Module V – Advanced Fire Modeling

Principals of Fire Behavior

Joint EPRI/NRC-RES Fire PRA Workshop
August 13-17, 2018

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A Collaboration of the Electric Power Research Institute (EPRI) & U.S. NRC Office of Nuclear Regulatory Research (RES)

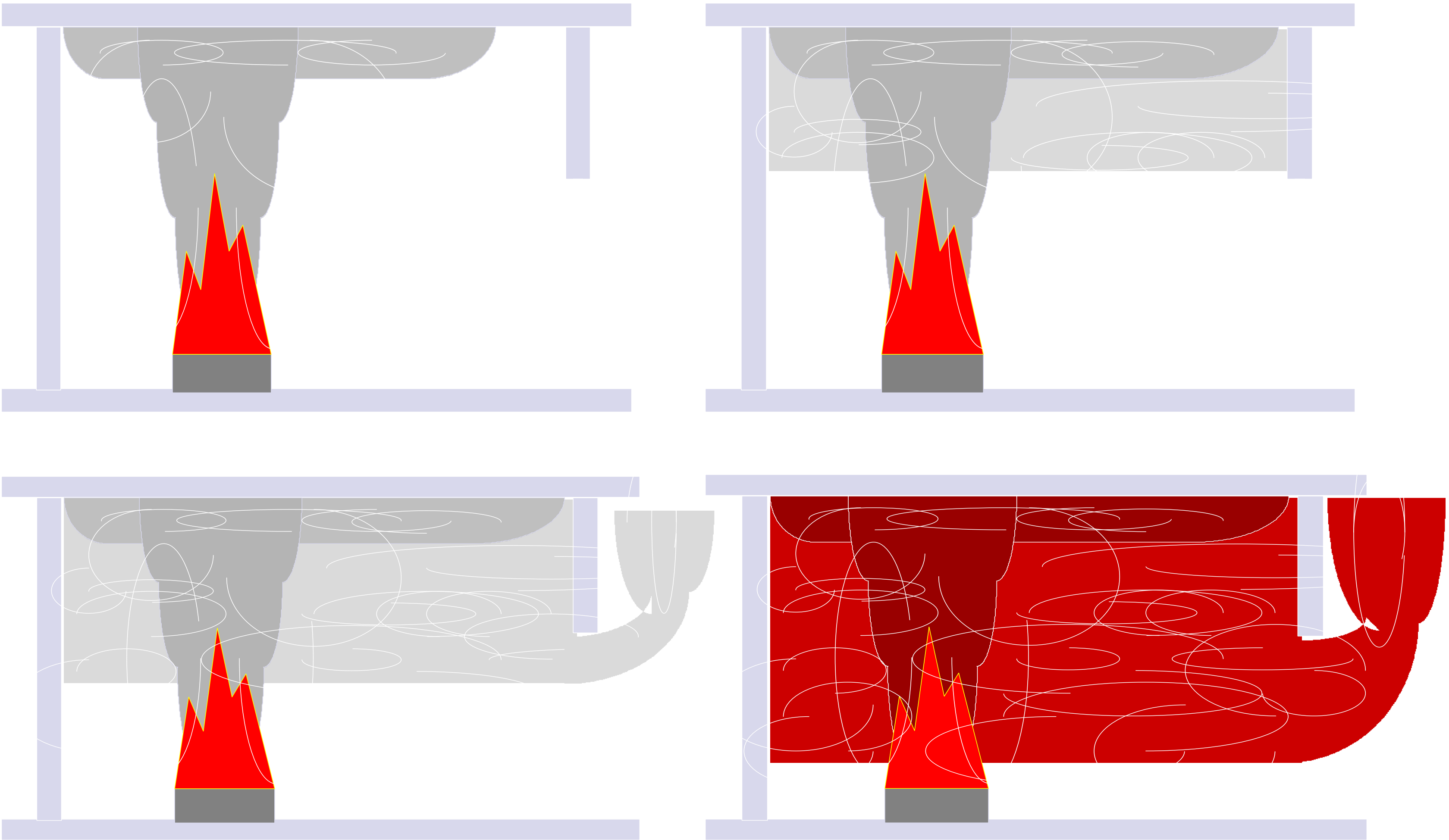
Topics

- Stages / elements of enclosure fires
- Ignition and heat release
  - CHRISTIFIRE (Cable Heat Release, Ignition, Spread in Trays in Fire)
- Fire plumes and ceiling jets
- Heat and smoke detection
- Structural response / damage
- Cable response / damage
  - CAROLFIRE (Cable Response to Live Fire)

Fire scenario development / analysis

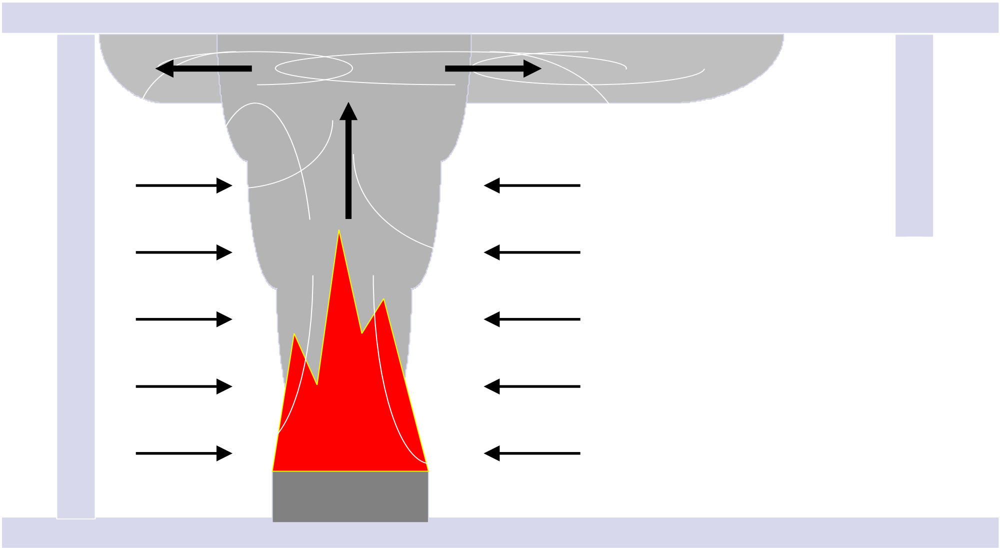
- To analyze fire scenarios, need to consider:
  - Stage(s) of fire development to include in analysis
  - Elements to include in fire scenario (fuels, targets ...)
  - Data sources for elements (HRRs, properties, damage criteria)
  - Fire modeling tool(s) to be used for the analysis
    - Empirical correlations (Heskestad plume, MQH, FPA ...)
    - Zone model (CFAST, MAGIC)
    - CFD model (FDS)
- This module provides overview of fire modeling concepts

Stages of enclosure fires



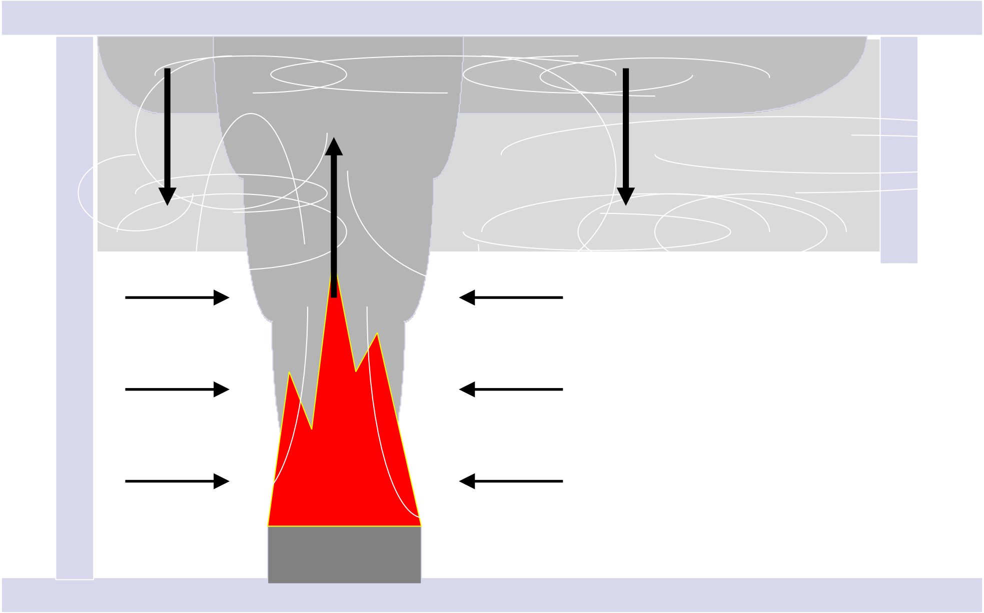
Stage 1 - Fire plume / ceiling jet period

- Buoyant gases rise to ceiling in fire plume
- Ceiling jet spreads radially until confined
- Plume entrains surrounding air
- Temperature decays rapidly with height and radial distance



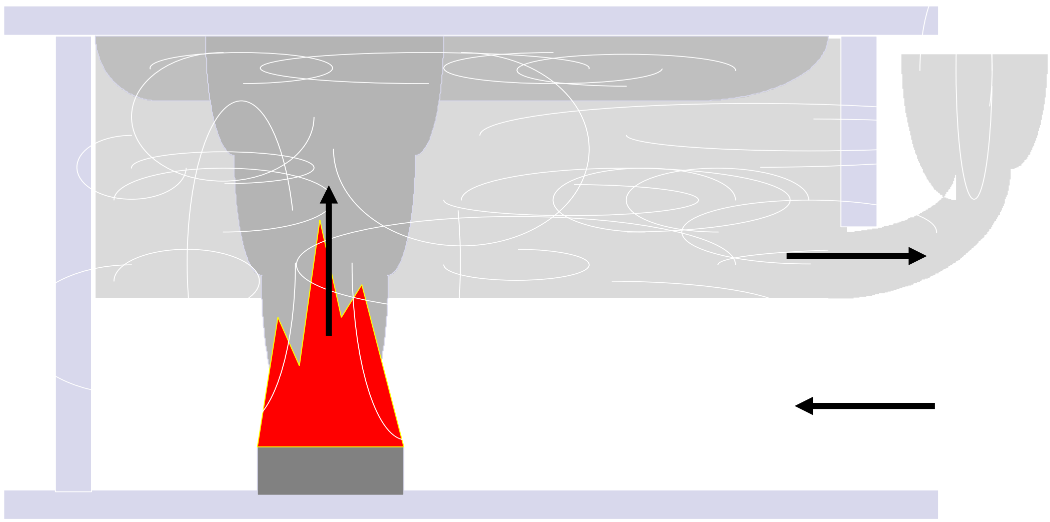
Stage 2 - Enclosure smoke filling period

- Period begins when ceiling jet reaches walls
- Period ends when smoke flows through vents
- Smoke layer fills due to entrainment / expansion



Stage 3 - Preflashover vented period

- Quasi-steady mass balance develops
- Smoke layer equilibrates at balance point
- Mass balance influenced by sizes, shapes and locations of vents and by mechanical ventilation
- Mass balance influences energy/species balances



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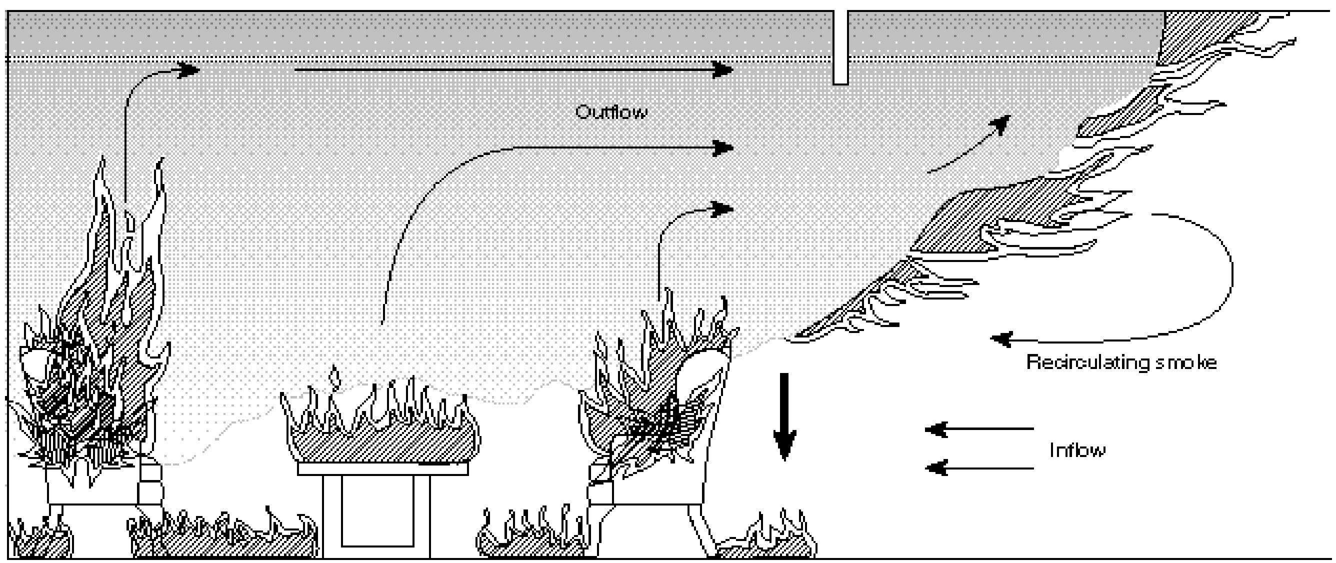
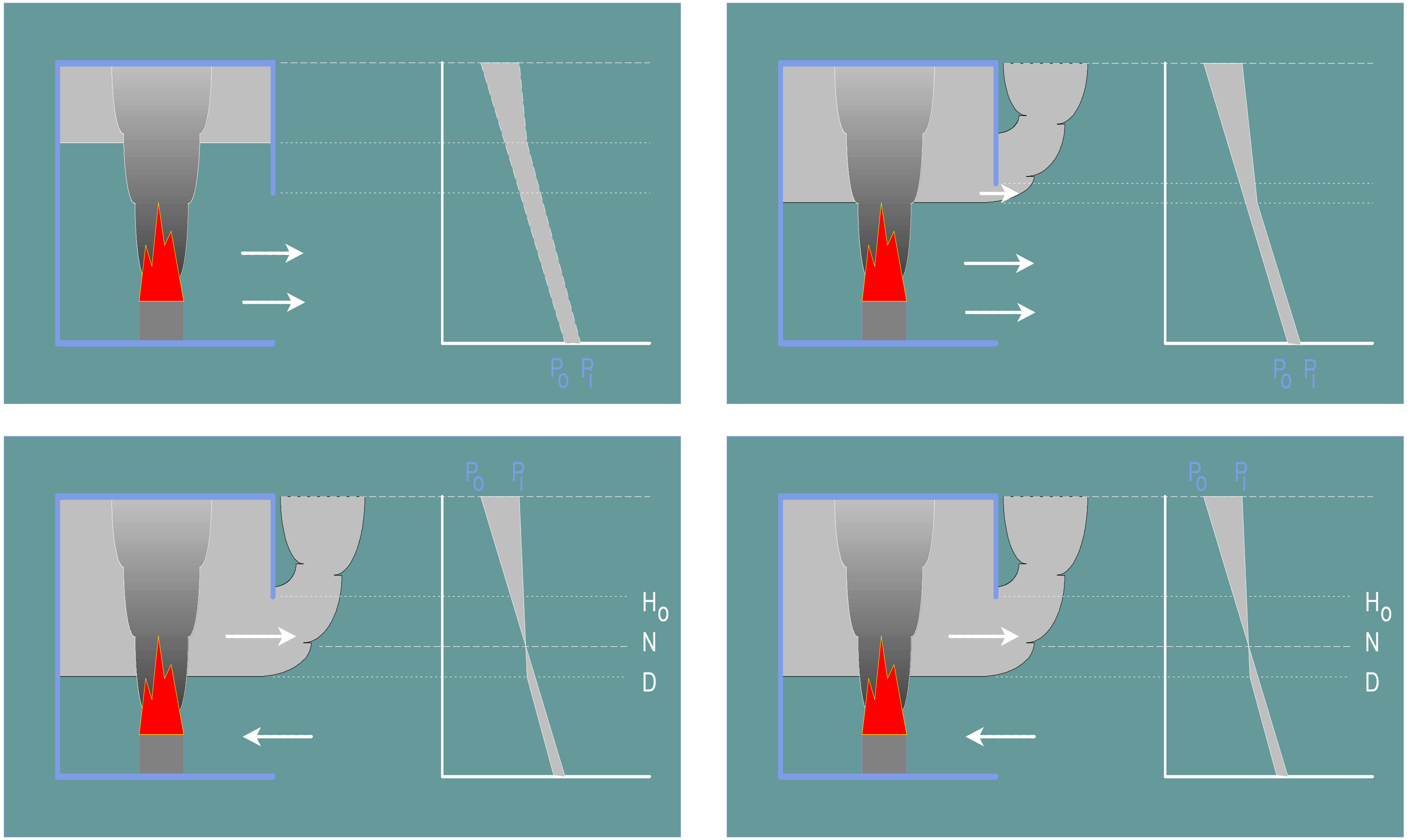
Stage 4 - Postflashover vented period

- Period begins when secondary fuels begin to ignite from radiant exposure
- Post-flashover fires frequently become ventilation-limited, with flames extending out of vents
- Underventilation affects smoke production

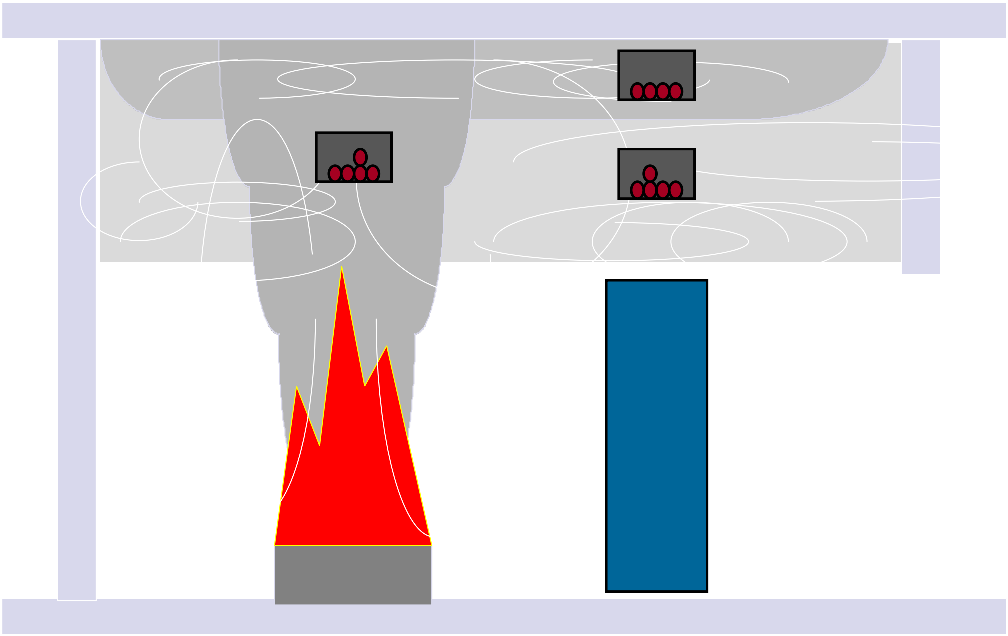


Vent flow stages



Elements of enclosure fires

- Fire source
- Fire plume
- Ceiling jet
- Upper gas layer
- Lower gas layer
- Vents / ventilation
- Boundaries
- Targets



Elements of enclosure fires

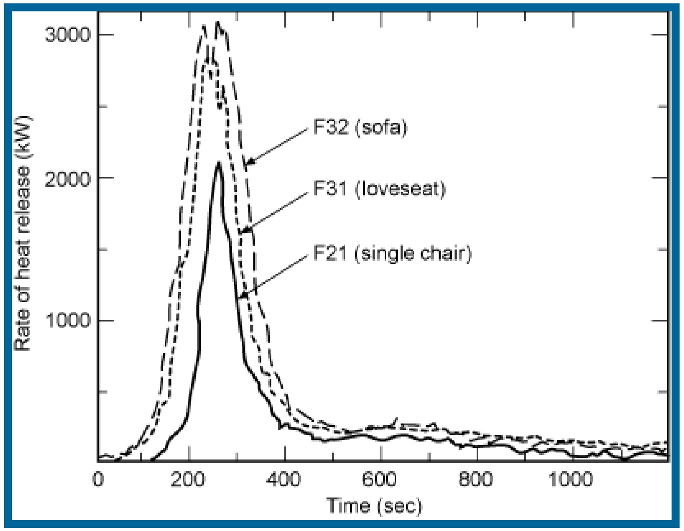
DESIGN ELEMENT	EXAMPLE TYPES	PHYSICAL ATTRIBUTES	GEOMETRIC ATTRIBUTES
FUELS	FINISHES FURNISHINGS	MATERIALS QUANTITIES RELEASE RATES	LOCATIONS DIMENSIONS
BOUNDARIES	WALLS CEILINGS FLOORS	MATERIALS	LOCATIONS DIMENSIONS
TARGETS	PEOPLE EQUIPMENT PRODUCTS	DAMAGE CRITERIA	LOCATIONS DIMENSIONS
NATURAL VENTILATION	DOORS WINDOWS	STATUS ACT. PARAMETER	LOCATIONS DIMENSIONS
MECHANICAL VENTILATION	INJECTION EXTRACTION BALANCED	FLOW RATES STATUS ACT. PARAMETER	LOCATIONS DIMENSIONS

Design fire

- HRR as function of time is termed the *design fire*
- Approaches to determining *design fire*:
  - Knowledge of amount/type of combustibles
    - Object assumed to ignite and burn at known rate
    - HRR history based on experimental data
  - Knowledge of occupancy
    - Little detailed data regarding specific fuels
    - Design fire based on statistics / engineering judgment

The fire source

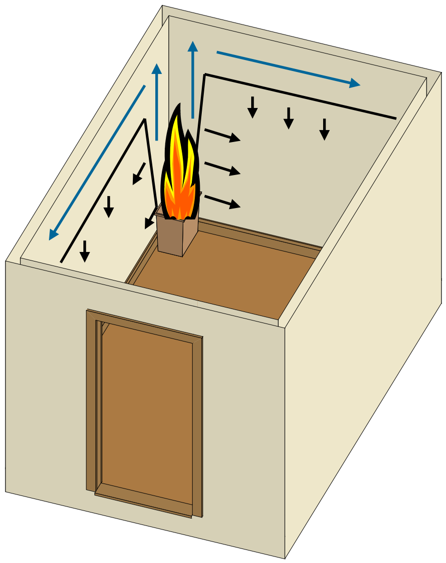
- First item
  - Ignition
  - Growth rate
  - Peak HRR
  - Burning duration
- Secondary items
  - Time to ignition
  - Burning histories



Factors controlling HRRs

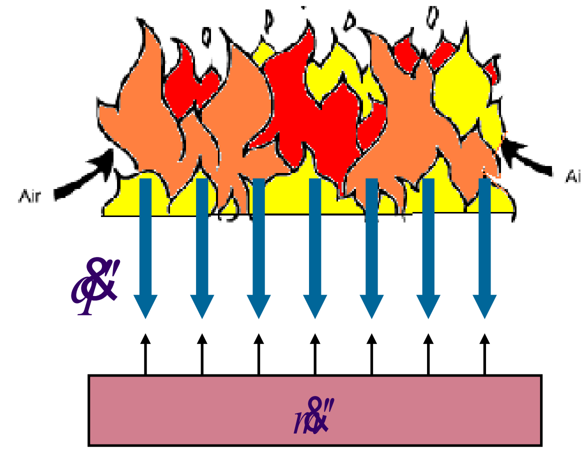
- Ignition scenarios
  - Ignition source magnitude
  - Ignition source duration
- Fuel characteristics
  - Type
  - Quantity
  - Orientation
- Enclosure effects
  - Radiation enhancement
  - Oxygen vitiation



Heat release rate

$$\dot{Q} = \dot{m}'' A \Delta H_c$$



$\dot{m}''$	Mass loss rate per unit area
A	Area of fuel that is burning
ΔH_c	Fuel heat of combustion

APPROX. HEATS OF COMBUSTION

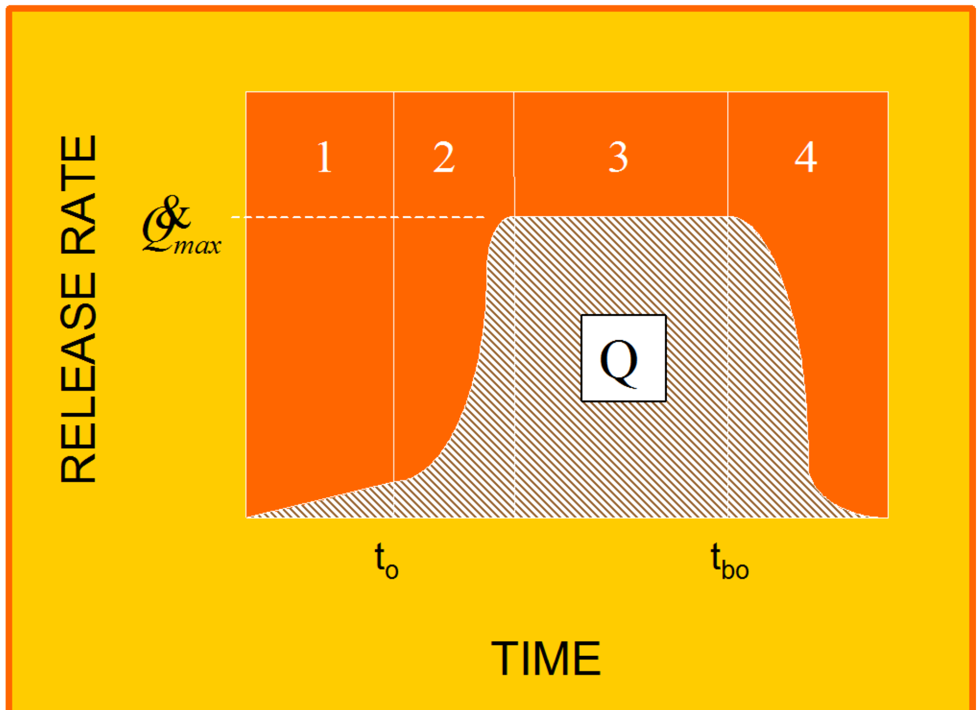
FUEL	ΔH_c (kJ/g)
WOOD	15.0
POLYURETHANE	30.0
HEPTANE	44.5

