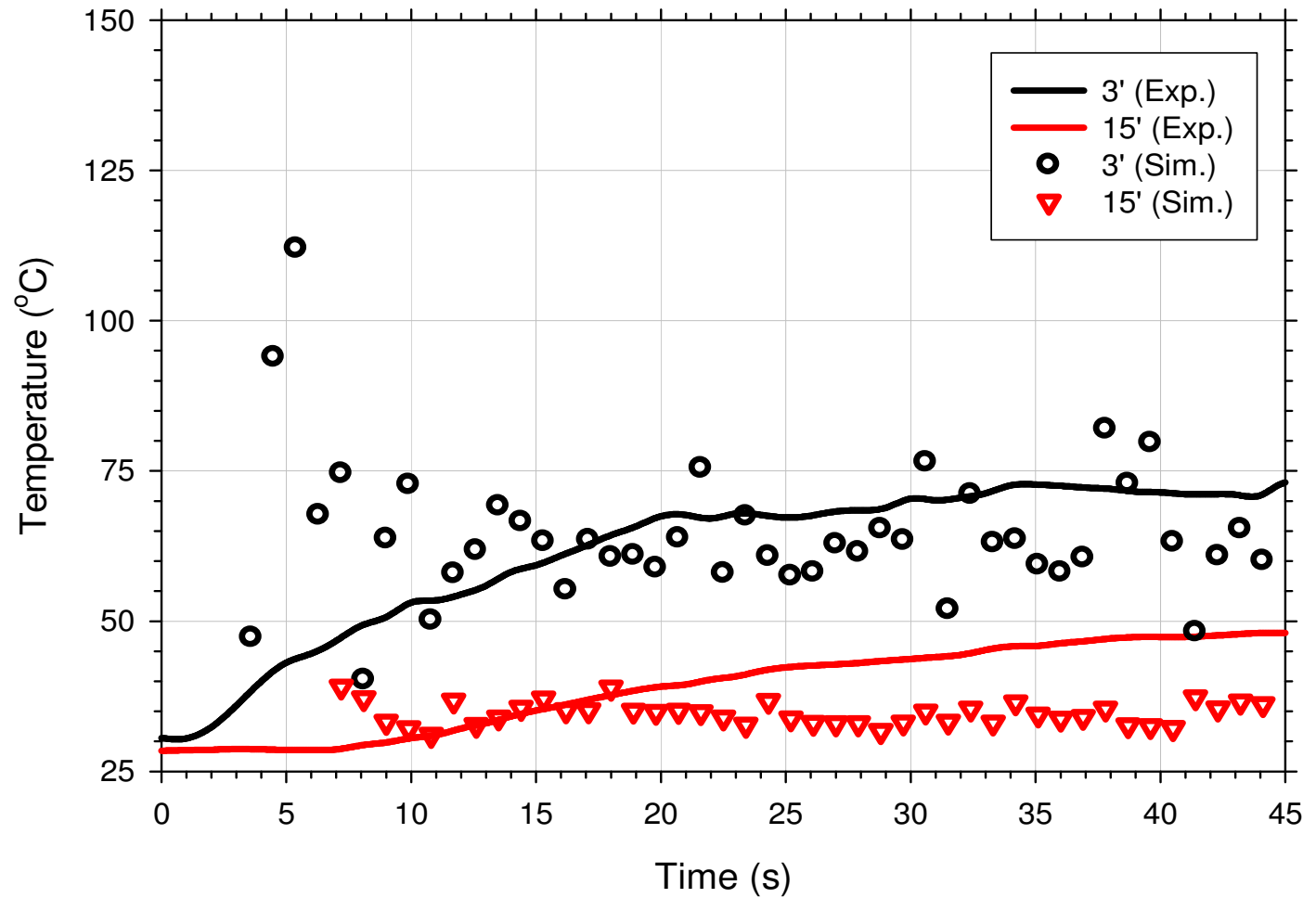


Simulation Validation (NIJ)





Simulation Validation (FPRF @ 12ft)



