



Validation of Modeling Tools for Detection Design in High Airflow Environments

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MODELING DETECTION RESPONSE

Establish validated computer model for high sensitivity smoke detection response in IT/Telecom environments

- Conducted for the National Fire Protection Research Foundation
- Phase 1 effort reviewed capabilities of existing models and identified gaps required to apply to specific application/environment
  - Applicable smoke and fire sources not well characterized
  - Detection response to smoke types or at high air velocity unknown
  - No full scale validation data available

OBJECTIVES

Phase 2 effort: Eliminate gaps and provide computer model for performance based design and development of prescriptive code

1. **Identify smoke sources**
2. **Characterize smoke and heat sources as input to computer models**
   - Representative of IT/Telecom environments
   - Smoke Production Rate
   - Heat Release Rate (HRR)
3. **Develop response curves for smoke detectors (obscuration) to local smoke concentration (mass)**
4. **Conduct full scale validation testing using characterized sources and detectors**
5. **Model various scenarios to develop prescriptive code**

TASK 1-3: BENCH SCALE TESTING

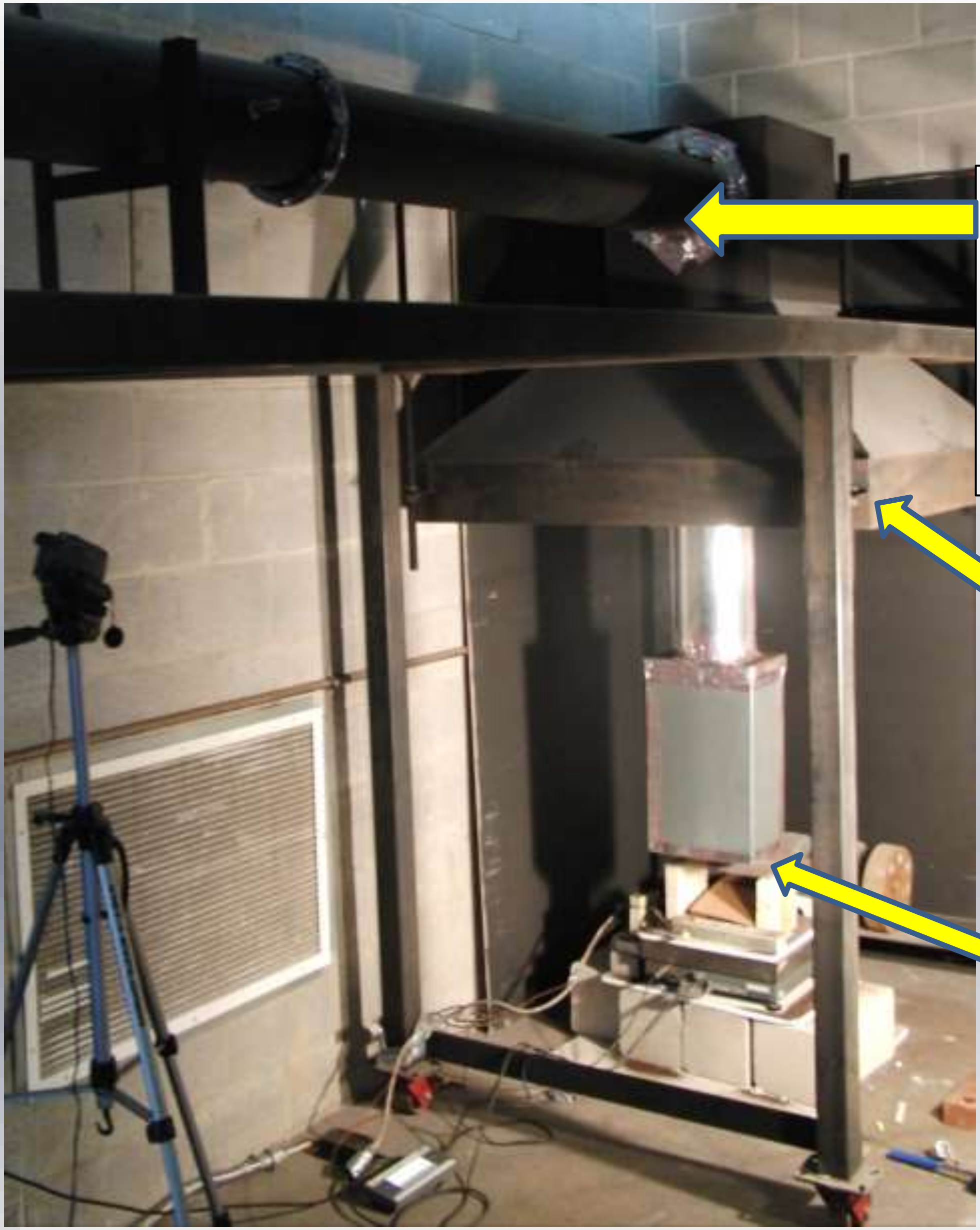
Bench scale tests conducted:

- Identify and select representative fire/smoke sources
- Characterize the smoke and heat production rates
- Quantify the response of smoke detectors to various source smoke

Construct instrumented test facility to evaluate sources and detectors

- Variable source heating and air flow conditions
- Independent smoke mass measurement
- Expose multiple smoke detectors
  - Variable local air velocities
  - Monitor smoke obscuration

TEST SETUP



Instrumented Duct

Laser/White light extinction

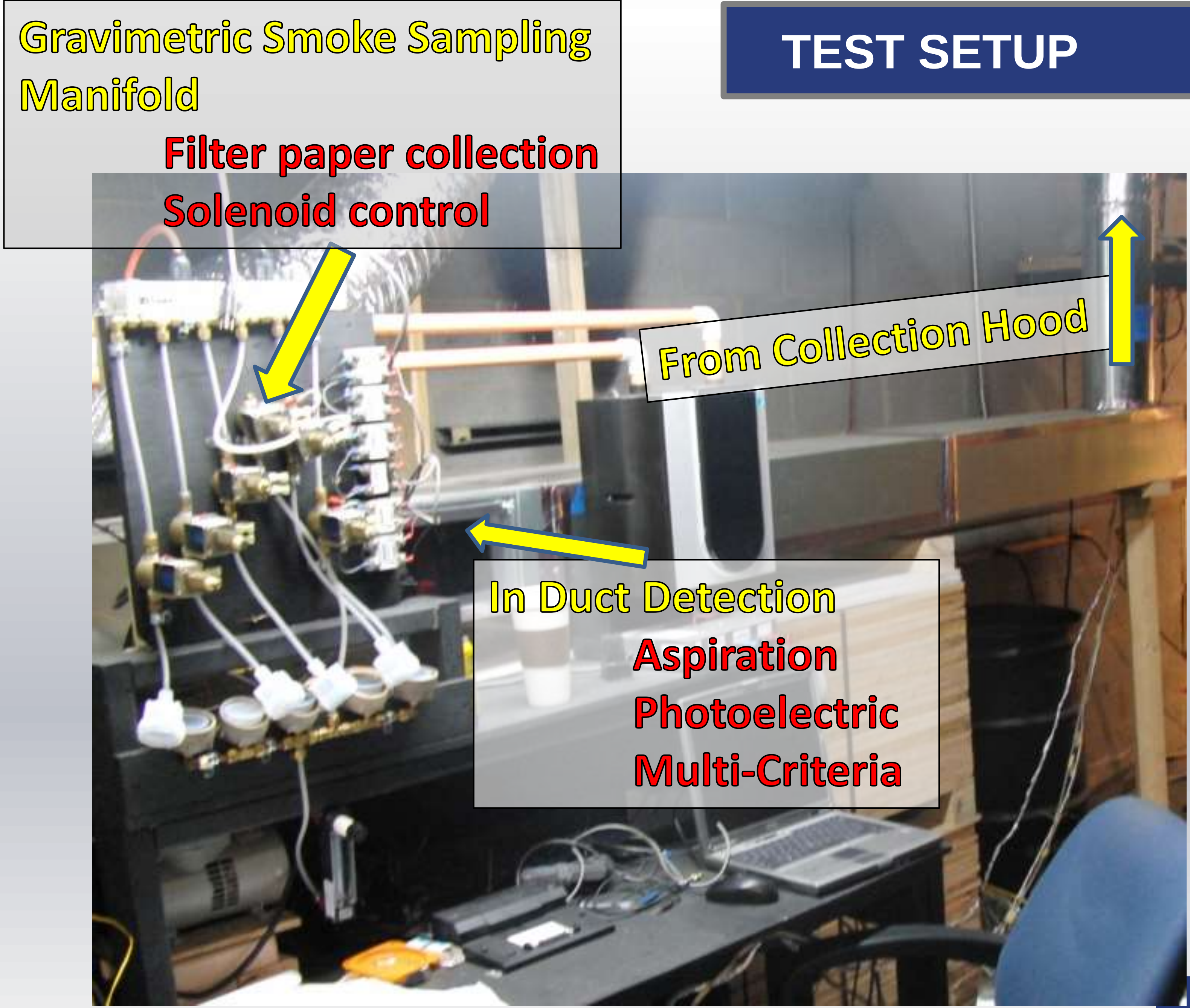
O_2 Calorimetry

Collection Hood

Variable air flow rate

Fire Source

TEST SETUP


Gravimetric Smoke Sampling Manifold
Filter paper collection
Solenoid control
From Collection Hood
In Duct Detection
Aspiration
Photoelectric
Multi-Criteria