Phases of Fire Development

Total heat released by fire: $Q = \int_o^t \dot{Q}(t)dt$

Approximate burnout time: $t_b = t_{bo} - t_o \approx \dfrac{Q}{\dot{Q}_{max}}$

1. Incipient Stage
2. Growth Stage
3. Full-Developed
4. Decay/Burnout



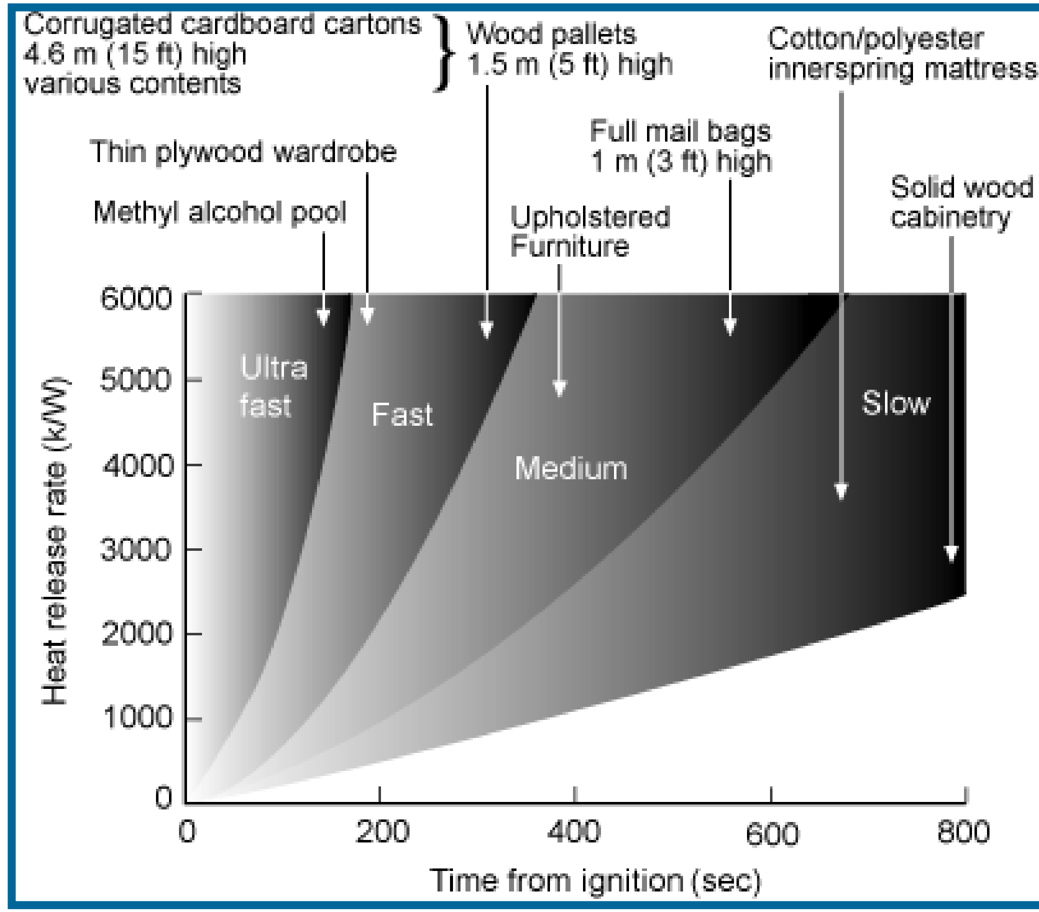
Fire growth characterization

- Power law

$$\dot{Q} = \dot{Q}_o \left(\frac{t}{t_g} \right)^n$$

- Exponential

$$\dot{Q} = \dot{Q}_o \, exp\left(\frac{t}{\tau_g} \right)$$



t^2 characterization

$$\dot{Q} = \dot{Q}_o \left(\frac{t}{t_g} \right)^2 \quad ; \quad \dot{Q}_o = 1055 \text{ kW} \quad ; \quad \alpha = \frac{\dot{Q}_o}{t_g^{\,2}}$$

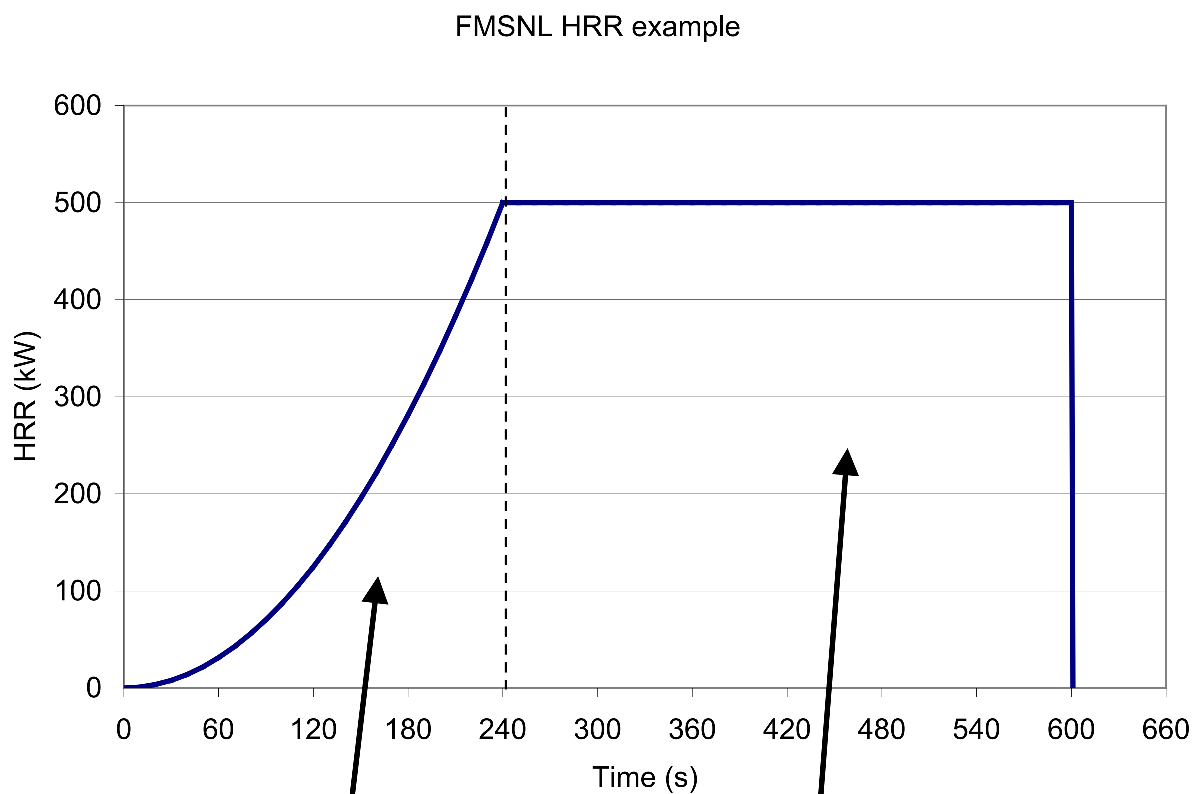
Growth rate	t_g (s)	α (kW/s^2)
Slow	600	0.003
Medium	300	0.012
Fast	150	0.047
Ultrafast	75	0.188

Fire growth characterization example

- In the FMSNL fire test series, many of the tests were conducted using a gas burner programmed to grow as a t-squared fire to reach a HRR of 500 kW in 4 minutes, then to maintain a constant HRR of 500 kW for another 6 minutes
  - What does this HRR curve look like?
  - How much energy is released during the growth phase?
  - How much energy is released during the entire test?

Fire growth characterization

- Example



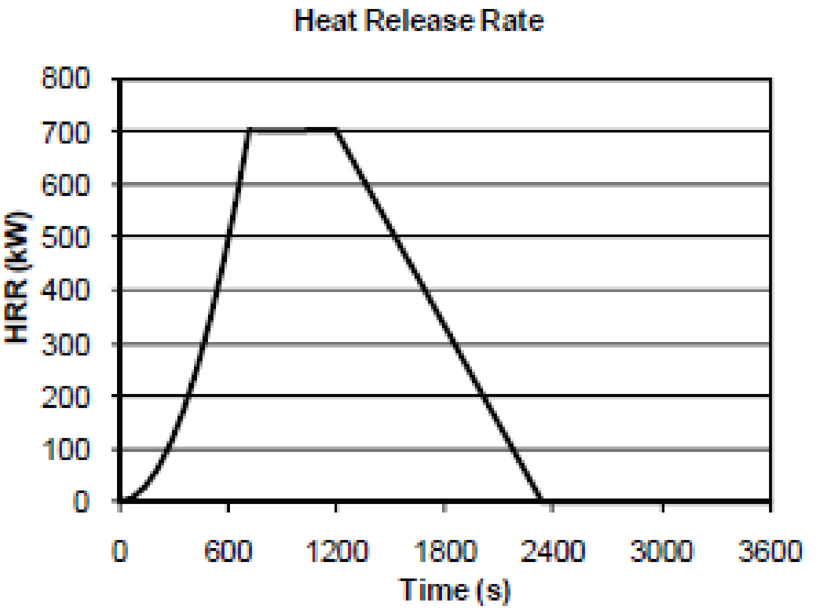
$$Q_{240s} = \int_0^{240} \frac{\dot{Q}_g}{t_g^2} t^2 dt = \frac{\dot{Q}_g}{t_g^2}\frac{t^3}{3} = \frac{500}{240^2}\frac{240^3}{3} = 40 \text{ MJ}$$

$$Q_{600\,\text{s}} = \int_{240}^{600} \dot{Q}\,dt = 500 \cdot 360 = 180 \text{ MJ}$$

HRR example – cabinet fire

Table G-1
Recommended HRR Values for Electrical Fires

Ignition Source	HRR kW (Btu/s)		Gamma Distribution	
	75th	98th	α	β
Vertical cabinets with qualified cable, fire limited to one cable bundle	69 [1] (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Vertical cabinets with qualified cable, fire in more than one cable bundle	211 [2] (200)	702 [3] (665)	0.7 (0.7)	216 (204)
Vertical cabinets with unqualified cable, fire limited to one cable bundle	90 [4] (85)	211 [2] (200)	1.6 (1.6)	41.5 (39.5)
Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	232 [5] (220)	464 [6] (440)	2.6 (2.6)	67.8 (64.3)
Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	232 [5] (220)	1002 [7] (950)	0.46 (0.45)	386 (366)
Pumps (electrical fires) [8]	69 (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Motors [8]	32 (30)	69 (65)	2.0 (2.0)	11.7 (11.1)
Transient Combustibles [9]	142 (135)	317 (300)	1.8 (1.9)	57.4 (53.7)



HRR taken from Appendix G, NUREG/CR 6850 (EPRI 1011989)

HRR example – cabinet fire

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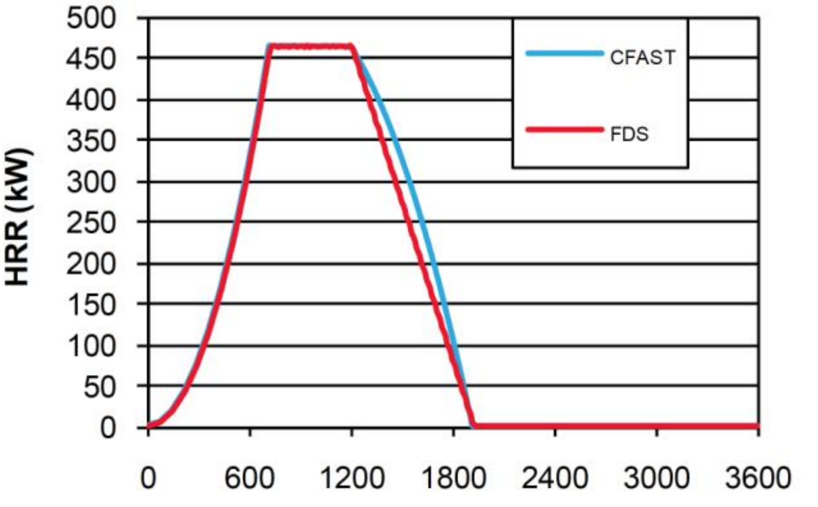


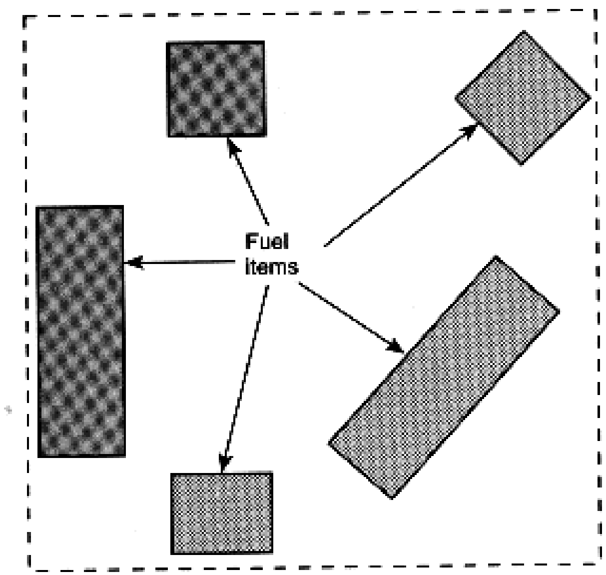
HRR taken from Appendix G, NUREG/CR 6850 (EPRI 1011989)

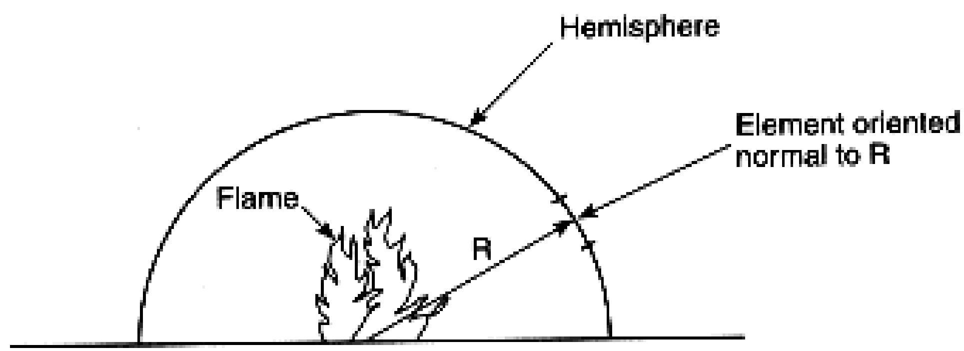
Secondary item ignition

- Factors
  - Heat flux from primary fire
  - Ease of ignition of target

- Point source estimate

$$\dot{q}''_r = \frac{\chi_r \dot{Q}_f}{4\pi R^2 \cos(\theta)}$$





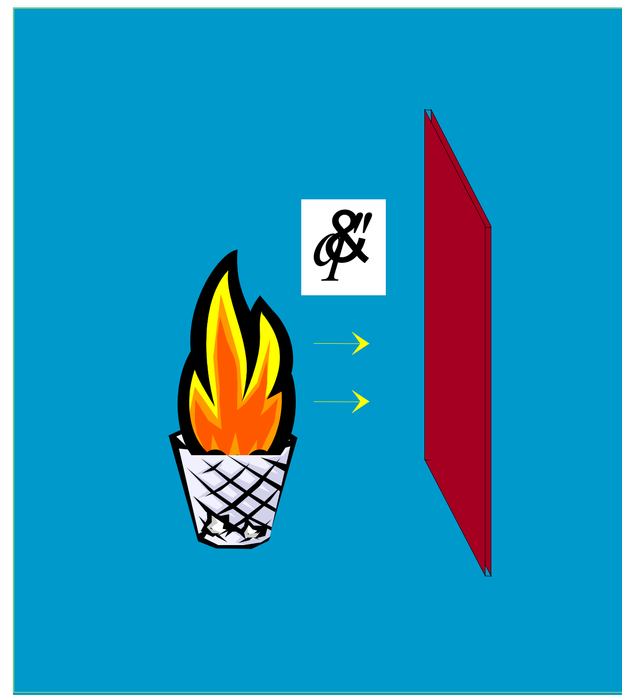
Secondary item ignition

- Ignition time estimates (constant heat flux)
  - Thermally thick materials (most materials of interest in NPPs)

$$t_{ig} = \frac{\pi}{4} k\rho c \left[\frac{T_{ig} - T_o}{\dot{q}''} \right]^2$$

  - Thermally thin materials

$$t_{ig} = \frac{T_{ig} - T_o}{\dot{q}'' / \rho c \delta}$$



Summary

- Engineers need to specify design fires
  - Judgment required
  - Some data available - relatively sparse
  - For NPP applications, data in NUREG CR-6850 typically used
- Design fire specified in terms of HRR(t)
  - Simple case - incipient/growth/steady/decay
  - Complex case - multiple stages pieced together
- Design fire drives consequence analysis
  - Single most important / uncertain factor

Cable Heat Release, Ignition, and Spread in Tray Installations during Fire

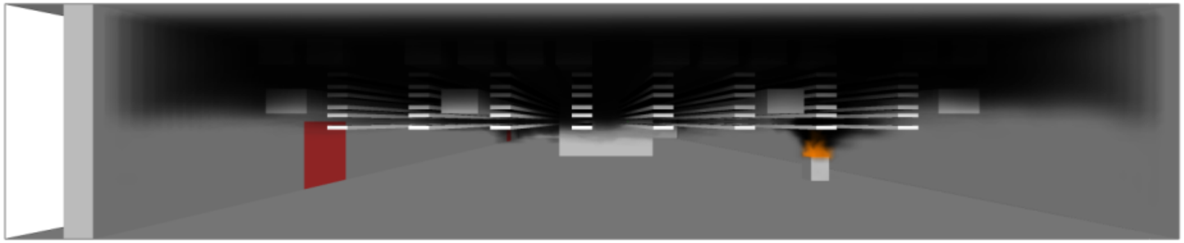
(CHRISTIFIRE) Phase I

Kevin McGrattan, Andrew Lock, Nathan Marsh, Marc Nyden
National Institute of Standards and Technology
Gaithersburg, Maryland, USA

David Stroup and Jason Dreisbach
U.S. Nuclear Regulatory Commission
Washington, D.C., USA

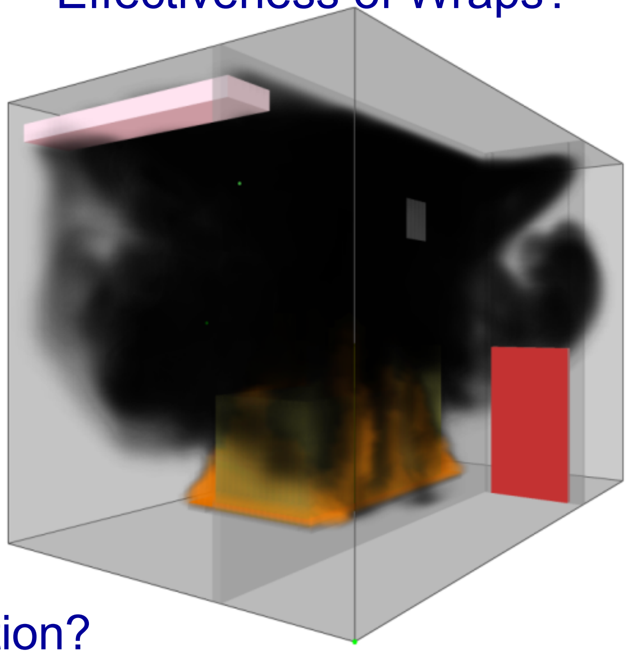
What's the Problem?

Answer: Very little useful information on cables for fire modeling

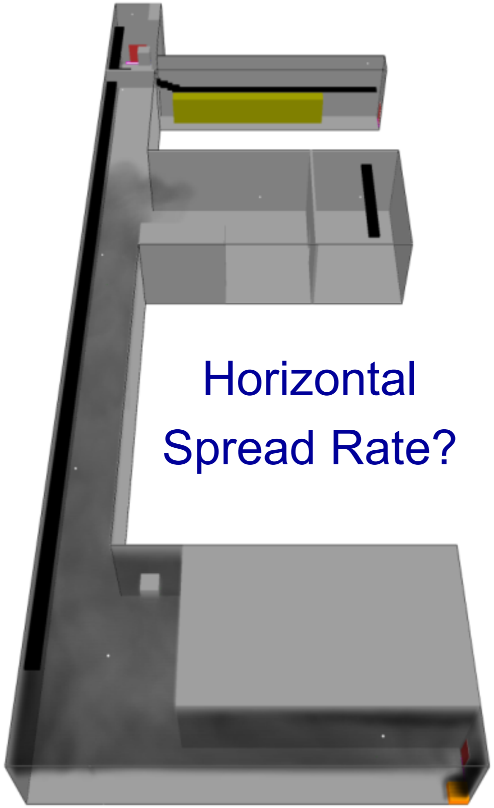


Tray to Tray Spread?

Effectiveness of Wraps?

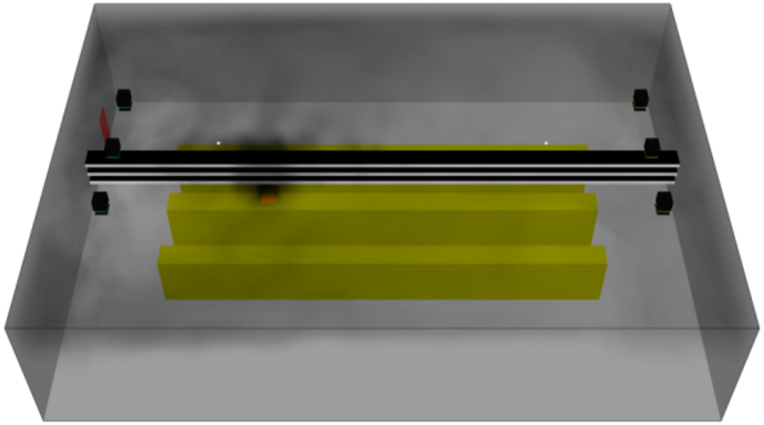


Vertical Spread Rate?



Horizontal Spread Rate?

Ignition?



Current Guidance for Modeling Cables

EPRI 1011989 NUREG/CR-6850
Final Report

EPRI/NRC-RES
Fire PRA Methodology for Nuclear Power Facilities
Volume 2: Detailed Methodology

Electric Power Research Institute
3420 Hillview Avenue
Palo Alto, CA 94303

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

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Problems going from "bench" to full-scale

Table R-1
Bench Scale HRR Values Under a Heat Flux of 60 kW/m^2, q_{bs} [R-4]

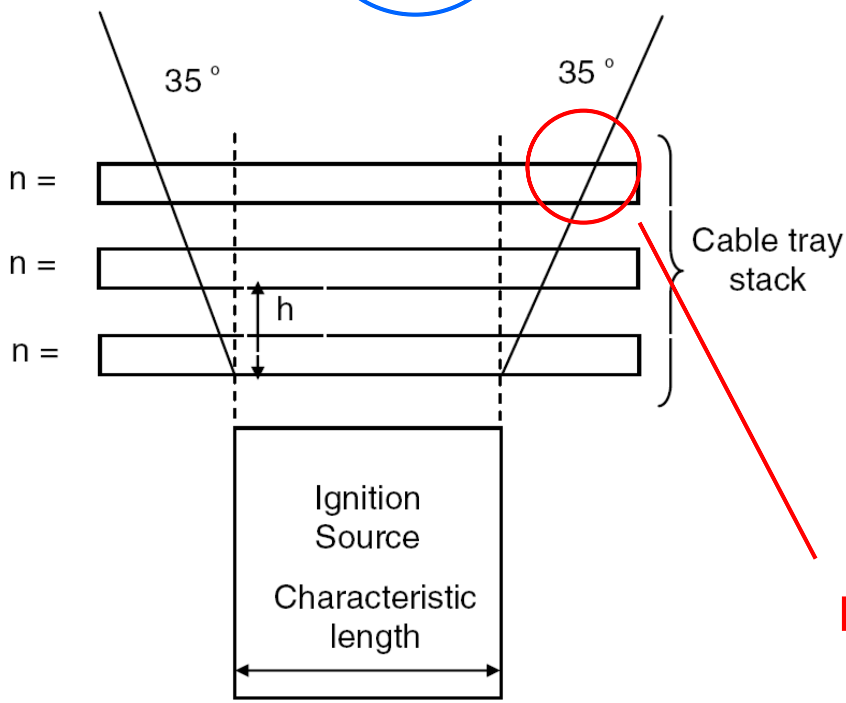
Material	Bench Scale HRR [kW/m^2]
XPE/FRXPE	475
XPE/Neoprene	354
XPE/Neoprene	302
XPE/XPE	178
PE/PVC	395
PE/PVC	359
PE/PVC	312
PE/PVC	589
PE, Nylon/PVC, Nylon	231
PE, Nylon/PVC, Nylon	218

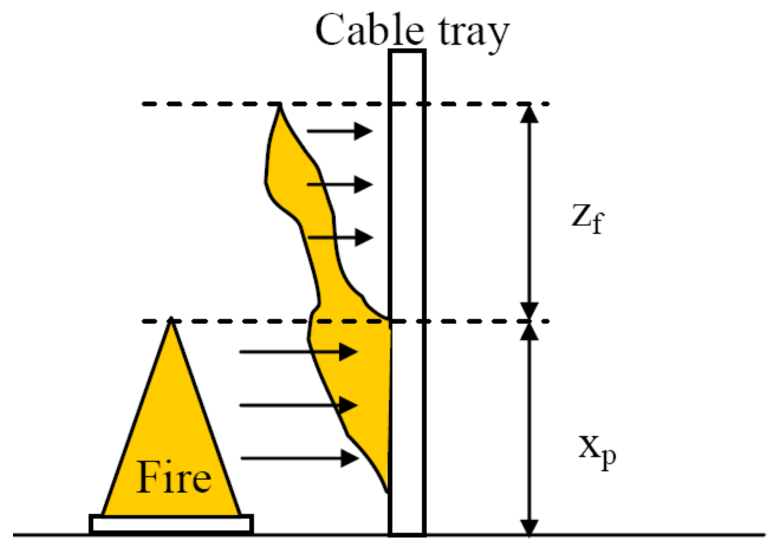
Which HRR to Use?

