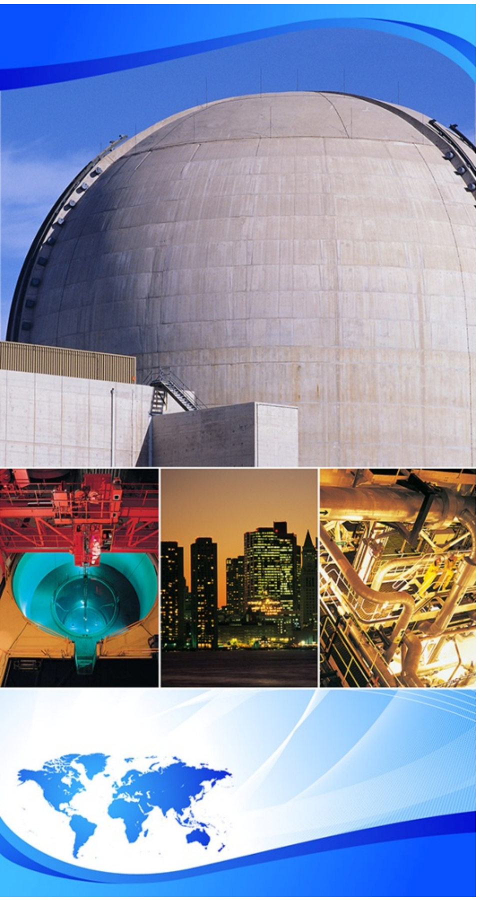


EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5

Advanced Fire Modeling
Day 1 - PM Session
Overview of FMAG, Fire Model V&V, Uncertainty Analysis

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

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

Advanced Fire Modeling

- Course Objectives
  - Fire modeling for nuclear power plant (NPP) applications
  - Fire modeling uncertainty estimation
- Approach
  - Evaluate fire scenarios relevant to NPPs
  - Use models evaluated in verification and validation (V&V) study
  - Demonstrate capability and limitations of each model type
  - Quantify uncertainty as part of the fire modeling analysis
  - Identify relevant sensitivity analyses to support use of results

Background

- NFPA issued the first edition of NFPA 805 in 2001
- NRC amended 10 CFR 50.48(c) in 2004 to employ NFPA 805 as alternative to existing deterministic requirements
- NFPA 805 requires that
  - Fire models shall be verified and validated (section 2.4.1.2.3)
  - Only fire models that are acceptable to the authority having jurisdiction (AHJ) shall be used in fire modeling calculations (section 2.4.1.2.1)
- NRC/RES and EPRI completed V&V project for five fire modeling tools in 2007
  - Results documented in NUREG-1824, EPRI 1011999

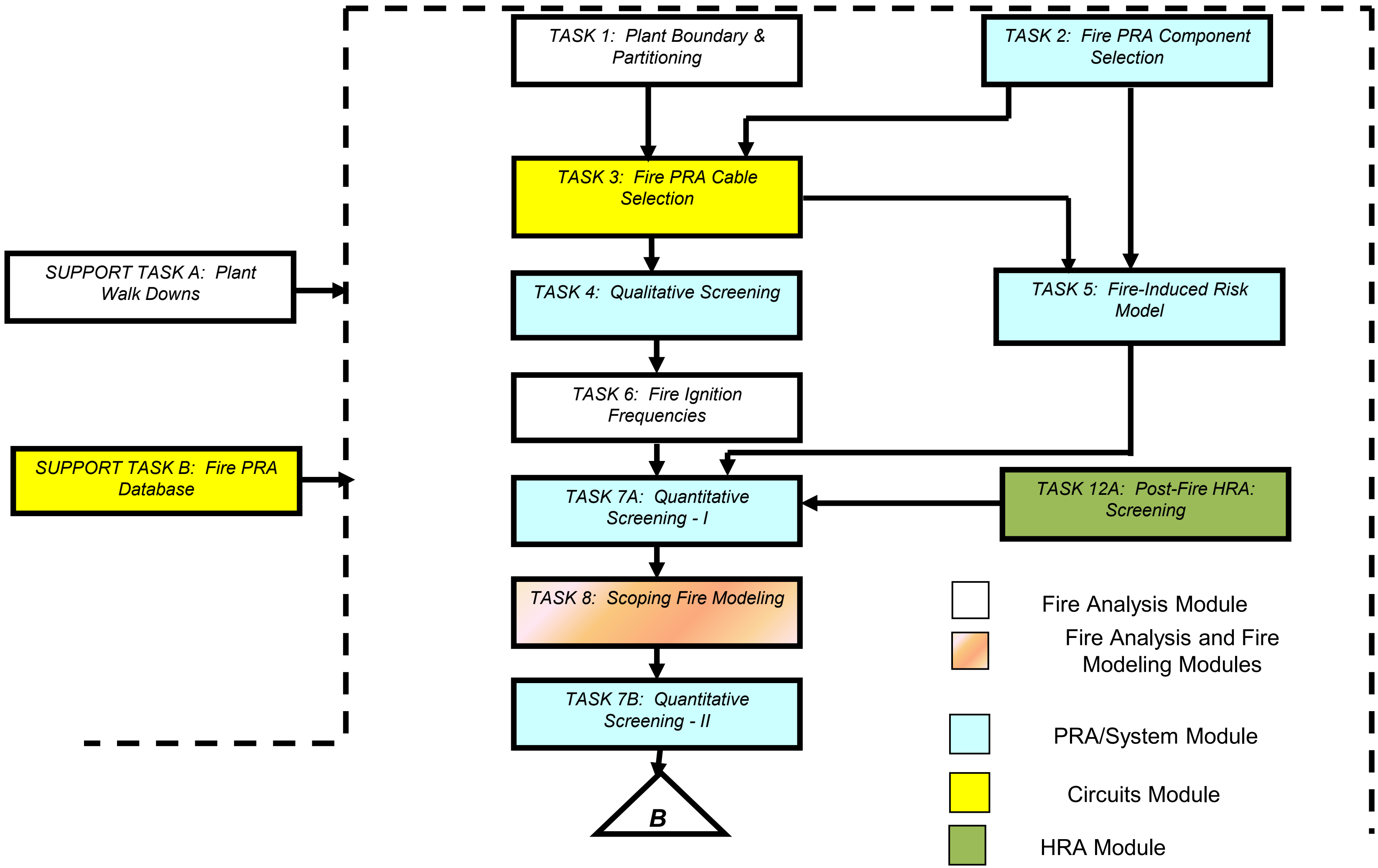
NUREG 1934 / EPRI 1023259 – NPP FIRE MAG

- The objective of this document is to describe the process of conducting fire modeling analyses for commercial nuclear power plant applications
- The process addresses the following technical elements
  - Selection and definition of fire scenarios
  - Determination and implementation of input values
  - Sensitivity analysis
  - Uncertainty quantification
  - Documentation
- The document provides generic guidance, recommended best practices, and example applications

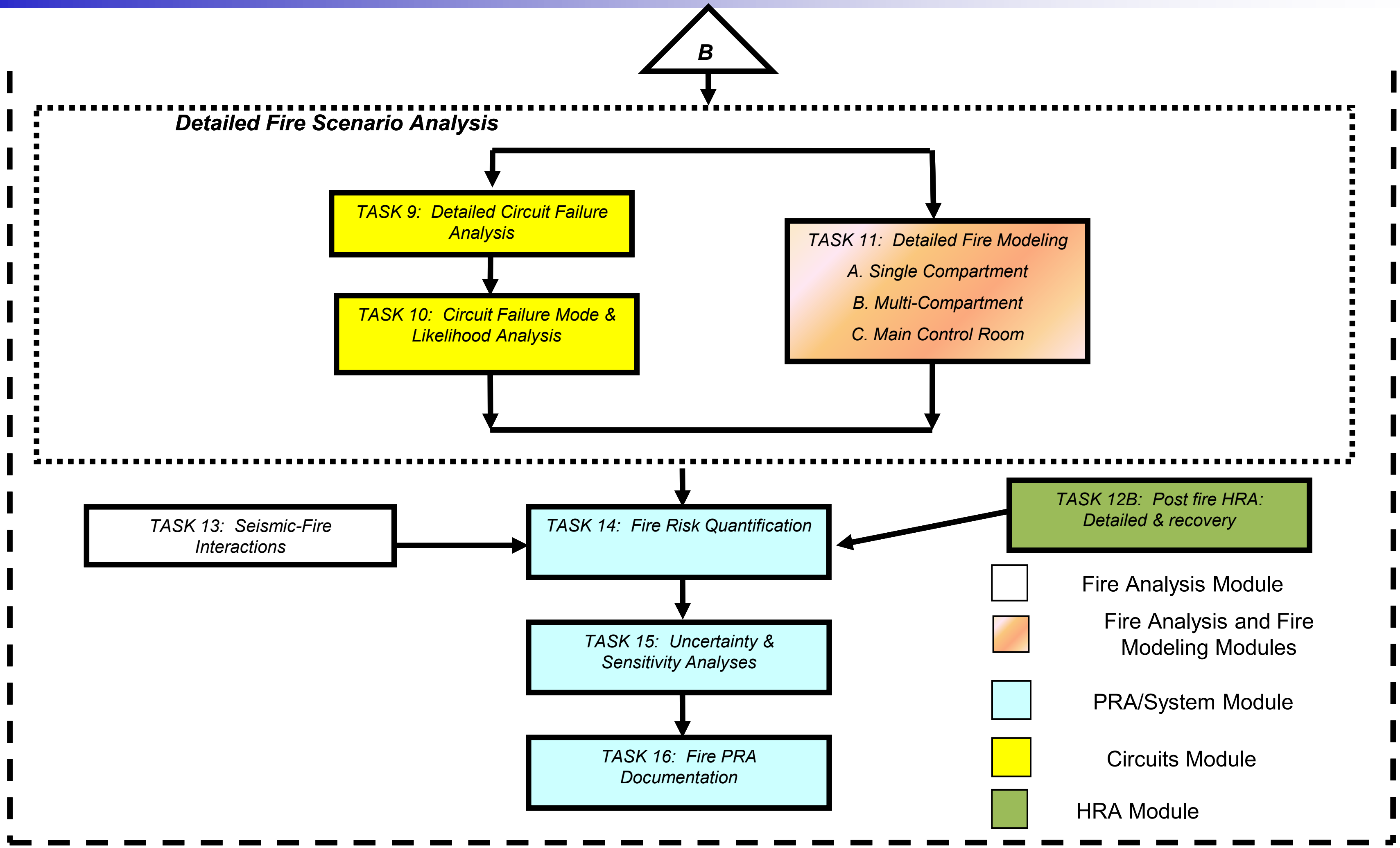
NUREG 1934 / EPRI 1023259 – NPP FIRE MAG

- Users with following expertise will benefit the most :
  - General knowledge of the behavior of compartment fires
  - General knowledge of basic engineering principles, specifically thermodynamics, heat transfer, and fluid mechanics
  - Ability to understanding the basis of mathematical models involving algebraic and differential equations
- Further training resources
  - Academic courses
  - Short courses
  - Written materials

Overall fire PRA structure – NUREG 6850



Overall fire PRA structure – NUREG 6850



Fire Modeling Theory

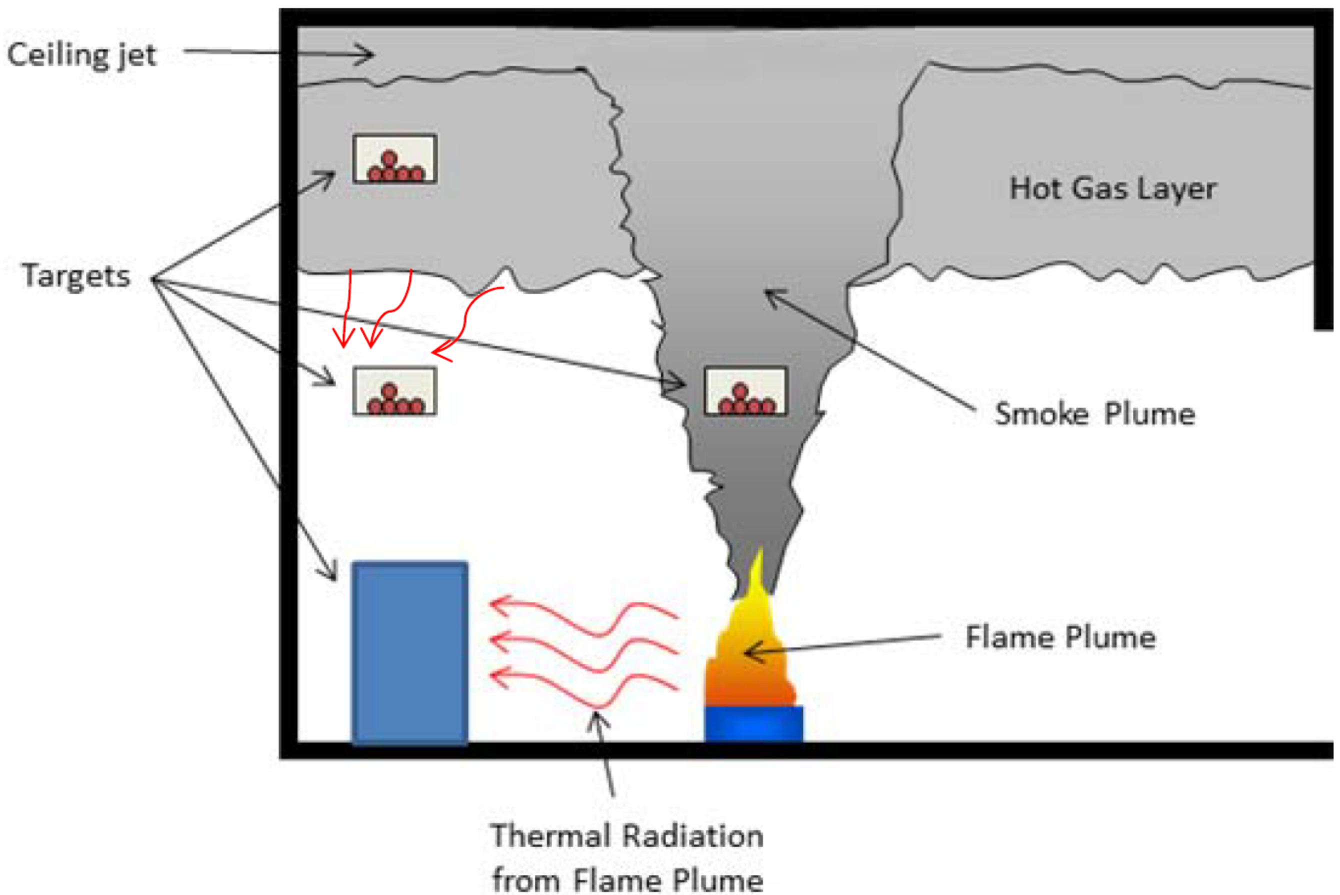


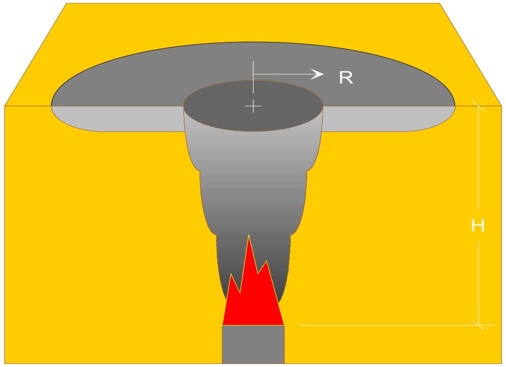
Figure 1-1. Characteristics of compartment fires.

Fire Modeling Theory

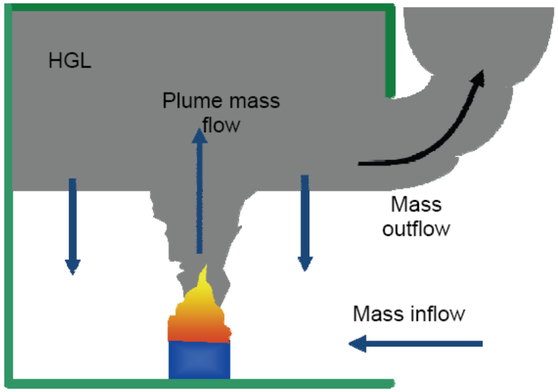
- Parameters of interest in fire modeling analyses:
  - Rate of smoke production
  - Rate of smoke filling
    - HGL interface position
  - Properties of the fire plume and ceiling jet
    - Temperatures / velocities
  - Properties of the HGL
    - Temperature / smoke concentration / visibility
  - Target response to incident heat flux
    - Nuclear safety targets (cables, equipment, operators …)
    - Fire protection targets (sprinklers, detectors …)

Fire Models In NUREG 1934 / EPRI 1023259

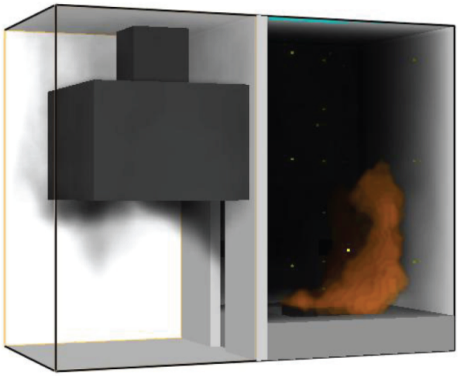
- Algebraic models (1.4.1)
  - FDTs
  - FIVE-rev1



- Zone models (1.4.2)
  - CFAST
  - MAGIC



- CFD models (1.4.3)
  - FDS



Fire Model V&V

- Fire models shall only be applied within the limitations of the given model and shall be verified and validated.
- Validation
  - Is the physics right?
  - Are the right equations being solved?
- Verification
  - Is the math right?
  - Are the selected equations being solved correctly?
- NUREG-1824, EPRI 1011999 - Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications

NFPA 805 Fire Modeling Applications

- NFPA 805 requirements associated with fire modeling are organized in two sections
  - Section 2.4.1.4 describes the requirements associated with the fire modeling tools selected for the analysis.
  - Section 4.2.4.1 describes requirements for the implementation of a performance-based fire modeling analysis.

NFPA 805 Fire Modeling Applications

- NFPA 805 Section 2.4.1.2 describes the requirements for the use of fire models, which include:
  - The use of fire models acceptable to the AHJ
  - The application of fire models within their range and limitations
- Chapter 2 of NUREG 1934, EPRI 1023259 provides guidance on
    - Ensuring the model is within the range of limitations
    - Ensuring specific fire model applications are within the scope of existing V&V studies
    - What steps should be taken if they are not

NFPA 805 Fire Modeling Applications

- NFPA 805 Section 4.2.4.1 describes the process to follow when using fire modeling to address variances from deterministic requirements (VFDRs):
  - Identify Targets (NFPA 805 § 4.2.4.1.1)
  - Establish Damage Thresholds (NFPA 805 § 4.2.4.1.2)
  - Determine Limiting Conditions (NFPA 805 § 4.2.4.1.3)
  - Establish Fire Scenarios (NFPA 805 § 4.2.4.1.4)
  - Protection of Required Nuclear Safety Success Paths (NFPA 805 § 4.2.4.1.5)
  - Operations Guidance (NFPA 805 § 4.2.4.1.6)

Fire Modeling in Support of Fire PRA

- Fire PRA applies fire modeling in the fire scenario development and analysis process
  - A fire scenario in a Fire PRA is often modeled as a progression of damage states over time
  - It is initiated by a postulated fire involving an ignition source
  - Each damage state is characterized by a time and a set of targets damaged within that time
  - Fire modeling is used to determine the targets affected in each damage state and the associated time at which this occurs

Fire Modeling in Support of Fire PRA

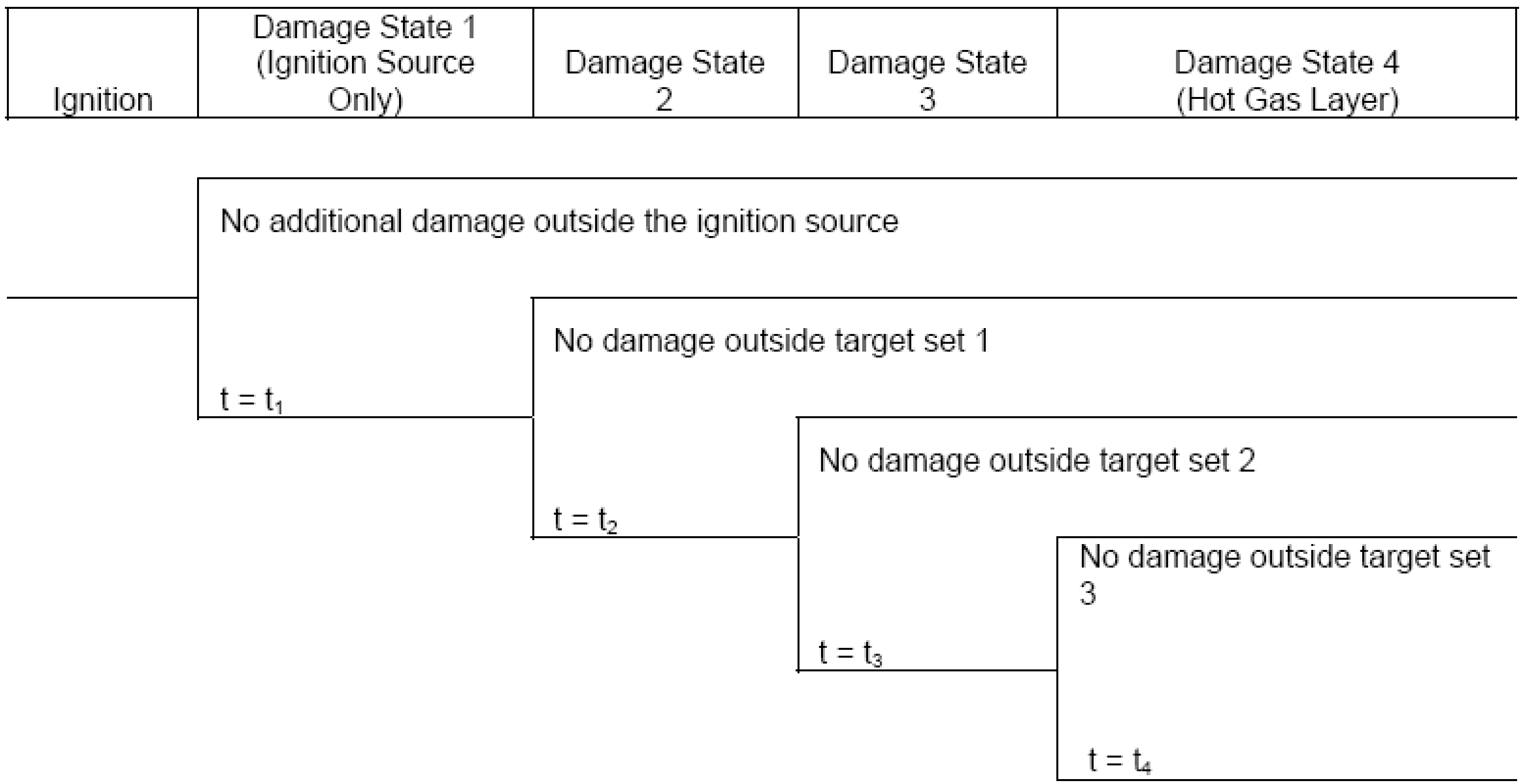


Figure 1-4: Event tree depicting scenario progression modeled in a Fire PRA

Fire Modeling Process

- Step 1
  - Define modeling goals
- Step 2
  - Characterize fire scenarios
- Step 3
  - Select fire models
- Step 4
  - Calculate fire conditions
- Step 5
  - Sensitivity / uncertainty analyses
- Step 6
  - Document the analysis

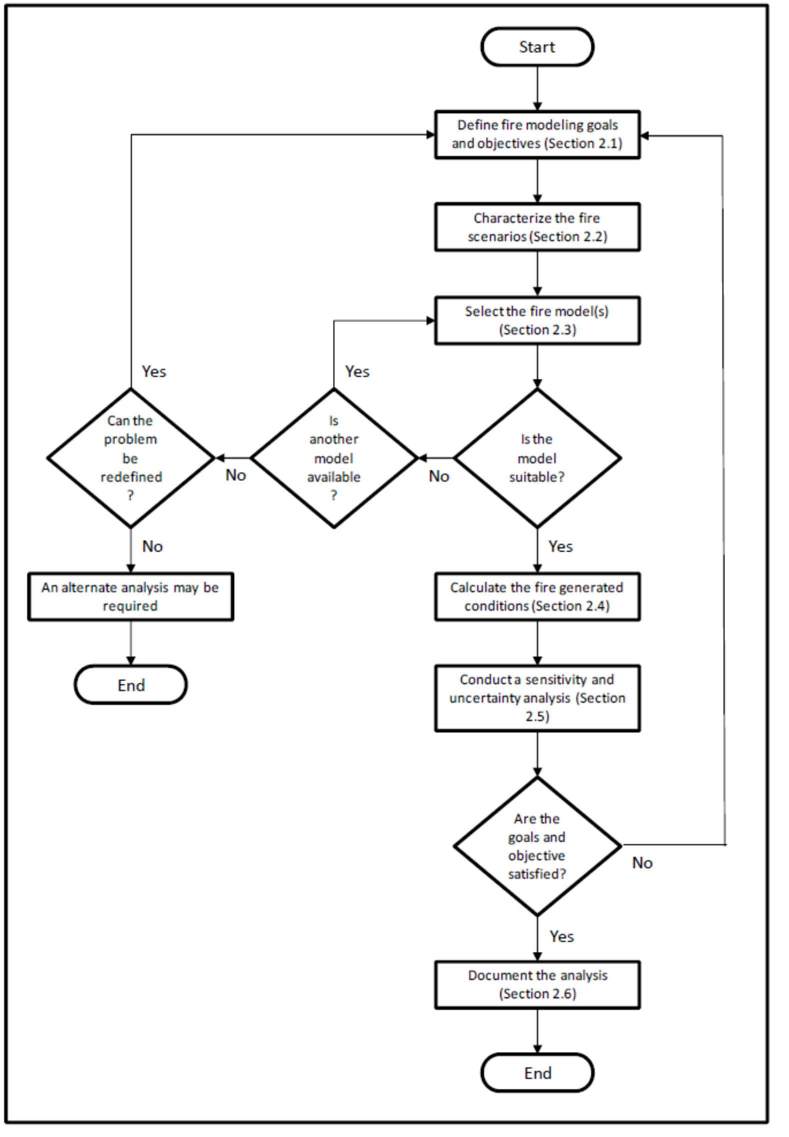


Figure 2-1. Fire modeling process.

Step 1 - Define Modeling Goals

- Establishment of general goals and performance objectives specific to the fire modeling application
- Example of a general goal
  – Demonstrate that targets required for safe shutdown remain free from fire damage (deterministic goal) … to a specified level of probability (probabilistic goal)
- Example of a specific performance objective
  – Evaluate if a fire in Fire Area "X" involving Panel "Y" could cause the surface temperature of Cable "Z" to exceed 330 °C (625 °F)

Step 1 - Define Modeling Goals

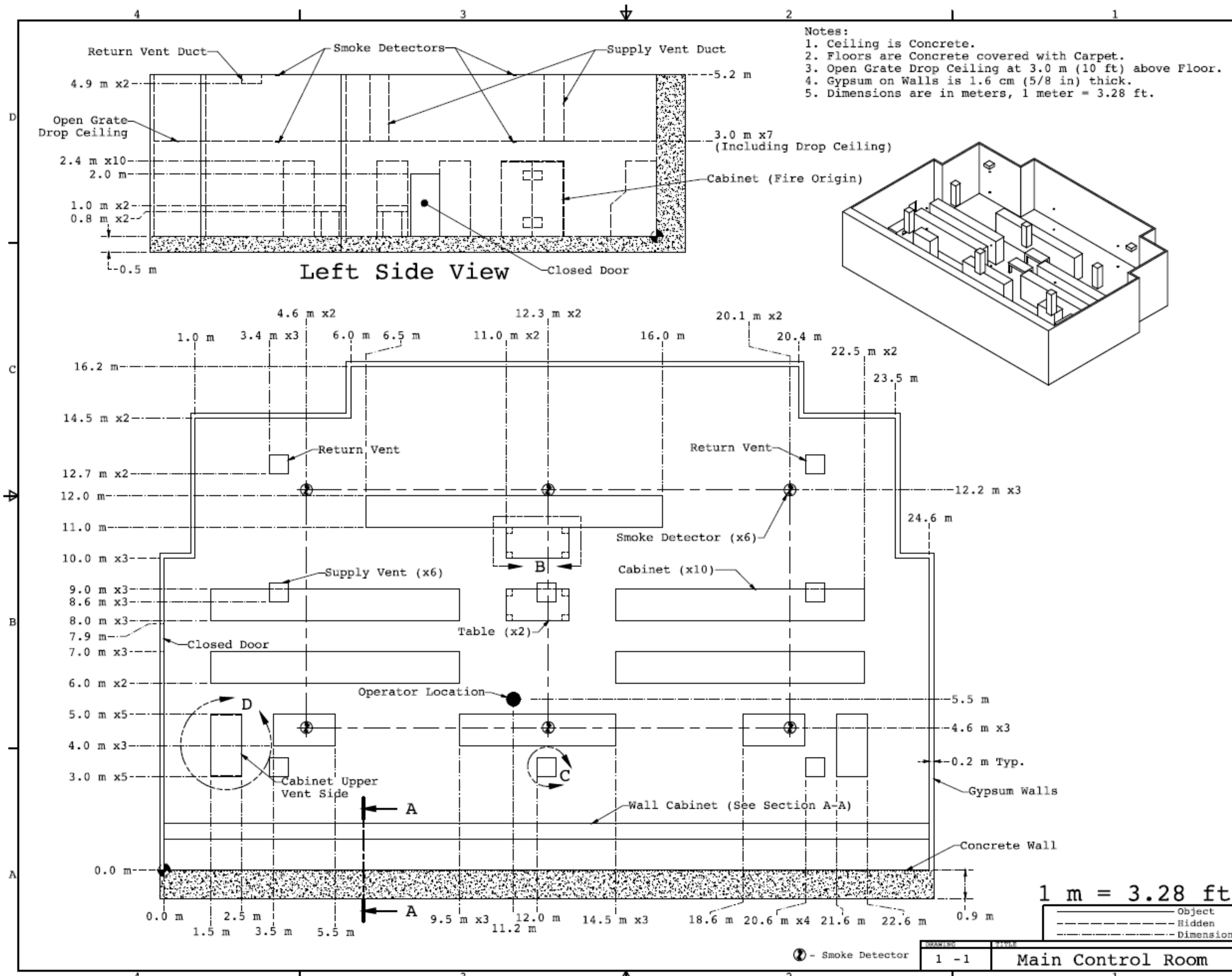
- Maximum acceptable surface temperature for a cable, component, secondary combustible, structural element, or fire-rated construction
- Maximum acceptable incident heat flux for a cable, component, structural element, or secondary combustible
- Maximum acceptable exposure temperature for a cable, component, structural element, or secondary combustible
- Maximum acceptable enclosure temperature
- Maximum smoke concentration or minimum visibility
- Maximum or minimum concentration of one or more gas constituents, such as carbon monoxide, oxygen, hydrogen cyanide

Step 2 - Characterize Fire Scenarios

- A fire scenario is defined as a set of elements needed to describe a fire incident
- These elements are typically specified in fire models
- These elements include the following:
  - Enclosure details
  - Fire location within the enclosure
  - Fire protection features that will be credited
  - Ventilation conditions
  - Target location(s)
  - Secondary combustibles
  - Source fire

Step 2 - Characterize Fire Scenarios

- **Enclosure details**
- Enclosure details include
  - The identity of the enclosures included in the fire model analysis
  - The physical dimensions of these enclosures
  - The boundary materials of each enclosure


Notes:
1. Ceiling is Concrete.
2. Floors are Concrete covered with Carpet.
3. Open Grate Drop Ceiling at 3.0 m (10 ft) above Floor.
4. Gypsum on Walls is 1.6 cm (5/8 in) thick.
5. Dimensions are in meters, 1 meter = 3.28 ft.
Return Vent Duct
Smoke Detectors
Supply Vent Duct
4.9 m x2
5.2 m
Open Grate Drop Ceiling
3.0 m x7 (Including Drop Ceiling)
2.4 m x10
2.0 m
Cabinet (Fire Origin)
1.0 m x2
0.8 m x2
0.5 m
Left Side View
Closed Door
4.6 m x2
12.3 m x2
20.1 m x2
1.0 m
3.4 m x3
6.0 m
6.5 m
11.0 m x2
16.0 m
20.4 m
22.5 m x2
23.5 m
16.2 m
14.5 m x2
Return Vent
Return Vent
12.7 m x2
12.0 m
12.2 m x3
11.0 m
24.6 m
Smoke Detector (x6)
10.0 m x3
B
Cabinet (x10)
Supply Vent (x6)
9.0 m x3
8.6 m x3
8.0 m x3
7.9 m
Table (x2)
Closed Door
7.0 m x3
6.0 m x2
Operator Location
5.5 m
D
5.0 m x5
4.6 m x3
4.0 m x3
0.2 m Typ.
3.0 m x5
Cabinet Upper Vent Side
C
Gypsum Walls
A
Wall Cabinet (See Section A-A)
Concrete Wall
0.0 m
A
0.0 m
1.5 m
2.5 m
3.5 m
5.5 m
9.5 m x3
11.2 m
12.0 m
14.5 m x3
18.6 m
20.6 m x4
21.6 m
22.6 m
0.9 m
1 m = 3.28 ft
Object
Hidden
Dimension
- Smoke Detector
DRAWING
1 -1
TITLE
Main Control Room

Step 2 - Characterize Fire Scenarios

- **Fire location**
- The location depends on the fire modeling goal, the target location, and the fire modeling tool selected
- Examples:
  - Targets in the fire plume or ceiling jet
  - Targets affected by flame radiation
  - Targets engulfed in flames
  - Targets immersed in the Hot Gas Layer

Step 2 - Characterize Fire Scenarios

- **Credited fire protection**
- Fire protection features to be credited in a fire modeling analysis usually require a fire protection engineering evaluation of the system's effectiveness
  - Assessment of the system compliance with applicable codes, including maintenance and inspection
  - Assessment of the system performance against particular fire scenarios being considered.
- Fire modeling tools within this course may not be able to model the impact of some of the fire protection features credited in a given scenario.

Step 2 - Characterize Fire Scenarios

- **Ventilation conditions**
- Ventilation conditions include:
  - Mechanical ventilation
    - Normal HVAC / purge mode
  - Natural ventilation
    - Door / window / damper / vent positions

- Target location(s)
- The physical dimensions of the target relative to the source fire or the fire model coordinate system.

Step 2 - Characterize Fire Scenarios

- **Secondary combustibles**
- Any combustible materials that, if ignited, could affect the exposure conditions to the target set considered.
  - Intervening combustibles, which are those combustibles located between the source fire and the target, are examples of secondary combustibles
- Secondary combustibles include both fixed and transient materials
- Secondary combustibles take on the characteristics of a target prior to their ignition

Step 2 - Characterize Fire Scenarios

- **Source fire**
- The source fire is the forcing function for the fire scenario
- Common fuel packages include electrical panels and transformers, cables, transient combustible material, lubricant reservoirs, and motors
- The source fire is typically characterized by a heat release rate history
- Other important aspects include the physical dimensions of the burning object, its composition, and its behavior when burning

Step 3 - Select Fire Models

- Fire models can be classified into three groups:
  - Algebraic models
  - Zone models
  - CFD models
- The level of effort required to describe a scenario and the computational time consumed by each group increase in the order in which they are listed.
  - Combination of all three types of models may be useful for analyzing a specific problem.

Step 3 - Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

Fire Model Class	Examples	Typical Applications	Advantages	Disadvantages
Algebraic models	FDT[S] FIVE-Rev1	Screening calculations; zone of influence; target damage by thermal radiation, Hot Gas Layer, or thermal plume acting in isolation.	Simple to use; minimal inputs; quick results; ability to do multiple parameter sensitivity studies.	Limited application range; treats phenomena in isolation; typically applicable only to steady state or simply defined transient fires (e.g., proportional to the square of time or t^2 fires).

Step 3 - Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

Fire Model Class	Examples	Typical Applications	Advantages	Disadvantages
Zone Model	CFAST MAGIC	Detailed fire modeling in simple geometries; often used to compute hot gas temperatures and target heat fluxes.	Simple to use; couples Hot Gas Layer and localized effects; quick results; ability to do multiple parameter sensitivity studies.	Error increases with increasing deviation from a rectangular enclosure; large horizontal flow paths not well treated.

Step 3 - Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

Fire Model Class	Examples	Typical Applications	Advantages	Disadvantages
Computation Fluid Dynamics Model	FDS	Detailed fire modeling in complex geometries, including computing time to target damage and habitability (MCR abandonment or manual action feasibility).	Ability to simulate fire conditions in complex geometries and with complex vent conditions.	Significant effort to create input files and post-process the results; long simulation times; difficult to model curved geometry, smoke detector performance, and conditions after sprinkler actuation.

Step 3 - Select Fire Models

- **Fire Dynamics Tools (FDTs)**
- FDTs is a set of algebraic models preprogrammed into spreadsheets
- The FDTs library is documented in NUREG-1805 and Supplement 1 (2011)
- The NRC maintains a website where both new and updated spreadsheets are posted:

www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/finalreport/index.html

- See NUREG-1934, EPRI 1011999 Table 2-2 for complete list of FDTs routines

Step 3 - Select Fire Models

- **Fire-Induced Vulnerability Evaluation (FIVE)-Rev1**
- Five-Rev 1 is a set of algebraic models preprogrammed into spreadsheets
- The FIVE-Rev 1 library is documented in EPRI 1002981
- See NUREG-1934, EPRI 1011999 Table 2-3 for complete list of FIVE-Rev 1 routines

Step 3 - Select Fire Models

- **Consolidated Fire Growth and Smoke Transport (CFAST)**
- CFAST is a multi-room two-zone computer fire model
- The model subdivides a compartment into two control volumes
  - A relatively hot upper layer (i.e., the HGL)
  - A relatively cool lower layer
  - Conditions within each control volume are considered as uniform at any time, with no spatial variations within a control volume
- For some application the two-zone assumption may not be appropriate
  - Long hallways / Tall shafts

Step 3 - Select Fire Models

- **MAGIC**
- MAGIC is a two-zone computer fire model, developed and maintained by EdF specifically for use in NPP analysis
- MAGIC is fundamentally similar to CFAST and solves the same basic set of predictive differential equations

Step 3 - Select Fire Models

- **Fire Dynamics Simulator (FDS)**
- FDS is a CFD model of fire-driven fluid flow
- The model numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow, with an emphasis on smoke and heat transport from fires
- FDS computes the temperature, density, pressure, velocity, and chemical composition within each grid cell at each time step
  - There are typically hundreds of thousands to several million grid cells, and thousands to hundreds of thousands of time steps in a FDS simulation

Table 2-5. Summary of selected normalized parameters for application of the validation results to NPP fire scenarios (NUREG-1824/EPRI 1011999, 2007).

Quantity	Normalized Parameter	General Guidance	Validation Range
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^2 \sqrt{gD}}$	Ratio of characteristic velocities. A typical accidental fire has a Froude number of order 1. Momentum-driven fire plumes, like jet flares, have relatively high values. Buoyancy-driven fire plumes have relatively low values.	0.4 – 2.4
Flame Length Ratio	$\frac{H_f + L_f}{H_c}$ $\frac{L_f}{D} = 3.7\,\dot{Q}^{*2/5} - 1.02$	A convenient parameter for expressing the "size" of the fire relative to the height of the compartment. A value of 1 means that the flames reach the ceiling.	0.2 – 1.0
Ceiling Jet Distance Ratio	$\frac{r_{\text{cj}}}{H_c - H_f}$	Ceiling jet temperature and velocity correlations use this ratio to express the horizontal distance from target to plume.	1.2 – 1.7
Equivalence Ratio	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2} \dot{m}_{O_2}}$ $\dot{m}_{O_2} = \begin{cases} 0.23 \times \frac{1}{2} A_0 \sqrt{H_0} \text{ (Natural)} \\ 0.23\,\rho_\infty \dot{V} \text{ (Mechanical)} \end{cases}$	The equivalence ratio relates the energy release rate of the fire to the energy release that can be supported by the mass flow rate of oxygen into the compartment, $\dot{m}_{O_2}$. The fire is considered over- or under-ventilated based on whether φ is less than or greater than 1, respectively. The parameter, r, is the stoichiometric ratio.	0.04 – 0.6

Quantity	Normalized Parameter	General Guidance	Validation Range
Compartment Aspect Ratio	L/H_c or W/H_c	This parameter indicates the general shape of the compartment.	0.6 – 5.7
Radial Distance Ratio	$\frac{r}{D}$	This ratio is the relative distance from a target to the fire. It is important when calculating the radiative heat flux.	2.2 – 5.7

Step 3 - Select Fire Models

- Fire parameters may fall outside their validation range defined in NUREG-1824 , EPRI 1011999
- The predictive capabilities of the fire models in many scenarios can extend beyond the range
- Analyst is required to address these situations
- Sensitivity analyses can be used to address these scenarios

Step 4 - Calculate Fire Conditions

- This step involves running the model(s) and interpreting the results.
- The process includes
  - Determine the output parameters of interest
  - Prepare the input file
  - Run the computer model
  - Interpret the model results
  - Arrange output data in a form that is suitable for the goal

Step 5 - Sensitivity And Uncertainty Analyses

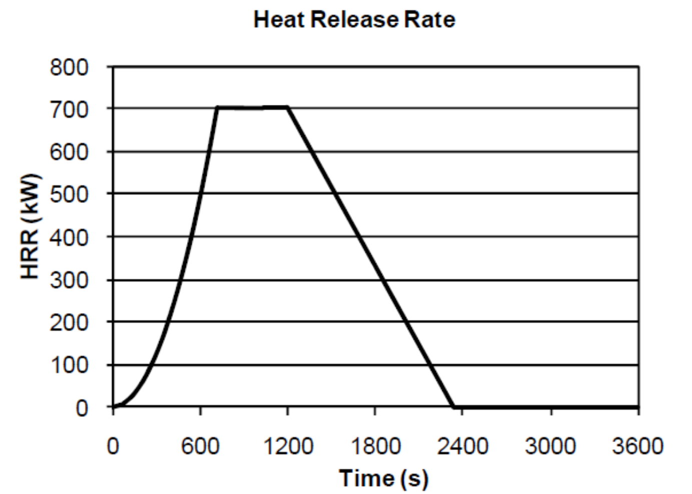
- A comprehensive treatment of uncertainty and sensitivity analyses are an integral part of a fire modeling analysis
- Model uncertainty
  - Models are developed based on idealizations of the physical phenomena and simplifying assumptions
- Parameter uncertainty
  - Many input parameters are based on available generic data or on fire protection engineering judgment

Step 6 - Document The Analysis

- Information needed to document fire scenario selection will be gathered from a combination of observations made during engineering walkdowns and a review of existing plant documents and/or drawings
  - Marked up plant drawings.
  - Design basis documents (DBDs).
  - Sketches.
  - Write-ups and input tables.
  - Software versions, descriptions, and input files.
- A reviewer should be able to reproduce the results of a fire scenario analysis from the information contained within the documentation

Fire Modeling Elements – Heat Release Rate

- Three questions usually have to be answered to adequately assess the heat release rate of a fire:
  - How fast does the fire grow?
  - What is the peak intensity of the fire?
  - How long does the fire burn?
- Other factors:
  - Fire elevation
  - Fire location relative to targets or obstructions
  - Soot yield
  - Radiative fraction
  - Yield factors



Fire Modeling Elements – Area Configuration

- Compartment geometry
- Compartment Boundary materials

Table 3-1. Material Properties

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Source
Brick	0.8	2600	0.8	NUREG-1805, Table 2-3
Concrete	1.6	2400	0.75	NUREG-1805, Table 2-3
Copper	386	8954	0.38	SFPE Handbook, Table B.6
Gypsum	0.17	960	1.1	NUREG-1805, Table 2-3
Plywood	0.12	540	2.5	NUREG-1805, Table 2-3
PVC	0.192	1380	1.289	NUREG/CR-6850, Appendix R
Steel	54	7850	0.465	NUREG-1805, Table 2-3
XLP	0.235	1375	1.390	NUREG/CR-6850, Appendix R

Fire Modeling Elements – Ventilation Effects

- Ventilation openings
  - Vertical (doors / windows)
  - Horizontal (ceiling / floor vents)
- Leakage paths
- Mechanical ventilation
  - Injection
  - Extraction
  - Recirculation

Fire Modeling Elements – Targets

- Targets are objects of interest than can be affected by the fire-generated conditions
- Targets typically consist of
  - Cables in conduits
  - Cables in raceways
  - Plant equipment or
  - Plant personnel
- Targets are characterized by
  - Location,
  - Orientation (i.e. facing the fire, HGL, floor, etc.)
  - Damage criteria and
  - Thermophysical properties

Fire Modeling Elements – Secondary Combustibles

- Intervening combustibles should be described in terms of their locations as well as in terms of their relevant thermophysical and flammability properties
- Representing intervening combustibles in fire models presents technical challenges that the analyst should consider
  - Obtaining the necessary geometric and thermophysical properties representing the intervening combustible and
  - The ability of the computer tools to model the fire phenomena (e.g., fire propagation).

Representative Fire Scenarios

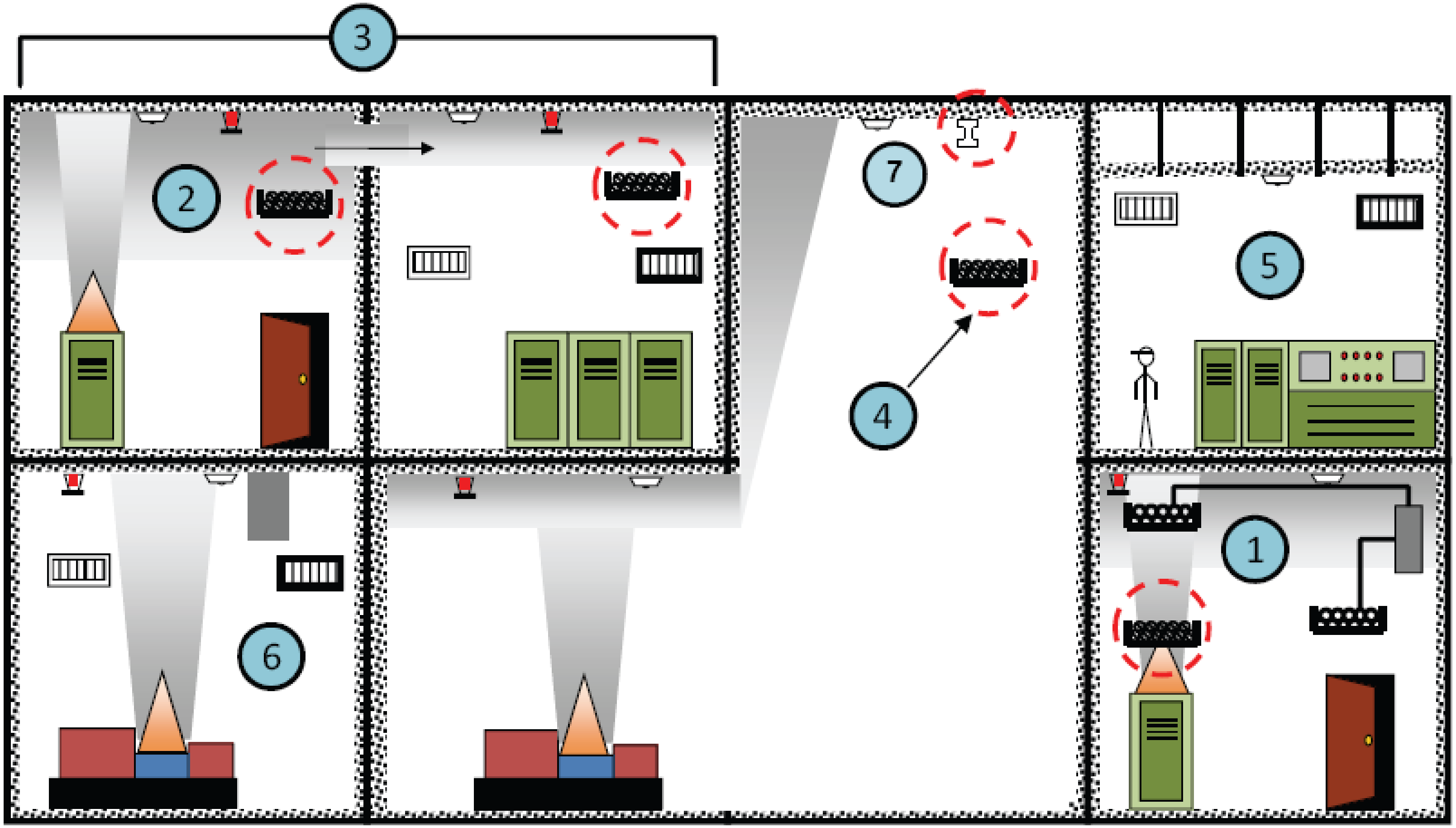


Figure 3-1. Pictorial representation of the fire scenario and corresponding technical elements described in this section.

Scenario 1 – Targets in the Flames or Plume

- This scenario consists of a target (electrical cable in a raceway) immediately above an ignition source (electrical cabinet)
- Objective: Calculate the time to damage for a target immediately above a fire
- **Examples B and E**

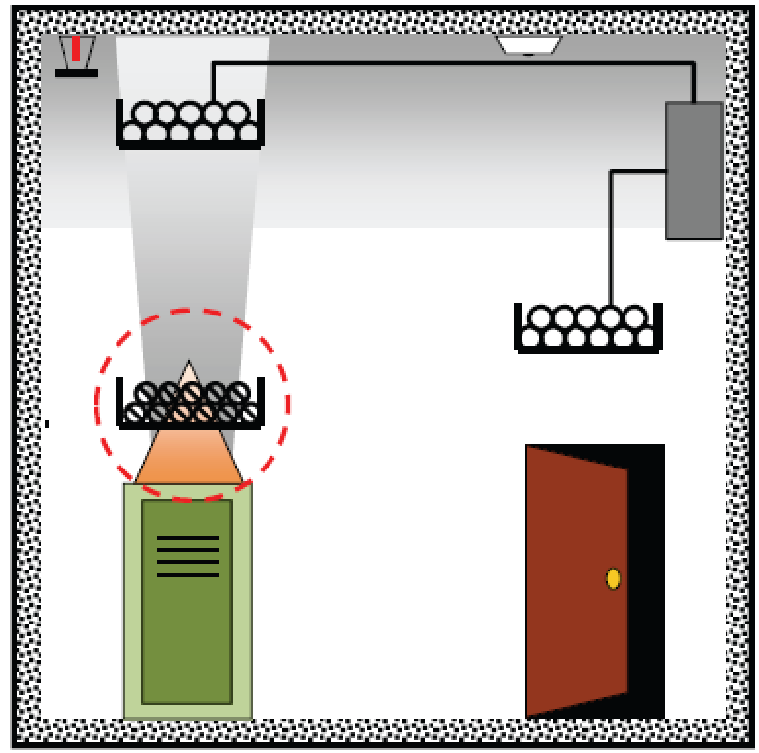


Figure 3-3. Pictorial representation of scenario 1

Scenario 2 – Targets Inside or Outside the Hot Gas Layer

- This scenario consists of a target, ignition source, and perhaps a secondary fuel source
- Objective: Calculate the time to damage for the target if it is inside or outside the Hot Gas Layer
- **Examples C and E**

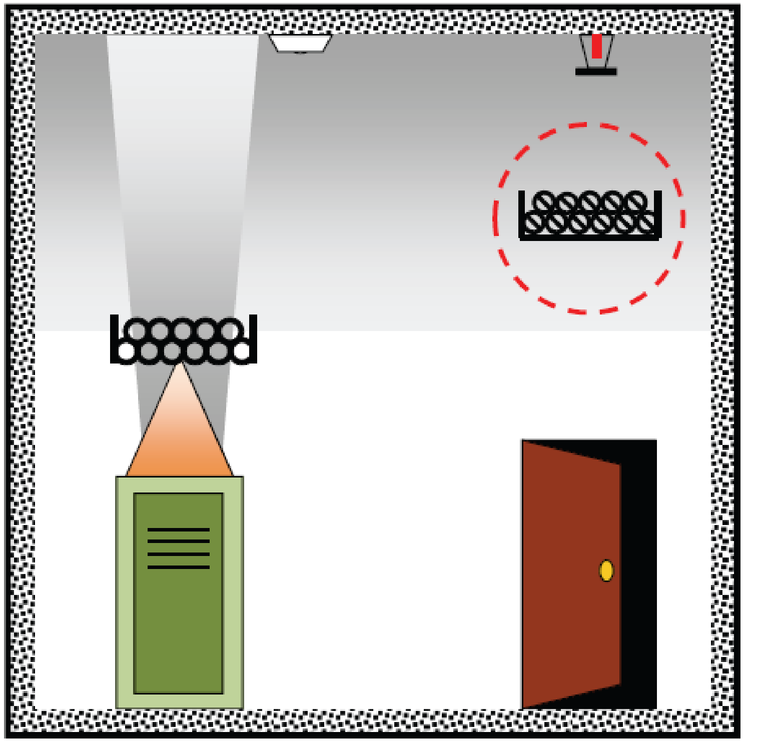


Figure 3-4 Pictorial representation of scenario 2

Scenario 3 –
Targets Located in Adjacent Rooms

- This scenario consists of a target in a room adjacent to the room of fire origin
- Objective: Calculate the time to damage for a target in a room next to the room of fire origin
- **Example G**

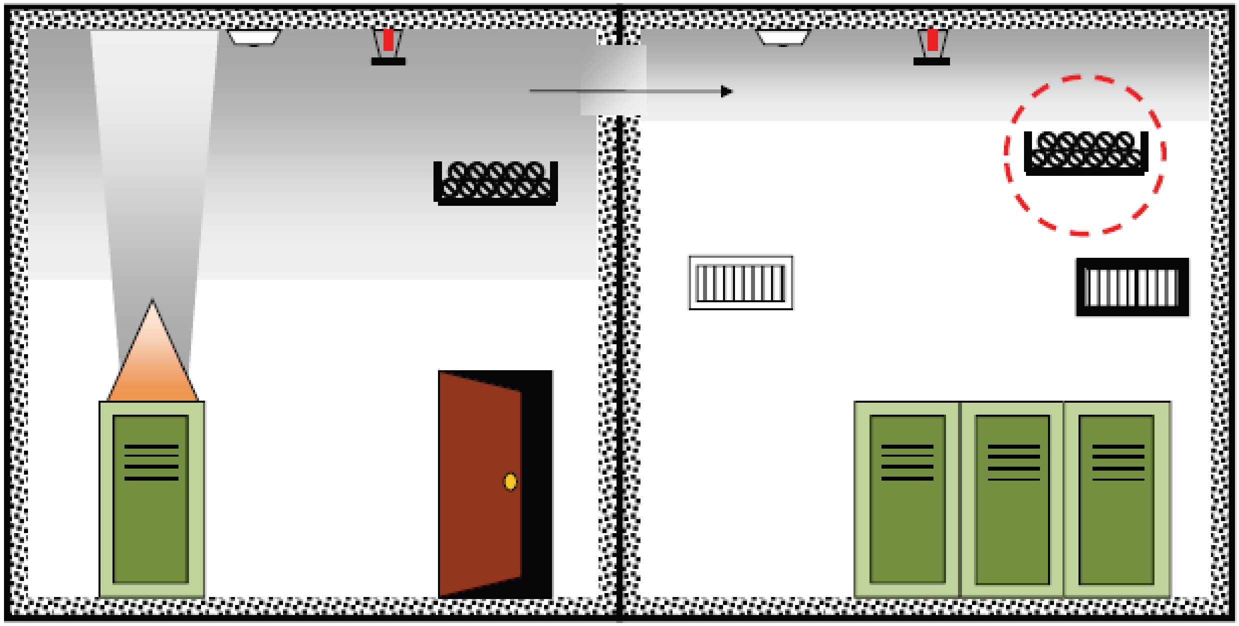


Figure 3-5. Pictorial representation of scenario 3

Scenario 4 – Targets in Rooms with Complex Geometries

- This scenario involves a room with an irregular ceiling height
- Objective: Calculate the time to damage for a target in a room with a complex geometry
- **Examples D and H**

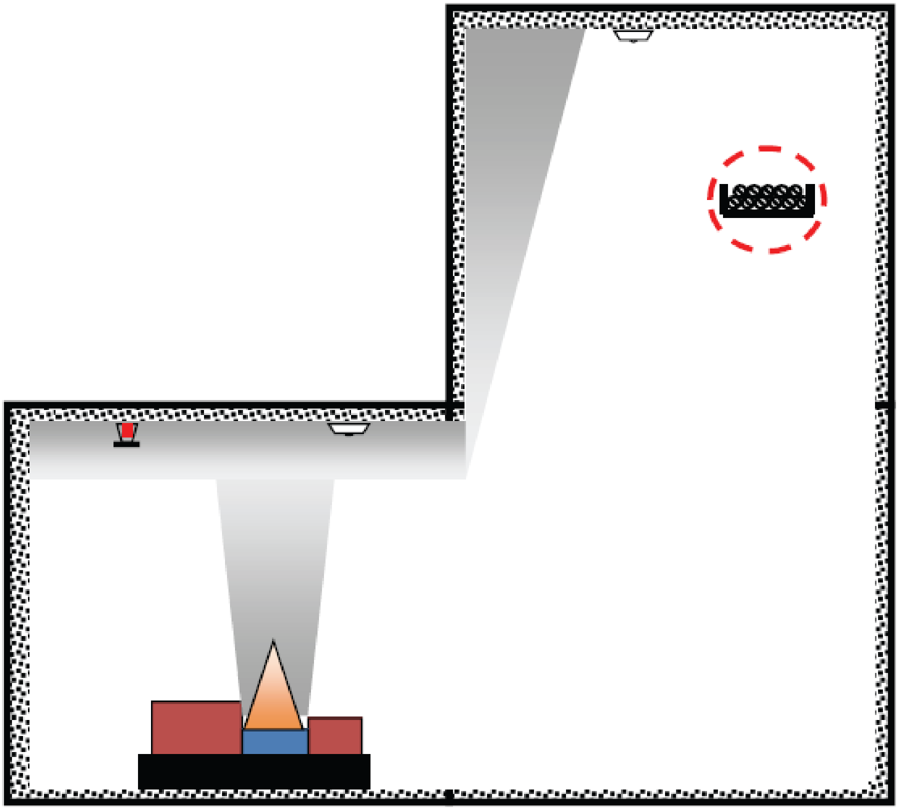


Figure 3-6. Pictorial representation of scenario 4

Scenario 5 –
Main Control Room Abandonment

- This scenario consists of a fire (electrical cabinet fire within the main control board) that may force operators out of the control room
- Objective: Determine when control room operators will need to abandon the control room due to fire-generated conditions
- **Example A**

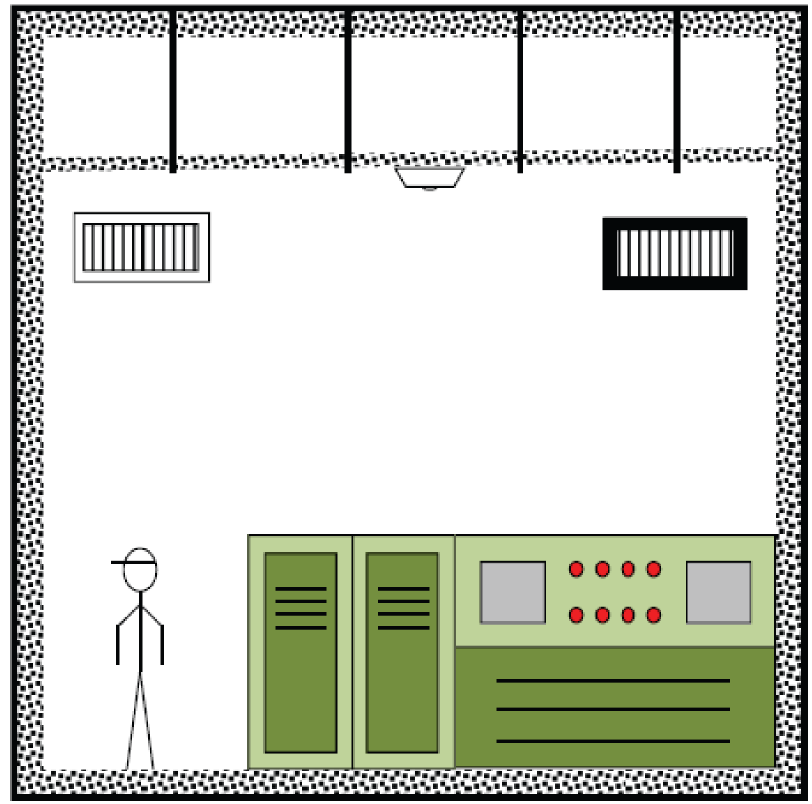
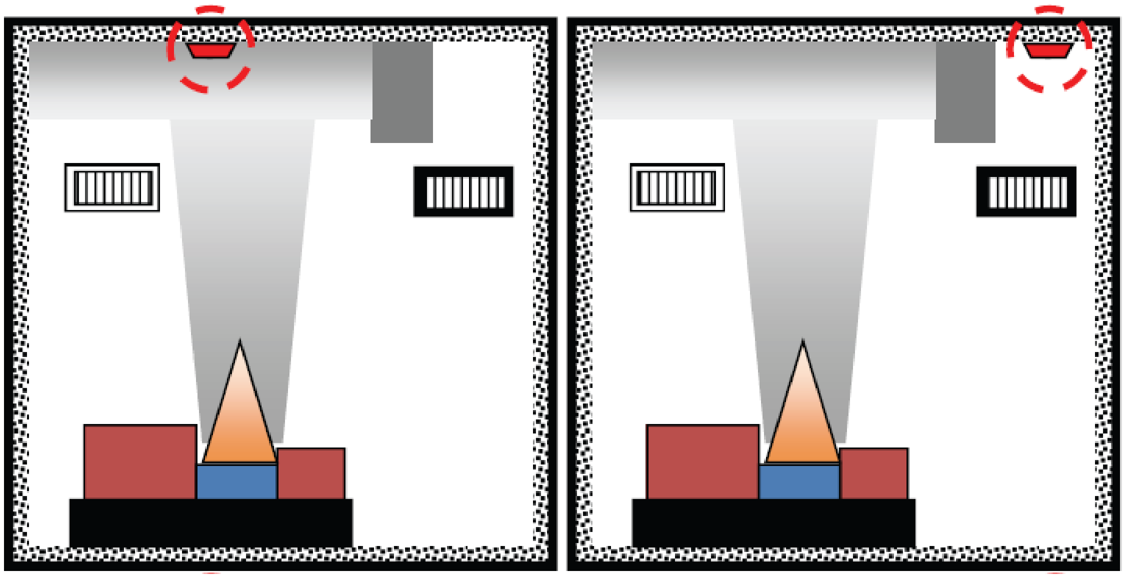


Figure 3-7. Pictorial representation of scenario 5

Scenario 6 – Smoke Detection and Sprinkler Activation

- This scenario addresses smoke/heat detector or sprinkler activation
- Objective: Calculate the response time of a smoke or heat detector that may be obstructed by ceiling beams, ventilation ducts, etc.
- **Examples B and E**



Scenario 7 – Fire Impacting Structural Elements

- This scenario consists of fire impacting exposed structural elements
- Objective: Characterize the temperature of structural elements exposed to a nearby fire source
- **Example F**

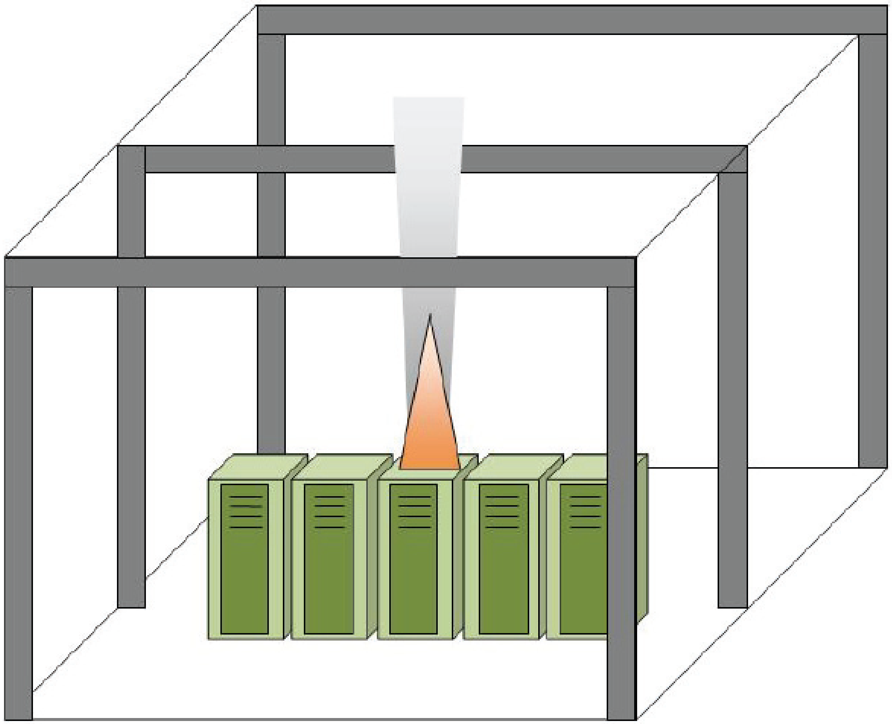
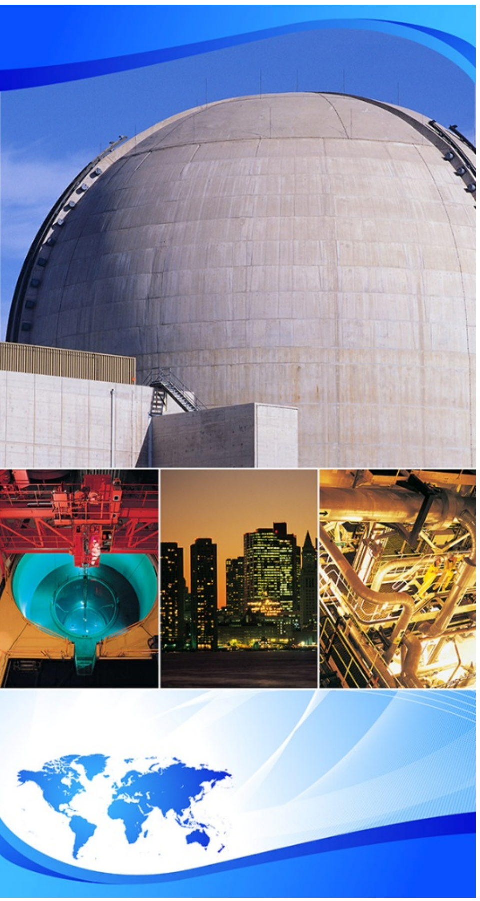


Figure 3-9. Pictorial representation of scenario 7

Summary

- The purpose of this module has been to introduce the following concepts relevant to NPP applications:
  - The fire modeling process
  - The fire modeling tools
  - Representative fire modeling scenarios
  - Uncertainty / sensitivity analyses
- On Day 2 we will review fire modeling concepts
- On Days 3 and 4, we will consider the 8 example fire modeling scenarios in more detail
- On Friday, you will perform your own analyses
  - Think about scenarios you would like to address



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5
Advanced Fire Modeling
Fire Model V&V

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

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

Fire Model Verification and Validation

- ASTM E 1355, Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models
  - **Verification**: the process of determining that the implementation of a calculation method accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method. Is the Math right?
  - **Validation**: the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method. Is the Physics right?
  - This presentation focuses primarily on validation.

Important Measurements/ Parameters

- Room Temperature
  - Main control room abandonment study
  - Targets in room of fire origin or adjacent compartments
- Flame height, Plume & Ceiling jet temperature
  - Target heating and target temperature near the ignition source

Important Measurements/ Parameters

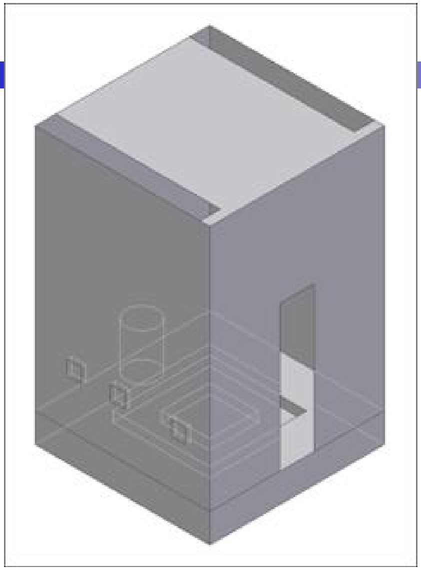
- Oxygen & smoke concentration
  - Main control room habitability
- Room pressure
  - Issues related to mechanical ventilation and/or smoke migration
- Target/wall heating and target/wall temperature
  - Most fire scenarios throughout the plant

How were the experiments selected?

- Selection Criteria: High-Quality Experiments
  - Large-scale experiments
  - Availability of data
  - Directly applicable to nuclear power plant applications
  - Accurate measurement of the fire heat release rate
  - Well documented
  - Uncertainty analysis useful
- Selection Process
  - Extensive review of fire literature
  - Scarcity of high-quality large-compartment fire test data
  - Typical industry tests: proprietary, reduced-scale, not NPP related

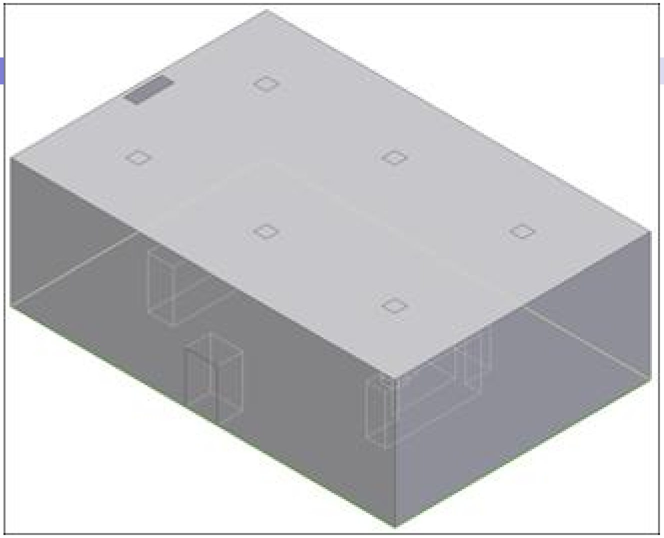
Pump Room

ICFMP BE #4, 5



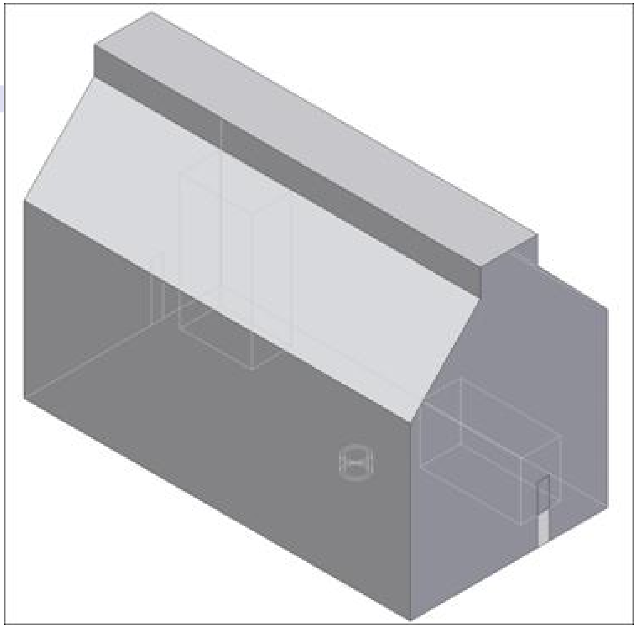
Main Control Room

FM/SNL



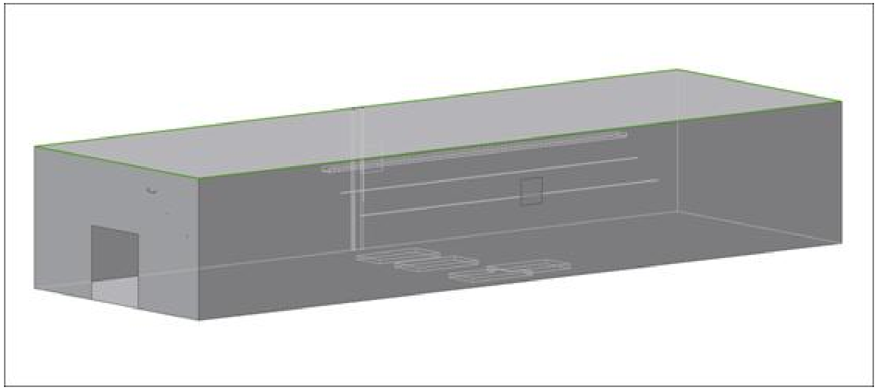
Turbine hall

ICFMP BE# 2



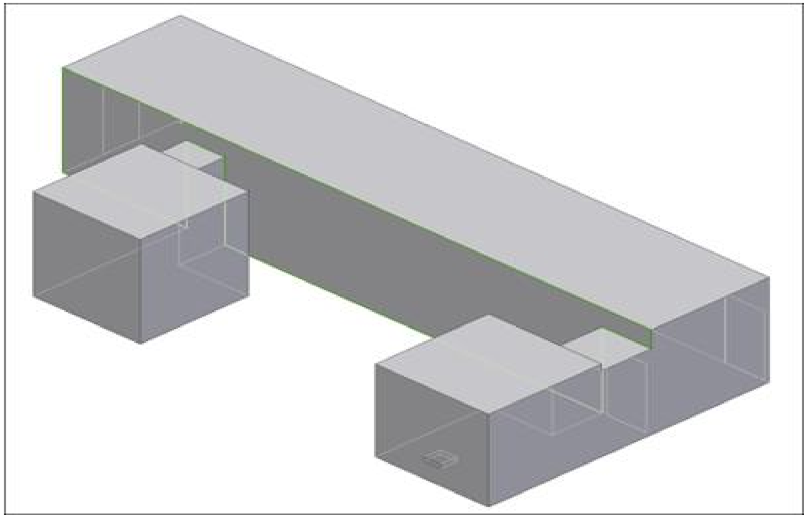
Misc.