FIRE SOURCES

- Propylene Gas
  - Small flaming gas jet
  - Controllable standardized source
  - High soot yield

- Electrical Cables
  - Smoldering PVC jacketed wires
  - Bundle of cables heated with temperature controlled cartridge heater
  - UL TC-ER rated for cable trays

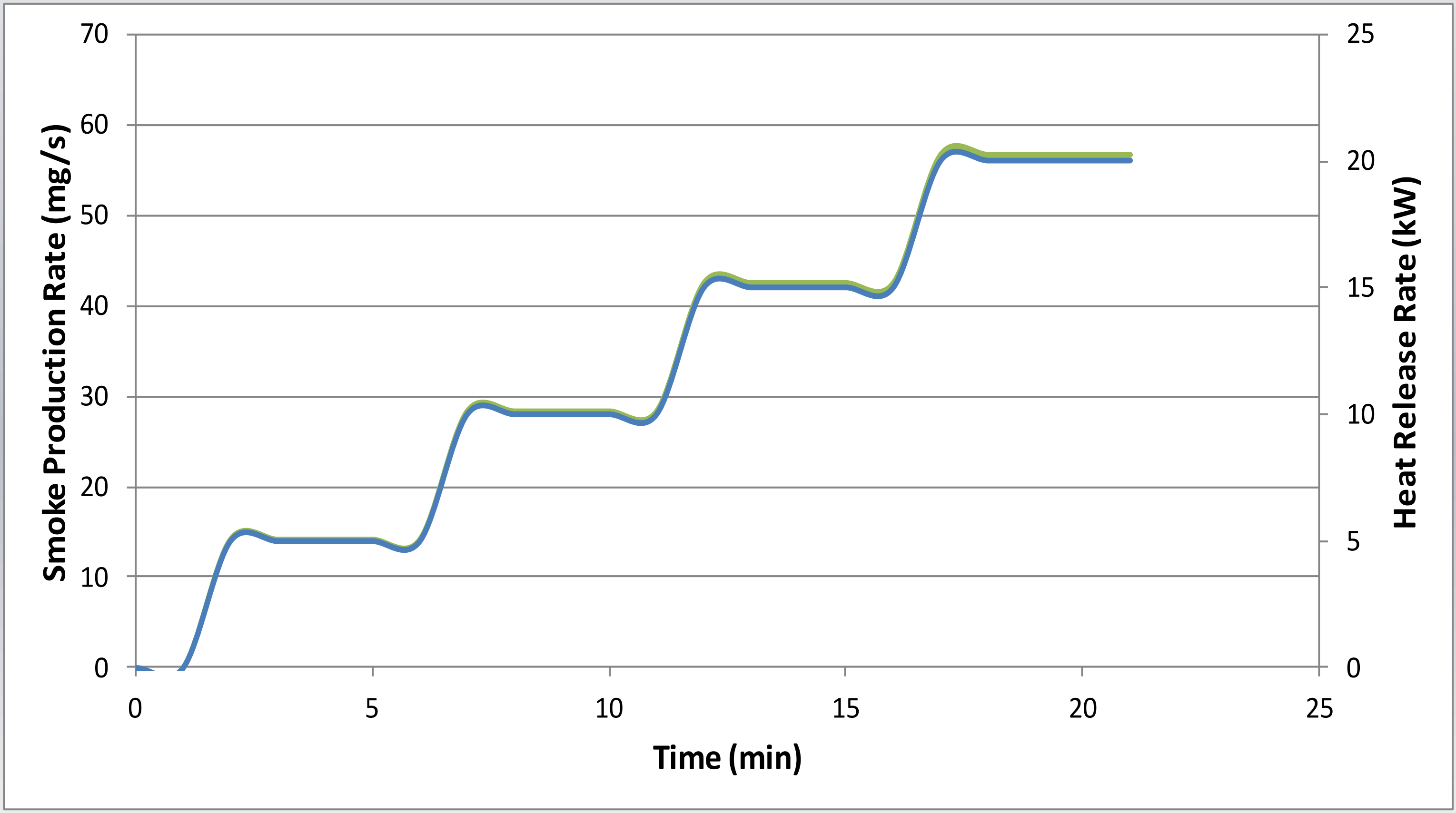
FIRE SOURCES

- Flaming polyethylene foam block
  - Anti-static packaging foam block ignited with isopropyl alcohol
  - No smoldering phase – flaming only
- Computer Circuit boards
  - Two boards sandwiched around temperature controlled cartridge heater

FIRE SOURCE CHARACTERIZATION

Propylene gas

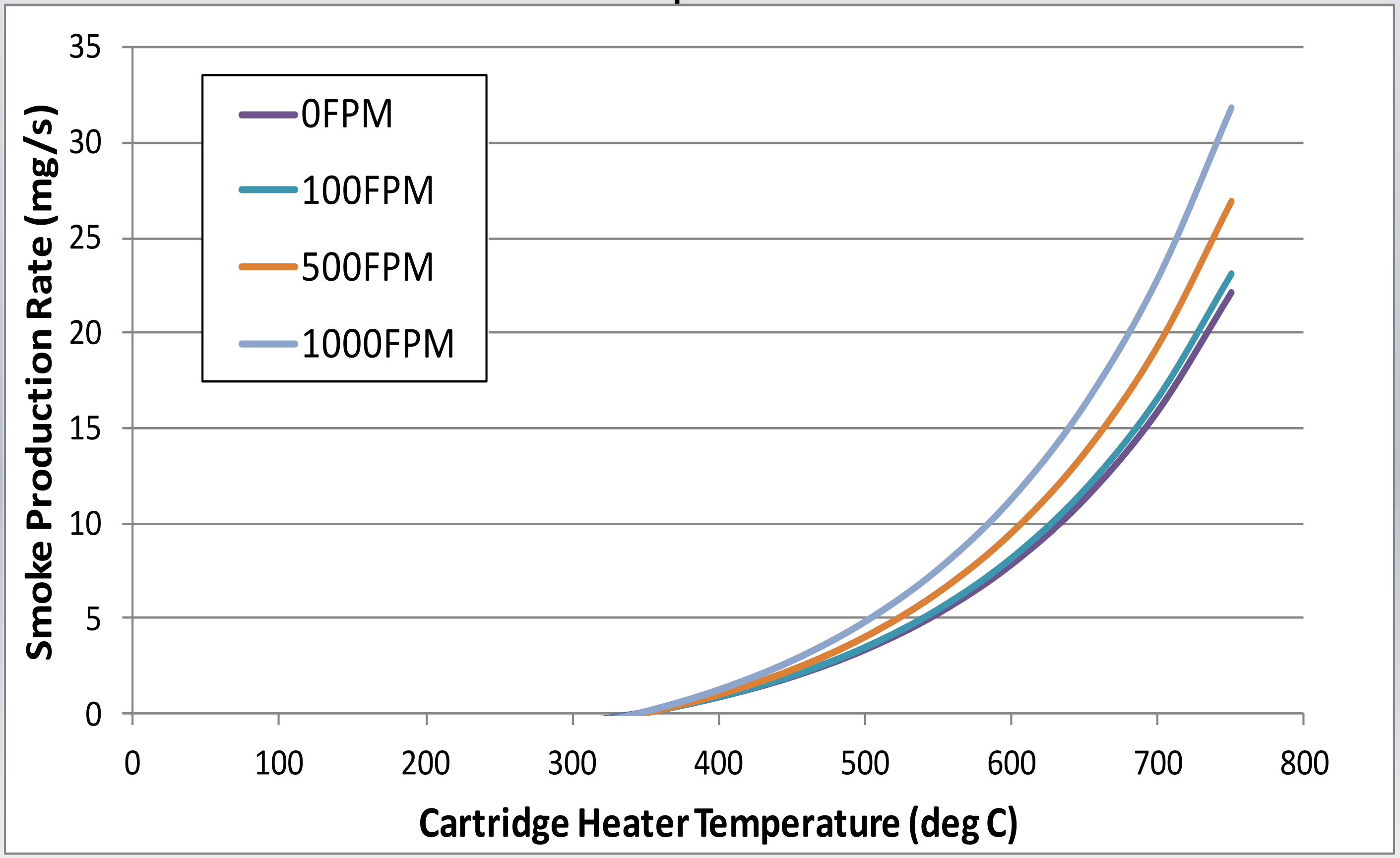
Soot yield as a function of gas burning rate



FIRE SOURCE CHARACTERIZATION

Electrical Cables

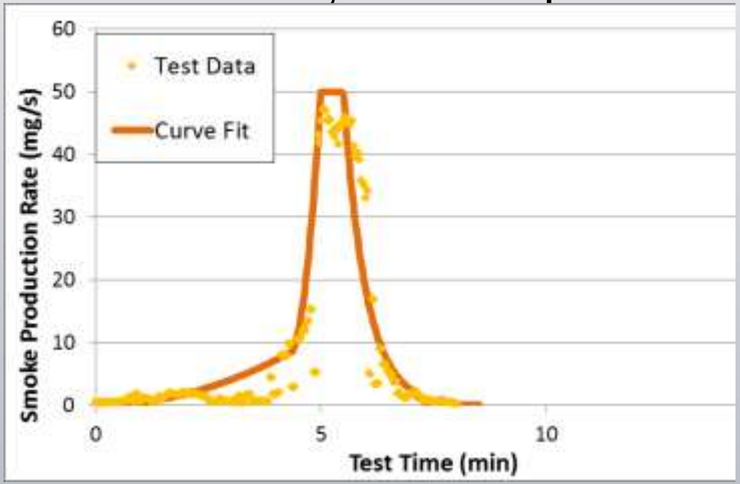
Soot yield as a function of air flow rate and heater temperature