Current Guidance on Flame Spread

$$v = \frac{4\left(\dot{q}''_f\right)^2 \delta_f}{\pi (k \rho c)\left(T_{ig} - T_{amb}\right)^2}$$

Vague or ill-defined parameters





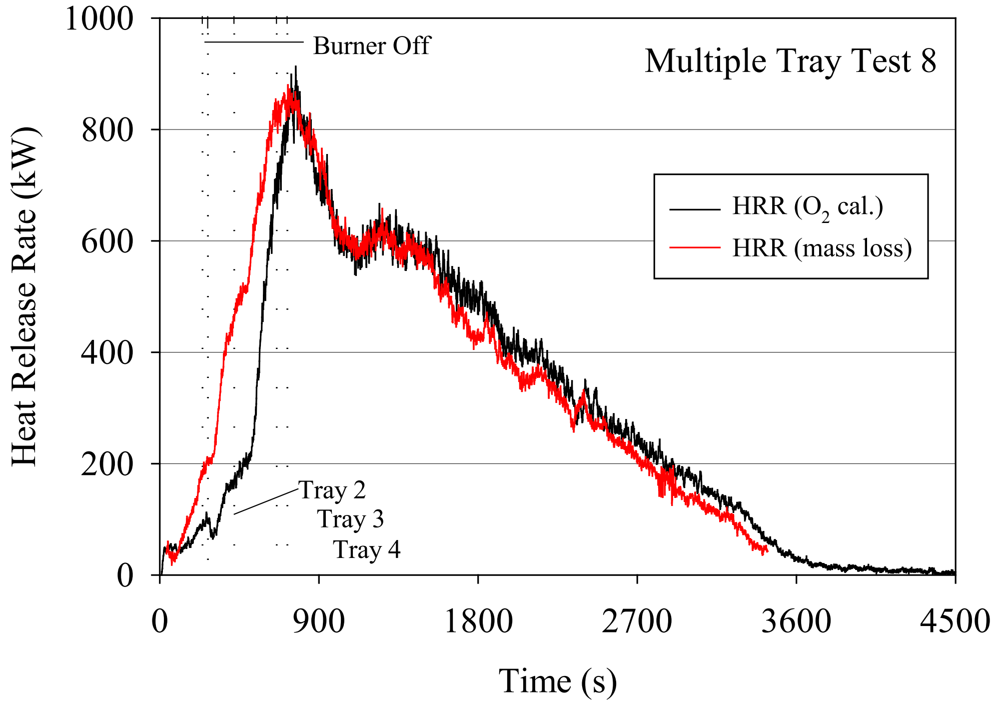
Based on only one experiment

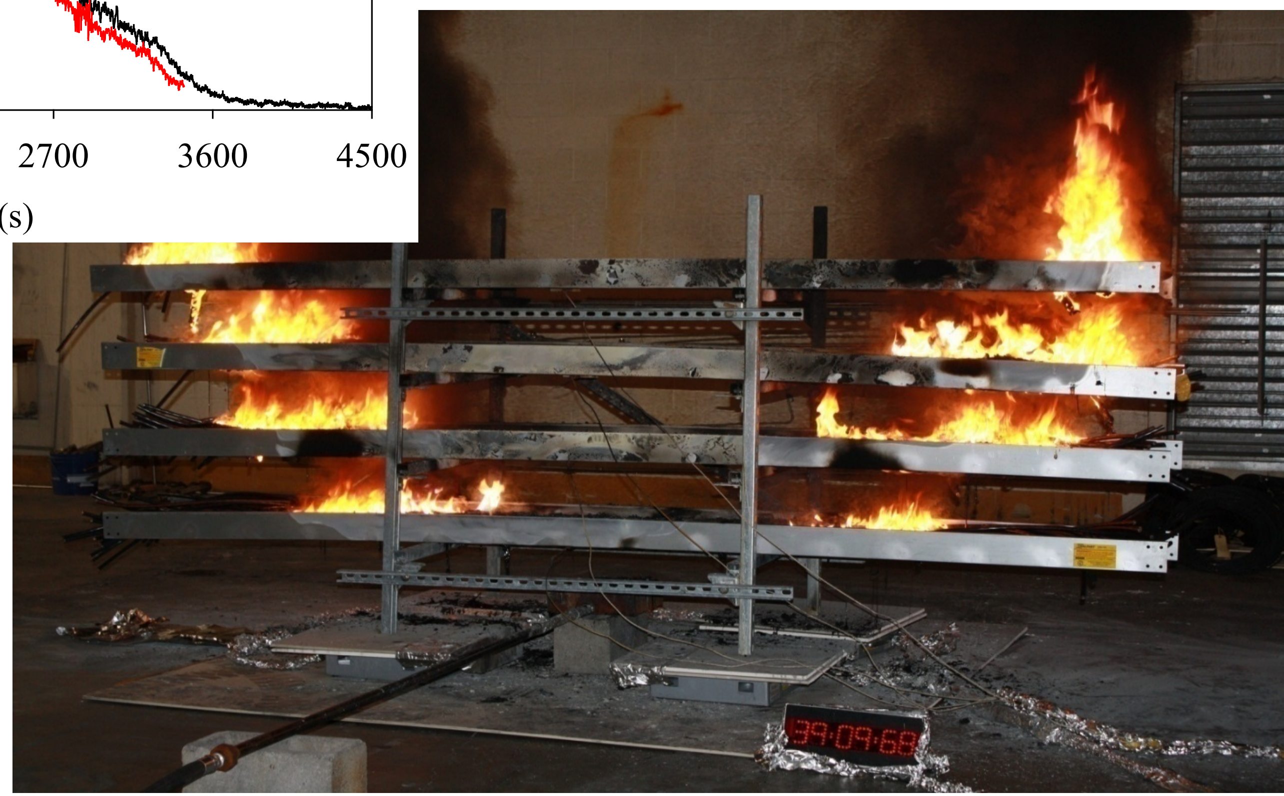
Cables used in CHRISTIFIRE

Thermoplastic cables tend to melt and drip; Electrical failure ~200 °C

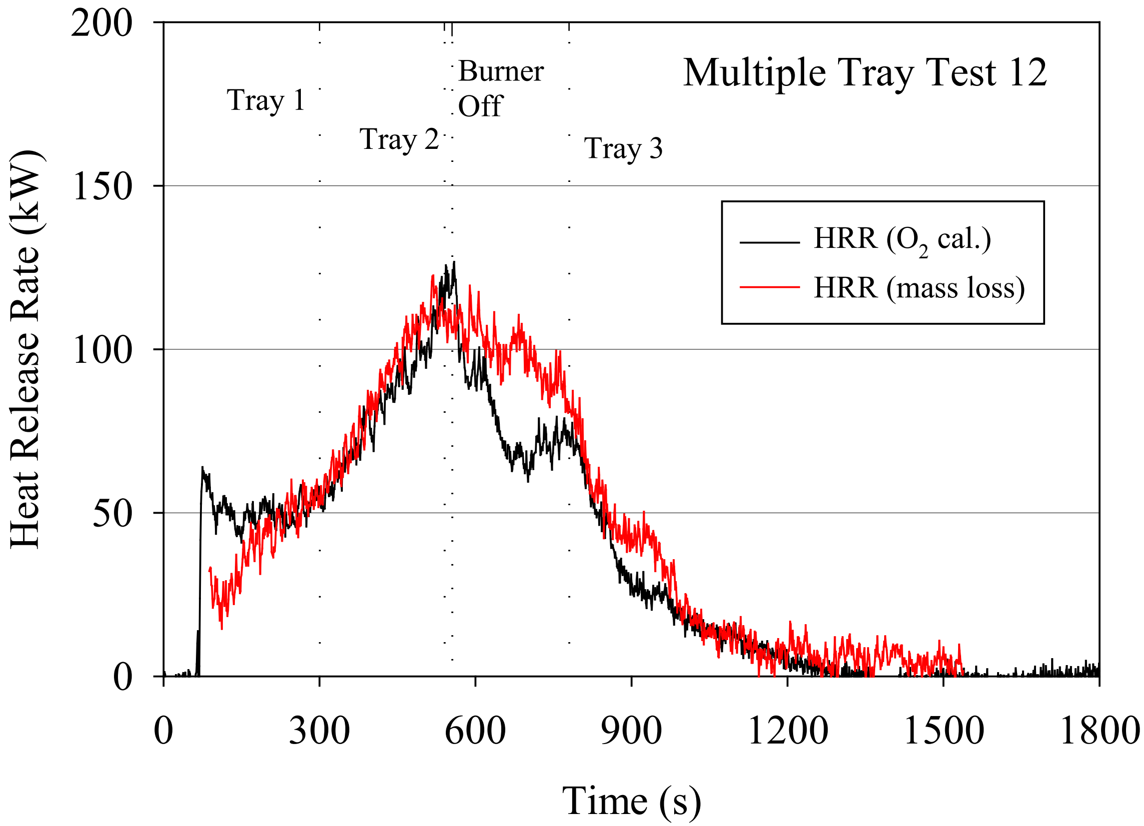
Thermoset cables tend to char and smolder; Electrical failure ~400 °C

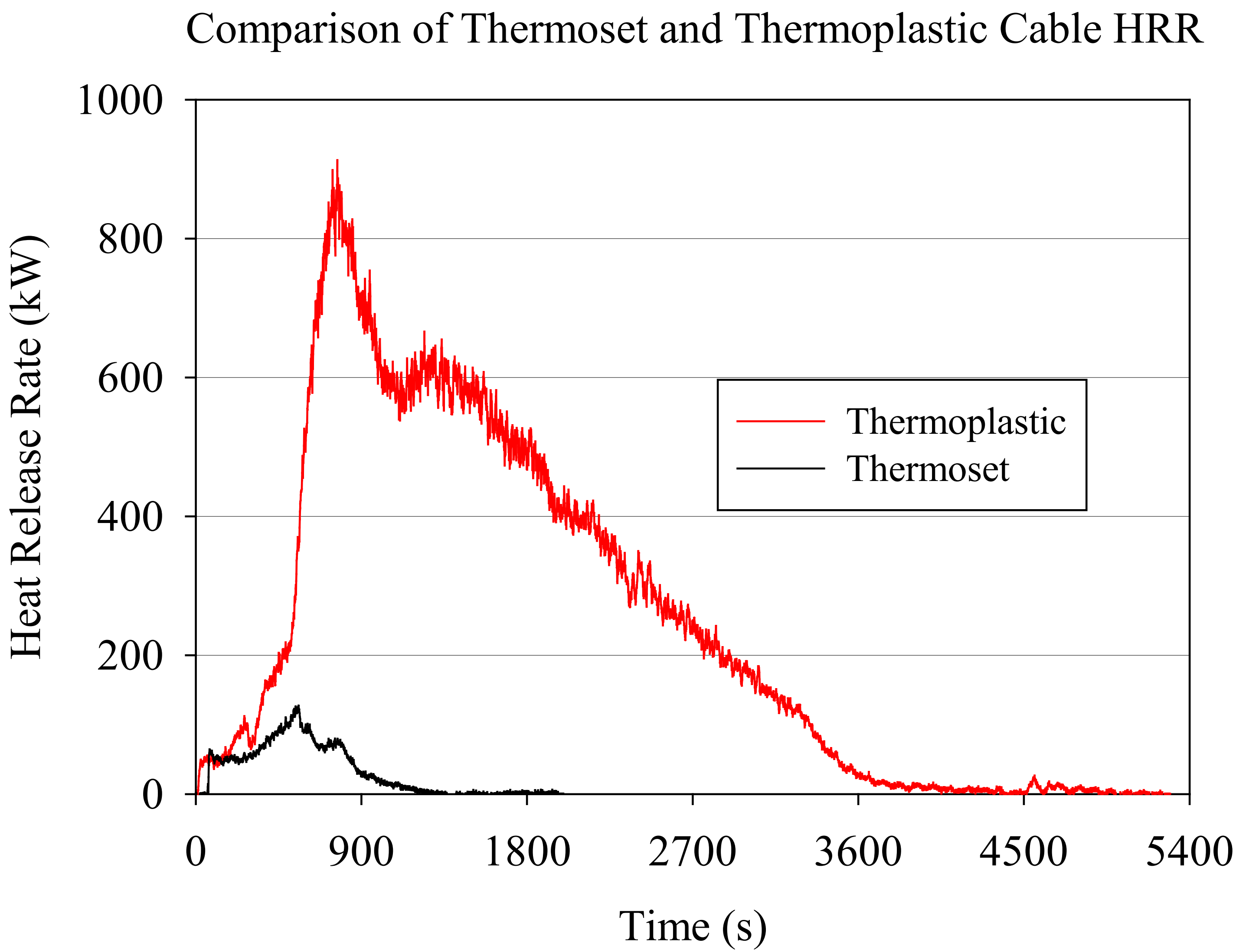
Thermoplastic Cable



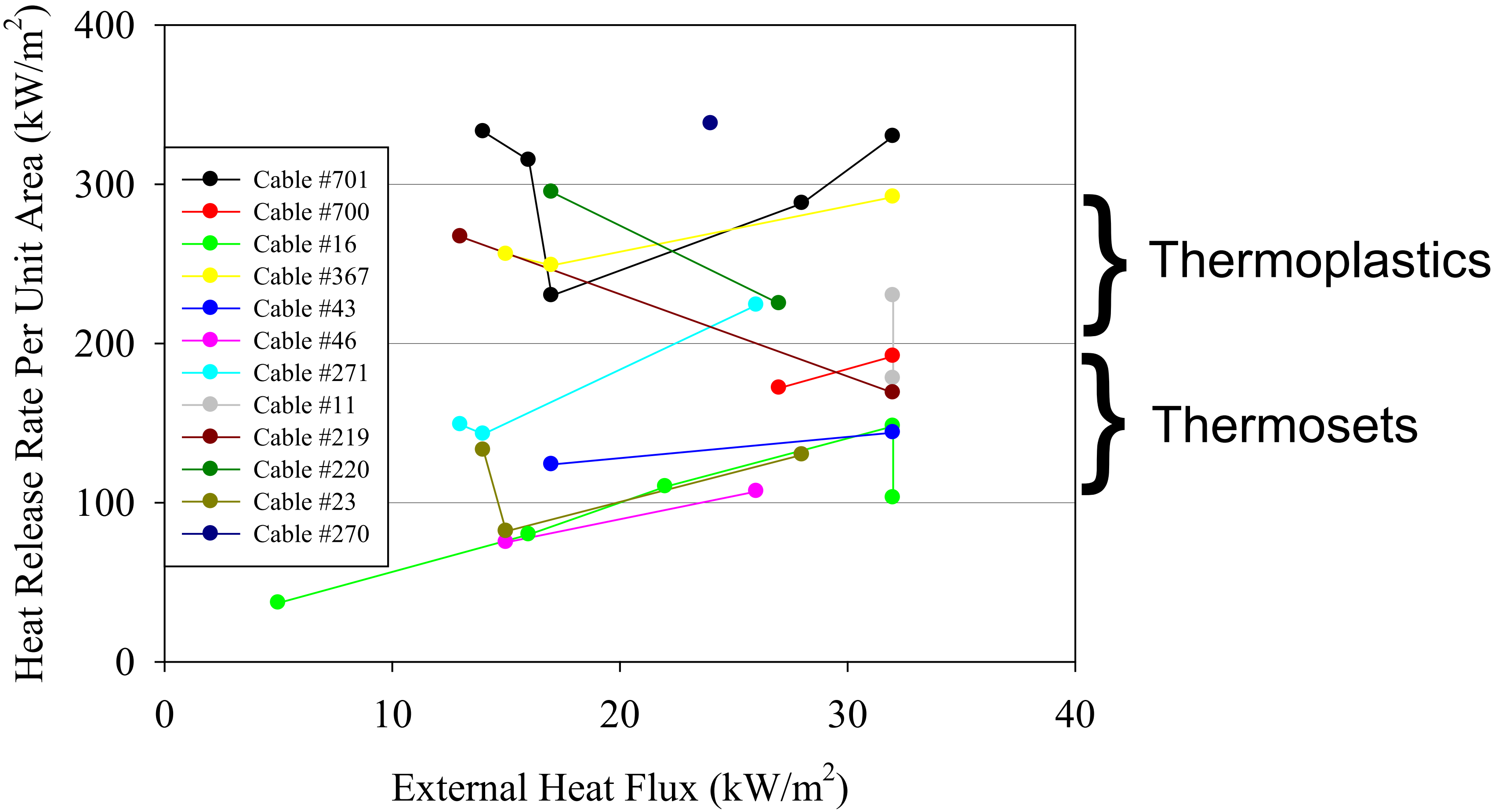


Thermoset Cable



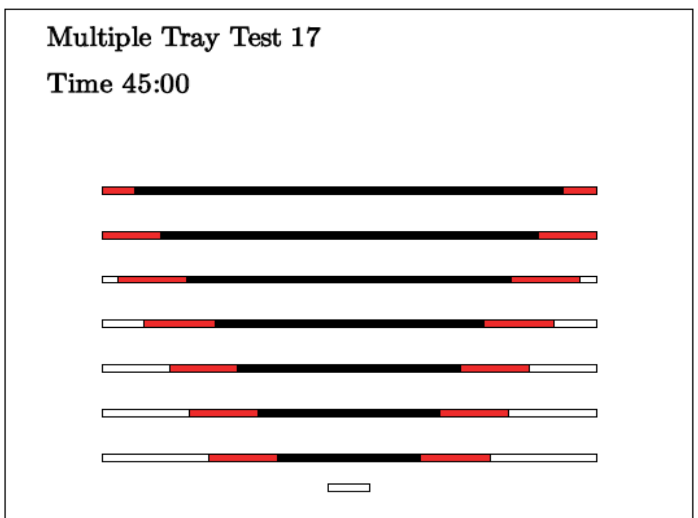

Comparison of Thermoset and Thermoplastic Cable HRR
Heat Release Rate (kW)
1000
800
600
400
200
0
Time (s)
0
900
1800
2700
3600
4500
5400
Thermoplastic
Thermoset