ICFMP BE# 3



Multi-compartment

NBS



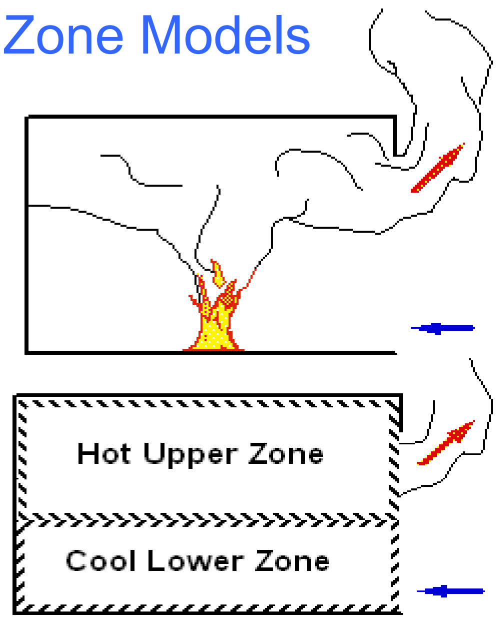
Fire Models Selected

Fire Dynamics Tools (FDT^S^)	NRC Spreadsheets
FIVE-Rev1	EPRI Spreadsheets
Cons. Fire & Smoke Transport (CFAST)	NIST zone model
MAGIC	Electricite de France zone
Fire Dynamics Simulator (FDS)	NIST CFD Model

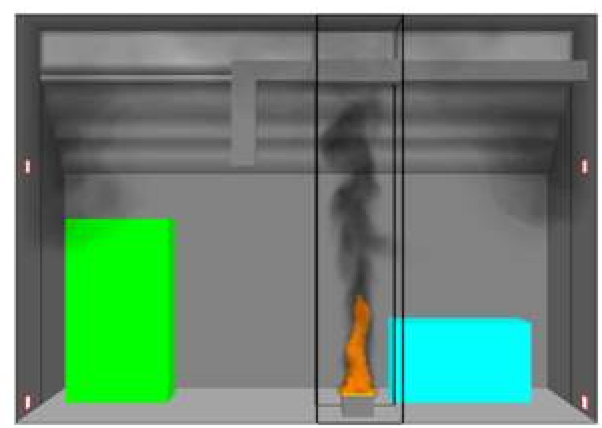
Spreadsheets

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

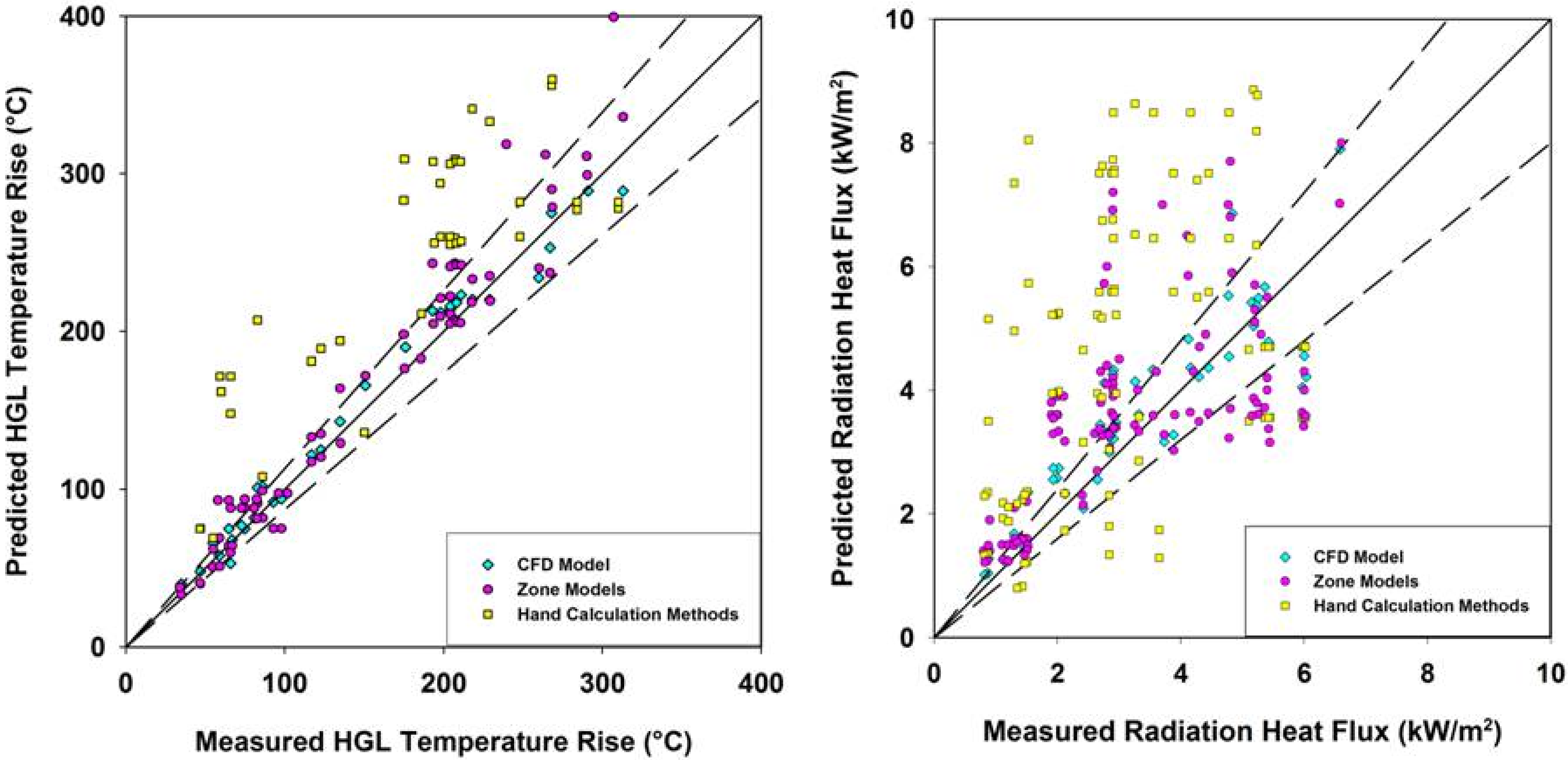
Zone Models



Field Models



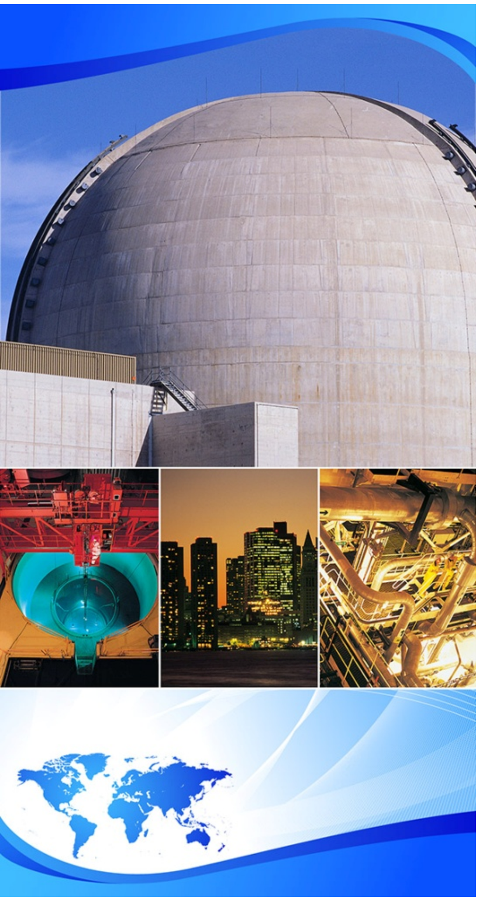
Quantitative V&V Results



Measured vs. Predicted Hot Gas Layer Temperature Rise (left) and Measured vs. Predicted Heat Flux (right)

Results of the V&V

Parameter				Fire Model		
		FDT^{s}	FIVE-Rev1	CFAST	MAGIC	FDS
Hot gas layer temperature ("upper layer temperature")	Room of Origin	YELLOW+	YELLOW+	GREEN	GREEN	GREEN
	Adjacent Room	N/A	N/A	YELLOW	YELLOW+	GREEN
Hot gas layer height ("layer interface height")		N/A	N/A	GREEN	GREEN	GREEN
Ceiling jet temperature ("target/gas temperature")		N/A	YELLOW+	YELLOW+	GREEN	GREEN
Plume temperature		YELLOW–	YELLOW+	N/A	GREEN	YELLOW
Flame height		GREEN	GREEN	GREEN	GREEN	YELLOW
Oxygen concentration		N/A	N/A	GREEN	YELLOW	GREEN
Smoke concentration		N/A	N/A	YELLOW	YELLOW	YELLOW
Room pressure		N/A	N/A	GREEN	GREEN	GREEN
Target temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Radiant heat flux		YELLOW	YELLOW	YELLOW	YELLOW	YELLOW
Total heat flux		N/A	N/A	YELLOW	YELLOW	YELLOW
Wall temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Total heat flux to walls		N/A	N/A	YELLOW	YELLOW	YELLOW



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5

Advanced Fire Modeling Uncertainty Analysis

Joint RES/EPRI Fire PRA Workshop
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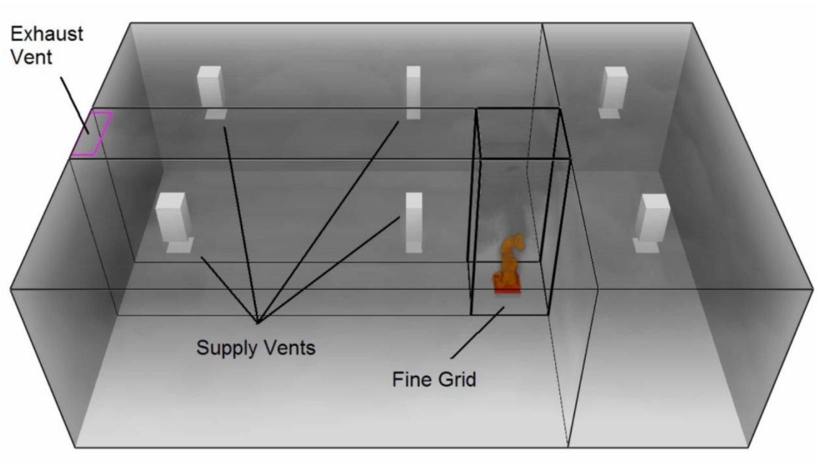
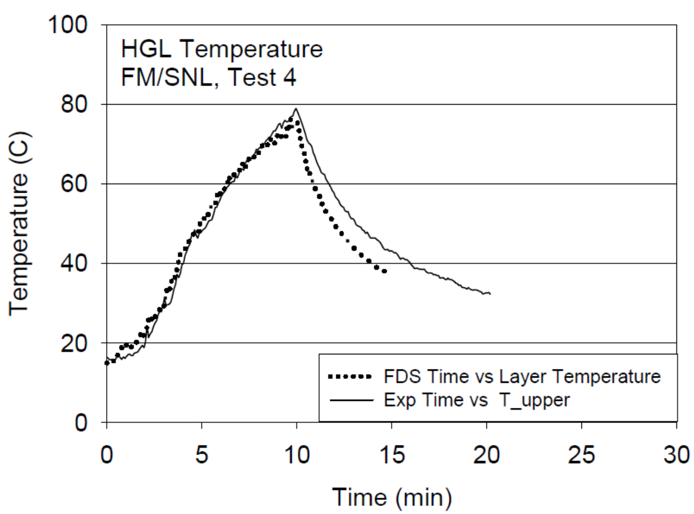
What is Uncertainty?

- Parameter Uncertainty – refers to the contribution of the uncertainty in the input parameters to the total uncertainty of the simulation
- Model Uncertainty – refers to the effect of the model assumptions, simplified physics, numerics, etc.
- Completeness Uncertainty – refers to physics that are left out of the model. For most, this is a form of Model Uncertainty.

Fire Model Validation Study, NUREG-1824





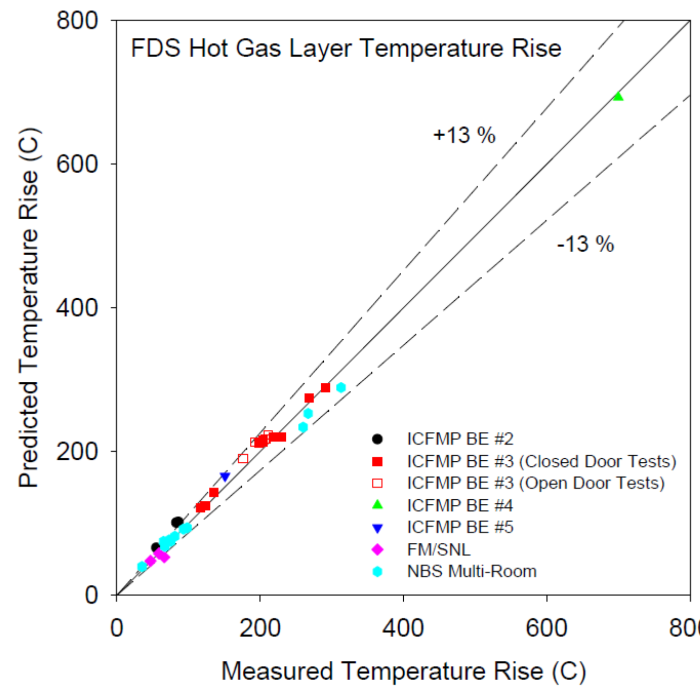


Table 4-1. Results of the V&V study, NUREG-1824 (EPRI 1011999).

Output Quantity	FDTs		FIVE		CFAST		MAGIC		FDS		Exp
	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	$\tilde{\sigma}_E$
HGL Temperature Rise*	1.44	0.25	1.56	0.32	1.06	0.12	1.01	0.07	1.03	0.07	0.07
HGL Depth*	N/A		N/A		1.04	0.14	1.12	0.21	0.99	0.07	0.07
Ceiling Jet Temp. Rise	N/A		1.84	<u>0.29</u>	1.15	<u>0.24</u>	1.01	0.08	1.04	0.08	0.08
Plume Temperature Rise	0.73	<u>0.24</u>	0.94	<u>0.49</u>	1.25	0.28	1.01	0.07	1.15	<u>0.11</u>	0.07
Flame Height**	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.
Oxygen Concentration	N/A		N/A		0.91	<u>0.15</u>	0.90	0.18	1.08	0.14	0.05
Smoke Concentration	N/A		N/A		2.65	<u>0.63</u>	2.06	<u>0.53</u>	2.70	<u>0.55</u>	0.17
Room Pressure Rise	N/A		N/A		1.13	0.37	0.94	0.39	0.95	0.51	0.20
Target Temperature Rise	N/A		N/A		1.00	0.27	1.19	0.27	1.02	0.13	0.07
Radiant Heat Flux	2.02	<u>0.59</u>	1.42	0.55	1.32	0.54	1.07	0.36	1.10	0.17	0.10
Total Heat Flux	N/A		N/A		0.81	0.47	1.18	0.35	0.85	0.22	0.10
Wall Temperature Rise	N/A		N/A		1.25	0.48	1.38	0.45	1.13	0.20	0.07
Wall Heat Flux	N/A		N/A		1.05	0.43	1.09	0.34	1.04	0.21	0.10

I.D. indicates insufficient data for the statistical analysis.
N/A indicates that the model does not have an algorithm to compute the given Output Quantity.
Underlined values indicate that the data failed a normality test because of the relatively small sample size.
* The algorithm used to compute the layer temperature and depth for the model FDS is described in NUREG-1824.
** All of the models except FDS use the Heskestad Flame Height Correlation (Heskestad, *SFPE Handbook*). These models were shown to be in qualitative agreement with the experimental observations, but there was not enough data to further quantify this assessment.

Procedure for Calculating Model Uncertainty

1. Express the predicted value in terms of a rise above ambient. For example, subtract the ambient temperature from the predicted temperature. Call this value M.
2. Find the values of model bias and relative standard deviation from table on previous slide. Compute the mean and standard deviation of normal distribution:

$$\mu = M/\delta \qquad \sigma = \tilde{\sigma}_M (M/\delta)$$

3. Compute the probability of exceeding the critical value:

$$P(x > x_c) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{x_c - \mu}{\sigma\sqrt{2}}\right)$$

4.3.1 Example 1: Target Temperature

Suppose that cables within a compartment are assumed to fail if their surface temperature reaches 330 °C (625 °F). The model FDS predicts that the maximum cable temperature due to a fire in an electrical cabinet is 300 °C (570 °F). What is the probability that the cables could fail?

Step 1: Subtract the ambient value of the cable temperature, 20 °C (68 °F) to determine the predicted temperature *rise*. Refer to this value as the *model prediction*:

$$M = 300 - 20 = 280°\text{C} \tag{4-6}$$

Step 2: Refer to Table 4-1, which indicates that, on average, FDS overpredicts Target Temperatures with a bias factor, δ, of 1.02. Calculate the *adjusted model prediction*:

$$\mu = \frac{M}{\delta} = \frac{280}{1.02} = 275°\text{C} \tag{4-7}$$

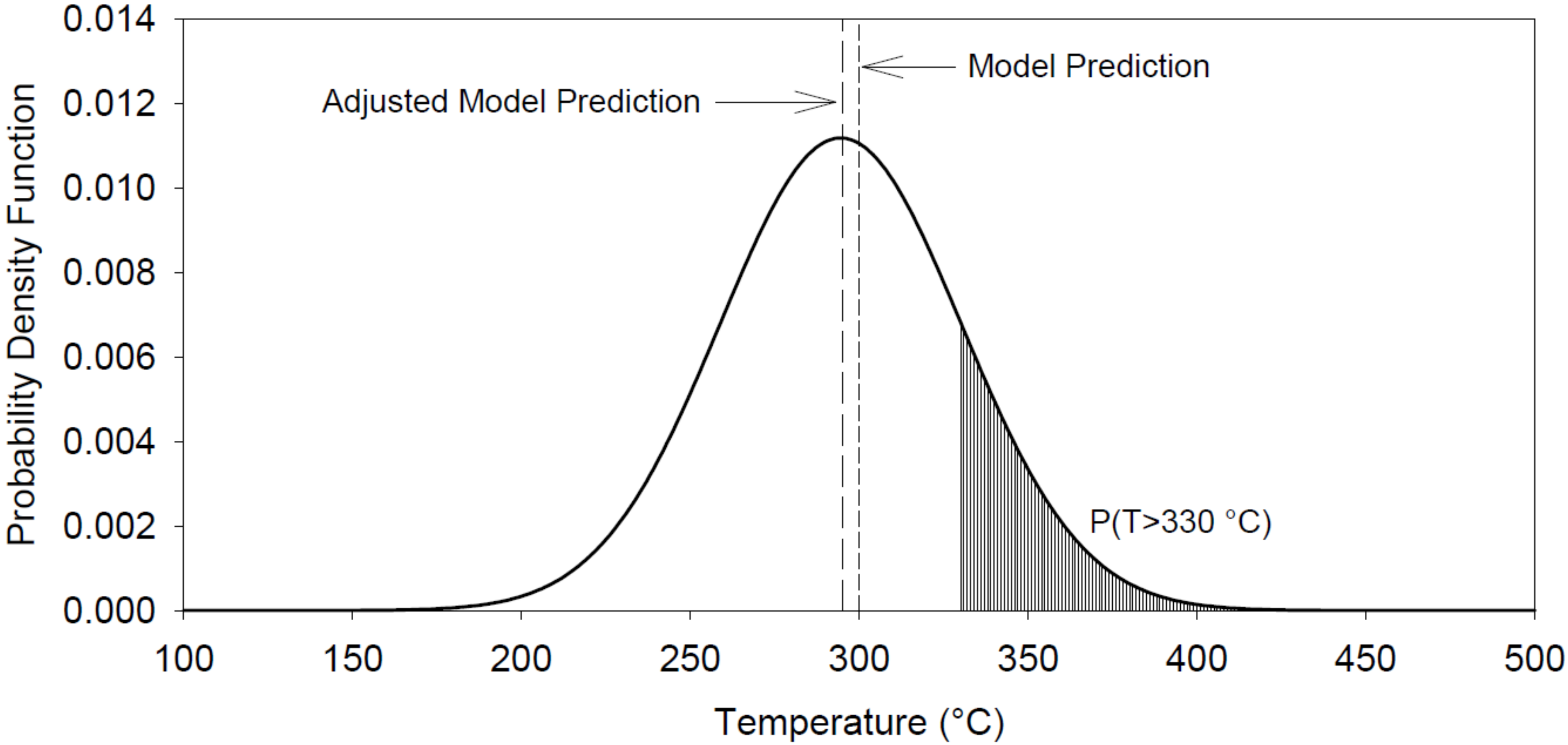
Referring again to Table 4-1, calculate the standard deviation of the distribution:

$$\sigma = \tilde{\sigma}_M \left(\frac{M}{\delta}\right) = 0.13 \left(\frac{280}{1.02}\right) = 36°\text{C} \tag{4-8}$$

Step 3: Calculate the probability that the actual cable temperature would exceed 330°C:

$$P(T > 330) = \frac{1}{2}\,\text{erfc}\left(\frac{T - T_0 - \mu}{\sigma\sqrt{2}}\right) = \frac{1}{2}\,\text{erfc}\left(\frac{330 - 20 - 275}{36\sqrt{2}}\right) = 0.16 \tag{4-9}$$

The process is shown graphically in Figure 4-3. The area under the “bell curve” for temperatures higher than 330 °C (625 °F) represents the probability that the actual cable temperature would exceed that value. Note that this estimate is based only on the model uncertainty.


0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Probability Density Function
Model Prediction
Adjusted Model Prediction
P(T>330 °C)
100
150
200
250
300
350
400
450
500
Temperature (°C)

4.3.2 Example 2: Critical Heat Flux

As part of a screening analysis, the model MAGIC is used to predict the radiant heat flux from a fire to a nearby group of thermoplastic cables. According to NUREG/CR-6850 (EPRI 1011989), Appendix H, one of the damage criteria for thermoplastic cables is a radiant heat flux to the target cable that exceeds 6 kW/m^2. The model, by coincidence, predicts a heat flux of 6 kW/m^2. What is the probability that the actual heat flux from a fire will be 6 kW/m^2 or greater? Assume for this exercise that the model input parameters are not subject to uncertainty, only the model itself.

Step 1: Unlike in the previous example, there is no need to subtract an ambient value of the heat flux (it is zero). Thus, the *model prediction* is:

$$M = 6 \text{ kW/m}^2 \qquad (4\text{-}10)$$

Step 2: Refer to Table 4-1, which indicates that, on average, MAGIC overpredicts Radiant Heat Flux with a bias factor, δ, of 1.15. Calculate the *adjusted model prediction*:

$$\mu = \frac{M}{\delta} = \frac{6}{1.15} \approx 5.2 \text{ kW/m}^2 \qquad (4\text{-}11)$$

Referring again to Table 4-1, calculate the standard deviation of the distribution:

$$\sigma = \tilde{\sigma}_M \left(\frac{M}{\delta}\right) = 0.36\left(\frac{6}{1.15}\right) \approx 1.9 \text{ kW/m}^2 \qquad (4\text{-}12)$$

Step 3: Calculate the probability that the actual heat flux, $\dot{q}''$, will exceed the critical value of the heat flux, $\dot{q}_c'' = 6 \text{ kW/m}^2$:

$$P(\dot{q}'' > 6) = \frac{1}{2}\,\text{erfc}\left(\frac{\dot{q}_c'' - \mu}{\sigma\sqrt{2}}\right) = \frac{1}{2}\,\text{erfc}\left(\frac{6 - 5.2}{1.9\sqrt{2}}\right) \approx 0.34 \qquad (4\text{-}13)$$

This is a somewhat surprising result. Even though the model predicts a peak radiant heat flux equal to the critical value, there is only a one in three chance that the actual heat flux would exceed this value. This is mainly due to the fact that MAGIC has been shown to over-predict the heat flux by about 15%.

Sensitivity Analysis to Address Parameter Uncertainty

$$\text{Output Quantity} = \text{Constant} \times (\text{Input Parameter})^{\text{Power}}$$

Example: MQH correlation states that the HGL temperature rise is proportional to the HRR to the 2/3 power:

$$T - T_0 = C\dot{Q}^{2/3}$$

$$\frac{\Delta T}{T - T_0} \approx \frac{2}{3}\frac{\Delta \dot{Q}}{\dot{Q}}$$

Table 4-3. Sensitivity of model outputs from Volume 2 of NUREG-1824 (EPRI 1011999).

Output Quantity	Important Input Parameters	Power Dependence
HGL Temperature	HRR Surface Area Wall Conductivity Ventilation Rate Door Height	2/3 -1/3 -1/3 -1/3 -1/6
HGL Depth	Door Height	1
Gas Concentration	HRR Production Rate	1/2 1
Smoke Concentration	HRR Soot Yield	1 1
Pressure	HRR Leakage Rate Ventilation Rate	2 2 2
Heat Flux	HRR	4/3
Surface/Target Temperature	HRR	2/3

Suppose, for example, that as part of an NFPA 805 analysis the problem is to determine the Limiting Fire Scenario for a particular compartment whose HGL temperature is not to exceed 500 °C (930 °F). Assume that the geometrical complexity of the compartment rules out the use of the empirical and zone models, and that FDS has been selected for the simulation.

Step 1: Determine an appropriate maximum expected fire heat release rate. For this example, suppose that a 98th percentile HRR for the electrical cabinet fire, 702 kW, has been determined to be the MEFS. Choose a model and calculate the peak HGL temperature.

Step 2: Assume that FDS predicts 450 °C (840 °F) for the selected fire scenario. Adjust the prediction to account for the model bias, δ (See Table 4-1):

$$T_{\text{adj}} = T_0 + \frac{T - T_0}{\delta} = 20 + \frac{450 - 20}{1.03} \approx 437^\circ\text{C} \qquad (4\text{-}17)$$

Step 3: Calculate the change in HRR required to increase the HGL temperature to 500 °C (930 °F):

$$\Delta\dot{Q} \approx \frac{3}{2}\dot{Q}\,\frac{\Delta T}{T_{\text{adj}} - T_0} = \frac{3}{2}702\,\frac{500 - 437}{417} = 159\ \text{kW} \qquad (4\text{-}18)$$

This calculation suggests that adding an additional 159 kW to the original 702 kW will produce an HGL temperature in the vicinity of 500 °C (930 °F). This result can be double-checked by re-running the model with the modified input parameters.

Propagating Uncertainty

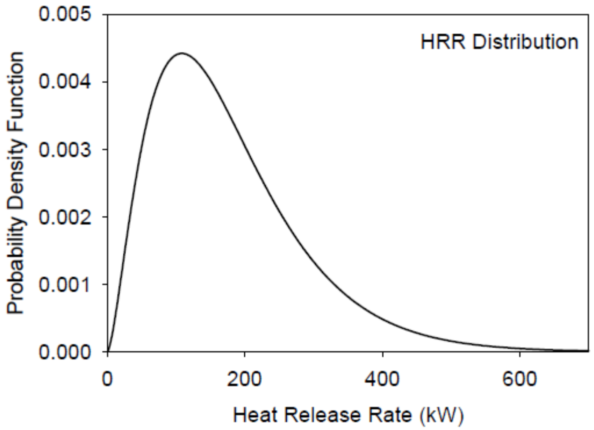
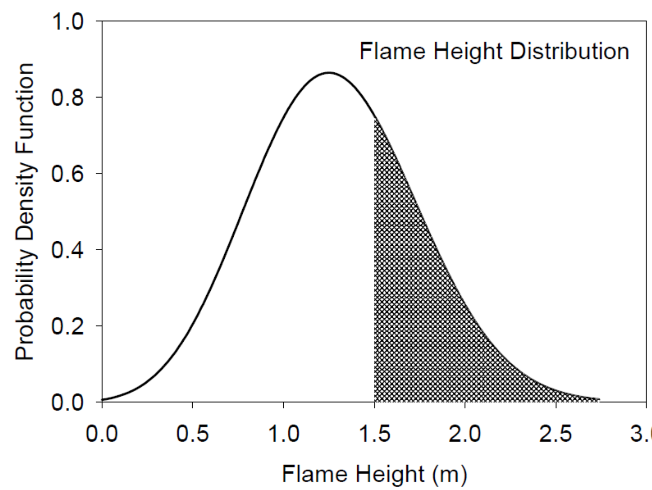
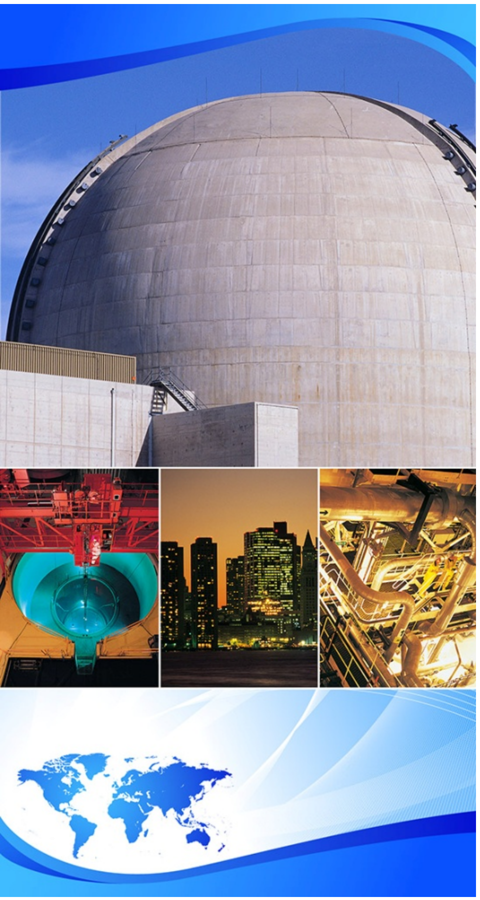


Figure 4-4. Distribution of HRR for an electrical cabinet fire.

$$L_f = 0.235\,\dot{Q}^{2/5} - 1.02\,D$$

$$f(L_f) = \frac{g(\dot{Q};\alpha,\beta)}{\left|\frac{dL_f}{d\dot{Q}}\right|} = g(\dot{Q};\alpha,\beta)\,\frac{\dot{Q}^{3/5}}{0.094}$$





EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5

Advanced Fire Modeling
Day 2 - AM Session
Principles of Fire Behavior

Joint RES/EPRI Fire PRA Workshop
July and October 2013
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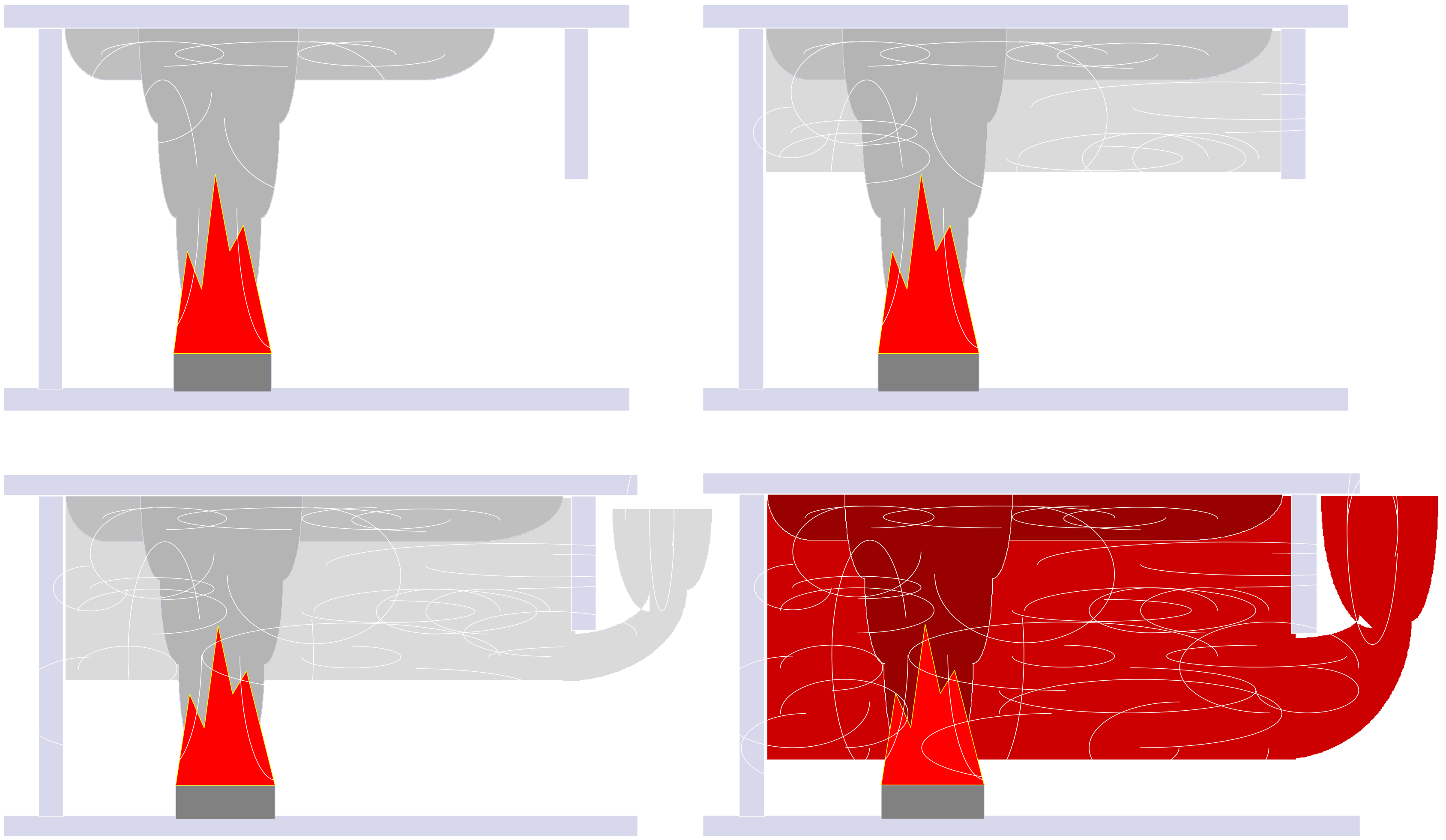
Topics

- Stages / elements of enclosure fires
- Ignition and heat release
  - CHRISTIFIRE
- Fire plumes and ceiling jets
- Heat and smoke detection
- Structural response / damage
- Cable response / damage
  - CAROLFIRE

Stages of enclosure fires



Stages of enclosure fires

- NUREG 1805

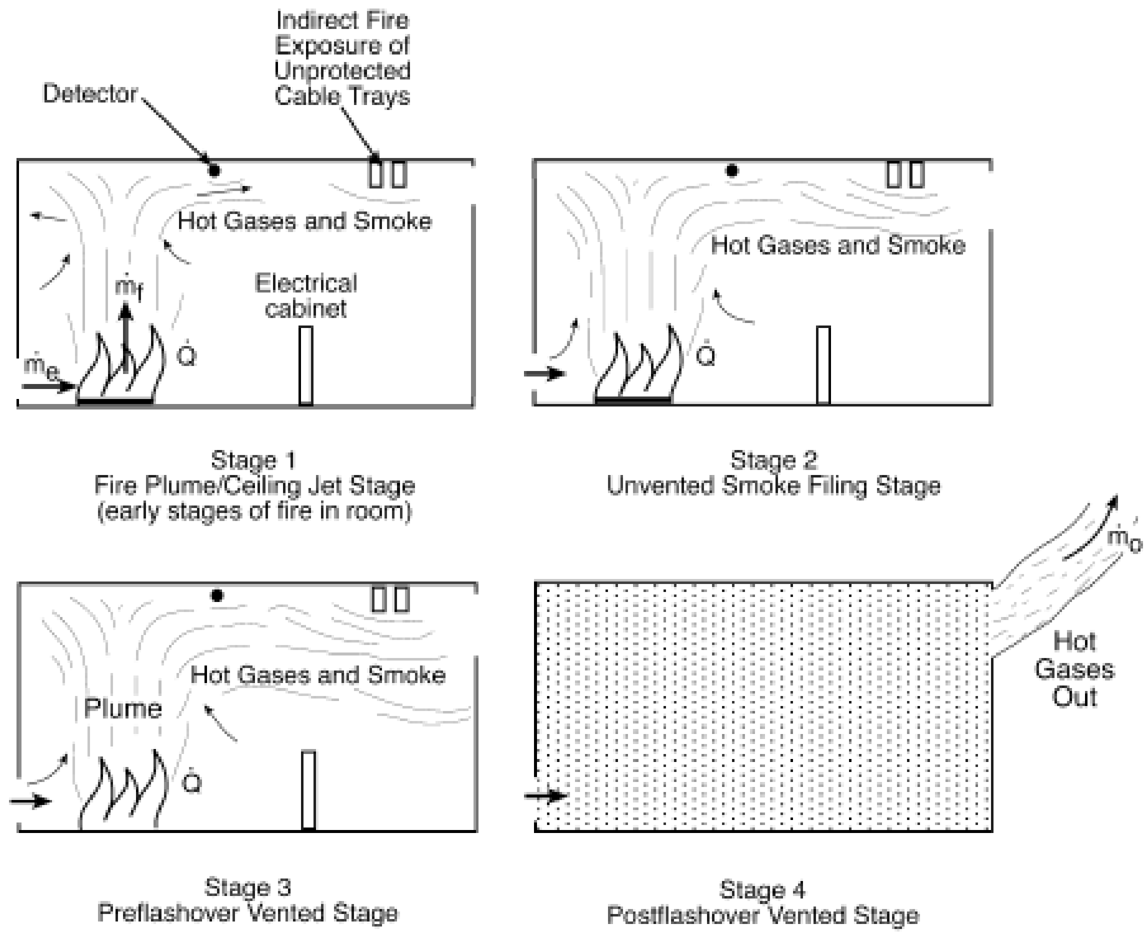
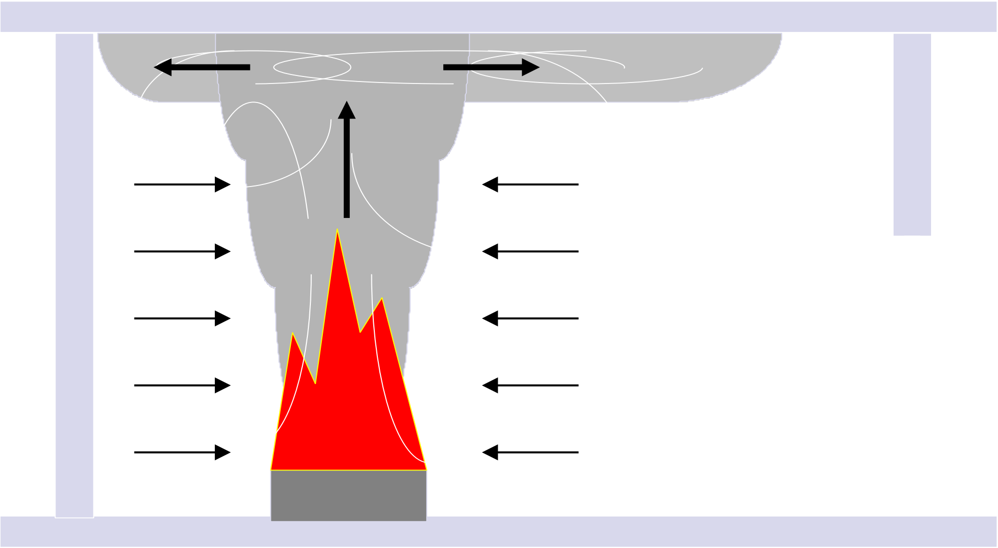


Figure 2-2 Stages of Compartment Fire

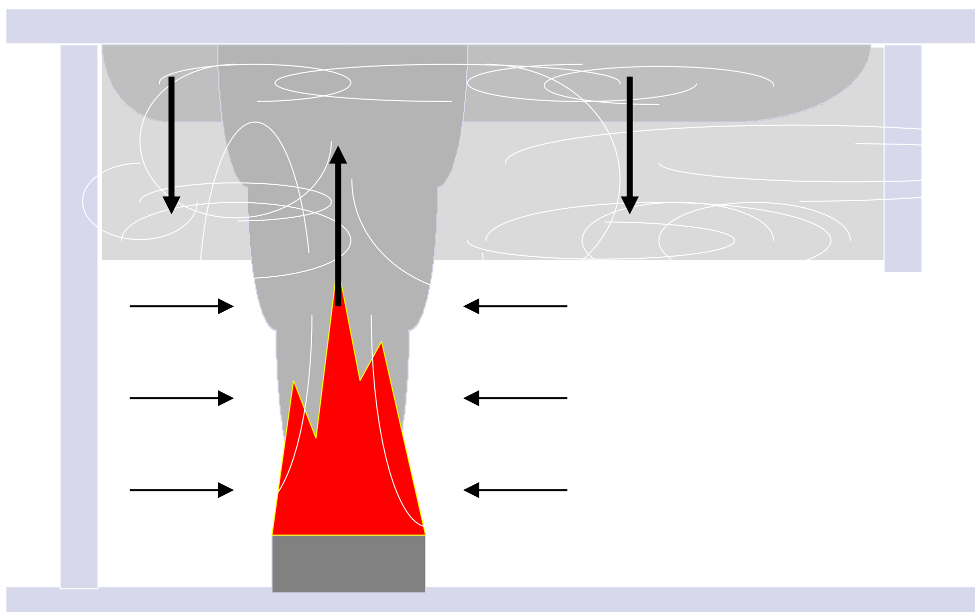
Stages of enclosure fires
Stage 1 - Fire plume / ceiling jet period

- 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



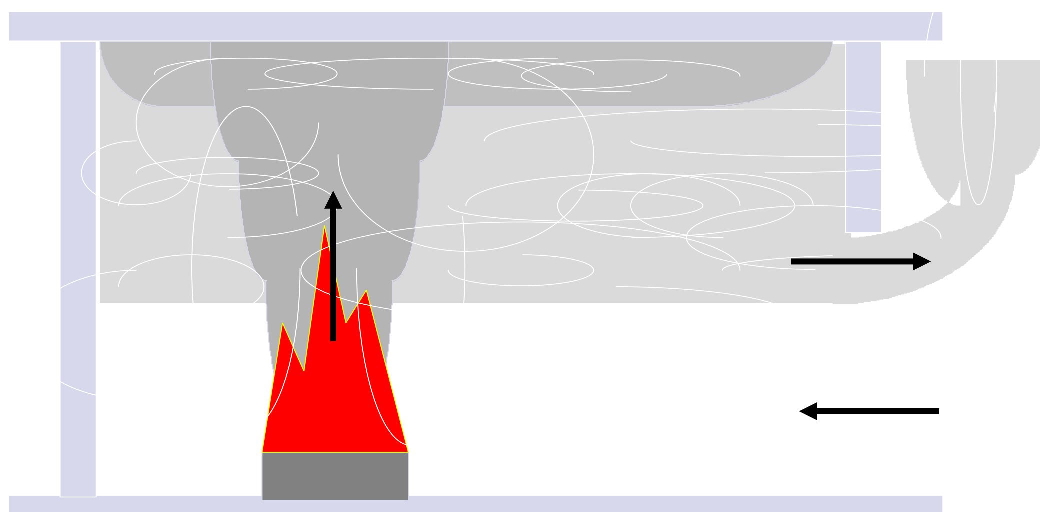
Stages of enclosure fires
Stage 2 - Enclosure smoke filling period

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



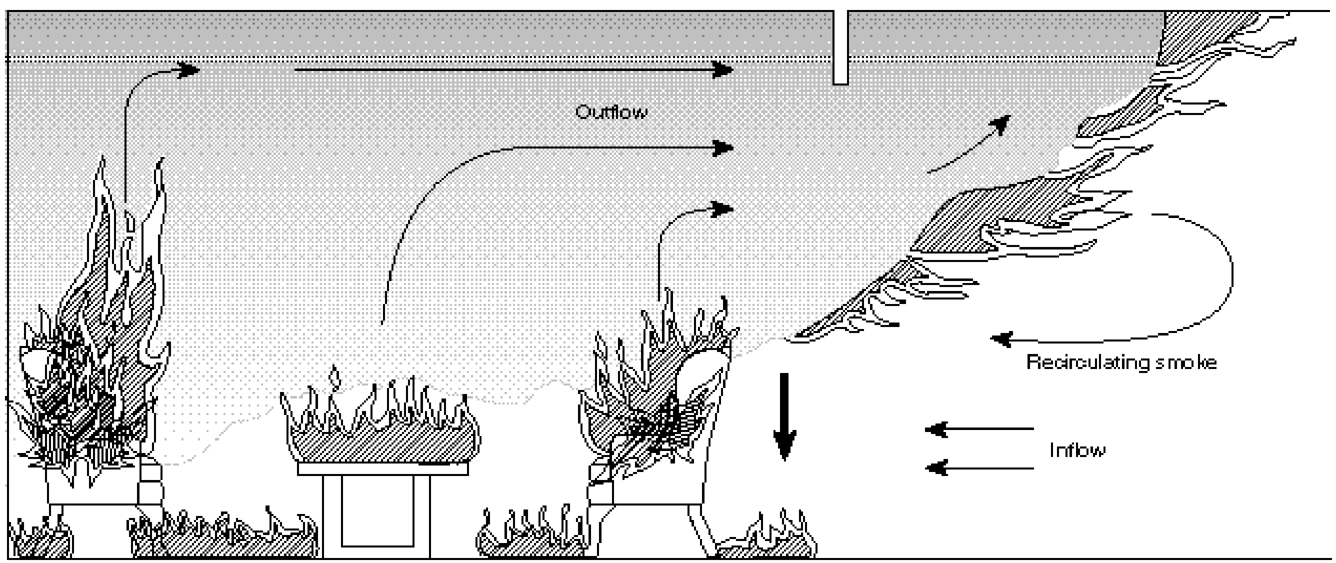
Stages of enclosure fires
Stage 3 - Preflashover vented period

- 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

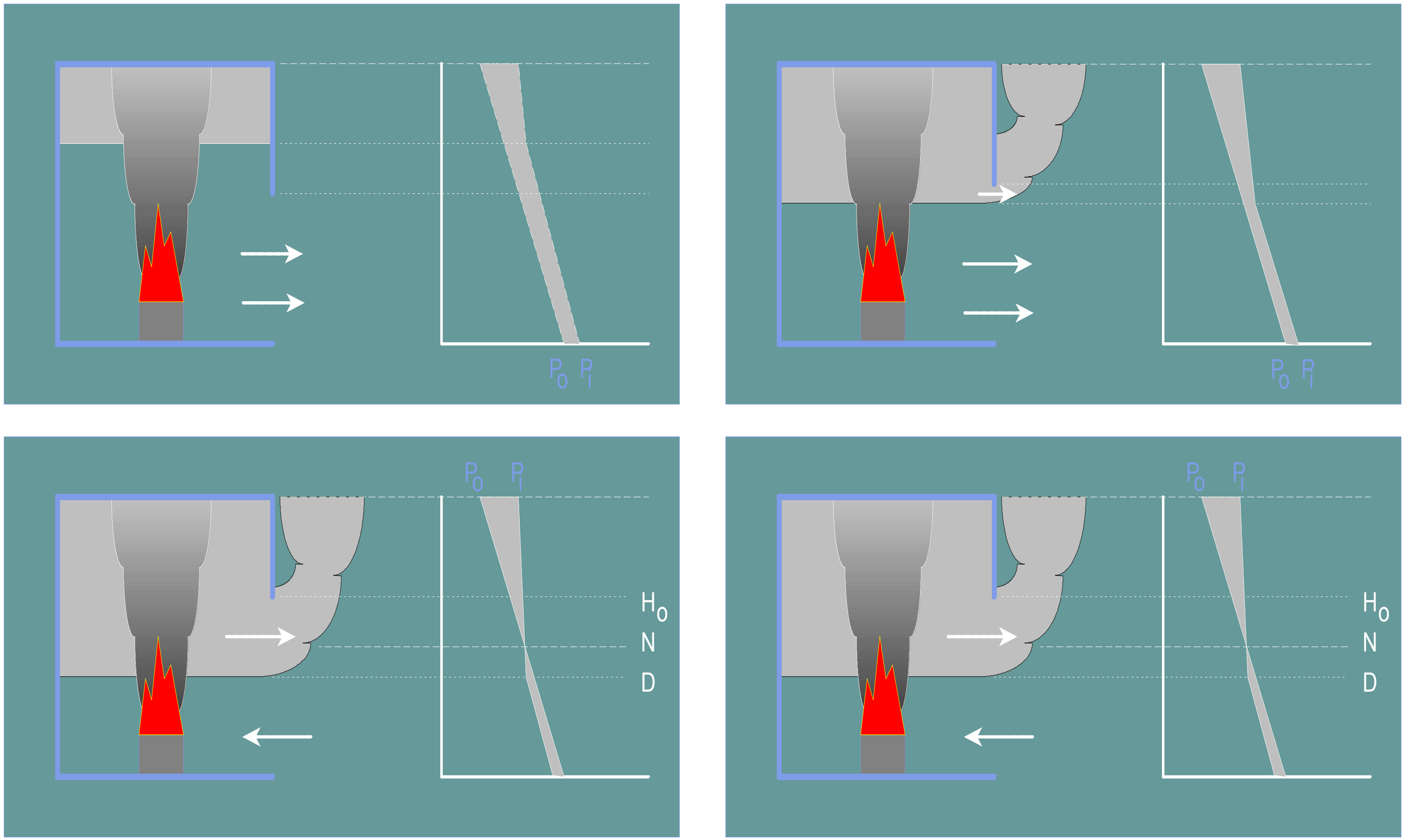


Stages of enclosure fires
Stage 4 - Postflashover vented period

- 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

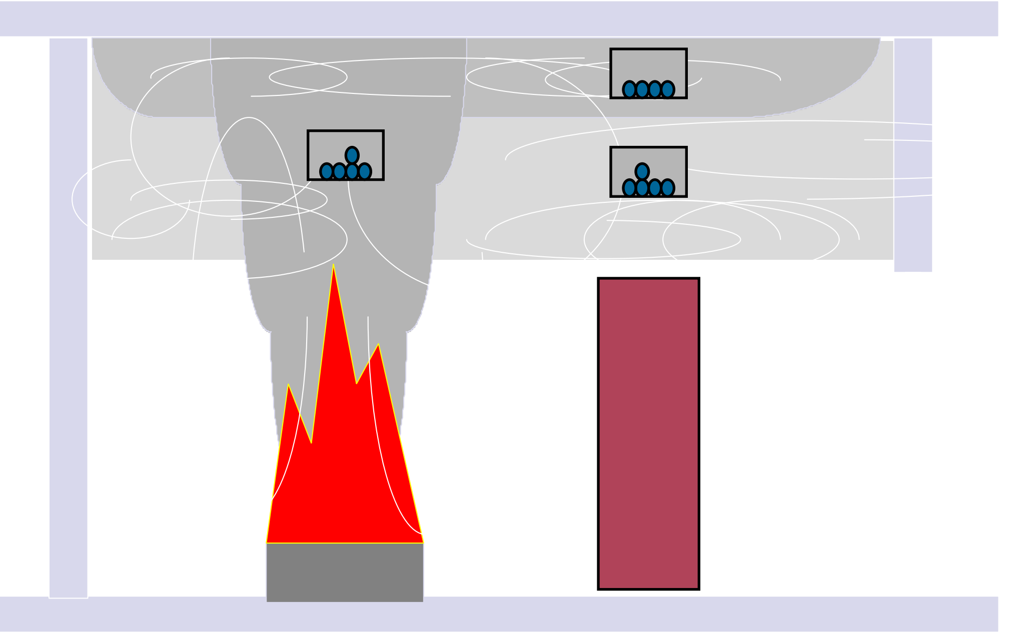


Vent flow stages



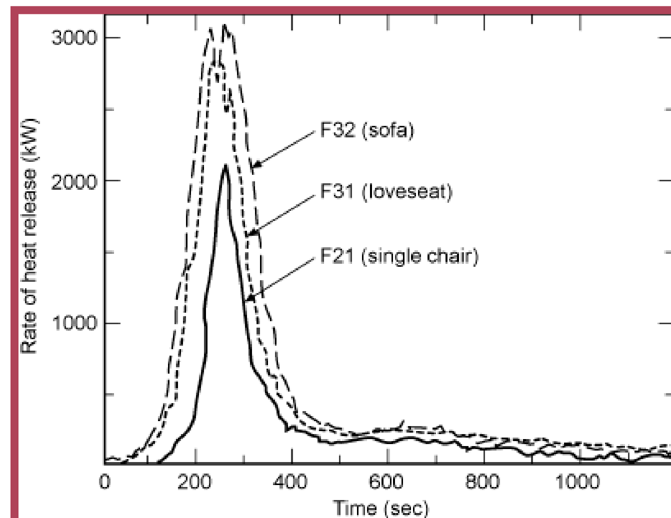
Elements of enclosure fires

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



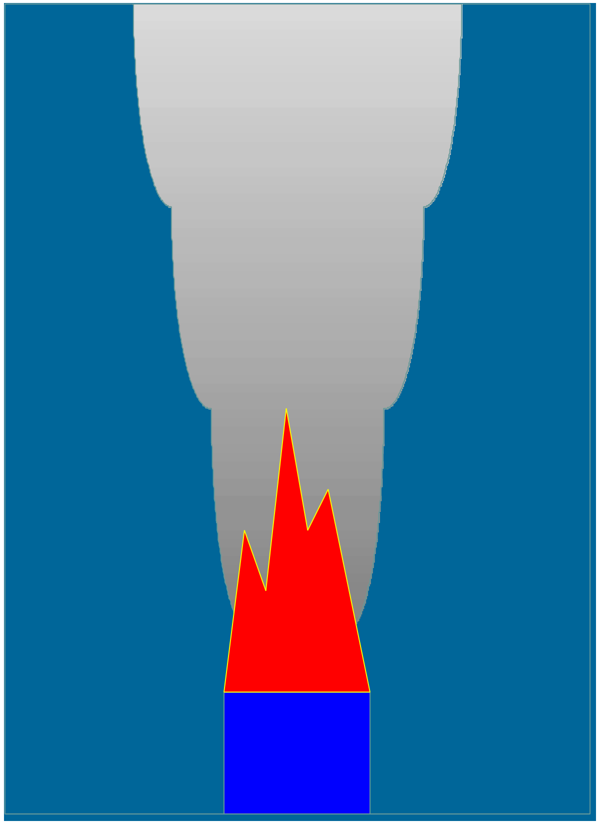
The fire source

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



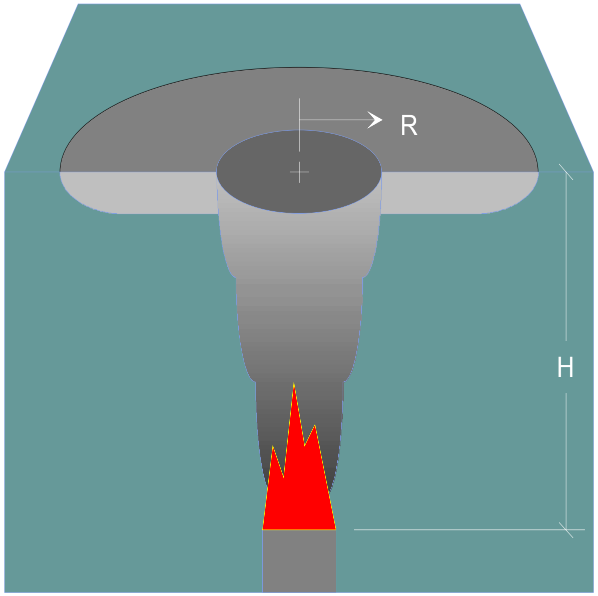
The fire plume

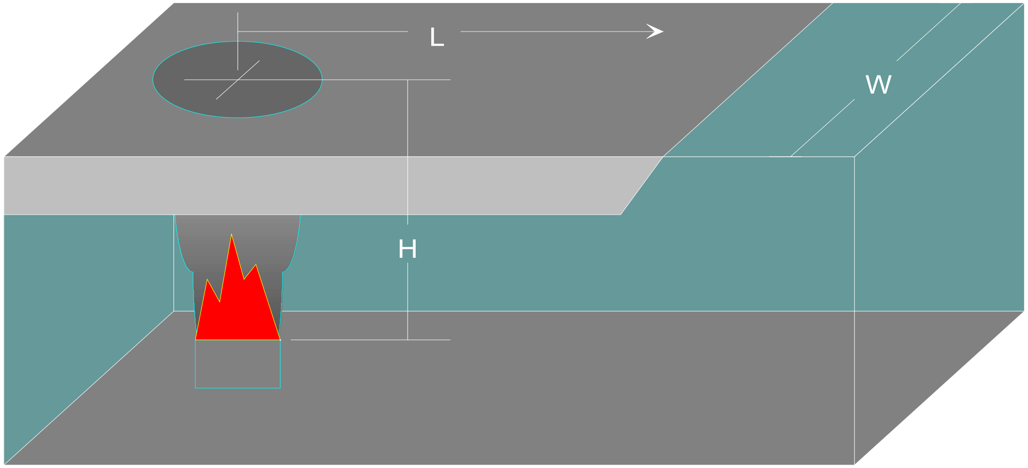
- Issues
  - Entrainment (m as f(Q, z))
  - Temperature (T_{pl} as f(Q, r, z))
  - Wall / corner effects



The ceiling jet

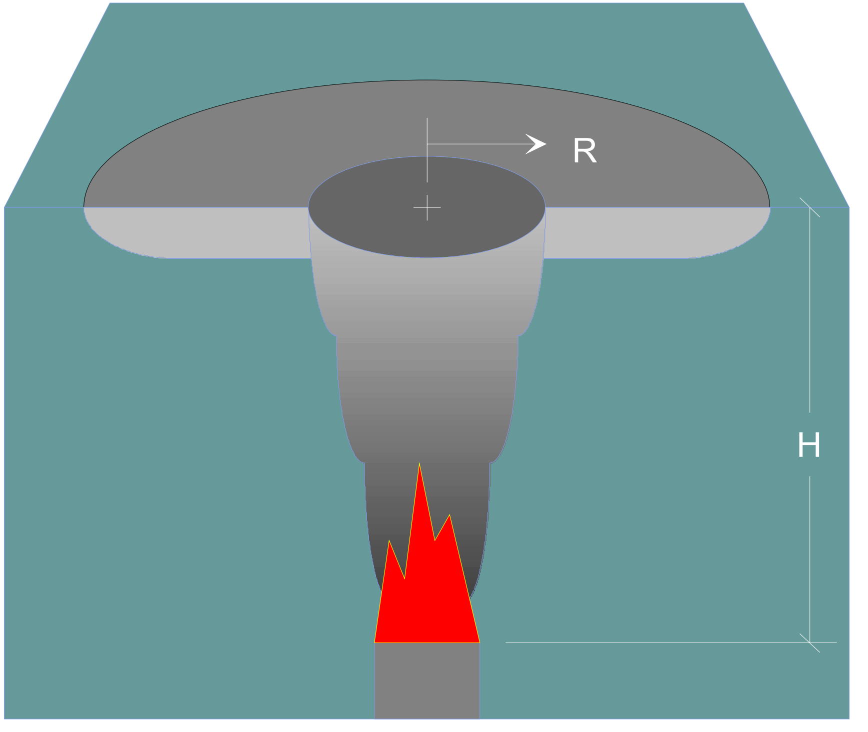
- Types
  - Unconfined
  - Confined
  - Other (sloped, obstructed …)





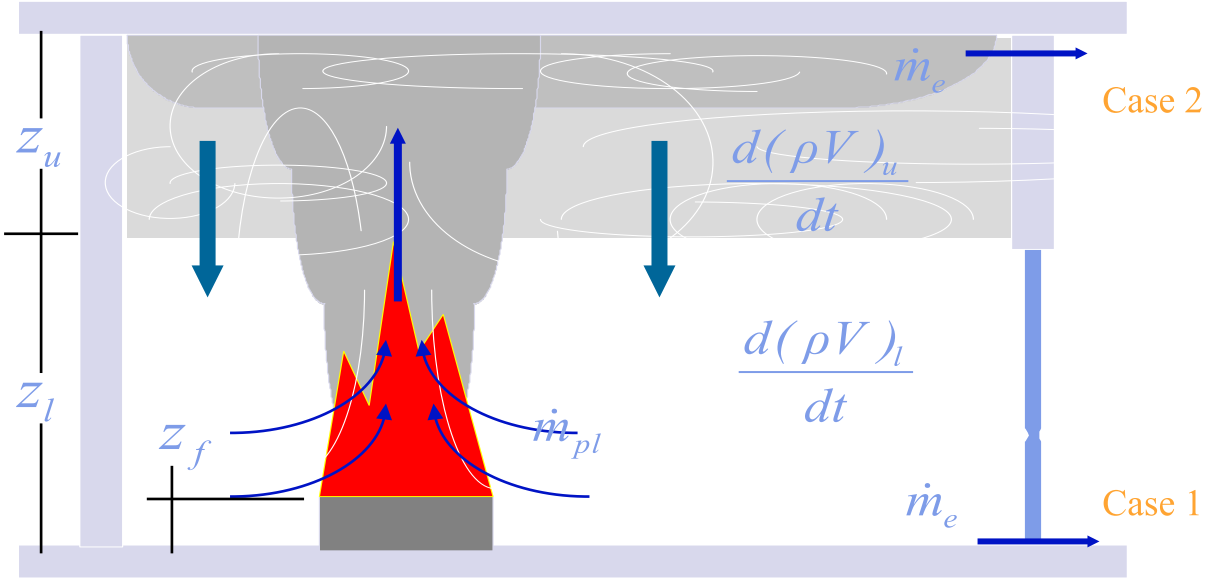
The ceiling jet

- Features
  - Relatively thin layer beneath ceiling (~0.1H)
  - Temperature, velocity decay as f(r)
- Analysis issues
  - Patterns
  - Target damage
  - Fire detector operation



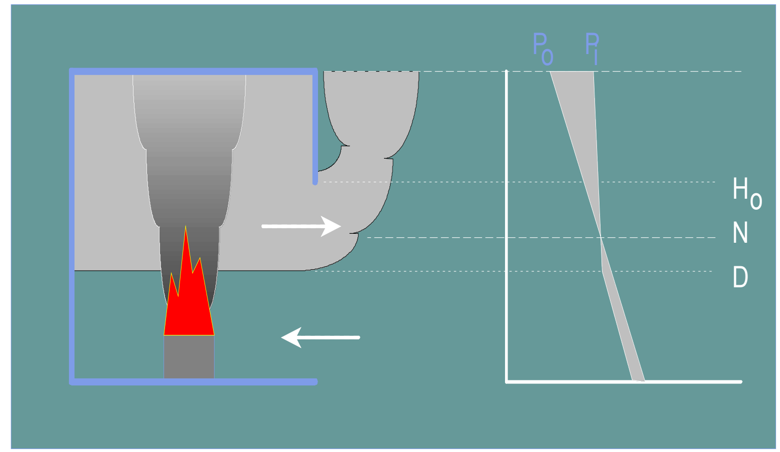
Hot gas layer

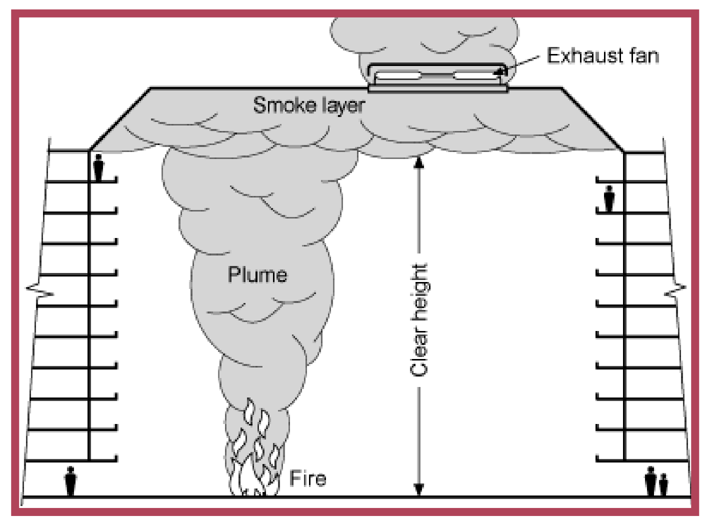
- Issues
  - Descent (filling) rate as f(t)
  - Temperature and smoke concentrations
  - Equilibrium position



Vents / ventilation systems

- Types
  - Natural ventilation
    - Wall openings
    - Floor / ceiling openings
  - Mechanical ventilation
    - Injection
    - Extraction
    - Balanced
- Issues
  - Impact on temperature and smoke conditions





Vents / ventilation systems

- Types of mechanical ventilation systems
  - Injection
  - Extraction
  - Balanced
  - Recirculation

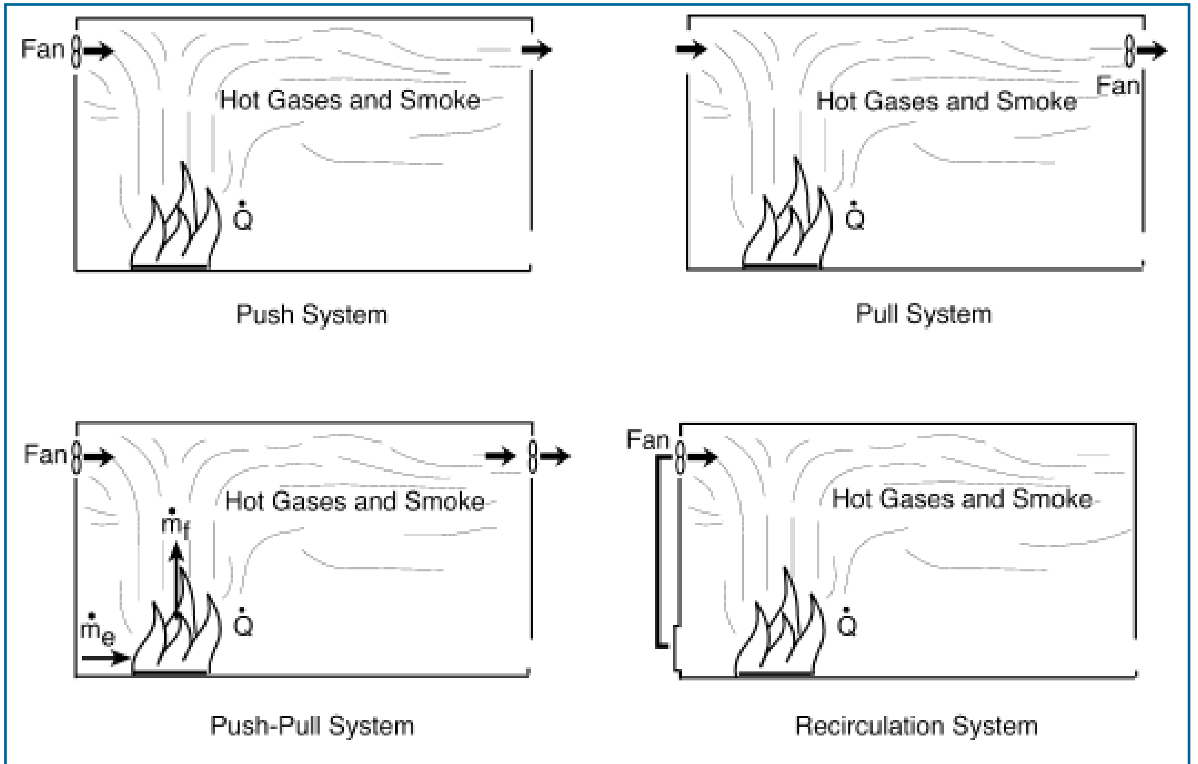
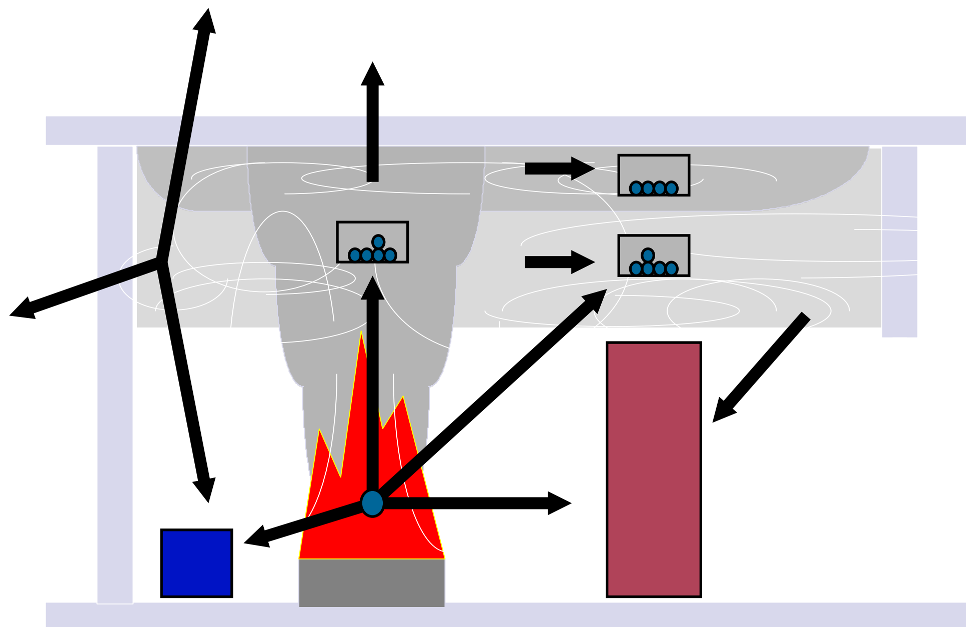


Figure 2-3 Types of Mechanical Ventilation Systems

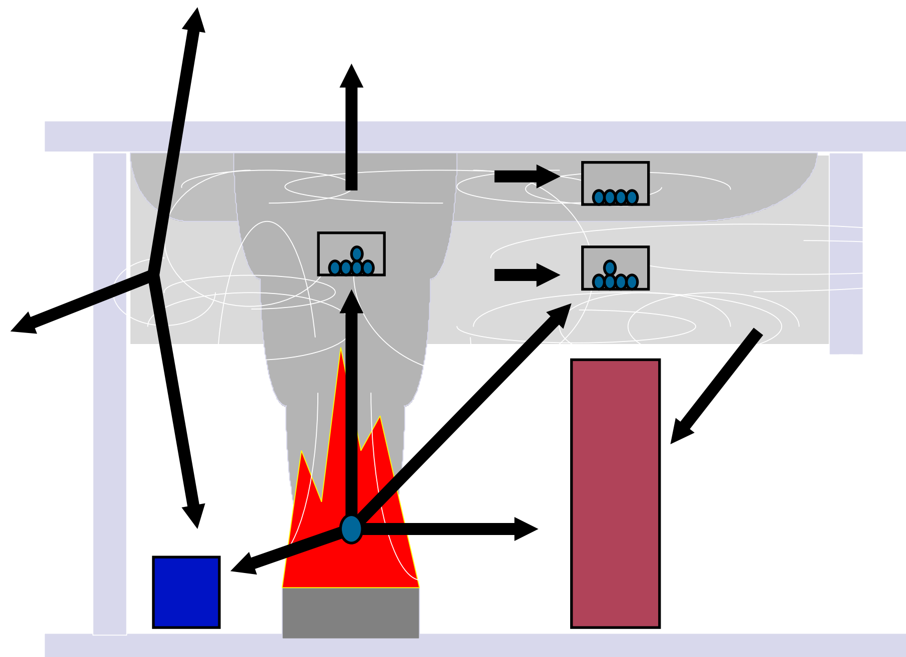
Boundaries

- Types
  - Walls / ceiling / floor
  - Columns / beams
- Issues
  - Heat transfer
    - Thermal inertia
  - Ignition / damage
  - Stability



Targets

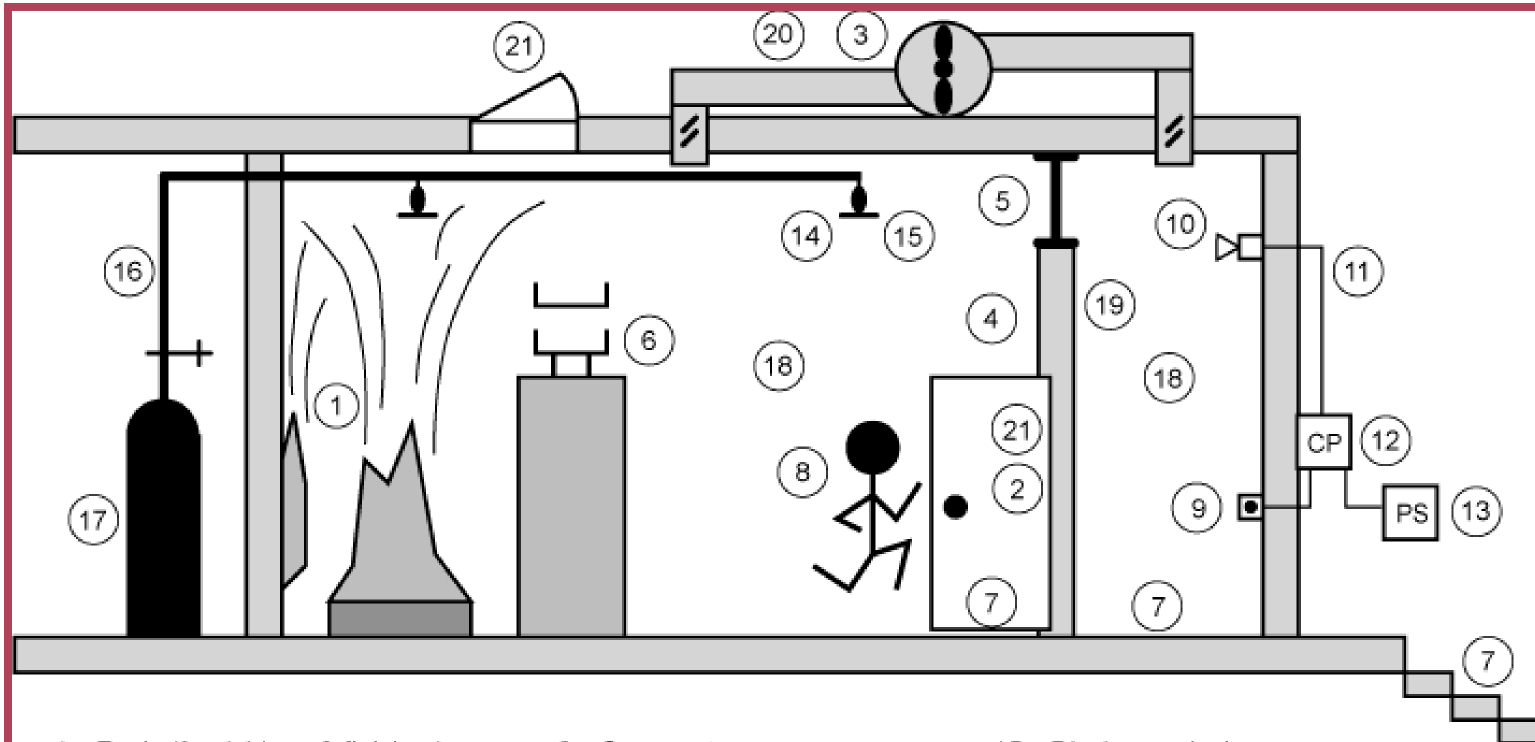
- Types
  – People (moving targets)
  – Fire protection devices
  – Equipment / structure
- Issues
  – Injury
  – Activation / damage
  – Operability



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

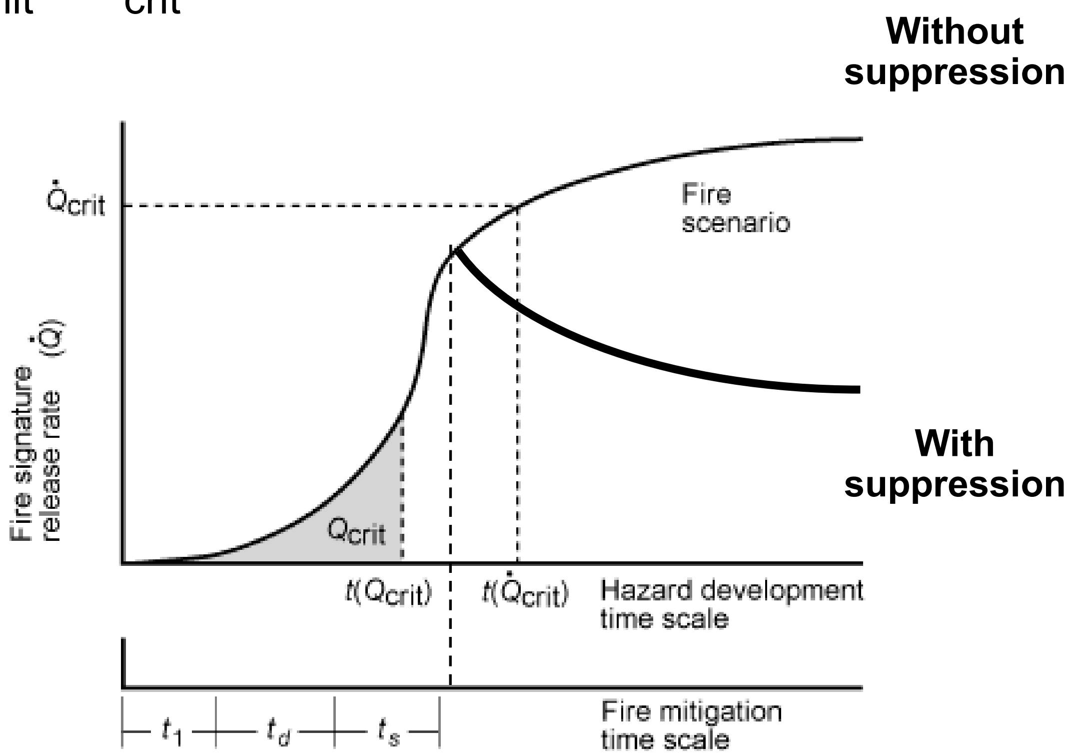
Elements of enclosure fires



1. Fuels (furnishings & finishes)
2. Natural ventilation openings
3. Mechanical ventilation systems
4. Enclosure boundaries
5. Structural elements
6. Operational elements
7. Egress path components
8. Occupant
9. Alarm initiating devices
10. Alarm indicating devices
11. Alarm system circuits
12. Control panel
13. Power supply
14. Detection devices
15. Discharge devices
16. Distribution system
17. Suppressant supply
18. Smoke zones
19. Smoke barriers
20. Smoke-control systems
21. Smoke vents

Fire scenario description

- Hazard development time scale
- Fire mitigation time scale
- Objective: $t_{mit} < t_{crit}$



Summary – elements of enclosure fires

- Analysis of enclosure fire dynamics requires consideration of thermal sciences
  - Heat transfer – ignition / boundary heat losses ...
  - Fluid mechanics – plumes / vent flows ...
  - Thermodynamics – Smoke layer / lower layer ...