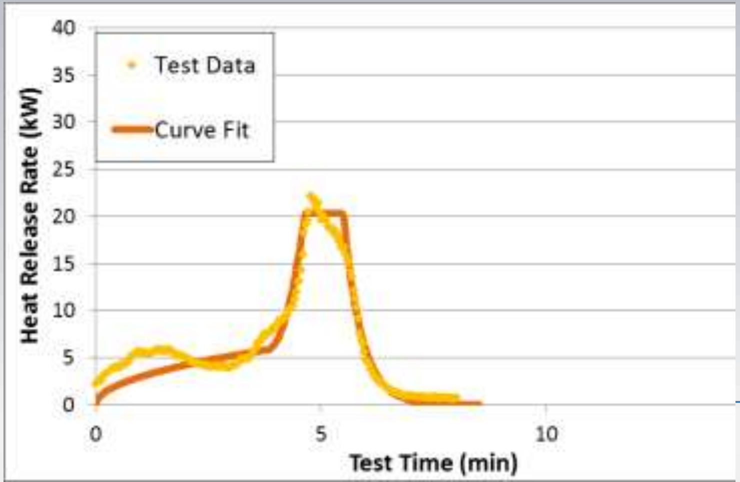


FIRE SOURCE CHARACTERIZATION

Flaming Foam

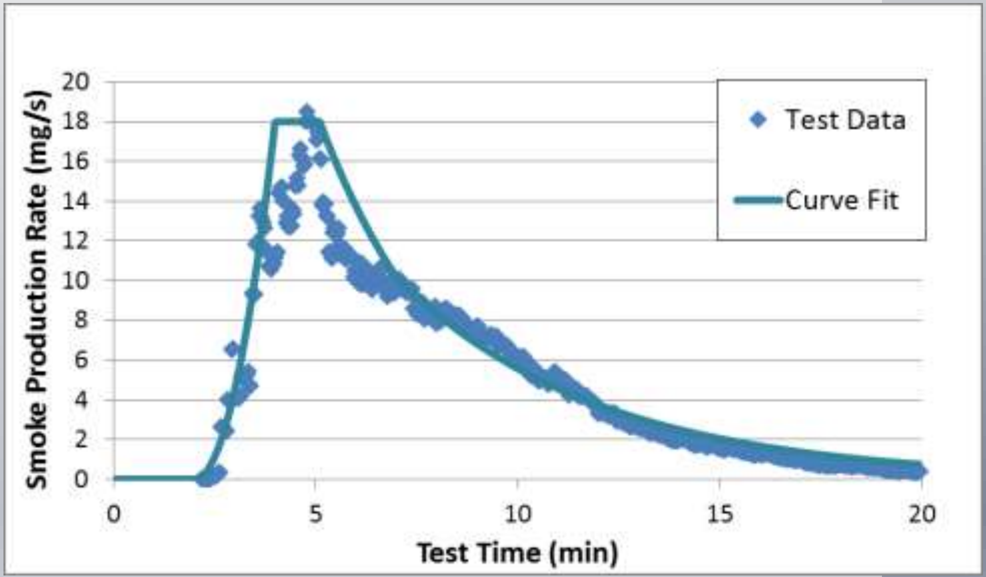
Curve fits for transient soot yield, heat release, and CO production





Circuit Boards

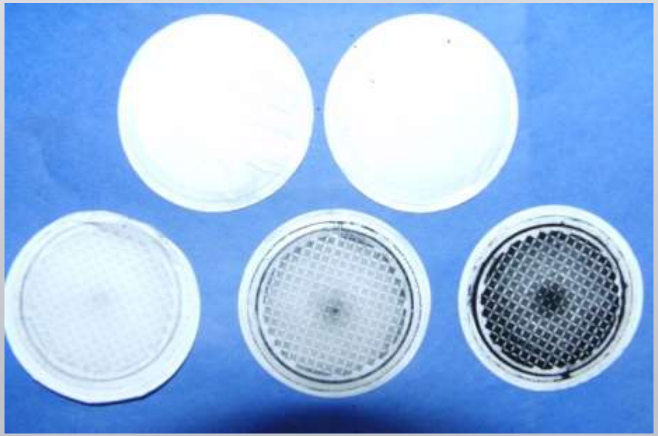
Curve fits for transient soot yield



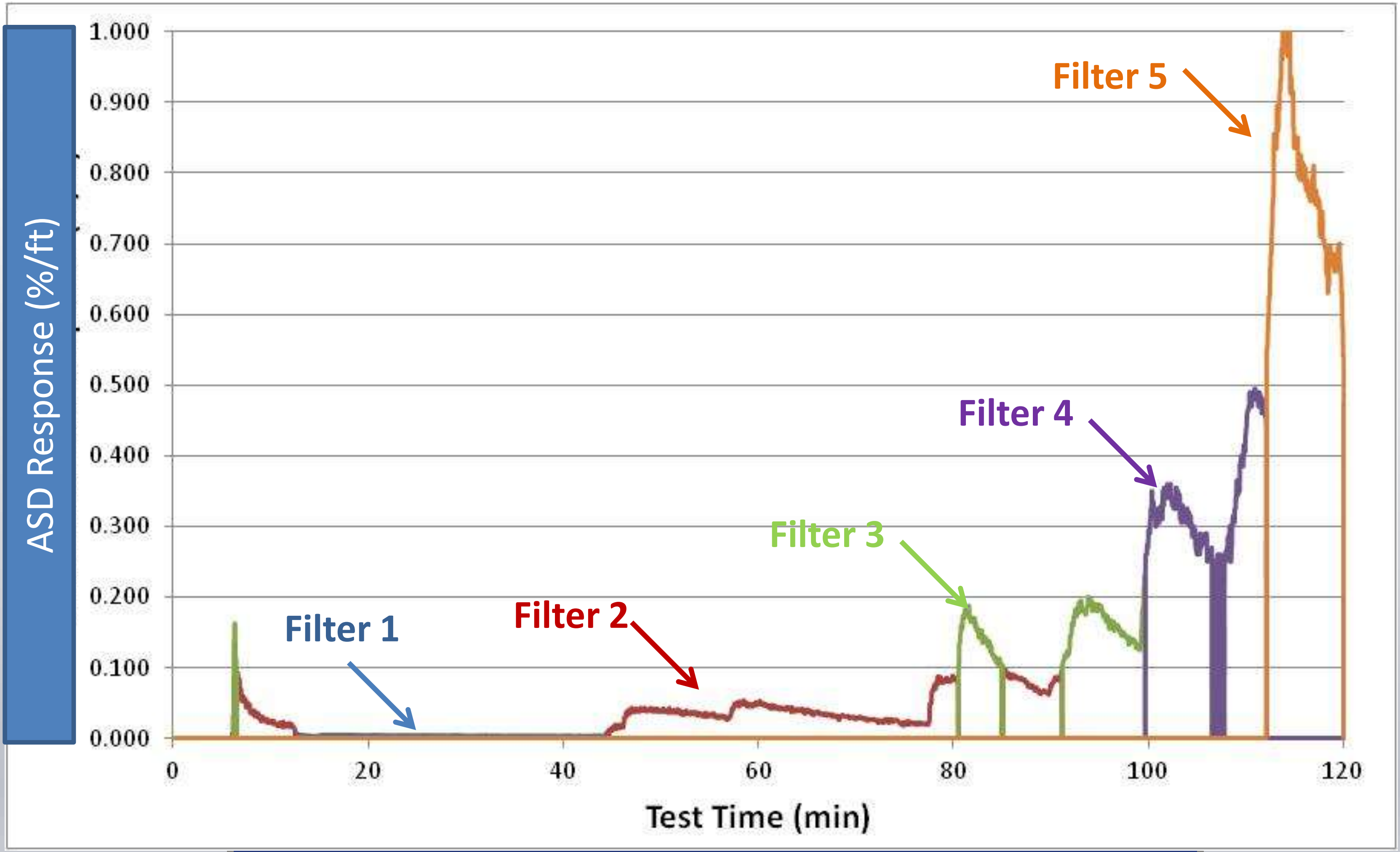
DETECTION RESPONSE

Gravimetric smoke collection manifold

- Aspiration Smoke Detector Response (%/ft) → Select filter for collection
  - **ASD** < 0.001 %/ft → No Filter
  - 0.001 ≤ **ASD** < 0.10 %/ft → Filter 1
  - 0.10 ≤ **ASD** < 0.25 %/ft → Filter 2
  - 0.25 ≤ **ASD** < 0.5 %/ft → Filter 3
  - 0.5 ≤ **ASD** < 1.0 %/ft → Filter 4
  - 1.0 %/ft ≤ **ASD** → Filter 5