Results of Radiant Panel Experiments

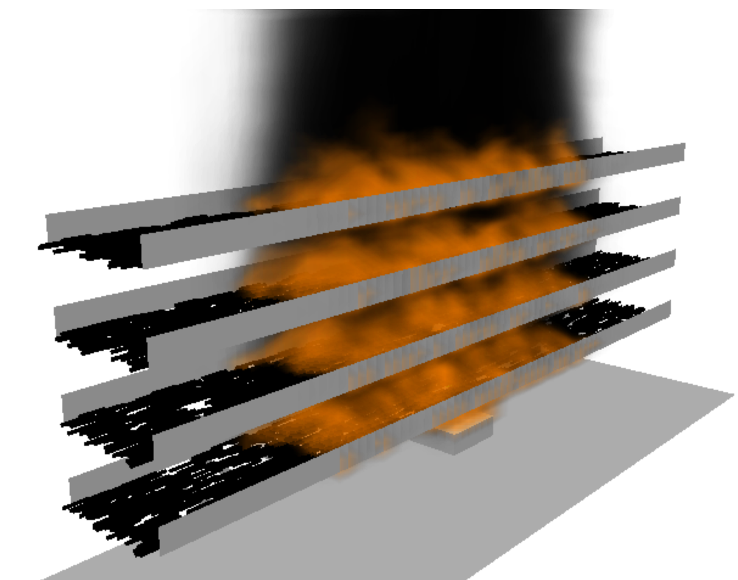


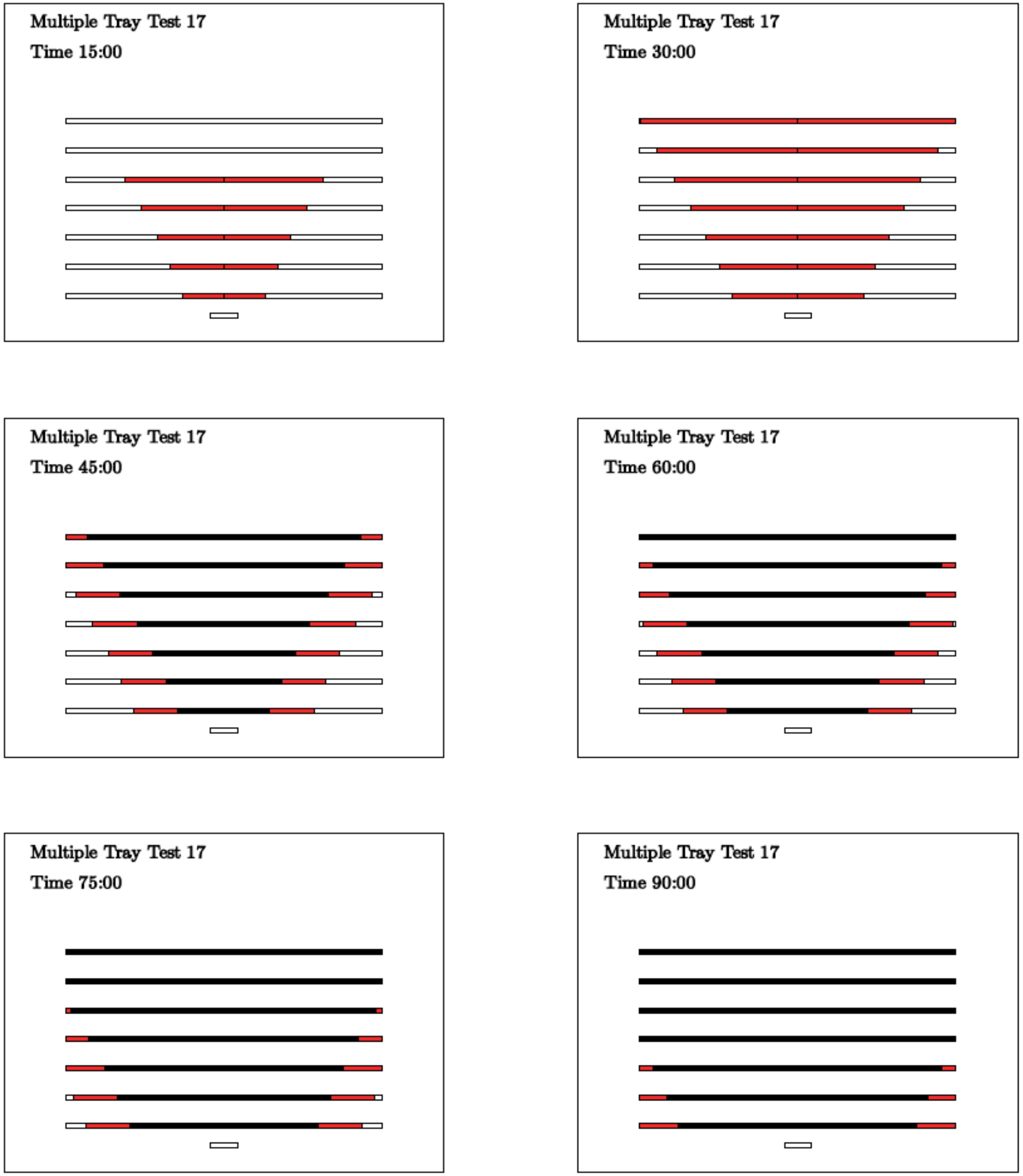
Modeling

The Easy Way



The Hard Way





FLASH-CAT

Flame Spread over
Horizontal Cable
Trays

Required Data

Cable mass/length

Non-metal mass fraction

Ignition

5-4-3-2-1 minute rule

Upward Spread

35° spread angle

Burning Rate

250 kW/m² thermoplastics

150 kW/m² thermosets

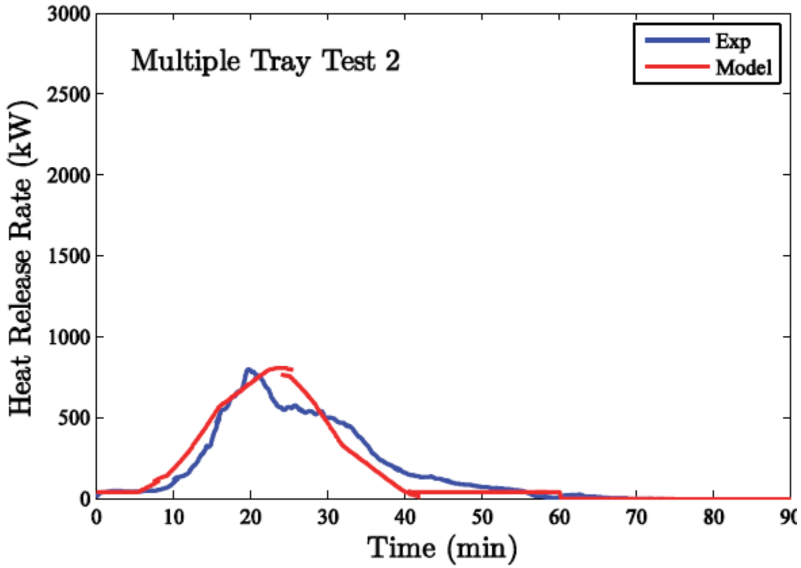
Lateral Spread

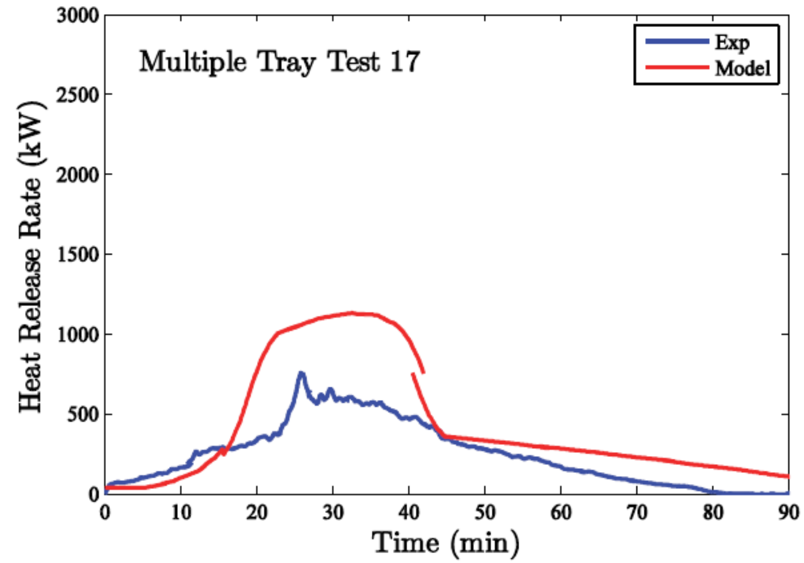
3.2 m/h thermoplastics

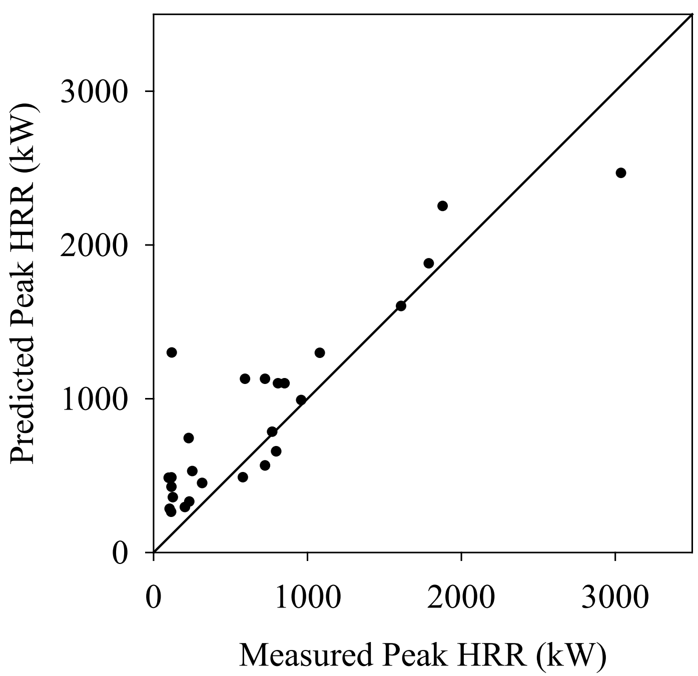
1.1 m/h thermosets

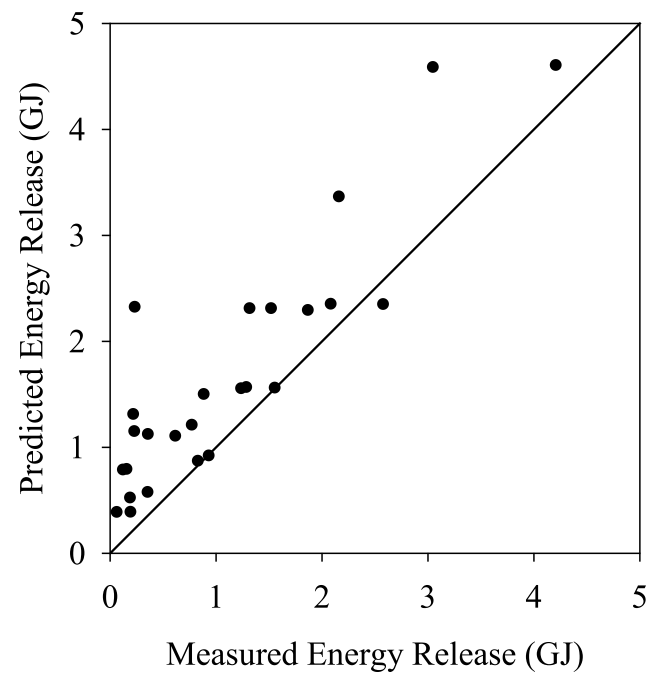
Heat of Combustion

16 MJ/kg for all

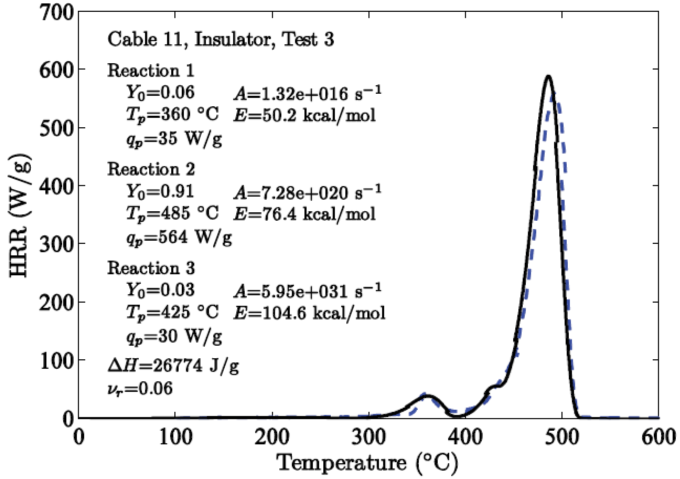

Multiple Tray Test 2
Exp
Model
Heat Release Rate (kW)
Time (min)

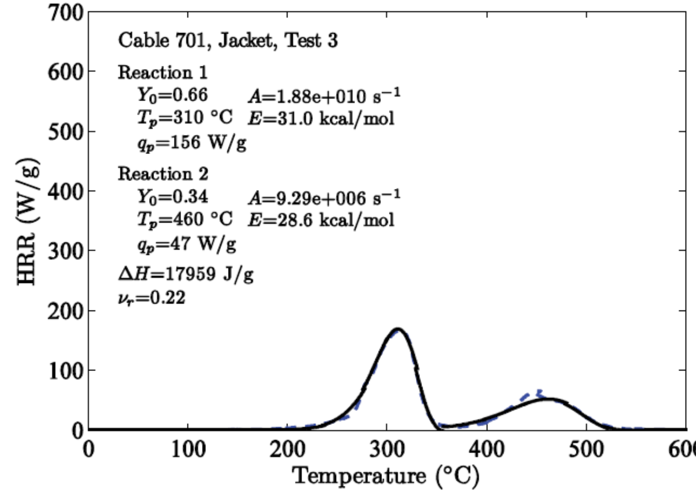

Multiple Tray Test 17
Exp
Model
Heat Release Rate (kW)
Time (min)

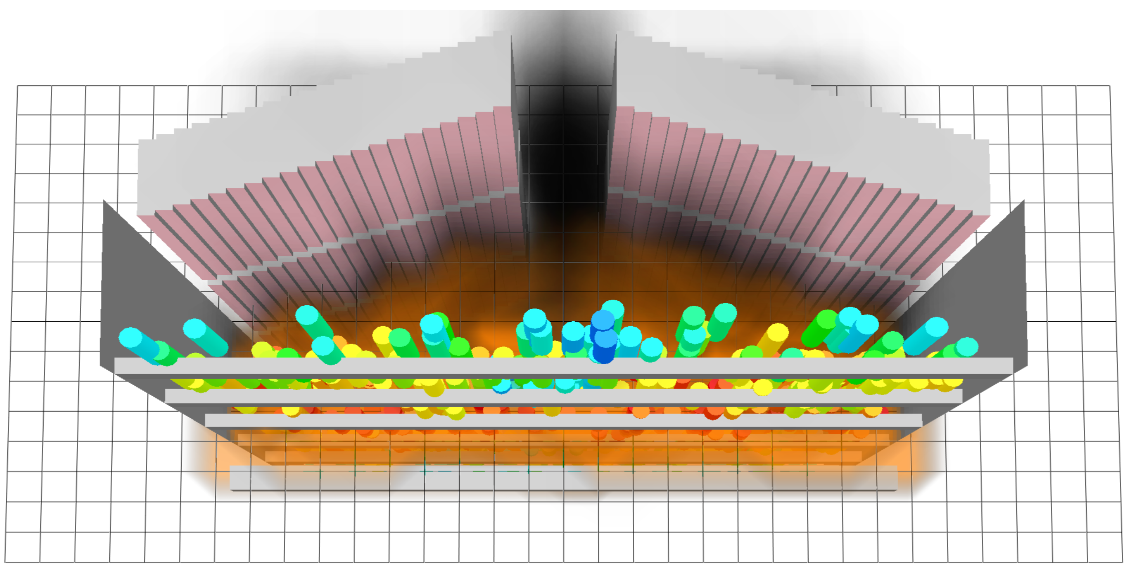

Predicted Peak HRR (kW)
Measured Peak HRR (kW)


Predicted Energy Release (GJ)
Measured Energy Release (GJ)

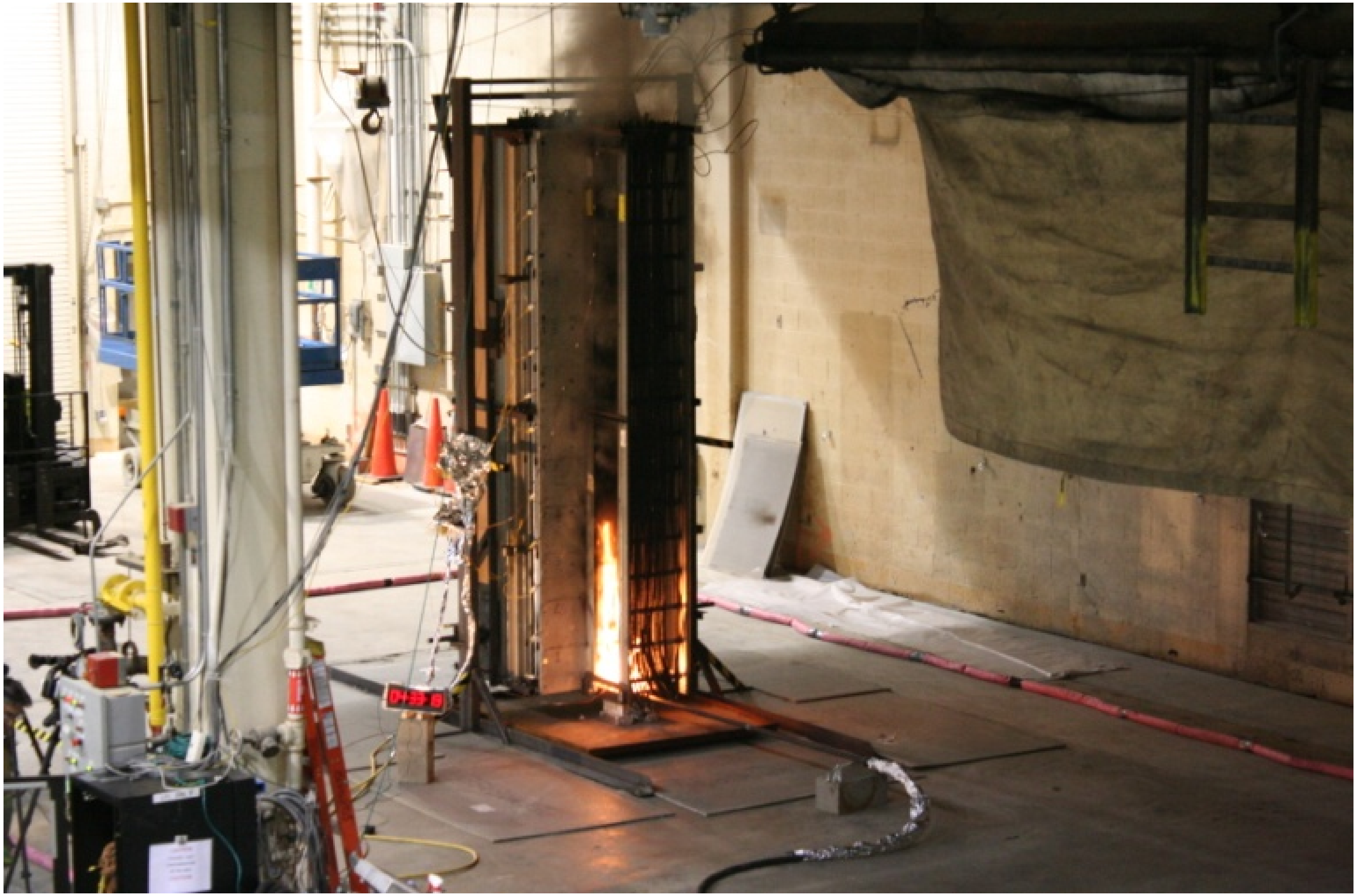
Fire Dynamics Simulator (FDS)

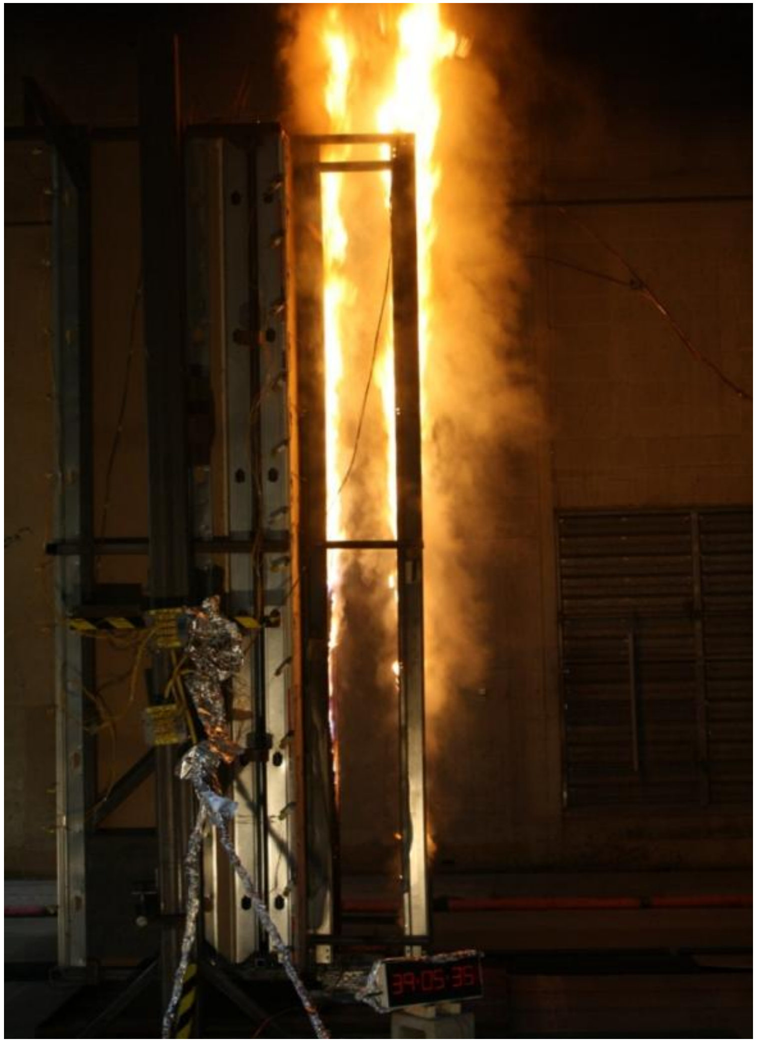






Vertical cable fire spread experiments at NIST




39:05:35

Corridor Fire Spread Experiments at NIST

Cable fire spread in a corridor, courtesy NIST.

The spread rate of a fire can be estimated from:

$$v \propto \frac{(\dot{q}_{\mathrm{f}}'')^2 \, \delta_{\mathrm{f}}}{\pi \, (k\rho c) \left(T_{\mathrm{ign}} - T_{\infty}\right)^2}$$

If the cables are located within the Hot Gas Layer (HGL), the spread rate could increase by a factor of 10.

$$\frac{v_2}{v_1} = \left(\frac{T_{\mathrm{ign}} - T_{\infty}}{T_{\mathrm{ign}} - T_{\mathrm{HGL}}}\right)^2 = \left(\frac{400 - 20}{400 - 280}\right)^2 \cong 10$$

FLASH-CAT

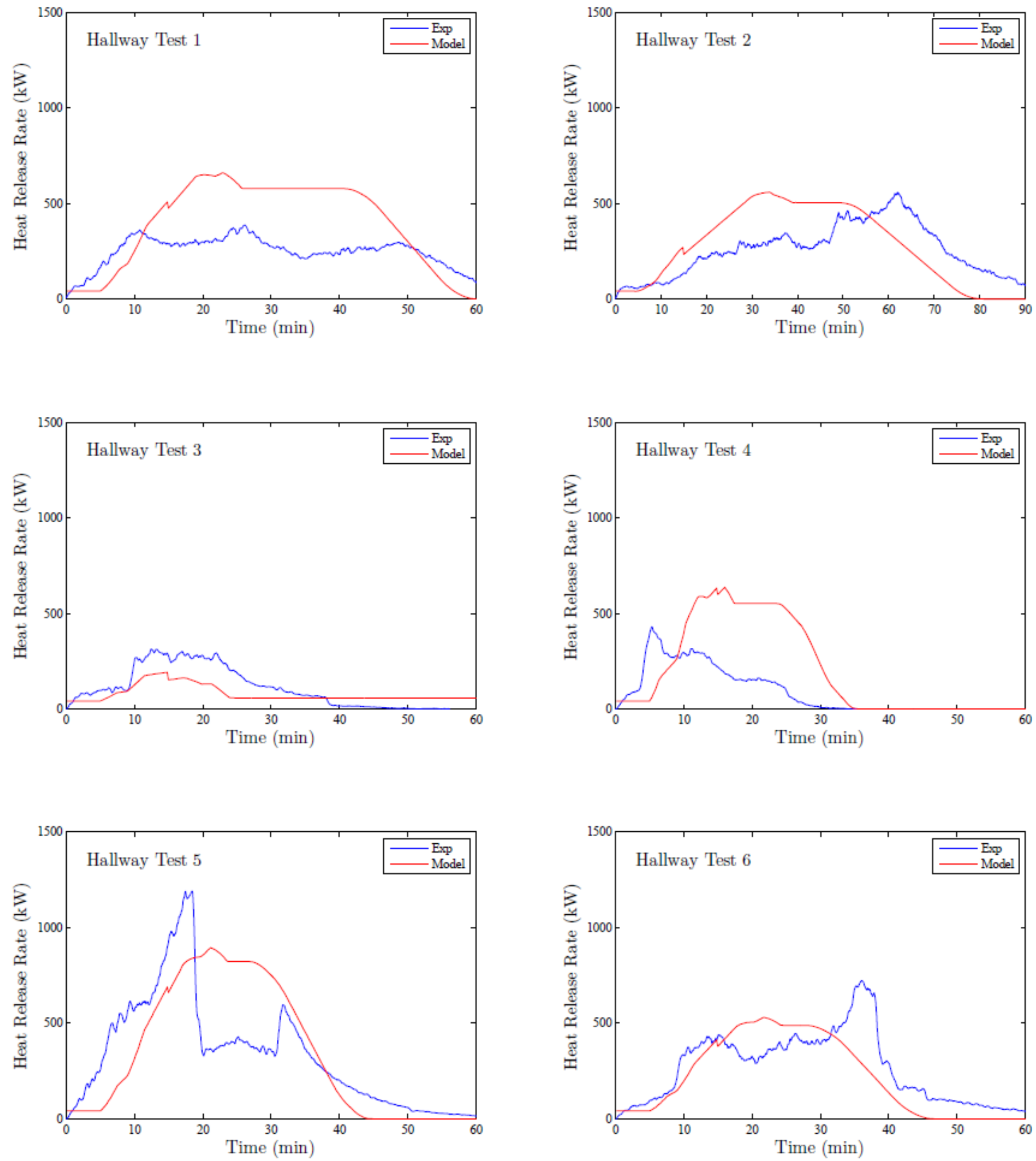
Flame Spread over

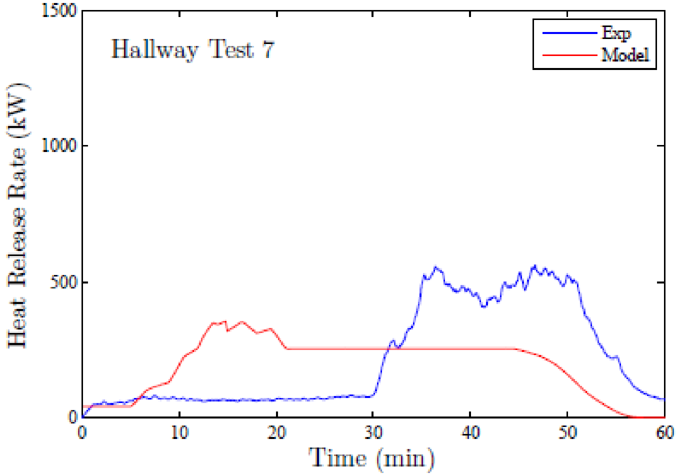
Horizontal Cable

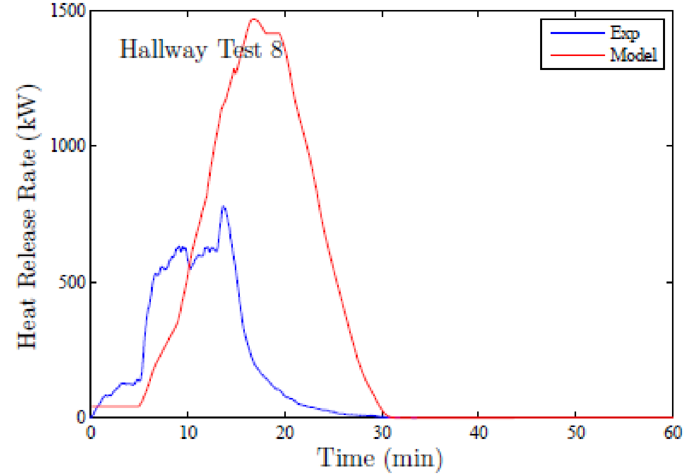
Trays

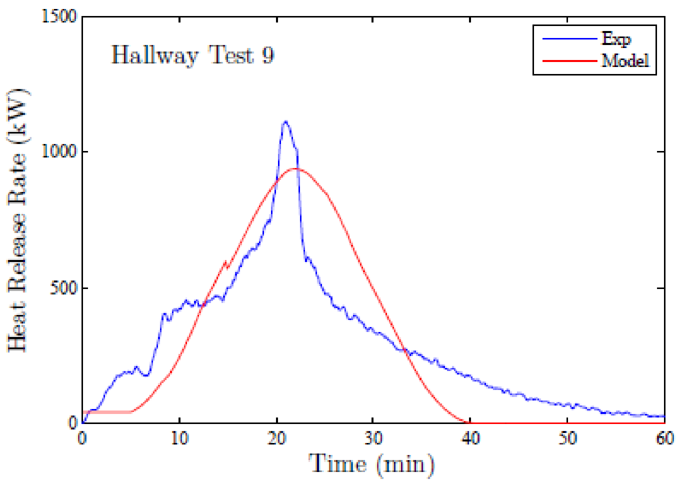
Results of Hallway

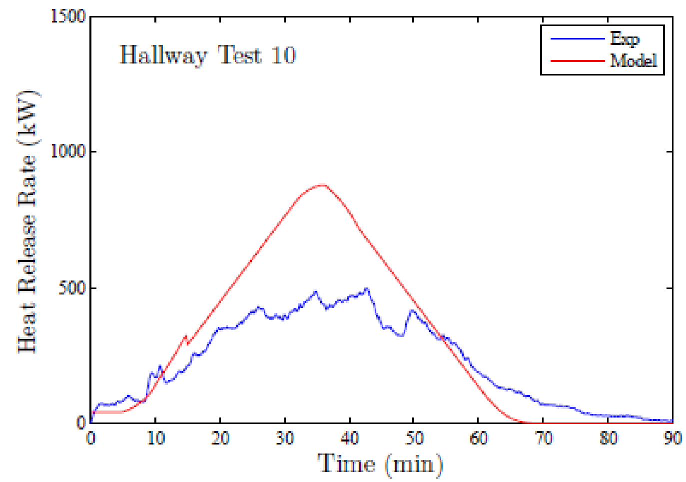
Experiments




Hallway Test 7
Exp
Model
Heat Release Rate (kW)
Time (min)
0
500
1000
1500
0
10
20
30
40
50
60

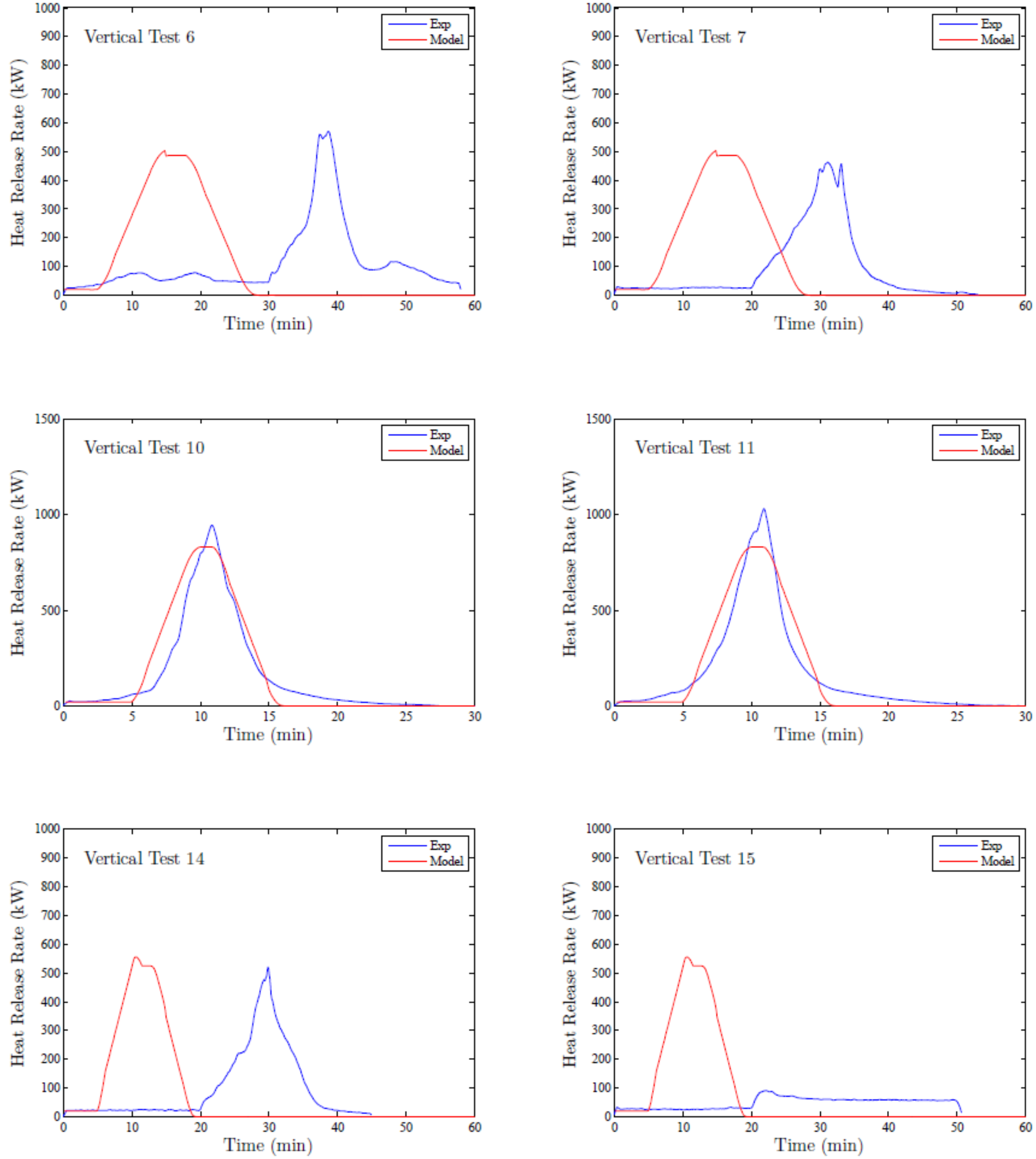

Hallway Test 8
Exp
Model
Heat Release Rate (kW)
Time (min)
0
500
1000
1500
0
10
20
30
40
50
60


Hallway Test 9
Exp
Model
Heat Release Rate (kW)
Time (min)
0
500
1000
1500
0
10
20
30
40
50
60


Hallway Test 10
Exp
Model
Heat Release Rate (kW)
Time (min)
0
500
1000
1500
0
10
20
30
40
50
60
70
80
90

FLASH-CAT

Vertical Tray Results



Results of CHRISTIFIRE Phase 2

Average heat release rates for thermoplastic and thermoset cables are consistent with Phase 1 experiments and FLASH-CAT modeling.