- These features are embedded in computer-based fire models
  - Should understand the basics before using models (i.e., don't treat computer models as black boxes)

Ignition and heat release

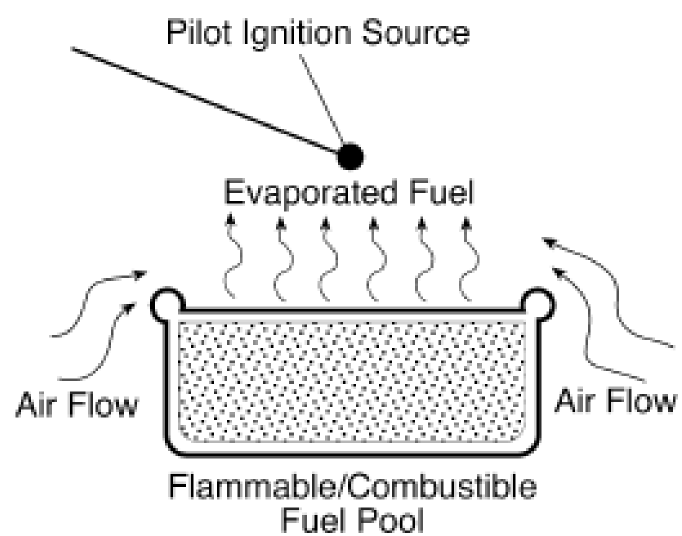
- Ignition of liquids
  - Thin films / pools / sprays / cascades
- Ignition of solids
  - Thermally thin materials
  - Thermally thick materials
- Heat release rates
  - Heat release rate characterizations
  - Experimental measurements / methods
  - Data resources

Ignition of liquids

- Ignition of liquids is actually the ignition of vapors rising from the fuel surface
- Liquid vapor pressures are typically expressed in terms of the Clausius-Clapeyron equation

$$\ln(P) = \frac{RT}{\Delta H_{vap}} + C$$

- Ignition occurs when there is a flammable mixture of fuel vapor and air at the location of a competent ignition source



Ignition of liquids

- Combustible liquids are classified by flashpoint (FP)
  - Flashpoint is the lowest temperature at which a flammable vapor / air mixture exists at the fuel surface
- Flashpoints are measured in a number of different standard test methods
  - Open cup vs. closed cup
- DOT classifications are commonly used to distinguish the volatility of liquid fuels
  - Flammable liquids have FP < 100 F
  - Combustible liquids have FP > 100 F

Ignition of liquids

- Thin films
  - Thin films of liquids are typical in spill scenarios where a small quantity of liquid spreads on floor
  - At temperatures above the flashpoint of the liquid, a thin film can be readily ignited
  - At temperatures below the flashpoint of the liquid, the liquid temperature must be raised to its flashpoint
    - On heavy substrates, such as concrete floors, this can require considerable energy input
    - On porous substrates, such as carpet, wicking occurs

Ignition of liquids

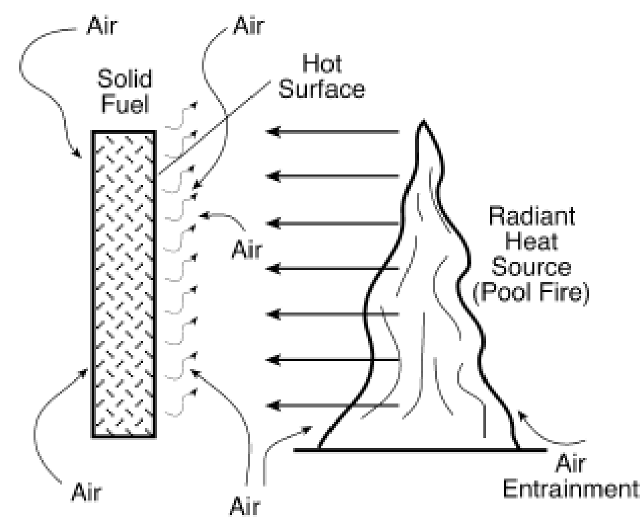
- Pools
  - At temperatures above the flashpoint of the liquid, a pool can be readily ignited
    - Above the fire point, liquid will continue to burn
    - Fire point typically a few degrees higher than FP
  - At temperatures below flashpoint of the liquid, the liquid temperature must be raised to its flashpoint
    - Circulation patterns in pool can dissipate considerable heat from localized ignition source
    - A wick traps liquid, permitting localized ignition
      - e.g., Hurricane lamp / porous lagging on pipes

Ignition of liquids

- Sprays
  - Pressurized leaks can cause the discharge of atomized sprays
  - Such sprays are relatively easy to ignite, even if the liquid is above its flashpoint
    - This is due to high surface area / volume ratio of small droplets
    - e.g., Oil burner
- Cascades
  - Cascading liquids can have characteristics of thin films and sprays,
    - Difficult to generalize about ignition characteristics

Ignition of solids

- Solid fuels pyrolyze or vaporize under incident heat flux
  - Combustible vapors released from the fuel surface
- Ignition occurs when fuel vapors form flammable mixture with air in presence of ignition source near fuel surface
- Concept of effective ignition temperature is still widely used



Ignition of solids

- Thermally thin solid
  - A material that develops a uniform temperature through its cross-section under heating
    - A material with a low Biot number
- Thermally thick solid
  - A material that develops significant temperature gradients at the fuel surface under heating
    - A material that can be treated as a semi-infinite solid during the time period of interest (i.e., ignition time)

Ignition of solids

- Thermally thin solids – example
- Solution – Case 1

$$t_{ig} = \frac{\rho \delta c \Delta T_{ig}}{\alpha \dot{q}''} = \frac{0.30\, kg/m^2 \cdot 1.2\, kJ/kg.K \cdot (300-20)K}{0.90 \cdot 35\, kW/m^2} = 3.2\, s$$

Ignition of solids

- Thermally thick solids
  - For a constant net heat flux at fuel surface, the time to ignition can be calculated as:

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

  - The net heat flux does not typically stay constant, even for a constant radiative heat flux
    - As the surface heats up, reradiation and convection from the surface become increasingly important

Ignition of solids

- Thermally thick solids
  - Critical heat flux is the minimum heat flux that will cause ignition within a prescribed exposure period
    - 20 minutes is commonly used, but is arbitrary
  - Time to ignition is then calculated as

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

  - TRP is "thermal response parameter" defined by Tewarson

Ignition of solids

- Thermally thick solids – representative properties

Table 6-3. Critical Heat Flux and Thermal Response Parameters of Selected Materials (Tewarson, 1995, © SFPE. With permission.)

Material	Critical Heat Flux (CHF) (kW/m^2)	Thermal Response Parameter (TRP) ($kW\text{-}sec^{1/2}/m^2$)
Electrical Cables: Power		
PVC/PVC	13–25	156–341
PE/PVC	15	221–244
PVC/PE	15	263
Silicone/PVC	19	212
Silicone/crosslinked polyolefine	25–30	435–457
EPR (ethylene-propylene rubber/EPR)	20–23	467–567
XLPE/XLPE	20–25	273–386
XLPE/EVA (ethyl-vinyl acetate)	12–22	442–503
XLPE/Neoprene	15	291
XLPO/XLPO	16–25	461–535
XLPO, PVF, (polyvinylidine fluoride)/XLPO	14–17	413–639
EPR/Chlorosulfonated PE	14–19	283–416
EPR, FR	14–28	289–448

Ignition of solids

- Thermally thick solids – representative properties

Table 6-3. Critical Heat Flux and Thermal Response Parameters of Selected Materials (Tewarson, 1995, © SFPE. With permission.)

Material	Critical Heat Flux (CHF) (kW/m^2)	Thermal Response Parameter (TRP) (kW-sec$^{1/2}$/m^2)
Synthetic Materials		
Polypropylene	15	193
Nylon	15	270
Polymethylmethacrylate (PMMA)	11	274
Polycarbonate	15	331
Polycarbonate panel	16	420
Natural Materials		
Wood (red oak)	10	134
Wood (Douglas fir)	10	138
Wood (Douglas fir/fire retardant, FR)	10	251
Corrugated paper (light)	10	152

Ignition of solids

- Thermally thick solids – example
  - A rigid polyurethane foam insulation board has a thermal inertia of 9.5×10^{-4} $(kW/m^2.K)^2s$ and an effective ignition temperature of 400°C.
  - A wooden panel has a thermal inertial of 0.14 $(kW/m^2.K)^2s$ and an effective ignition temperature of 300°C.
  - Both materials have thermal absorptivities of 0.90.
  - Each material is subjected to a constant net heat flux at the surface of 30 kW/m^2
  - Estimate the time to ignition of each material

Ignition of solids

- Thermally thick solids – example
- Solution
  - PU foam

$$t_{ig} = \frac{\pi k \rho c}{4}\left[\frac{\Delta T_{ig}}{\alpha \dot{q}''_i}\right]^2 = \frac{\pi \cdot 9.5 \times 10^{-4}}{4}\left[\frac{380}{30}\right]^2 = 0.12\,s$$

  - PW panel

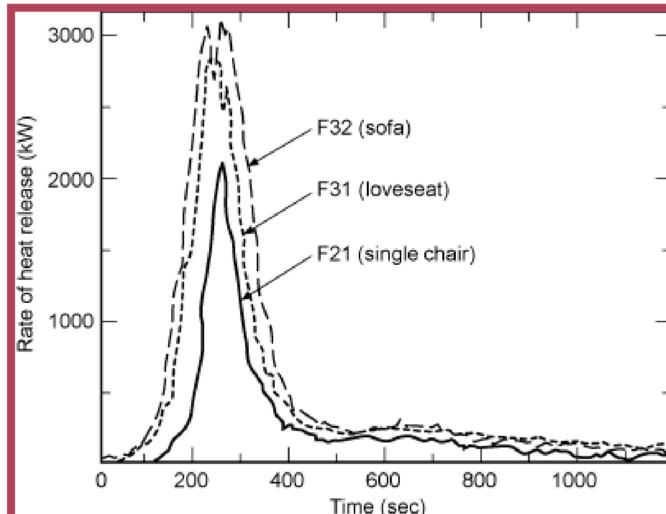
$$t_{ig} = \frac{\pi \cdot 0.14}{4}\left[\frac{280}{30}\right]^2 = 9.6s$$

Ignition of solids

- Thermally thick solids
  - Governing material property for ignition is $k\rho c$
    - Low density materials heat up faster and ignite sooner than higher density materials
  - Need to select material properties from the literature with caution, particularly for use in computer-based models such as FDS
    - Effective material properties derived based on different assumptions from those used in FDS
    - Evaluation of authoritative material properties is an area of active research currently sponsored by NIST

Fire source issues

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



Design fire

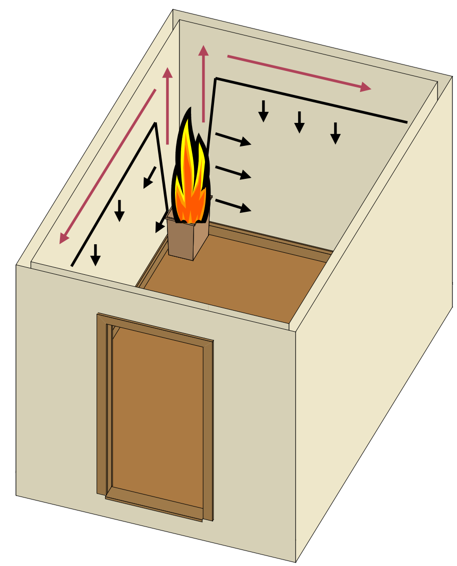
- HRR as f(t) is termed the *design fire*
- Approaches to determining *design fire*:
  - Knowledge of amount/type of combustibles
    - Object assumed to ignite and burn at known rate
    - Rate based on experimental data
  - Knowledge of occupancy
    - Little detailed data regarding specific fuels
    - Design fire based on statistics / eng. judgment

Design fire issues

- Target damage
  - Target vulnerability vs exposure conditions
- Structural stability
  - Fully developed post-flashover fire
  - Relatively long time frame (~1/2 -3 hours)
- Occupant escape / firefighting response
  - Developing fire
  - Relatively short time frame (<~1/2 hour)
- No exact methodology or procedure
  - Requires engineering judgment

Factors controlling HRRs

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



Mass burning rate

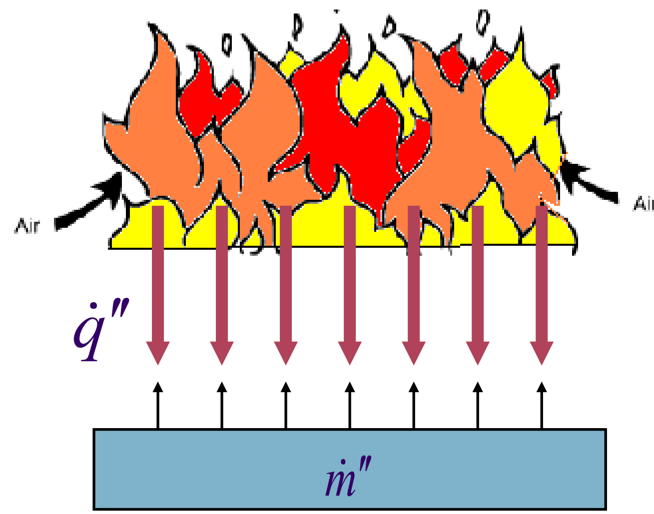
$$\dot{m}'' = \frac{\dot{q}''}{L} (g/m^2 s)$$

- LIQUIDS AT BOILING POINT

  q" Net heat flux to fuel surface

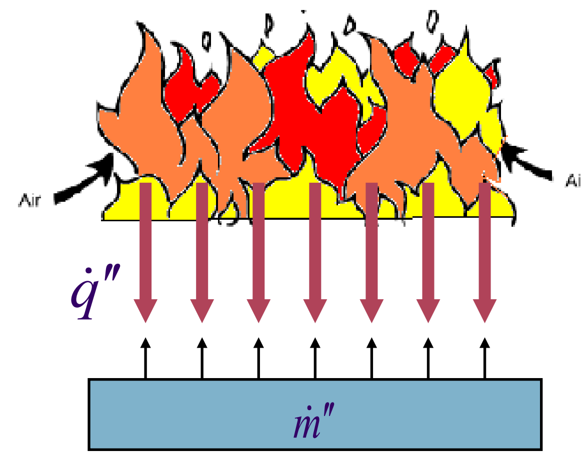
  L Heat of gasification

- HEAT OF GASIFICATION, L
  - LIQUIDS: $L = \Delta h_{vap} + C_{liq}(T_b - T_o)$
    - (0.3 - 1.5 kJ/g typical)
  - SOLIDS: EFFECTIVE PROPERTY
    - (1 - 5 kJ/g typical)



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

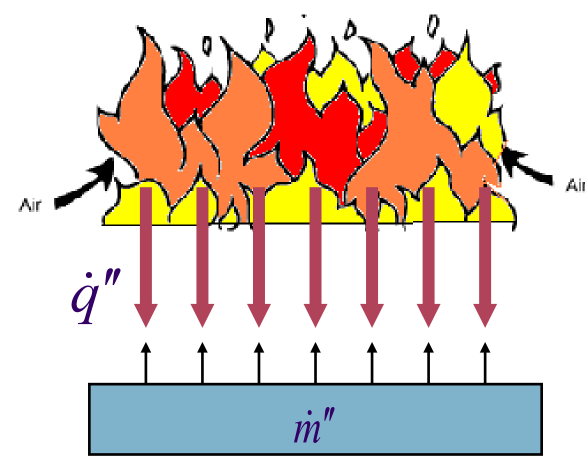
FUEL	ΔH_c (kJ/g)
WOOD	15.0
POLYURETHANE	30.0
HEPTANE	44.5

Combustibility ratio (or HRP)

$$\dot{Q} = \dot{m}'' A \Delta H_c = \dot{q}'' A \left(\frac{\Delta H_c}{L} \right)$$

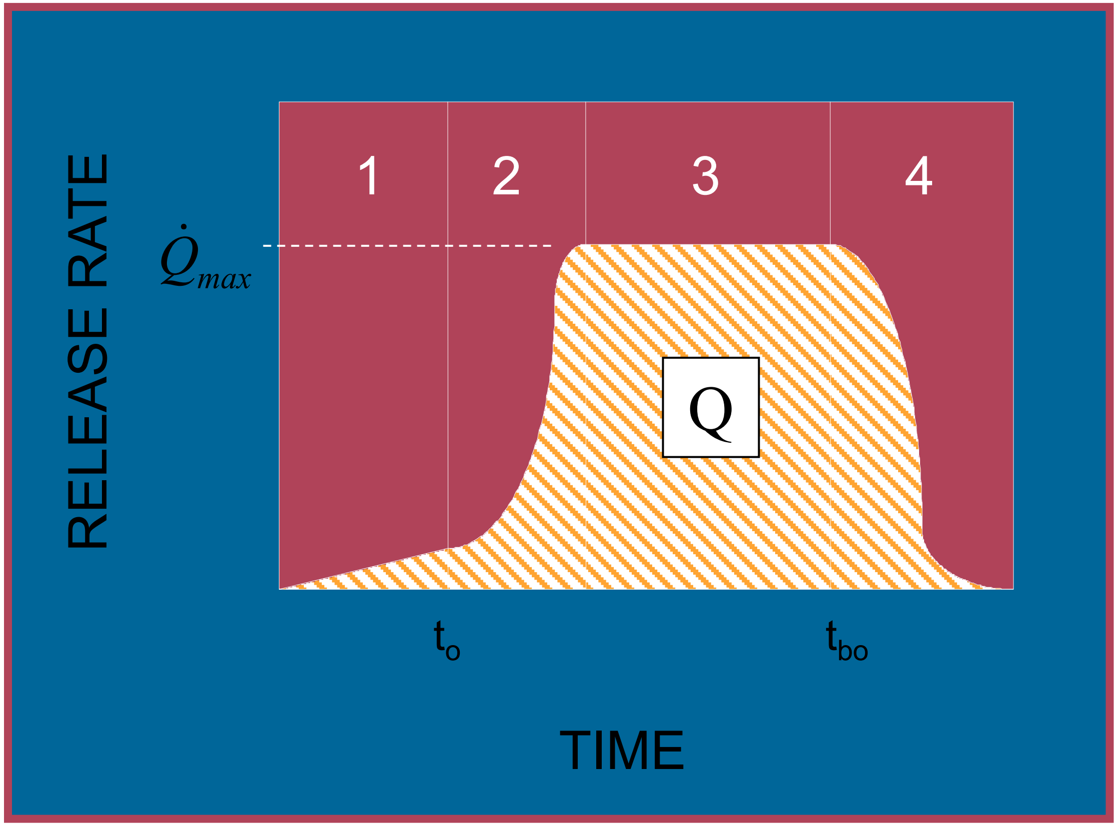
- Representative values of $(\Delta H_c / L)$

Fuel	Combustibility ratio $\Delta H_c / \Delta H_g$
Red oak (solid)	2.96
PVC (granular)	6.66
Nylon (granular)	13.10
PMMA (granular)	15.46
Methanol (liquid)	16.50
Polypropylene (granular)	21.37
Polystyrene (granular)	23.04
Polyethylene (granular)	24.84
Styrene (liquid)	63.30
Heptane (liquid)	92.83



Phases of fire development

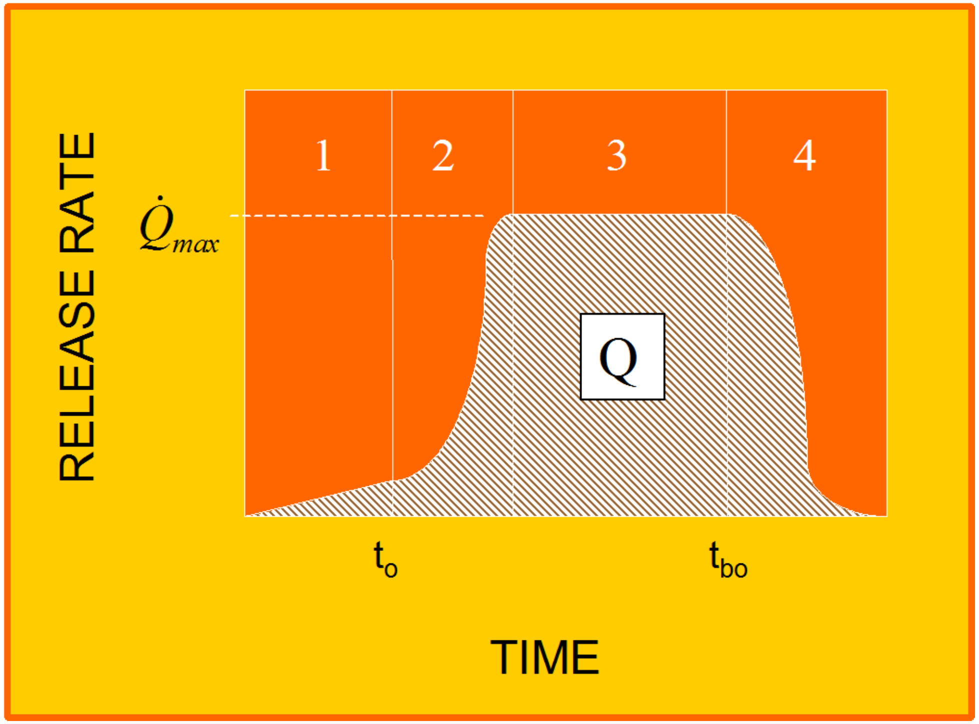
- Incipient
- Growth
- Fully developed
- Decay / burnout



Burning duration

- Heat released by fire $$Q = \int_o^t \dot{Q}(t)dt$$
- Burnout approximation

$$t_b = t_{bo} - t_o \approx \frac{Q}{\dot{Q}_{max}}$$



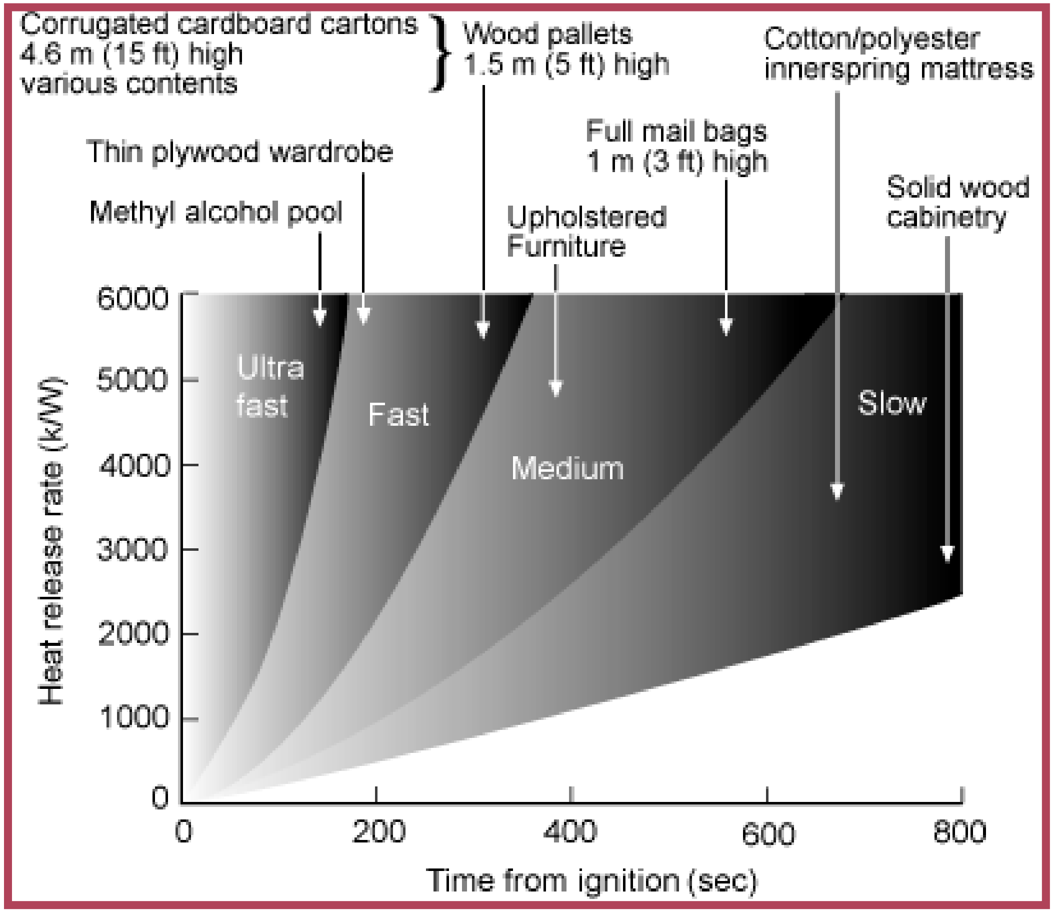
Fire growth characterization

- 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

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

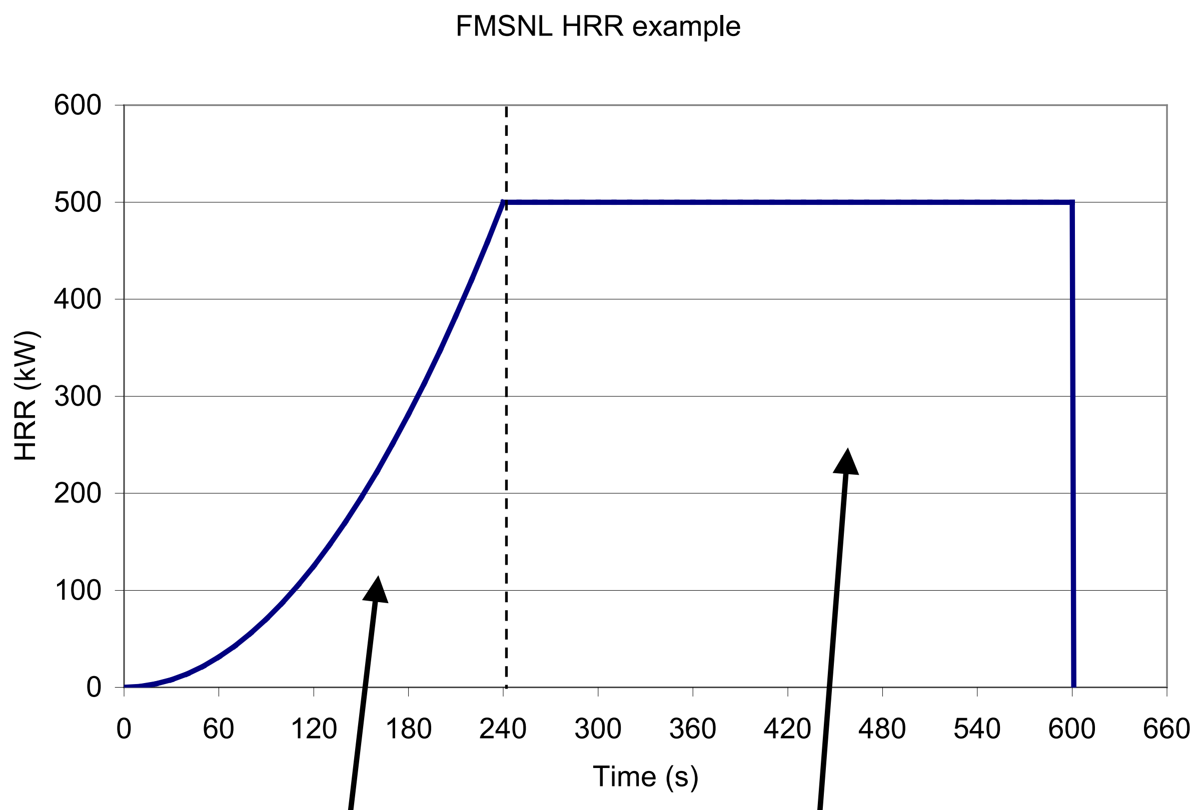
Growth rate	t_g (s)	α (kW/s^2)
Slow	600	0.003
Medium	300	0.012
Fast	150	0.047
Ultrafast	75	0.188

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



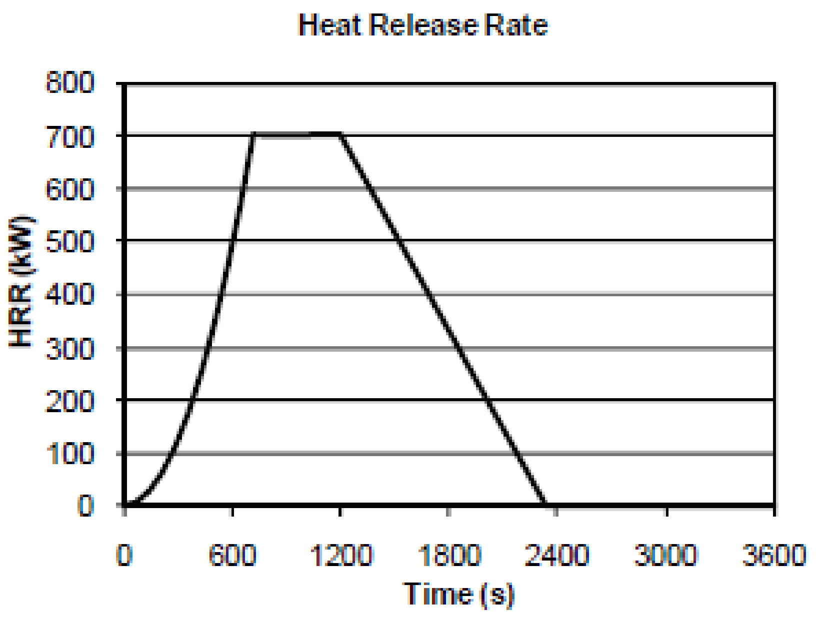
$$Q_{240s} = \int_0^{240} \frac{\dot{Q}_g}{t_g^2} t^2 dt = \frac{\dot{Q}_g}{t_g^2} \frac{t^3}{3} = \frac{500}{240^2} \frac{240^3}{3} = 40MJ$$

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

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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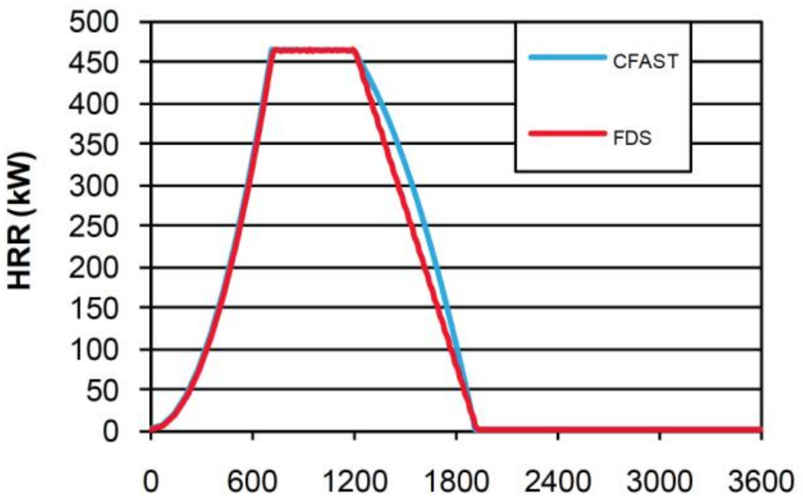
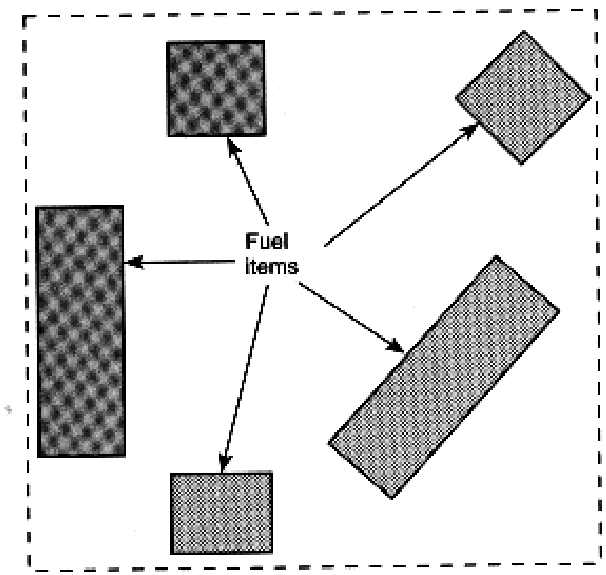


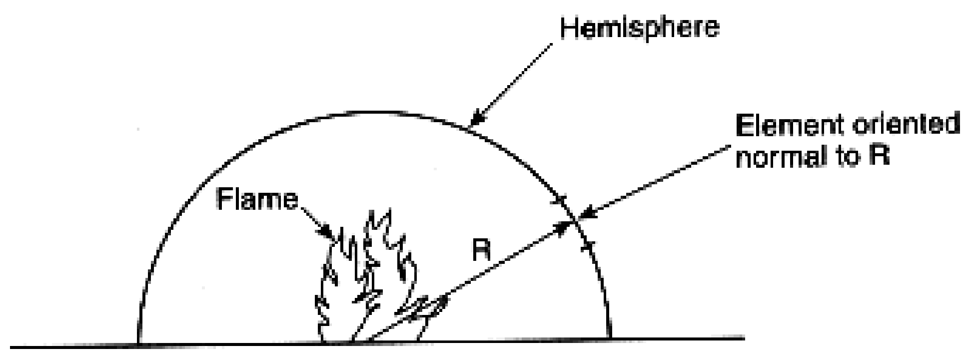
HRR taken from Appendix G, NUREG/CR 6850 (EPRI 1011989)

Secondary item ignition

- Factors
  - Heat flux from primary fire
  - Ease of ignition of target
- Point source estimate

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





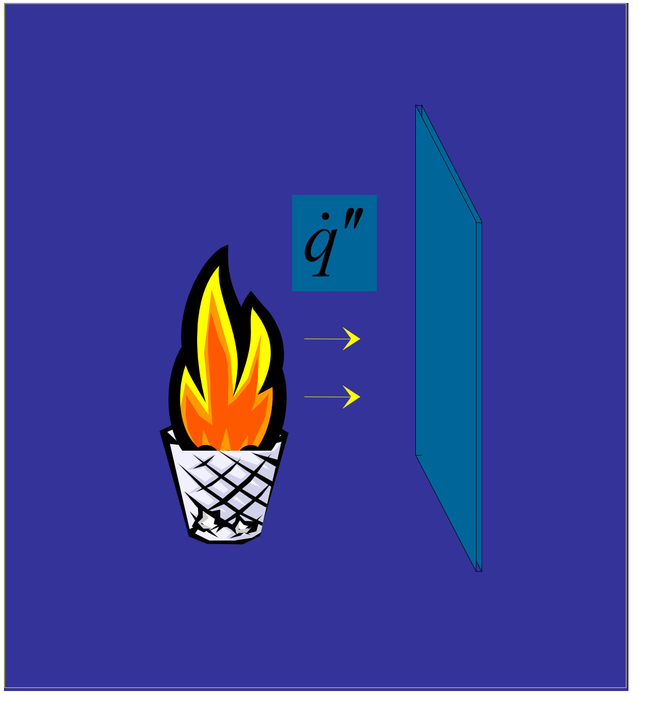
Secondary item ignition

- Ignition time estimates (constant heat flux)
  - Thermally thick materials

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

  - 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
- 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

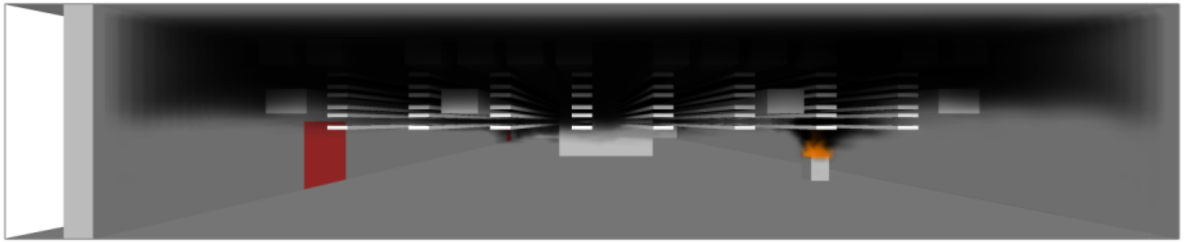
(CHRISTIFIRE) Phase I

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

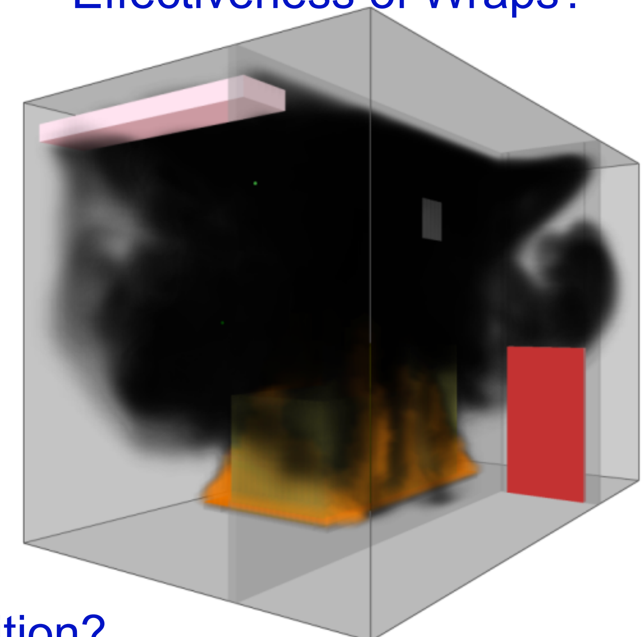
What's the Problem?

Answer: Very little useful information on cables for fire modeling

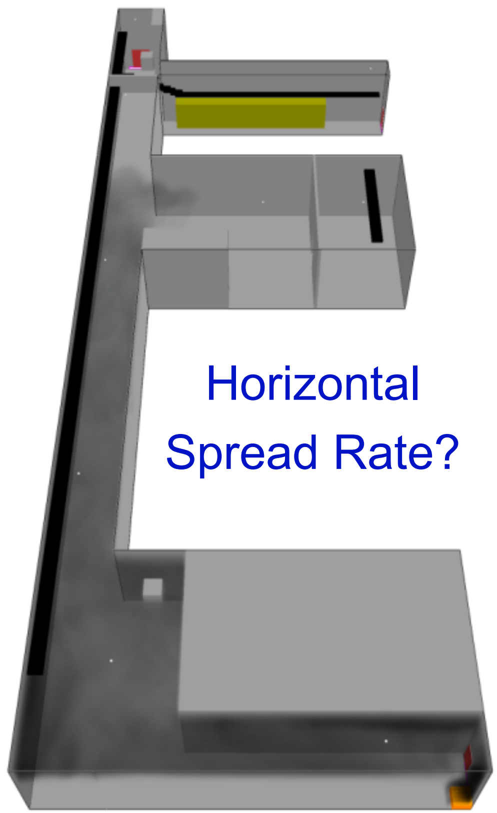


Tray to Tray Spread?

Effectiveness of Wraps?

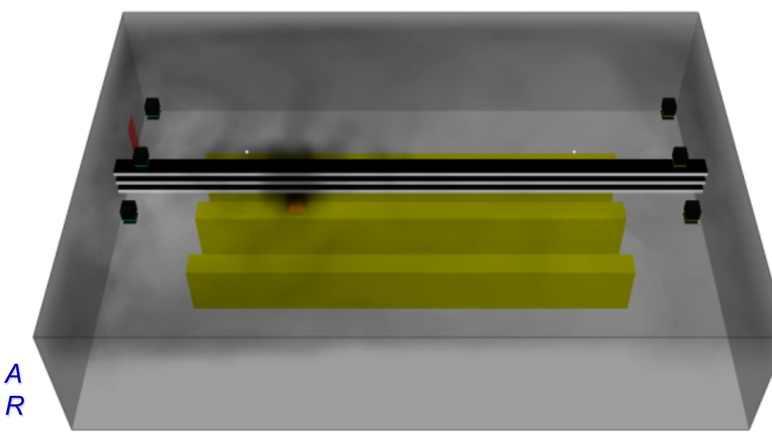


Vertical Spread Rate?



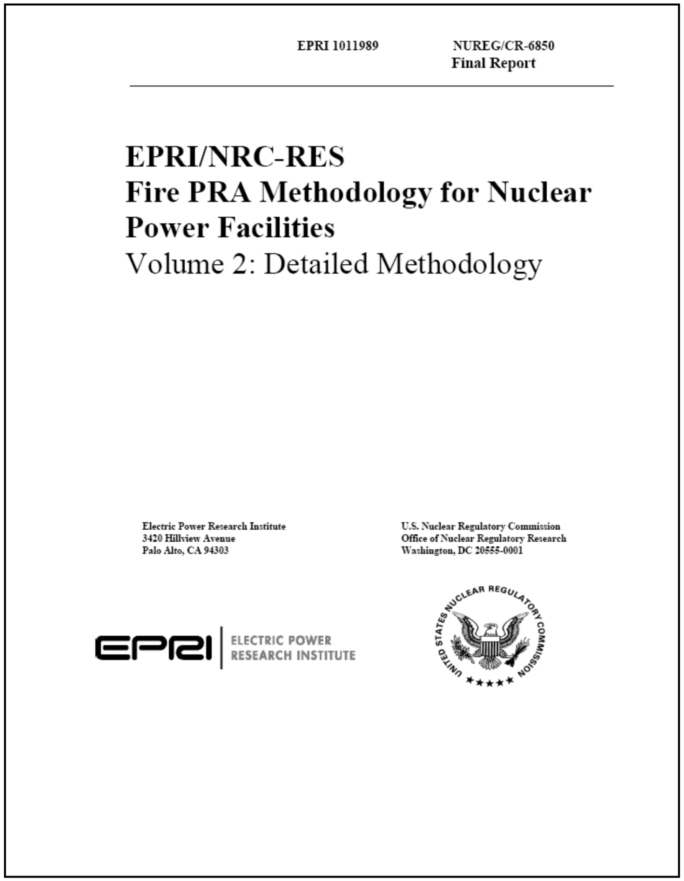
Horizontal
Spread Rate?

Ignition?



A
R

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

EPRI ELECTRIC POWER RESEARCH INSTITUTE

UNITED STATES NUCLEAR REGULATORY COMMISSION

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]

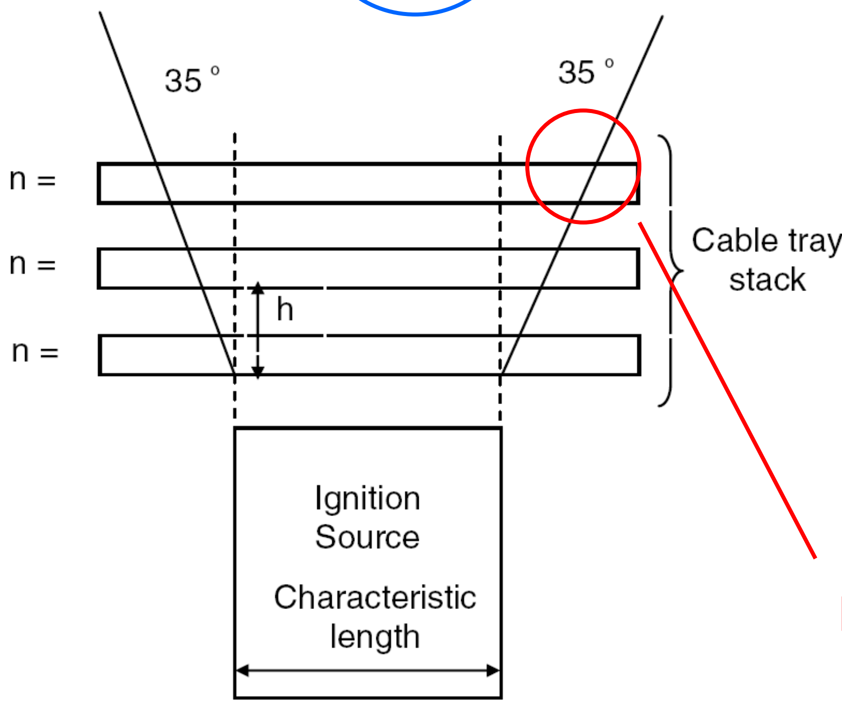
Material	Bench Scale HRR [kW/m^2]
XPE/FRXPE	475
XPE/Neoprene	354
XPE/Neoprene	302
XPE/XPE	178
PE/PVC	395
PE/PVC	359
PE/PVC	312
PE/PVC	589
PE, Nylon/PVC, Nylon	231
PE, Nylon/PVC, Nylon	218

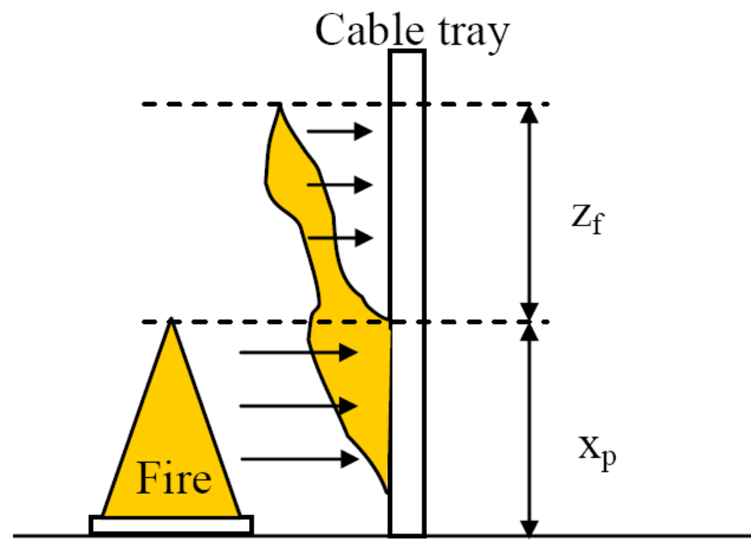
Which HRR to Use?

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





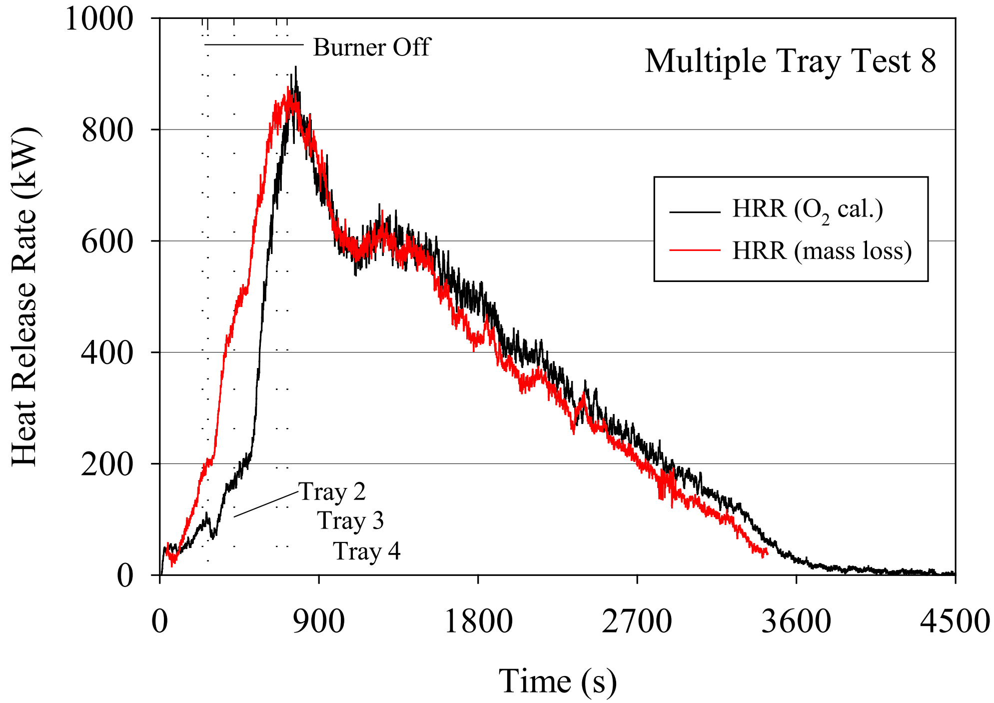
Based on only one experiment

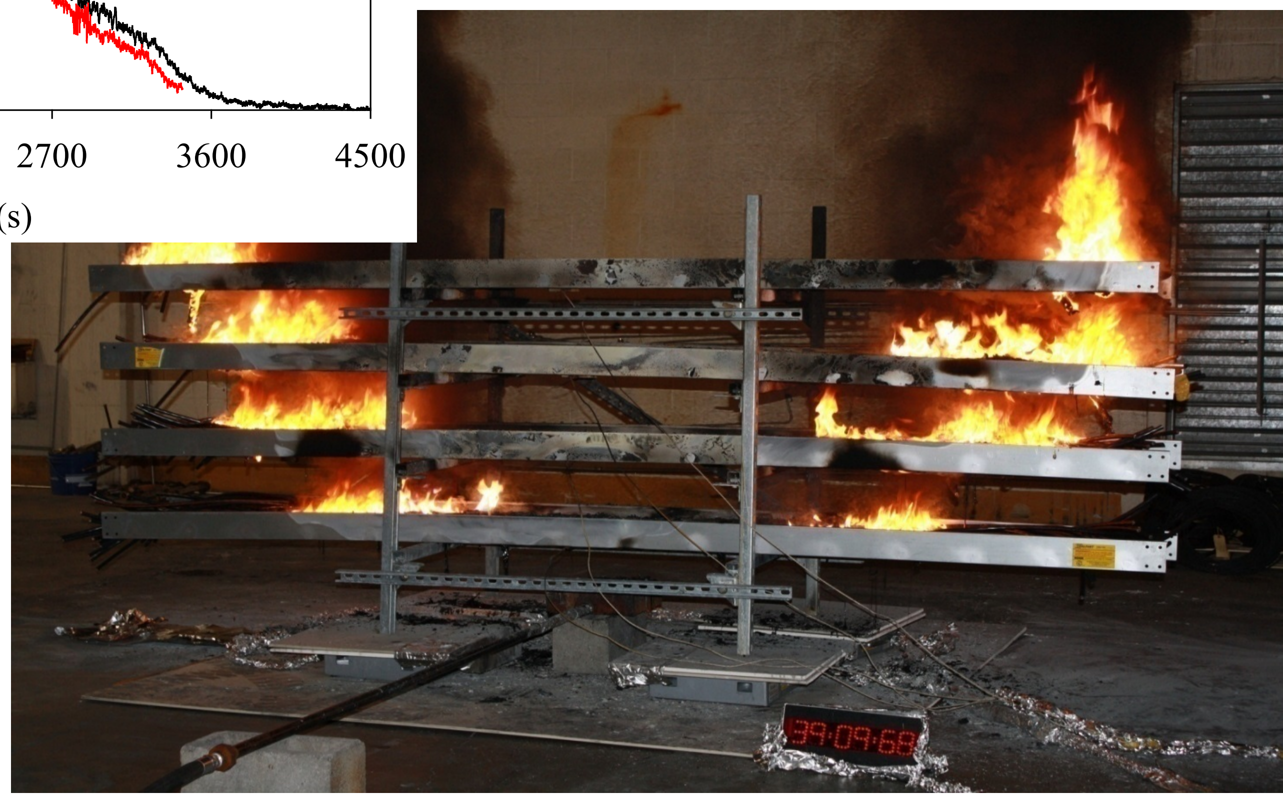
Cables used in CHRISTIFIRE

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

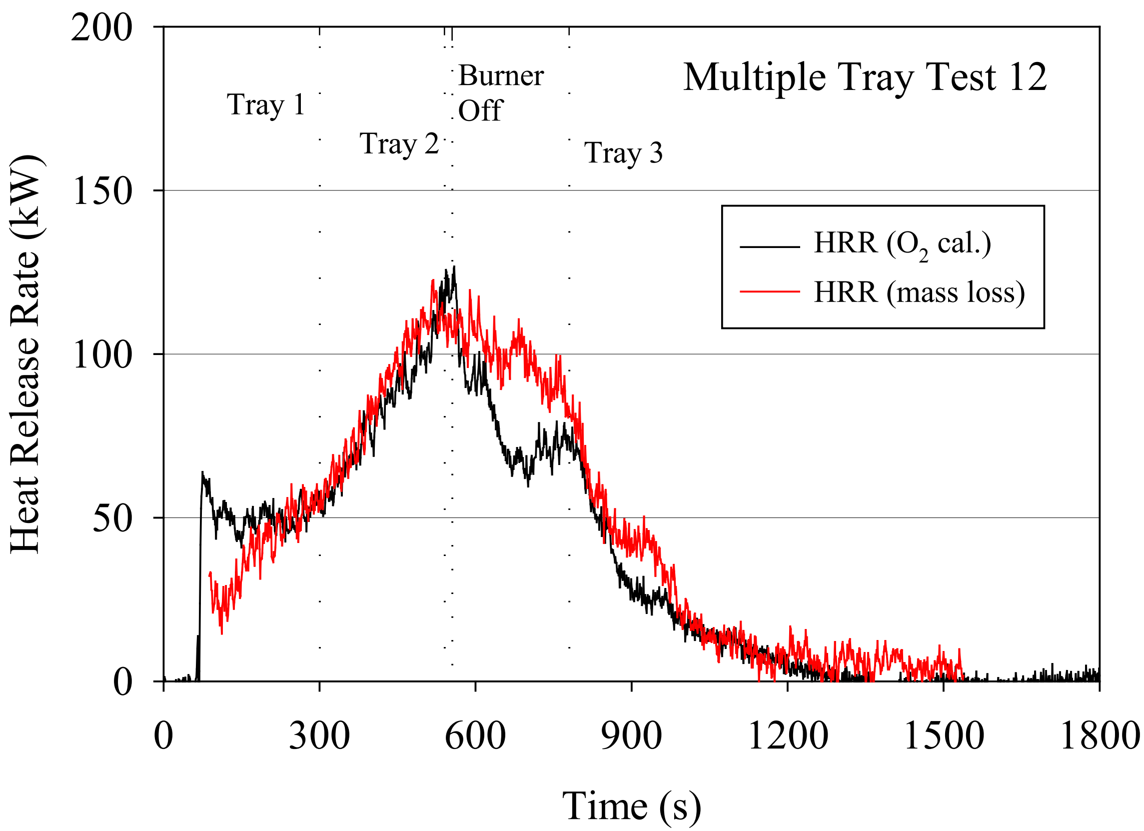
Thermoset cables tend to char and smolder; Electrical failure ~400 °C

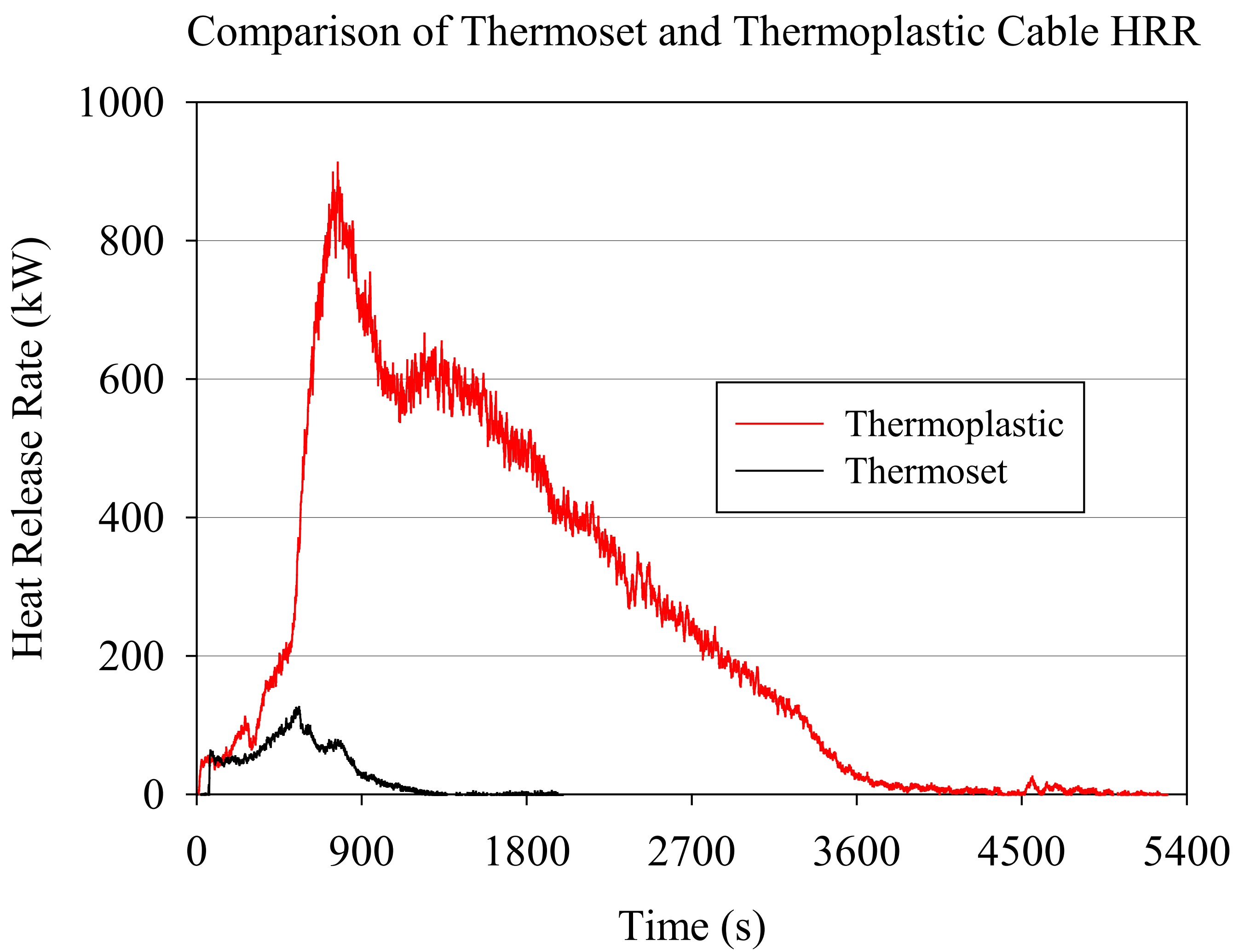
Thermoplastic Cable



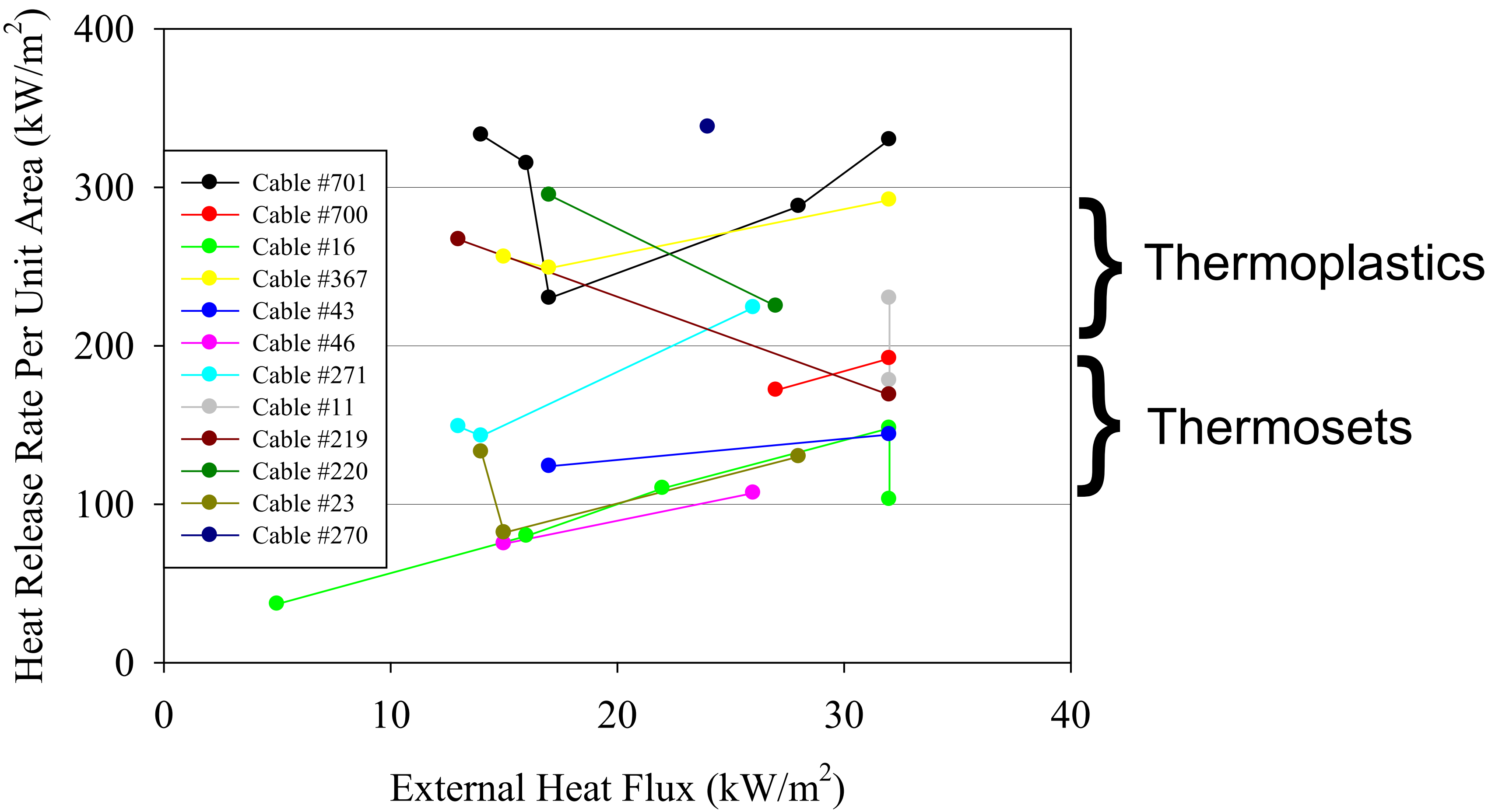


Thermoset Cable



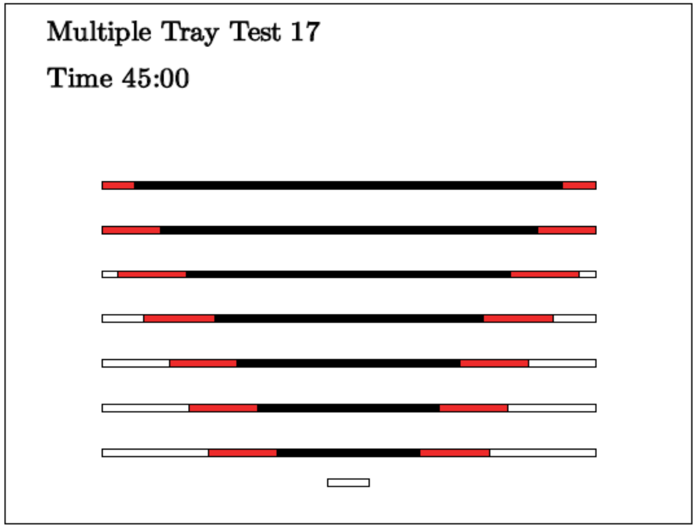

Comparison of Thermoset and Thermoplastic Cable HRR
Heat Release Rate (kW)
1000
800
600
400
200
0
0
900
1800
2700
3600
4500
5400
Time (s)
Thermoplastic
Thermoset

Results of Radiant Panel Experiments

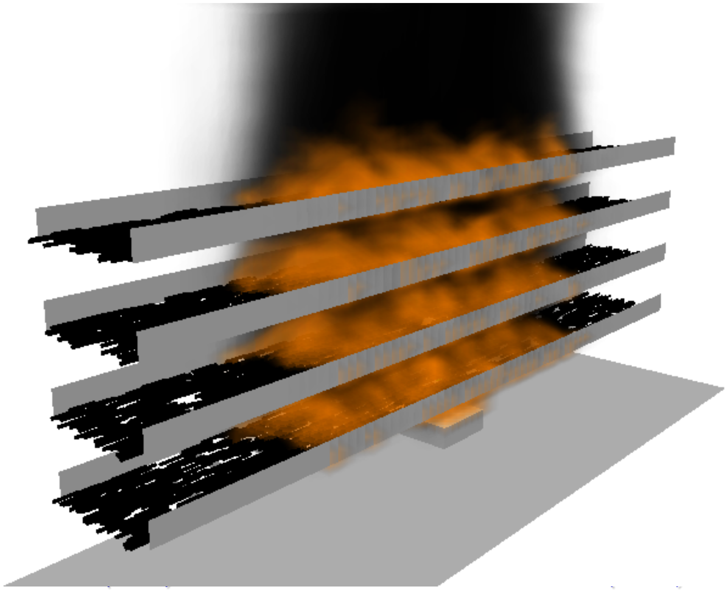


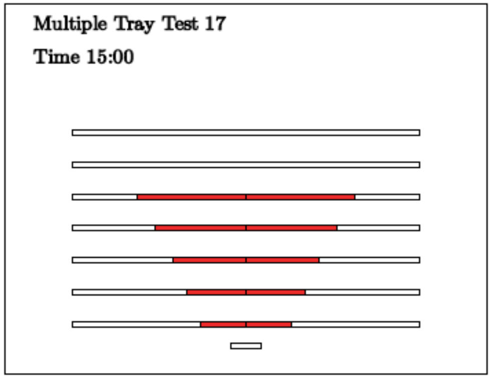
Modeling

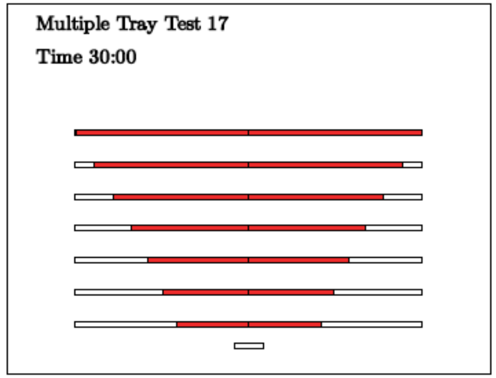
The Easy Way

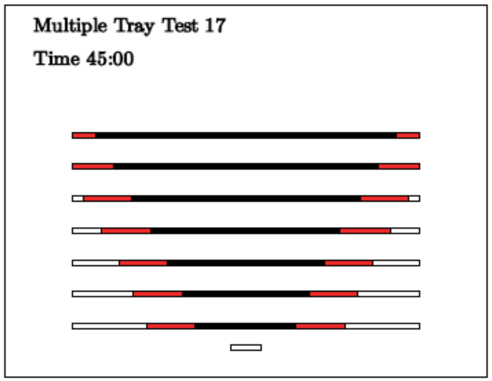


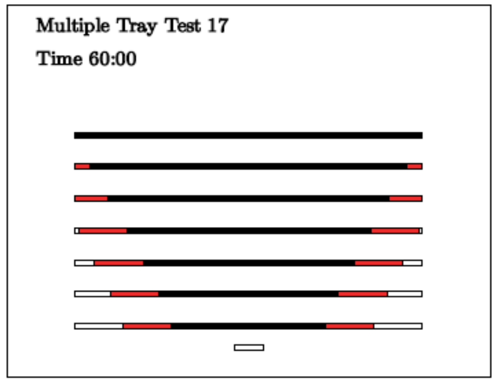
The Hard Way

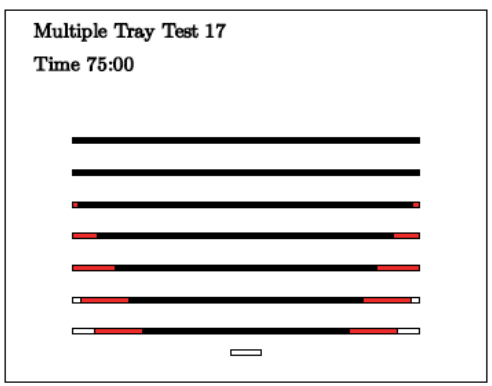


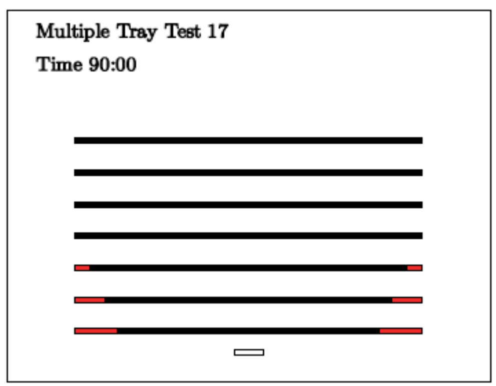












FLASH-CAT

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

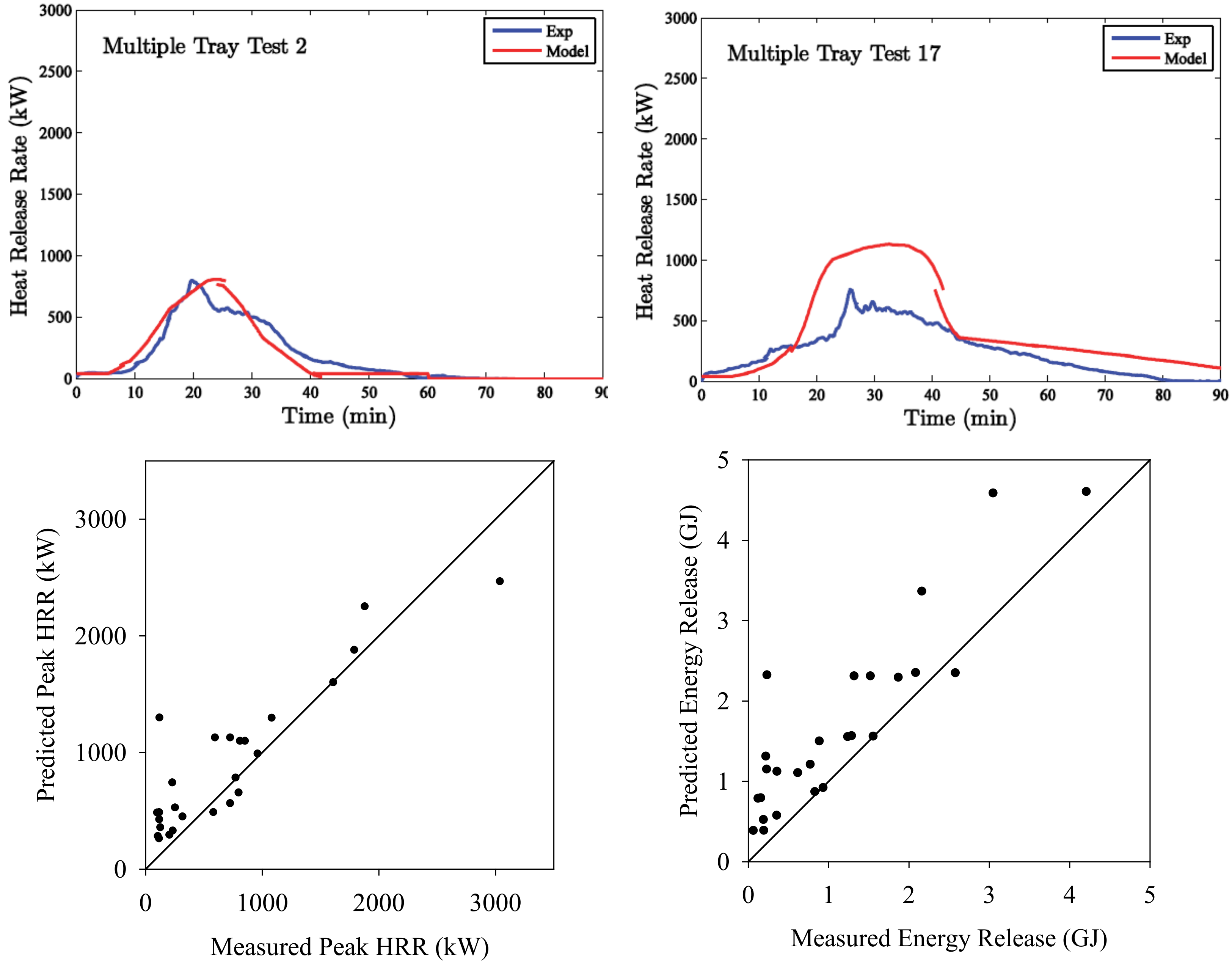
Lateral Spread

3.2 m/h thermoplastics

1.1 m/h thermosets

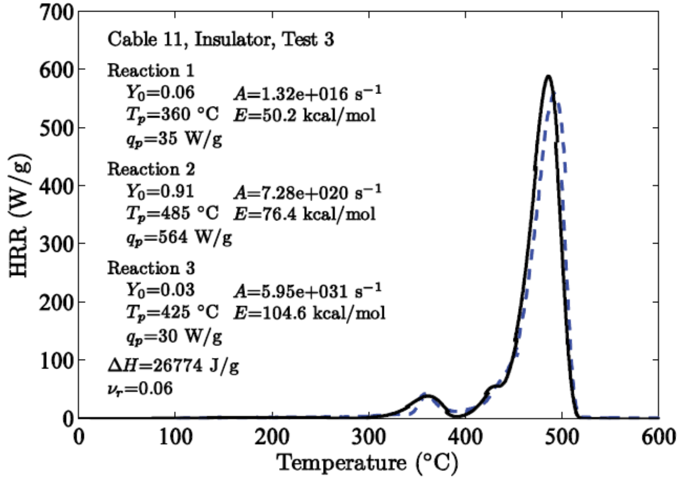
Heat of Combustion

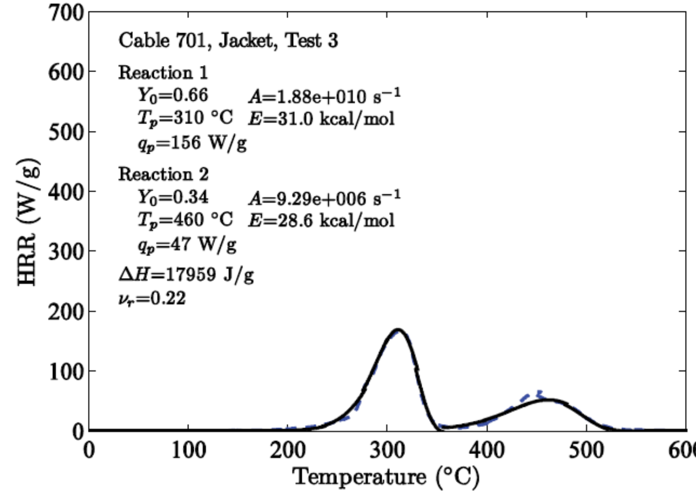
16 MJ/kg for all

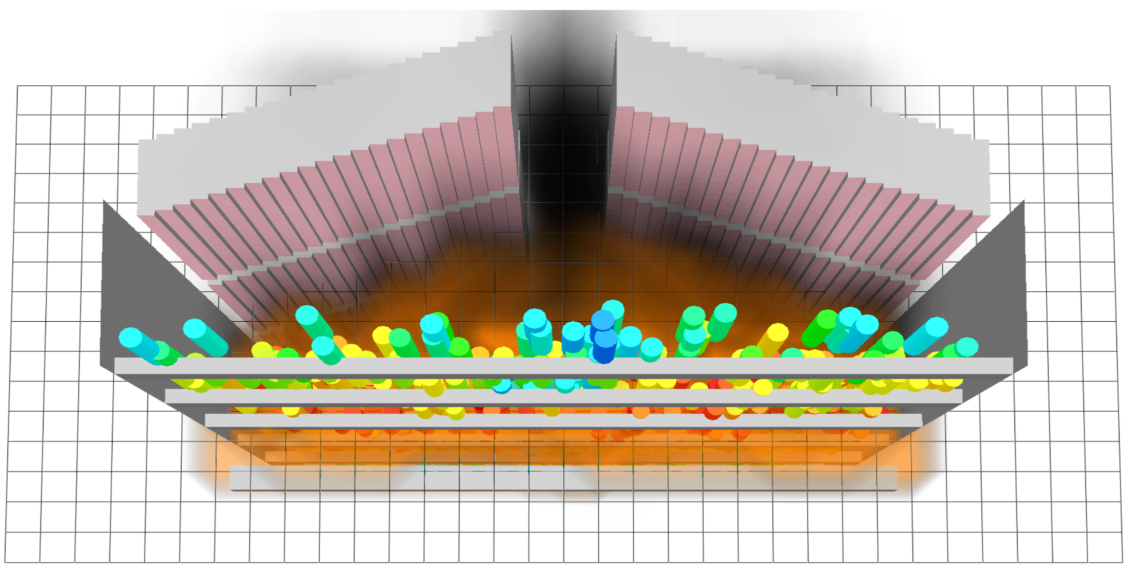


Multiple Tray Test 2
Exp
Model
Heat Release Rate (kW)
Time (min)
Multiple Tray Test 17
Exp
Model
Heat Release Rate (kW)
Time (min)
Predicted Peak HRR (kW)
Measured Peak HRR (kW)
Predicted Energy Release (GJ)
Measured Energy Release (GJ)