- Filter weighed to measured collected smoke mass
- Correlate average mass concentration with average detector response

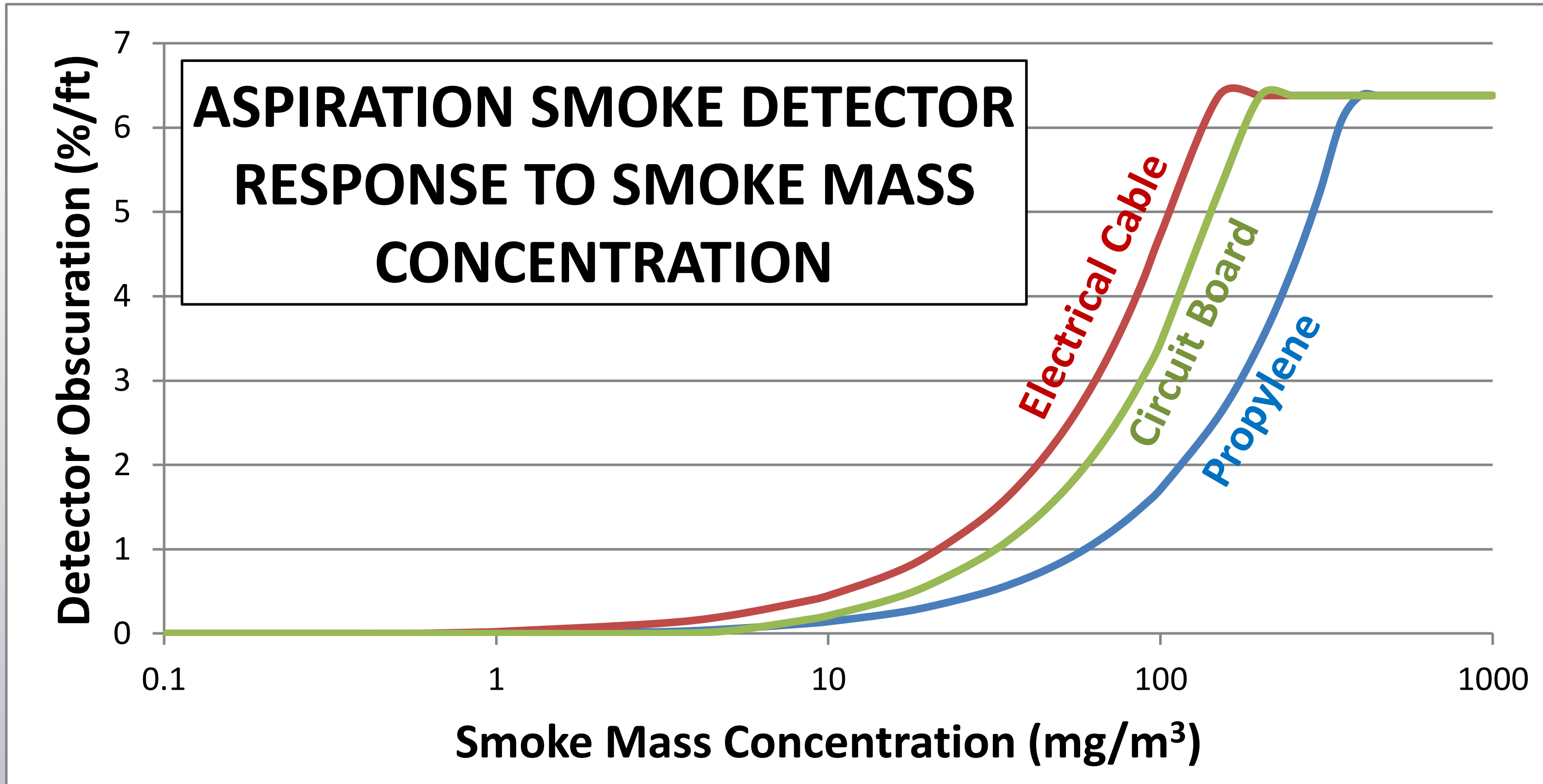


GRAVIMETRIC FILTER COLLECTION

Collect Smoke On Filter Based on ASD Detector Response

Determine Average Smoke Mass Concentration During Collection

Detector Response Correlated as Sensitive as 0.001%/ft



DETECTION RESPONSE CORRELATION

Unique response for each fire type and detector type

Predict detector response from mass concentration at detector location for different design fires

RESULTS AND APPLICABILITY

Small scale data can:

- Provide model input curves for heat and smoke sources
- Predict detector response from local smoke mass concentrations
  - Identify minimum fire size or time for detection
  - Determine optimum detection installation locations
  - Select optimum detector response thresholds (%/ft) for specific fires

Limitations

- Range of materials/fire scenarios characterized
- Number of detector models tested (1 ASD, photoelectric)

APPLICATION

Smoke Transport Model (e.g. FDS)

Detector Response Criteria (New Data)

User Selected Fire Source Input (New Data)

Use Response data to determine:

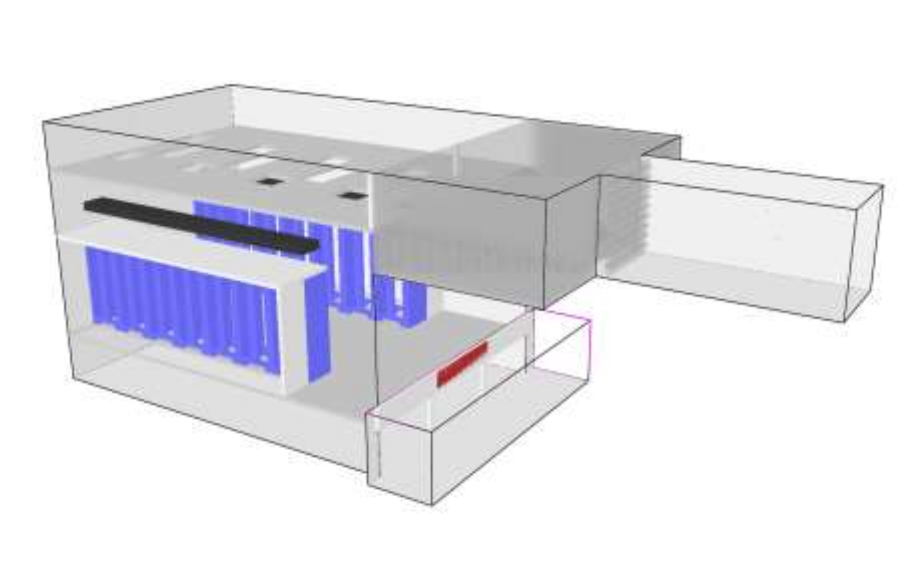
- **Alarm Threshold**
- **Time to detect**
- **Time for operator action**
- **Compare detection alternatives**

Validated model for future performance based detection design and prescriptive code development

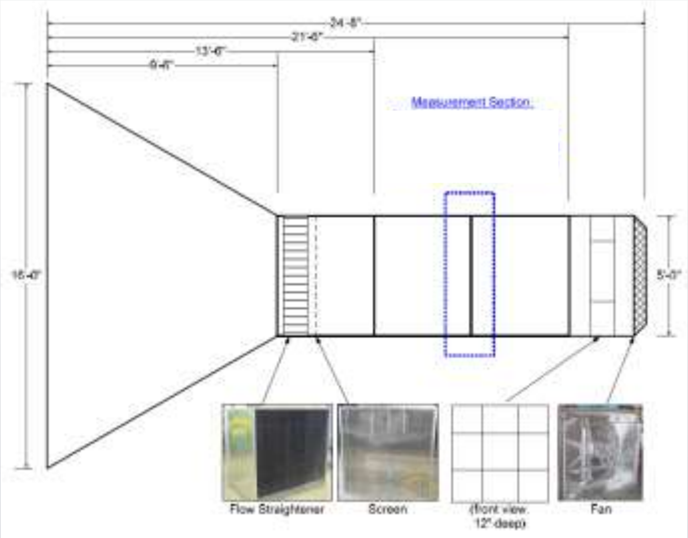
FM SLIDES HERE

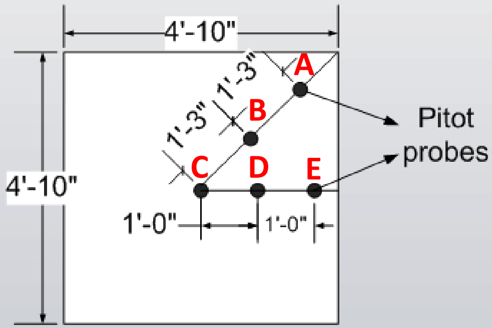
TASK 4: MODEL VALIDATION

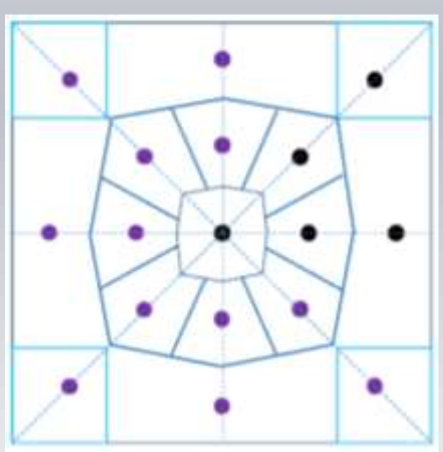
- FDS v6
- Lagrangian particles for floor/ceiling tiles and screens
- Uniform 3 inch mesh (480,000 grid cells)
- No heat transfer (heat sources small compared to flow rate)