Fire spread rates are roughly a factor of 10 greater for multiple vertical trays or horizontal trays close to ceilings (or within the hot gas layer).

CHRISTIFIRE Report, NUREG/CR-7010

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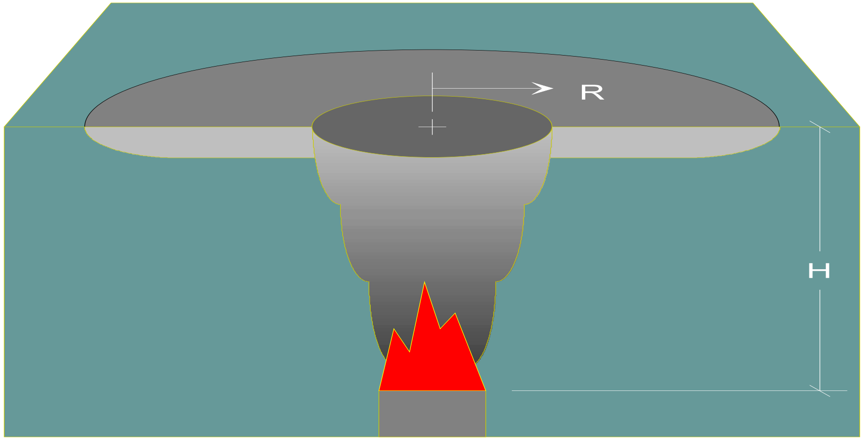
Fire plumes and ceiling jets

- Describe fire plume and ceiling jet phenomena
- Discuss the theory behind fire plume correlations
- Appreciate the role of plume entrainment on fire conditions within an enclosure
- Calculate fire plume and ceiling jet conditions, including temperatures and velocities, for different correlations

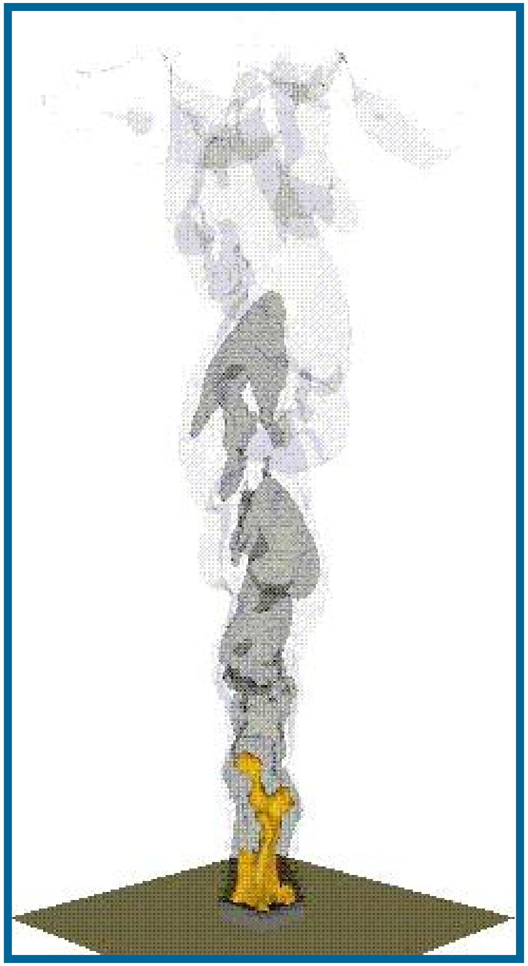


References – fire plumes

- *Enclosure Fire Dynamics*
  - Chapter 4 - Fire plumes and flame heights
- *SFPE Handbook*
  - Chapter on Flame Height
  - Chapter on Fire Plumes

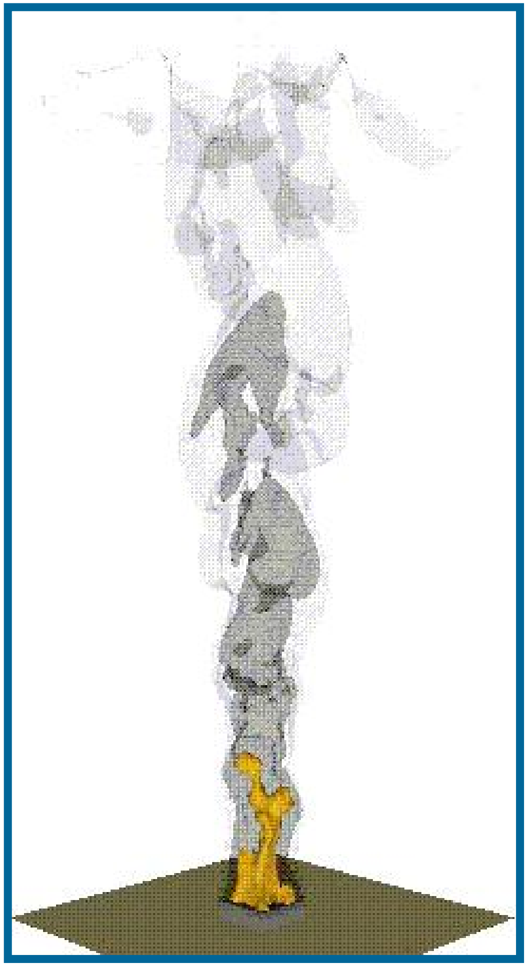
Fire plume issues

- Transports combustion products / entrained air vertically to ceiling
- Causes formation and descent of smoke layer
- Elevated temperatures and velocities expose targets located in plume



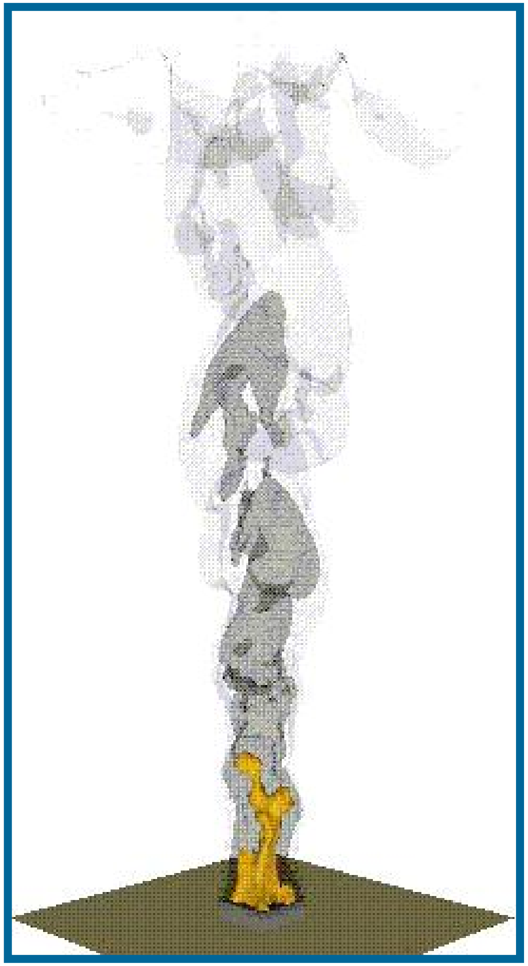
Types of fire plumes

- Axisymmetric plumes
- Line plumes
- Window plumes
- Balcony spill plumes
- Other …



Axisymmetric fire plumes

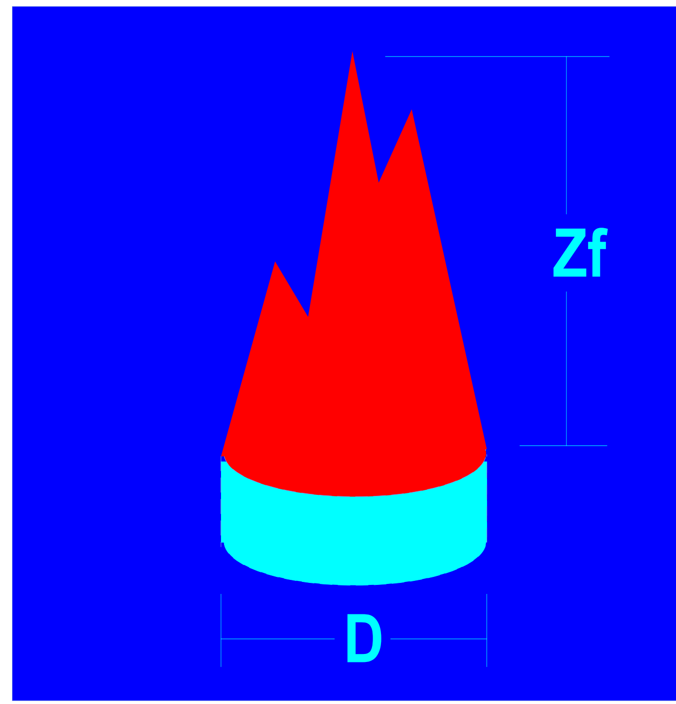
- Correlations
  - Morton-Taylor-Turner (ideal)
  - Zukoski
  - Heskestad
  - McCaffrey
  - Alpert
  - Alpert & Ward
  - Thomas
- Typically use Heskestad correlation



Heskestad flame height correlation

$$Z_f = 0.23\dot{Q}^{2/5} - 1.02D$$

$$\frac{Z_f}{D} = 3.7Q^{*2/5} - 1.02$$



The Heskestad plume

Effective flame height

$$z_L = z_o + 0.166\dot{Q}_c^{2/5}$$

– Mass Entrainment
Flame region ($z < z_L$)

$$\dot{m}_{pl} = 0.0054\dot{Q}_c z / z_L$$

– Mass Entrainment
Plume region ($z > z_L$)

$$\dot{m}_{pl} = 0.071\dot{Q}_c^{1/3}(z - z_o)^{5/3} + 0.0018\dot{Q}_c$$

The Heskestad plume

- Plume centerline temperature
  - Continuous flame region $\Delta T \approx 900°C$
  - Plume region

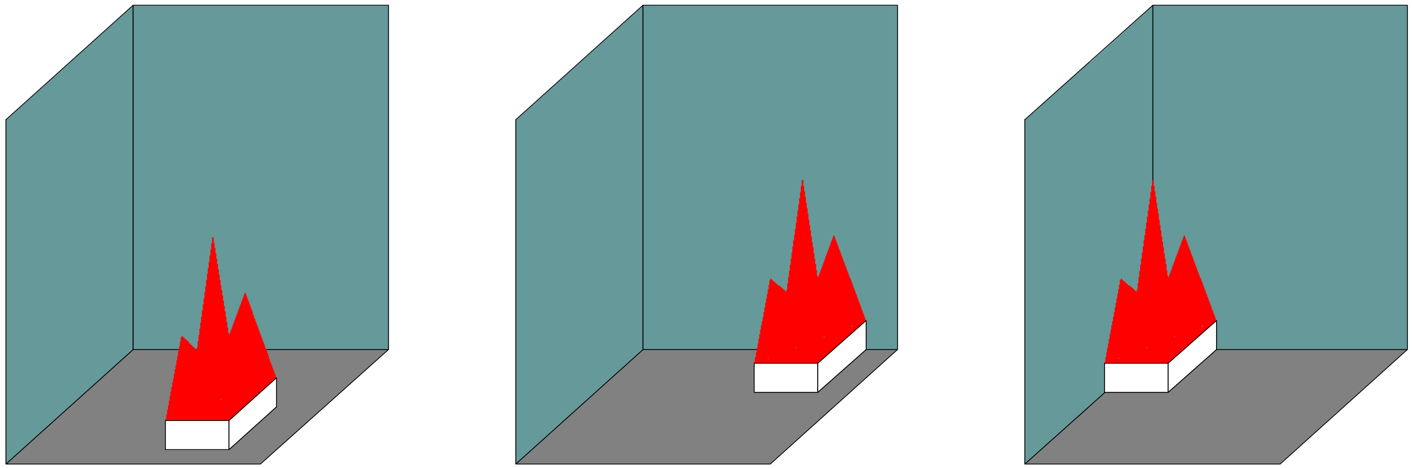
$$\frac{\Delta T_o}{T_\infty} = 9.1\left(\frac{\dot{Q}_c}{\sqrt{g}\rho_\infty c_p T_\infty}\right)^{2/3}(z - z_o)^{-5/3} \approx 0.085\frac{\dot{Q}_c^{2/3}}{(z - z_o)^{5/3}}$$

$$\Delta T_o \approx 25\frac{\dot{Q}_c^{2/3}}{(z - z_o)^{5/3}}$$

Fire location factors

- Multiply HRR by fire location factor
  - Fires in the open: $k_{lf} = 1$
  - Fires along walls: $k_{lf} = 2$
  - Fires in corners: $k_{lf} = 4$

These values are going to change based on new research



Corner Fire Test, NIST, 2017, 400 kW Fire

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Wall Fire Test, NIST, 2017, 400 kW Fire

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Fire plume - example

- In the FM/SNL fire test series, the room height was 6.1 m and the burner was 0.1 m above the floor
- For many tests, the fire HRR was 500 kW and the burner diameter was 0.9 m
- What would be the plume centerline temperature rise and velocity at the ceiling based on the Heskestad plume correlation?

Fire plume - example

- Solution – plume temperature
  - First calculate the virtual origin elevation

$$z_o = 0.083\dot{Q}^{2/5} - 1.02D = 0.083(500)^{2/5} - 1.02(0.9)$$
$$= 0.08$$

  - Then calculate the plume centerline temp rise

$$\Delta T_o \approx 25\frac{\dot{Q}_c^{2/3}}{(z - z_o)^{5/3}} = 25\frac{(350)^{2/3}}{(6 - 0.08)^{5/3}}$$
$$= 64K$$

Fire plume - example

- Solution – plume velocity

$$u_o = 1.03\left(\frac{\dot{Q}_c}{z - z_o}\right)^{1/3} = 1.03\left(\frac{350}{6 - 0.08}\right)^{1/3}$$

$$= 4.0\, m/s$$

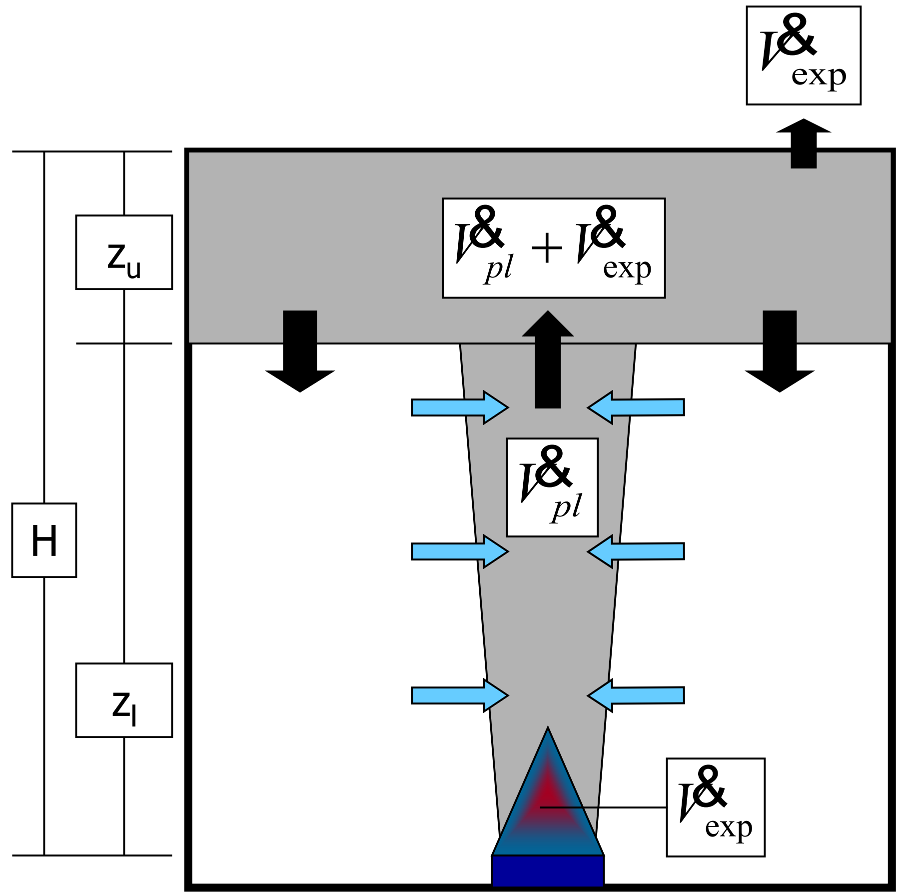
Enclosure smoke filling

- The ASET model

$$\frac{dV_u}{dt} = A\frac{dz_u}{dt} = \dot{V}_{pl} + \dot{V}_{exp}$$

- Analytical solutions
  - Expansion negligible
  - Leak at ceiling only

$$\frac{dV_u}{dt} = A\frac{dz_u}{dt} = \dot{V}_{pl}$$



Summary – fire plumes

- Plume important for number of reasons
  - Temperatures/velocities/heat fluxes at targets
  - Smoke layer filling / exhaust rates
  - Smoke concentrations

- Correlations available for some scenarios
  - Axisymmetric / line plumes
  - Windows / balconies (limited theory / data)

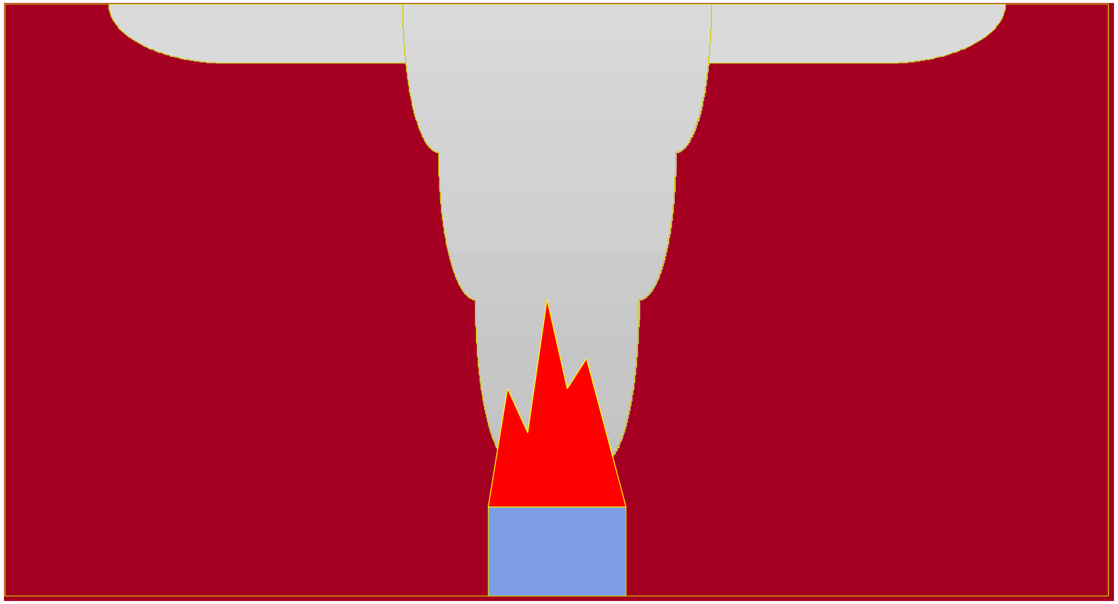
  - For NPP applications, generally use Heskestad correlations

Summary – fire plumes

- Limited/no correlations for other scenarios
  - 3D fuel sources (e.g., racks, sprays …)
  - Obstructions in plume / flow field
  - Sloped / stepped ceilings
  - Wind / mechanical ventilation
- CFD models can address scenarios where correlations are inappropriate

Ceiling jet topics

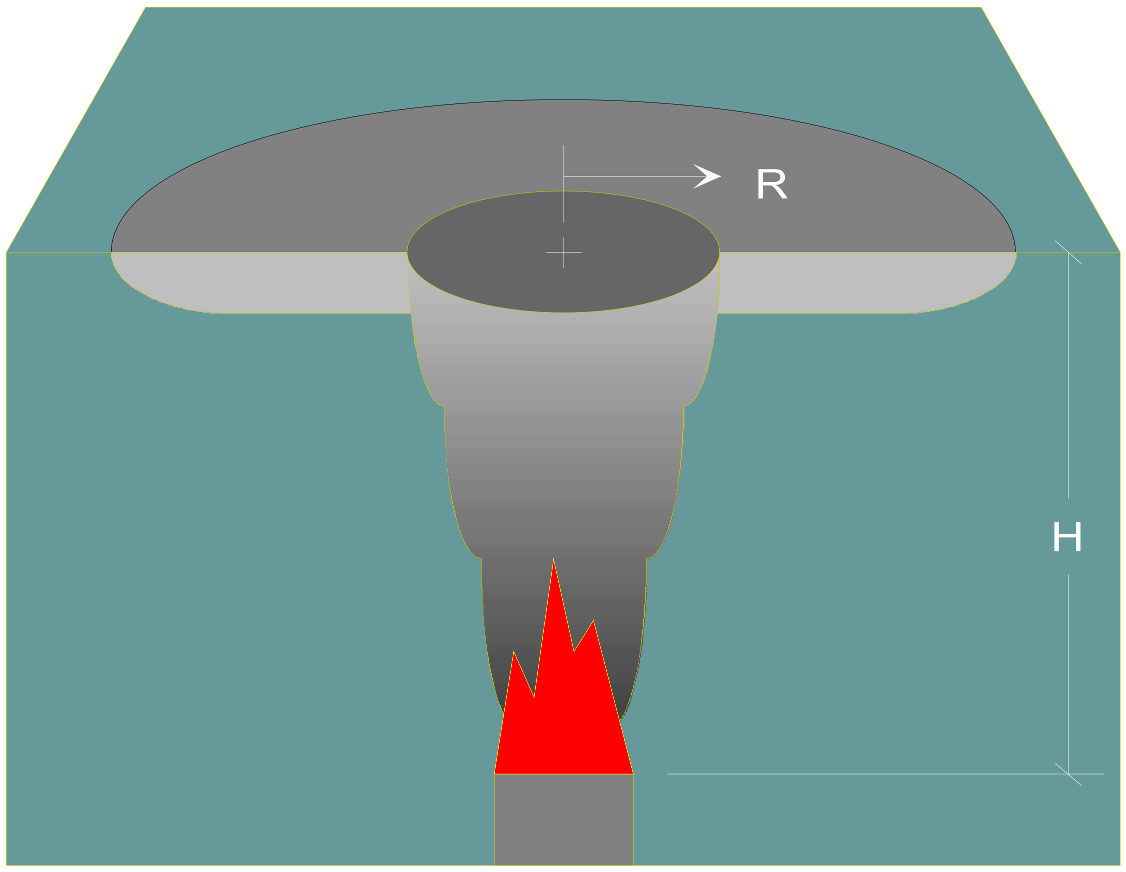
- Unconfined ceiling jets
- Confined ceiling jets
- Ceiling jet correlations
  - Temperature
  - Velocity