Comparison of NIJ Results

Technology	Location	Experimental Activation Time (min.)	FDS Simulation Activation Time (min.)	Geiman Threshold Results (min.)		
				20%	50%	80%
Ionization	DR	8.3	11.0	11.0	11.0	11.0
Ionization		8.3	11.0			
Ionization		9.2	11.0			
Photoelectric		11.8	11.0	11.0	11.0	11.0
Photoelectric		11.8	11.1			
Photoelectric		12.0	11.1			
Ionization	BR	9.7	11.5	11.5	11.5	11.5
Ionization		9.5	11.5			
Ionization		10.4	11.5			
Photoelectric		12.3	11.5	11.5	11.5	11.7
Photoelectric		12.1	11.5			
Photoelectric		12.3	11.6			

- Predicted lag behind experimental for ionization
- Predicted within 1 minute of experimental for photoelectric
- Predicted responses from both methodologies comparable





Comparison of FPRF Results

- Both methodologies predict early response
- Predicted responses within 3s of each other
- All predictions within 30s of actual activation times

Technology	Location (m [ft])	Experimental Activation Time (s)	FDS Simulation Activation Time (s)	Geiman Threshold Results		
				20%	50%	80%
Ionization	0.9 [3]	12.5	4	2.7	2.7	2.7
Photoelectric		10	3.6	2.7	2.7	2.8
Ionization	2.7 [9]	21	6.2	4.3	4.4	4.5
Photoelectric		16	6.1	4.5	4.5	4.6
Ionization	4.6 [15]	23.5	8.9	6.4	6.4	6.6
Photoelectric		25.5	8.5	6.5	6.5	6.7
Ionization	6.4 [21]	29	12.4	9.1	9.3	9.9
Photoelectric		36	11.6	9.4	9.8	13.7



Summary Geiman Thresholds Method

- Little to no difference for 20, 50, and 80% thresholds for cases evaluated
- Detector response predictions within
 - 25 to 163s for NIJ
 - 10 to 27s for FPRF



Summary Cleary/FDS Detector Model

- Varying dwell/mixing constants found to have very little impact on Cleary detector response predictions for cases evaluated
- Detector response predictions within
 - 34 to 163s for NIJ
 - 6 to 24s for FPRF



Conclusions

- For the cases evaluated, detector response prediction methodologies within 1 to 6 seconds
- Predicted activation times within 10 – 163s of experimental values
- Rapid smoke increase with ceiling jet



Conclusions

- Robustness of Methodologies
 - Geiman Thresholds
 - Simulation Accuracy (Fire / Smoke / Transport)
 - Selection of appropriate threshold level
 - FDS Detector Model
 - Simulation Accuracy (Fire / Smoke / Transport)
 - Selection of appropriate input parameters w.r.t. detector
 - Selection of appropriate threshold level



Research Needs

- Smoke yields
 - Evaluate differences in small and large-scale
 - Measure for realistic fuel packages
- Soot deposition
- Smoldering fires
 - Quantify burning rates
 - Characterize yields
 - Develop FDS inputs
- More Validation

Reports

- Gottuk, D., Mealy, C., and Floyd, J., “Smoke Transport and FDS Validation,” *Fire Safety Science – Proceedings of the 9th International Symposium*, International Association of Fire Safety Science, Karlsruhe, Germany, September 21–26, 2008, pp. 129–140.
- Mealy, C., Floyd, J., and Gottuk, D., “Smoke Detector Spacing Requirements Complex Beamed and Sloped Ceilings, Volume 1: Experimental Validation of Smoke Detector Spacing Requirements,” The Fire Protection Research Foundation, Quincy, MA, April 2008.
- Geiman, J.P. and Gottuk, D.T., "Evaluation of Smoke Detector Response Estimation Methods: Part I – Optical Density, Temperature Rise and Velocity at Alarm," *Journal of Fire Protection Engineering*, **16** (4), November 2006, pp. 251–268.
- Geiman, J.A. and Gottuk, D.T., “Alarm Thresholds for Smoke Detector Modeling,” *Fire Safety Science—Proceedings of the Seventh International Symposium*, Evans, D.D. (ed.), International Association for Fire Safety Science, Worcester, MA, June 16–21, 2002, pp. 197–208.

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