TOTAL FAN FLOW RATE





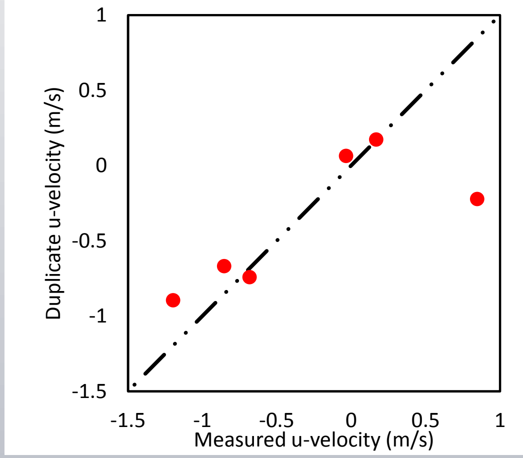


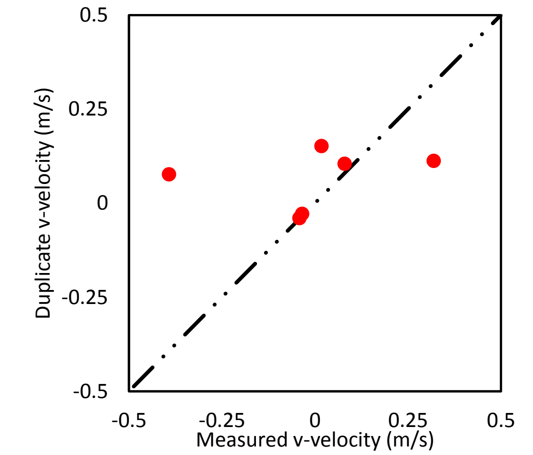
Fuel	Location	Low (37 %) Fan Speed (cfm)	High (100 %) Fan Speed (cfm)
Propane	Subfloor	8560	26270
Propane	Hot Aisle	8370	26640
Circuit Board	Cabinet	8810	27220
Polyethylene	Cold Aisle	8500	26240
Average		8560	26590

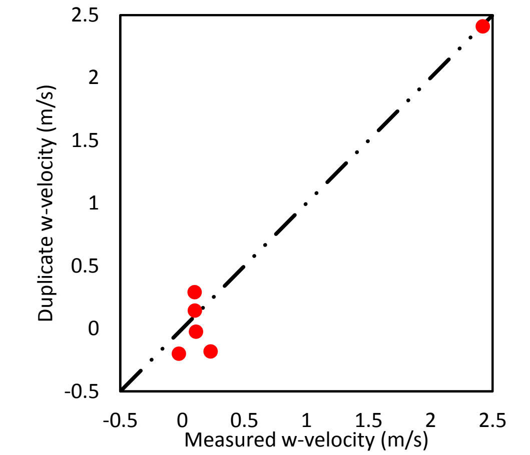
VELOCITY TESTS

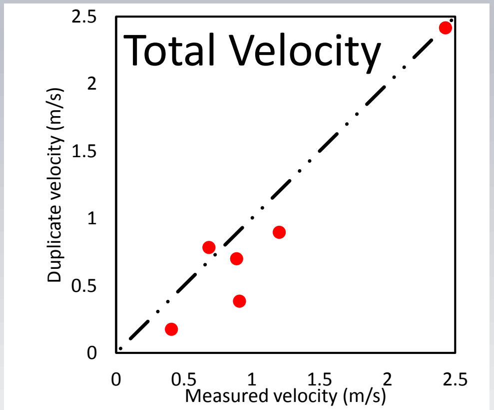
- 6 pairs of data points that were symmetric or repeat
- Comparing points gives a 53 % expanded error, point-by-point from 1 % to 118 %