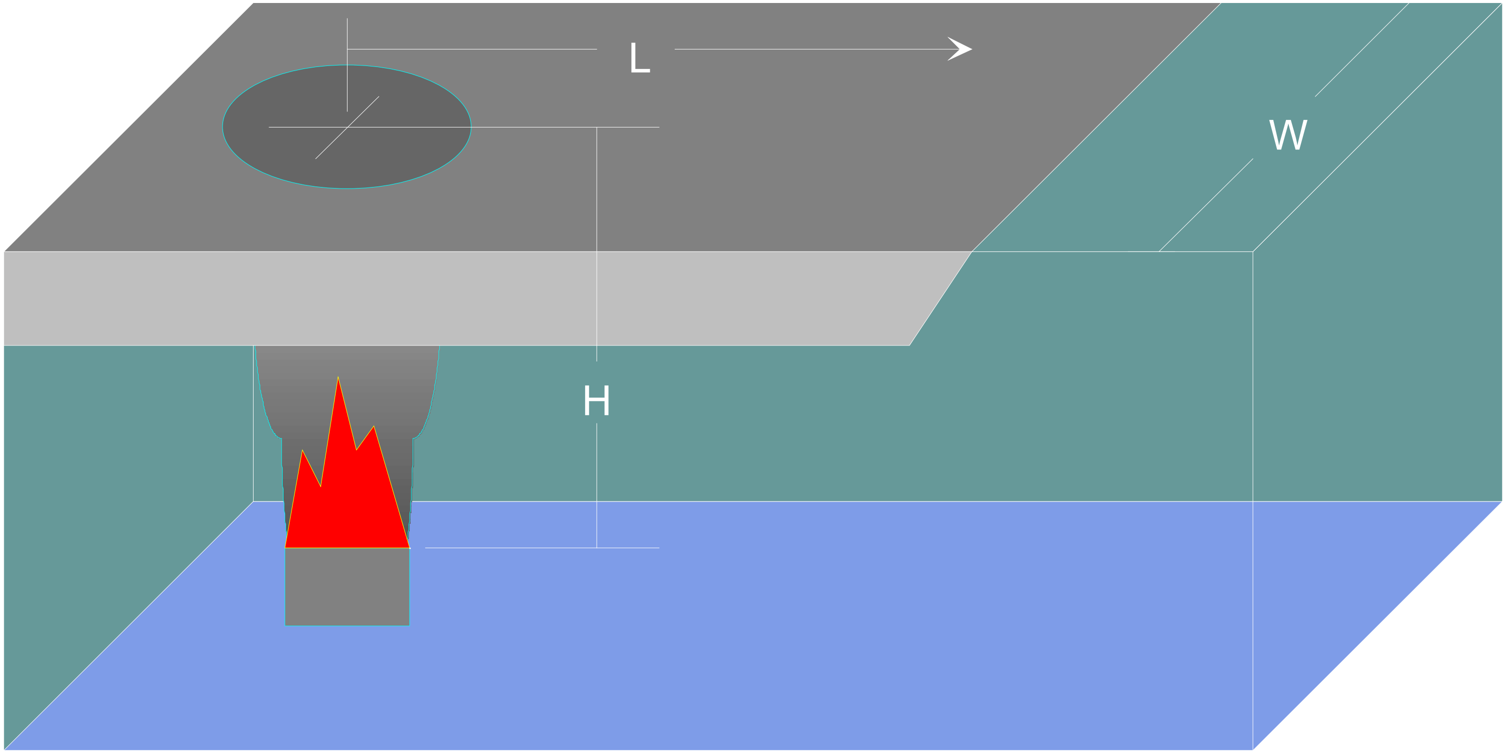
References – ceiling jets

- *SFPE Handbook*
  – Chapter on Ceiling Jet Flows

Unconfined ceiling jets



Confined ceiling jets



Unconfined ceiling jet

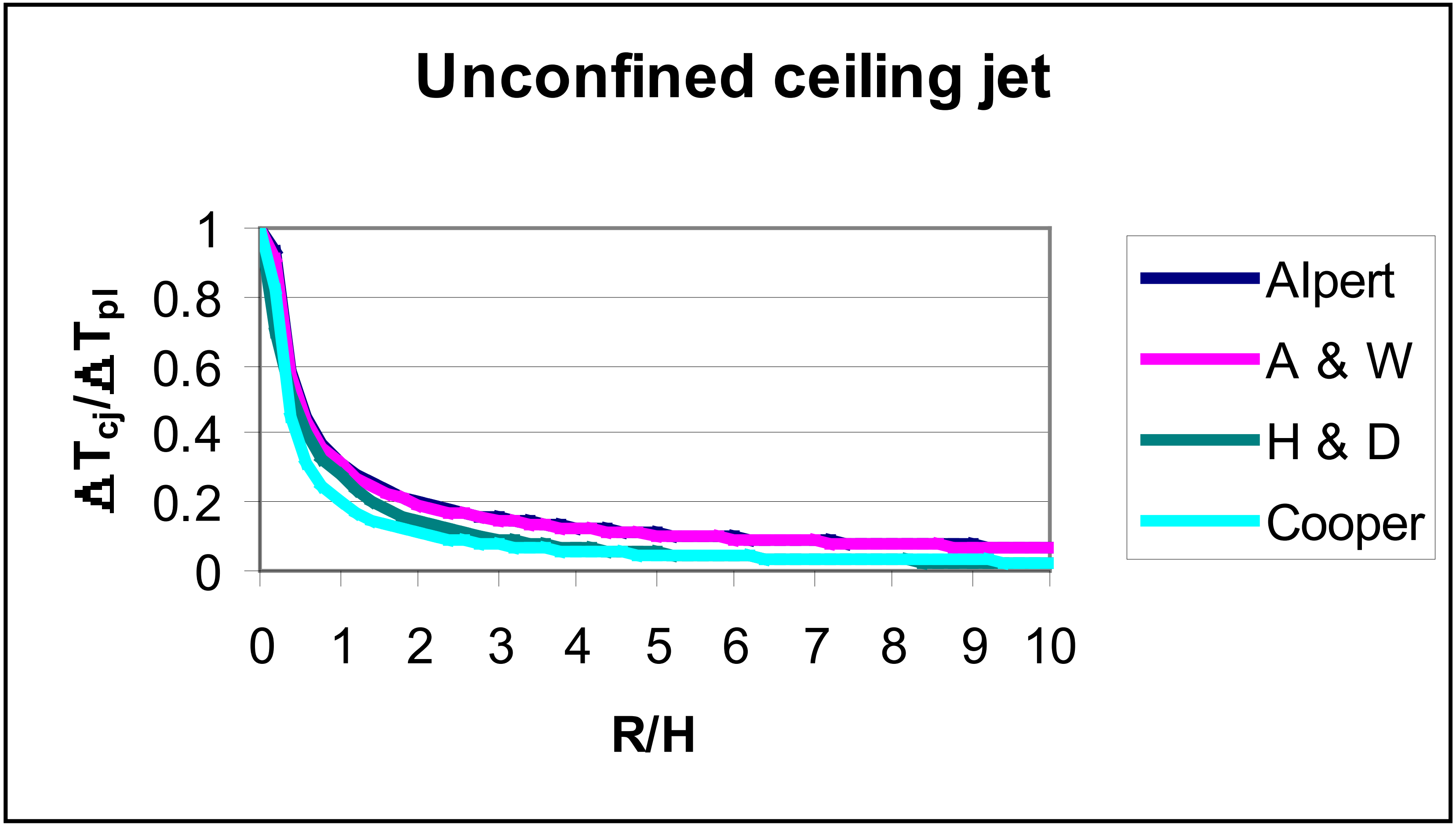
- Temperature correlations
  - Alpert

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.32}{\left(R/H\right)^{2/3}} \qquad \Delta T_{pl} = 16.9\frac{\dot{Q}^{2/3}}{H^{5/3}}$$

  - Alpert and Ward

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.31}{\left(R/H\right)^{2/3}} \qquad \Delta T_{pl} = 22.0\frac{\dot{Q}_c^{2/3}}{H^{5/3}}$$

Temperature correlations

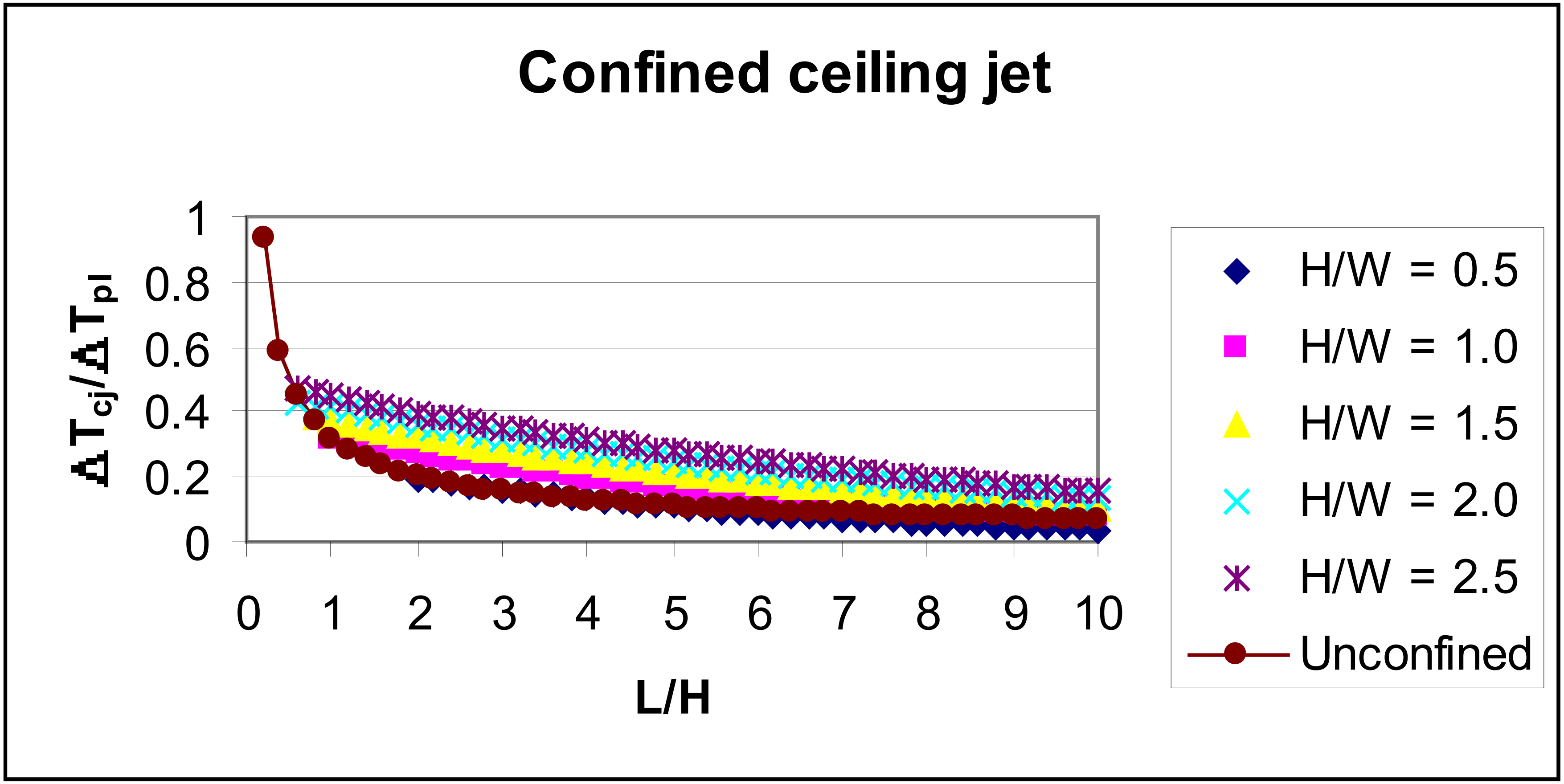


Confined ceiling jet

- Temperature correlation
  – Delichatsios

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = 0.37\left[\frac{H}{W}\right]^{1/3} \exp\left[-0.16\left(\frac{L}{H}\right)\left(\frac{W}{H}\right)^{1/3}\right]$$

Ceiling jet temperatures



Unconfined ceiling jet

- Velocity correlation
  - Alpert

$$\frac{u}{u_o} = \frac{0.2}{(R/H)^{5/6}}$$

  - Note that according to this correlation the velocity decreases as the flow moves away from the source

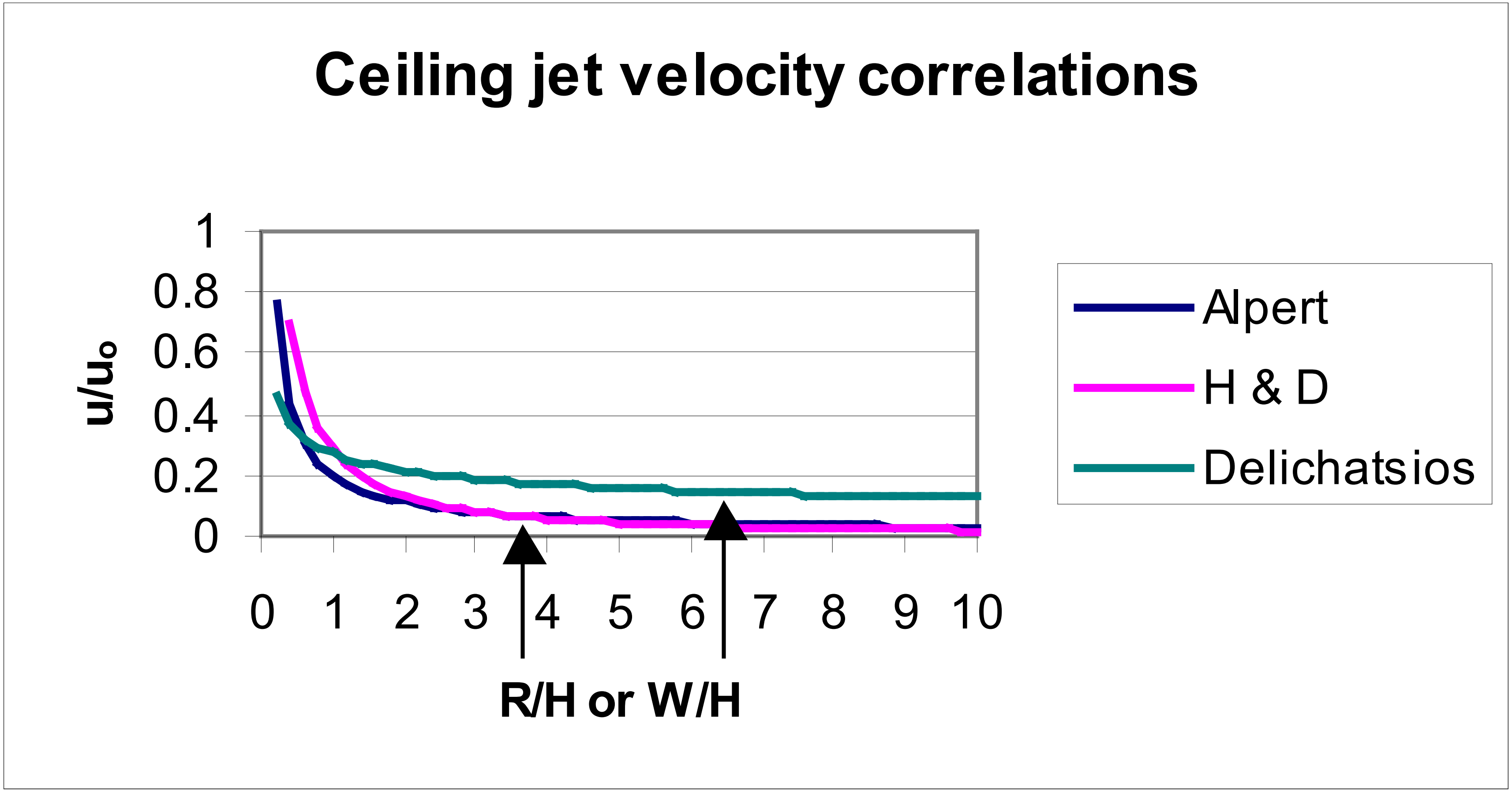
Confined ceiling jet

- Velocity correlation
  - Delichatsios

$$\frac{u}{u_o} = \frac{0.27}{(W/H)^{1/3}}$$

  - Note that according to this correlation the velocity does not change as the flow moves down the corridor

Ceiling jet velocities



Ceiling jet - example

- In the FM/SNL enclosure, what would be the ceiling jet temperature and velocity at a radial distance of 3.0 m (10 ft) from the plume centerline for a HRR of 500 kW?

Ceiling jet - example

- Solution
  - R/H = 3.0 / 6.0 = 0.5
  - Temperature rise

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.31}{\left(R/H\right)^{2/3}} = 0.49$$

$$\Delta T_{cj} = 0.49 \Delta T_{pl}$$
$$= 0.49(64) = 32$$

  - Velocity

$$\frac{u}{u_o} = \frac{0.2}{(R/H)^{5/6}} = 0.36$$

$$u = 0.36 u_o$$
$$= 0.36(4) = 1.44\, m/s$$

Summary – ceiling jets

- Ceiling jets form when buoyant plume gases are trapped beneath ceiling
- Temperature / velocity correlations exist for some conditions
  - Unconfined, horizontal, smooth ceiling
  - Confined, horizontal, smooth ceiling
- For other conditions, such as obstructed or sloped ceilings, CFD model needed
  - In many NPP applications, the ceiling is highly obstructed ("cluttered"), so CFD modeling may be necessary

Fire plume / ceiling jet summary

- Fire plumes and ceiling jets are important aspects of enclosure fire dynamics
- Temperature, velocity and entrainment correlations exist for a few idealized geometries
  – These correlations are used for hand calculations and in zone models
- Fire plume / ceiling jet flows are calculated directly in CFD models such as FDS

Heat and smoke detection

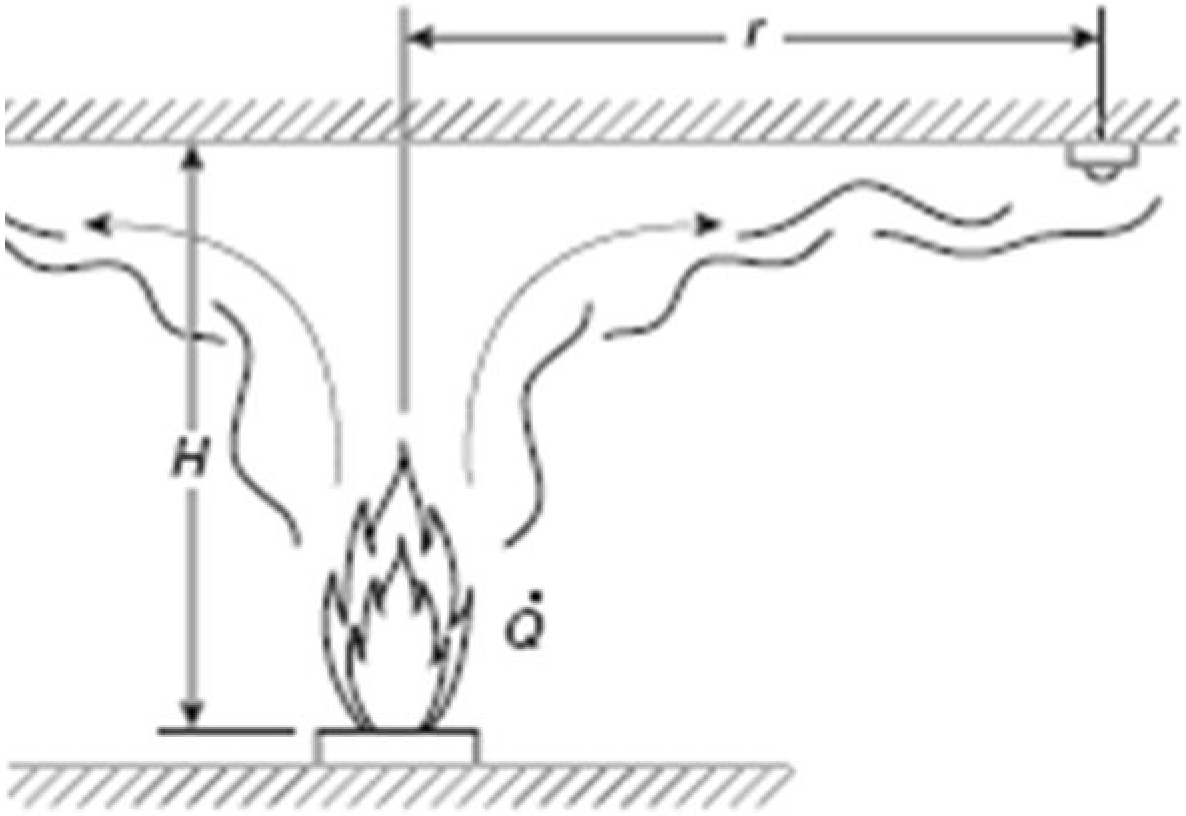
- Understand terminology used to describe the activation of fire detection devices
- Appreciate the role of different variables in estimating fire detector activation and structural damage times
- Calculate the response of fire detectors to fire plume and ceiling jet conditions

References - detection

- *Enclosure Fire Dynamics*
  - Chapter 4 - Fire plumes and ceiling jets
- *SFPE Handbook*
  - Chapter on Fire plumes
  - Chapter on Ceiling jet flows
  - Chapter on Design of detection systems

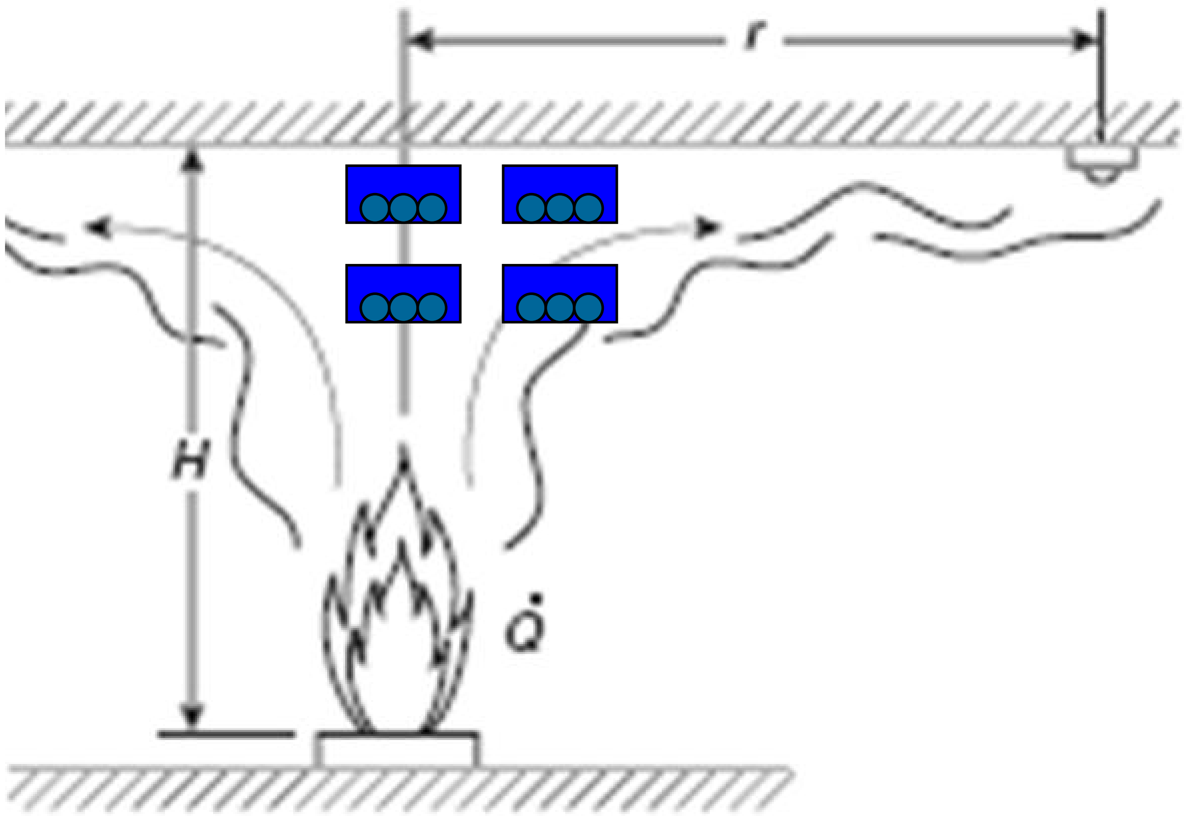
Overview of methods to predict heat / smoke detector activation

- Idealized geometry – smooth flat ceiling



Overview of methods to predict heat / smoke detector activation

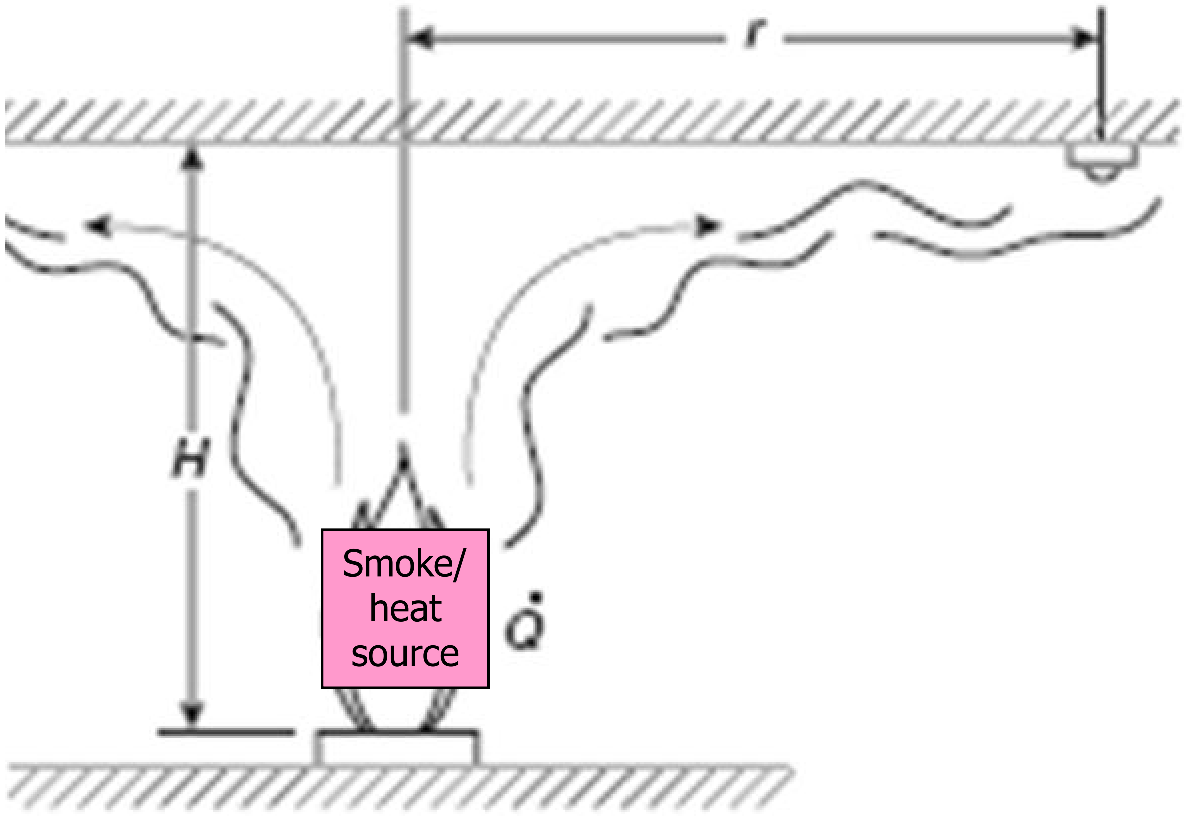
- Realistic geometry – obstructed ceiling