Fire Dynamics Simulator (FDS)

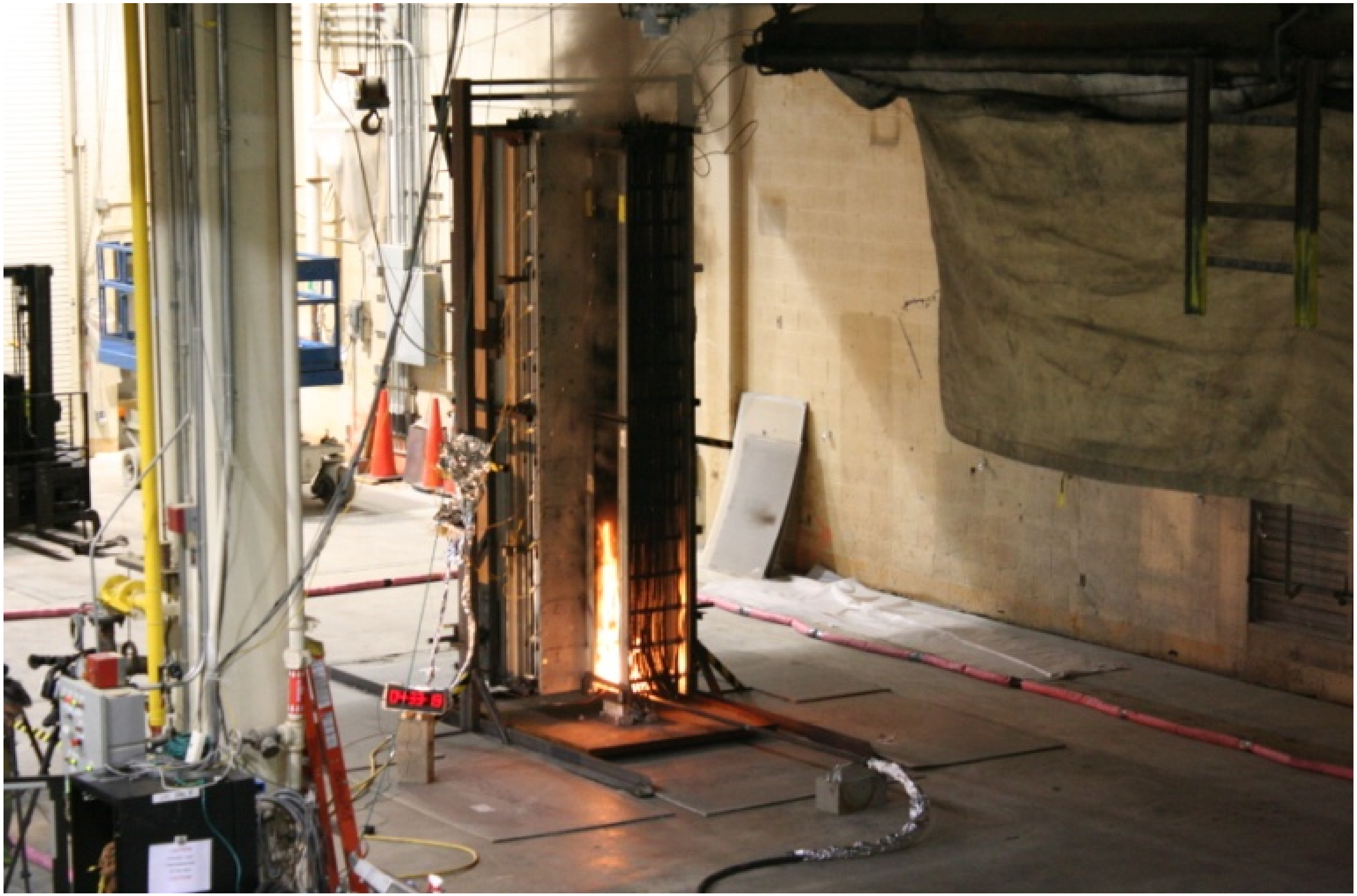


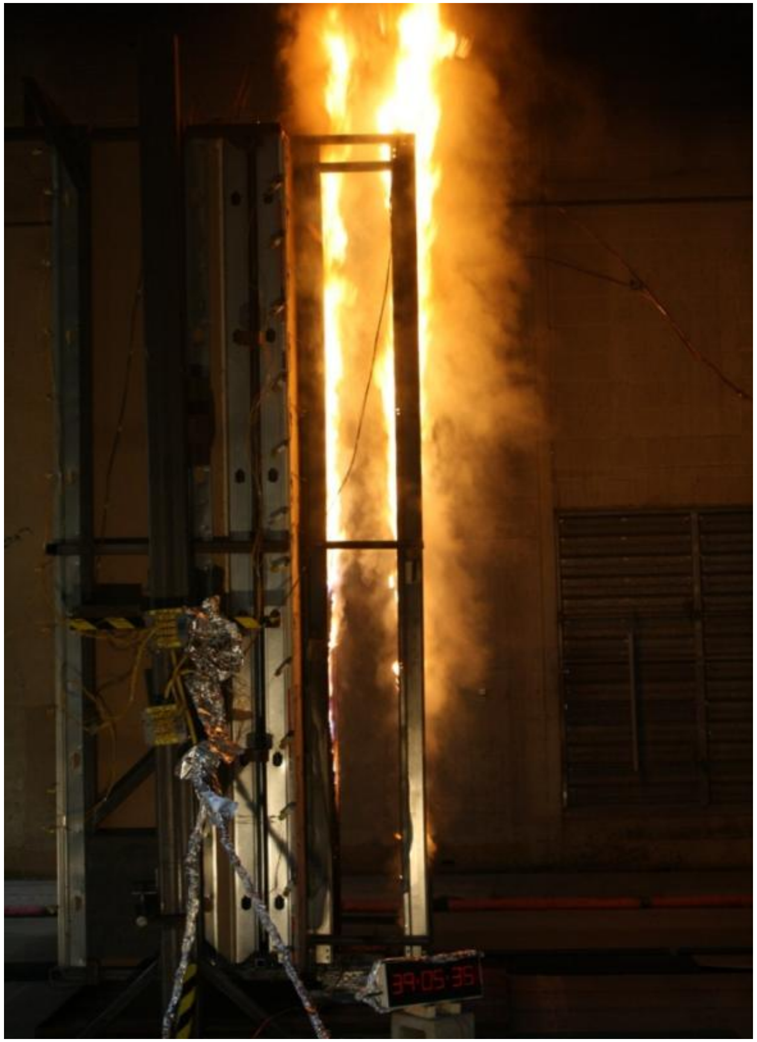




A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Vertical cable fire spread





Hallway Tests


35:06:58

The spread rate of a fire can be estimated from:

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

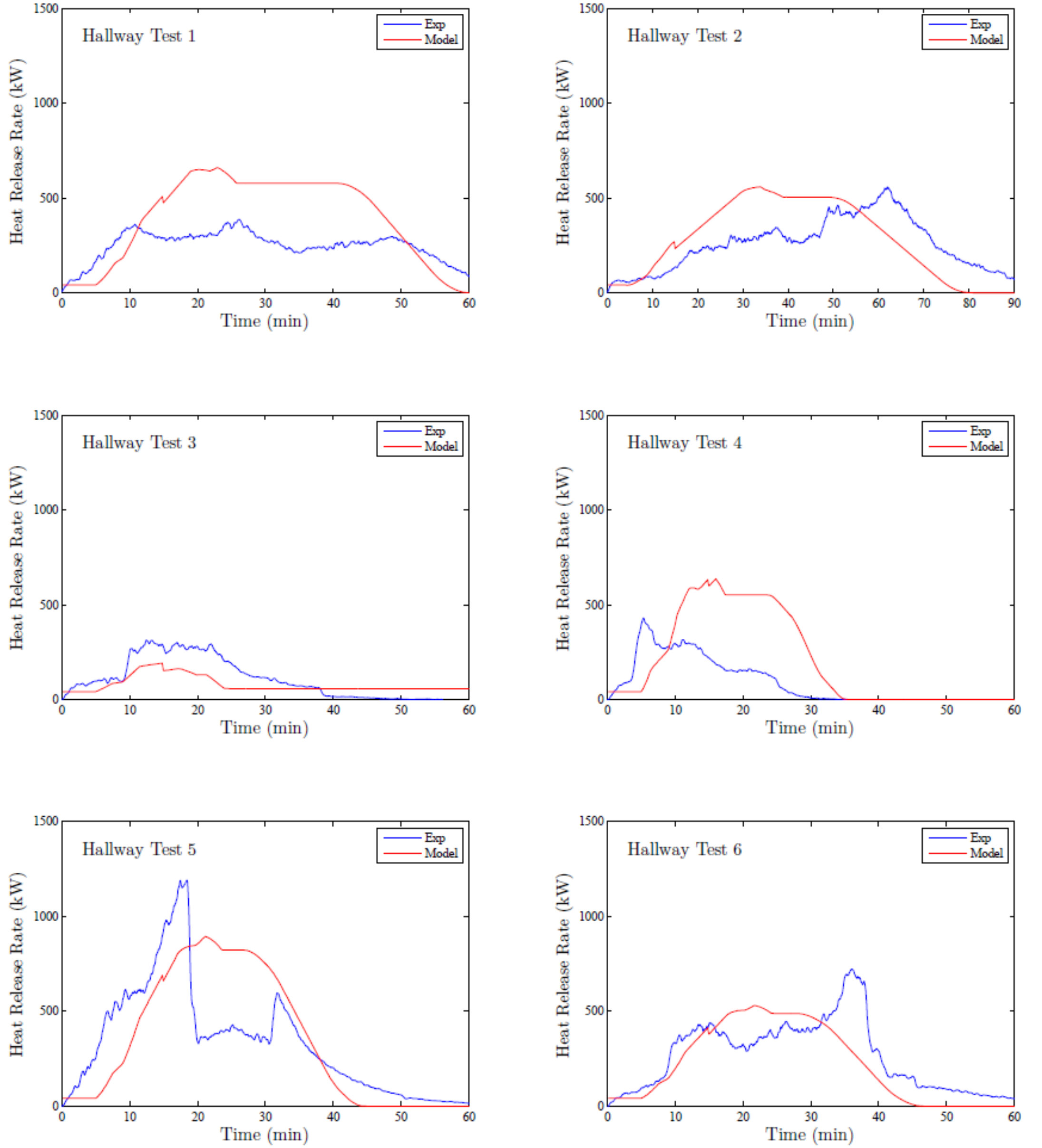
If the cables are located within the Hot Gas Layer (HGL), the spread rate could increase by a factor of 10.

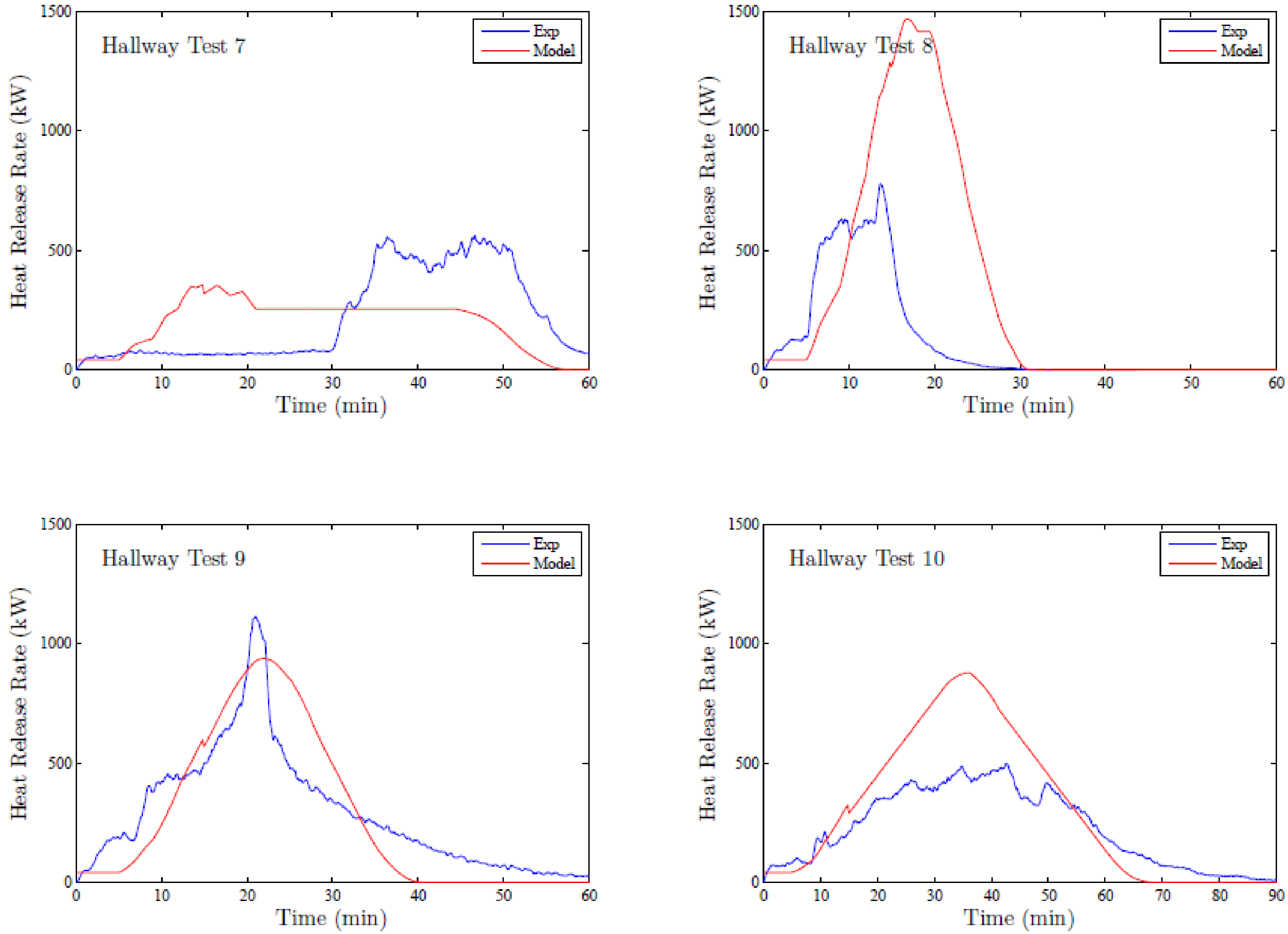
$$\frac{v_2}{v_1} = \left(\frac{T_{ign} - T_\infty}{T_{ign} - T_{HGL}}\right)^2 = \left(\frac{400 - 20}{400 - 280}\right)^2 \cong 10$$

FLASH-CAT

<u>Fla</u>me <u>S</u>pread over <u>H</u>orizontal <u>Ca</u>ble <u>T</u>rays

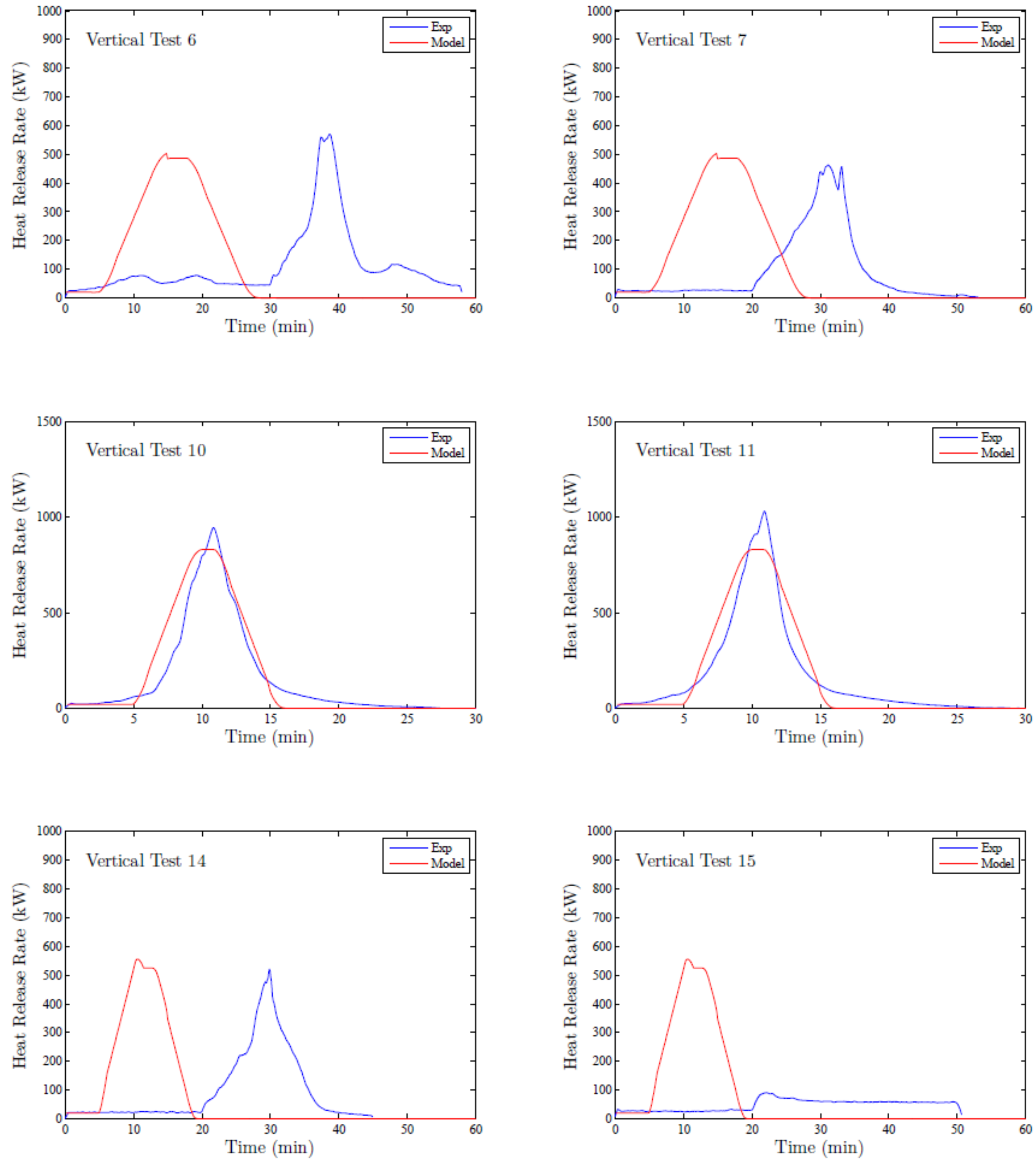
Results of Hallway Experiments




Hallway Test 7
Exp
Model
Heat Release Rate (kW)
Time (min)
Hallway Test 8
Hallway Test 9
Hallway Test 10
0
500
1000
1500
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

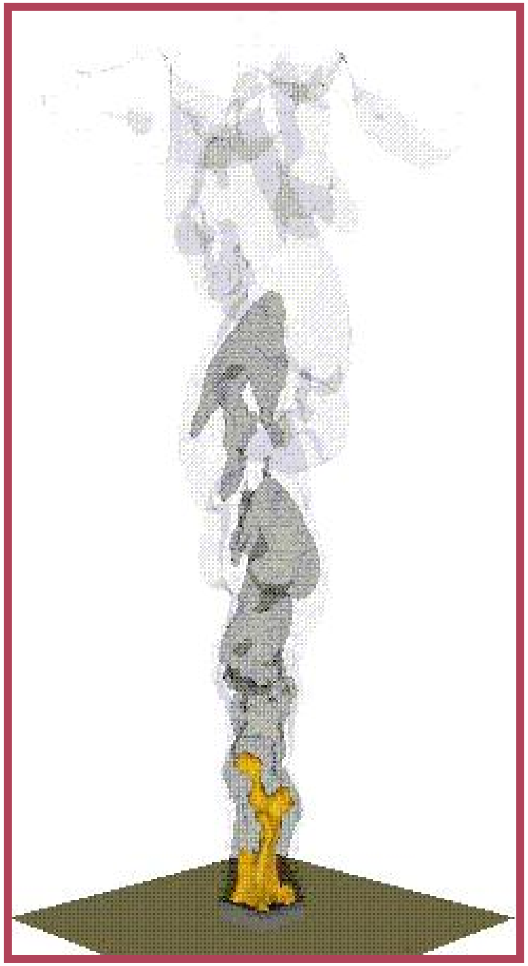
- Describe fire plume and ceiling jet phenomena
- Discuss the theory behind fire plume correlations
- Appreciate the role of plume entrainment on fire conditions within an enclosure
- Calculate fire plume and ceiling jet conditions, including temperatures and velocities, for different correlations

References – fire plumes

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

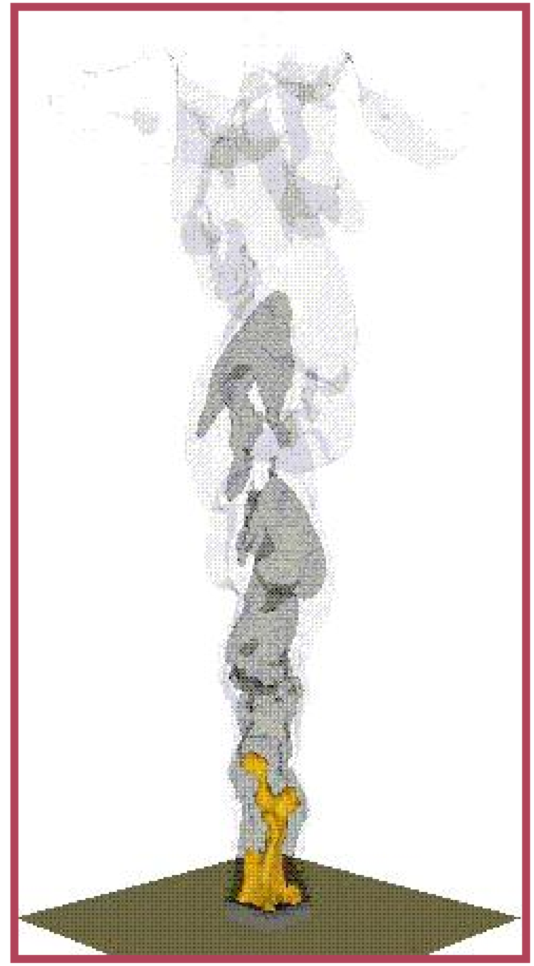
Fire plume issues

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



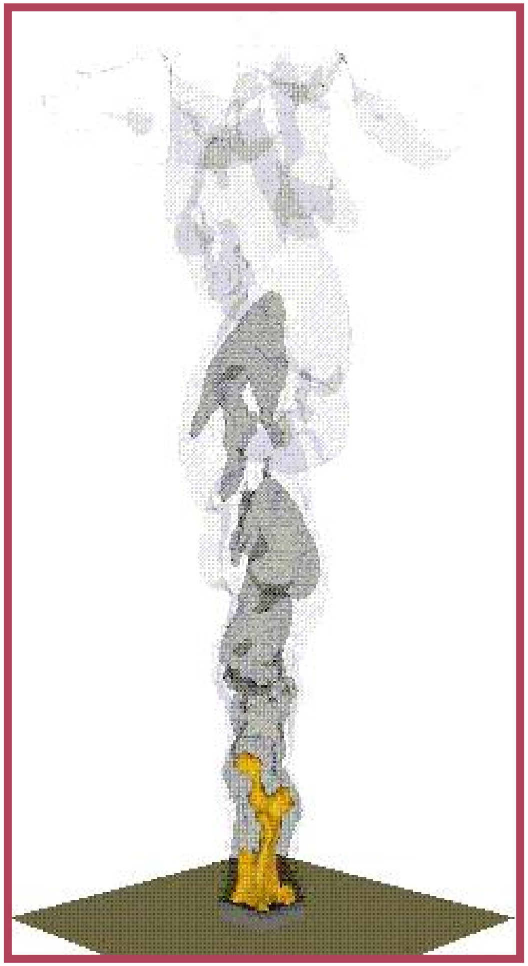
Fire plume topics

- Types of plumes
- Flame heights
- Flame/plume temperatures
- Entrainment in fire plumes
- Gas velocities in fire plumes



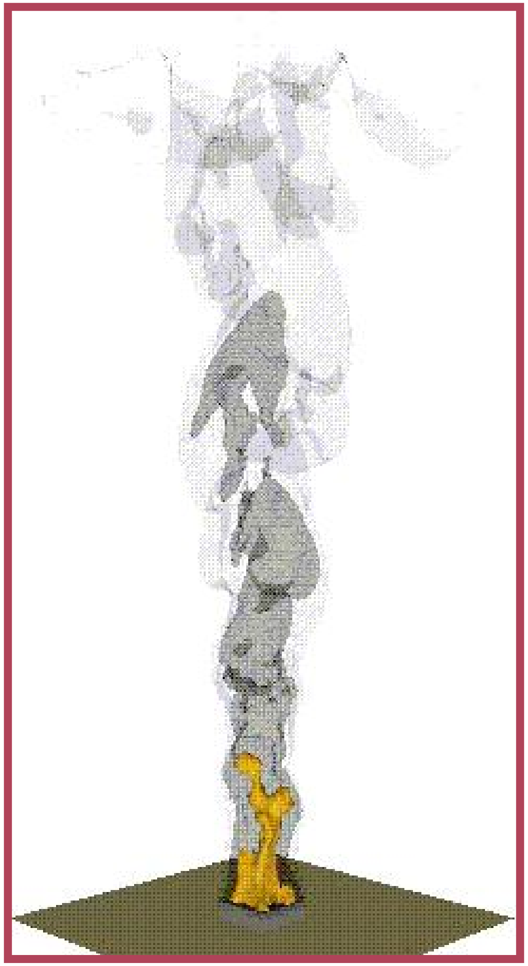
Types of fire plumes

- 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

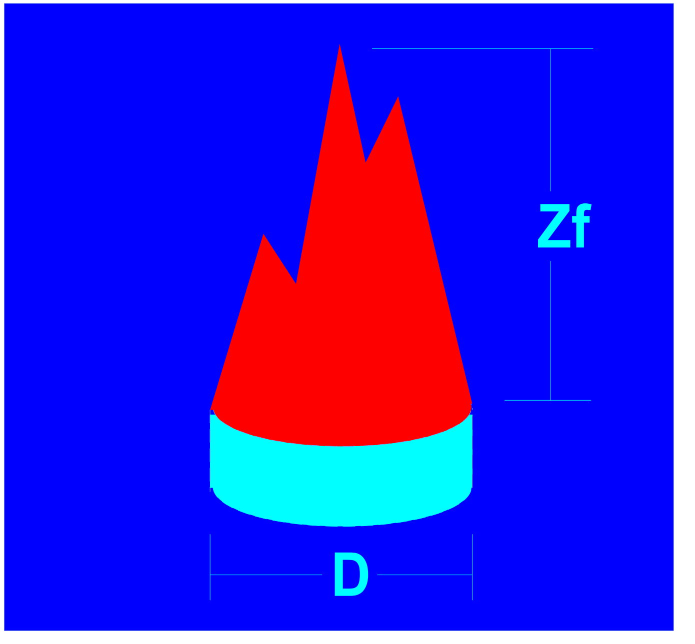


Flame height correlation

- Heskestad correlation

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

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



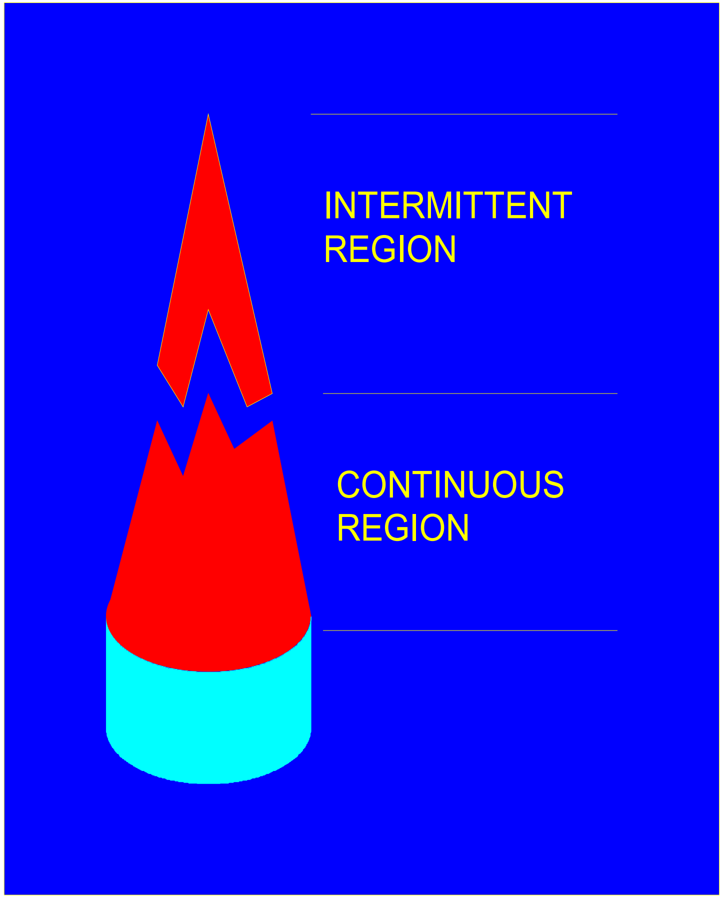
Flame height correlation

- McCaffrey correlation
  - Continuous flame

$$Z_{fc} = 0.08\dot{Q}^{2/5}$$

  - Intermittent flame

$$Z_{fi} = 0.20\dot{Q}^{2/5}$$



The Heskestad plume

- Plume width

$$b_{\Delta T} = 0.12\sqrt{\frac{T_o}{T_\infty}}(z - z_o) \qquad b_u \approx 1.1 b_{\Delta T}$$

- Plume centerline velocity

$$u_o = 3.4\left(\frac{\dot{Q}_c \cdot g}{\rho_\infty c_p T_\infty}\right)^{1/3} \cdot (z - z_o)^{-1/3} = 1.03\left(\frac{\dot{Q}_c}{z - z_o}\right)^{1/3}$$

The Heskestad plume

- Gaussian temperature / velocity profiles
  - Temperature

$$\Delta T = \Delta T_o \exp\left(-(R / \sigma_{\Delta T})^2 \right)$$

$$\sigma_{\Delta T} = 1.2 b_{\Delta T}$$

  - Velocity

$$u = u_o \exp\left(-(R / \sigma_u)^2 \right)$$

$$\sigma_u = 1.2 b_u$$

The Heskestad plume

- Plume entrainment
  - Effective flame height

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

  - Flame region ($z < z_L$)

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

  - 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

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

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

The McCaffrey plume

- Plume entrainment
  - Continuous flame region

$$\frac{\dot{m}_{pl}}{\dot{Q}} = 0.011\left(\frac{z}{\dot{Q}^{2/5}}\right)^{0.566}$$

  - Intermittent flame region

$$\frac{\dot{m}_{pl}}{\dot{Q}} = 0.026\left(\frac{z}{\dot{Q}^{2/5}}\right)^{0.909}$$

  - Plume region

$$\frac{\dot{m}_{pl}}{\dot{Q}} = 0.124\left(\frac{z}{\dot{Q}^{2/5}}\right)^{1.895}$$

The McCaffrey plume

- Plume temperature

$$\frac{\Delta T_o}{T_\infty} = \left(\frac{\kappa}{0.9\sqrt{2g}}\right)^2 \left(\frac{z}{\dot{Q}^{2/5}}\right)^{2\eta-1}$$

  - Continuous flame region

$$\kappa = 6.8; \eta = 1/2 \qquad \Delta T_o = 867°C$$

  - Intermittent flame region

$$\kappa = 1.9; \eta = 0 \qquad \Delta T_o = 68\frac{\dot{Q}^{2/5}}{z}$$

  - Plume region

$$\kappa = 1.1; \eta = -1/3 \qquad \Delta T_o = 23\frac{\dot{Q}^{2/3}}{z^{5/3}}$$

The Alpert plume

- Plume velocity / temperature

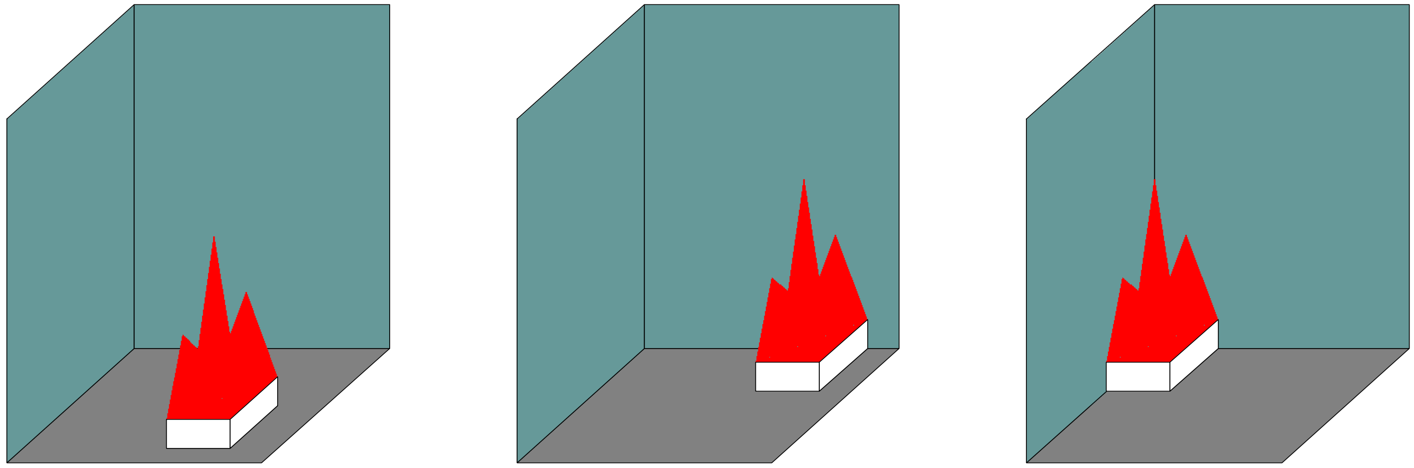
$$u_{pl} = 0.95\left[\frac{\dot{Q}}{z}\right]^{1/3}$$

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

  – Based on total theoretical HRR
  – Used in DETACT model

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: $k_{lf} = 4$



Fire plume - example

- In the FMSNL 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

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

$$= 4.0\, m/s$$

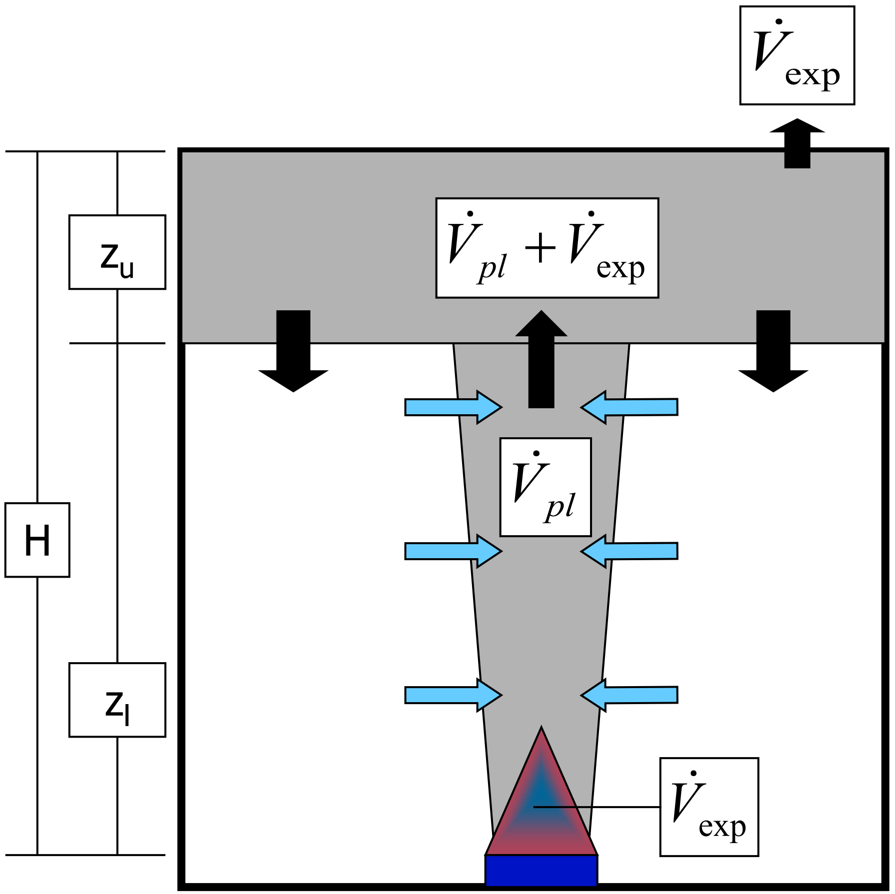
Enclosure smoke filling

- 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

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



Smoke management (purge)

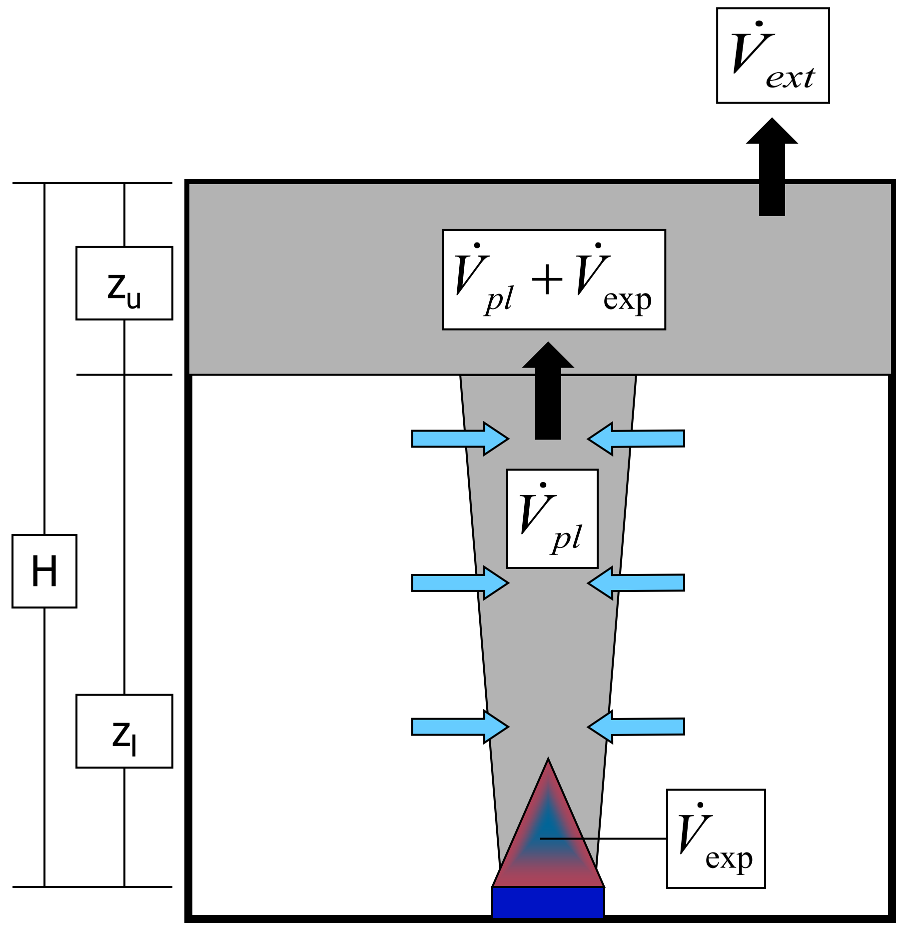
- Extraction method

$$\frac{dV_u}{dt} = 0 = \dot{V}_{u,in} - \dot{V}_{u,out}$$

$$\dot{V}_{u,in} = \dot{V}_{pl} + \dot{V}_{\exp}$$

$$\dot{V}_{u,out} = \dot{V}_{ext}$$

$$\boxed{\dot{V}_{ext} = \dot{V}_{pl} + \dot{V}_{\exp}}$$



Smoke management (purge)

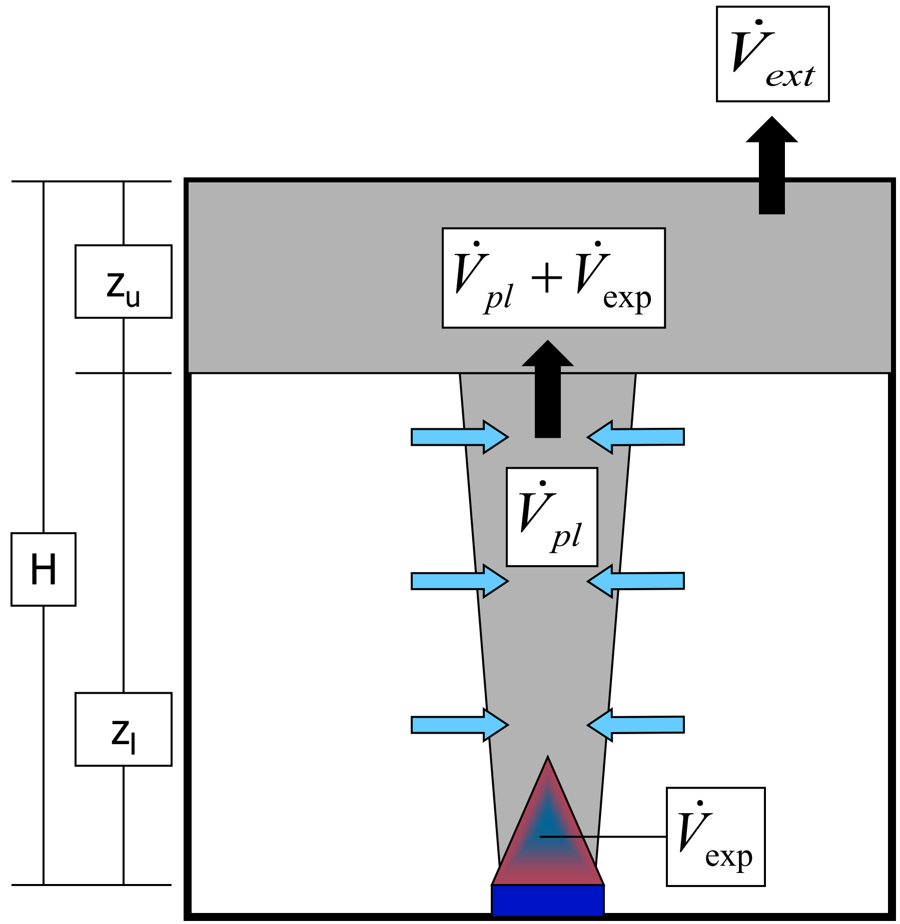
- Smoke layer temperature

$$\Delta T = \frac{\dot{Q}_{net}}{\dot{m}c_p}$$

$$\dot{Q}_{net} = \rho_o c_p T_o \dot{V}_{\exp}$$

$$\dot{m} = \rho_o \dot{V}_{in}$$

$$\boxed{\frac{\Delta T}{T_o} = \frac{\dot{V}_{\exp}}{\dot{V}_{in}} = \frac{\dot{V}_{\exp}}{\dot{V}_{pl}}}$$



Summary – fire plumes

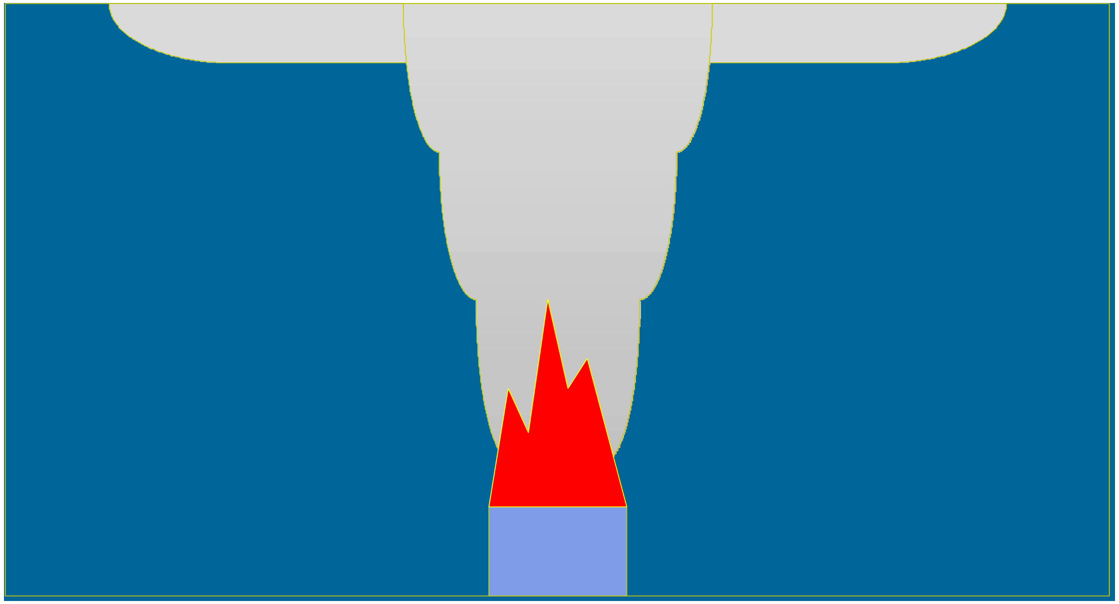
- Plume important for number of reasons
  - Temperatures/velocities/heat fluxes at targets
  - Smoke layer filling / exhaust rates
  - Smoke concentrations
- Correlations available for some scenarios
  - Axisymmetric / line plumes
  - Windows / balconies (limited theory / data)

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
- Field models can address scenarios where correlations are inappropriate

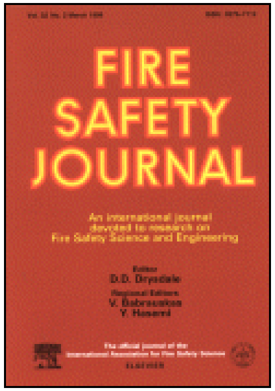
Ceiling jet topics

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

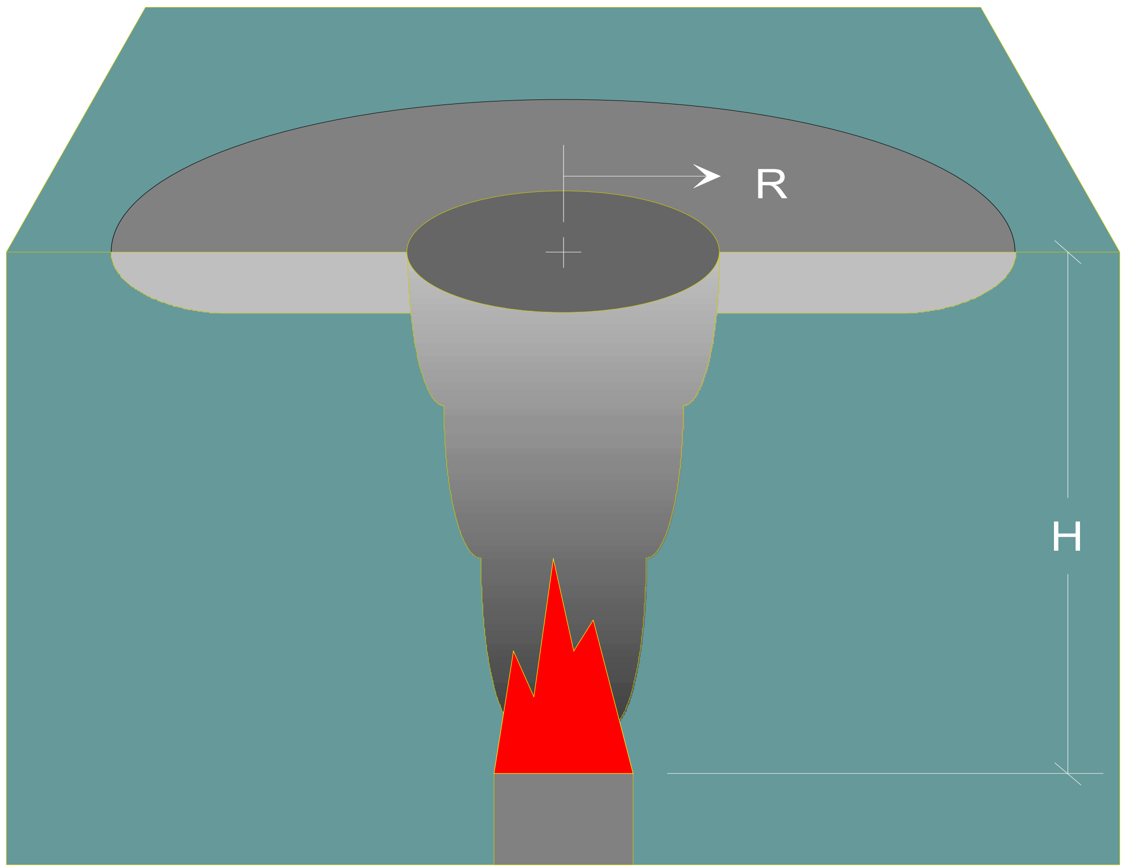


References – ceiling jets

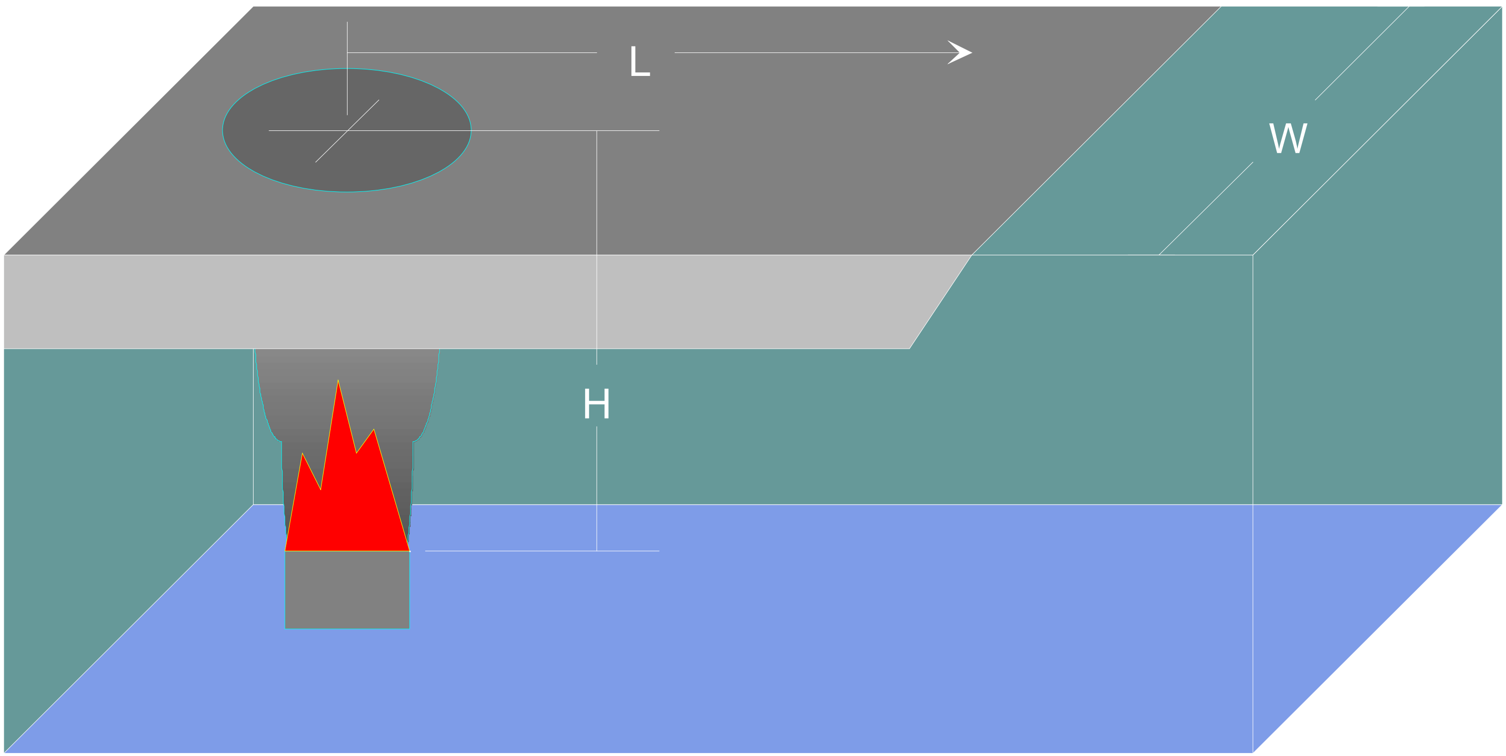
- *SFPE Handbook*
  - Chapter on Ceiling Jet Flows
- "Fire Plumes and Ceiling Jets"
  - C. Beyler
  - Fire Safety Journal
  - Vol. 11, 1986
  - pp. 53-75



Unconfined ceiling jets



Confined ceiling jets



Unconfined ceiling jet

- Temperature correlations
  - Alpert

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

  - Alpert and Ward

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

Unconfined ceiling jet

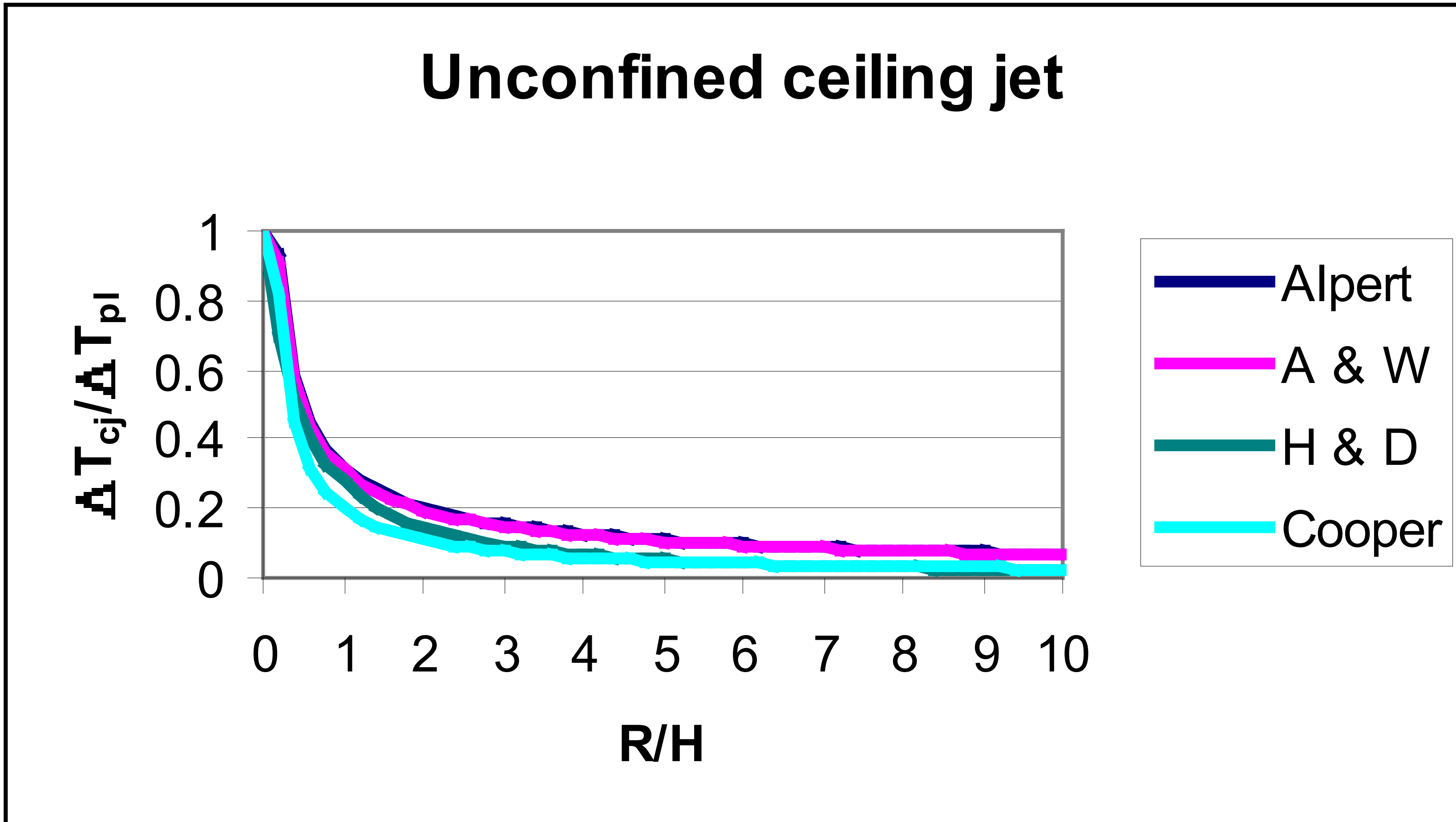
- Temperature correlations
  - Heskestad and Delichatsios

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.11}{\left(0.188 + 0.313R/H\right)^{4/3}} \qquad \Delta T_{pl} = 25\frac{\dot{Q}^{2/3}}{H^{5/3}}$$

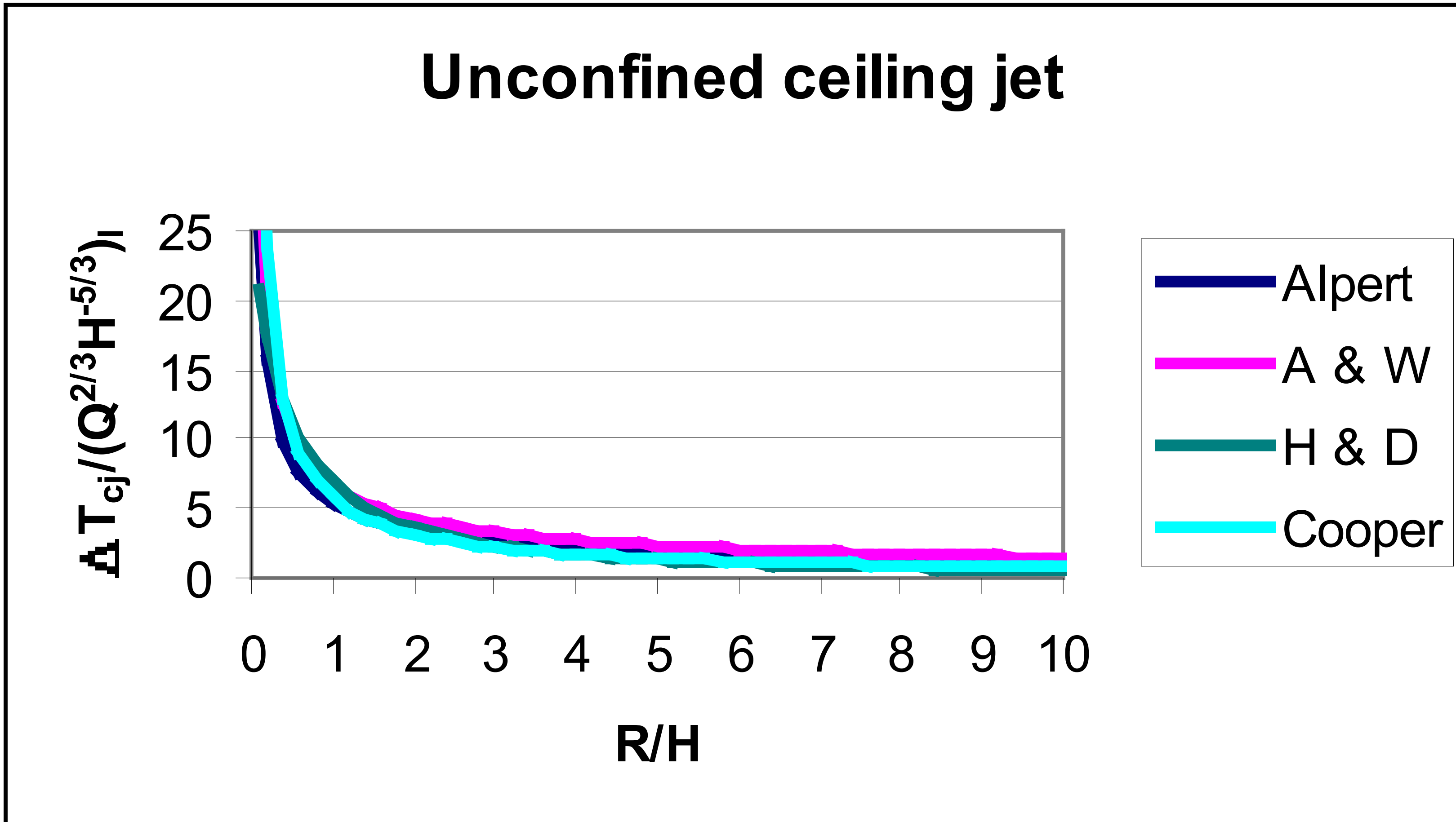
  - Cooper

$$\frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.20}{\left(R/H\right)^{0.88}} \qquad \Delta T_{pl} = 28.1\frac{\dot{Q}^{2/3}}{H^{5/3}}$$

Temperature correlations



Temperature correlations

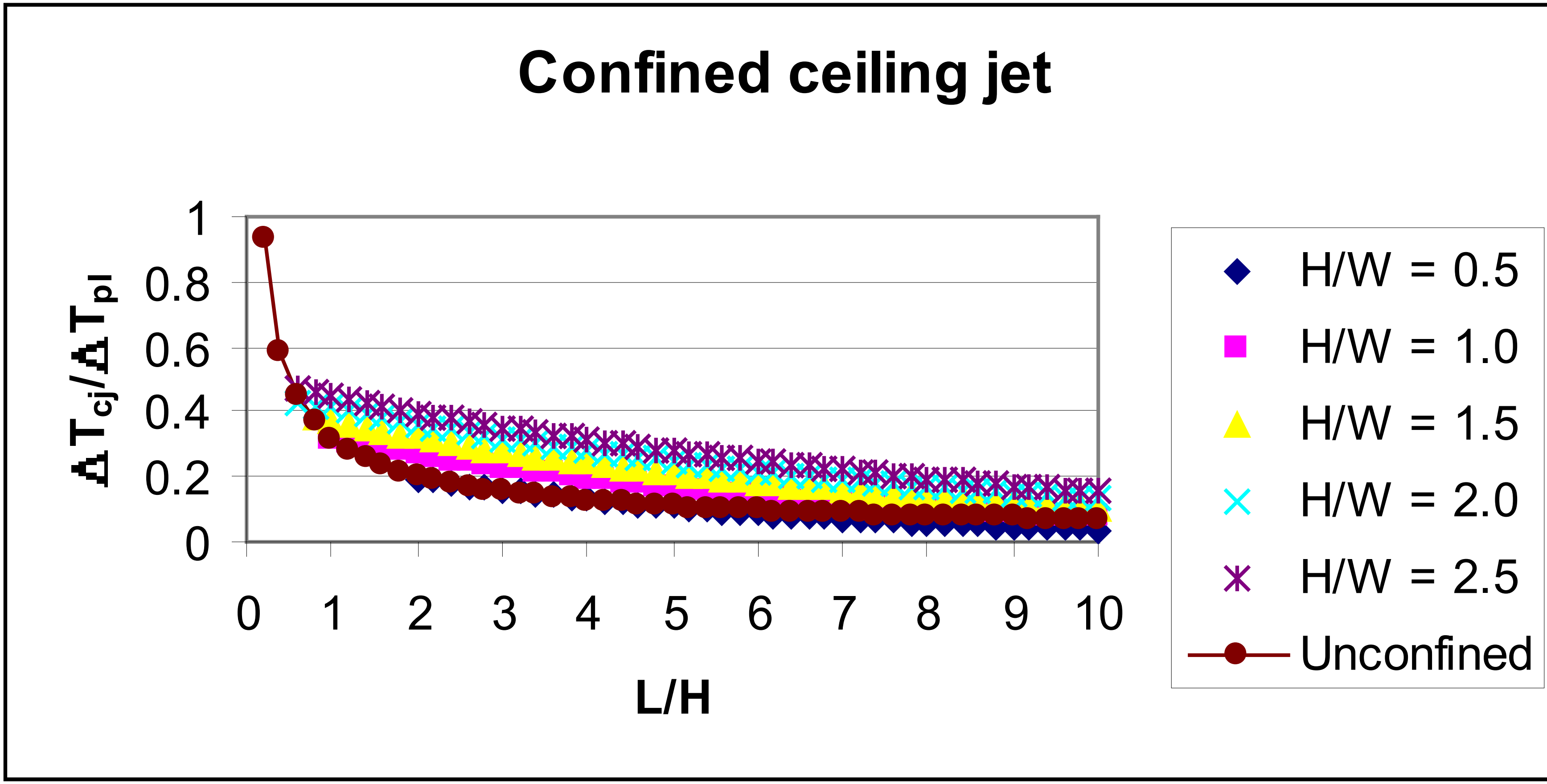


Confined ceiling jet

- 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 correlations
  - Alpert

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

  - Heskestad and Delichatsios

$$\frac{u}{u_o} = \frac{0.18}{(R/H)^{0.63}(0.188 + 0.313R/H)^{2/3}}$$

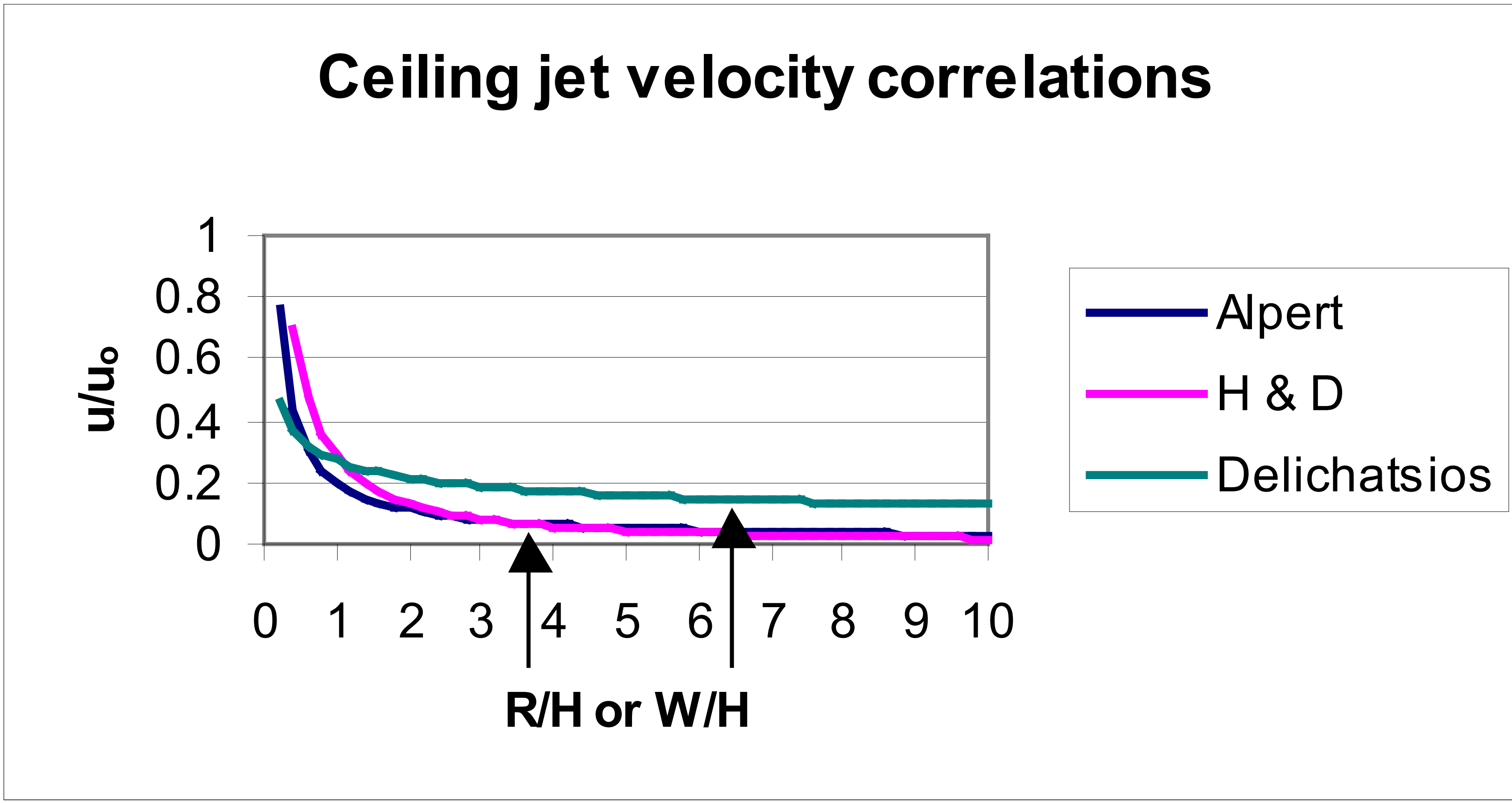
Confined ceiling jet

- 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 FMSNL 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

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

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

  - 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, field model needed

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 field models such as FDS

Heat and smoke detection

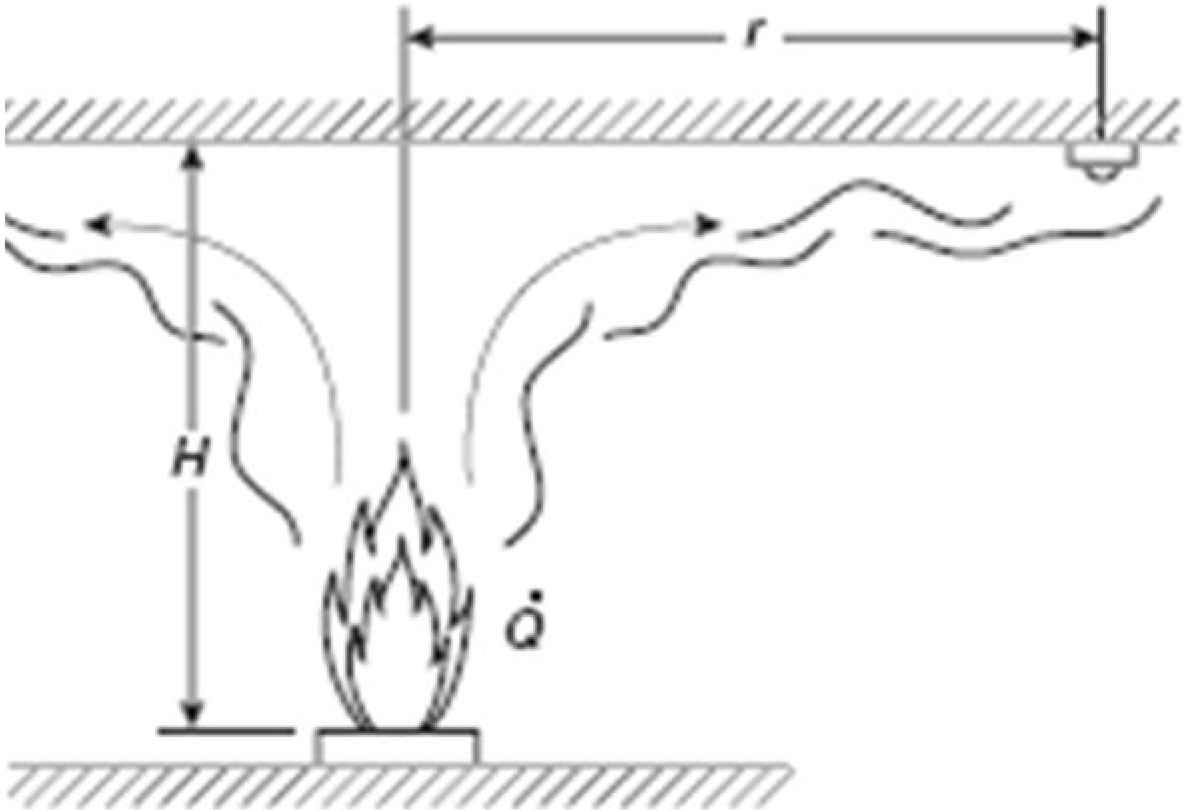
- Understand terminology used to describe the activation of fire detection devices
- Appreciate the role of different variables in estimating fire detector activation and structural damage times
- Calculate the response of fire detectors to fire plume and ceiling jet conditions