All Components



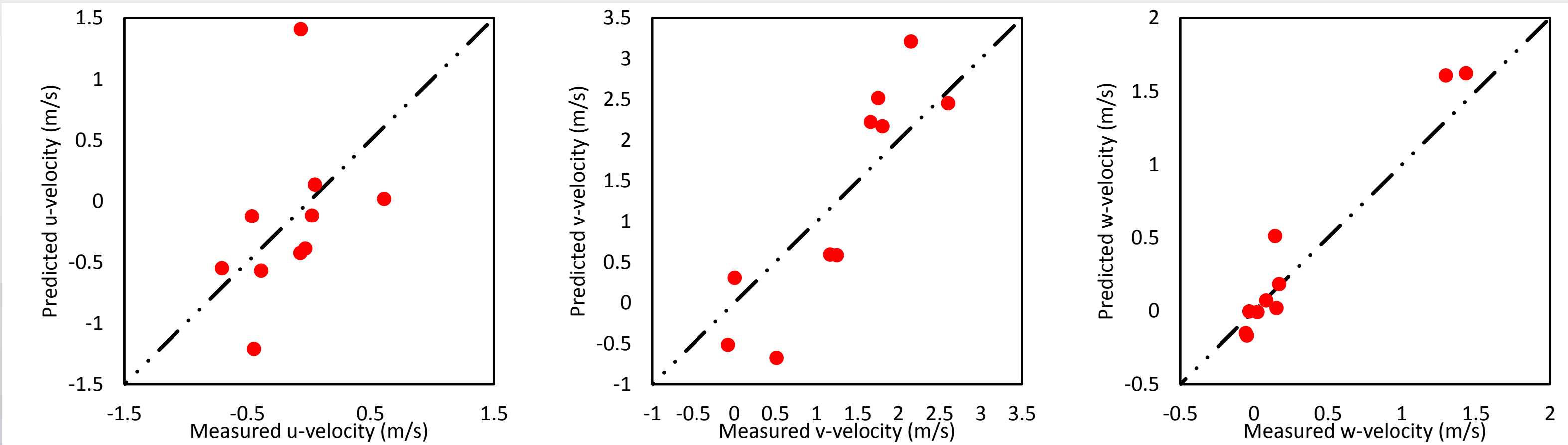




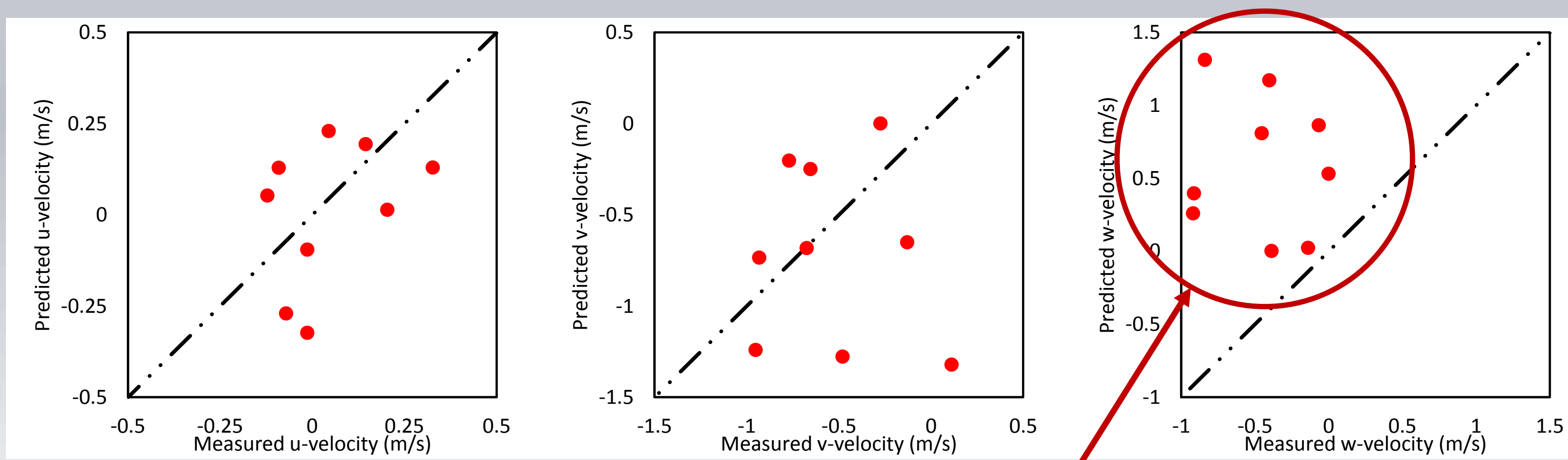


VELOCITY PREDICTIONS

Subfloor

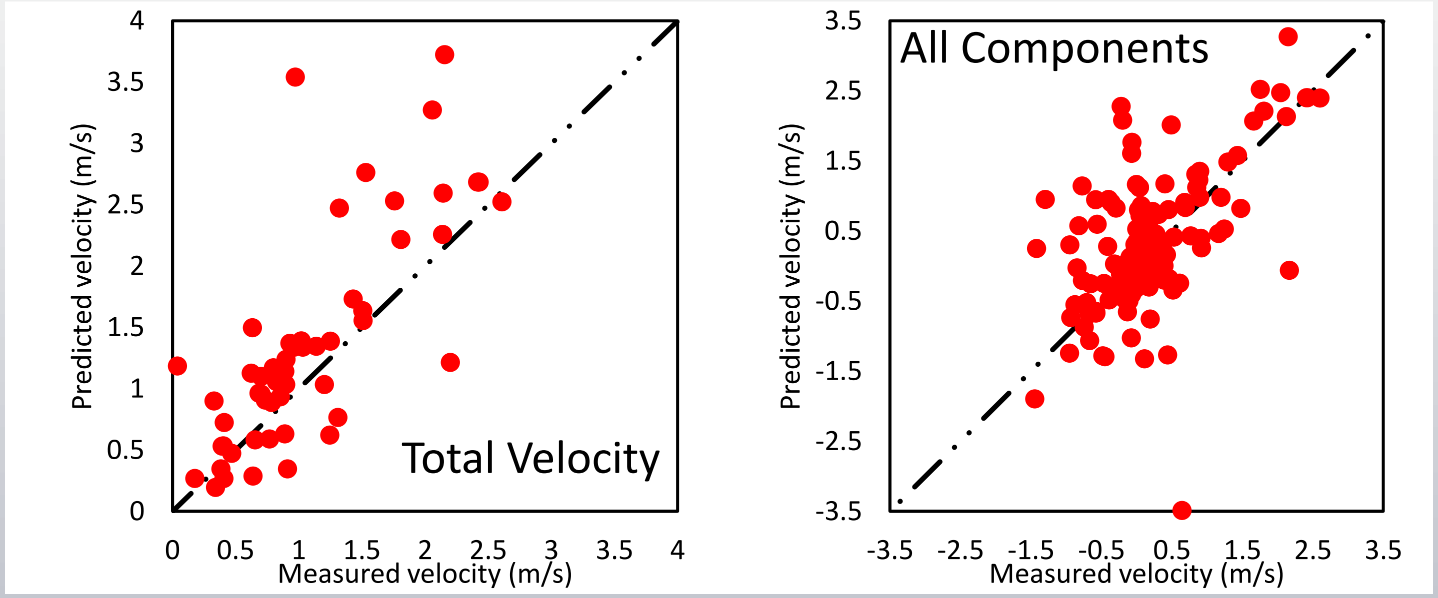


Centerline of Hot Aisle



All measured points negative

VELOCITY PREDICTIONS



- Propagating repeat measure error and exhaust flow measurement error (assumed 7 %) is a 55 % measurement error
- Model error (cannot be less than measurement) is 65 % with a 1.19 bias (suggests fan flow may be over estimated)

Detector Response Error

- Combination of response correlation error and smoke source error.
- Smoke source error (does not include error from differences in FM setup):
  - Propylene: 10 % (primarily flow meter error at low flow rates)
  - Circuit board: 43 % (plateau variance during testing)
  - Polyethylene foam: 15 % (plateau variance during testing)
- Correlation error (average variance in repeat measurements during correlation development)

Detector	Propylene		Board		Foam	
	Ave	Range	Ave	Range	Ave	Range
VIEW	44 %	15 – 120 %	135 %	4.2 – 340 %	52 %	5.4 – 150 %
FAAST	28 %	18 – 56 %	90 %	8.7 – 130 %	83 %	26 – 260 %
True Alarm	29 %	7 – 120 %	190 %	5.4 – 1100 %	40 %	0 – 120 %

Detector Response Error

- Propagation of error (smoke source and response):

Detector	Propylene	Board	Foam
VIEW	45 %	135 %	53 %
FAAST	51 %	100 %	93 %
True Alarm	33 %	191 %	43 %

PROPYLENE – LOW SPEED, HOT AISLE

Detector Location		Detection Response (% /ft)					
Height	Position	VIEW (45 % exp. error)		TrueAlarm (51 % exp. error)		FAAST (33 % exp. error)	
		FDS	FM	FDS	FM	FDS	FM
Subfloor	West	0.0	None	0.03	0.00	0.02	0.00
	Center	0.02	None	0.03	0.00	0.02	0.00
	East	0.02	None	0.03	0.00	0.02	0.00
Ceiling	West	1.30	1.40	2.27	2.16	0.57	0.36
	Center	0.01	None	0.05	0.00	0.02	0.01
	East	0.15	None	0.31	0.08	0.09	0.00
Ceiling Plenum	West	0.64	0.77	1.07	1.88	0.29	0.17
	Center	0.56	0.10	1.34	0.62	0.28	0.07
	East	0.33	0.10	0.68	0.49	0.16	0.07

- Other propylene tests similar
- In locations with high response, predictions within uncertainty
- In predictions with low response, predictions not always within uncertainty
- Response correlations primarily based on higher response data using least squares fit. Expect higher relative error for low responses.

CIRCUIT BOARD

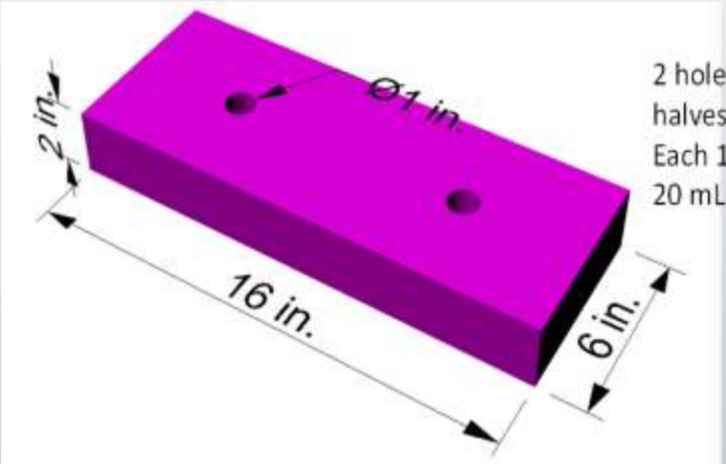
- Hughes test configuration was vertical
- FM test configuration was horizontal (kept gap between boards parallel to airflow)
- Likely some impact to smoke generation

CIRCUIT BOARD – LOW SPEED

Detector Location		Detection Response (% /ft)					
Height	Position	VIEW (135 %)		TrueAlarm (100 %)		FAAST (191 %)	
		FDS	FM	FDS	FM	FDS	FM
Subfloor	West	None	None	None	0.00	None	0.000
	Center	None	None	None	0.01	None	0.000
	East	None	None	None	0.01	None	0.000
Ceiling	West	None	None	None	0.08	None	0.004
	Center	0.07	None	0.29	0.21	0.067	0.000
	East	0.00	None	0.01	0.02	0.005	0.000
Ceiling Plenum	West	None	None	None	0.00	None	0.004
	Center	0.07	0.20	0.28	0.98	0.073	0.024
	East	None	0.05	0.11	0.07	0.012	0.008

- Higher response within test uncertainty.
- Lower response outside uncertainty.
- No or very low response generally match

POLYETHYLENE FOAM



2 holes centered on block halves
Each 1 in. deep filled with 20 mL 2-propanol

- Initial testing with Hughes source had no response.
- Source modified to be two blocks high.
- Observed behavior in FM test different from Hughes test (no collapse to pool)
- Unknown impact on smoke generation rate

POLYETHYLENE FOAM – LOW SPEED

Detector Location		Detection Response (% /ft)					
Height	Position	VIEW (53 % exp. error)		TrueAlarm (93 % exp. error)		FAAST (43 % exp. error)	
		FDS	FM	FDS	FM	FDS	FM
Subfloor	West	0	None	0.01	0.02	0.054	0.000
	Center	0.03	None	0.01	0.04	0.054	0.000
	East	0.03	None	0.01	0.16	0.054	0.000
Ceiling	West	0.45	0	0.28	0.32	1.74	0.043
	Center	None	None	0.00	0.01	0.12	0.000
	East	None	None	0.00	0.00	0.13	0.000
Ceiling Plenum	West	0.42	0	0.25	0.01	1.33	0.024
	Center	0.11	None	0.09	0.01	1.01	0.004
	East	None	None	0.03	0.00	0.48	0.002

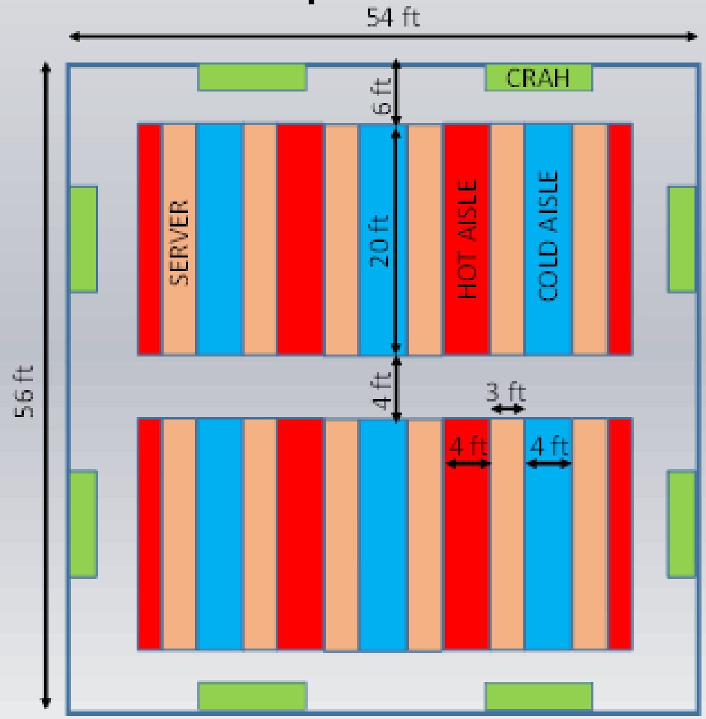
- Poor agreement, likely change in smoke source
- Relative agreement good: locations with higher measured response have higher predicted response