Overview of methods to predict heat / smoke detector activation

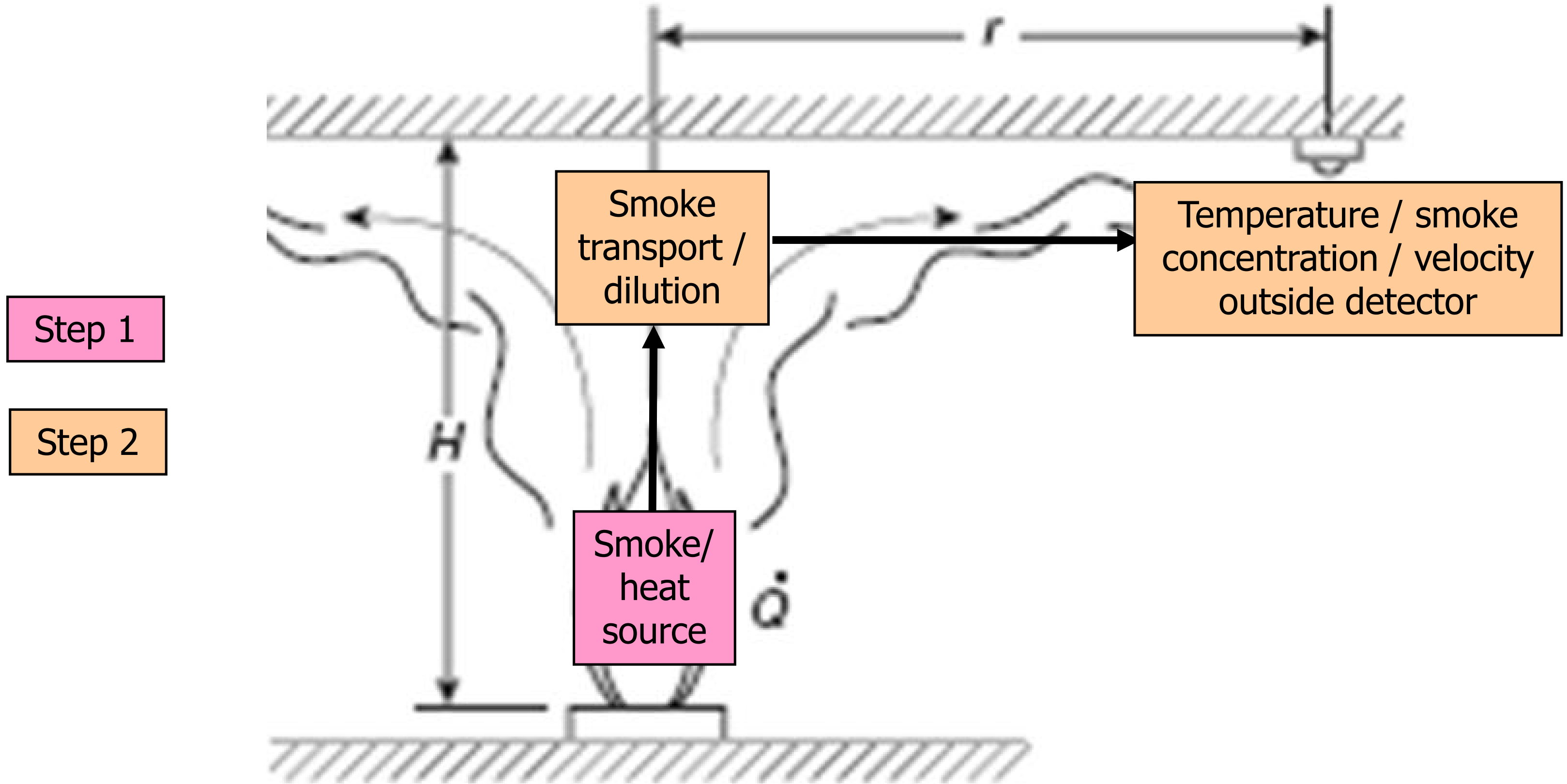
- Step 1. Specify heat/smoke release rates

Step 1



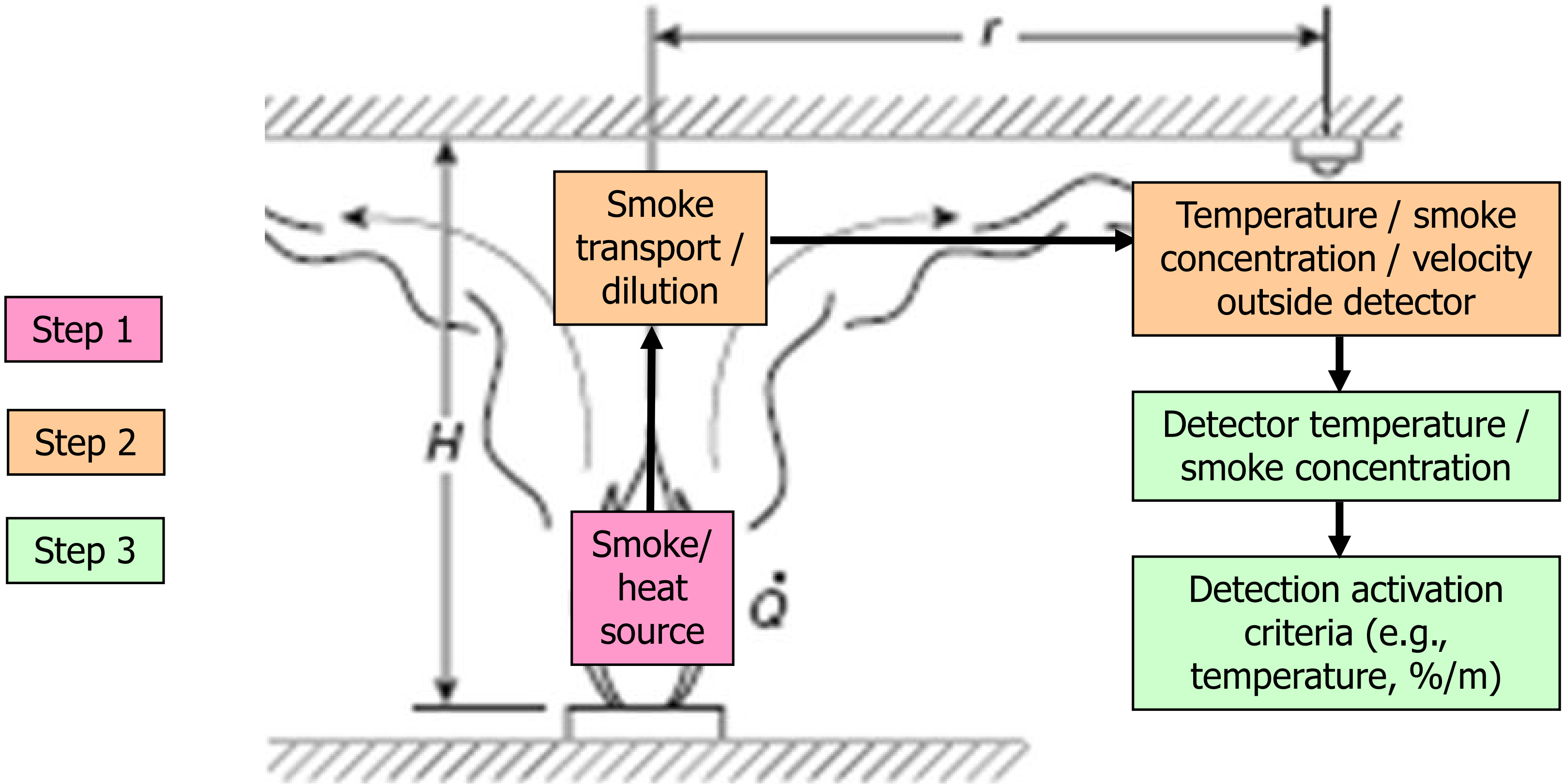
Overview of methods to predict heat / smoke detector activation

- Step 2. Calculate temperature / smoke concentration outside detector



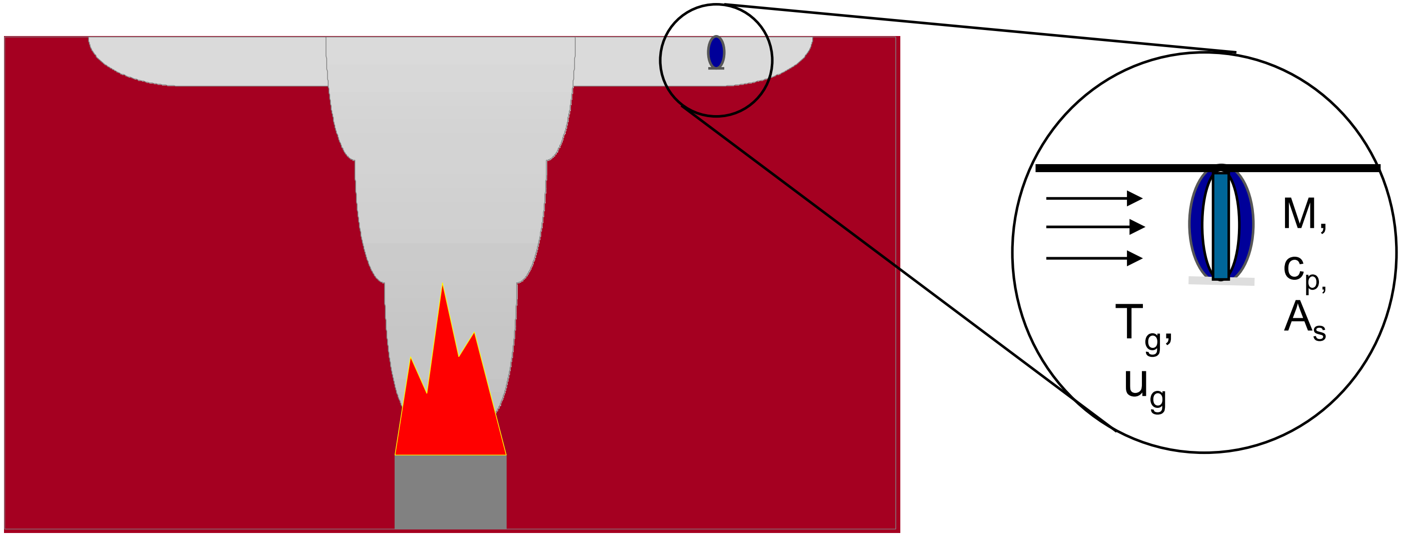
Overview of methods to predict heat / smoke detector activation

- Step 3. Calculate detector response to local environmental conditions



The DETACT model

- A first order response model for predicting fire detector activation based on convective heating and a lumped capacity analysis



Bases

- Heat balance at detector $\dot{q}_{abs} = \dot{q}_{in} - \dot{q}_{out}$
- Convective heating only $\dot{q}_{in} = h_c A_s (T_g - T_d)$
- Lumped capacity analysis $\dot{q}_{abs} = mc_p \frac{dT_d}{dt}$
- Negligible losses (basic model) $\dot{q}_{out} \approx 0$

Solution

- Predictive equation for temperature rise

$$\frac{dT_d}{dt} = \frac{h_c A_s}{mc_p}(T_g - T_d) = \frac{(T_g - T_d)}{\tau}$$

- Definition of detector time constant

$$\tau \equiv \frac{mc_p}{h_c A_s}$$

  – Time constant not really constant because it depends on heat transfer coefficient, which depends on gas velocity

Response Time Index

For cylinders in cross flow $h_c \sim \sqrt{u_g}$

Implications $\tau \sim 1/\sqrt{u_g}$ $\tau\sqrt{u_g} = const$

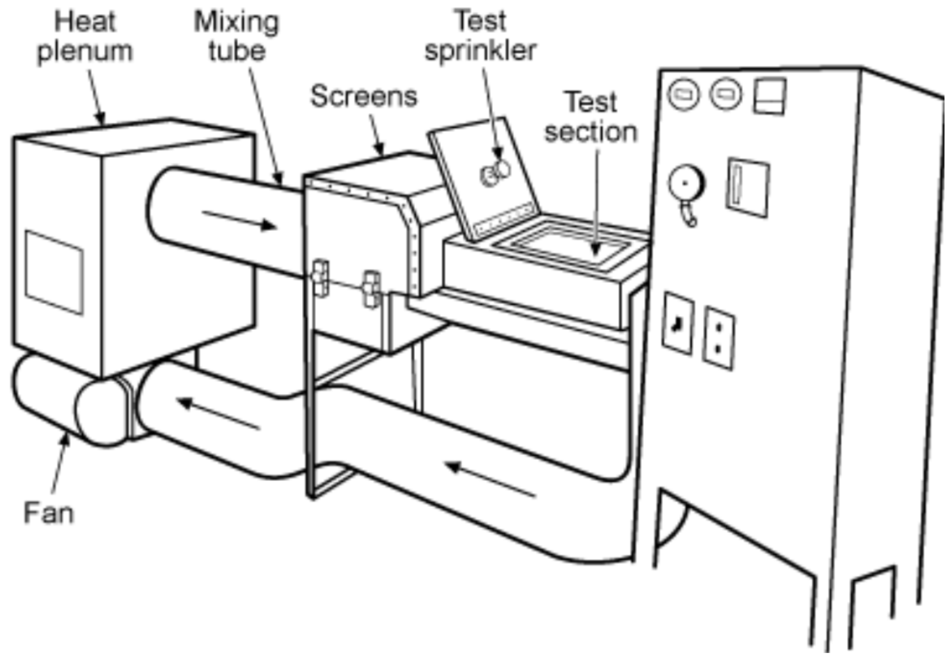
Definition of RTI $RTI \equiv \tau\sqrt{u_g}$

Predictive equation

$$\frac{dT_d}{dt} = \frac{\sqrt{u_g}}{RTI}(T_g - T_d)$$

RTI determination (1)

- Plunge test
  - T_g = constant
  - u_g = constant
  - T_{act} = known

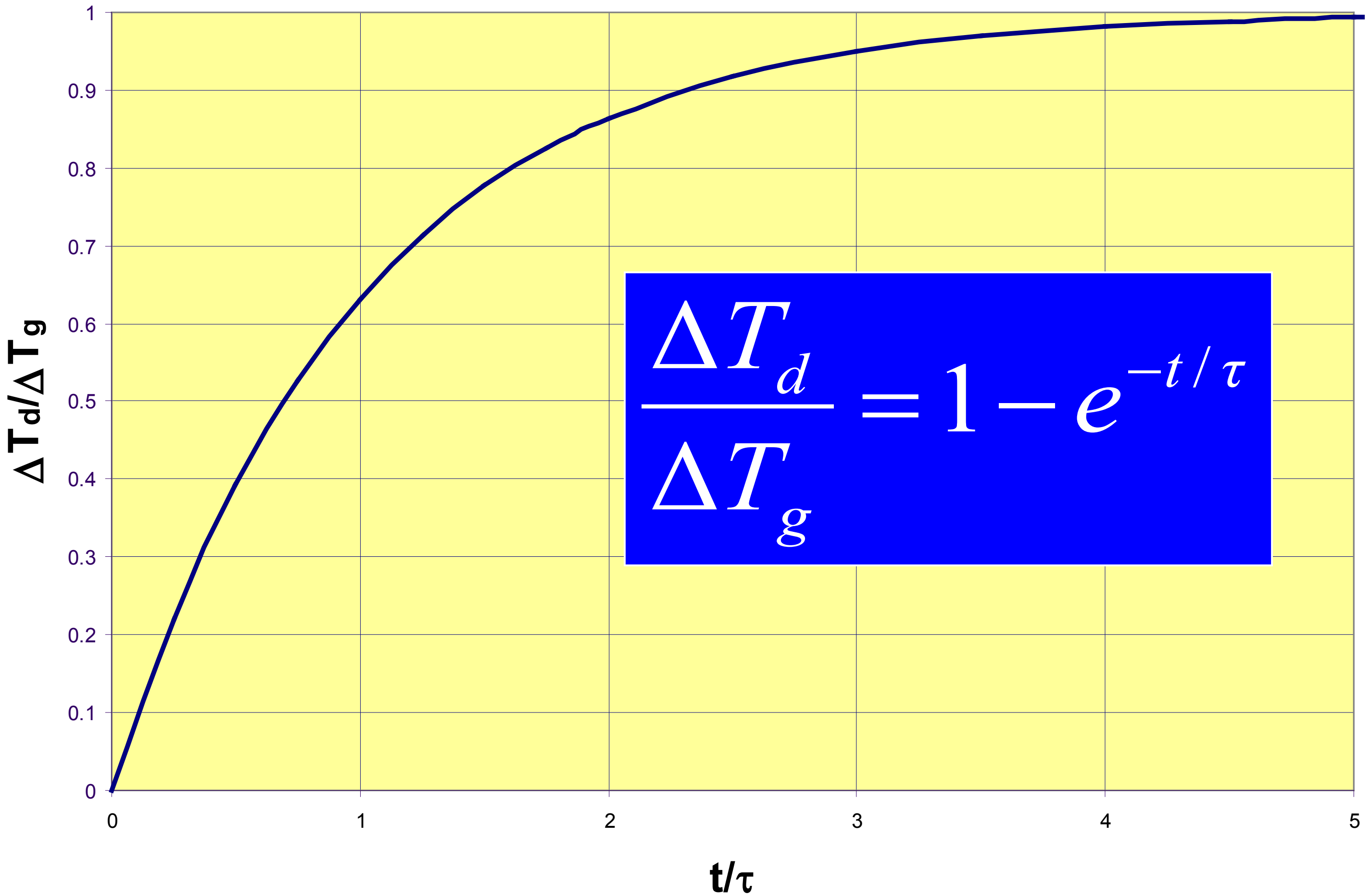


- Analytical solution

$$\frac{\Delta T_d}{\Delta T_g} = 1 - e^{-t/\tau_o}$$

$$\frac{\Delta T_{act}}{\Delta T_g} = 1 - e^{-t_{act}\sqrt{u_o}/RTI}$$

Plunge test



$$\frac{\Delta T_d}{\Delta T_g} = 1 - e^{-t/\tau}$$

DETACT formulation

- *Euler* equation for T_d

$$T_d^{(t+\Delta t)} = T_d^{(t)} + \frac{dT_d}{dt}\Delta t$$

- Substitute equation for dT_d/dt

$$T_d^{(t+\Delta t)} = T_d^{(t)} + \frac{\sqrt{u_g^{(t)}}}{RTI}\left(T_g^{(t)} - T_d^{(t)}\right)\Delta t$$

- Evaluation requires RTI, $T_g(t)$ and $u_g(t)$

Detector activation

- Fixed temperature devices $$T_d > T_{act} \Rightarrow t_{act}$$
- Rate-of-rise devices $$\frac{dT_d}{dt} > \frac{dT_{act}}{dt} \Rightarrow t_{act}$$
  - Typical value of dT_{act}/dt: 8.3ºC (15 ºF) /min

Sprinkler activation

- Generic sprinkler temperature ratings
  - From NUREG 1805

Table 10-2. Generic Sprinkler Temperature Rating ($T_{activation}$)

Temperature Classification	Range of Temperature Ratings °C (°F)	Generic Temperature Ratings °C (°F)
Ordinary	57–77 (135–170)	74 (165)
Intermediate	79–107 (175–225)	100 (212)
High	121–149 (250–300)	135 (275)
Extra high	163–191 (325–375)	177 (350)
Very extra high	204–246 (400–475)	232 (450)
Ultra high	260–302 (500–575)	288 (550)
Ultra high	343 (650)	288 (550)

Sprinkler activation

- Generic sprinkler RTIs
  - From NUREG 1805

Table 10-3. Generic Sprinkler Response Time Index (RTI)

Common Sprinkler Type	Generic Response Time Index RTI $(m\text{-}sec)^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34

Heat detector activation

- Generic heat detector RTIs
  – From NFPA 72

UL Listed Spacing	UL Listed Activation Temperature						All FM Listed Temps.
(ft/m)	128°F (53°C)	135°F (57°C)	145°F (63°C)	160°F (71°C)	170°F (77°C)	196°F (91°C)	
10/3.1	894/494	738/408	586/324	436/241	358/198	217/120	436/241
15/4.6	559/309	425/235	349/193	246/136	199/110	101/56	246/136
20/6.1	369/204	302/167	235/130	157/87	116/64	38/21	157/87
25/7.6	277/153	224/124	174/96	107/59	72/40	---	107/59
30/9.2	212/117	179/99	136/75	81/45	49/27	---	81/45
40/12.2	159/88	128/71	92/51	40/22	---	---	
50/15.3	132/73	98/54	67/37	---	---	---	
70/21.4	81/45	54/30	20/11	---	---	---	

Notes: 1. RTIs are shown in $(ft\text{-}s)^{1/2}/(m\text{-}s)^{1/2}$

Gas parameters - T_g, u_g

- Alpert correlation used in DETACT model (unconfined ceiling jet)
  - Temperature

$$\Delta T_{g,pl} = 16.9 \frac{\dot{Q}^{2/3}}{H^{5/3}}$$

$$\frac{\Delta T_{g,cj}}{\Delta T_{g,pl}} = \frac{0.3}{(r/H)^{2/3}}$$

Velocity

$$u_{g,pl} = 1.0 \left(\frac{\dot{Q}}{H} \right)^{1/3}$$

$$\frac{u_{g,cj}}{u_{g,pl}} = \frac{0.2}{(r/H)^{5/6}}$$

Sprinkler activation example

- Assume sprinklers are installed on a 3m x 3m (10 ft x 10 ft) spacing in the FMSNL test room
- The FM/SNL test room is 18 m (60 ft) long x 12 m (40 ft) wide x 6 m (20 ft) high
- For a quasi-steady fire with a HRR of 500 kW, estimate the activation time for a sprinkler with
  - T_{act} = 74 C
  - RTI = 130 $(m\text{-}s)^{1/2}$

Sprinkler activation example

- Solution
  - Step 1 – determine radial position of sprinkler

$$R = \frac{\sqrt{S^2 + S^2}}{2} = \frac{S}{\sqrt{2}} = \frac{3}{\sqrt{2}} = 2.1\,m \qquad \frac{R}{H} = \frac{2.1}{6.0} = 0.35$$

  - Step 2 – calculate gas temperature / velocity at sprinkler

$$\Delta T_{g,pl} = 16.9 \frac{\dot{Q}^{2/3}}{H^{5/3}} = 54\,C \qquad u_{g,pl} = 1.0 \left(\frac{\dot{Q}}{H} \right)^{1/3} = 4.4\,m/s$$

$$\Delta T_{g,cj} = \frac{0.3}{(r/H)^{2/3}} \Delta T_{g,pl} = 33\,C \qquad u_{g,cj} = \frac{0.2}{(r/H)^{5/6}} u_{g,pl} = 2.1\,m/s$$

Sprinkler activation example

- Solution
  - Step 3 – Calculate sprinkler response
  - The next step would normally be to calculate the activation time of the sprinkler
  - But note that the gas temperature at the sprinkler is only 53 C (20+33) for this example, while the sprinkler activation temperature is 74 C
  - So the 500 kW fire would not activate the sprinkler until the hot gas layer forms and the ceiling jet temperature exceeds the activation temperature

Smoke detector activation (temperature model)

- Heat detector analogy
  - Treat smoke detector as low RTI device
    - Cannot use zero - Divide by zero error
    - Hand calculations - use $T_d = T_g$
  - Assume ΔT_{act} ~ 15 ºC (or less)
  - Questions regarding validity
    - Relies on optical density analogy
    - Smoke detectors don't always respond to optical density

Smoke detector activation (Heskestad model)

Smoke concentration in detector chamber, Y_c

$$\frac{dY_c}{dt} = \frac{Y_s(t) - Y_c(t)}{\delta t_c} \qquad \delta t_c = L / u$$

u is the local gas velocity outside the detector

L is the characteristic entry length of the detector

Y_s is the smoke concentration outside the detector

Y_c is the smoke concentration in the detection chamber

Need to know Y_c that causes detector activation

Structural steel damage

- Same concept as DETACT for steel

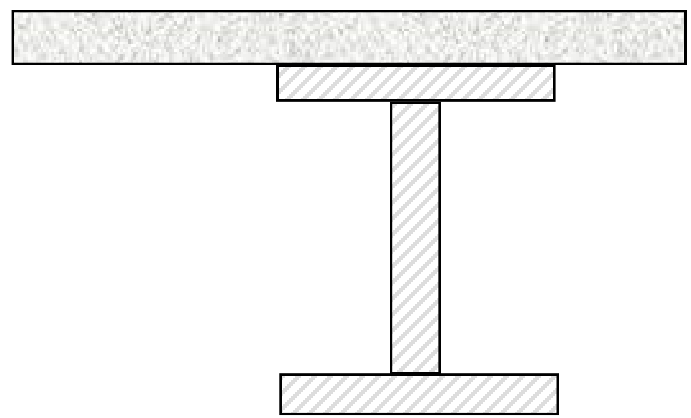
$$\frac{dT_s}{dt} = \frac{\dot{q}''_r A_s}{\rho V c_p} = \frac{\dot{q}''_r}{\rho c_p \left(V / A_s \right)} = \frac{\dot{q}''_r}{c_p \left(W / D \right)}$$