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

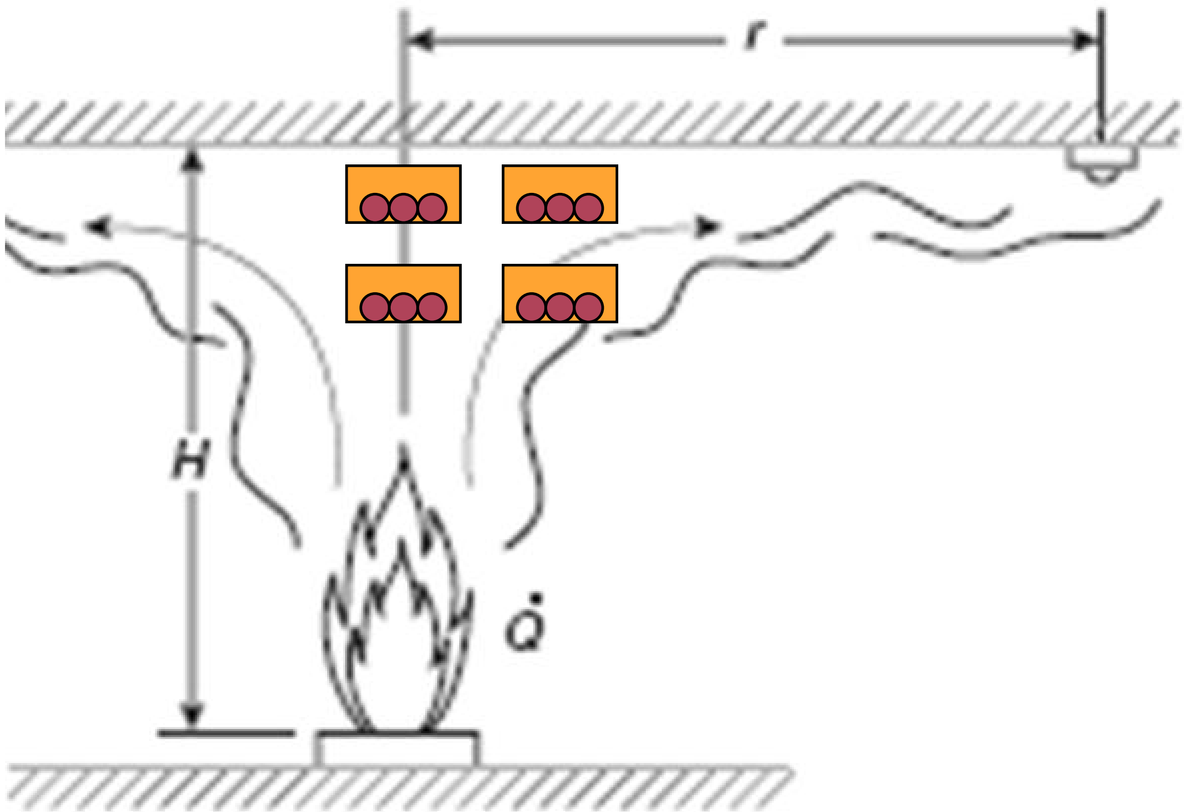
Overview of methods to predict heat / smoke detector activation

- Idealized geometry – smooth flat ceiling



Overview of methods to predict heat / smoke detector activation

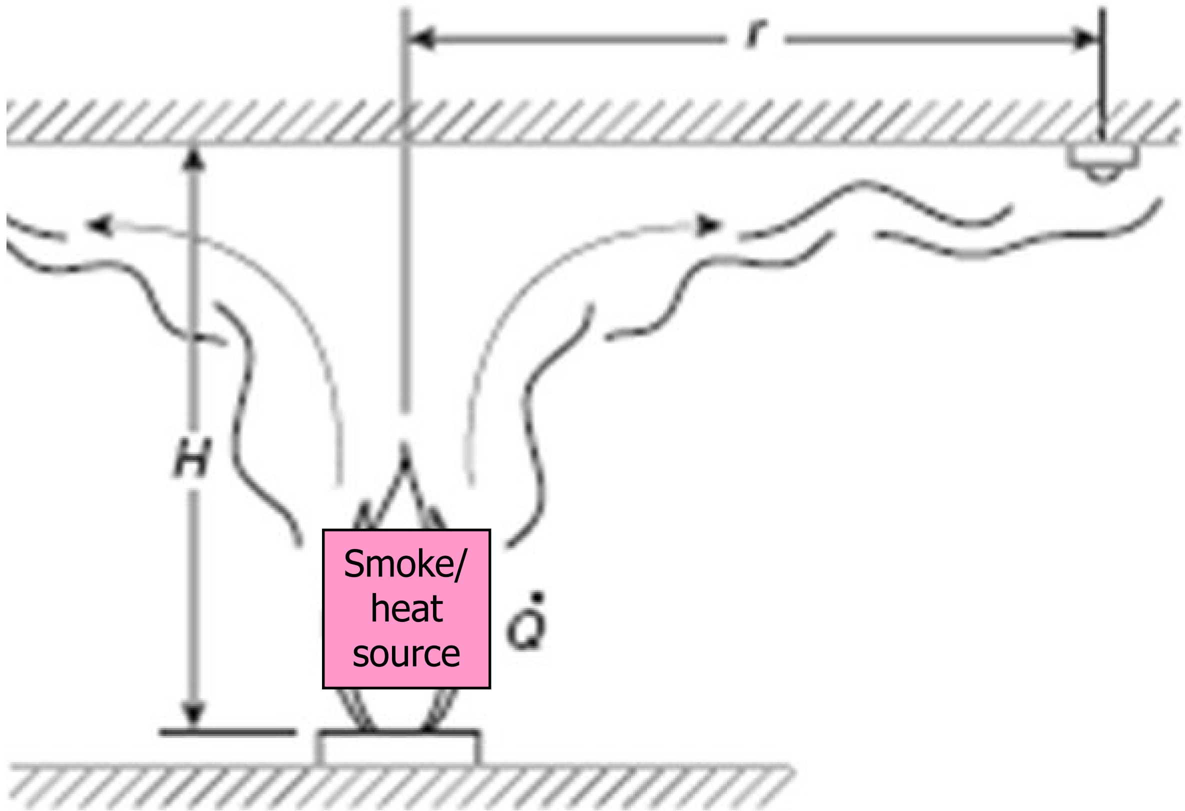
- Realistic geometry – obstructed ceiling



Overview of methods to predict heat / smoke detector activation

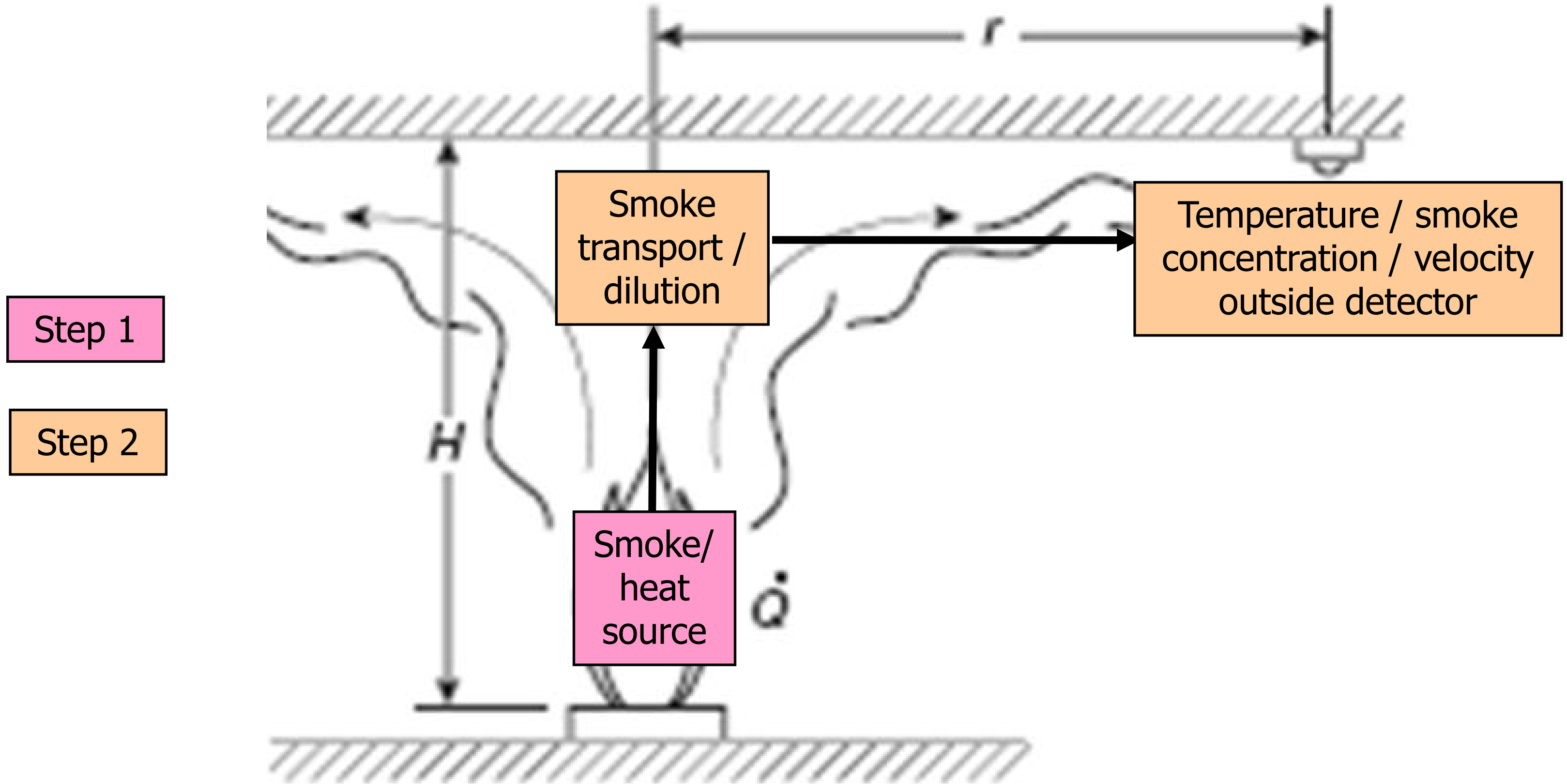
- Step 1. Specify heat/smoke release rates

Step 1



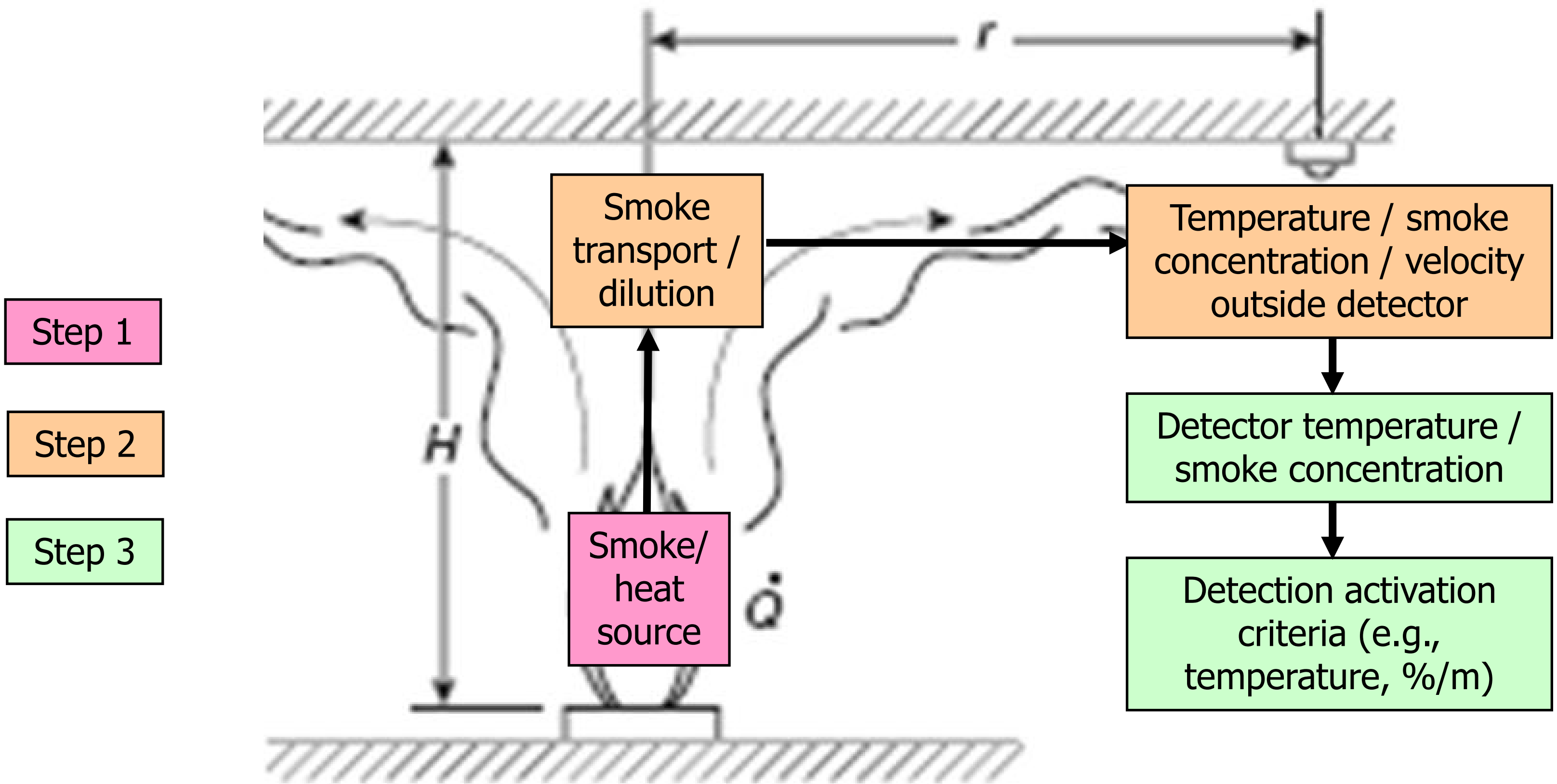
Overview of methods to predict heat / smoke detector activation

- Step 2. Calculate temperature / smoke concentration outside detector



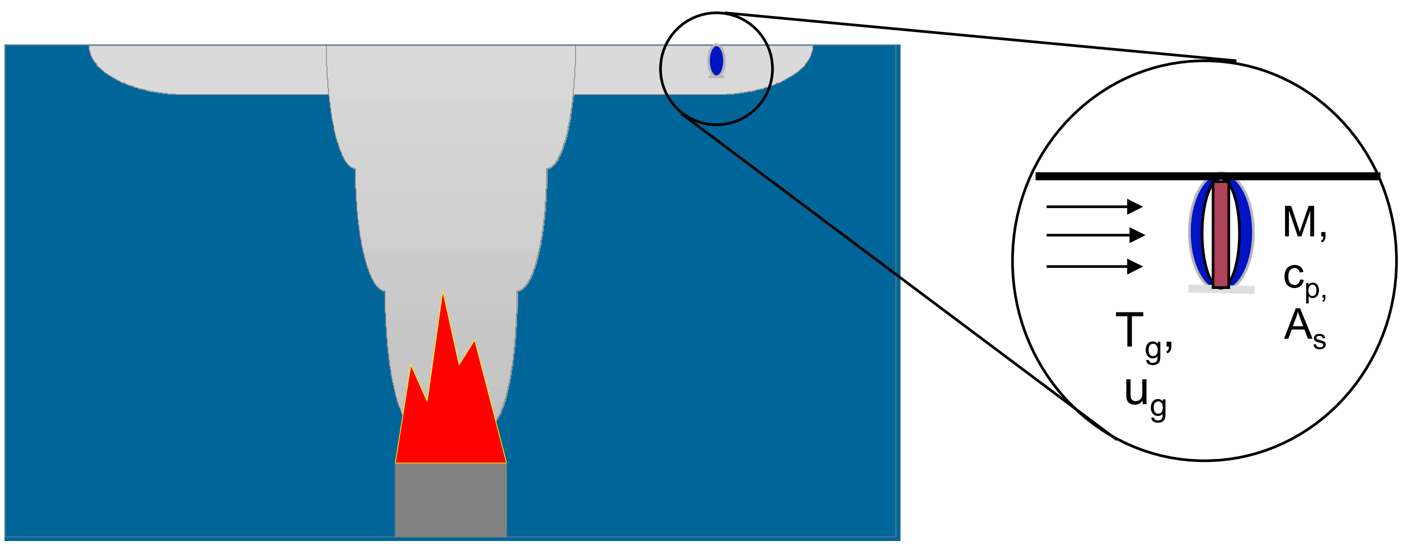
Overview of methods to predict heat / smoke detector activation

- 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 $\dot{q}_{abs} = mc_p \dfrac{dT_d}{dt}$
- 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

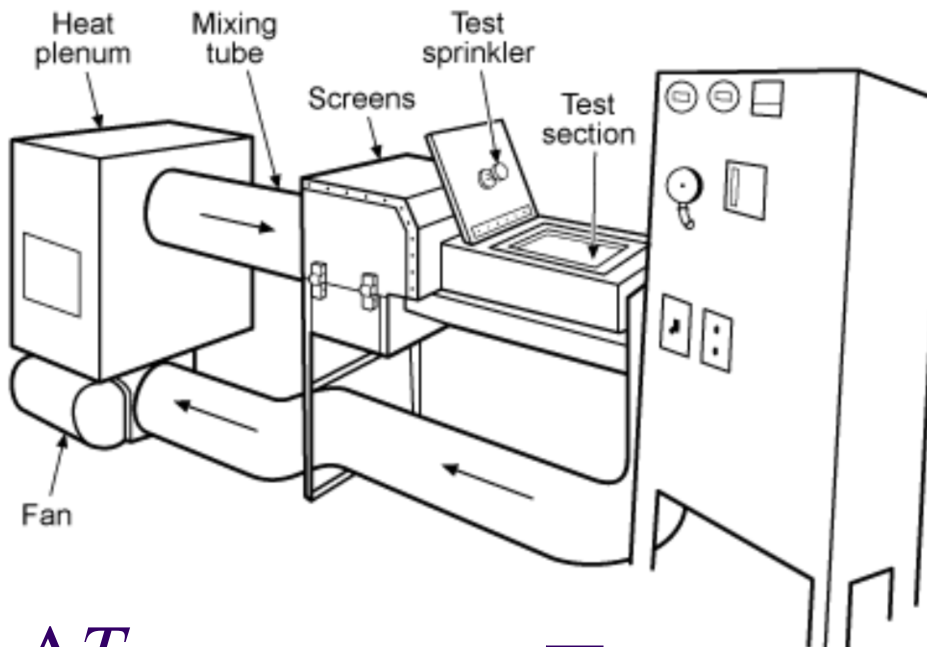
Response Time Index

- For cylinders in cross flow $h_c \sim \sqrt{u_g}$
- Implications $\tau \sim 1 \big/ \sqrt{u_g}$ $\quad \tau \sqrt{u_g} = const$
- 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

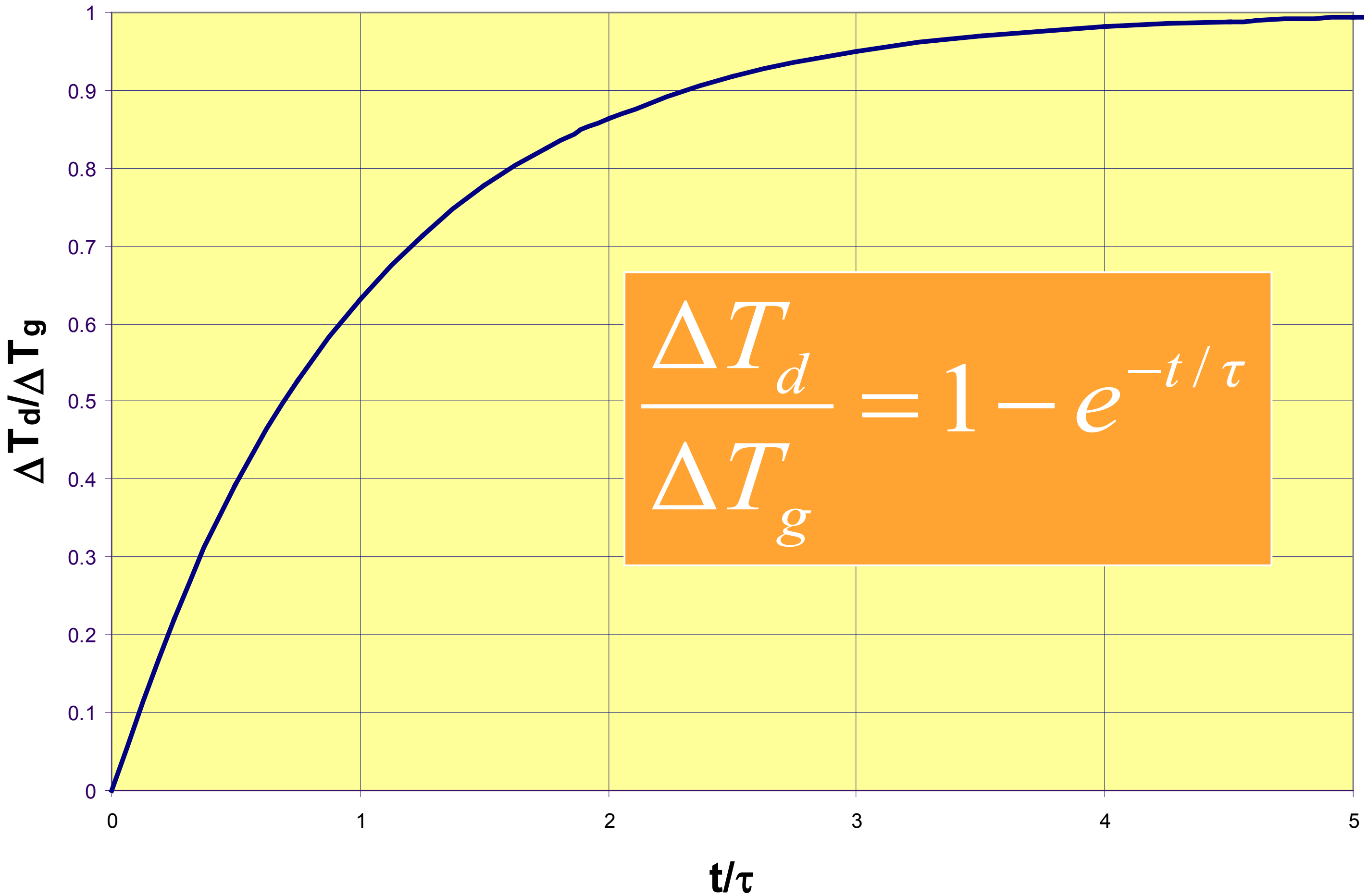


- Analytical solution

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

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

Plunge test



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
$\Delta T_d/\Delta T_g$
t/τ
$\frac{\Delta T_d}{\Delta T_g} = 1 - e^{-t/\tau}$

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 FMSNL 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

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

  - Step 2 – calculate gas temperature / velocity at sprinkler

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

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

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

Conduction effects

- Not significant for spot heat detectors, but may be significant for sprinklers
- Heat balance with losses to sprinkler pipe

$$mc_p \frac{dT_e}{dt} = h_c A\left(T_g - T_e\right) - C'\left(T_e - T_o\right)$$

  - Last term accounts for heat losses
- Conductance factor, C, defined as

$$C \equiv C' \cdot RTI / (mc_p)$$

Conduction effects

- Predictive equations

$$\frac{dT_e}{dt} = \frac{\sqrt{u_g}}{RTI}\left(T_g - T_e\right) - \frac{C}{RTI}\left(T_e - T_o\right)$$

$$\frac{d\Delta T_e}{dt} = \frac{\sqrt{u_g}}{RTI}\left(\Delta T_g - \left(1 + \frac{C}{\sqrt{u_g}}\right)\Delta T_e\right)$$

  - Values of C typically range from ~0 to 2 $(m/s)^{1/2}$
  - Note that basic predictive equation obtained when C = 0

Transport lag time

- Basic DETACT model is quasi-steady
  - Changes in conditions transmit instantly throughout the domain
- Can consider plume / ceiling jet transport lag times when they are significant

Smoke detector activation

- 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} ~ 15ºC (or less)
  - Questions regarding validity
    - Relies on optical density analogy
    - Smoke detectors don't always respond to optical density

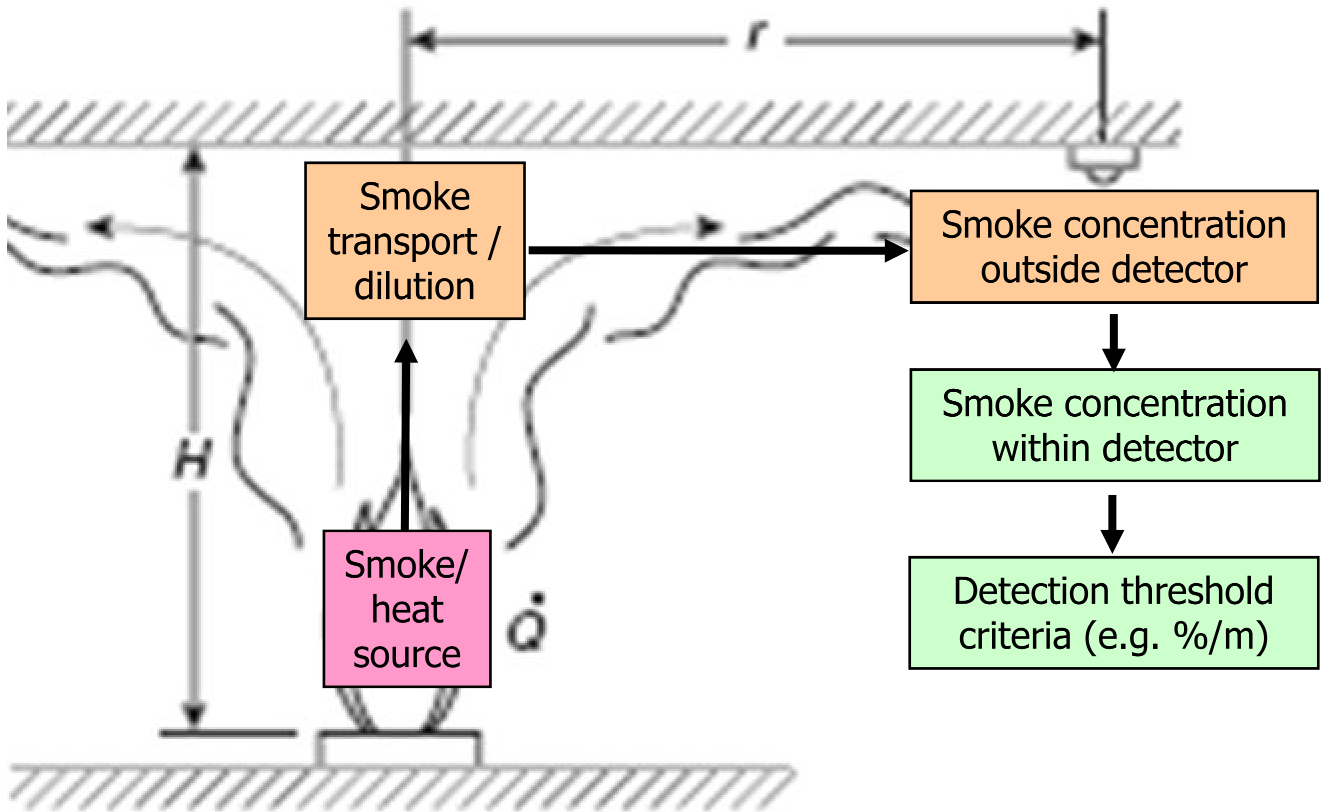
Smoke detector activation

- Overview

Step 1

Steo 2

Step 3



Smoke detector activation

- Smoke concentration in detector chamber, Y_c
  - Cleary's four-parameter model

$$\frac{dY_c}{dt} = \frac{Y_s(t - \delta t_e) - Y_c(t)}{\delta t_c} \qquad \delta t_e = \alpha_e u^{\beta_e}; \delta t_c = \alpha_c u^{\beta_c}$$

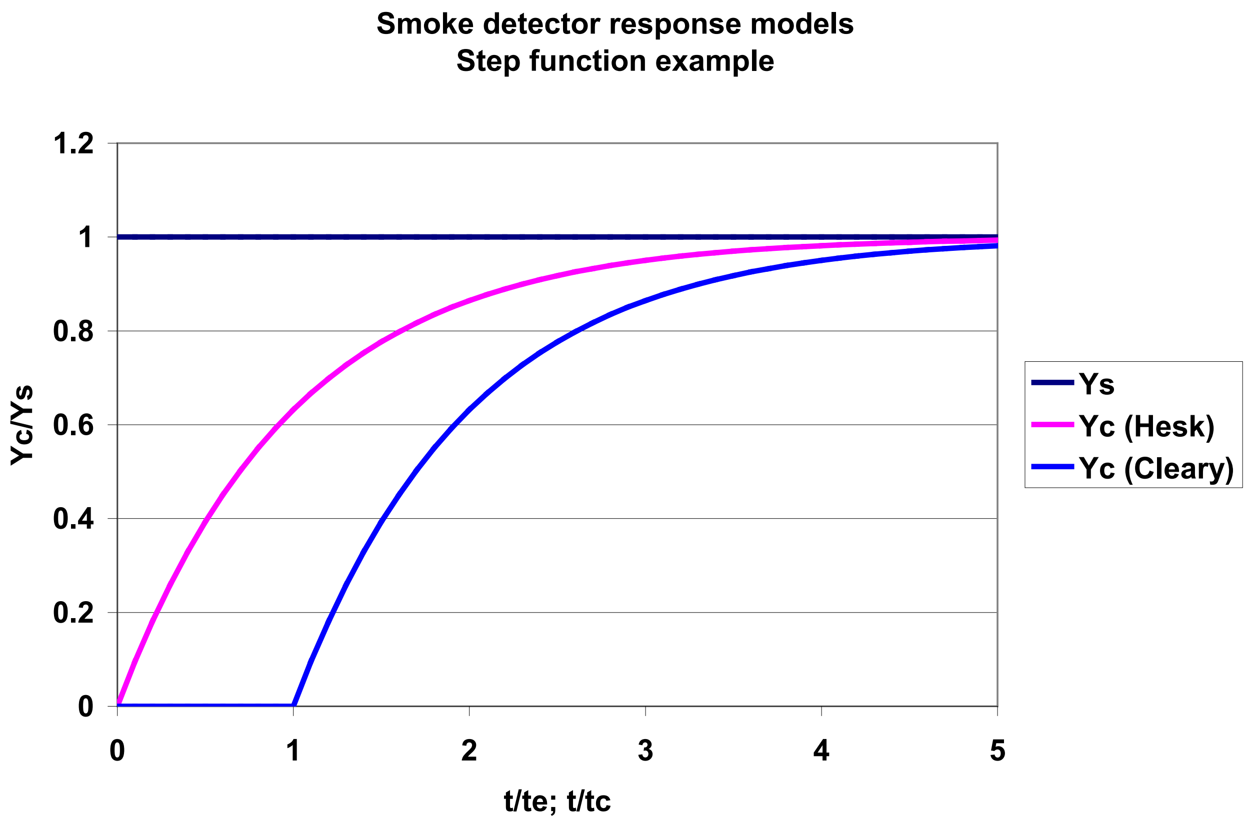
  - Heskestad's one-parameter model

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

    - u is the local gas velocity outside the detector
    - L is the characteristic entry length of the detector

Smoke detector activation

- Smoke concentration in detector chamber, Y_c



Smoke detector activation

- Relationship between smoke concentration and smoke obscuration
  - Smoke concentration expressed as soot mass fraction, Y_s
  - Extinction coefficient, k, expressed in terms of Y_s

$$k = k_m \rho Y_s \qquad k_m \cong 8700\, m^2 / kg$$

  - Transmission (%/m) expressed in terms of k

$$trans(\% / m) = 100(I / I_o) = 100 \exp(-k(1m))$$

  - Obscuration (%/m) expressed in terms of transmission

$$obs(\% / m) = 100 - trans(\% / m) = 100(1 - \exp(-k(1m)))$$

Structural steel damage

- Same concept as DETACT for steel

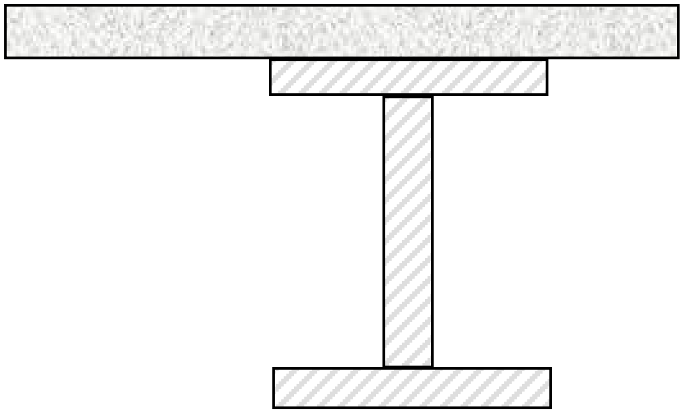
$$\frac{dT_s}{dt} = \frac{\dot{q}_t A_s}{\rho V c_p} = \frac{\dot{q}_t}{\rho c_p (V / A_s)} = \frac{\dot{q}_t}{c_p (W / D)}$$

- Steel properties

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

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

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



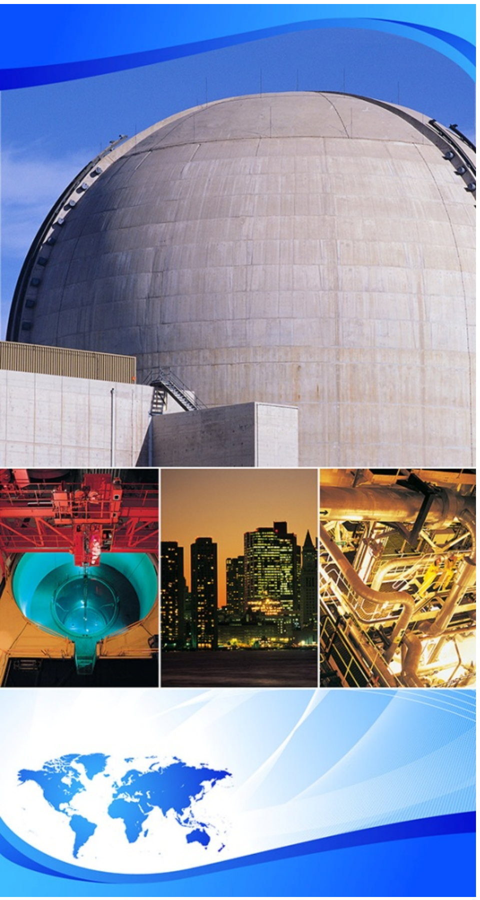
Structural damage

- Steel critical temperature, $T_c \approx 550°C$
- Evaluation of heat fluxes
  - Flame radiant heat flux
    - Applies in flame only
  - Plume convective heat flux
    - Applies in flame and plume
  - Radiant flux outside flame
    - Point source estimate
  - Based on Alpert & Ward FSJ article

$$\dot{q}_r = 160\, kW/m^2$$

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

$$\dot{q}_r = \frac{\chi_r \dot{Q}}{4\pi R^2}$$



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5

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

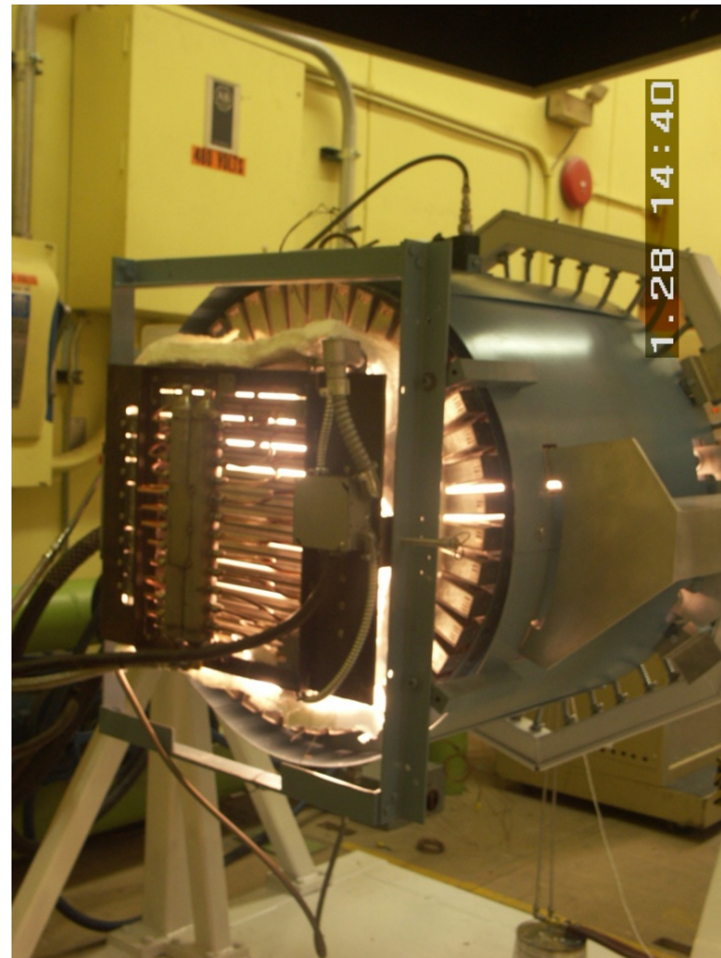
Kevin McGrattan
National Institute of Standards and Technology

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

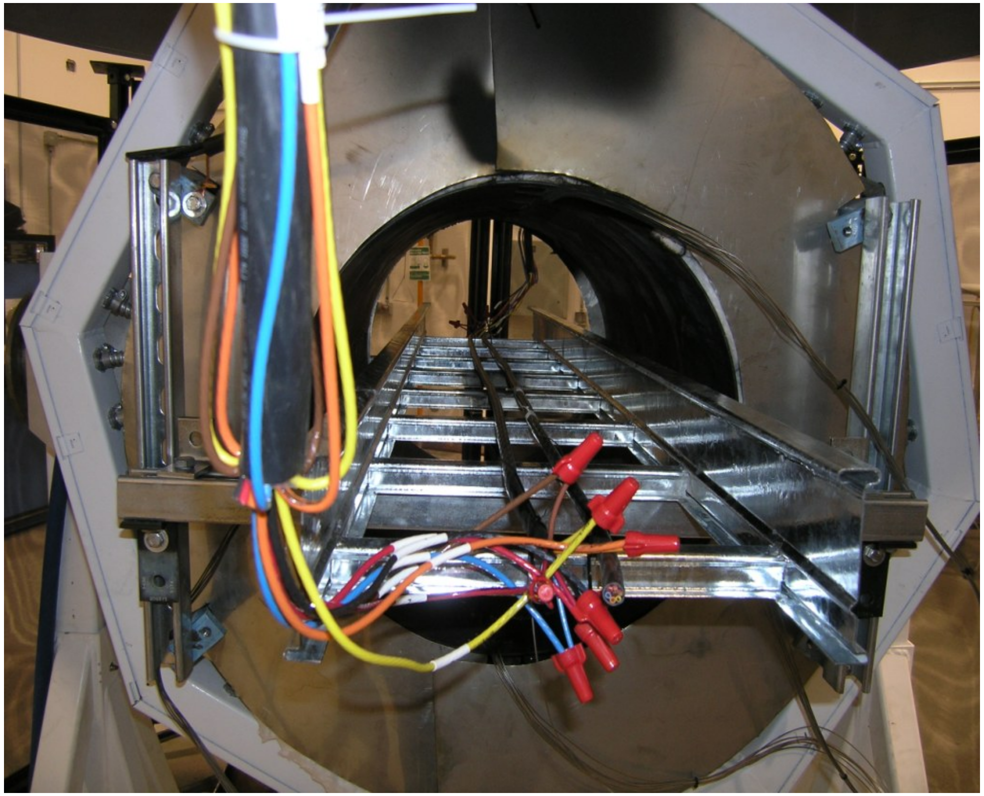
A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

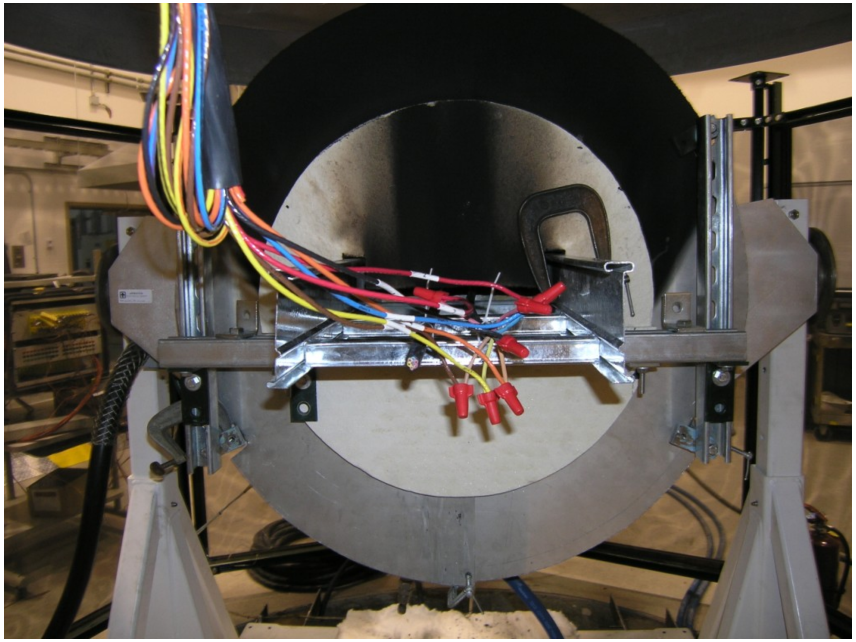
CAROLFIRE
(Cable Response to Live Fire)

- ***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

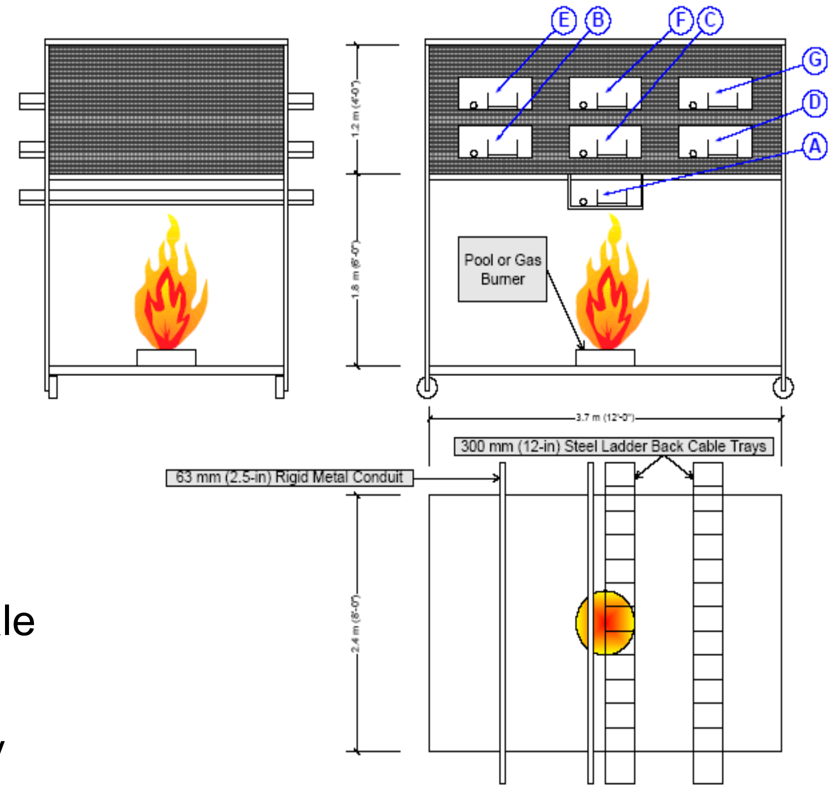




Intermediate-Scale Tests

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

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

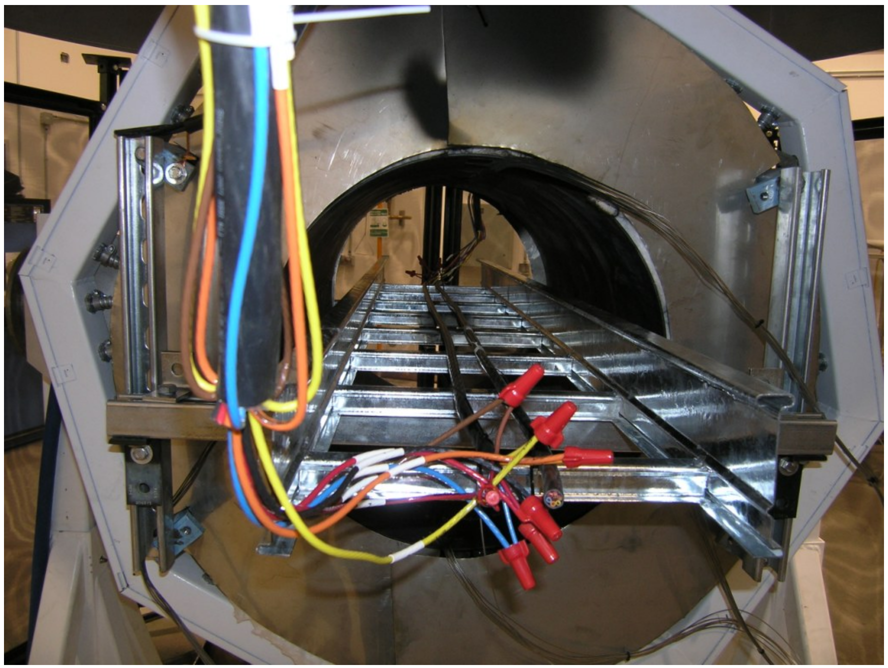
$$-k_s \frac{\partial T_s}{\partial r} = \dot{q}_c'' + \dot{q}_r''$$

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.

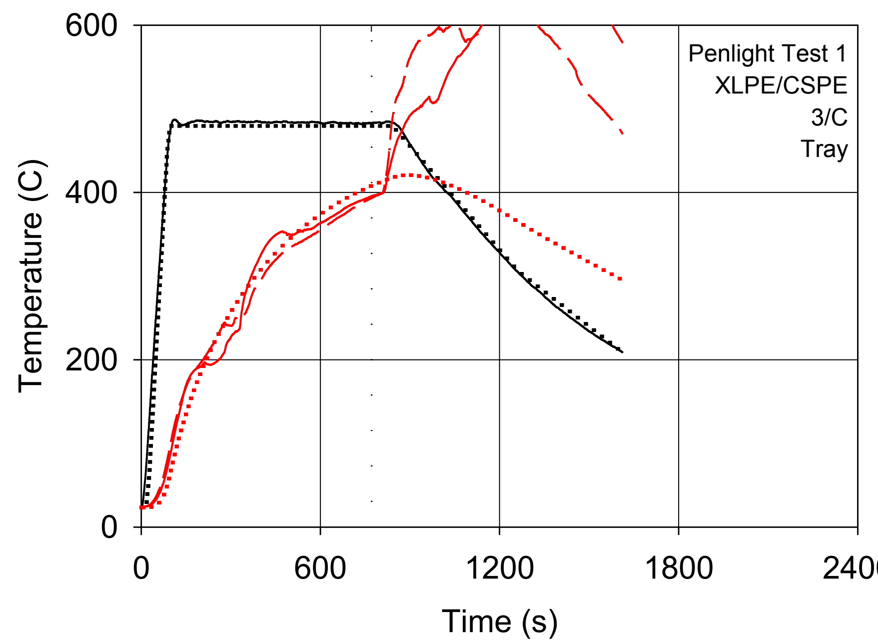
Source: Andersson and Van Hees, SP Fire, Sweden.

Single Cable

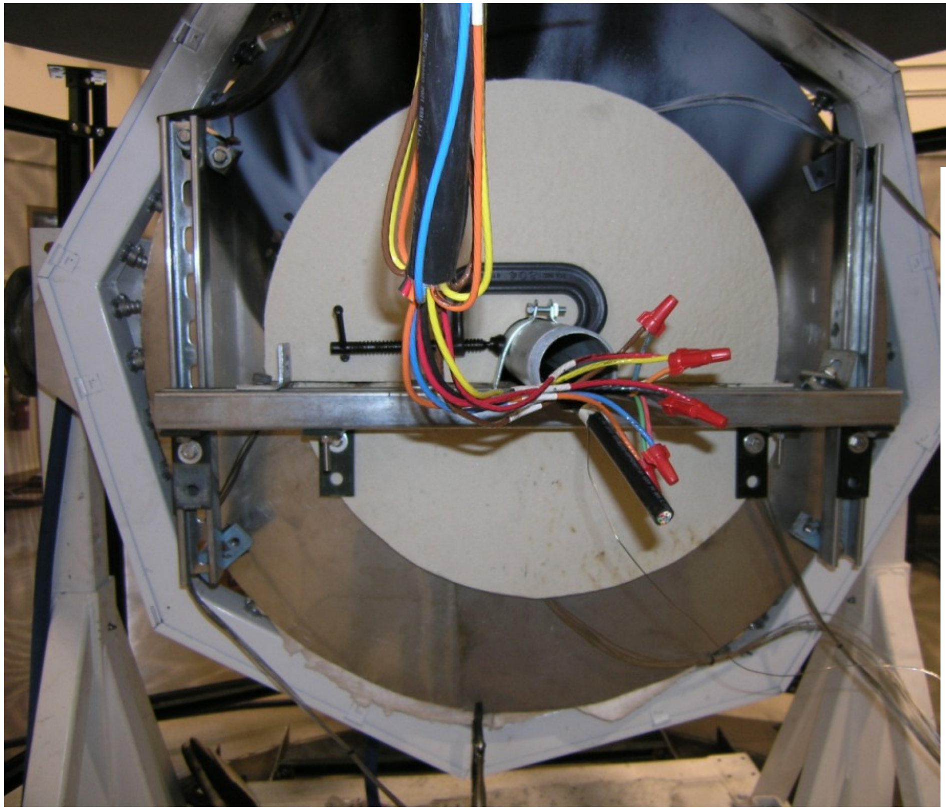


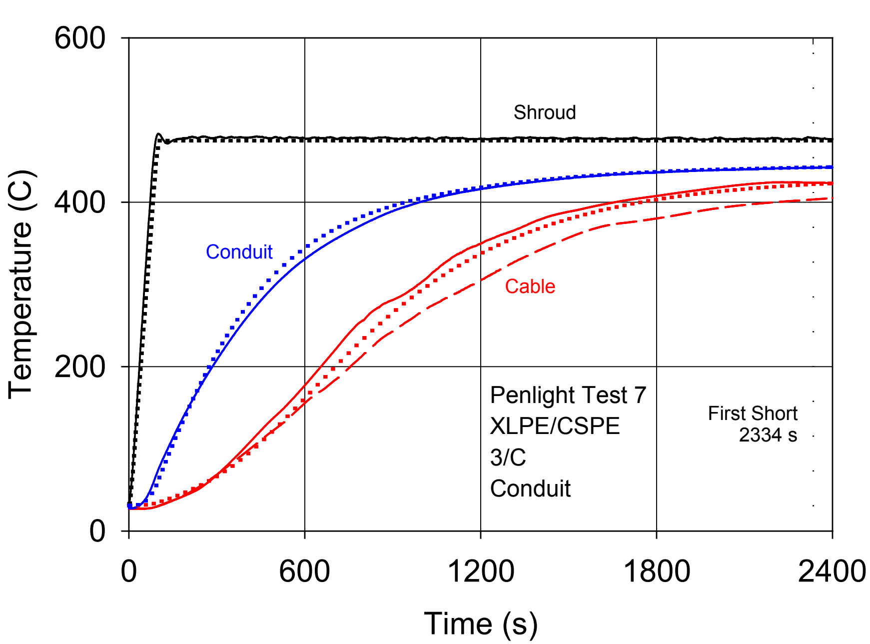
Courtesy Steve Nowlen and Frank Wyant

Sandia National Laboratory



Cable in a Conduit

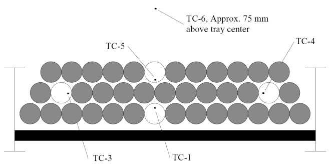


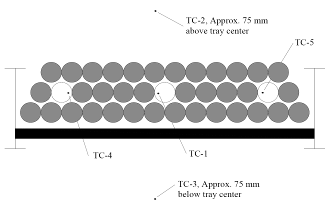


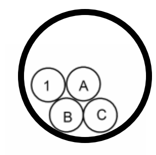
Courtesy Steve Nowlen and Frank Wyant

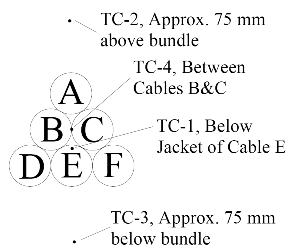
Sandia National Laboratory

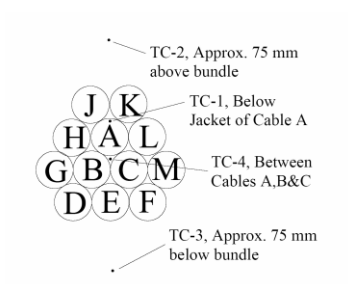
Intermediate-Scale Experiments

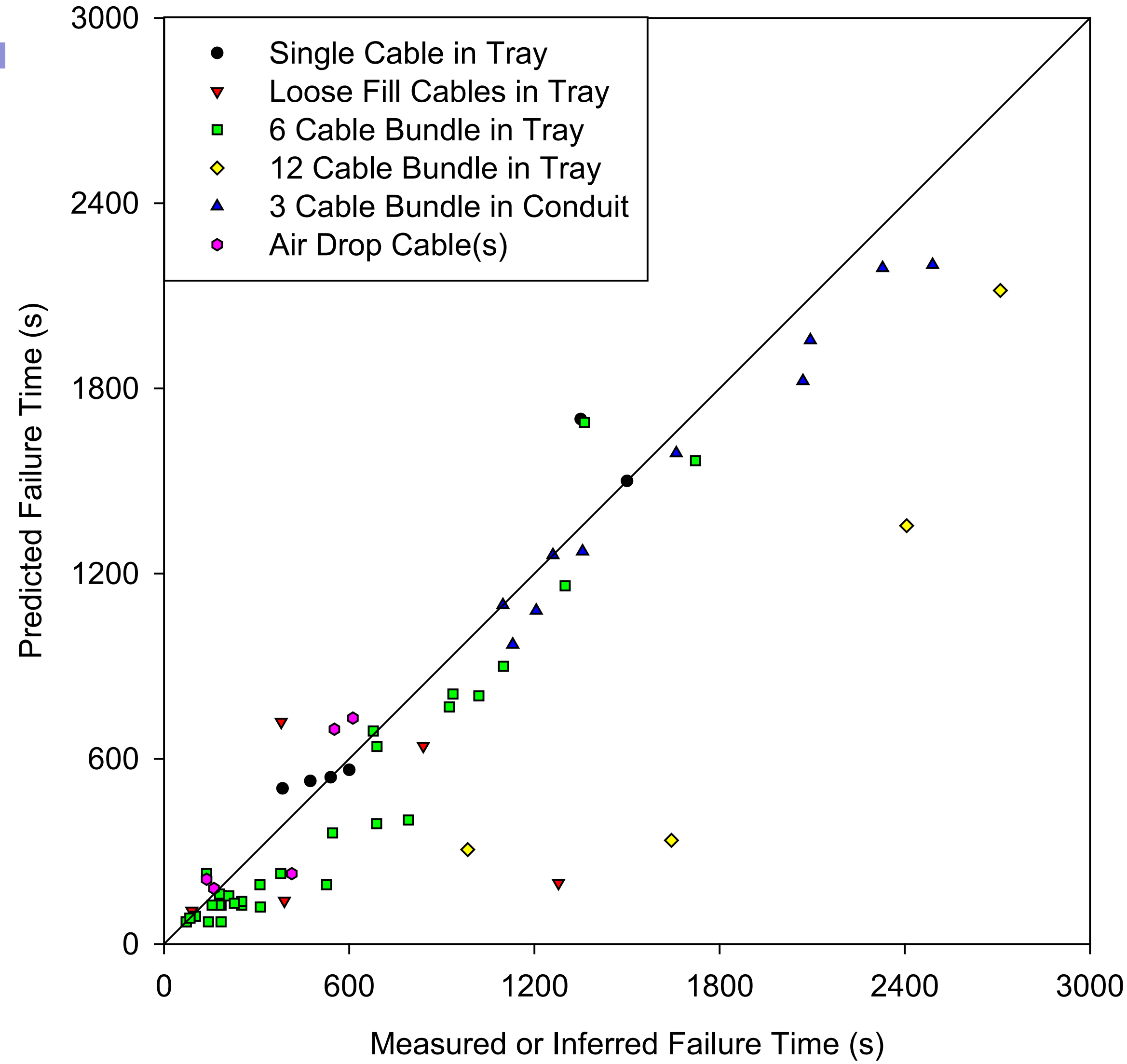






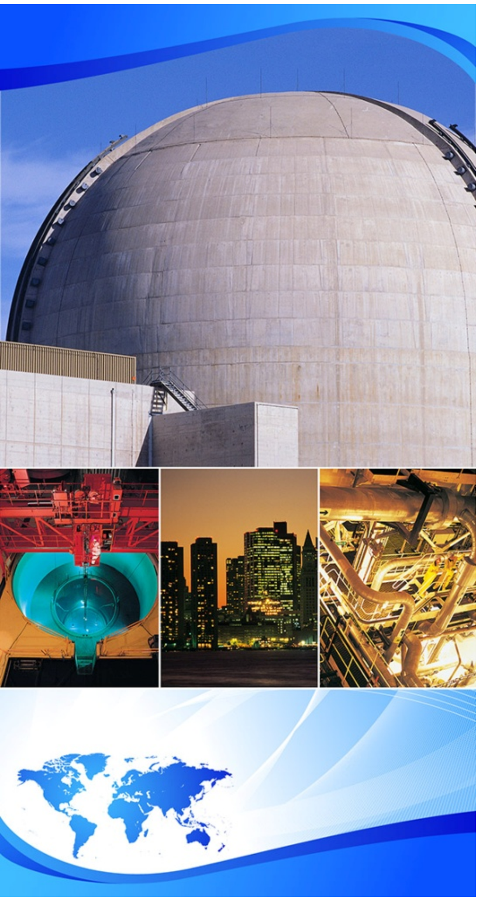






Summary

- 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



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5
Advanced Fire Modeling
Day 2 - PM Session
Fire Modeling Tools

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

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

Enclosure fire topics

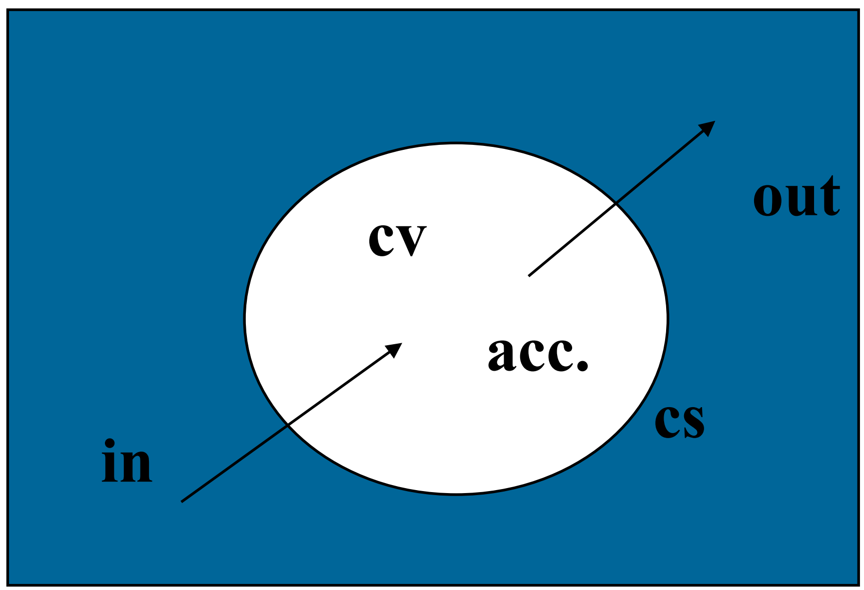
- Conservation equations and the hot gas layer
- Enclosure smoke filling
- Pressure profiles and vent flows
- Mechanical ventilation effects
- Hot gas layer temperature correlations/calculations
- Smoke concentrations and visibility
- Overview of FDS

References – enclosure fires

- SFPE Handbook
  - Chapter on “Compartment Fire Modeling”
  - Chapter on “Estimating Temperatures ...”
  - Chapter on “Enclosure Smoke Filling ...”
- Enclosure Fire Dynamics book
  - Chapter 8 - Conservation equations …
  - Chapter 6 - Gas temperatures ...

Conservation equations

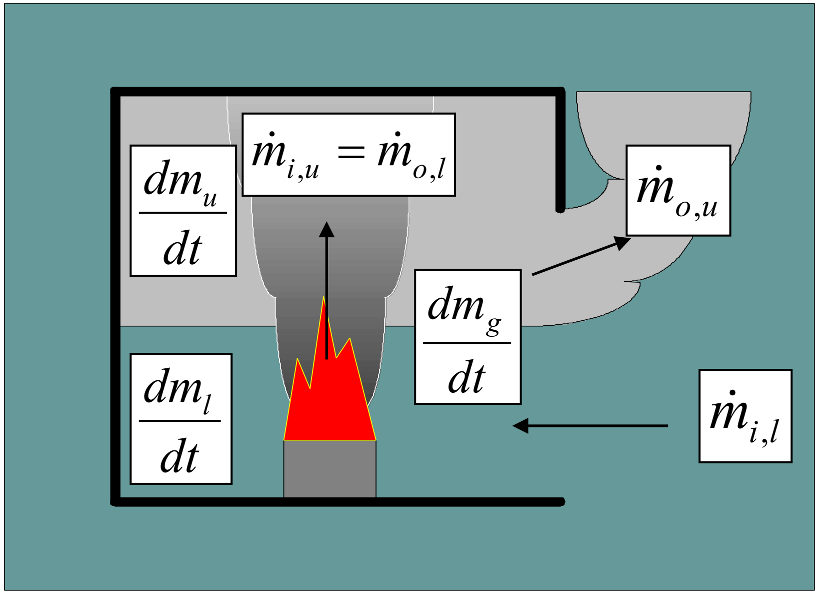
- Mass conservation
- Species conservation
- Energy conservation
- Momentum conservation



Mass conservation

{mass accumulated} = {mass in} - {mass out}

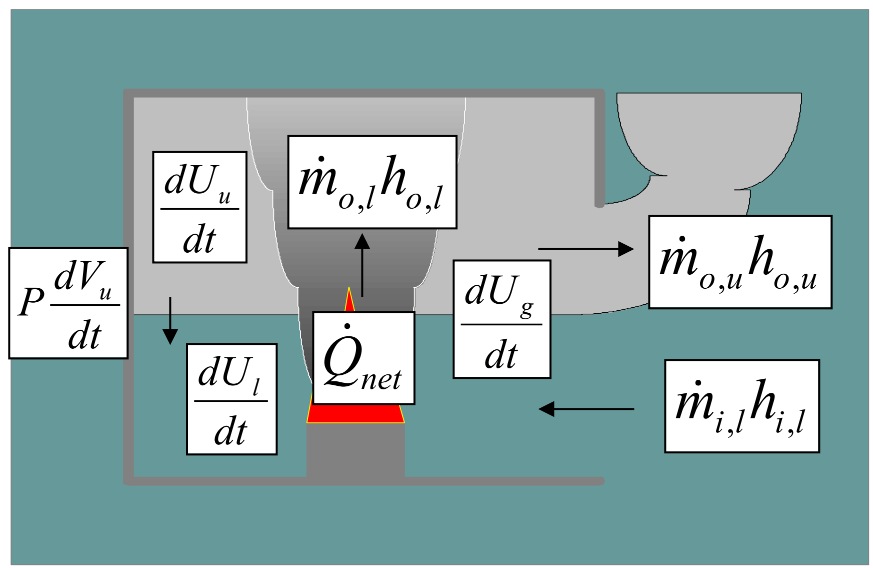
$$\frac{dm}{dt} = \frac{d(\rho V)}{dt} = \dot{m}_i - \dot{m}_o$$



Energy conservation

{energy accumulated} = {energy in} - {energy out} + {energy generated}

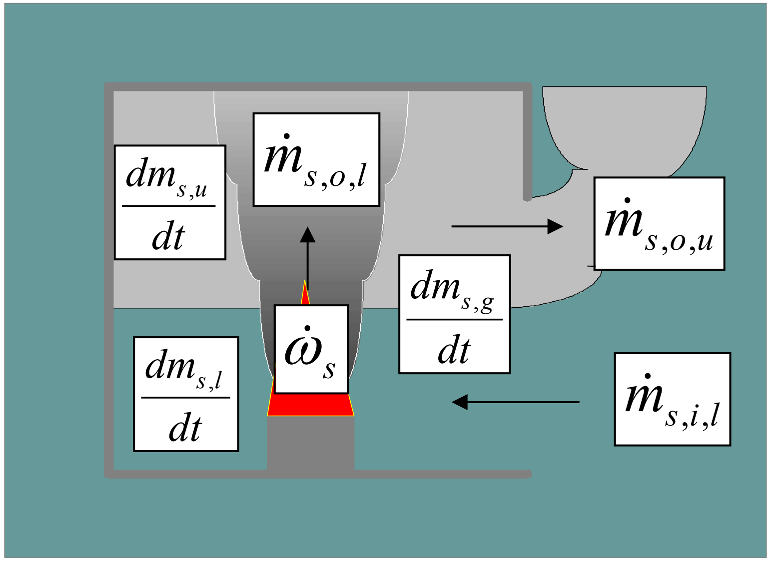
$$\frac{dU}{dt} = \frac{d(\rho u V)}{dt} = \dot{m}_i h_i - \dot{m}_o h_o - P\frac{dV}{dt} + \dot{Q}_{net}$$



Species conservation

{species accumulated} = {species in} - {species out} + {species generated}

$$\frac{dm_s}{dt} = \frac{d(\rho Y_s V)}{dt} = \dot{m}_{s,i} - \dot{m}_{s,o} + \dot{\omega}_s$$

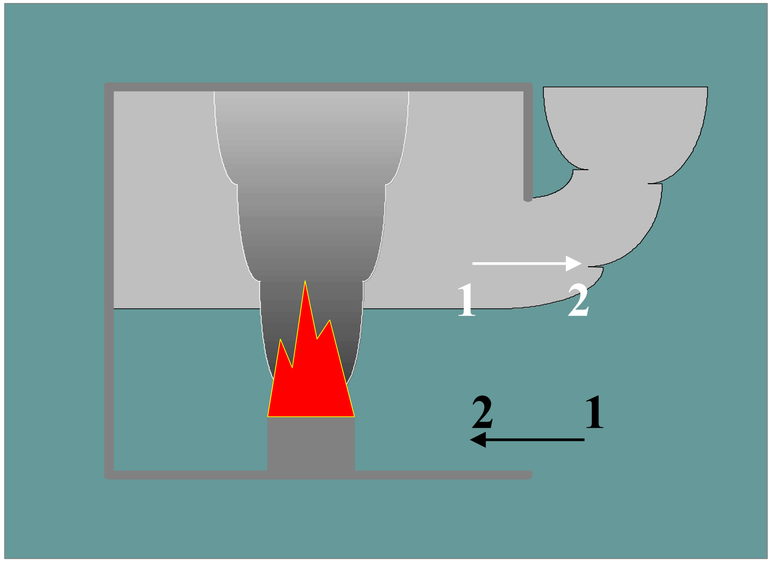


Momentum conservation

- Bernoulli's equation

$$\frac{P_1}{\rho_1} + \frac{V_1^{\,2}}{2} + z_1 g = \frac{P_2}{\rho_2} + \frac{V_2^{\,2}}{2} + z_2 g$$

  – Applied at vents only in zone models



Summary – control volumes

- Enclosure fire models are based on application of conservation equations to control volumes
  - Zone models - typically two control volumes
    - Upper (hot gas / smoke) layer / lower layer
    - Momentum considered only at vents
  - Field models – thousands or millions of cells
    - Conservation equations applied to each cell
      - Computationally intensive
    - Momentum considered for each cell

Thermodynamic properties

- Internal energy $$\frac{dU}{dt} = \dot{Q}_{net} - \dot{W}$$
- Enthalpy (specific) $$h = u + P / \rho$$
- Specific heats $$c_v = \frac{du}{dT} \qquad c_p = \frac{dh}{dT}$$
- Ideal gas law $$P = \rho RT \qquad R = c_p - c_v$$

Temperature effects

- Leaky compartment analysis
  - Mass balance (assume no mass inflow)

$$\dot{m}_e = -\frac{d(\rho V)}{dt} = -V\frac{d\rho}{dt}$$

  - Quasi-steady energy balance

$$\dot{Q}_{net} = \dot{m}_e h_e = \frac{-d(\rho V)}{dt} c_p T = \frac{-d\rho}{dt} c_p T V$$

Temperature effects

- Leaky compartment analysis
  - Ideal gas (constant pressure)

$$\frac{d\rho}{dt} = -\frac{\rho_a T_a}{T^2}\frac{dT}{dt}$$

  - Substitute and integrate

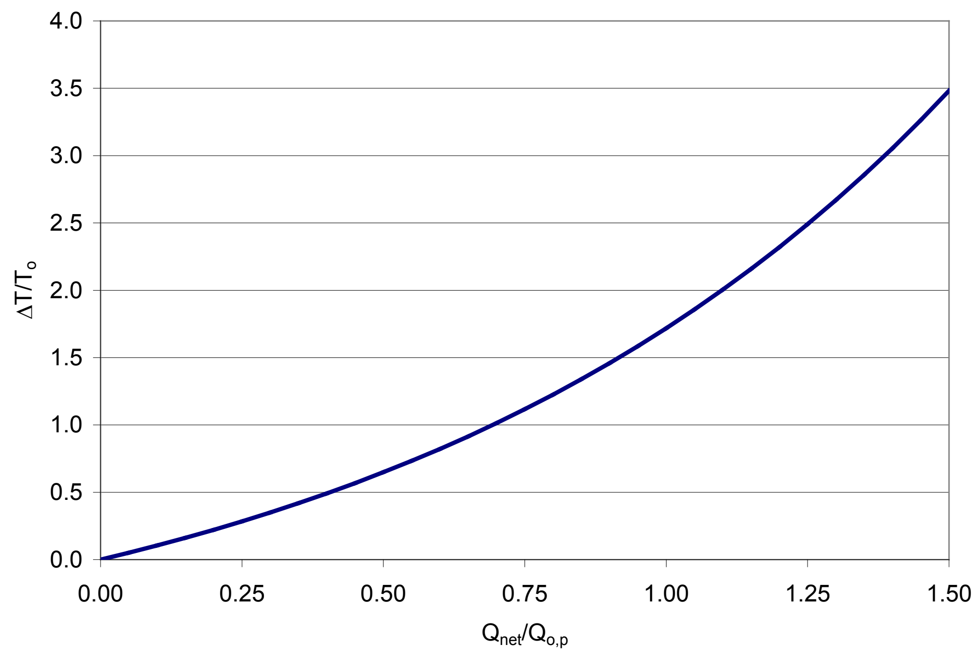
$$\int_{T_a}^{T}\frac{dT}{T} = \int_{o}^{t}\frac{\dot{Q}_n dt}{(\rho_a c_p T_a V)} = \frac{1}{Q_{po}}\int_{0}^{t}\dot{Q}_n dt$$

Temperature effects

- Leaky compartment analysis
  - Solution for average temperature rise

$$\frac{T}{T_a} = exp\left(\frac{Q_n}{Q_{po}}\right)$$

$$\frac{\Delta T}{T_a} = exp\left(\frac{Q_n}{Q_{po}}\right) - 1$$



Temperature effects

- Leaky compartment analysis
  - Example - average temperature rise
    - A fire with a constant HRR of 500 kW burns for 10 minutes in an enclosure with a heat loss fraction of 0.7 and dimensions of 18.3 m x 12.2 m x 6.1 m. What is average temperature rise after 10 minutes?

$$Q_n = (500\,kJ/s)(600\,s)(1-0.7) = 90{,}000\,kJ$$

$$Q_{po} = (353\,kJ/m^3)(60\,m^3) = 480{,}746\,kJ$$

$$\frac{\Delta T}{T_a} = \exp\left(\frac{Q_n}{Q_{po}}\right) - 1 = \exp\left(\frac{90{,}000}{480{,}746}\right) - 1 = 0.21$$

$$\Delta T = 0.21 T_a = 0.21(293K) = 60K$$

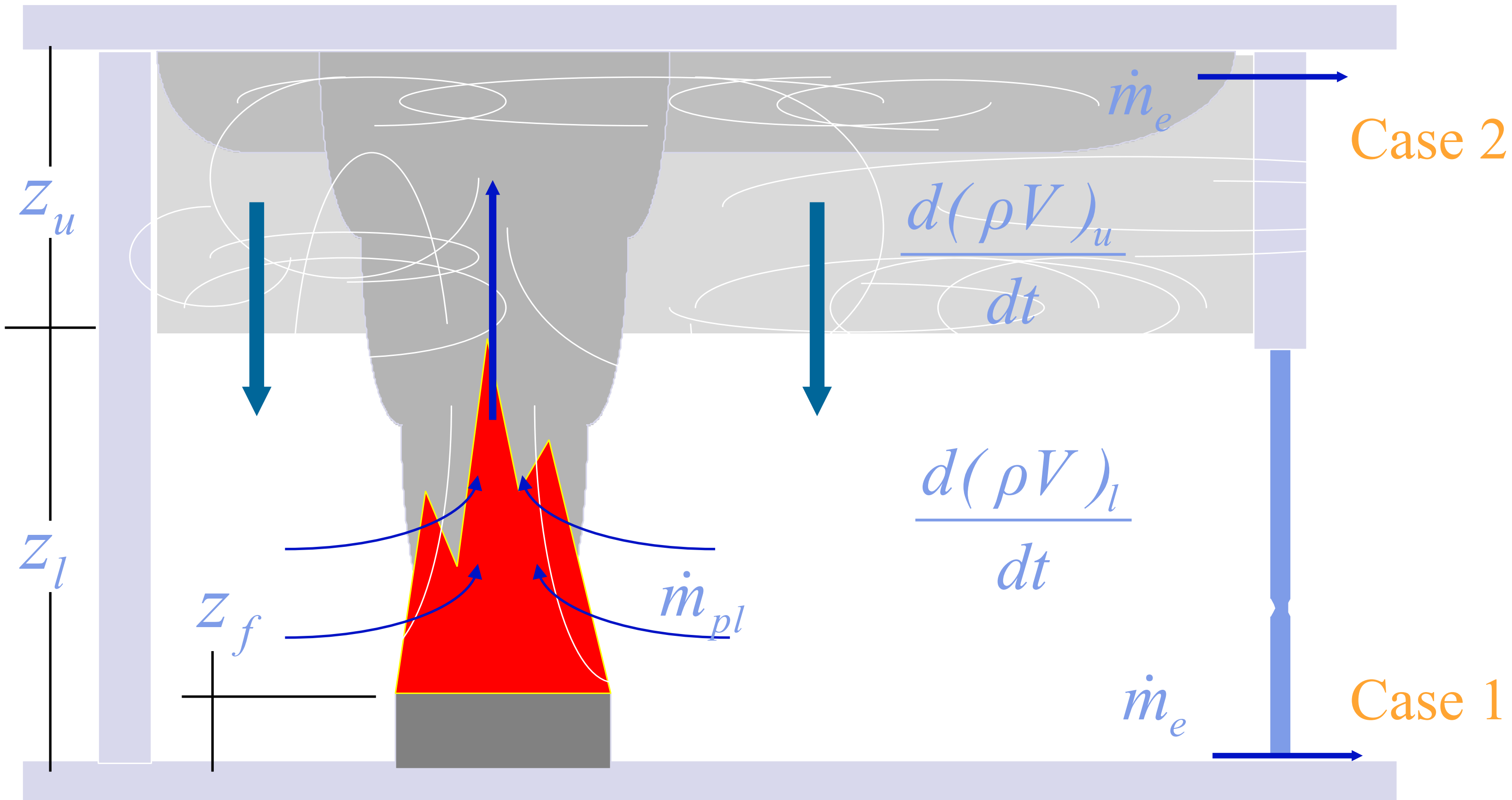
Oxygen limitations

- Caution must be exercised in calculating temperatures with the previous equation because oxygen depletion will eventually cause the fire to diminish in a closed room