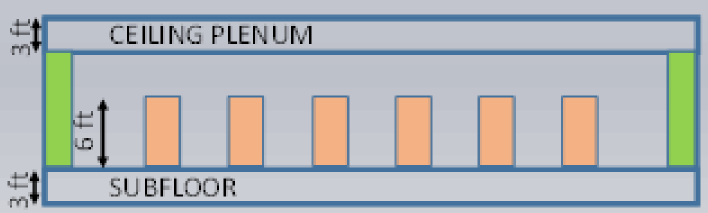
VALIDATION SUMMARY

- Velocities
  - Velocities well predicted for dominant flow direction (e.g. vertical at cold aisle floor, inlet flow in subfloor)
  - Velocity agreement poorer for non-dominant flows
  - Overall velocity prediction error equivalent to experimental error
- Detection Response
  - Propylene, best characterized source, predicted within uncertainty for higher levels of response.
  - Circuit board source (likely some orientation impact), generally predicted within uncertainty for higher levels of response
  - Poor agreement for polyethylene foam source

TASK 5: DEVELOP INSTALLATION GUIDANCE

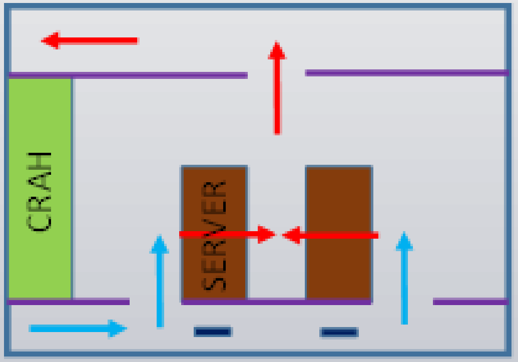
- Model a range of data center configurations, power densities, and smoke sources
- Develop placement and spacing recommendations based on predicted detection response



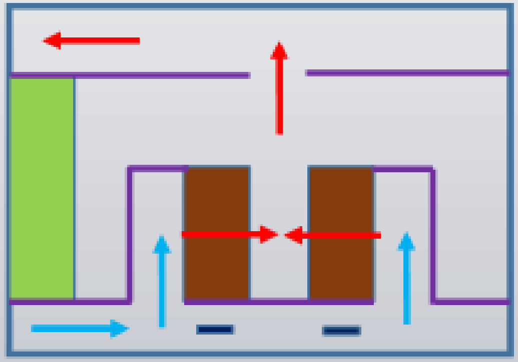


AIR FLOW CONFIGURATIONS

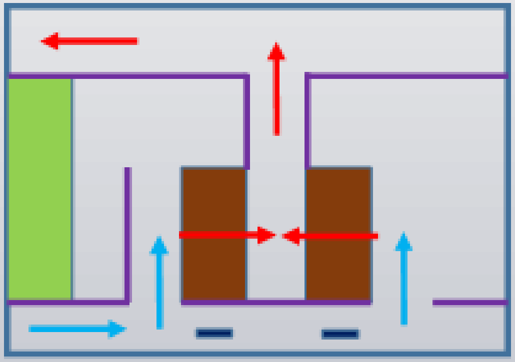
Ceiling plenum, subfloor, no confinement



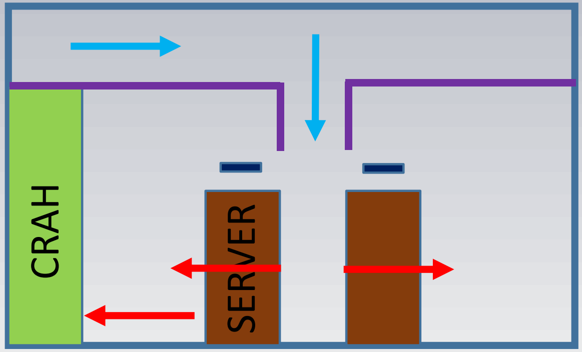
Ceiling plenum, subfloor, cold aisle confinement



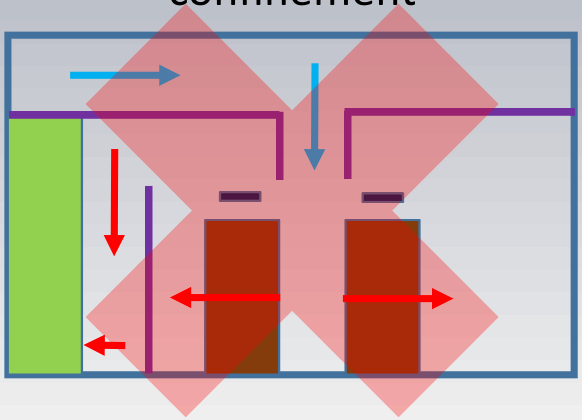
Ceiling plenum, subfloor, hot aisle confinement



Ceiling plenum, no subfloor, no confinement



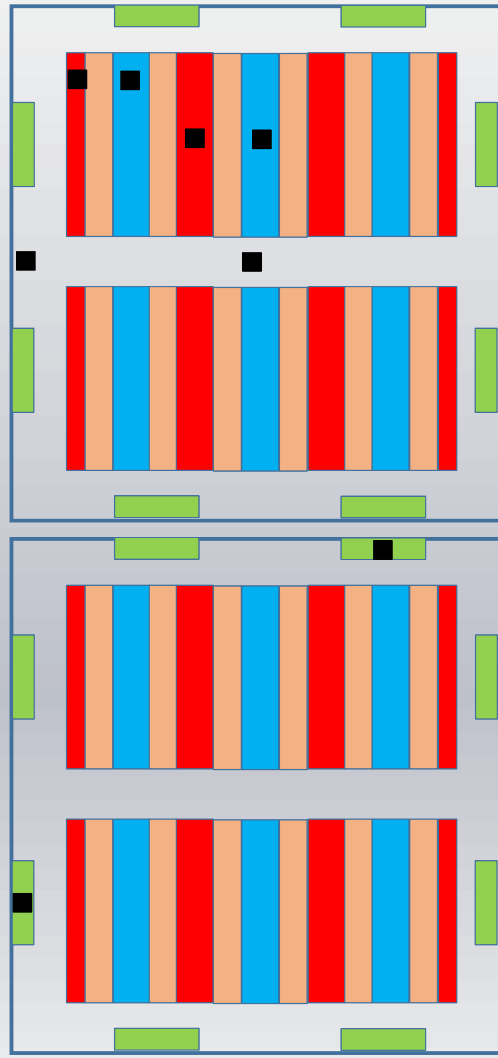
Ceiling plenum, no subfloor, CRAH confinement



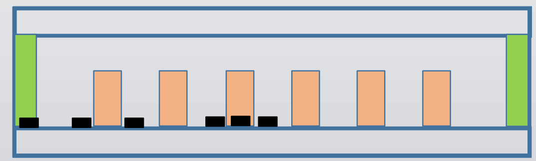
OTHER VARIABLES

- Power density: 50, 100, 200, 600, and 1000 W/ft^2
- Ceiling height: 10 ft and 20 ft (4 and 14 ft from top of servers to ceiling)
- Fire location: server cabinets, CRAH units, cable trays, aisles
- Smoke source type: Class A (aisles), cables (trays, server cabinets, CRAH), circuit boards (server cabinets)
- Recirculation: 0 % and 100 % (0 % used for most)