- Steel properties

$$\rho c_p \approx 3{,}666 \ \mathrm{kJ/(m^3 \cdot K)}$$

$$\frac{V}{A_s} = \frac{cross-section}{heated\ perimeter}$$

$$\frac{W}{D} = \frac{Weight / length}{heated\ perimeter}$$



Structural steel damage

- Steel critical temperature, $T_c \approx 550\ ^{o}C$
- Evaluation of heat fluxes
  - Flame radiant heat flux
    - Applies in flame only

$$\dot{q}''_{r} = 160\ \mathrm{kW/m^2}$$

  - Plume convective heat flux
    - Applies in flame and plume

$$\dot{q}''_{c} = 0.3\frac{(k_{lf}\dot{Q})}{H^2}$$

  - Radiant flux outside flame
    - Point source estimate

$$\dot{q}''_{r} = \frac{\chi_r \dot{Q}}{4\pi R^2}$$

  - Based on Alpert & Ward FSJ article

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Protecting People and the Environment

EPRI ELECTRIC POWER RESEARCH INSTITUTE

EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5

Advanced Fire Modeling Development of a Cable Response Model and Fire Model Verification and Validation

Kevin McGrattan

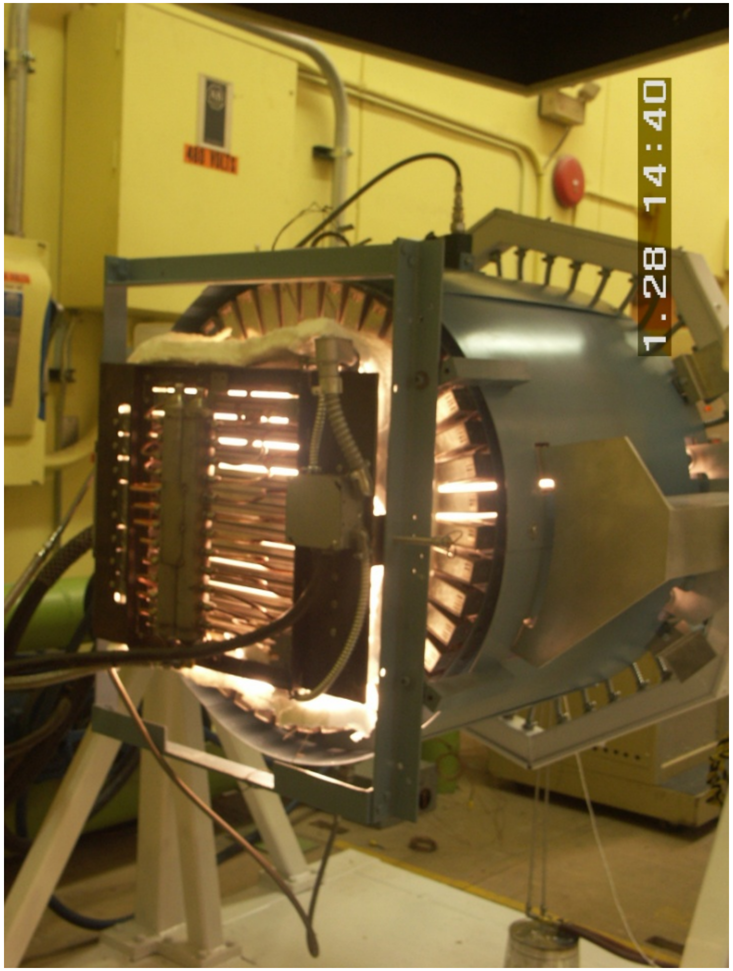
National Institute of Standards and Technology

Joint RES/EPRI Fire PRA Workshop

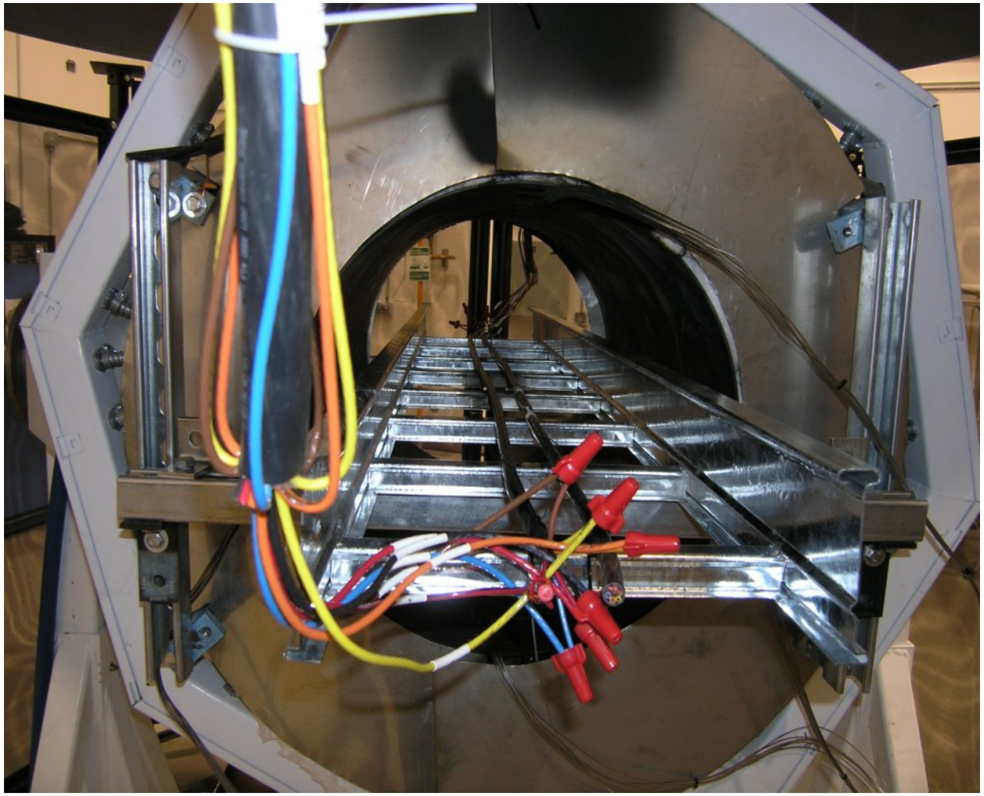
August 2018

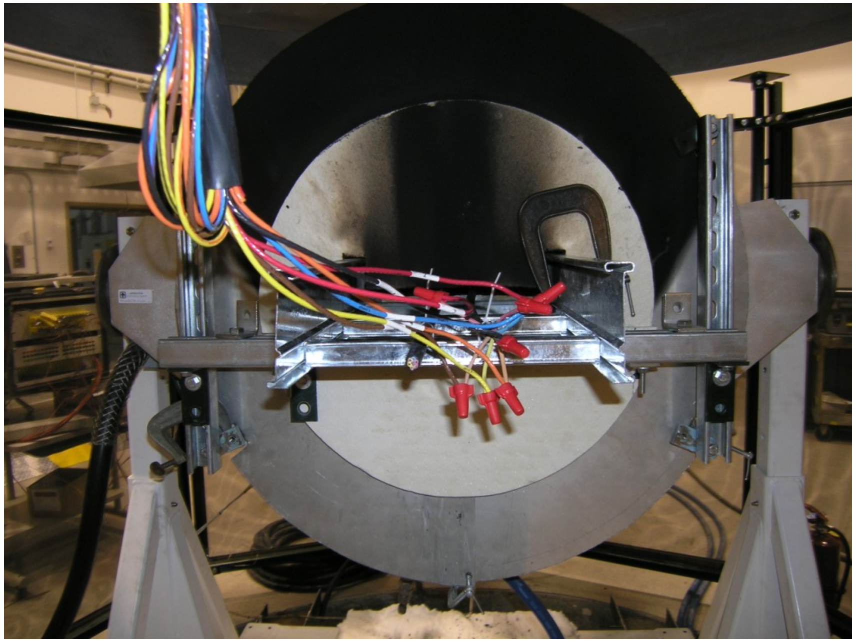
CAROLFIRE
(Cable Response to Live Fire)

- ***Penlight*** heats target cables via grey-body radiation from a heated shroud
- Well controlled, well instrumented tests
- Allows for many experiments in a short time
- Thermal response and failure for single cables and small cable bundles (up to six cables)
- Cable trays, air drops, conduits



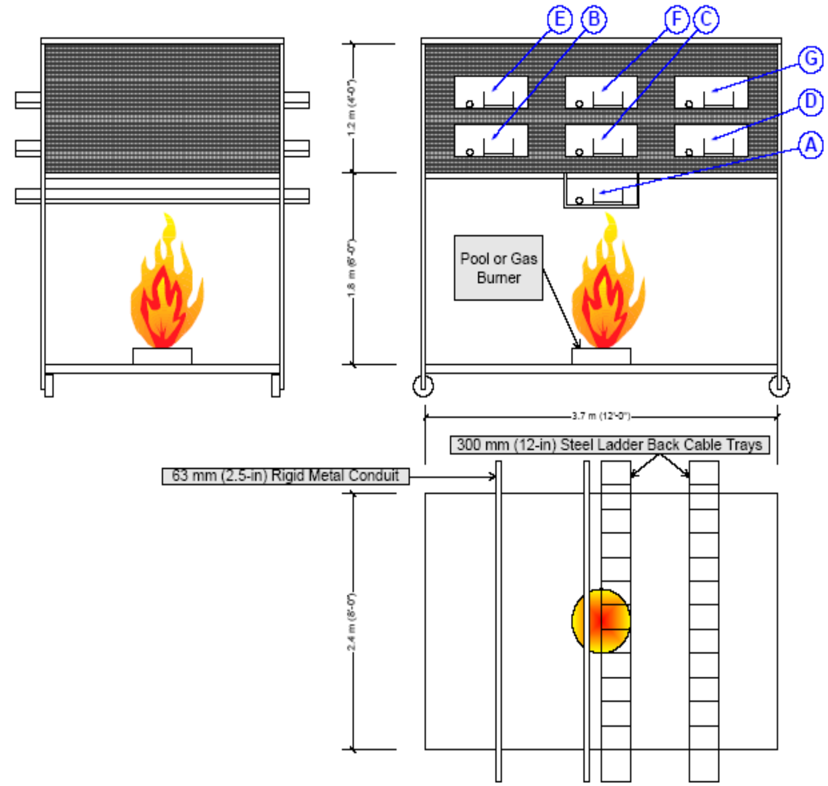
Typical Penlight setup





Intermediate-Scale Experiments

Courtesy Steve Nowlen and Frank Wyant, Sandia National Labs



- Less controlled, but a more realistic scale
- Hood is roughly the size of a typical ASTM E 603 type room fire test facility
- Propene (Propylene) burner fire (200 kW to 350 kW)
- Cables in trays, conduits and air drop

Simple Response Models in Fire

$$\frac{dT_l}{dt} = \frac{\sqrt{|\mathbf{u}|}}{\mathrm{RTI}}(T_g - T_l)$$

Solve for link temperature using velocity **u** and gas temperature from Fire Model. The RTI (Response Time Index) is unique to each sprinkler.

Source: Gunnar Heskestad, Factory Mutual

$$\frac{dY_c}{dt} = \frac{Y_e(t) - Y_c(t)}{L/\mathbf{u}}$$

Solve for smoke chamber concentration using external smoke concentration and velocity **u** from Fire Model. L is a length scale unique to each detector.

Cable Failure Model

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{k_s}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T_s}{\partial r} \right)$$

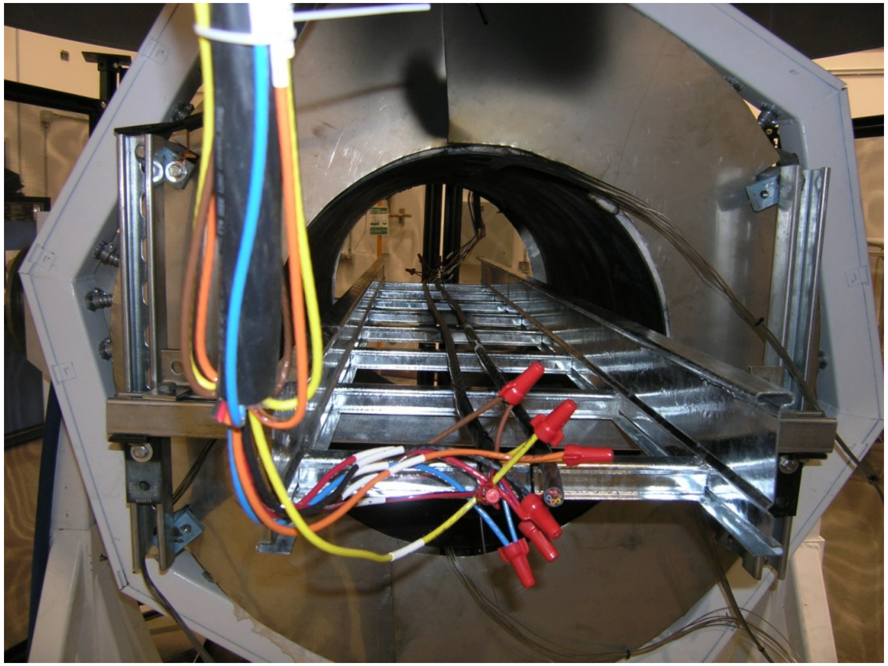
$$-k_s \frac{\partial T_s}{\partial r} = \dot{q}_c'' + \dot{q}_r''$$

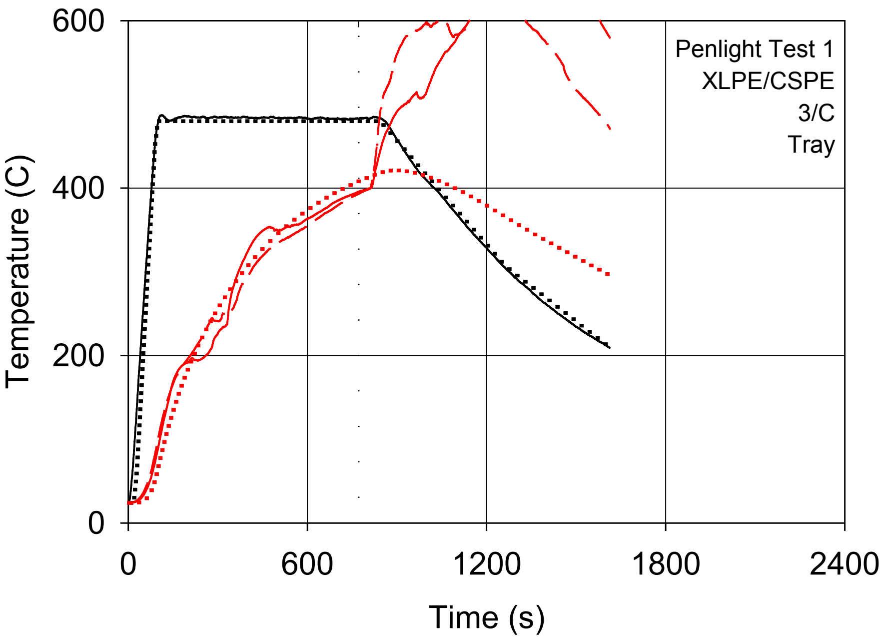
1-D heat conduction into homogenous cylinder. Thermal conductivity (k) and specific heat (c) assumed constant for all cables. Density (ρ) obtained from cable diameter and mass per unit length. Failure temperature obtained experimentally.

The Fire Model provides the convective and radiative heat flux at the cable surface.

Source: Andersson and Van Hees, SP Fire, Sweden.

Single Cable





Courtesy Steve Nowlen and Frank Wyant
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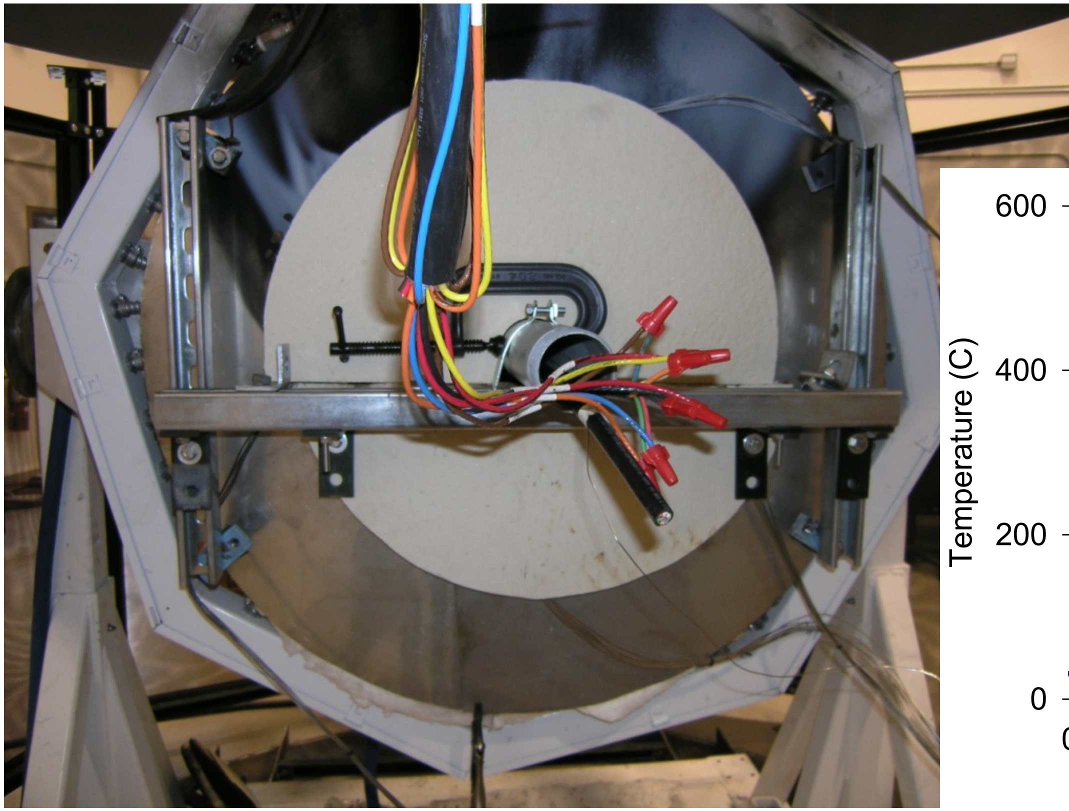
Cable in a Conduit



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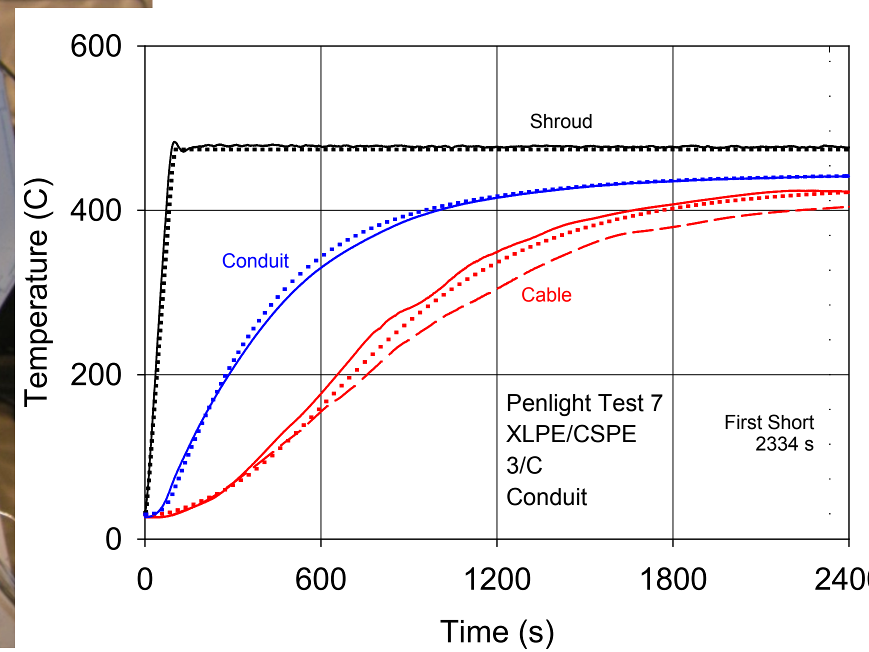
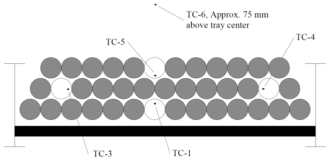
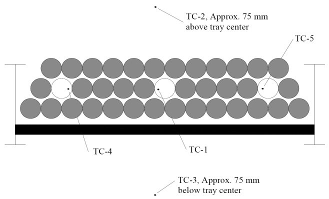
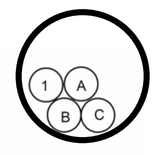
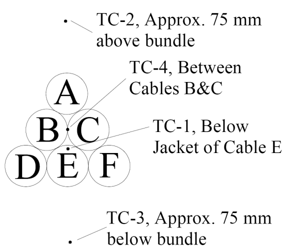


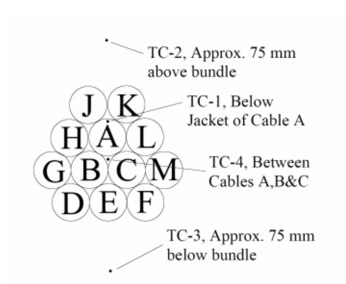
Intermediate-Scale Experiments

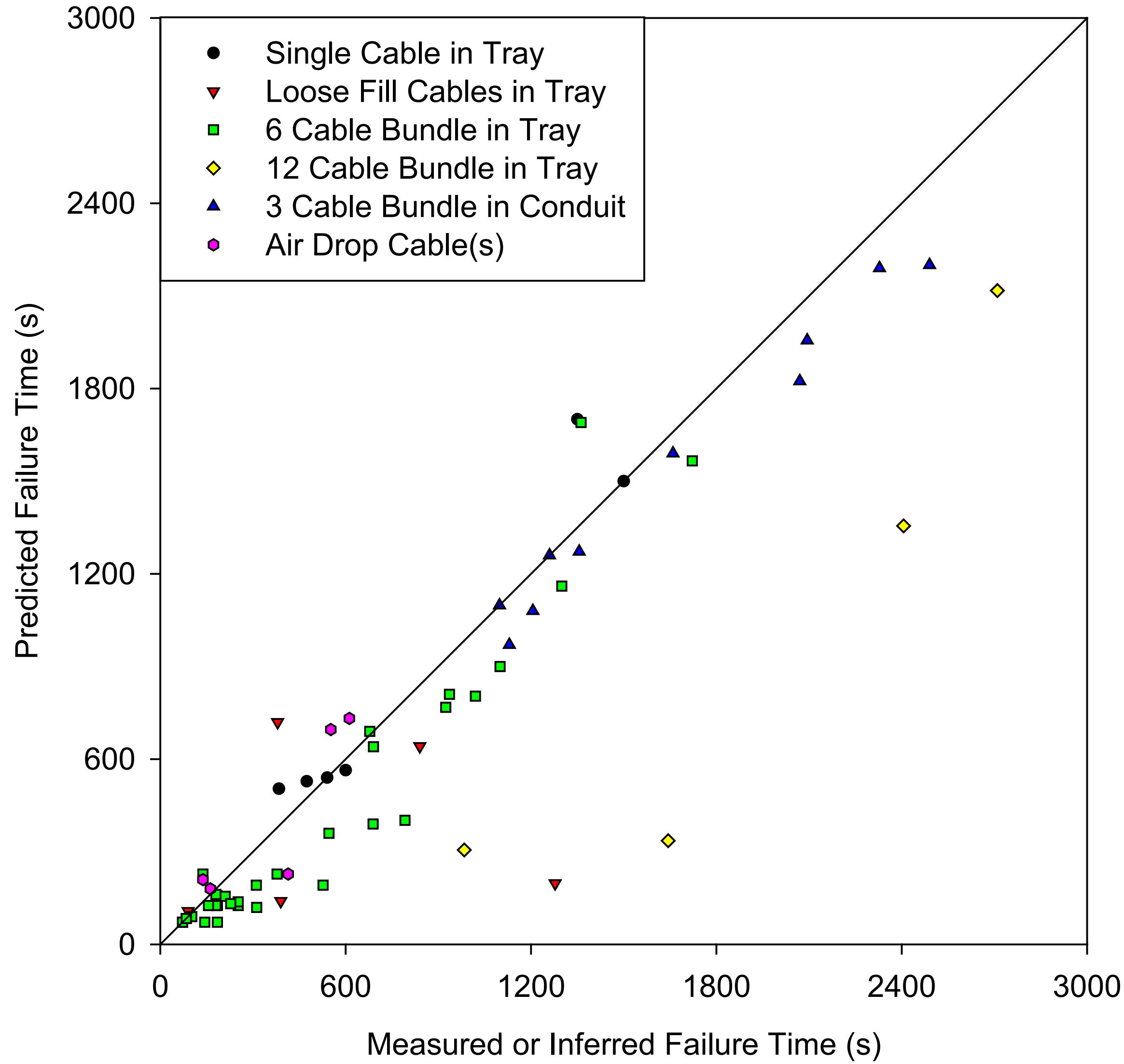












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Summary

- Methods to calculate fire detector response and structural / cable damage have been discussed
  - First-order response characteristics
  - Lumped capacity analysis (Low Biot No.)
- Methods require estimates for:
  - Heat flux or gas temperature at target
  - Thermal response properties of target
- Basic models use fire plume/ceiling jet correlations
  - Same predictive equations used in computer fire models, but temperatures / velocities calculated by models rather than specified by empirical correlations