- "Puffing" fires can occur in closed rooms because as the fire diminishes due to oxygen depletion, fresh air will be drawn into the room, which will allow the fire to reinvigorate

- The details of oxygen depletion are not presented here, but analysts should always be aware of the potential effects of oxygen depletion and limited ventilation

Enclosure smoke filling



Enclosure smoke filling
Case 1. Small leak at floor

- Mass balance on lower layer

$$\frac{d(\rho V)_l}{dt} = \rho_l \frac{dV_l}{dt} = -\left(\dot{m}_{pl} + \dot{m}_e\right)$$

- Volume balance on lower layer

$$\frac{dV_l}{dt} = \frac{-(\dot{m}_p + \dot{m}_e)}{\rho_l} = -\left(\dot{V}_{pl} + \dot{V}_{\exp}\right)$$

- Volume balance on upper layer

$$\frac{dV_u}{dt} = -\frac{dV_l}{dt} = \left(\dot{V}_{pl} + \dot{V}_{\exp}\right)$$

Enclosure smoke filling
Case 1. Small leak at floor

- Volumetric plume flow rate (Zukoski)

$$\dot{V}_{pl} = \frac{\dot{m}_{pl}}{\rho_l} = 0.21\left(\frac{g}{\rho_l c_p T_l}\right)^{1/3} \dot{Q}^{1/3} z^{5/3} = k_v \dot{Q}^{1/3} (z_l - z_f)^{5/3}$$

- Volumetric expansion rate

$$\dot{V}_{\exp} = \left(\frac{\dot{Q}_{net}}{\rho_l c_p T_l}\right) = \left(\frac{\dot{Q}_f (1-\chi_l)}{353(kJ/m^3)}\right)$$

- Upper layer descent rate (for flat ceiling)

$$\frac{dz_u}{dt} = \frac{1}{A_r}\frac{dV_u}{dt} = \frac{\left(\dot{V}_{pl} + \dot{V}_{\exp}\right)}{A_r}$$

Enclosure smoke filling
Case 2. Small leak at ceiling

- Mass balance on lower layer

$$\frac{d(\rho V)_l}{dt} = \rho_l \frac{dV_l}{dt} = -\dot{m}_{pl}$$

- Volume balance on lower layer

$$\frac{dV_l}{dt} = \frac{-\dot{m}_{pl}}{\rho_l} = -\dot{V}_{pl}$$

- Volume balance on upper layer

$$\frac{dV_u}{dt} = -\frac{dV_l}{dt} = \dot{V}_{pl}$$

Enclosure smoke filling
Case 2. Small leak at ceiling

- Volumetric plume flow rate (Zukoski)

$$\dot{V}_{pl} = \frac{\dot{m}_{pl}}{\rho_l} = 0.21\left(\frac{g}{\rho_l c_p T_l}\right)^{1/3} \dot{Q}^{1/3} z^{5/3} = k_v \dot{Q}^{1/3} (z_l - z_f)^{5/3}$$

- Upper layer descent rate (for flat ceiling)

$$\frac{dz_u}{dt} = \frac{1}{A_r}\frac{dV_u}{dt} = \frac{\dot{V}_{pl}}{A_r} = \frac{k_v}{A_r}\dot{Q}^{1/3}(H - z_u)^{5/3}$$

- Solution for smoke layer position

$$\int_0^{z_u} \frac{dz_u}{(H - z_u)^{5/3}} = \frac{k_v}{A_r}\int_0^t \dot{Q}^{1/3} dt$$

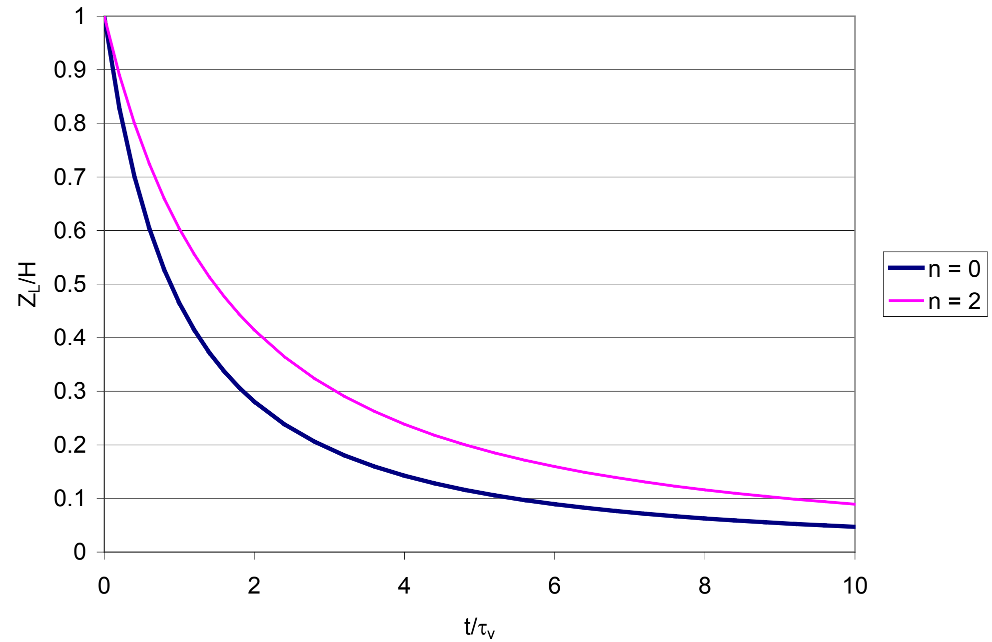
Enclosure smoke filling
Case 2. Small leak at ceiling

- Solution for smoke layer position for power law fire - $\dot{Q} = \alpha_n t^n$

$$\int_0^{z_u} \frac{dz_u}{(H - z_u)^{5/3}} = \frac{k_v}{A_r} \int_0^t (\alpha_n t^n)^{1/3} dt$$

$$\frac{z_u}{H} = 1 - \left[1 + \frac{2t}{(n+3)\tau_v} \right]^{-3/2}$$

$$\tau_V = \frac{V}{\dot{V}_{ent}} = \frac{AH}{k_v \dot{Q}^{1/3} H^{5/3}}$$



Enclosure smoke filling
Case 1. Small leak at floor

- Smoke layer temperature

$$\overline{T}_u(t) = \frac{\rho_l T_l}{\rho_u} = \frac{\rho_l T_l V_u}{m_u} = \rho_l T_l \left(\frac{\int_o^t \frac{dV_u}{dt} dt}{\int_o^t \frac{dm_u}{dt} dt} \right) = T_l \frac{\int_o^t (\dot{V}_{pl} + \dot{V}_{\exp}) dt}{\int_o^t \dot{V}_{pl} dt}$$

- Smoke layer oxygen concentration

$$Y_{O2,u}(t) = \frac{m_{O2,u}}{m_u} = \frac{\int_o^t \left[\left(\rho_l \dot{V}_{pl} Y_{O2,o} \right) - \left(\frac{\dot{Q}_f}{\Delta H_c / r_{O2}} \right) \right] dt}{m_u}$$

  – These equations generally require numerical integration

Enclosure smoke filling
Case 2. Small leak at ceiling

- Smoke layer temperature

$$\overline{T}_u(t) = \frac{\rho_l T_l}{\rho_u} = \frac{\rho_l T_l V_u}{m_u} = \rho_l T_l \left(\frac{\int_o^t \frac{dV_u}{dt} dt}{\int_o^t \frac{dm_u}{dt} dt} \right) = \frac{\rho_l T_l \int_o^t (\dot{V}_{pl}) dt}{\int_o^t \left(\rho_l \dot{V}_{pl} - \rho_u \dot{V}_{\exp} \right) dt}$$

- Smoke layer oxygen concentration

$$Y_{O2,u}(t) = \frac{m_{O2,u}}{m_u} = \frac{\int_o^t \left[\left(\rho_l \dot{V}_{pl} Y_{O2,o} \right) - \left(\frac{\dot{Q}_f}{\Delta H_c / r_{O2}} \right) - \left(\rho_u \dot{V}_{\exp} Y_{O2,u} \right) \right] dt}{m_u}$$

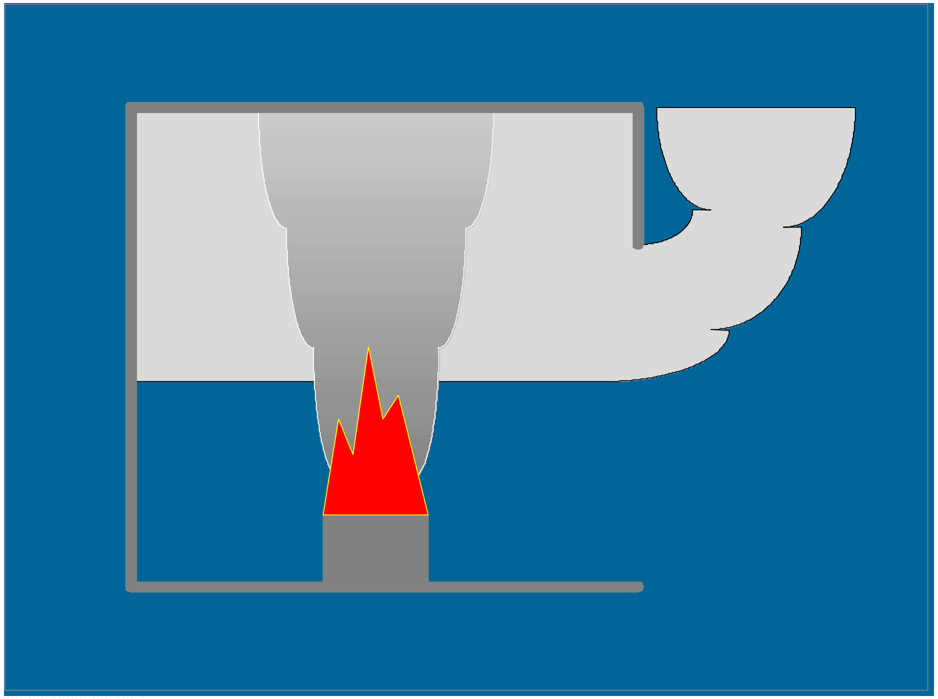
  – These equations generally require numerical integration

Summary – smoke filling

- Fire in enclosed spaces have been addressed in terms of:
  - Global (one-zone) analysis
  - Smoke layer descent (two-zone) analysis
- Bases of the ASET addressed
  - ASET does not address oxygen limitations
  - Unrealistic temperatures can be calculated
- Next step is to consider the effects of vent flows and mechanical ventilation

Vent flow topics

- Orifice flow equation
  - Application of Bernoulli's equation
- Hydrostatic pressure profiles in room fires
- Roof /floor vents
- Wall vents
  - Ventilation limit
- Multiple vents



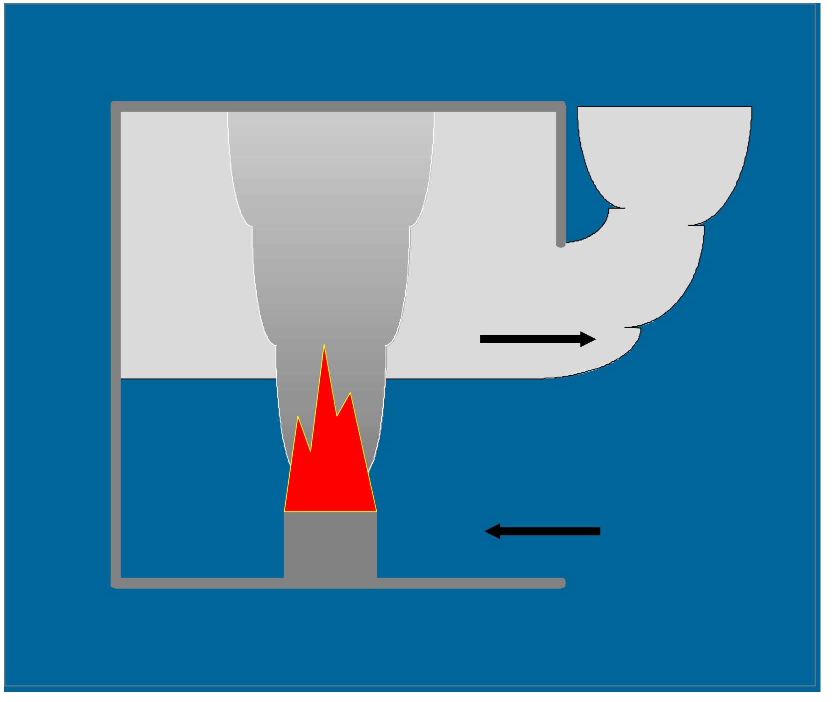
Orifice flow

- Mass flow rate

$$\dot{m} = C_D \rho A v$$

- Velocity

$$v = \sqrt{\frac{2\Delta P}{\rho}}$$



– Need pressure distribution to evaluate mass flow rate

Pressure distribution

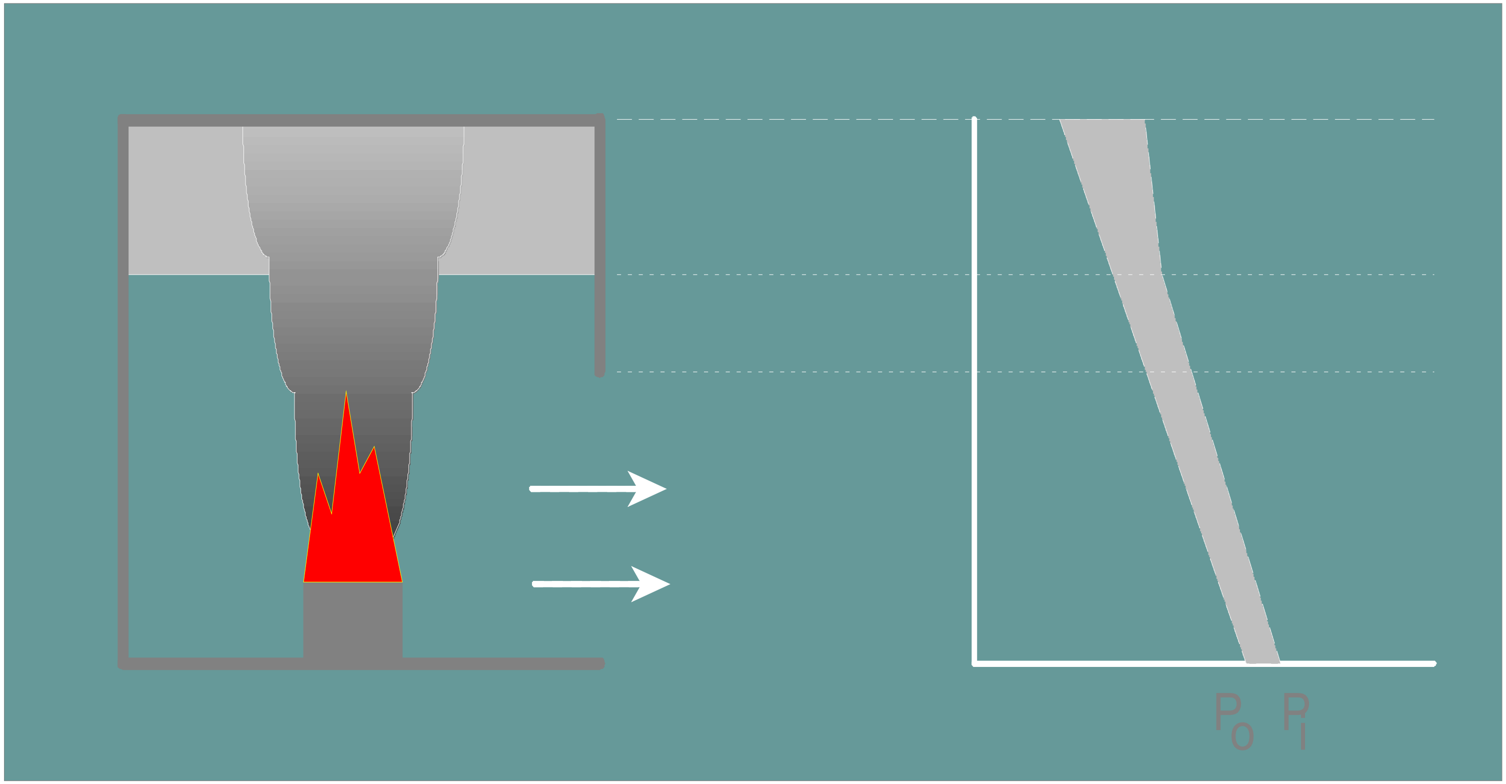
- Pressure differences arise from hydrostatic pressure differences

$$\frac{dP}{dz} = -\rho g = -\frac{\rho_o T_o}{T} g$$

- Pressure profiles go through series of stages

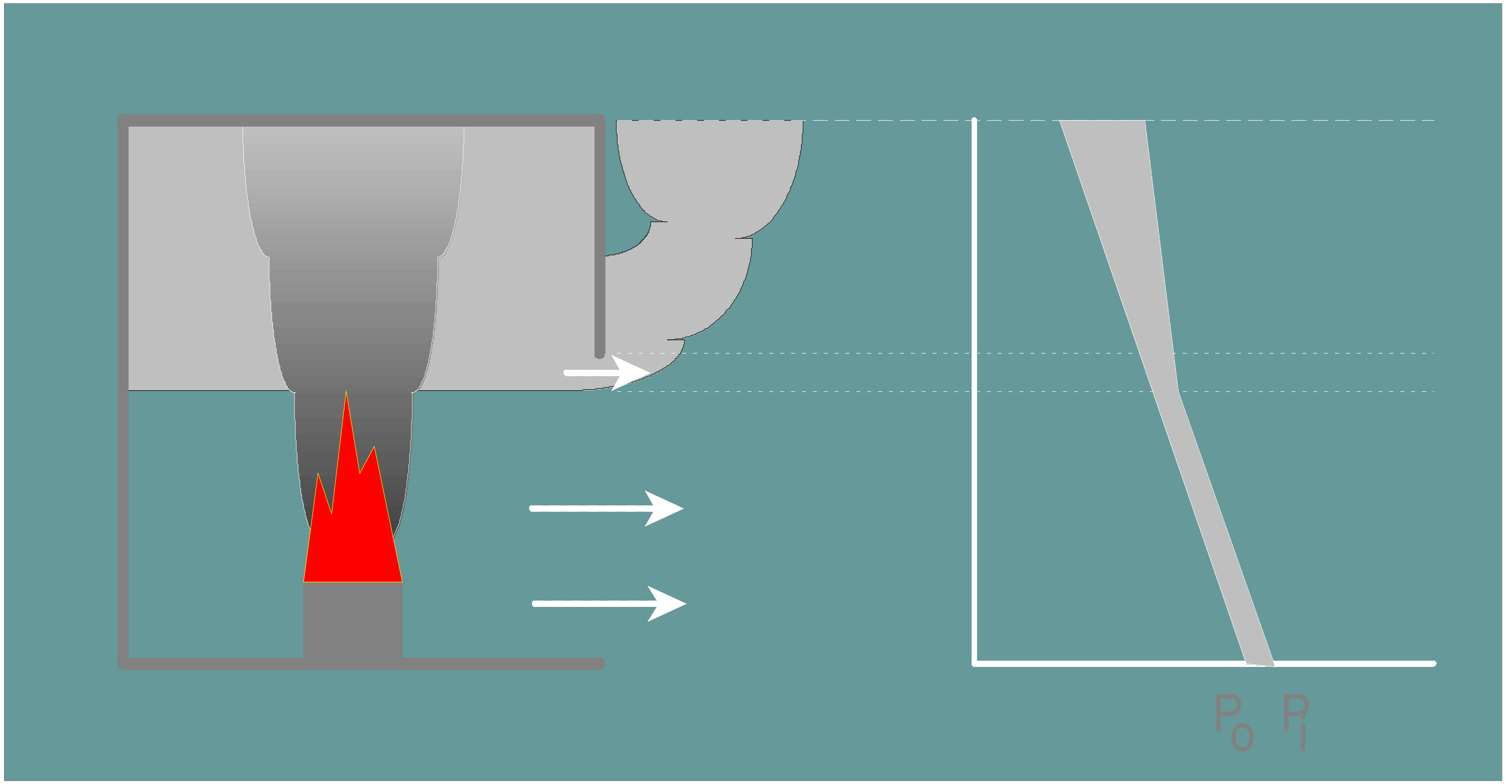
Pressure profile

PHASE 1



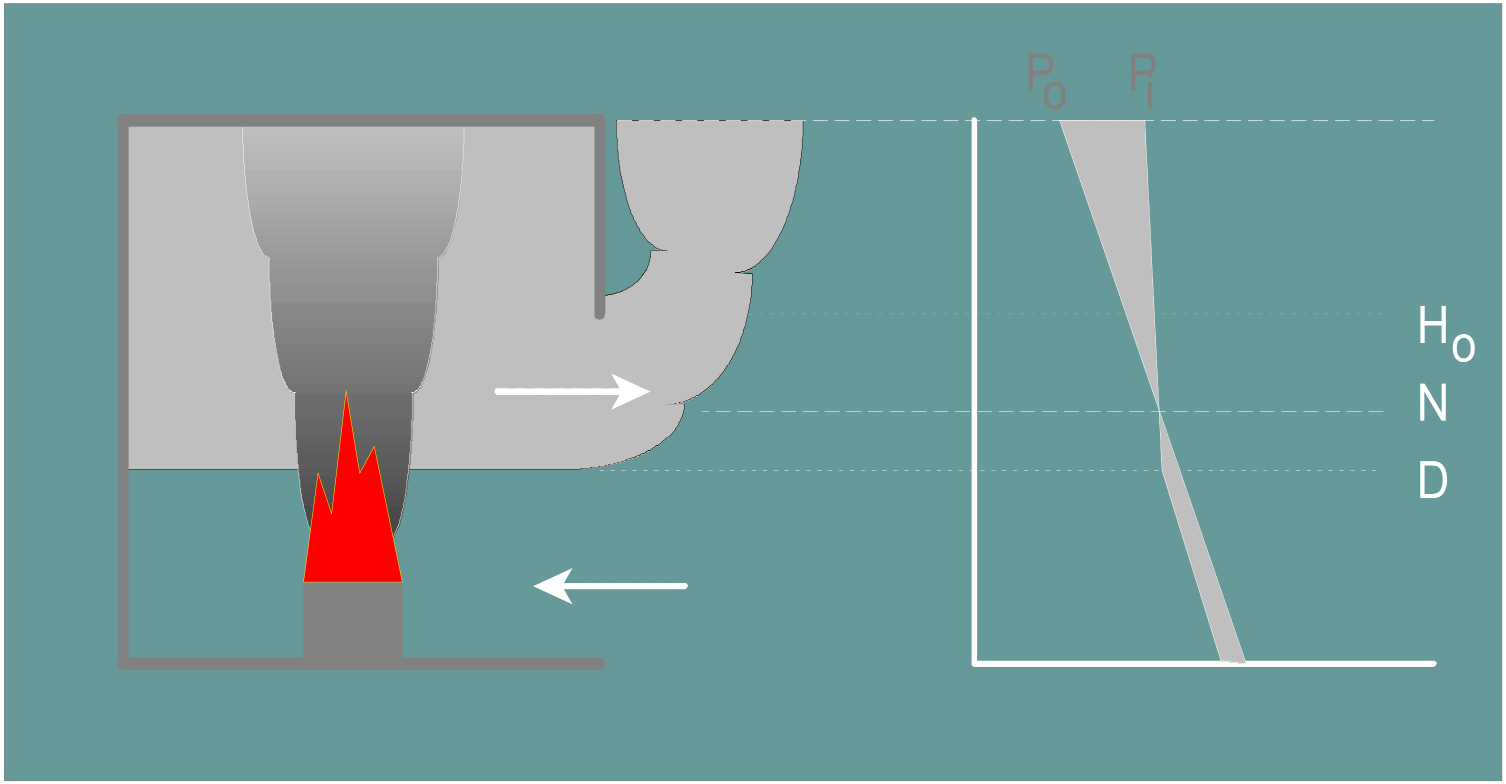
Pressure profile

PHASE 2



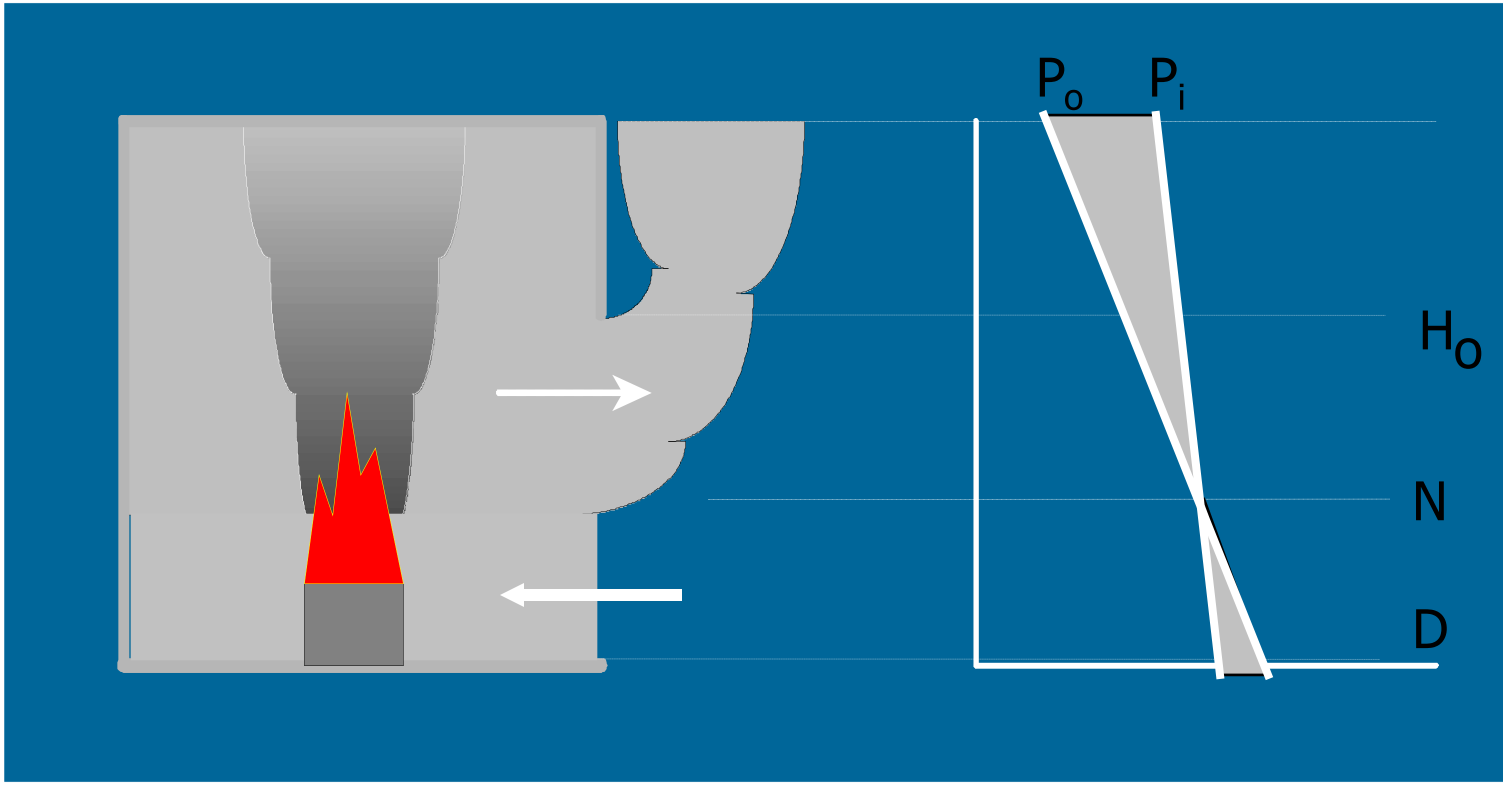
Pressure profile

PHASE 3



Pressure profile

PHASE 4



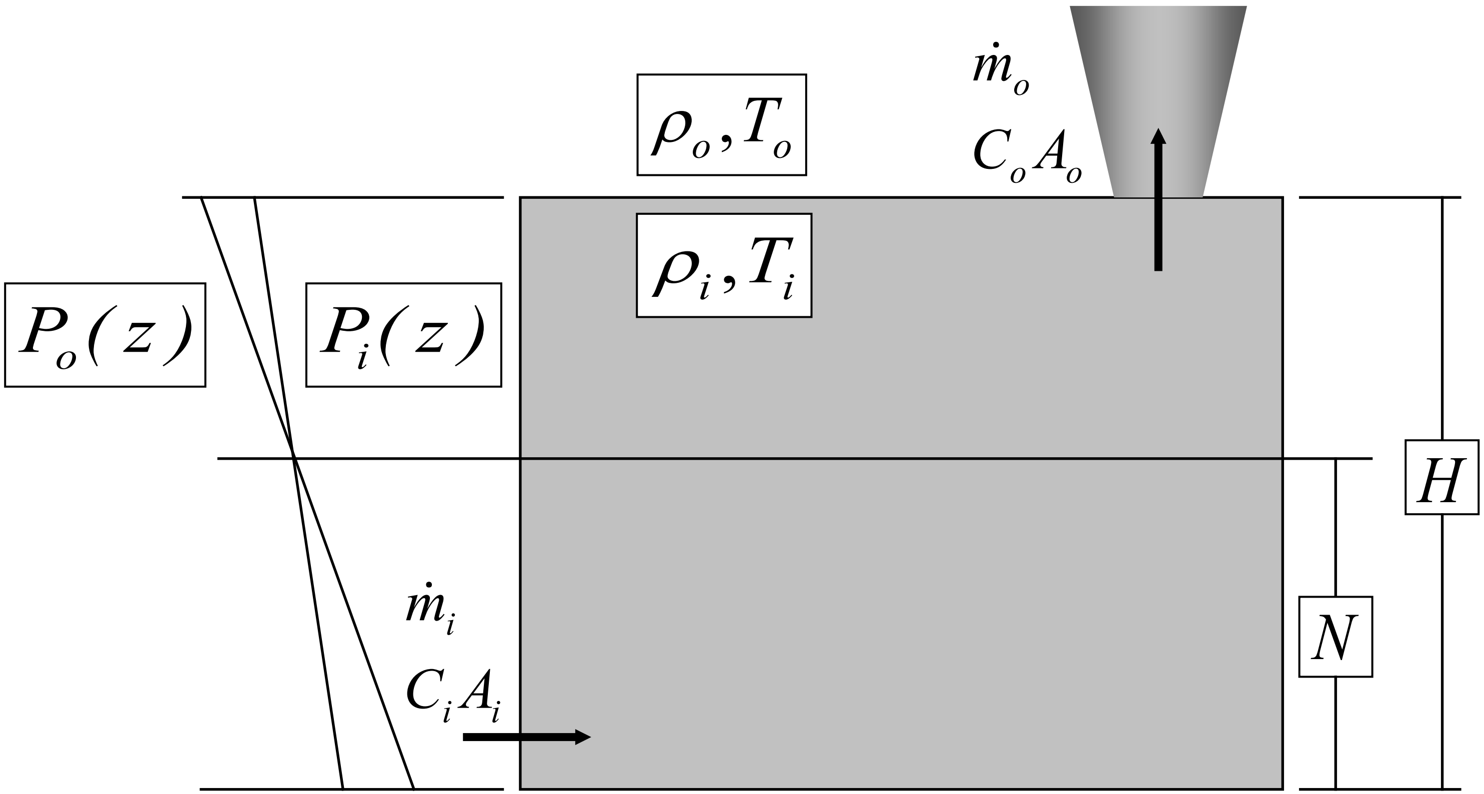
Vent flow cases

- Roof / floor vents
- Wall vents
- Combined / multiple

- One-zone
  - Stack effect
- Two-zone
  - Buoyancy
- Combined
  - Stack + buoyancy

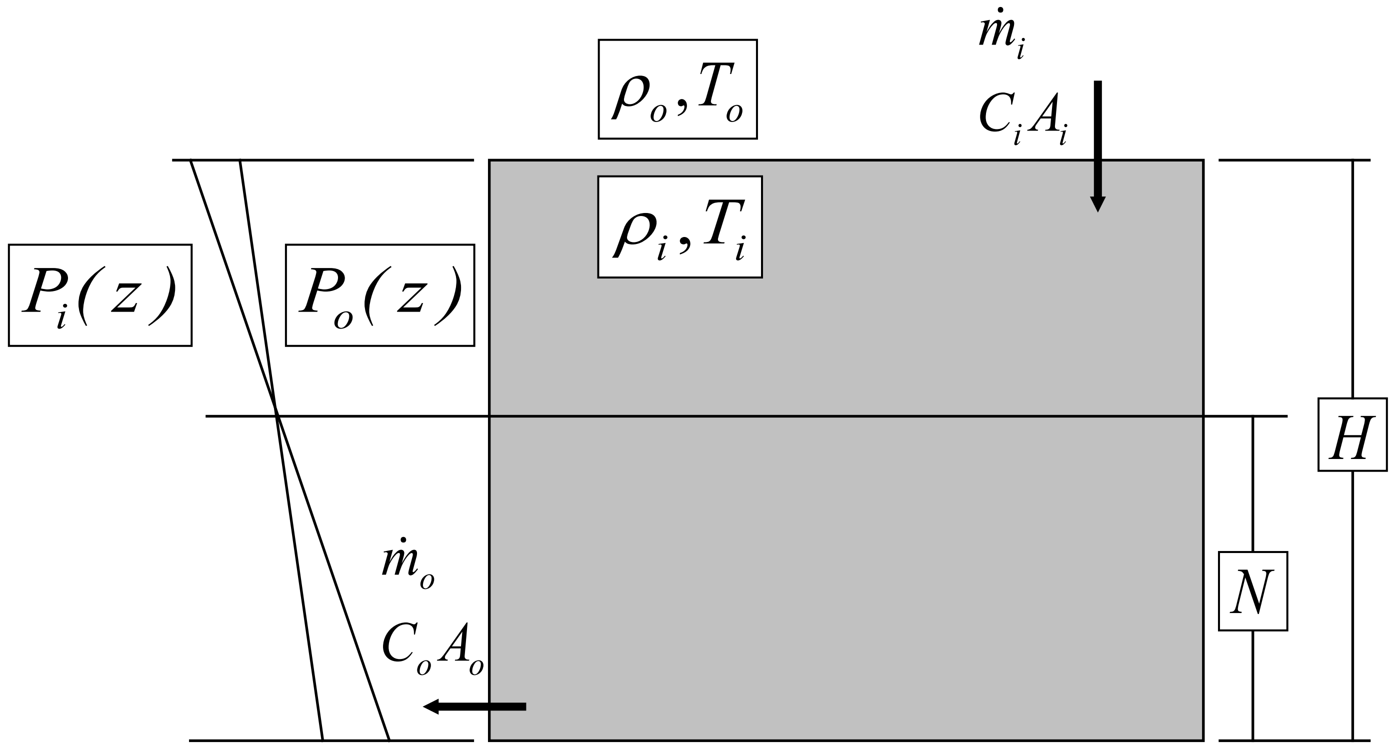
Roof / floor vents

- One zone (Stack effect only)
  - $T_i > T_o$ (Normal)



Roof / floor vents

- One zone (Stack effect only)
  - $T_i < T_o$ (Reverse)

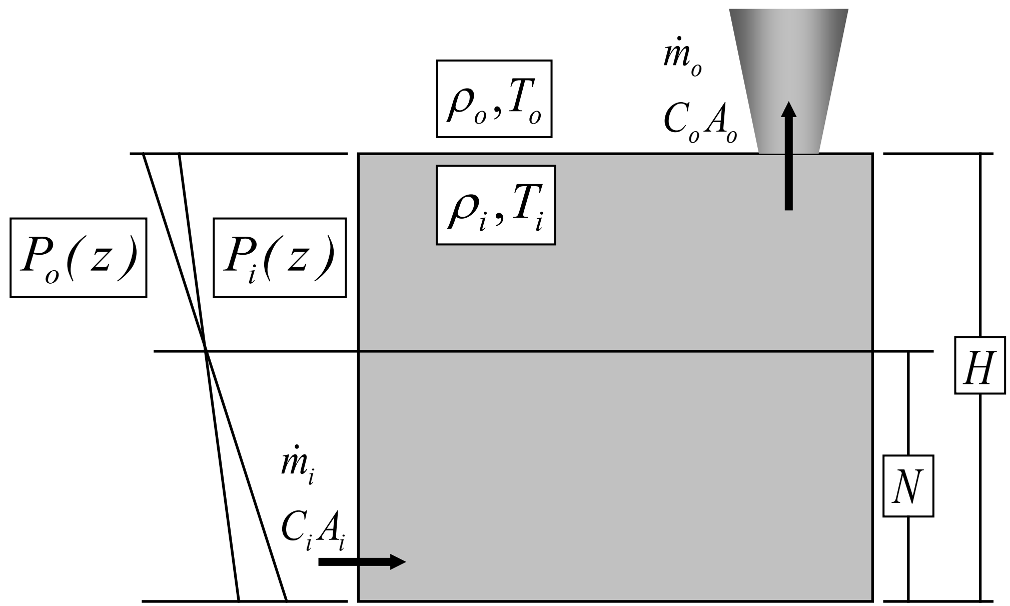


Roof / floor vents

- Normal stack effect case
- Evaluate pressure profiles
  - For uniform temperatures, uniform densities and linear pressure profiles

$$\frac{dP}{dz} = -\rho g$$

$$\int_{P_1}^{P_2} dP = -\rho g \int_{z_1}^{z_2} dz$$



Roof / floor vents

- Evaluate pressure difference at roof vent
- Pressures are equal at neutral plane, N

$$P_i(H) - P_i(N) = -\rho_i g(H - N)$$

$$P_o(H) - P_o(N) = -\rho_o g(H - N)$$

$$P_i(H) - P_o(H) = (\rho_o - \rho_i) g(H - N)$$

$$\Delta P_{io}(H) = (\rho_o - \rho_i) g(H - N)$$

Roof / floor vents

- Evaluate pressure difference at floor vent
- Pressures are equal at neutral plane, N

$$P_i(N) - P_i(0) = -\rho_i g(N - 0)$$

$$P_o(N) - P_o(0) = -\rho_o g(N - 0)$$

$$P_o(0) - P_i(0) = (\rho_o - \rho_i)gN$$

$$\Delta P_{oi}(0) = (\rho_o - \rho_i)gN$$

Roof / floor vents

- Evaluate vent flow rates

$$\dot{m} = \rho C_D A \sqrt{\frac{2\Delta P}{\rho}}$$

  – Roof vent

$$\dot{m}_o = C_o A_o \sqrt{2g(H-N)\rho_i \Delta\rho}$$

  – Floor vent

$$\dot{m}_i = C_i A_i \sqrt{2gN\rho_o \Delta\rho}$$

$$\Delta\rho = (\rho_o - \rho_i)$$

Roof / floor vents

- Equate mass flow rates $\dot{m}_o = \dot{m}_i$

$$C_o A_o \sqrt{2g(H-N)\rho_i \Delta\rho} = C_i A_i \sqrt{2gN\rho_o \Delta\rho}$$

- Solve for neutral plane height

$$\frac{N}{H} = \frac{1}{1+\left(\frac{\rho_o}{\rho_i}\right)\left(\frac{C_i A_i}{C_o A_o}\right)^2}$$

Roof / floor vents

- Substitute into mass flow equations
  - Mass inflow equation

$$\dot{m}_i = \rho_o C_i A_i \sqrt{\frac{2gH\left(1-\frac{T_o}{T_i}\right)}{1+\left(\frac{T_i}{T_o}\right)\left(\frac{C_i A_i}{C_o A_o}\right)^2}}$$

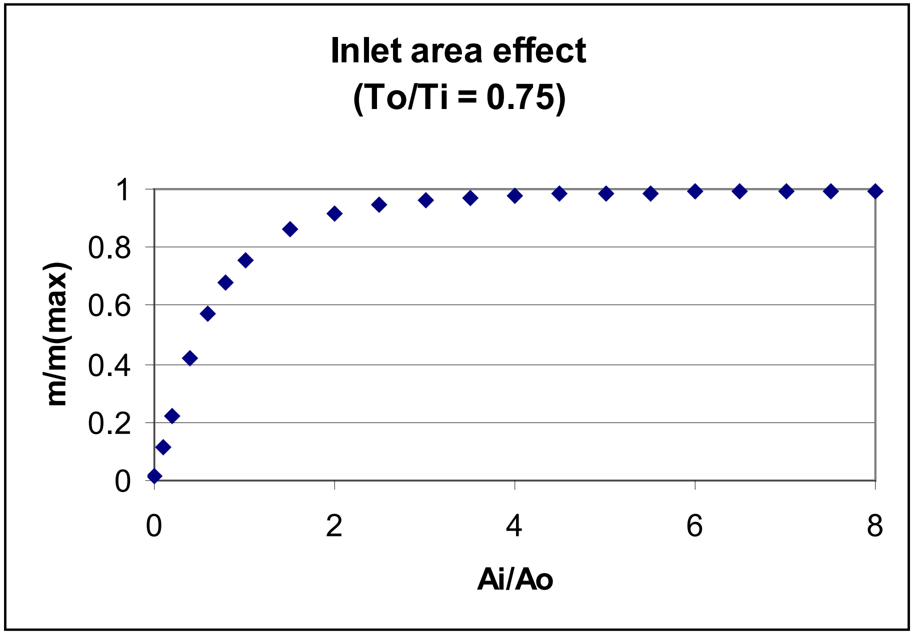
  - Mass outflow equation

$$\dot{m}_o = \rho_i C_o A_o \sqrt{\frac{2gH\left(\frac{T_i}{T_o}-1\right)}{1+\left(\frac{T_o}{T_i}\right)\left(\frac{C_o A_o}{C_i A_i}\right)^2}}$$

Roof / floor vents

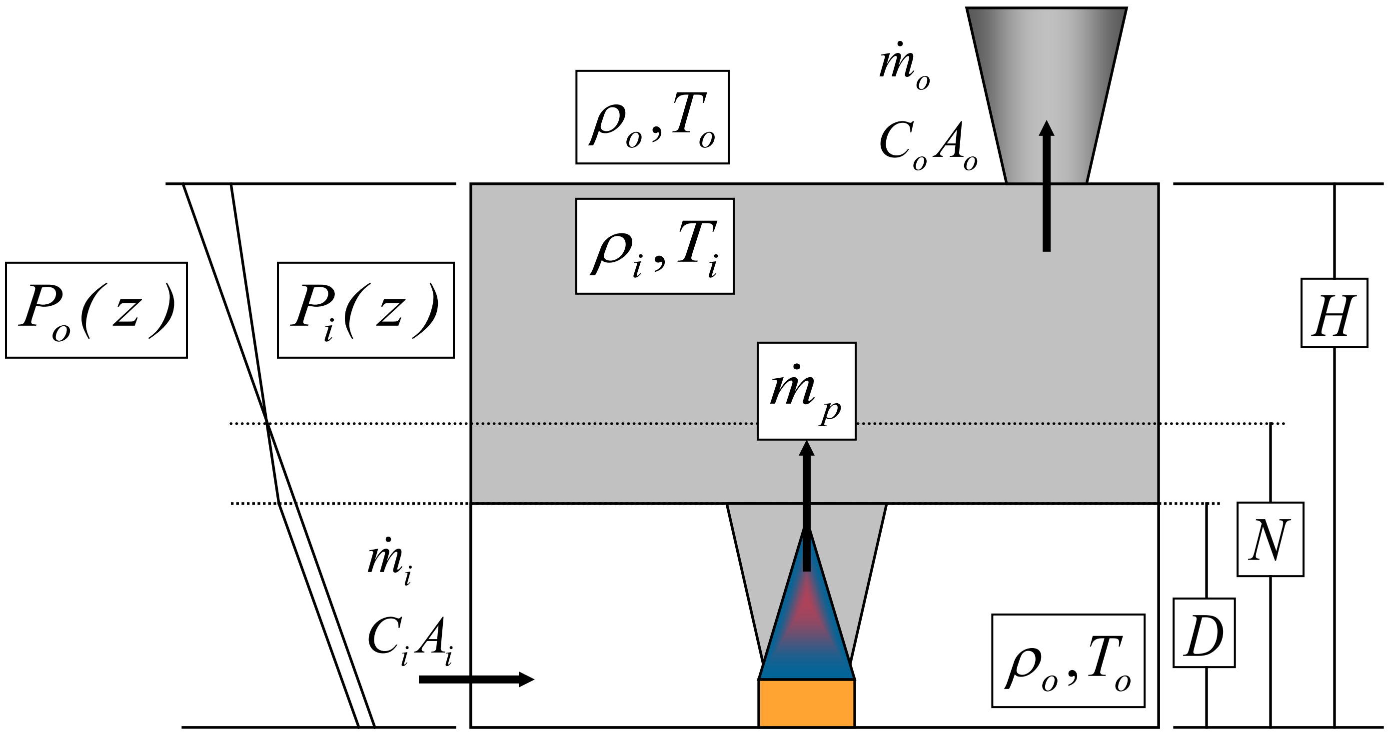
- Effect of inlet vent restriction

$$\frac{\dot{m}_o}{\dot{m}_{o,max}} = \sqrt{\frac{1}{1+\left(\frac{T_o}{T_i}\right)\left(\frac{C_o A_o}{C_i A_i}\right)^2}}$$



Roof / floor vents

- Two-zone analysis (Buoyancy only)



Roof / floor vents

- Two-zone analysis (Buoyancy only)
  - ΔP at roof same as for one-zone case

$$\Delta P(H) = (\rho_o - \rho_i) g (H - N)$$

  - ΔP at floor different from one-zone case

$$\Delta P(0) = (\rho_o - \rho_i) g (N - D)$$

Roof / floor vents

- Two-zone analysis (Buoyancy only)
  - Mass outflow term

$$\dot{m}_o = C_o A_o \sqrt{2g(H - N)\rho_i \Delta\rho}$$

  - Mass inflow term

$$\dot{m}_i = C_i A_i \sqrt{2g(N - D)\rho_o \Delta\rho}$$

Roof / floor vents

- Equate mass flow rates $\dot{m}_o = \dot{m}_i$

$$C_o A_o \sqrt{2g(H-N)\rho_i \Delta\rho} = C_i A_i \sqrt{2g(N-D)\rho_o \Delta\rho}$$

- Solve for relative neutral plane height

$$\frac{(N-D)}{(H-N)} = \left(\frac{\rho_i}{\rho_o}\right)\left(\frac{C_o A_o}{C_i A_i}\right)^2$$

Roof / floor vents

- Interested in distance (H-D), not (N-D), but note that (N-D) = (H-D)-(H-N):

$$\frac{(N-D)}{(H-N)} = \frac{(H-D)-(H-N)}{(H-N)} = \left(\frac{\rho_i}{\rho_o}\right)\left(\frac{C_o A_o}{C_i A_i}\right)^2$$

$$\frac{(H-D)}{(H-N)} = 1 + \left(\frac{\rho_i}{\rho_o}\right)\left(\frac{C_o A_o}{C_i A_i}\right)^2$$

  – Smoke layer depth in terms of neutral plane depth. Substitute into mass outflow equation.

Roof / floor vents

- Mass outflow equation

$$\dot{m}_o = \rho_i C_o A_o \sqrt{\frac{2g(H-D)\left(\frac{T_i}{T_o}-1\right)}{1+\left(\frac{T_o}{T_i}\right)\left(\frac{C_o A_o}{C_i A_i}\right)^2}}$$

  – This is same as one-zone case, but with overall height, H, replaced by smoke layer depth, (H-D).

Roof / floor vents

- Ideal gas manipulations

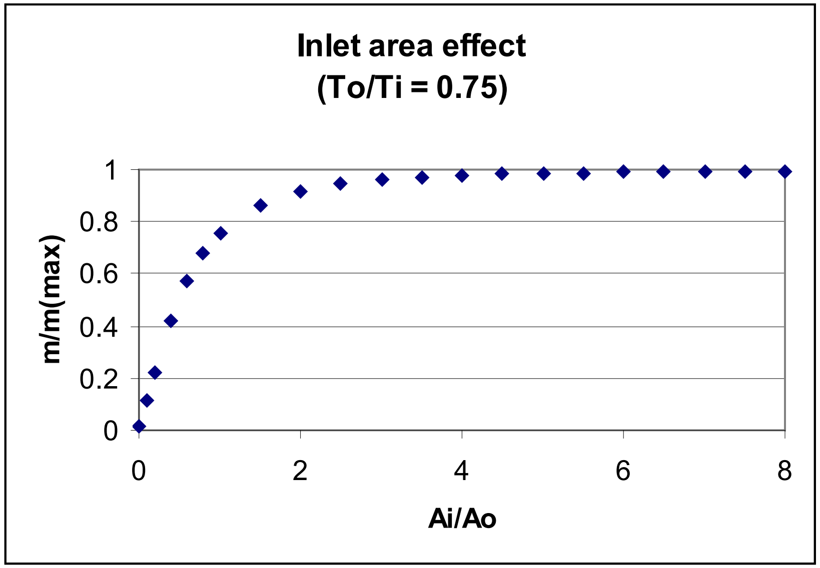
$$\rho_i \sqrt{\left(\frac{T_i}{T_o} - 1\right)} = \rho_o \sqrt{\frac{T_o}{T_i}\left(1 - \frac{T_o}{T_i}\right)} = \rho_o \sqrt{\frac{T_o \Delta T}{T_i^2}}$$

$$\dot{m}_o = \rho_o C_o A_o \sqrt{\frac{2g(H-D)\left(\frac{T_o \Delta T}{T_i^2}\right)}{1 + \left(\frac{T_o}{T_i}\right)\left(\frac{C_o A_o}{C_i A_i}\right)^2}}$$

Roof / floor vents

- Effect of inlet vent restriction (for $T_o/T_i=0.75$)
  - When $A_i = A_o$, vent only about 75% efficient
  - When $A_i = 2\ A_o$, vent is about 92% efficient
  - When $A_i = 3\ A_o$, vent is about 96% efficient

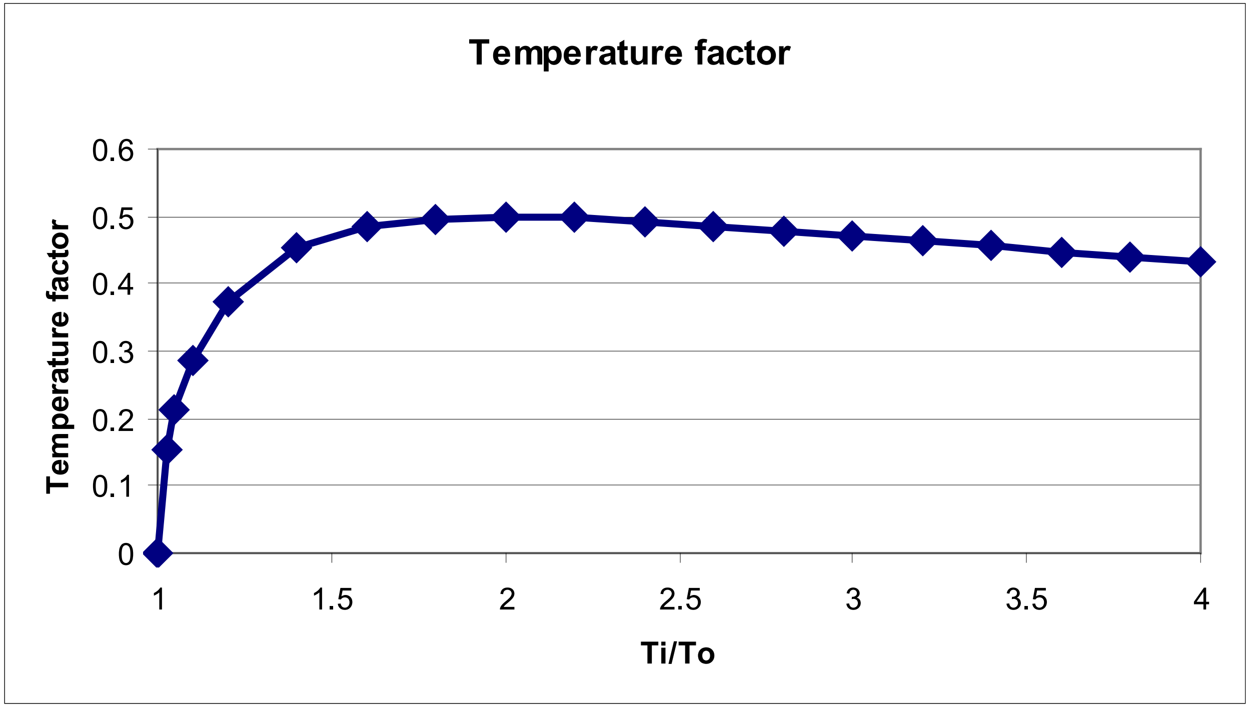
$$\frac{\dot{m}_o}{\dot{m}_{o,max}} = \sqrt{\frac{1}{1+\left(\frac{T_o}{T_i}\right)\left(\frac{C_o A_o}{C_i A_i}\right)^2}}$$



Roof / floor vents

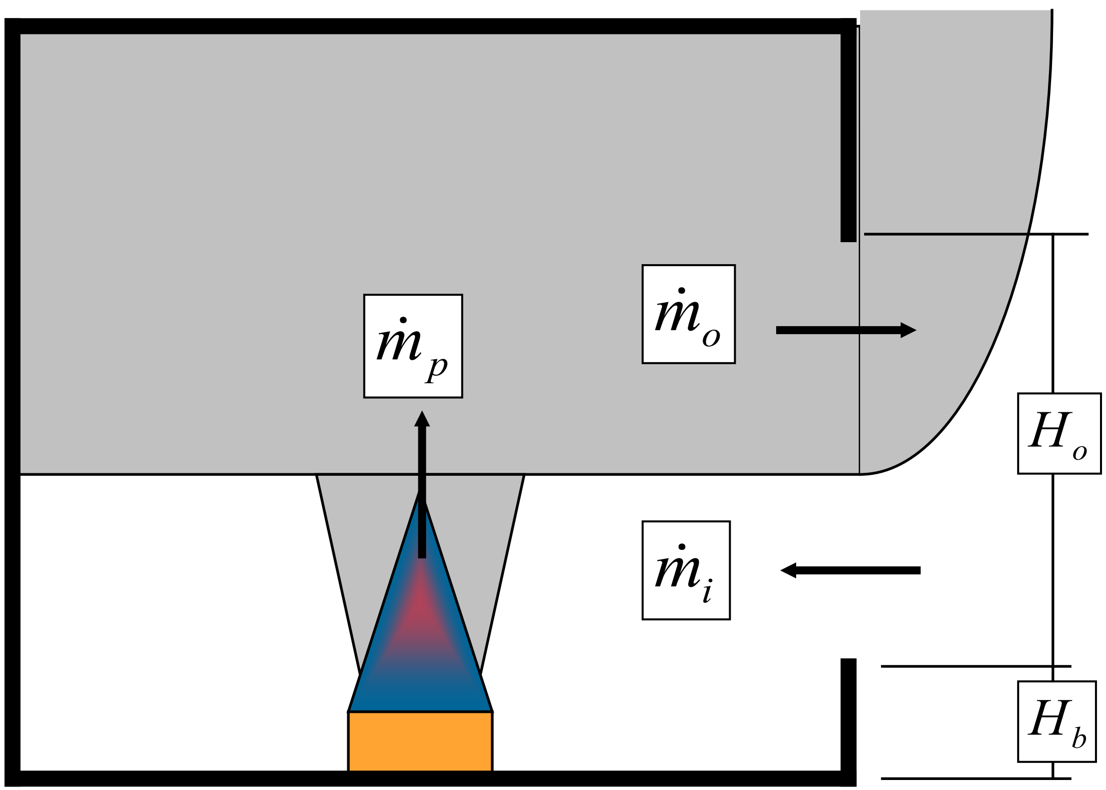
- Evaluation of temperature factor

$$\left(\frac{T_o \Delta T}{T_i^2}\right)^{1/2}$$



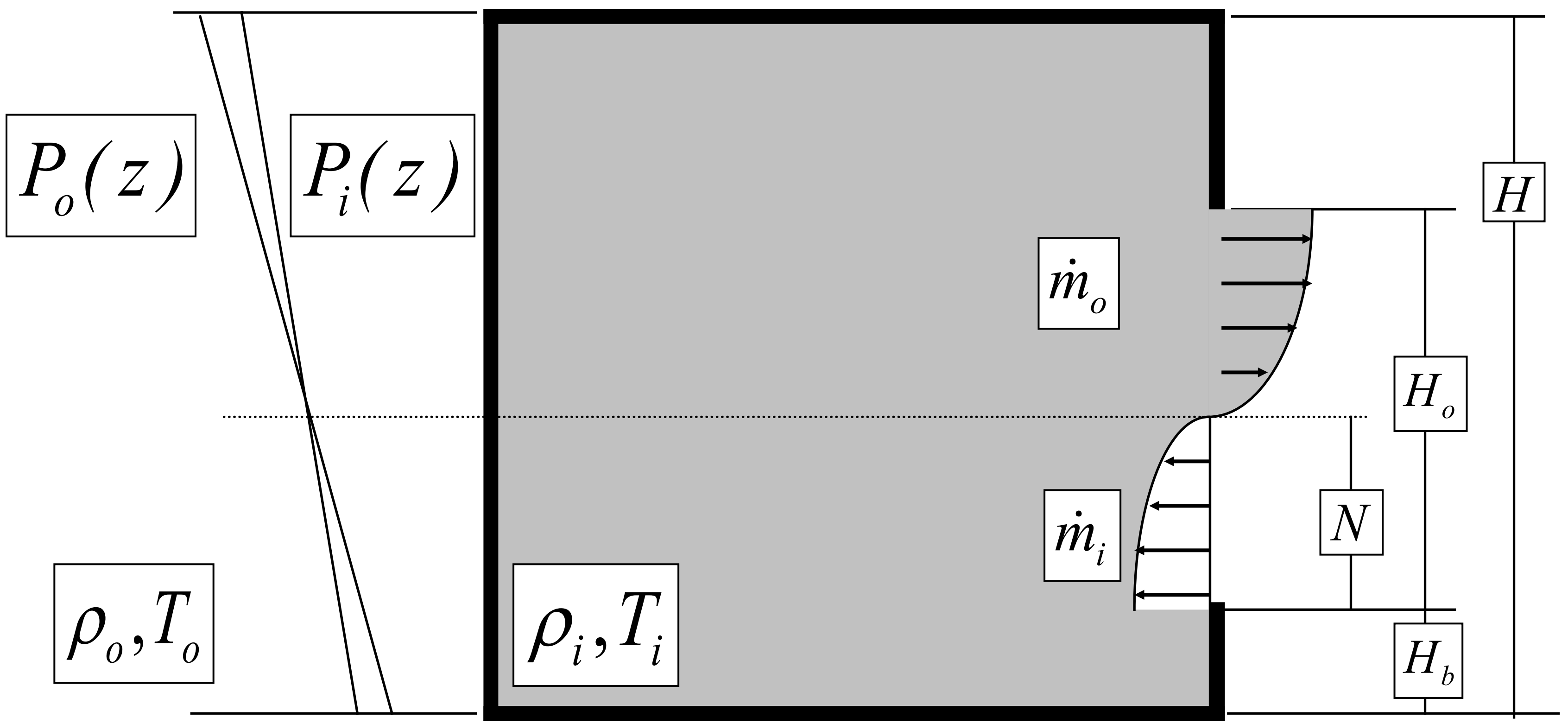
Wall vents

- Bidirectional flow through same vent



Wall vents

- One-zone analysis (Stack only - $T_i > T_o$)



Wall vents

- Pressure differential as f(z)

$$\Delta P(z) = (\rho_o - \rho_i) g (z - N)$$

- Velocity as f(z)
  - Outflow
    - z > N

$$v(z) = \sqrt{\frac{2\Delta P}{\rho}} = \sqrt{2g\left(\frac{\rho_o - \rho_i}{\rho_i}\right)(z - N)}$$

  - Inflow
    - z < N

$$v(z) = \sqrt{\frac{2\Delta P}{\rho}} = \sqrt{2g\left(\frac{\rho_o - \rho_i}{\rho_o}\right)(N - z)}$$

Wall vents

- Mass outflow rate as f(z)

$$\dot{m}_o = C_D \rho A v = C_D W_o \rho_i \int_N^{H_o} v(z)\,dz$$

$$\dot{m}_o = C_D W_o \rho_i \int_N^{H_o} \sqrt{2g\left(\frac{\rho_o - \rho_i}{\rho_i}\right)(z - N)}\,dz$$

$$\dot{m}_o = \frac{2}{3} C_D W_o \rho_i \sqrt{2g\left(\frac{\rho_o - \rho_i}{\rho_i}\right)}(H_o - N)^{3/2}$$

Wall vents

- Mass inflow rate as f(z)

$$\dot{m}_i = C_D \rho A v = C_D W_o \rho_o \int_0^N v(z) dz$$

$$\dot{m}_i = C_D W_o \rho_o \int_0^N \sqrt{2g\left(\frac{\rho_o - \rho_i}{\rho_o}\right)(N - z)} dz$$

$$\dot{m}_i = \frac{2}{3} C_D W_o \rho_o \sqrt{2g\left(\frac{\rho_o - \rho_i}{\rho_o}\right)} (N)^{3/2}$$

Wall vents

- Equate mass flow terms $\dot{m}_o = \dot{m}_i$

$$\frac{(H_o - N)^{3/2}}{(N)^{3/2}} = \frac{\rho_o}{\rho_i}\sqrt{\left(\frac{\rho_i}{\rho_o}\right)} = \sqrt{\left(\frac{\rho_o}{\rho_i}\right)} = \sqrt{\left(\frac{T_i}{T_o}\right)}$$

- Solve for neutral plane height

$$\frac{N}{H_o} = \frac{1}{1 + \left(\frac{T_i}{T_o}\right)^{1/3}}$$

Wall vents

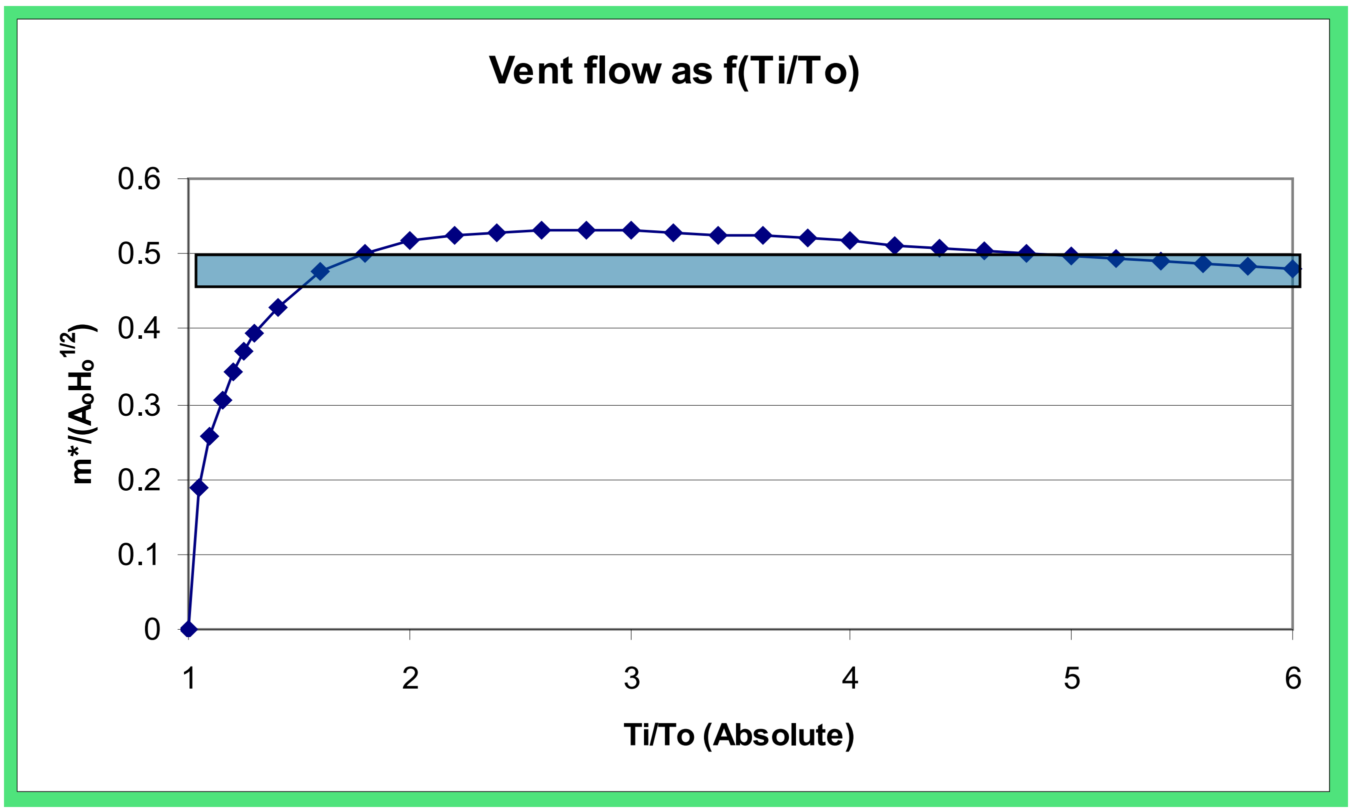
- Substitute into mass outflow equation

$$\dot{m}_o = \frac{2}{3} C_d \rho_o A_o \sqrt{H_o} \sqrt{2g} \left[\frac{T_o}{T_i} \left(1 - \frac{T_o}{T_i} \right) \right]^{1/2} \left(1 - \frac{1}{1 + (T_i / T_o)^{1/3}} \right)^{3/2}$$

- This is the ventilation limited flow through a single rectangular wall vent
- Flow is function of ventilation factor and temperature ratio

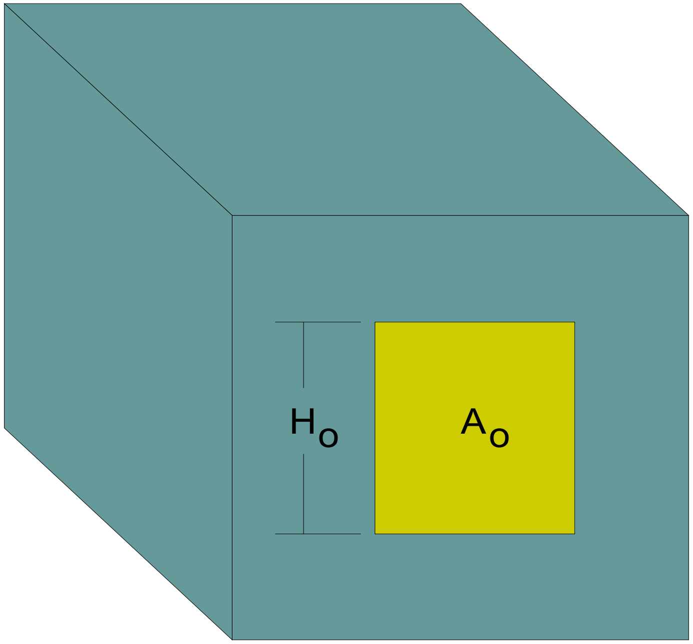
Wall vents

- Plot $\frac{\dot{m}_o}{A_o\sqrt{H_o}} = f\left(\frac{T_i}{T_o}\right)$ for C_d = 0.7, ambient air



The ventilation limit

- Rooms with single rectangular wall openings



$$\dot{m}_{max} \approx 0.5 A_o \sqrt{H_o}$$

$$\dot{Q}_{max} = \dot{m}_{max} \frac{\Delta H_c}{r}$$

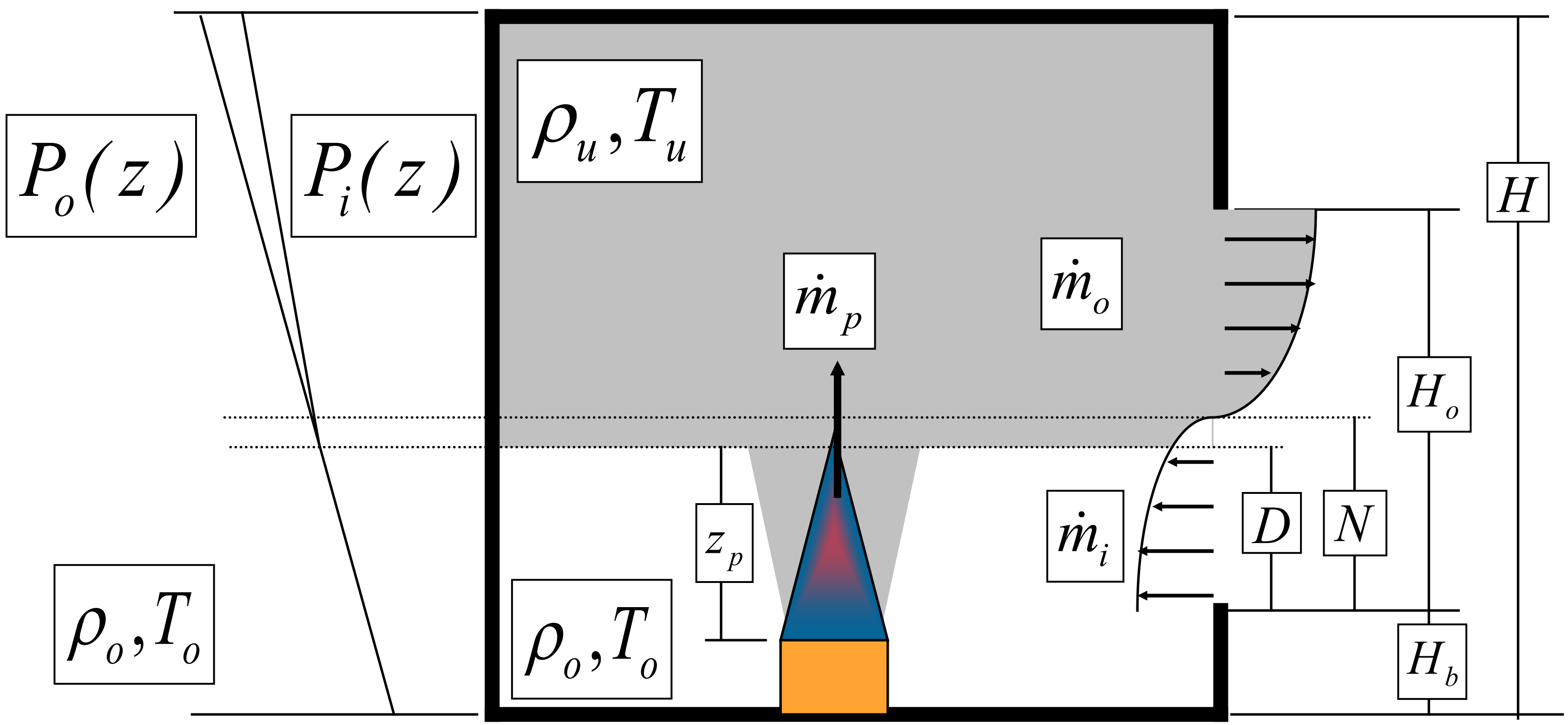
$$\dot{Q}_{max} \approx 1500 A_o \sqrt{H_o}$$

Example

- Calculate maximum air flow rate and heat release rate in standard room fire test enclosure with single doorway opening 0.76 m wide by 2.03 m high
  - VENTILATION FACTOR $A_oH_o^{1/2}$ = 2.2 $m^{5/2}$
  - MAX. MASS FLOW RATE = 1.1 kg/s
    - ~229 air changes per hour
  - MAX. HEAT RELEASE RATE = 3300 kW

Wall vents

- Two-zone analysis



Wall vents

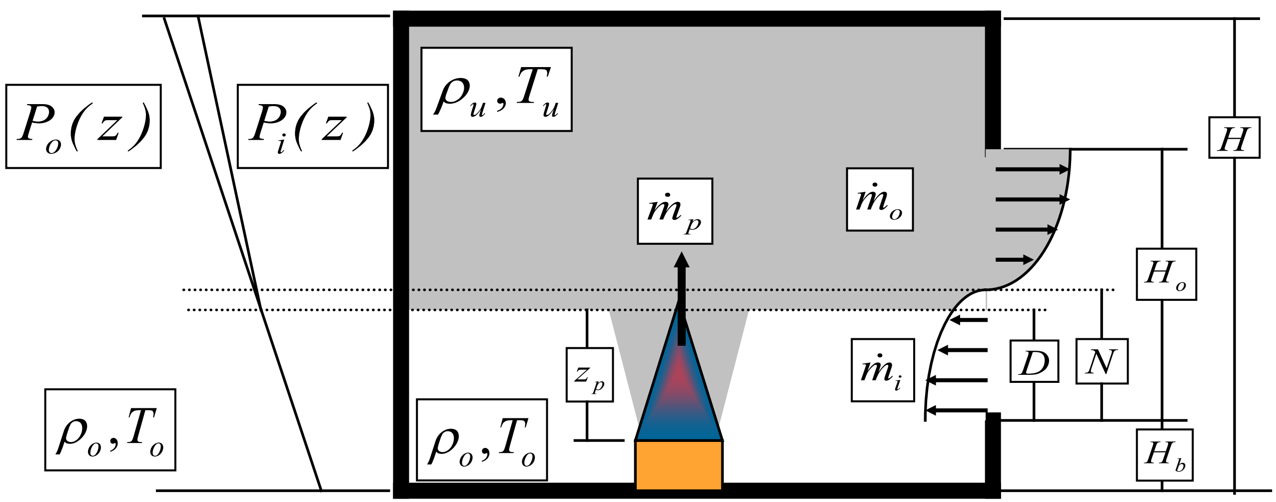
- Two-zone analysis
  - Upper layer analysis same as for one-zone

$$\dot{m}_o = \frac{2}{3} C_D W_o \rho_i \sqrt{2g\left(\frac{\rho_o - \rho_i}{\rho_i}\right)} \left(H_o - N\right)^{3/2}$$

  - Before onset of ventilation limited conditions, D and N approximately coincident

Wall vents

- Two-zone analysis
  - Elevation of D (and N) based on balance between plume entrainment and vent flow
  - Analysis similar to roof vent analysis



Wall vents

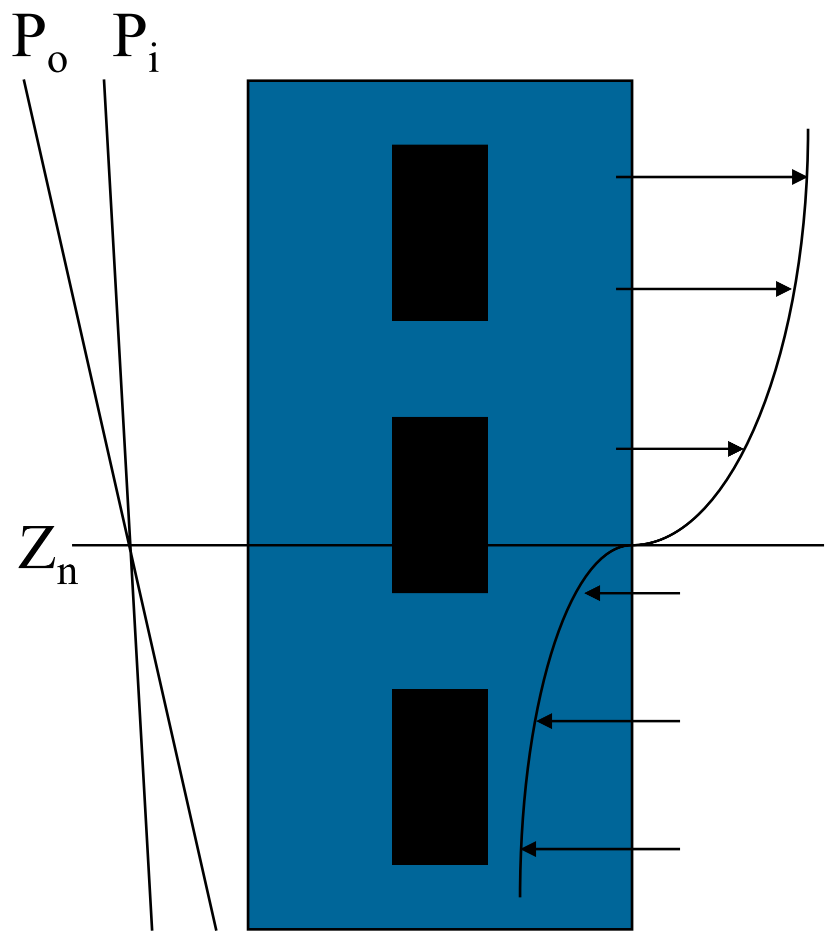
- Plume / wall vent flow balance $\dot{m}_o = \dot{m}_p$
  - Wall vent flow

$$\dot{m}_o = \frac{2}{3} C_D W_o \rho_i \sqrt{2g\left(\frac{\rho_o - \rho_i}{\rho_i}\right)} \left(H_o - N\right)^{3/2}$$

  - Plume flow
    - $z_p < z_l$ $\dot{m}_p = 0.0054 \dot{Q}_c z_p / z_L$
    - $z_p > z_l$ $\dot{m}_p = 0.071 \dot{Q}_c^{1/3} (z - z_o)^{5/3} + 0.0018 \dot{Q}_c$

Multiple vents

- Neutral plane occurs where
  - mass inflow = outflow
- Solution technique
  - Guess Z_n
  - Calculate m_o, m_i
  - Compare m_o, m_i
  - If $m_o \neq m_i$, adjust Z_n



Other factors

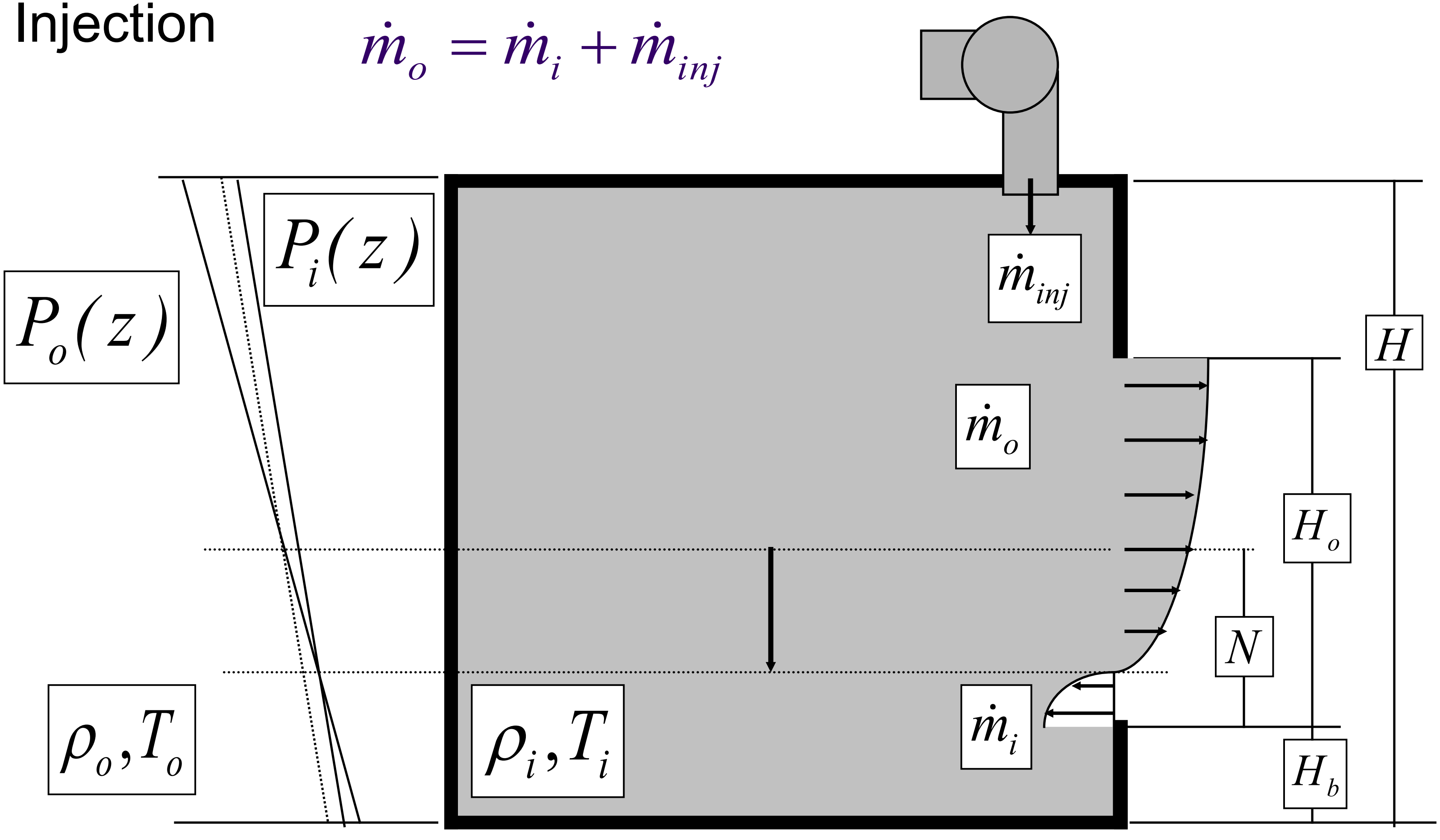
- Unsteady conditions
- Wind effects
- Mechanical ventilation
- Multiple rooms

- These are the factors that make computer models particularly useful!