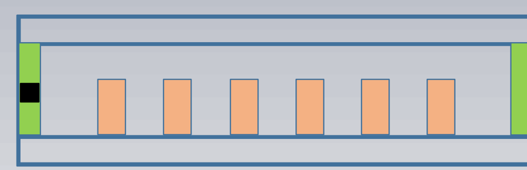
FIRE SOURCE LOCATIONS



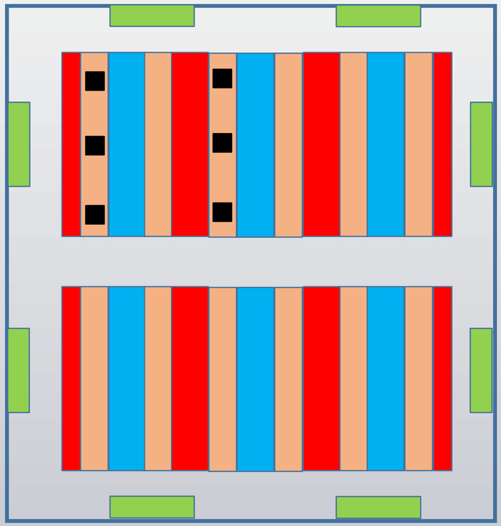
Class A Fire

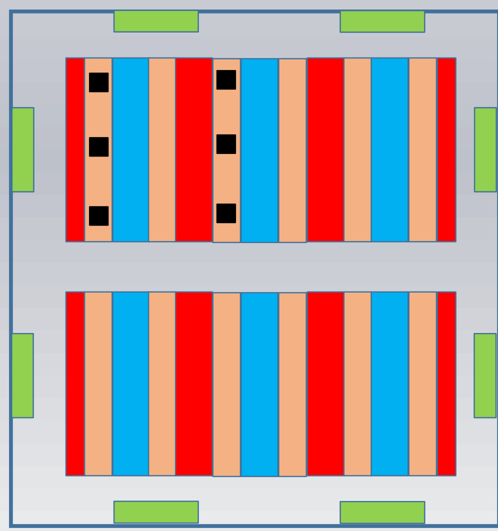


CRAH

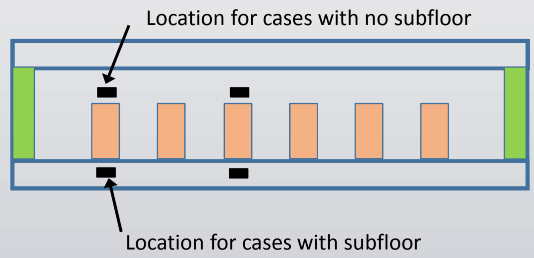


FIRE SOURCE LOCATIONS

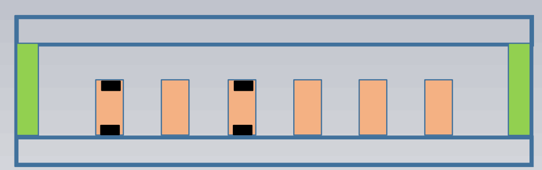




Cable Tray



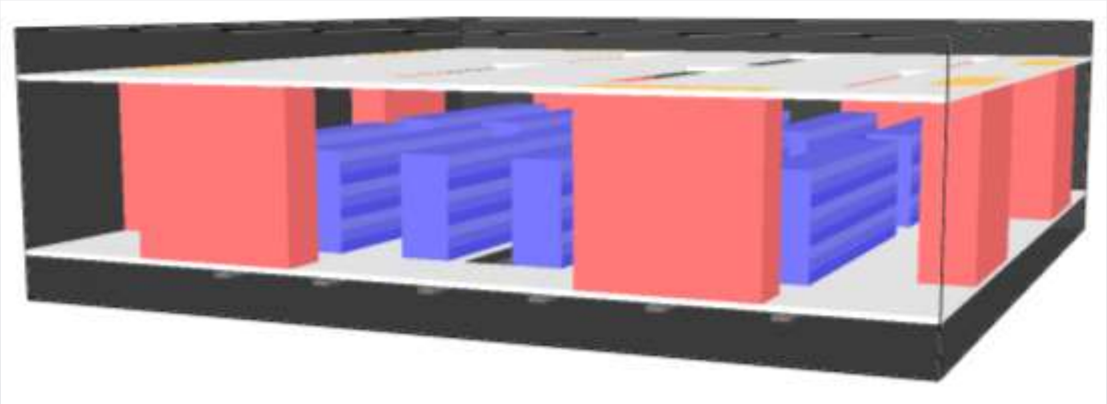
Server



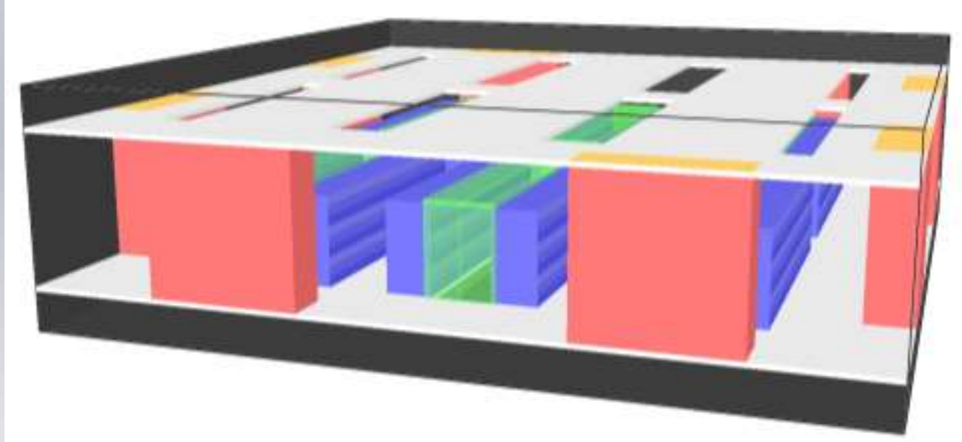
FDS MODEL DETAILS

- 4 inch mesh
- 4 meshes
- No surface heat transfer
- Constant specific heat
- Lagrangian particles for ceiling and floor openings

Plenum, subfloor, no confinement



Plenum, subfloor, cold confinement



DETECTION RESPONSE

- Plausible locations for detection: bottom of subfloor, bottom of suspended ceiling, roof of ceiling plenum, inside CRAH (supply or exhaust), ceiling of cold aisle
- Looked at low, medium, and high responses:
- TrueAlarm: 0.2, 0.5, 1 %/ft
- FAAST: 0.002, 0.02, 0.2, 1 %/ft
- VIEW: 0.02, 0.2, 1 %/ft

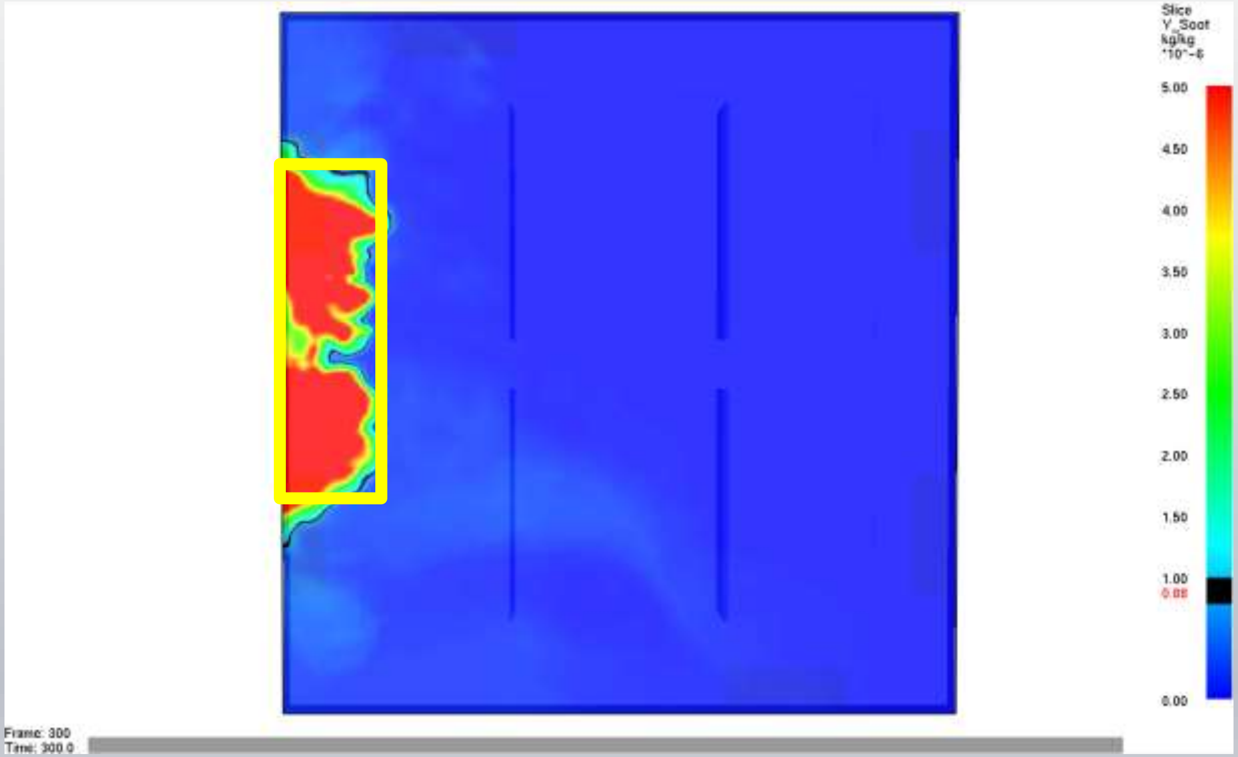
$$y_{detector} = a_{sv}v_{sv} + a_{dv}v_{dv} + a_f d + a_s s + c$$

- Fix source velocity (sv) based on source location, filter size (f), and detector velocity based on nominal detector flow (dv)

$$y_{detector} = a_s s + c_4(\text{source location, detector location})$$

- Solve for soot mass fraction (s) for each detection response level

DETECTION RESPONSE



Class A smoke source at 80 kW in size.
Black contour is VIEW 0.02 %/ft response
Estimate spacing based on area within contour

EARLY OBSERVATIONS FOR HIGH AIRFLOW

- With no recirculation CRAH detection not effective for smoldering sources
- Cold aisle detection effective for cable tray and Class A in cold aisle locations, otherwise in-effective
- Hot aisle detection effective for all sources, but spacing requirements can be small for smoldering sources.
- With no recirculation subfloor generally ineffective even for subfloor sources (smoke can quickly leave subfloor through cold aisles)
- For high air flows, detection will likely occur only at lowest sensitivity settings for smoldering sources.