Mechanical ventilation

- Injection

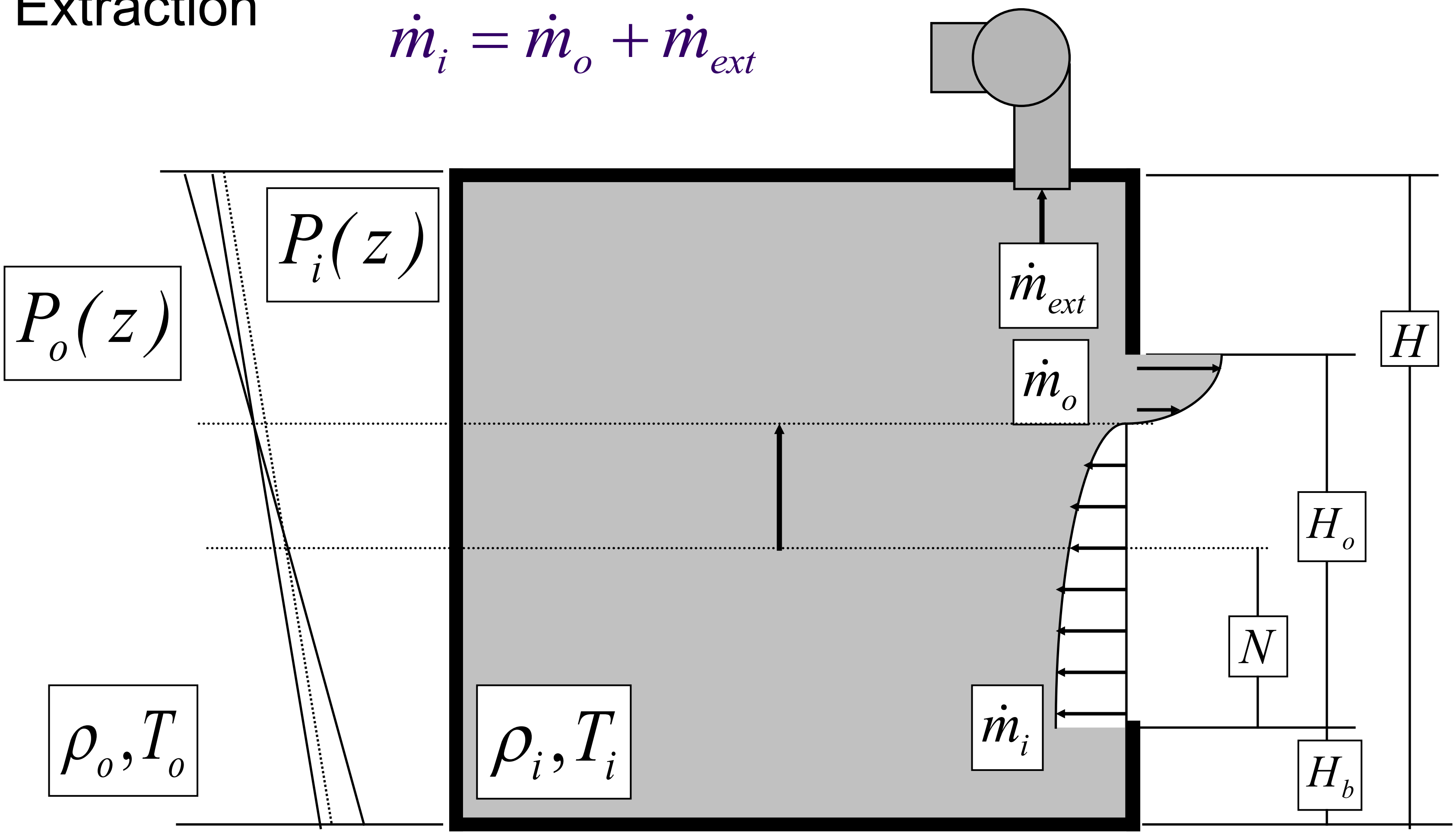
$$\dot{m}_o = \dot{m}_i + \dot{m}_{inj}$$



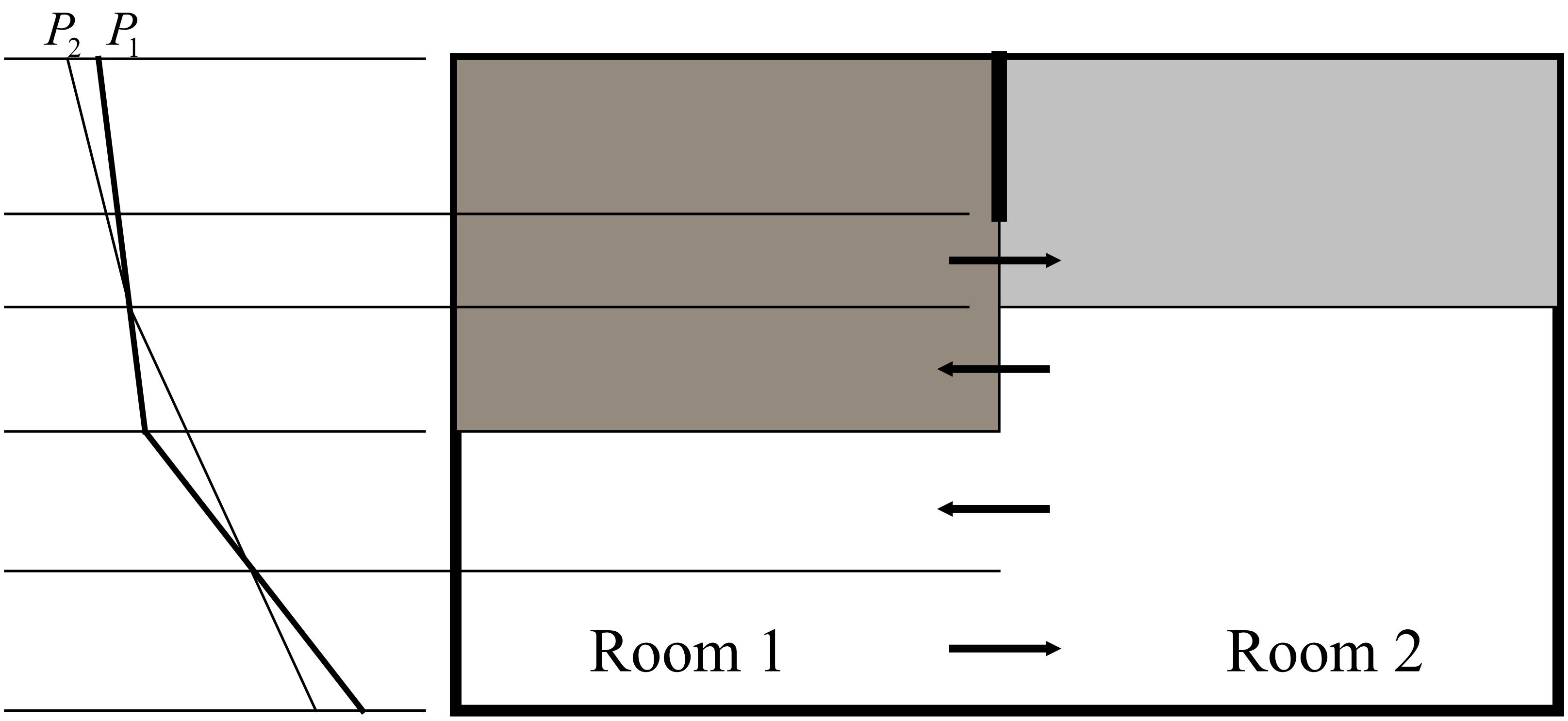
Mechanical ventilation

- Extraction

$$\dot{m}_i = \dot{m}_o + \dot{m}_{ext}$$



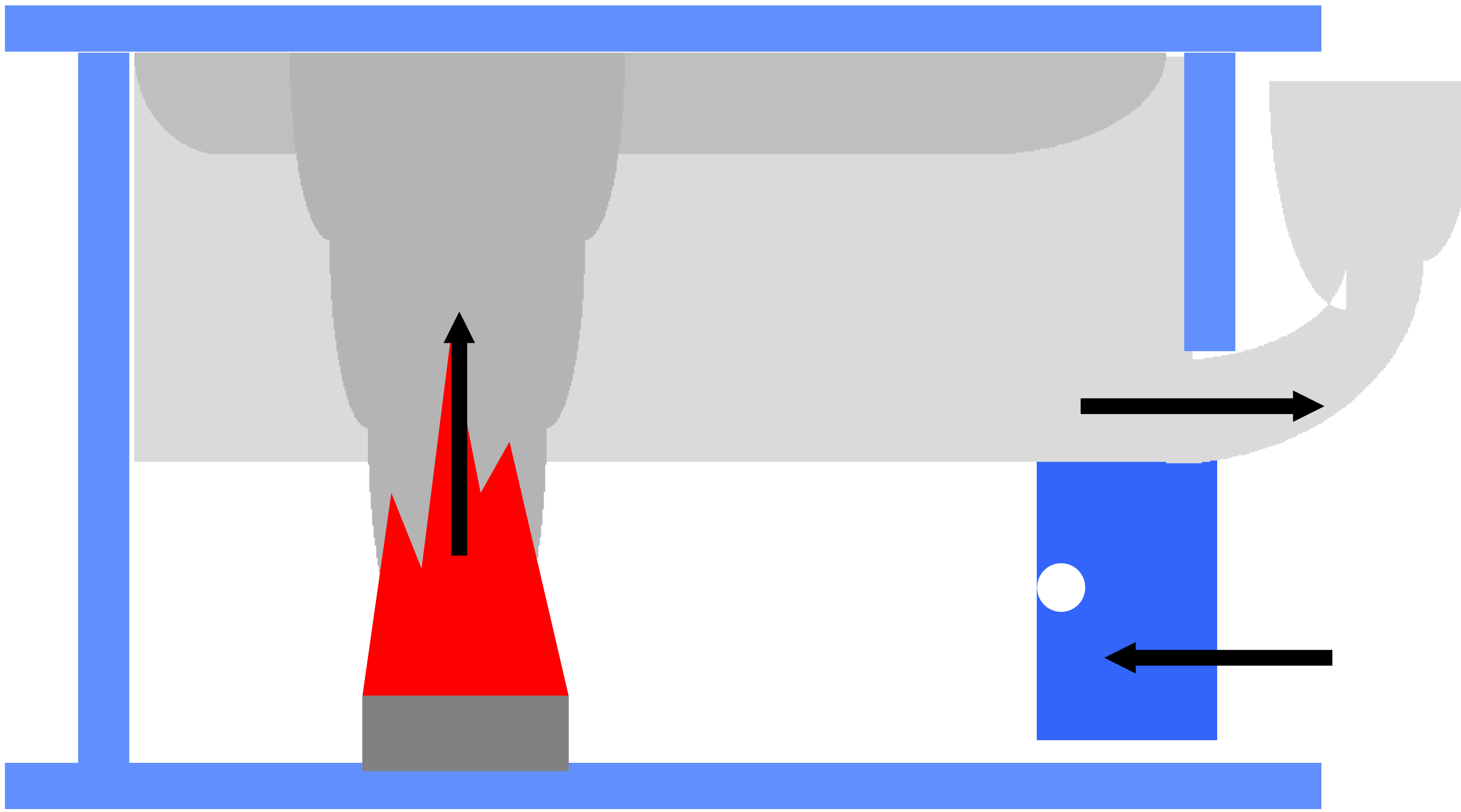
Multiple rooms



Summary – ventilation effects

- Vent flows are important aspect of enclosure fires, affecting mass / species / energy balances
- Issues related to roof vents and wall vents addressed
  - Flow rates and smoke layer heights
  - Constricted flow for roof vents
  - Ventilation limit for wall vents
- Other issues introduced
  - Wind / mechanical ventilation / multiple rooms

Preflashover vented period



Preflashover vented period

- Mass / species / energy balances
- Mechanical ventilation
- Vent flows
- Temperatures
- Gas / smoke concentrations
- Flashover estimates

Energy balance

- Upper layer balance

$$\dot{Q}_f = \dot{Q}_l + \dot{Q}_c$$

- Heat loss term

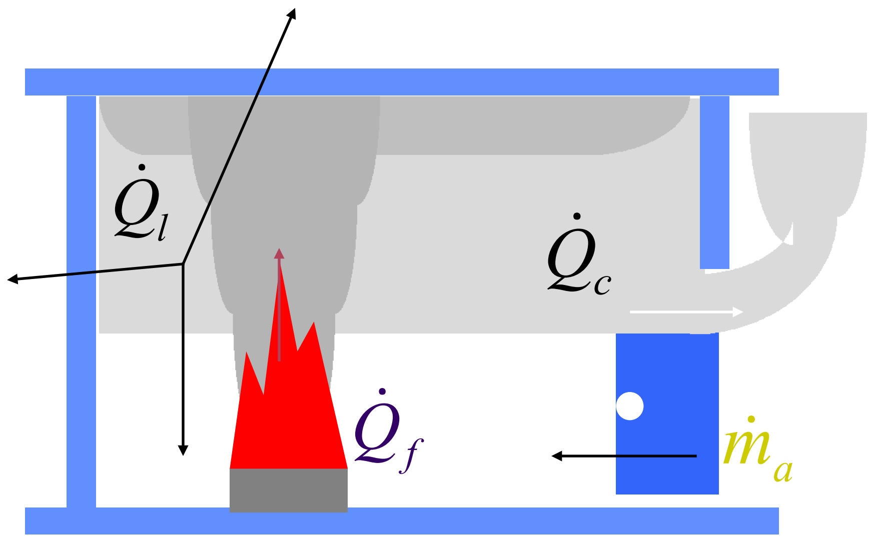
$$\dot{Q}_l = h_k A_s \Delta T$$

- Convective term

$$\dot{Q}_c = \dot{m}_a c_p \Delta T$$

- Solve for ΔT:

$$\Delta T = \frac{\dot{Q}_f}{\dot{m}_a c_p + h_k A_s} = \frac{\dot{Q}_{net}}{\dot{m}_a c_p}$$



The MQH correlation

- Dimensionless variables

$$\dot{m}_a \sim A_o \sqrt{H_o}$$

$$\frac{\Delta T}{T_o} = \frac{\dot{Q}_f}{\dot{m}_a c_p T_o + h_k A_s T_o} = \frac{\dot{Q}_f / \dot{m}_a c_p T}{1 + \dfrac{h_k A_s}{\dot{m}_a c_p}}$$

$$\frac{\Delta T}{T_o} = f\left[\frac{\dot{Q}_f}{\sqrt{g \rho_o c_p T_o A_o \sqrt{H_o}}}, \frac{h_k A_s}{\sqrt{g \rho_o c_p A_o \sqrt{H_o}}}\right]$$

The MQH correlation

- Statistical correlation of the form:

$$\frac{\Delta T}{T_o} = C\left(\frac{\dot{Q}_f}{\sqrt{g\rho_o c_p T_o} A_o \sqrt{H_o}}\right)^N \left(\frac{h_k A_s}{\sqrt{g\rho_o c_p} A_o \sqrt{H_o}}\right)^M$$

- Over 100 sets of room fire data
  - Fuels: Gas, wood, plastics
  - Range of room sizes, thermal properties
  - Bias towards low fires in center of room

The MQH correlation

- Values for C, N and M from regression:

$$\frac{\Delta T}{T_o} = 1.63 \left(\frac{\dot{Q}_f}{\sqrt{g \rho_o c_p T_o} A_o \sqrt{H_o}} \right)^{2/3} \left(\frac{h_k A_s}{\sqrt{g \rho_o c_p} A_o \sqrt{H_o}} \right)^{-1/3}$$

- For conventional values, this reduces to:

$$\Delta T = 6.85 \left(\frac{\dot{Q}_f^2}{A_o \sqrt{H_o} h_k A_s} \right)^{1/3}$$

Heat transfer coefficient

- Early stage - transient semi-infinite solid

$$\dot{q}'' = \frac{1}{\sqrt{\pi}}\sqrt{\frac{k\rho c}{t}}(T_g - T_o) \sim \sqrt{\frac{k\rho c}{t}}(T_g - T_o)$$

- Late stage - steady one-dimensional slab

$$\dot{q}'' = \frac{k}{\delta}(T_g - T_o)$$

- Effective heat transfer coefficient

$$h_k = MAX\left(\sqrt{\frac{k\rho c}{t}}, \frac{k}{\delta}\right)$$

Representative thermal properties

MATERIAL	k [kW/m.K]	p [kg/m3]	cp [kJ/kg.K]	a [m2/s]	kpc
Aluminum (pure)	2.06E-01	2710	0.895	8.49E-05	5.00E+02
Concrete	1.60E-03	2400	0.75	8.89E-07	2.88E+00
Aerated concrete	2.60E-04	500	0.96	5.42E-07	1.25E-01
Brick	8.00E-04	2600	0.8	3.85E-07	1.66E+00
Concrete block	7.30E-04	1900	0.84	4.57E-07	1.17E+00
Cement-asbestos board	1.40E-04	658	1.06	2.01E-07	9.76E-02
Calcium silicate board	1.25E-04	700	1.12	1.59E-07	9.80E-02
Alumina silicate block	1.40E-04	260	1	5.38E-07	3.64E-02
Gypsum board	1.70E-04	960	1.1	1.61E-07	1.80E-01
Plaster board	1.60E-04	950	0.84	2.01E-07	1.28E-01
Plywood	1.20E-04	540	2.5	8.89E-08	1.62E-01
Chipboard	1.50E-04	800	1.25	1.50E-07	1.50E-01
Fiber insulation board	5.30E-05	240	1.25	1.77E-07	1.59E-02
Glass fiber insulation	3.70E-05	60	0.8	7.71E-07	1.78E-03
Expanded polystyrene	3.40E-05	20	1.5	1.13E-06	1.02E-03

MQH correlation example

- Calculate the quasi-steady smoke layer temperature rise in the FMSNL enclosure based on the following assumptions:
  - Lining material is 2.54 cm thick gypsum wallboard
  - Fire burns at a steady HRR of 500 kW
  - There is a single 0.8 m wide by 2.0 m high door in one of the walls
  - There is no mechanical ventilation

MQH correlation example

- Solution:
  - Lining material is 2.54 cm thick gypsum wallboard
    - Want quasi-steady solution, so need k and d
    - $k = 1.7 \times 10^{-4}$ kW/m.K and $d = 0.0254$ m
    - $h_k = k/d = 6.7 \times 10^{-3}$ kW/m^2.K
  - Heat transfer surface area

$$A_s = 2 \cdot \left[(18.3 \times 12.2) + (18.3 \times 6.1) + (12.2 \times 6.1)\right] - (0.8 \times 2.0)$$
$$= 817\, m^2$$

  - Ventilation factor

$$A_o \sqrt{H_o} = 1.6\sqrt{2.0} = 2.26\, m^{5/2}$$

MQH correlation example

- Solution:

$$\Delta T = 6.85\left(\frac{\dot{Q}_f^2}{A_o\sqrt{H_o}h_k A_s}\right)^{1/3}$$

$$= 6.85\left(\frac{500^2}{(2.26)(6.7\times10^{-3})(817)}\right)^{1/3}$$

$$= 187C$$

MQH correlation example

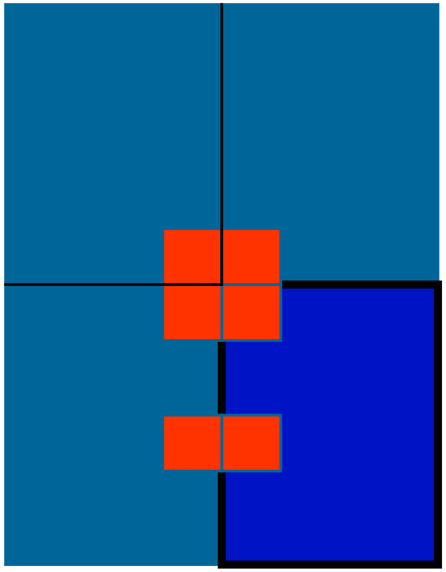
- Repeat the previous example calculation, but assume the fire only burns for 10 minutes
  - For this case, need to calculate the transient h_k:

$$h_k = \sqrt{\frac{k\rho c}{t}} = \sqrt{\frac{0.18}{600}} = 0.017\, kW/m^2.K$$

$$\Delta T = 6.85\left(\frac{500^2}{(2.26)(0.017)(817)}\right)^{1/3}$$

$$= 137C$$

Fires along walls and in corners

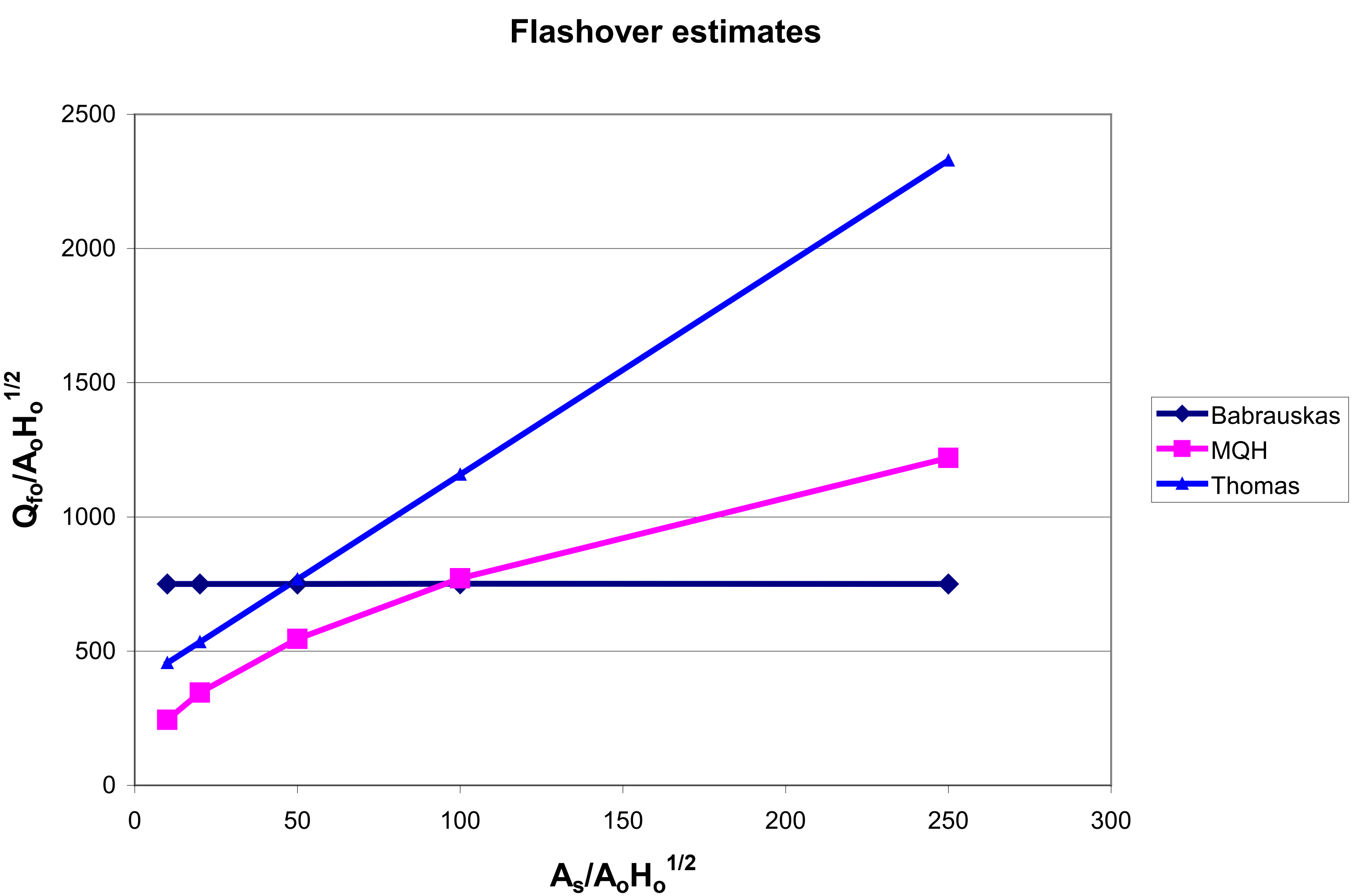


- Concept of reflection
  - Reduced entrainment rate
  - Higher temperatures
  - Longer entrainment height
- Mowrer and Williamson adjustment factors to MQH correlation
  - Fires along walls $$\Delta T = 1.3 \times \Delta T_{MQH}$$
  - Fires in corners $$\Delta T = 1.7 \times \Delta T_{MQH}$$

Flashover estimates

- Babrauskas $$\dot{Q}_{FO} = 750 A_o \sqrt{H_o}$$
- MQH $$\dot{Q}_{FO} = 610\left(A_o \sqrt{H_o} h_k A_s\right)^{1/2}$$
- Thomas $$\dot{Q}_{FO} = 7.8 A_s + 378 A_o \sqrt{H_o}$$
- Plot of $$\frac{\dot{Q}}{A_o \sqrt{H_o}} = f\left(\frac{A_s}{A_o \sqrt{H_o}}\right)$$

Flashover estimates



Flashover estimates

- Example: Determine the HRR to cause flashover in the standard fire test room
  - Dimensions: 2.4 m W x 3.6 m L x 2.4 m H

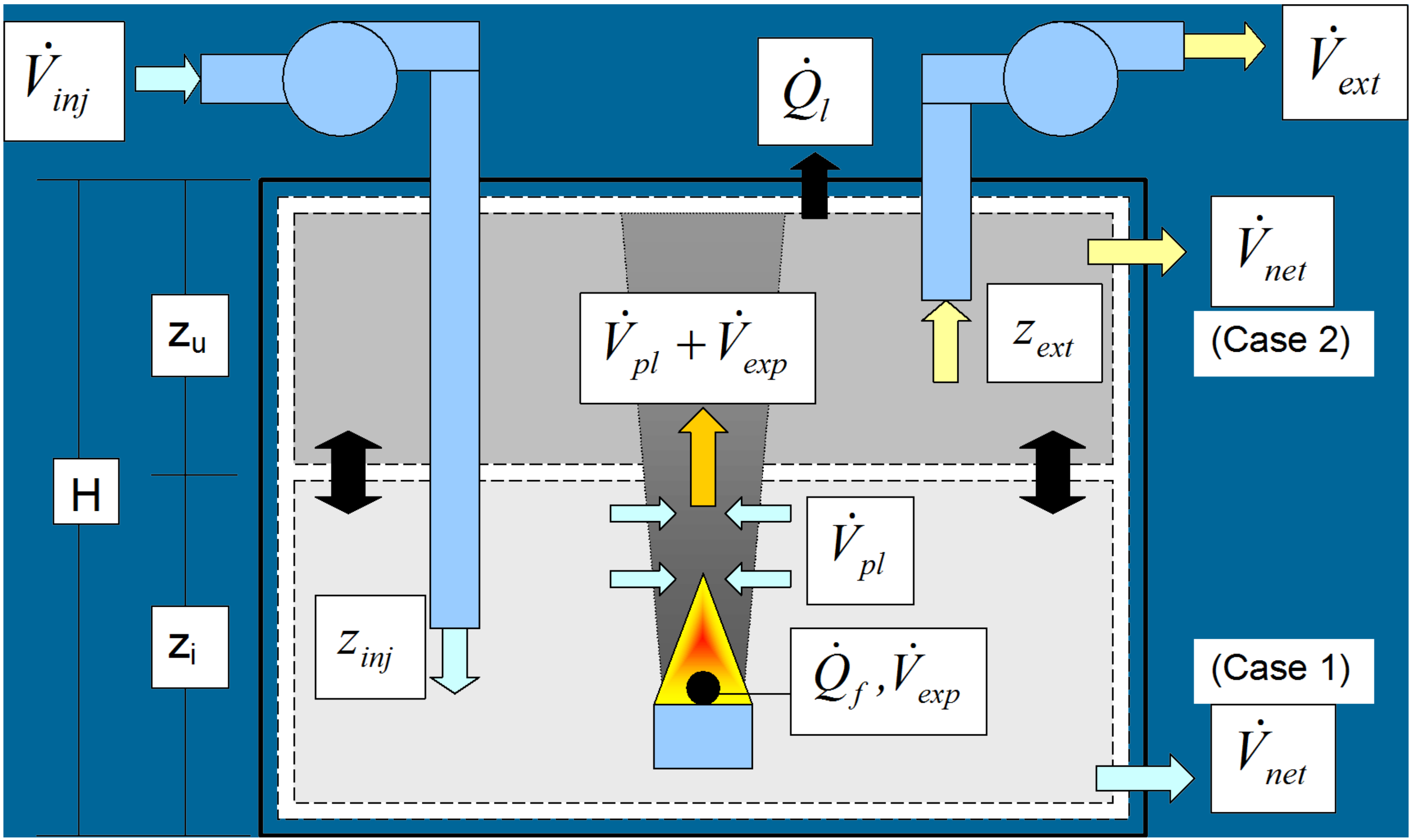
$$A_s = 4(2.4 \times 3.6) + 2(2.4 \times 2.4) = 46.1 m^2$$

  - Doorway: 0.8 m W x 2.0 m H

$$A_o \sqrt{H_o} = 1.6\sqrt{2.0} = 2.3 m^{5/2}$$

  - Babrauskas: $\dot{Q}_{FO} = 750 A_o \sqrt{H_o} = 750(2.3) \approx 1725 kW$
  - Thomas: $\dot{Q}_{FO} = 7.8(46.1) + 378(2.3) \approx 1230 kW$

Mechanically ventilated spaces



Mechanically ventilated spaces

- Foote-Pagni-Alvares correlation
  - Analogous to MQH correlation
  - Based on limited data in single enclosure
  - Quasi-steady temperature rise

$$\frac{\Delta T}{T_o} = 0.63\left(\frac{\dot{Q}_f}{\dot{m}c_p T_o}\right)^{0.72}\left(\frac{h_k A_s}{\dot{m}c_p}\right)^{-0.36}$$

Mechanically ventilated spaces

- Foote-Pagni-Alvares correlation example
  - Calculate the temperature rise in the FMSNL enclosure for a HRR of 500 kW and an mechanical ventilation rate of 10 ach
  - Solution
    - To = 293 K (remember to use absolute temperature)
    - h_k and A_s as in the MQH example
    - Mass flow rate calculated as

$$\dot{m} = \rho \dot{V} = (1.2 kg / m^3)(3.8 m^3 / s) = 4.6 kg / s$$

Mechanically ventilated spaces

- Foote-Pagni-Alvares correlation example
  - Solution

$$\frac{\Delta T}{T_o} = 0.63\left(\frac{\dot{Q}_f}{\dot{m}c_pT_o}\right)^{0.72}\left(\frac{h_kA_s}{\dot{m}c_p}\right)^{-0.36}$$

$$= 0.63\left(\frac{500}{(4.6)(1.0)(293)}\right)^{0.72}\left(\frac{(0.017)(817)}{(4.6)(1.0)}\right)^{-0.36}$$

$$= 0.21$$

$$\Delta T = 0.21T_o = 0.21(293) = 61K$$

Summary – mechanical ventilation

- Mechanical ventilation provides additional pathways for air and smoke flow
  - Influences mass, species and energy equations
- Injection tends to pressurize a fire room, pushing smoke out through leakage paths
- Extraction tends to depressurize a fire room, pulling fresh air in through leakage paths
- Locations of leakage paths (e.g., ceiling or floor) and location of smoke layer interface influence the effects of mechanical ventilation

Summary – preflashover fires

- Average upper layer temperature based on energy and mass balances
- Correlations developed for
  - closed-form estimates of preflashover temperatures
    - MQH correlation for naturally ventilated enclosures
    - FPA correlation for mechanically ventilated enclosures
  - flashover estimates
    - Babrauskas
    - MQH
    - Thomas

Smoke and visibility

- Light attenuation and visibility through smoke can be estimated based on the soot mass concentration within the smoke layer
- The light extinction coefficient, K, is directly proportional to the soot mass concentration as:

$$K = K_m \rho Y_{soot}$$

  - where K_m is the specific extinction coefficient and Y_s is the soot mass fraction in the smoke

Smoke and visibility

- Seader and Einhorn suggested values for Km of
  - *Km* = 7,600 m2/kg for flaming combustion and
  - *Km* = 4,400 m2/kg for pyrolysis smoke.
  - These values have been widely used for light attenuation and visibility calculations

- Mulholand and Croarkin have suggested a value of *Km* = 8,700 m2/kg for flaming combustion of wood and plastic fuels
  - This value is now more widely used (e.g., in FDS)

Smoke and visibility

- Light attenuation is calculated in accordance with Bougher's Law for monochromatic light:

$$I / I_o = e^{-KL}$$

- Visibility through smoke varies inversely with the light extinction coefficient:

$$S = C / K$$

  - where S is the visibility distance (m) and C is a constant related to the object being viewed

Smoke and visibility

- Mulholand gives the following values for C:
  - C = 8 for light-emitting signs $I / I_o = e^{-8} = 3.35 \times 10^{-4}$
  - C = 3 for light-reflecting signs $I / I_o = e^{-3} = 0.05$
- These values should be used with caution because they will depend on the ambient light levels

Smoke and visibility

- To calculate smoke obscuration and visibility, the soot mass fraction, Ys, is calculated
- First, the soot generation rate is calculated

$$\dot{m}_{s,gen} = f_s \dot{m}_f = \frac{\dot{Q}_f}{(\Delta H_c / f_s)}$$

  - where f_s is the soot yield of the fuel
  - Soot yields are tabulated in the SFPE Handbook (Tewarson chapter) for a large number of fuels

Smoke and visibility

- Representative soot yields

Table 18-3. Smoke Particulate Yield (Klote and Milke, 2002)

Material	Particulate Yield - y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool (100-percent)	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylmethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118

Smoke and visibility

- Soot mass concentration
  - Unventilated rooms:

$$\rho Y_s = \frac{\left(Q_f / V\right)}{(\Delta H_c / f_s)}$$

  - Ventilated rooms:

$$Y_s = \frac{\dot{m}_s}{\dot{m}_{tot}} = \frac{\left(\dot{Q}_f / \dot{V}\right)}{\rho(\Delta H_c / f_s)} \qquad \rho Y_s = \frac{\left(\dot{Q}_f / \dot{V}\right)}{(\Delta H_c / f_s)}$$

Smoke and visibility

- Unventilated room example
  - Estimate the average mass concentration of soot and the visibility distance within the 18.3 m by 12.2 m by 6.1 m FMSNL enclosure at 240 s and 600 s after ignition
    - Assume the enclosure is unventilated
    - Assume propylene (C_3H_6) is the fuel
    - Assume the fire grows as a t-squared fire to a HRR of 500 kW in 240 s, then burns at a constant HRR of 500 kW for another 360 s.

Smoke and visibility

- Unventilated room example
  - For propylene (C_3H_6)

$$\Delta H_c = 46.4\, MJ / kg_f$$

$$f_s = 0.095\, kg_s / kg_f$$

$$\Delta H_c / f_s = 488.4 MJ / kg_s$$

  - Fire heat release

$$Q_f(@240\ s) = \int_o^{240} \left(\frac{500}{(240)^2} \right) t^2 dt = \left(\frac{500}{(240)^2} \right) \left(\frac{(240)^3}{3} \right) = 40{,}000\, kJ$$

$$Q_f(@600\ s) = Q_f(@240\ s) + \int_{240}^{600} 500 dt = 40{,}000\, kJ + 180{,}000\, kJ = 220{,}000\, kJ$$

Smoke and visibility

- Unventilated room example
  - Heat release per unit volume

$$Q_f / V(@240\ s) = 40{,}000\, kJ / 1{,}382\, m^3 = 28.9\, kJ / m^3$$

$$Q_f / V(@600\ s) = 220{,}000\, kJ / 1{,}382\, m^3 = 159.2\, kJ / m^3$$

  - Soot mass concentration

$$\rho Y_{soot}(@240\, s) = \frac{28.9\, kJ / m^3}{488.42 \times 10^3\ kJ / kg_{soot}} = 5.92 \times 10^{-5}\, kg_{soot} / m^3$$

$$\rho Y_{soot}(@600\, s) = \frac{159.2\, kJ / m^3}{488.42 \times 10^3\ kJ / kg_{soot}} = 3.26 \times 10^{-4}\, kg_{soot} / m^3$$

Smoke and visibility

- Unventilated room example
  - Extinction coefficient

$$K(@240\,s) = K_m \rho Y_{soot} = (8{,}700\,m^2 / kg_{soot})(5.92\times10^{-5}\,kg_{soot} / m^3) = 0.52\,m^{-1}$$

$$K(@600\,s) = K_m \rho Y_{soot} = (8{,}700\,m^2 / kg_{soot})(3.26\times10^{-4}\,kg_{soot} / m^3) = 2.83\,m^{-1}$$

  - Visibility of light-reflecting sign through smoke

$$S(@240\,s) = 3/0.52\,m^{-1} = 5.8\,m\,(19\,ft)$$

$$S(@600\,s) = 3/2.83\,m^{-1} = 1.1\,m\,(3.6\,ft)$$

Smoke and visibility

- Ventilated room example
  - Estimate the average mass concentration of soot and the visibility distance within the 18.3 m by 12.2 m by 6.1 m FMSNL enclosure under quasi-steady conditions assuming the enclosure is mechanically ventilated at 10 ach
    - Assume propylene (C_3H_6) is the fuel burned in the FMSNL fire tests
    - Assume the fire burns at a constant HRR of 500 kW for another 360 s.

Smoke and visibility

- Ventilated room example
  - Volumetric flow rate

$$\dot{V} = \frac{10 \cdot (18.3m \times 12.2m \times 6.1m)}{3{,}600\, s} = 3.8m^3 / s$$

  - HRR/Volumetric flow rate

$$\dot{Q}_f / \dot{V} = \frac{500kW}{3.8m^3 / s} = 131.6\, kJ / m^3$$

Smoke and visibility

- Ventilated room example
  - Soot mass concentration

$$\rho Y_s = \frac{\left(\dot{Q}_f / \dot{V}\right)}{(\Delta H_c / f_s)} = \frac{131.6\,kJ/m3}{488.4\times10^3\,kJ/kg_s} = 2.7\times10^{-4}\,kg_s/m^3$$

  - Extinction coefficient

$$K = K_m \rho Y_{soot} = (8{,}700\,m^2/kg_s)(2.7\times10^{-4}\,kg_s/m^3) = 2.35\,m^{-1}$$

  - Visibility of light-reflecting sign through smoke

$$S = 3/2.35\,m^{-1} = 1.3\,m\,(4.2\,ft)$$

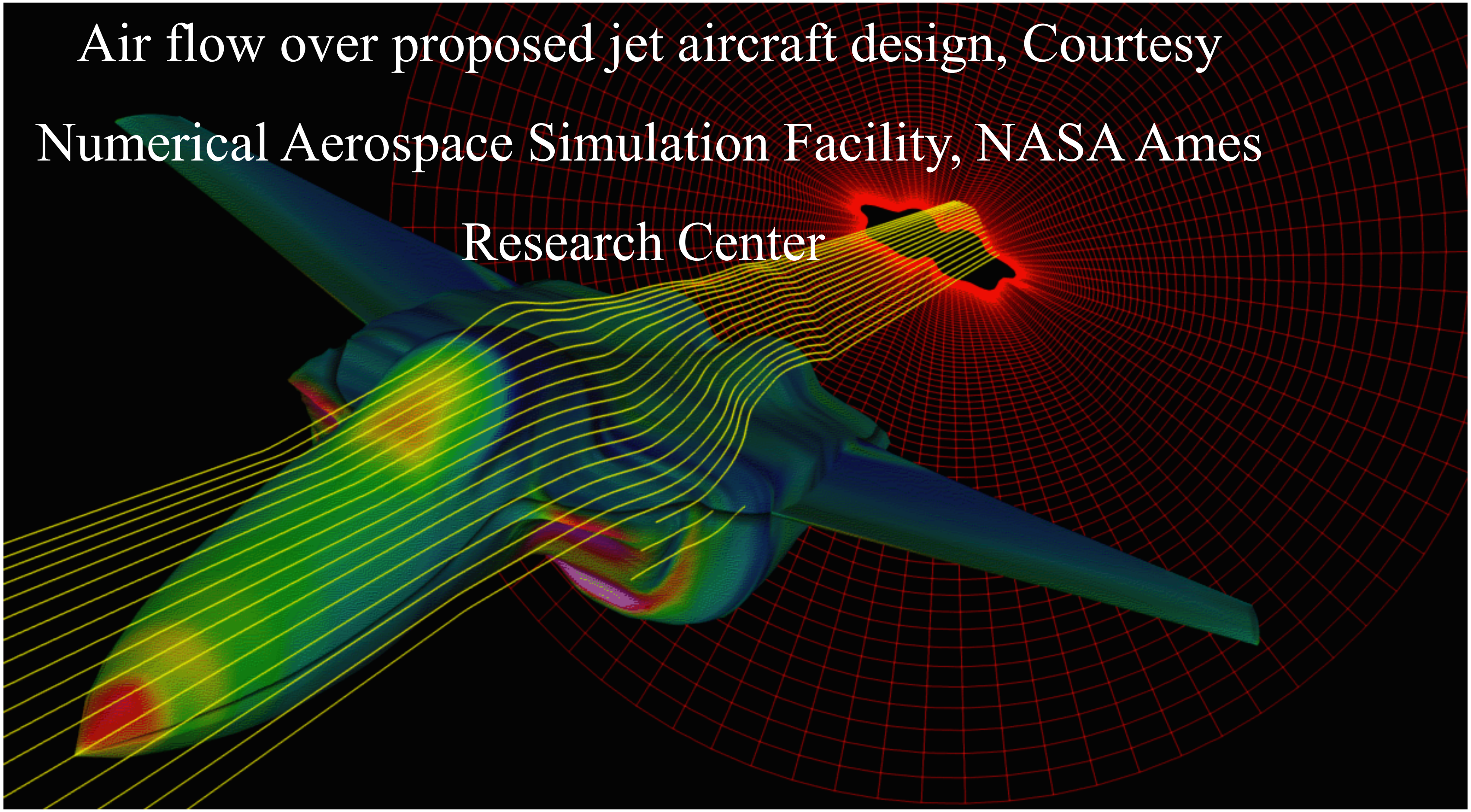
Summary – enclosure fires

- This presentation has introduced a number of important factors in enclosure fires
  - Two-layer zone modeling control volumes
  - Pressure effects in enclosure fires
  - Vent flows and mechanical ventilation
  - Smoke concentrations and visibility
- Computer-based fire models incorporate these effects in different ways
  - Should understand how models treat phenomena

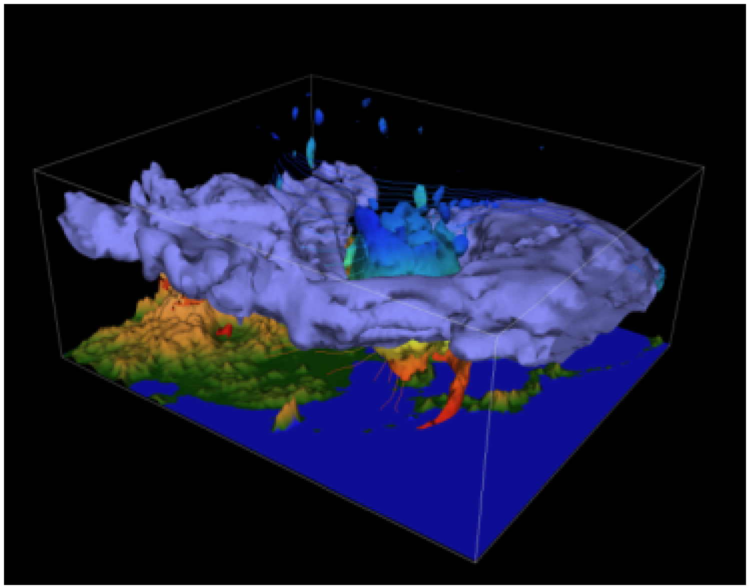
Overview of FDS

- Basic Assumptions of FDS
  - Low Mach Number Approximation
  - Large Eddy Simulation
  - Fire and Combustion Approaches
- Plume Simulations
- Verification and Validation
- Fire Modeling for FPE Design
- Fire Modeling for Fire Forensics and Reconstructions

Aerodynamics



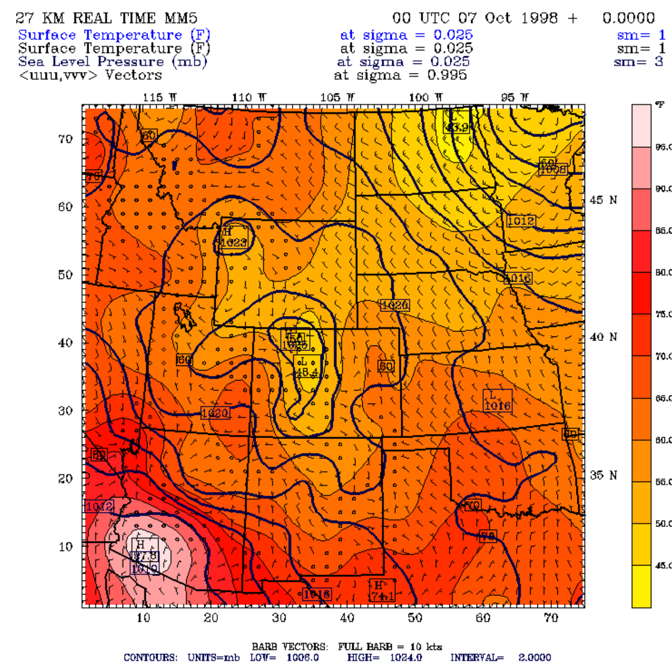
Weather Prediction



Development of a Cyclone in the Sea of Japan, Courtesy National Center for Atmospheric Research (NCAR)

Regional Weather Prediction, US Midwest and Mountain States,

Courtesy NCAR



Basic Conservation Equations for Single Species

Conservation of Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

Conservation of Momentum

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \rho \mathbf{u}\mathbf{u} = -\nabla p + \rho \mathbf{g} + \nabla \cdot \tau$$

Conservation of Energy

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot \rho h \mathbf{u} = \frac{Dp}{Dt} + \dot{q}''' + \nabla \cdot k \nabla T$$

Equation of State

$$p = \mathcal{R} \rho T$$

Turbulence

Large Eddy Simulation

Fire/Combustion

Low Mach Number

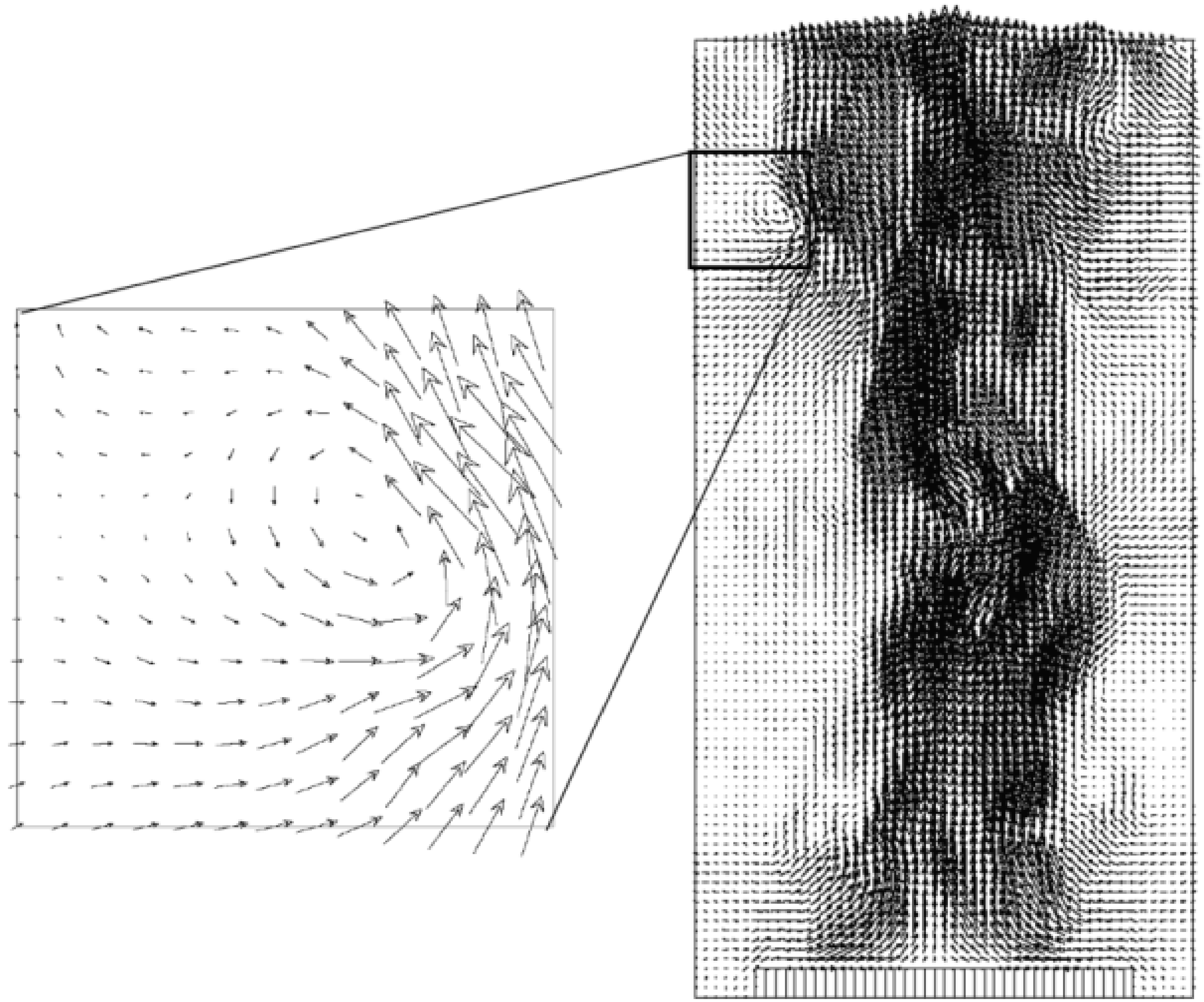
Approximation

$$p_0 = \mathcal{R} \rho T$$

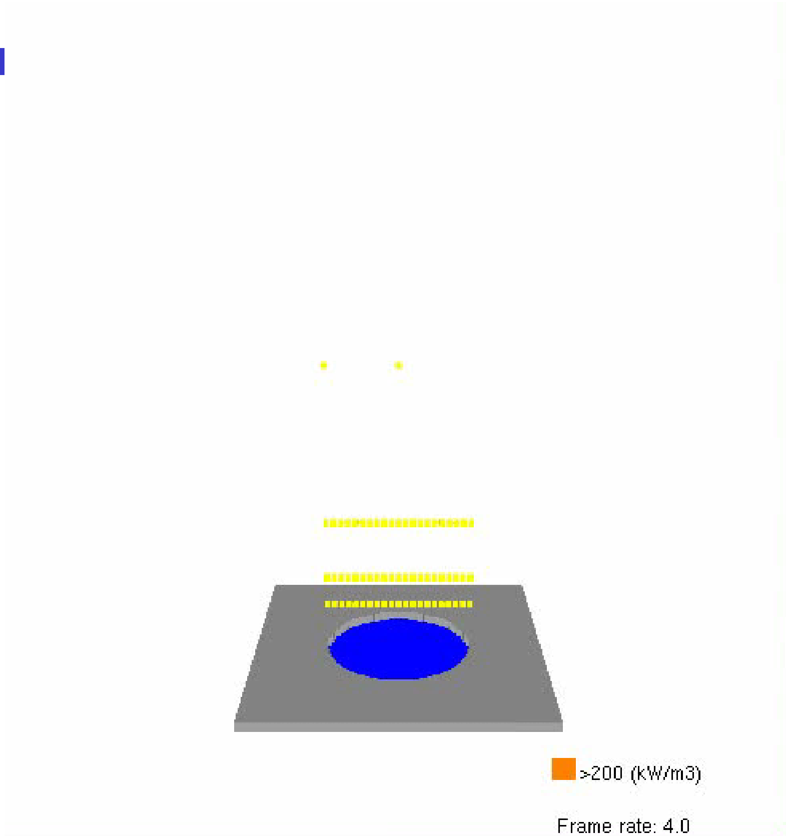
What are the unknowns? Density ρ; Velocity Components u, v, w; Enthalpy h, Pressure p

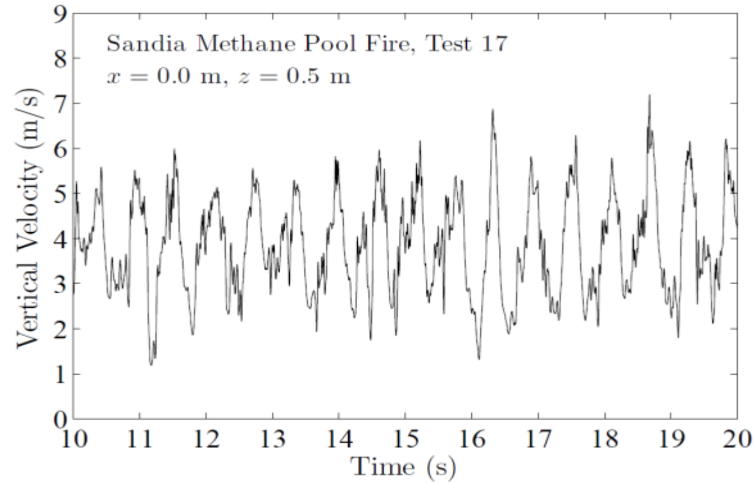
What needs to be provided? $\dot{q}'''$, the fire; τ, the (turbulent) viscous stresses, $\nabla \cdot k \nabla T$, thermal conductivity

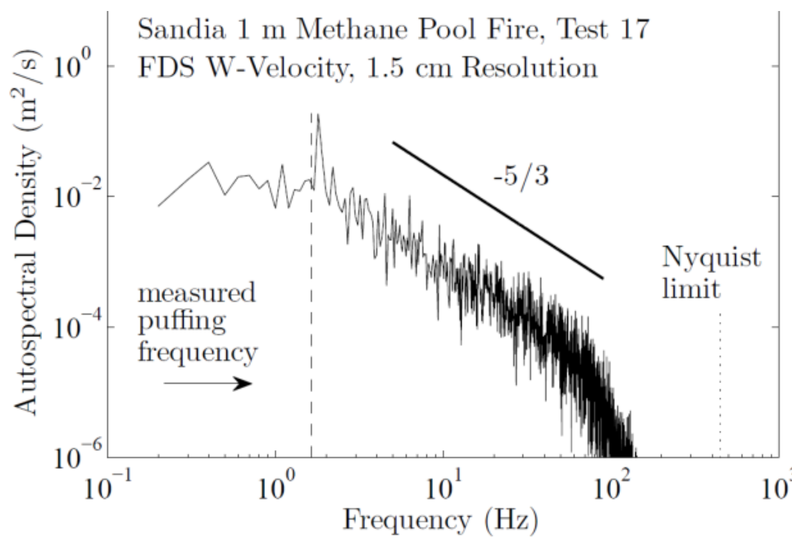
Large Eddy Simulation



Sandia 1 m CH4, Test 17, Measured Puffing Frequency = 1.65 Hz



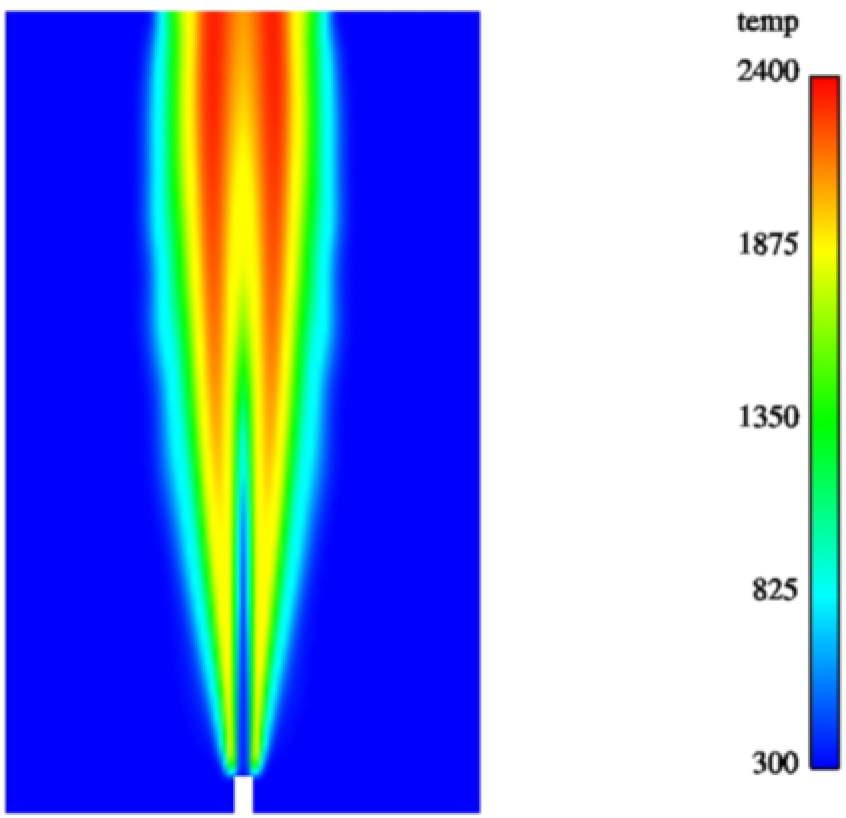




$$f \cong \frac{1.5}{\sqrt{D}} \text{ Hz}$$

S. R. Tieszen, T. J. O'Hern, R. W. Schefer, E. J. Weckman, and T. K. Blanchat, Experimental study of the flow field in and around a one meter diameter methane fire, Comb. Flame, 129:378-391, 2002.

Combustion

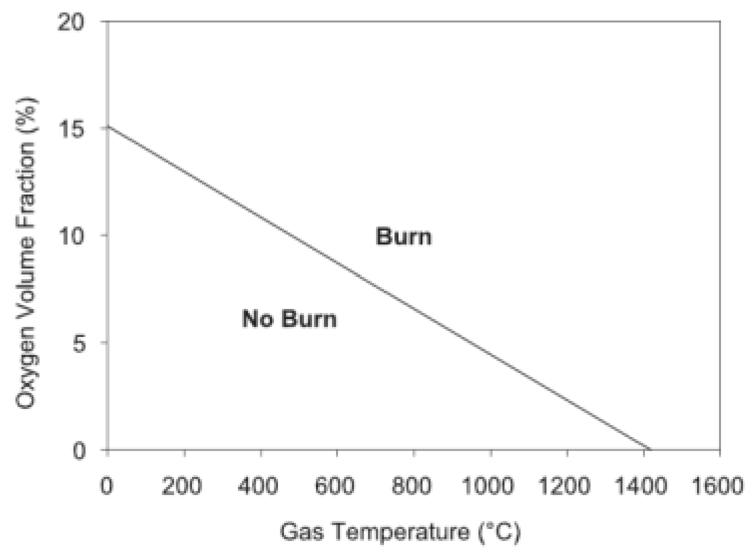


Simulation of a burner flame, courtesy Convergent Technologies

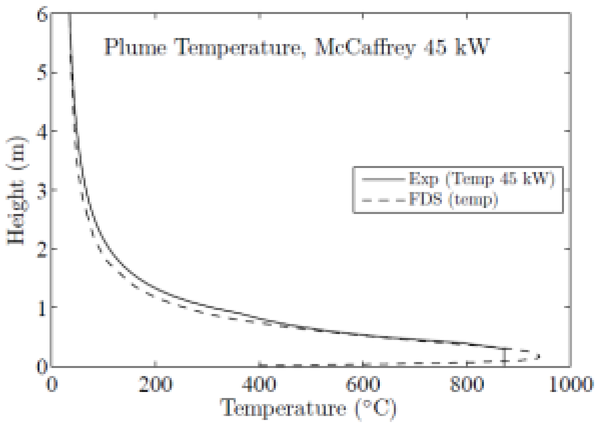
"Lumped Species" Approach

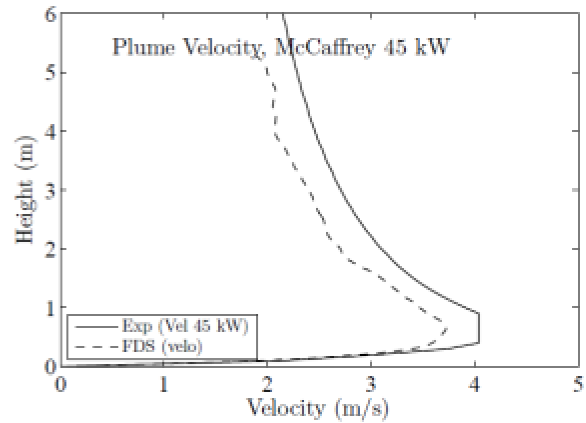
Generalization of the Mixture Fraction concept – instead of tracking a single variable, track at least two, the fuel and its products. This then allows for a local extinction model.

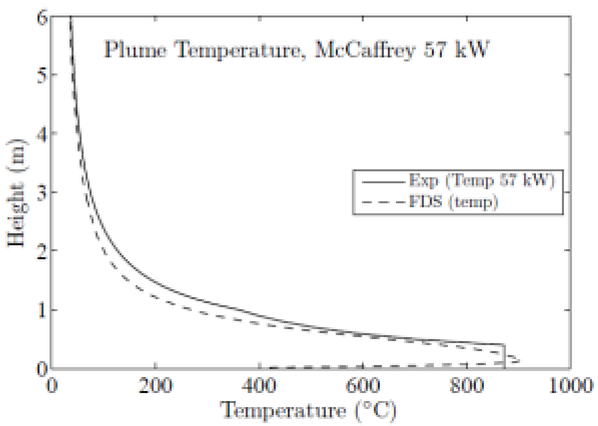
$$\underbrace{2\,(O_2 + (.79/.21)N_2)}_{\text{Background (Oxidant)},\ Z_0} + \underbrace{CH_4}_{\text{Fuel},\ Z_1} \longrightarrow \underbrace{CO_2 + 2H_2O + 2(.79/.21)N_2}_{\text{Products},\ Z_2}$$

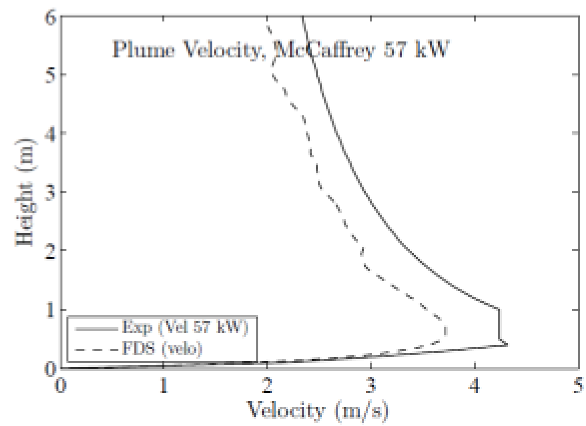


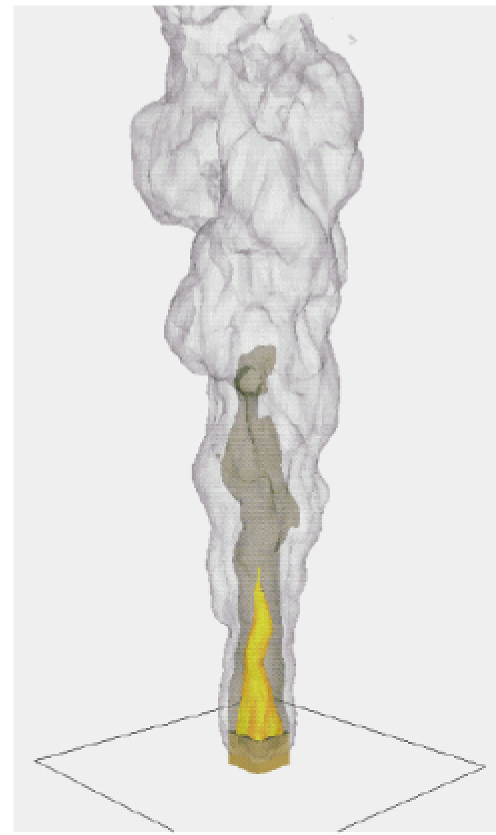
McCaffrey's Plume Measurements







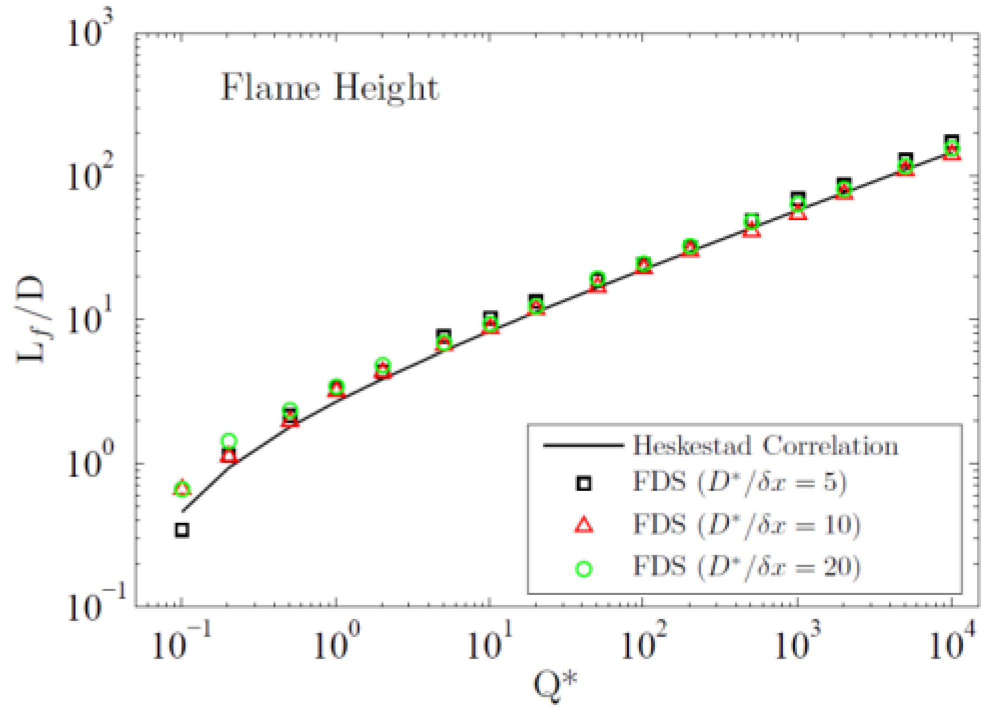




Heskestad Flame Height Correlation

$$\frac{L_f}{D} = 3.7\,(Q^*)^{2/5} - 1.02$$

$$Q^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}\, D^{5/2}}$$



Grid Resolution

Characteristic length scale for fire plume correlations:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \quad ; \quad Q^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}\, D^{5/2}} \quad ; \quad Q^* = \left(\frac{D^*}{D}\right)^{5/2}$$

Where does this characteristic length come from? Consider the Energy Conservation equation

$$\rho c_p \frac{DT}{Dt} = \dot{q}''' + \nabla \cdot k \nabla T + \quad \ldots$$

Non-dimensionalize according to

$$\mathbf{x}^* = \mathbf{x}/D^* \quad ; \quad \mathbf{u}^* = \mathbf{u}/\sqrt{gD^*} \quad ; \quad t^* = t/\sqrt{D^*/g} \quad ; \quad \rho^* = \rho/\rho_\infty \quad ; \quad T^* = T/T_\infty$$

The Energy equation is now written in non-dimensional form

$$\rho^* \frac{DT^*}{Dt^*} = \dot{q}'''^* + \nabla \cdot k^* \nabla T^* + \quad \ldots$$

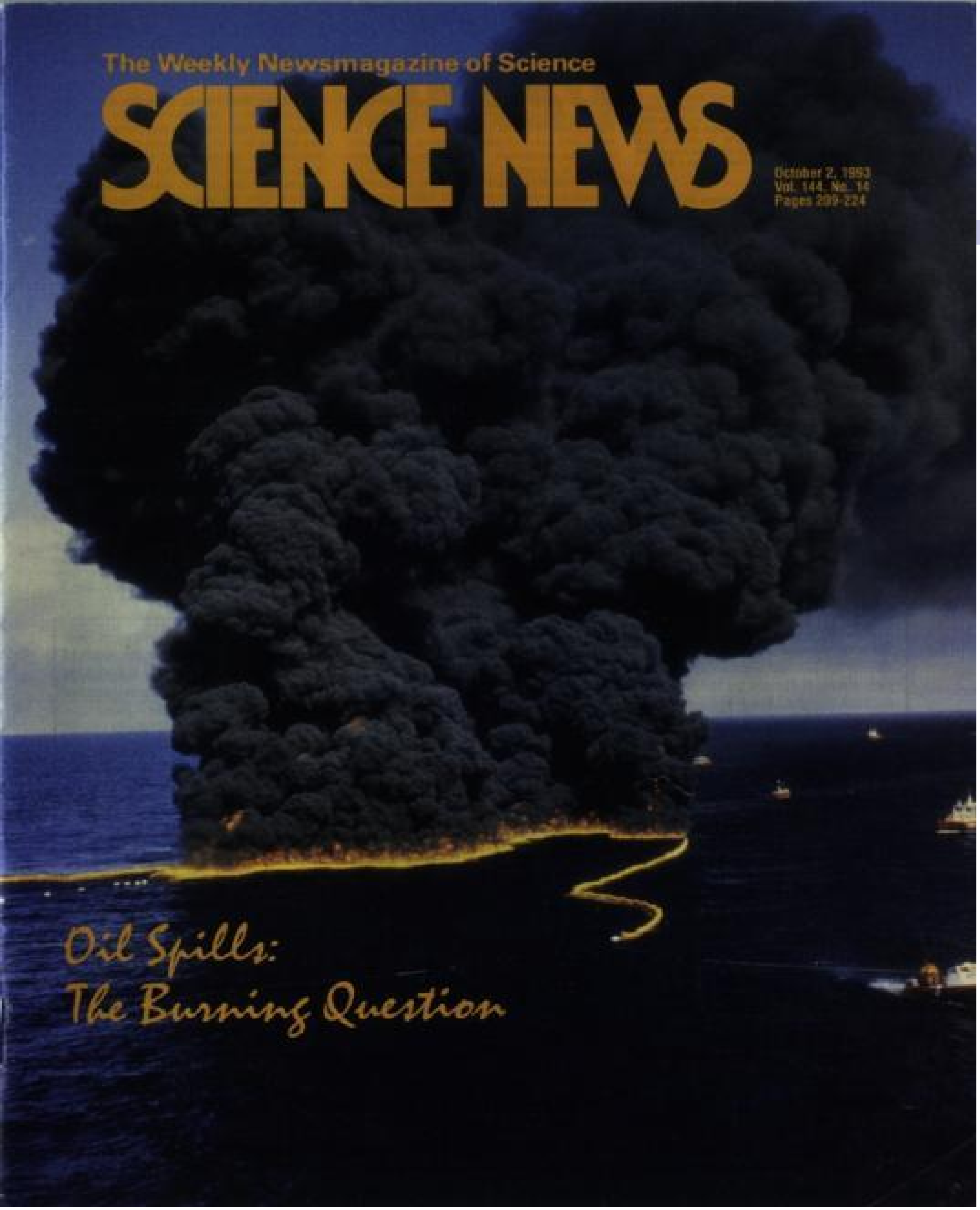
where

$$\dot{q}'''^* = \frac{\sqrt{D^*}}{\rho_\infty c_p T_\infty \sqrt{g}}\, \dot{q}'''$$

Integrating the local HRR over the entire domain

$$\int \dot{q}'''^*\, dV^* = \frac{\int \dot{q}'''\, dV}{\rho_\infty c_p T_\infty \sqrt{g}\, D^{*5/2}} = 1$$

15 m diesel fuel fire, Little Sand Island, Mobile Bay. Courtesy Doug Walton, NIST

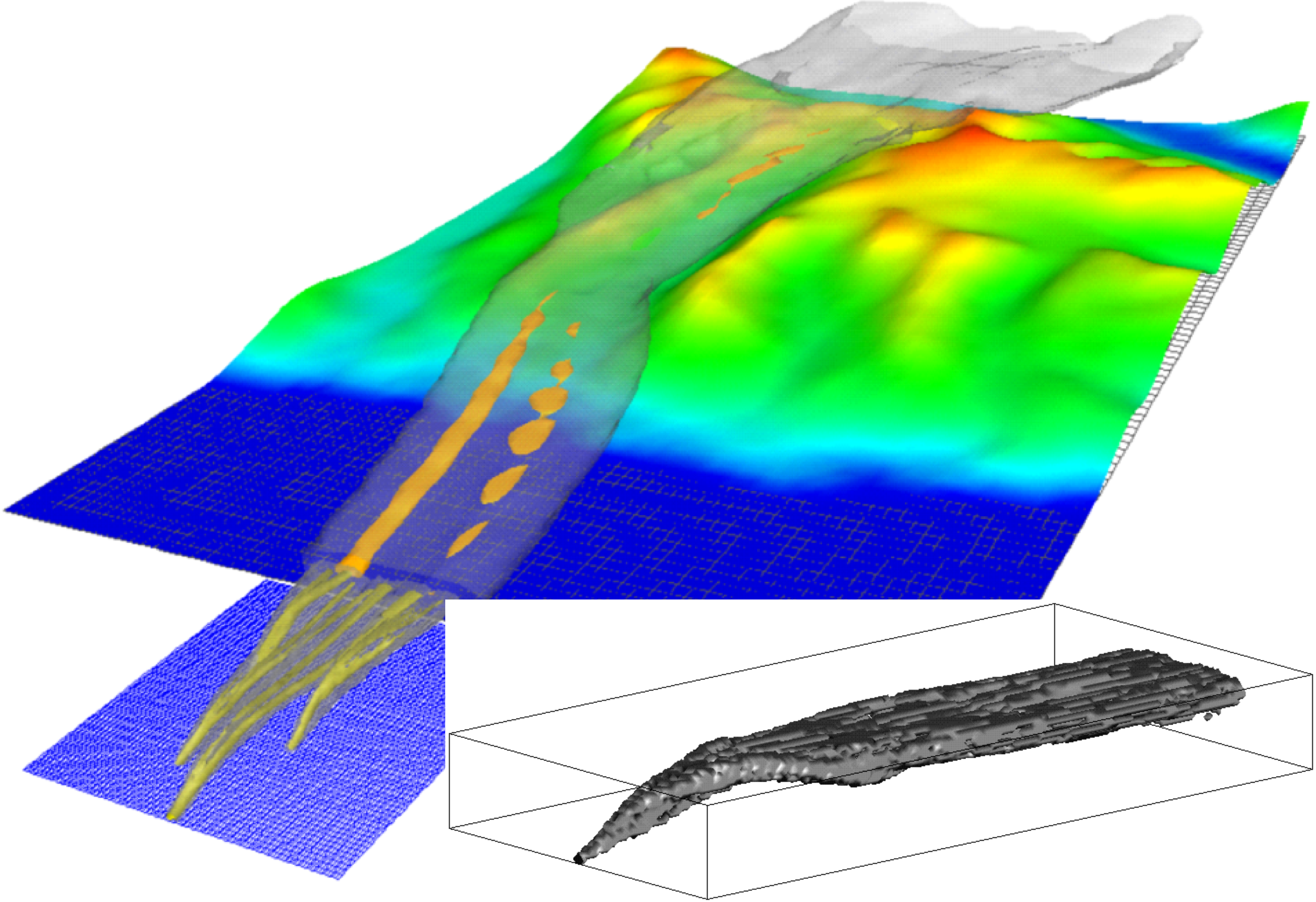


Case Study:

In situ burning
of spilled crude oil

Sponsors:

US Minerals Management Service
Alaska Department of
Environmental Conservation
US Coast Guard

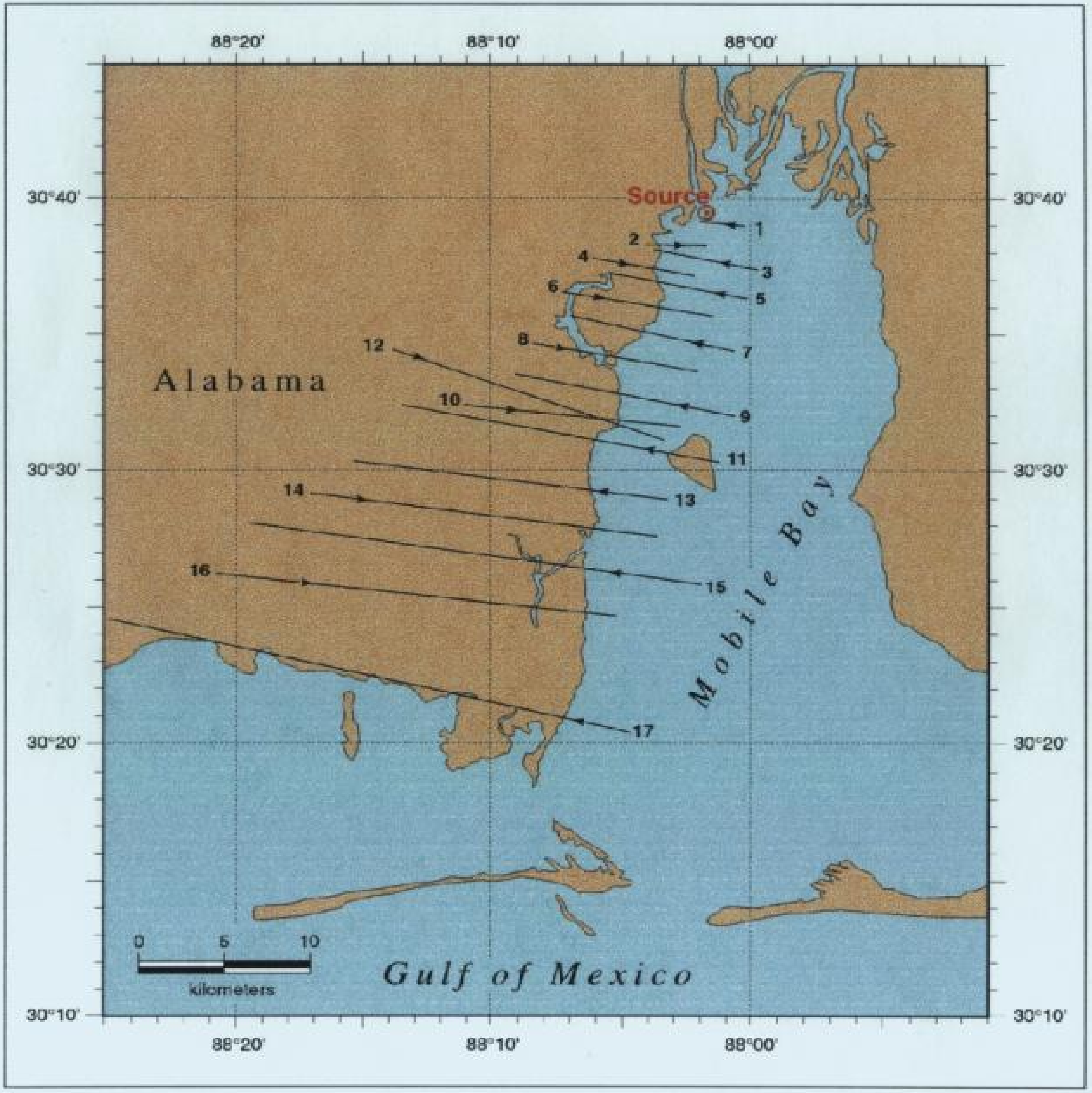


Alaska Clean Seas Oil Burn Experiment, Prudhoe Bay, 1994

NIST ALOFT Model –

A Large Outdoor Fire plume

Trajectory



Map showing flight path of aircraft performing Lidar measurements of the smoke plume, courtesy SRI, International

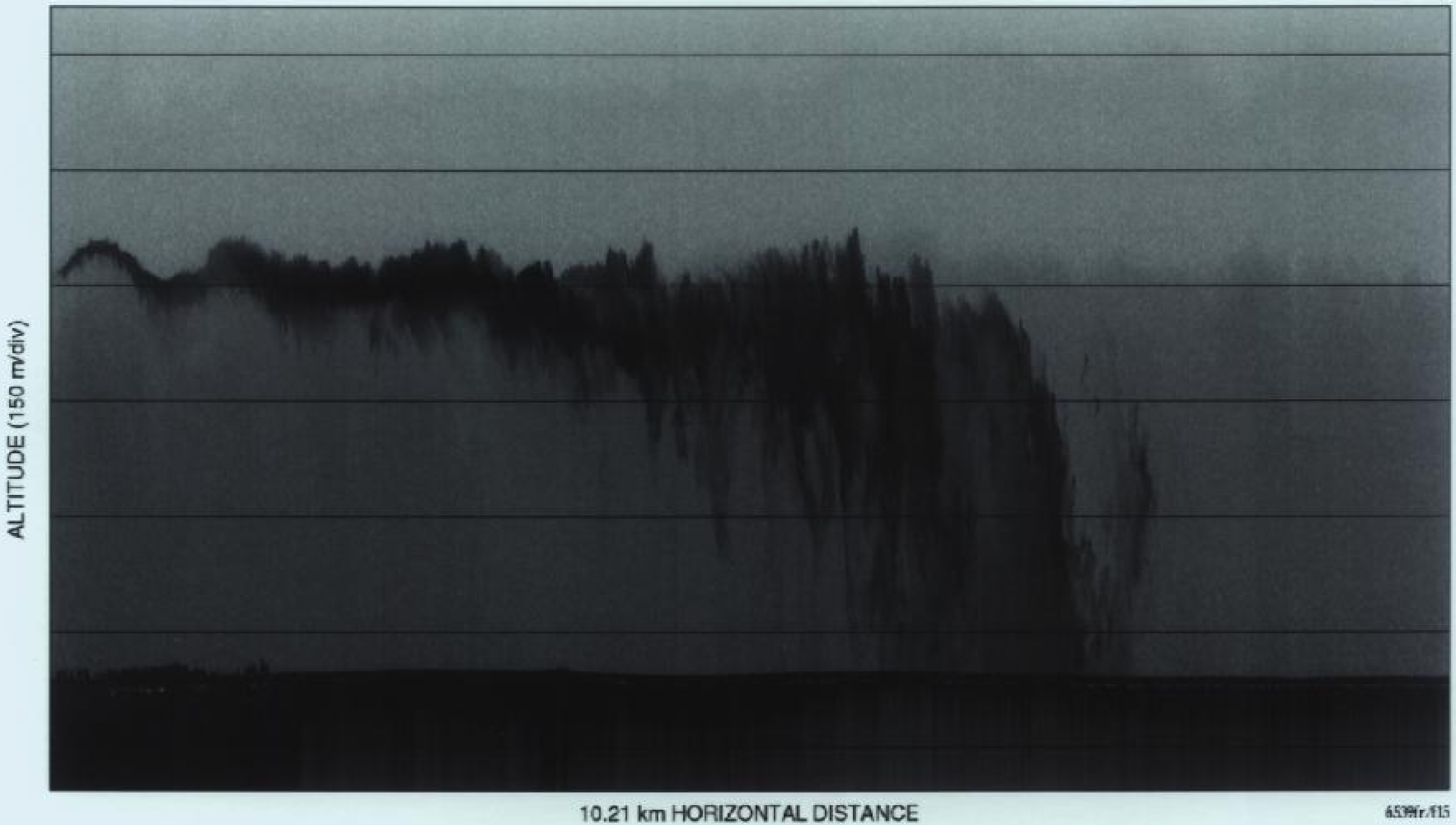
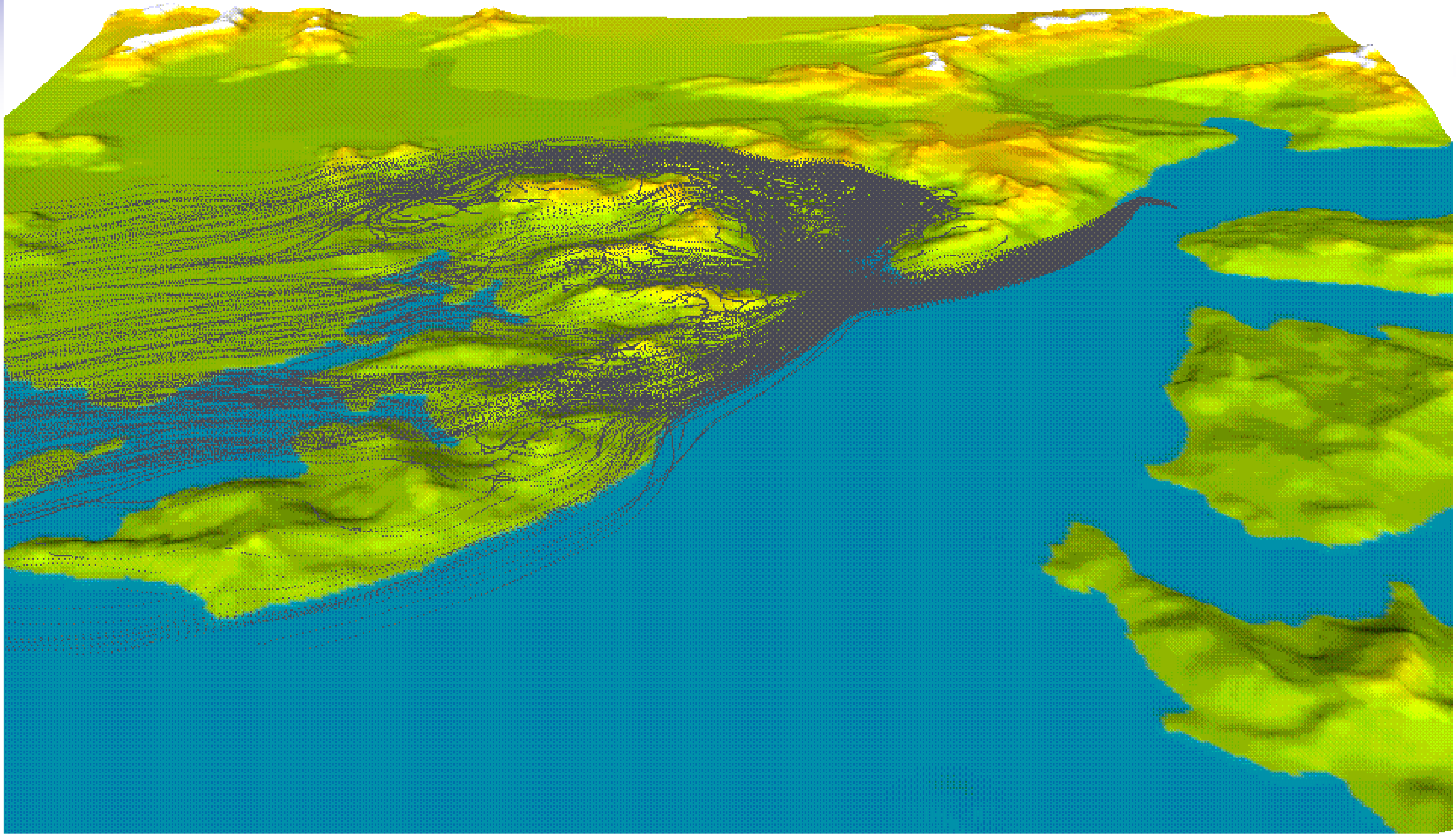
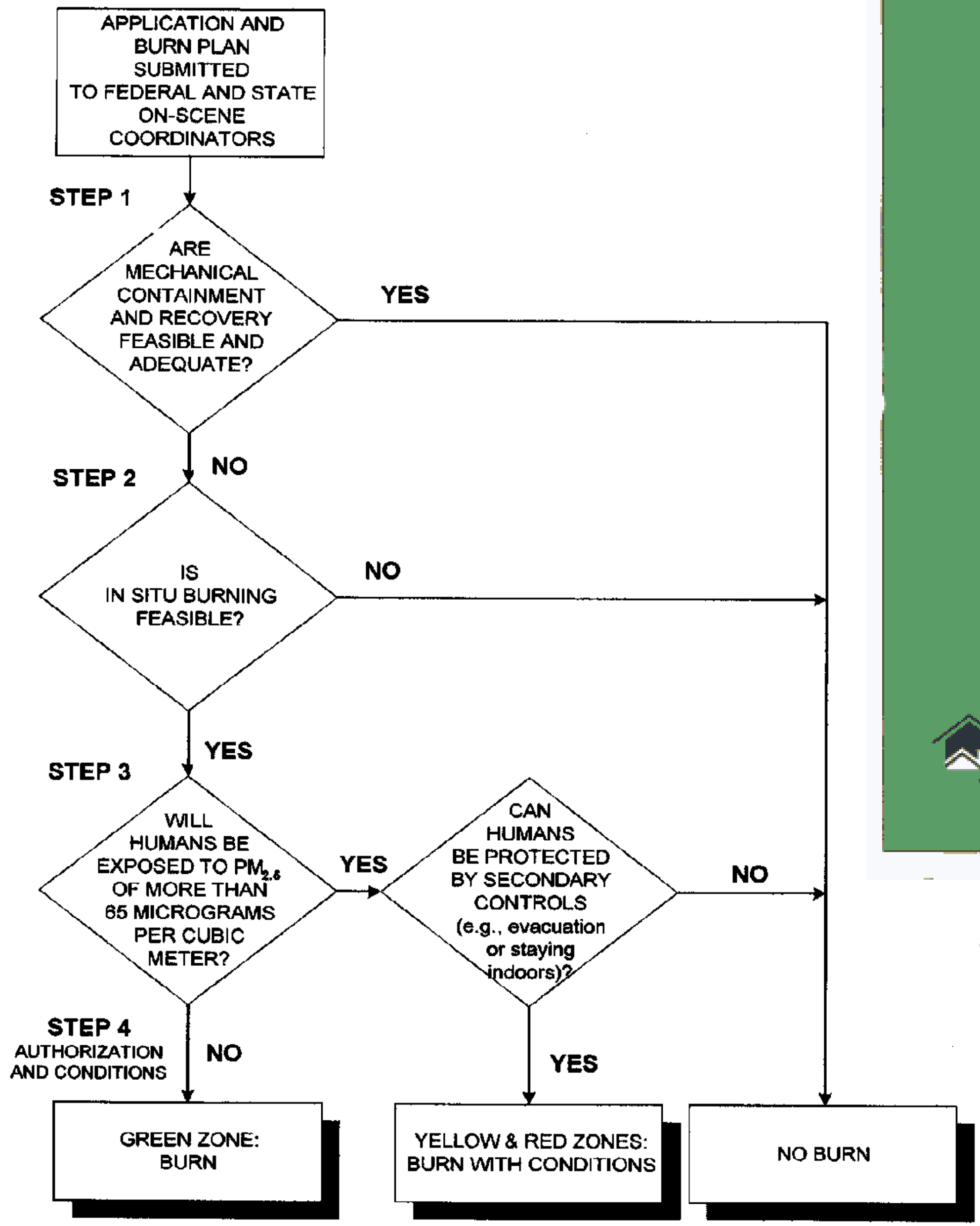


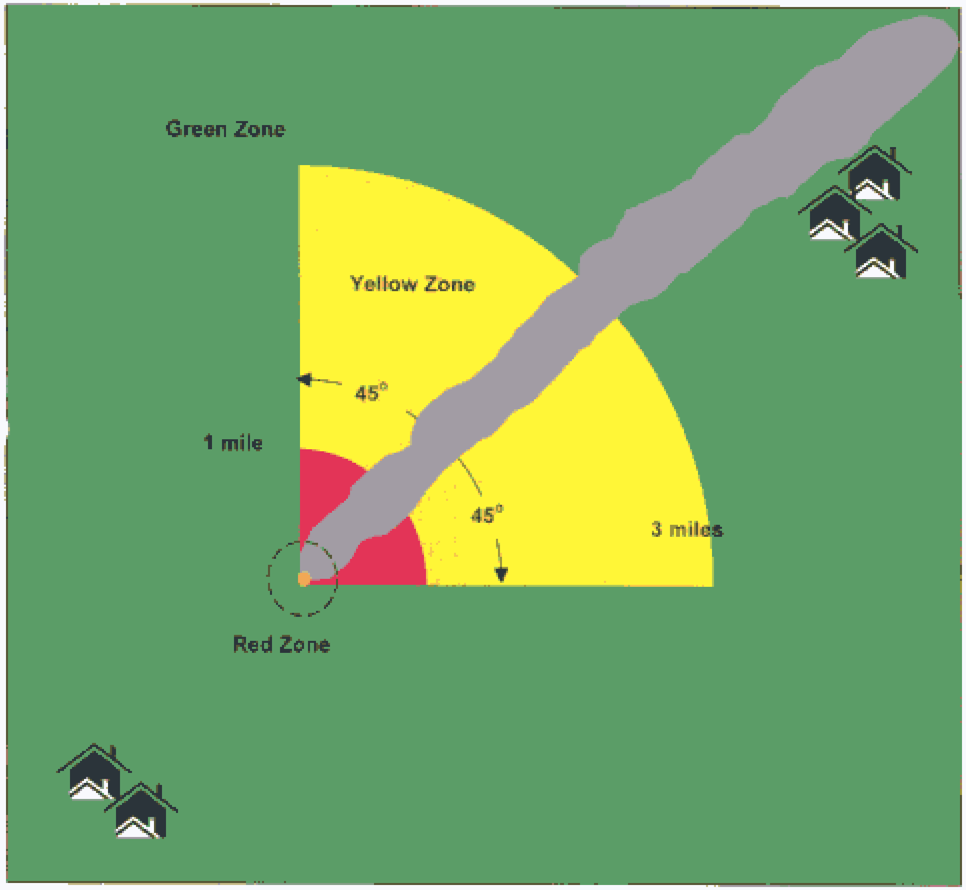
Figure 4. Airborne Lidar Altitude/Distance Grayscale Cross Section of Smoke Plume Structure – Mobile Bay, Burn 2, Pass 8, 26 October 1994

Smoke Trajectory from hypothetical burn, Valdez, Alaska



Terrain data courtesy US Geological Survey, Digital Elevation Maps





In Situ Burning Guidelines for Alaska

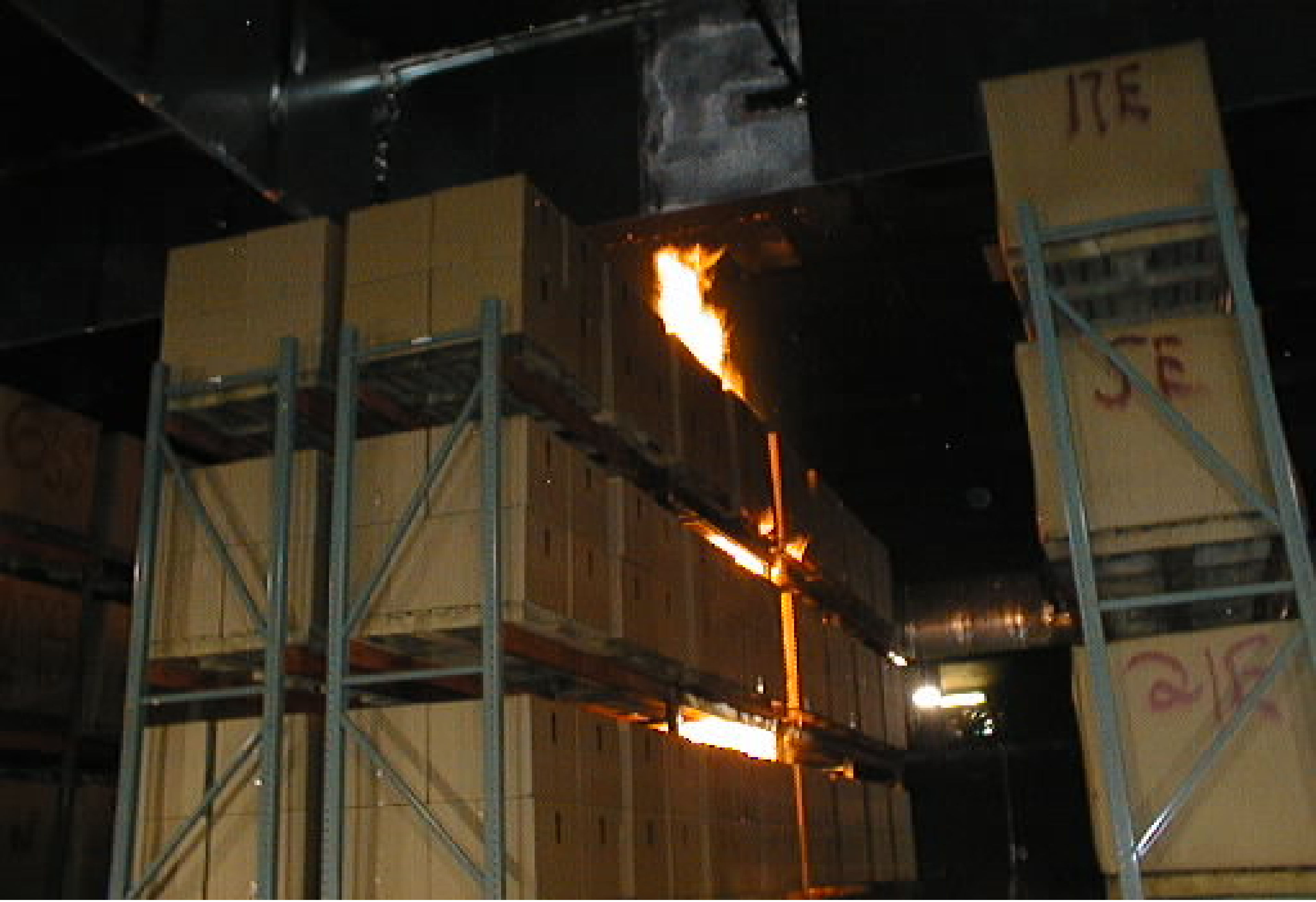
NFPRF Sprinkler/Vent/Draft Curtain Study

NISTIR 6196-1

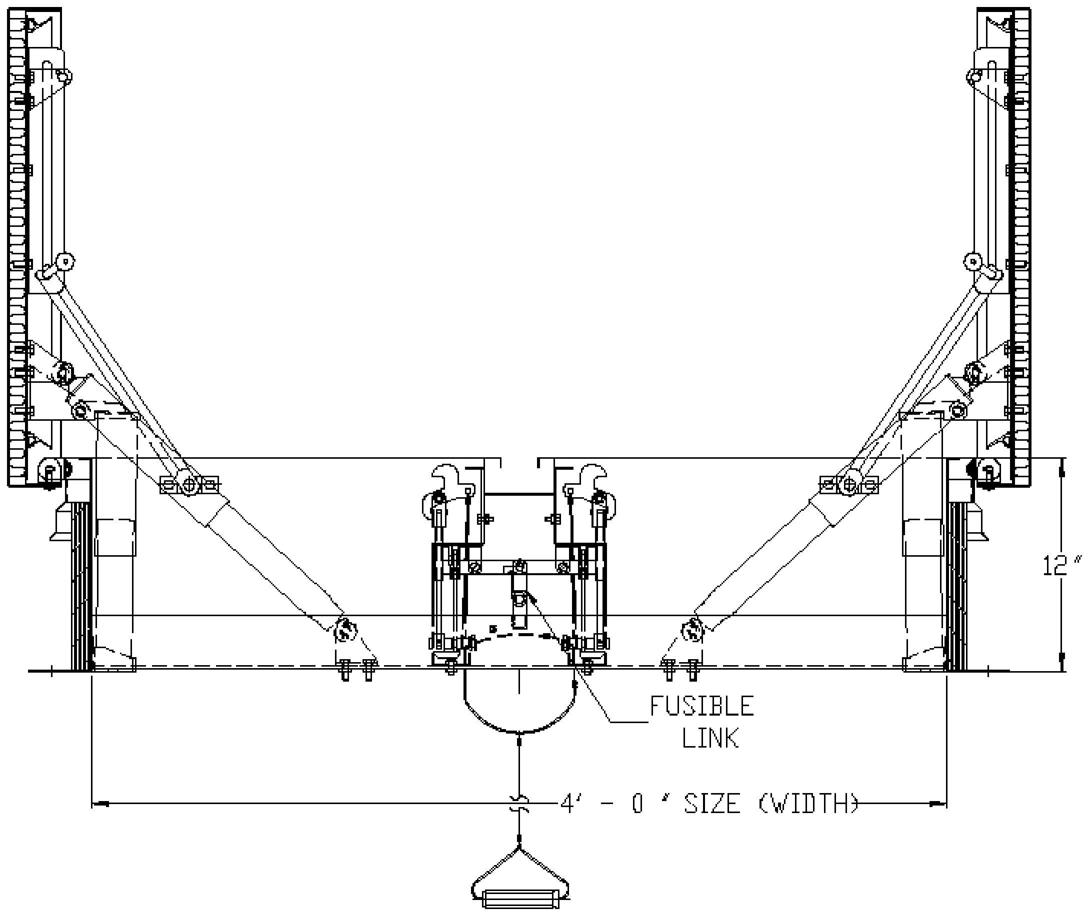
Sprinkler, Smoke & Heat Vent, Draft Curtain Interaction -- Large Scale Experiments and Model Development

Kevin B. McGrattan
Anthony Hamins
David Stroup

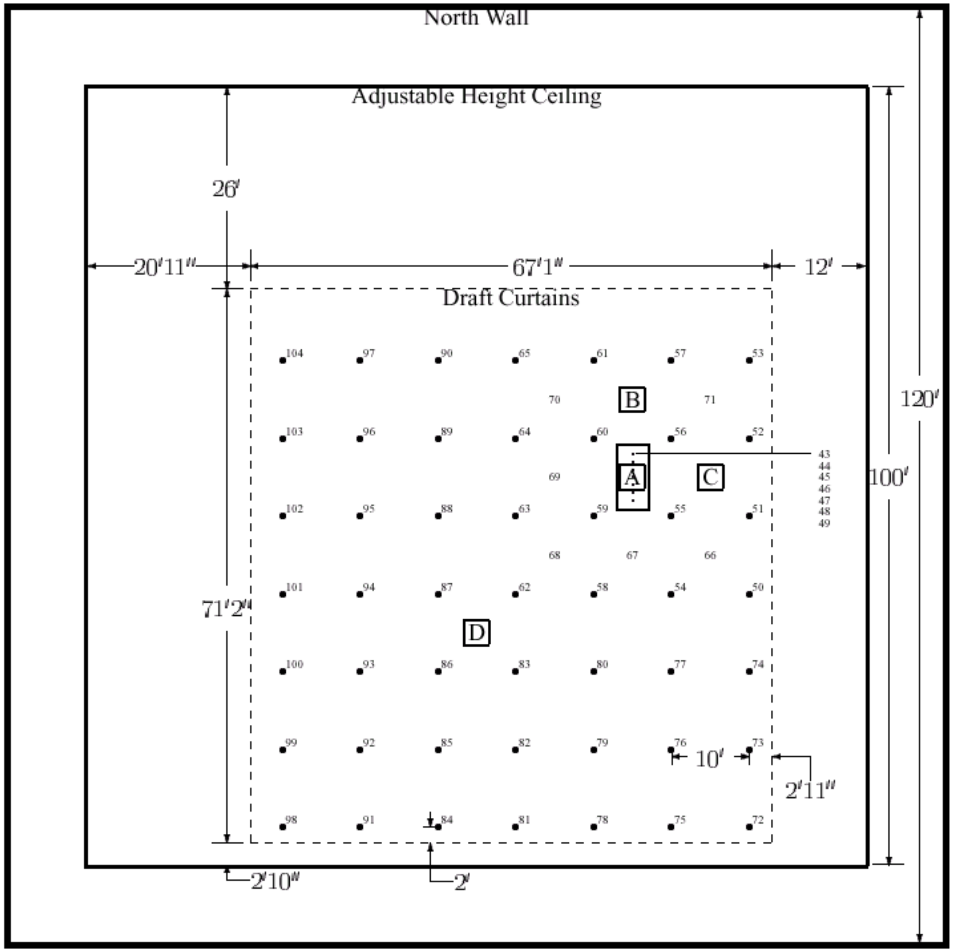
United States Department of Commerce
National Institute of Standards and Technology



Automatic Vent Diagram

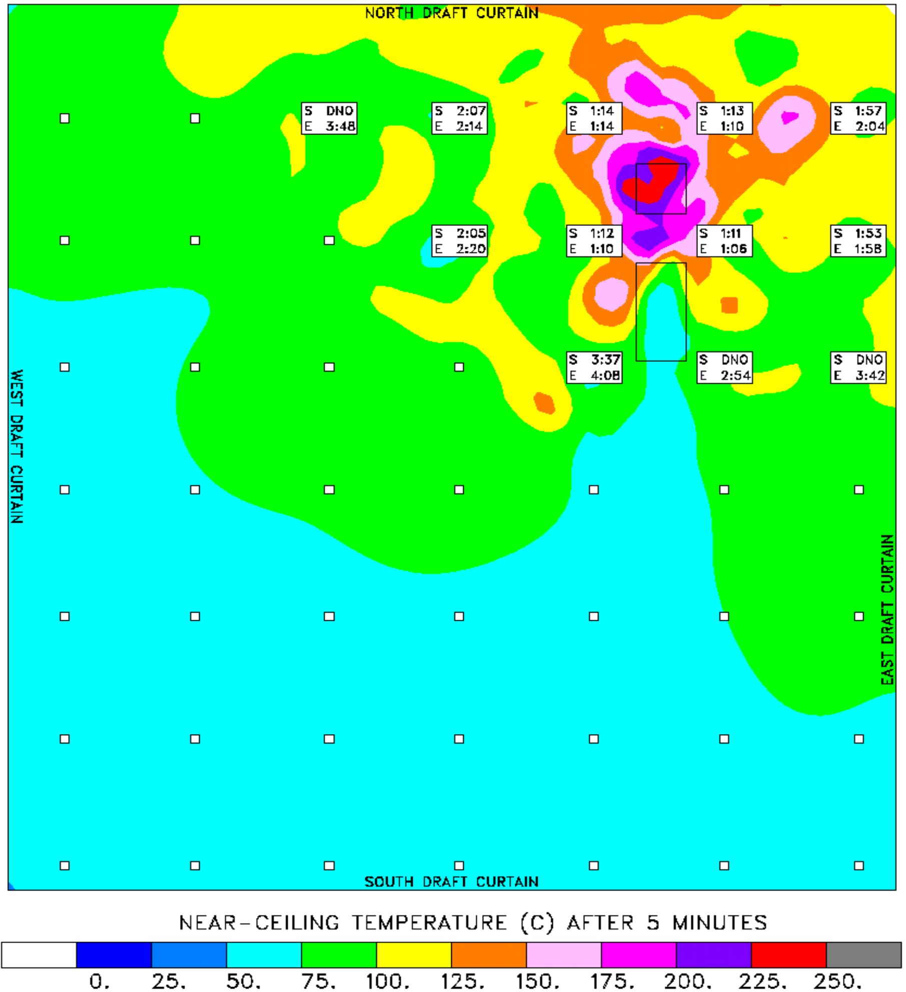


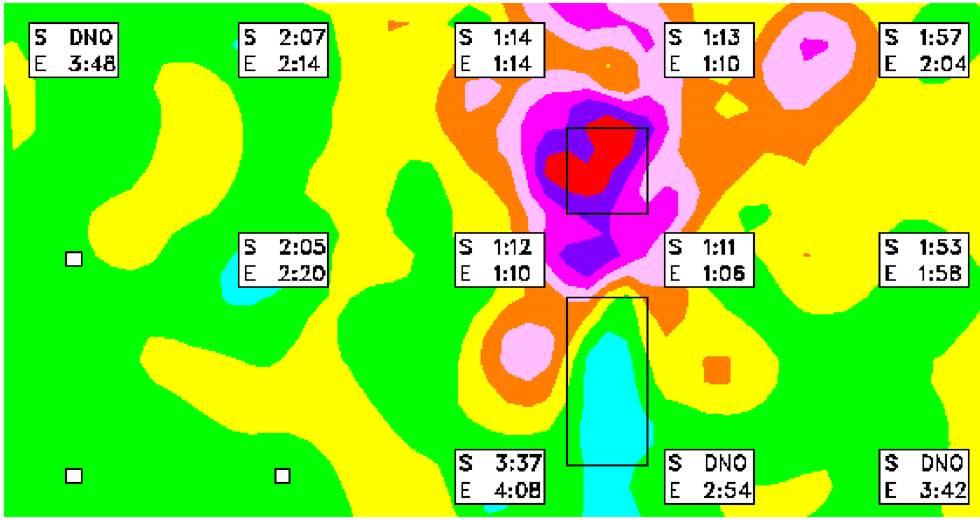
Heptane Spray Burner Layout (Series 1)



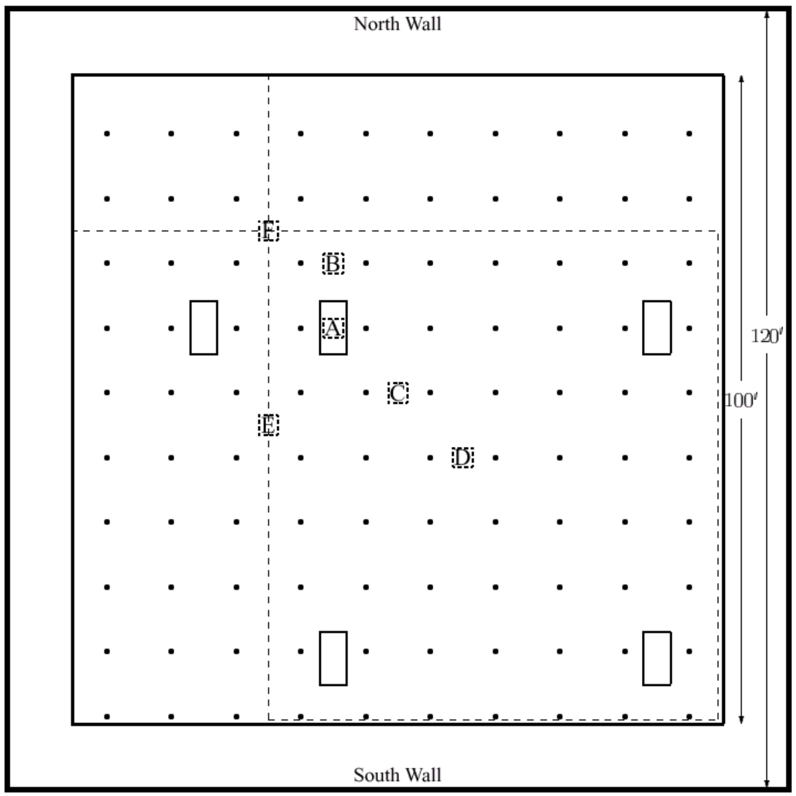
Sample Results

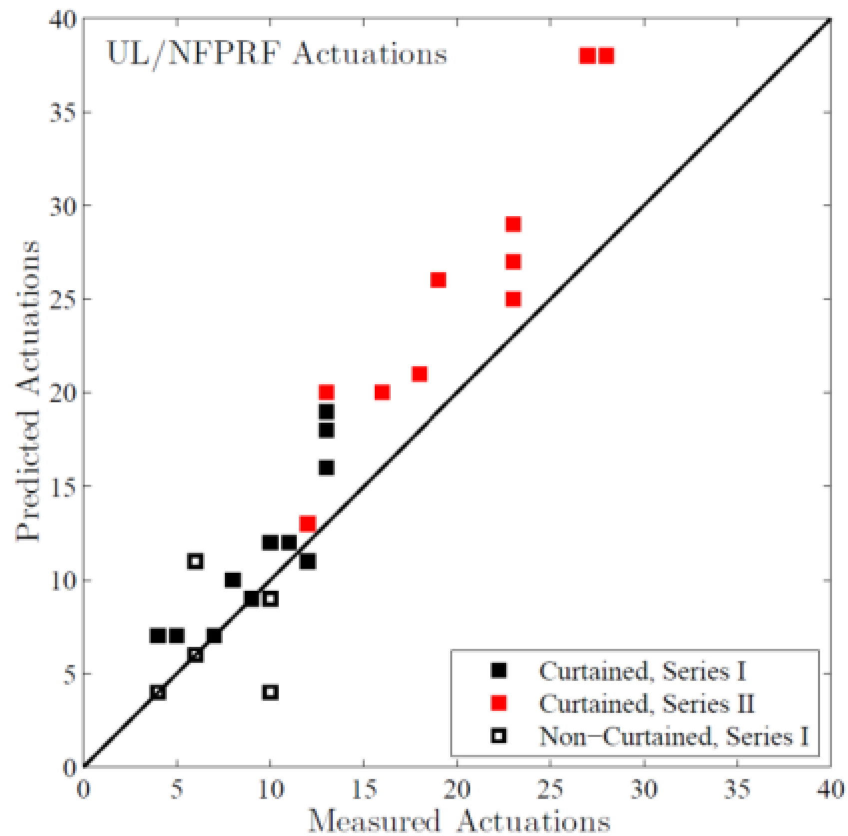
TEST 2 (VENT OPENED AT 0:40, 4.44 MW FIRE, DRAFT CURTAINS)



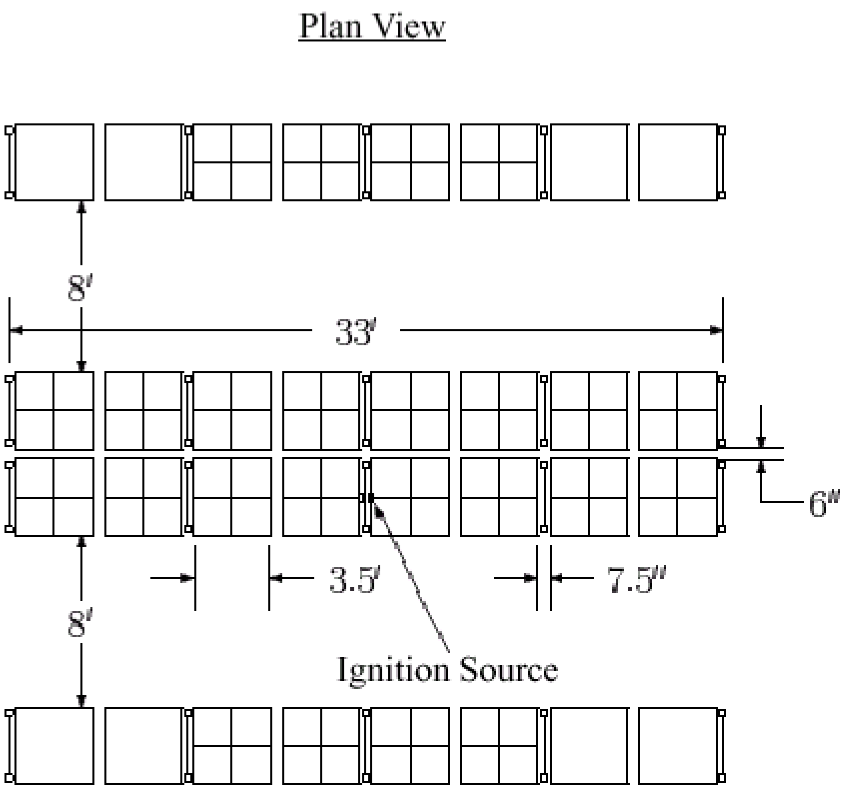


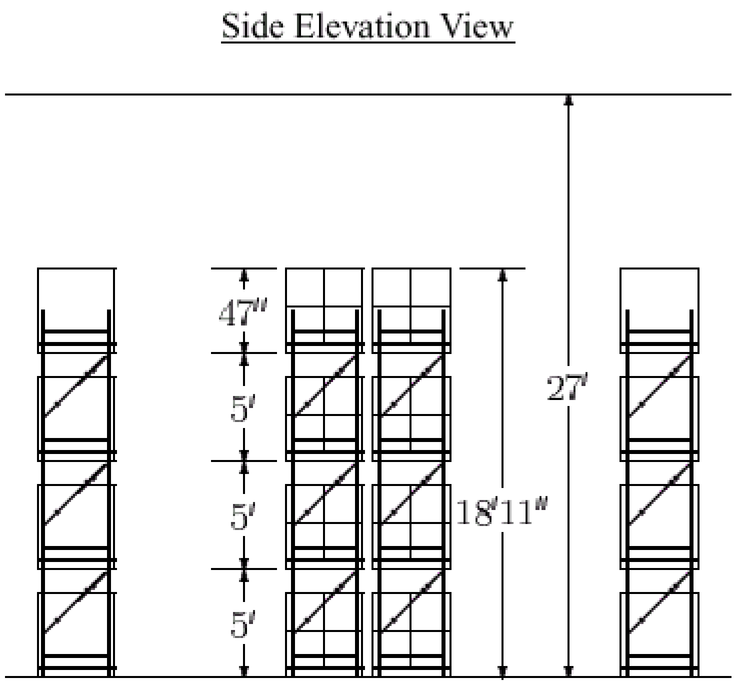
Heptane Series II Layout





Commodity Layouts

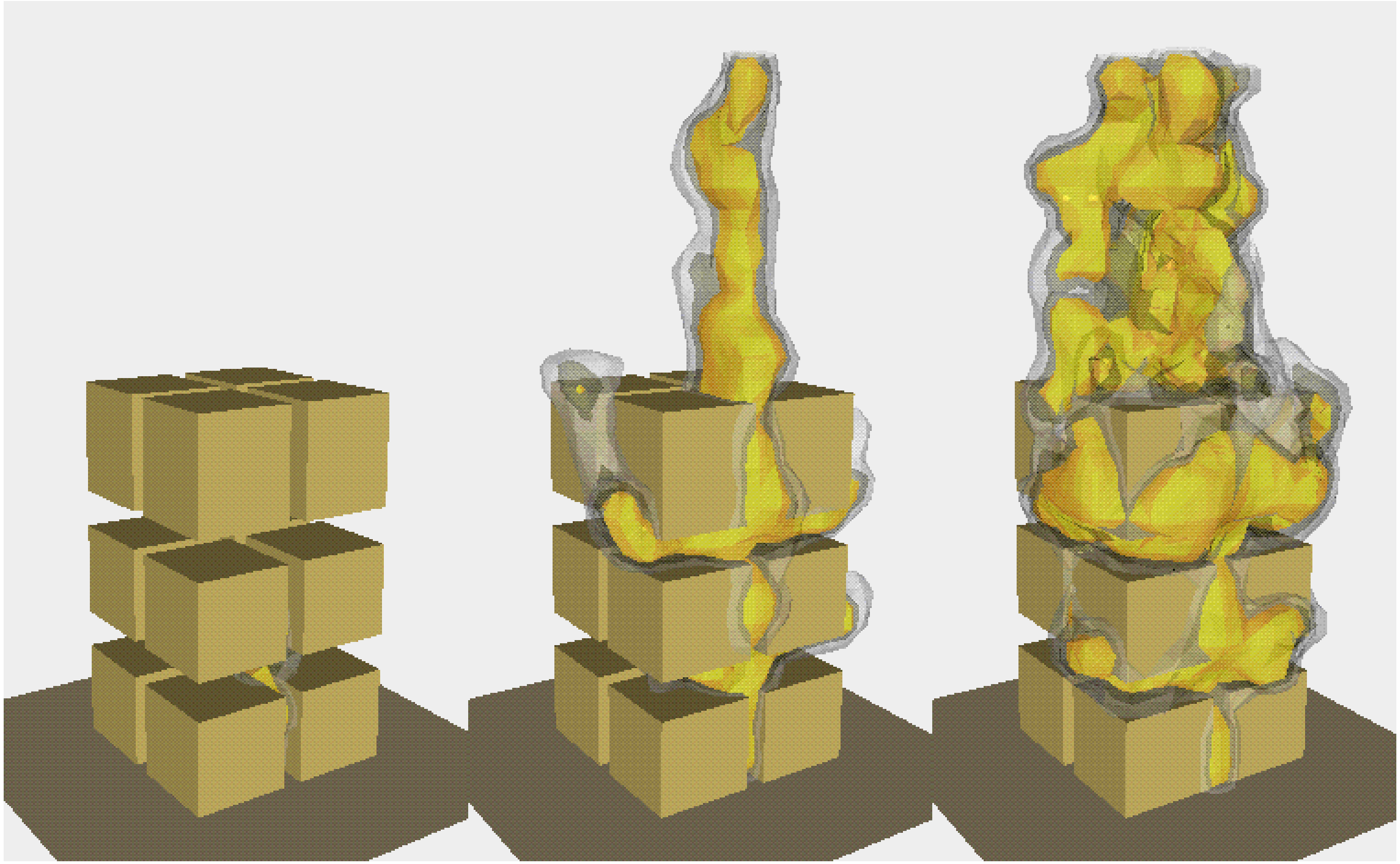




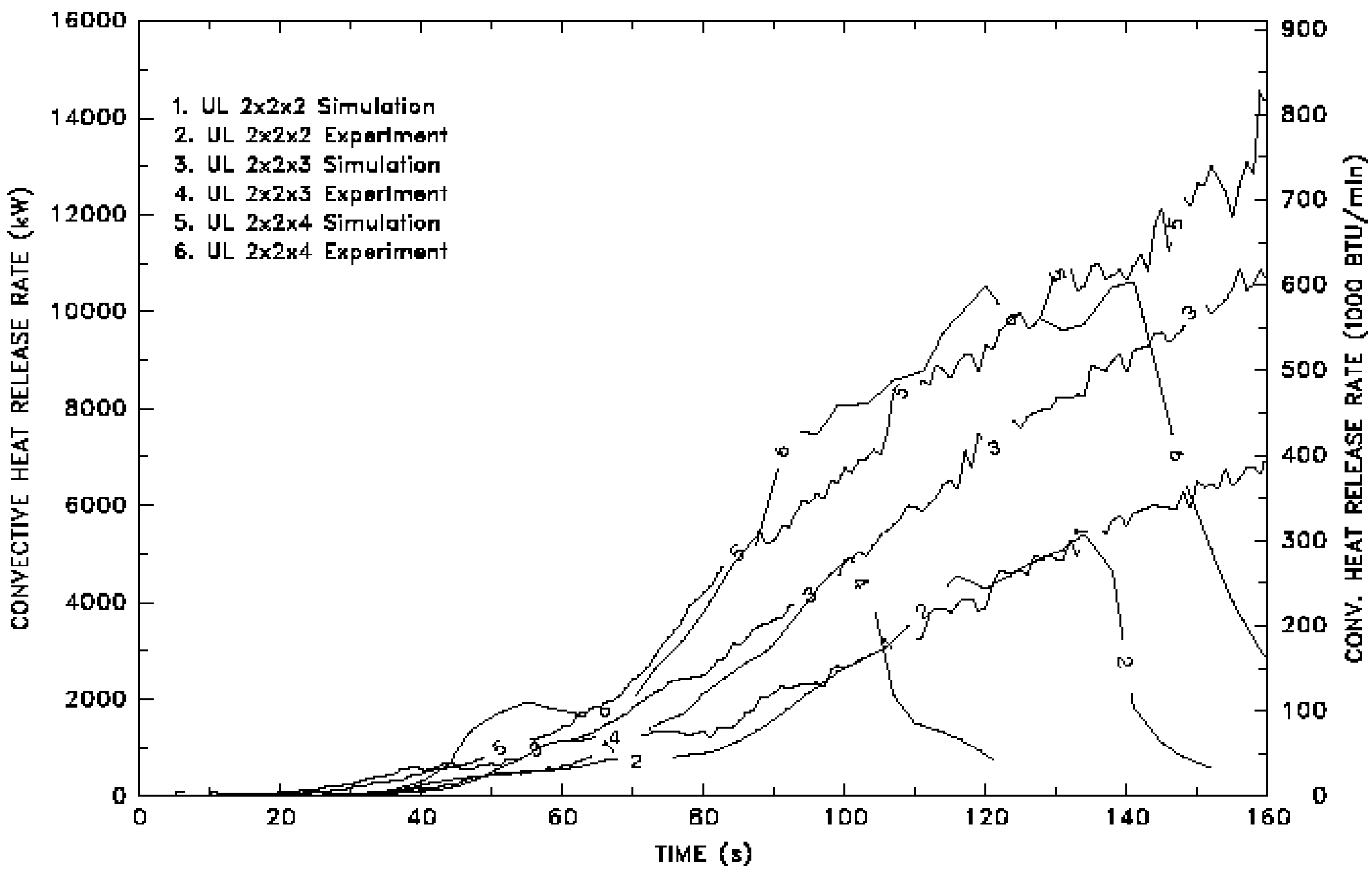
56W
46E
45E

Burning Boxes

Fire Growth

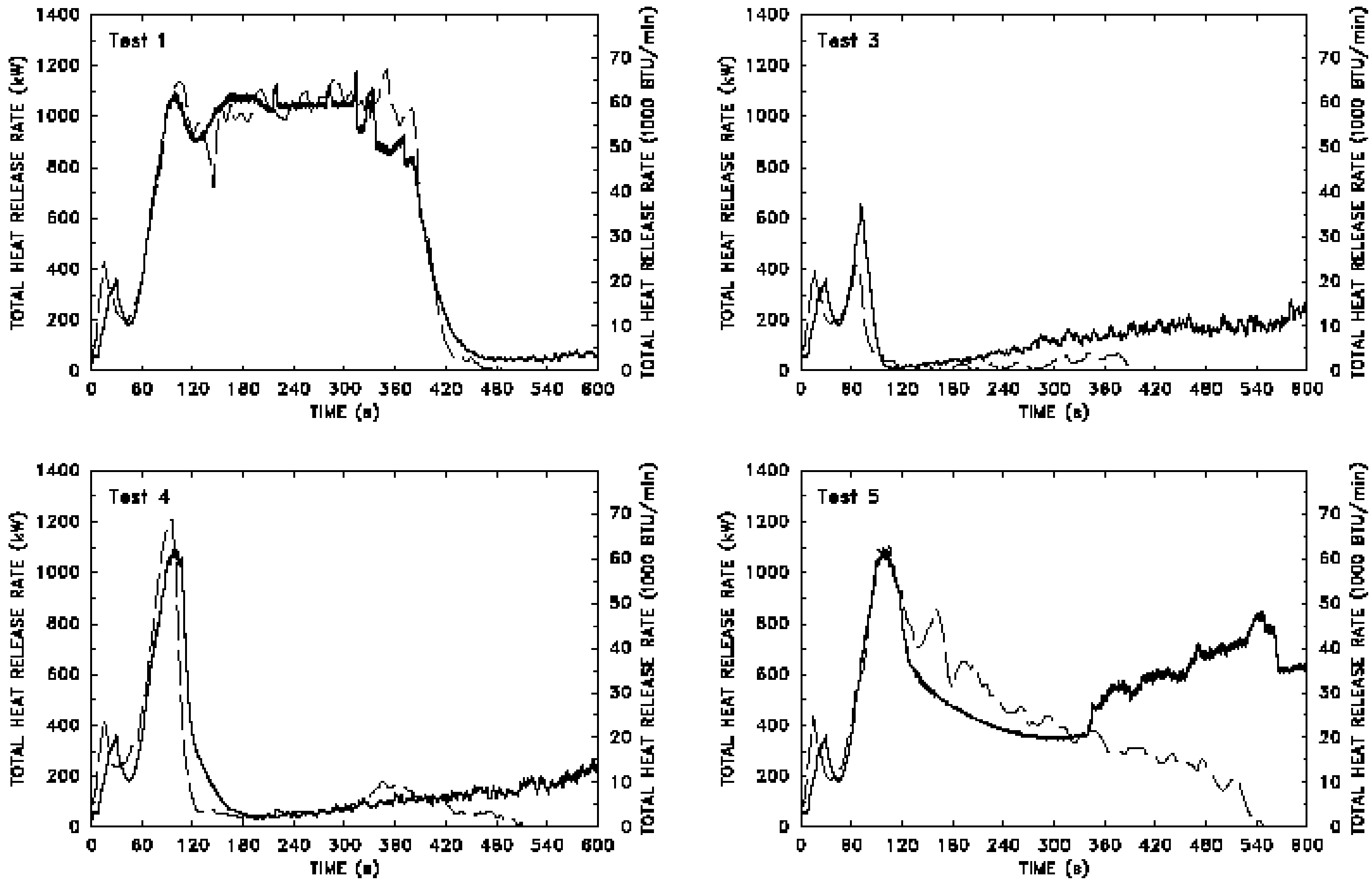


Fire Growth Validation

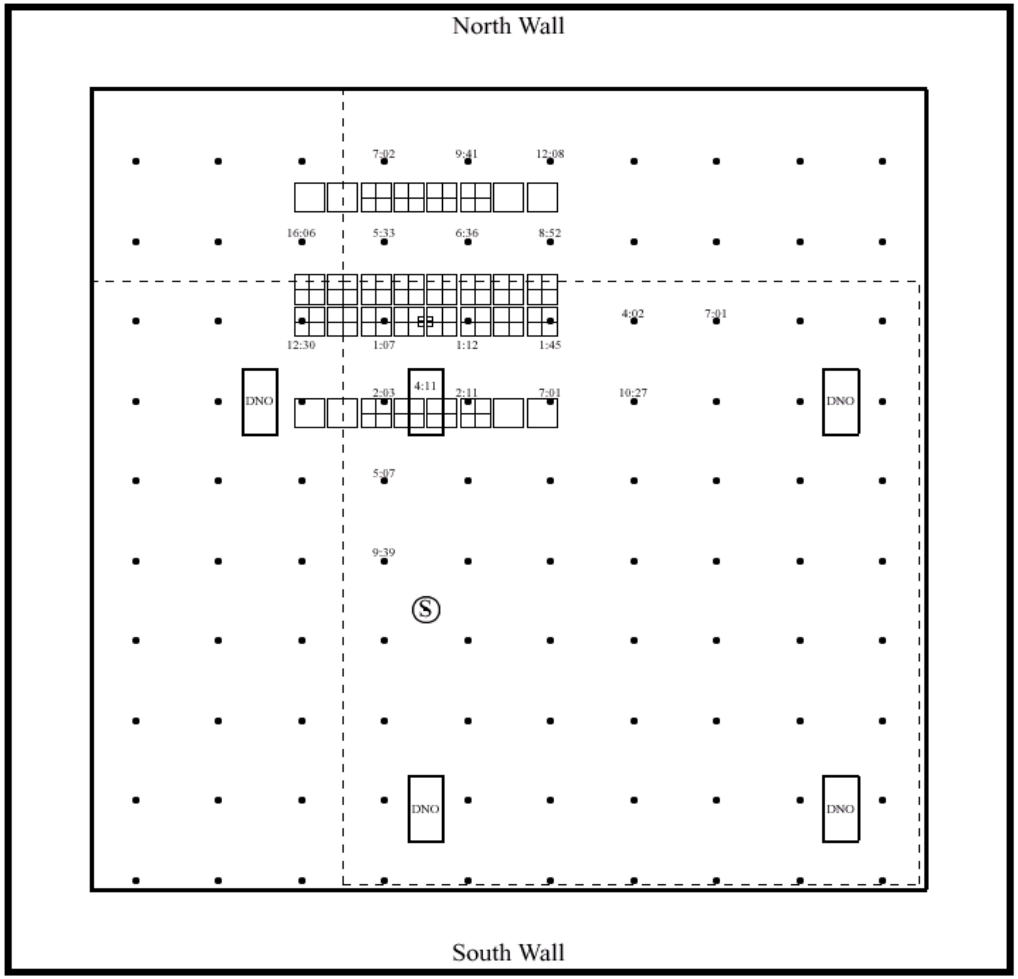


Suppression

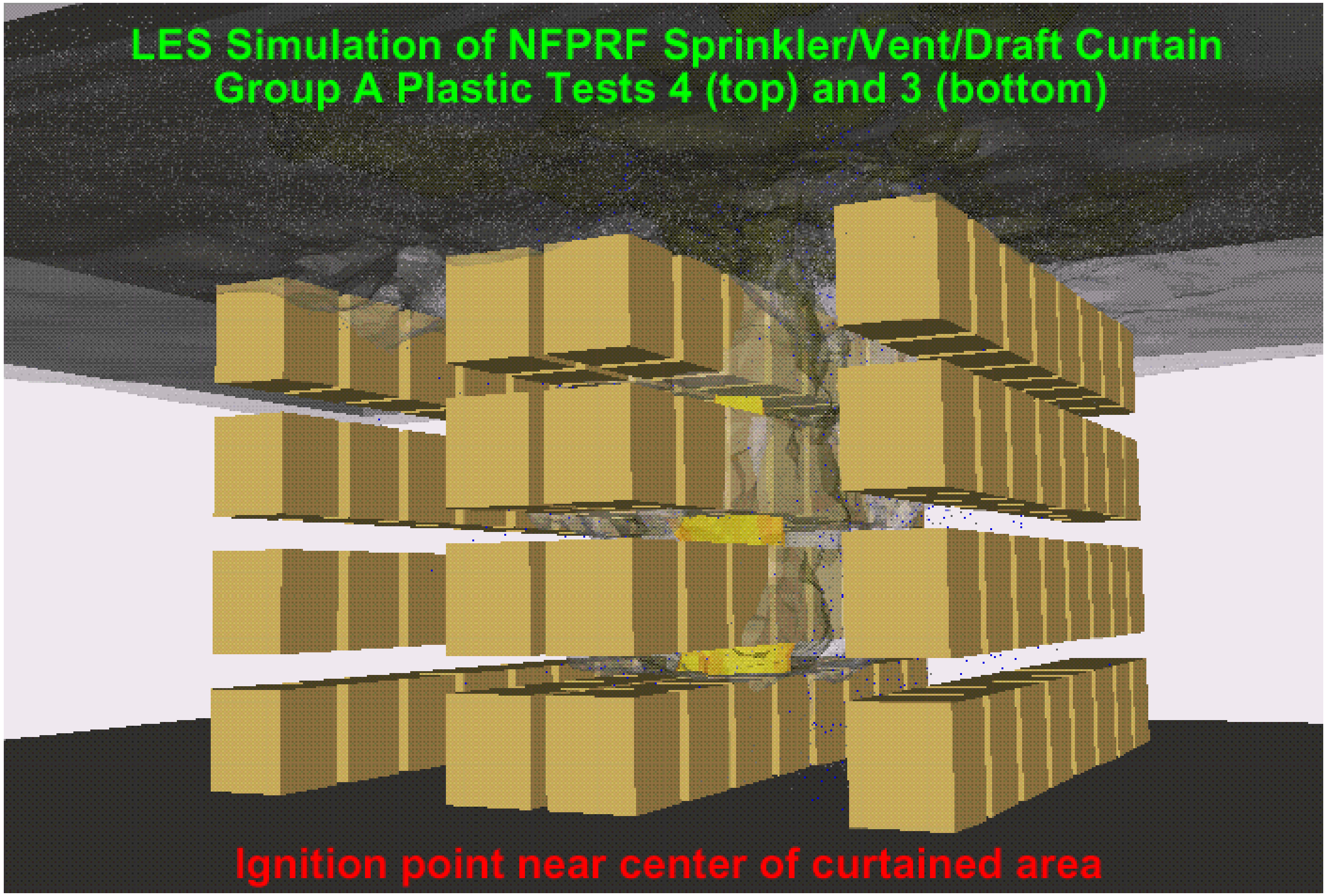
Suppression



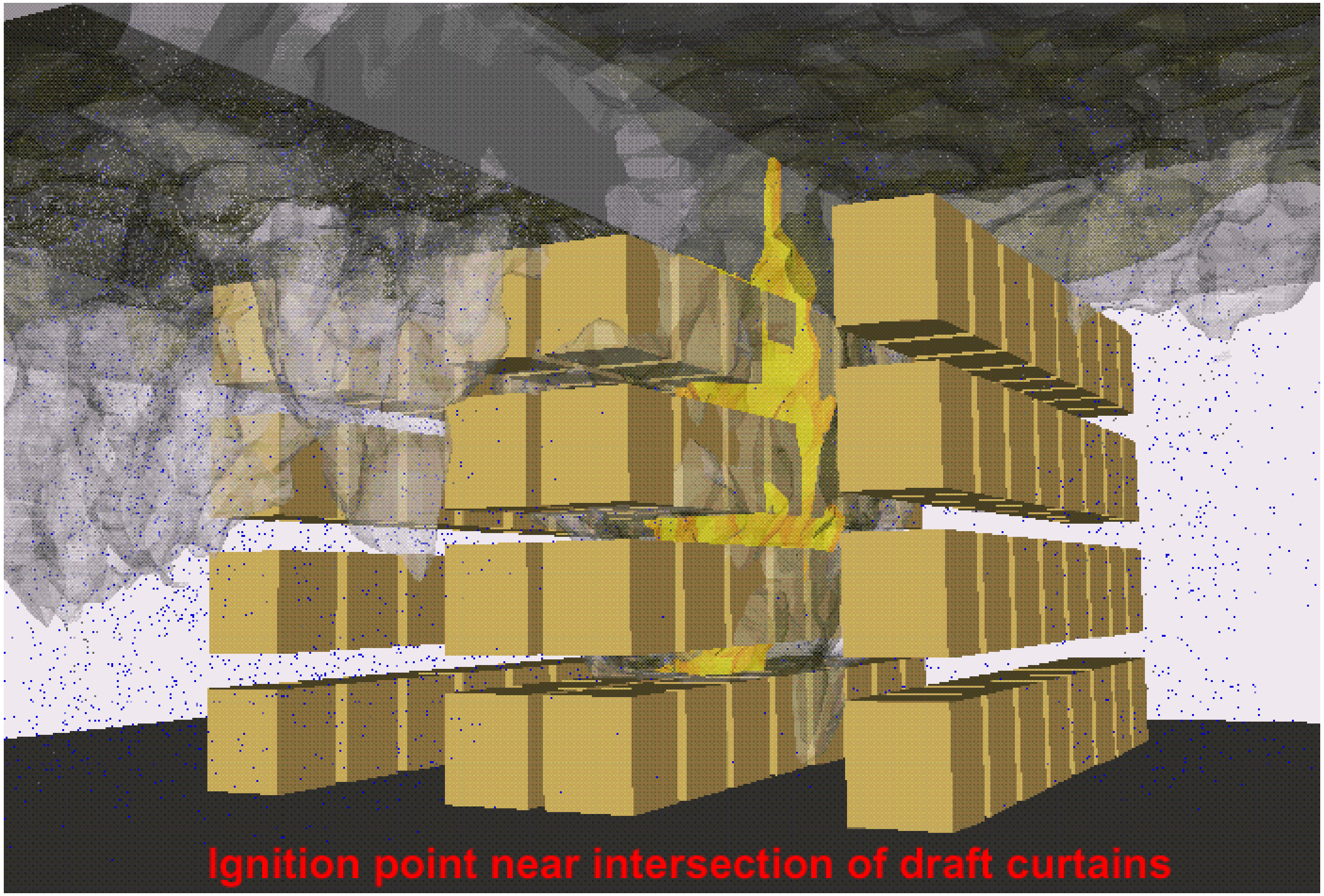
Commodity Layout

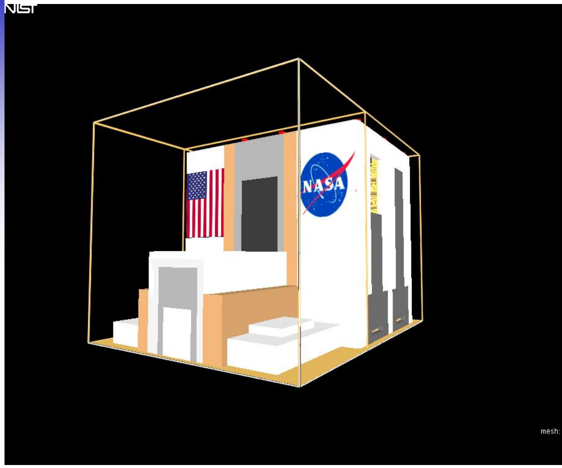


No Draft Curtains



Draft Curtains

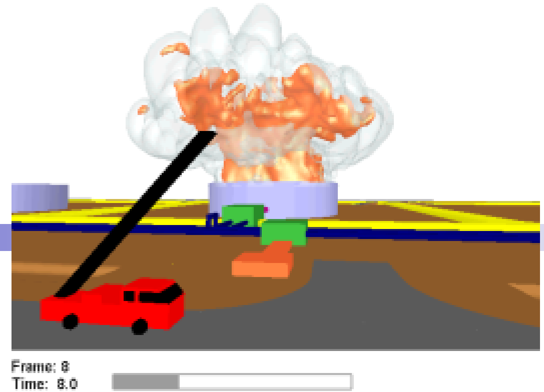




NASA Vehicle Assembly Building

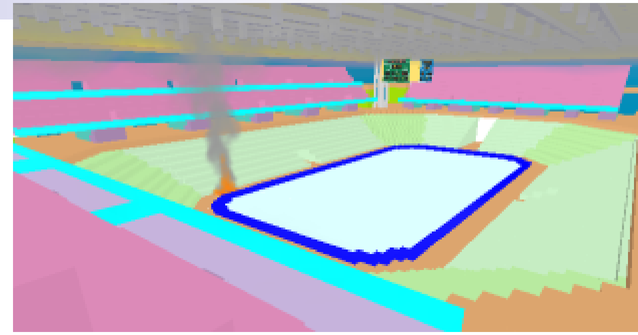
Kennedy Space Center

courtesy Rolf Jensen



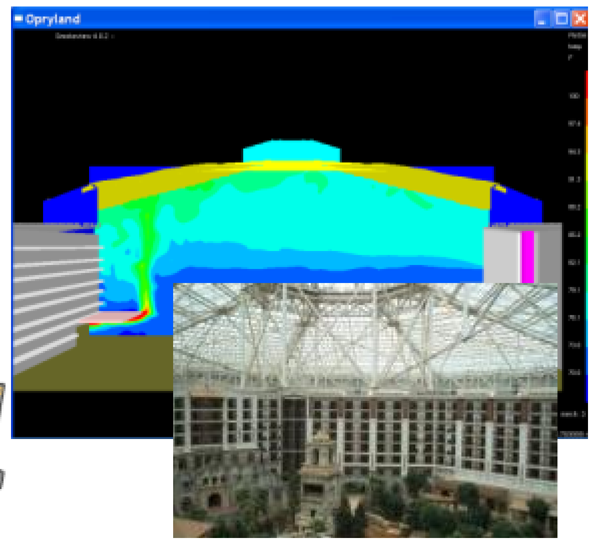
Tank Fire Analysis, courtesy

Combustion Science and Engineering

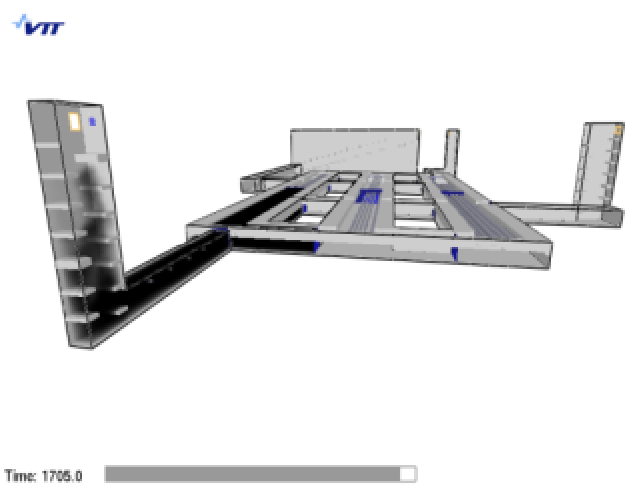


2006 Olympic Ice Hockey Stadium,

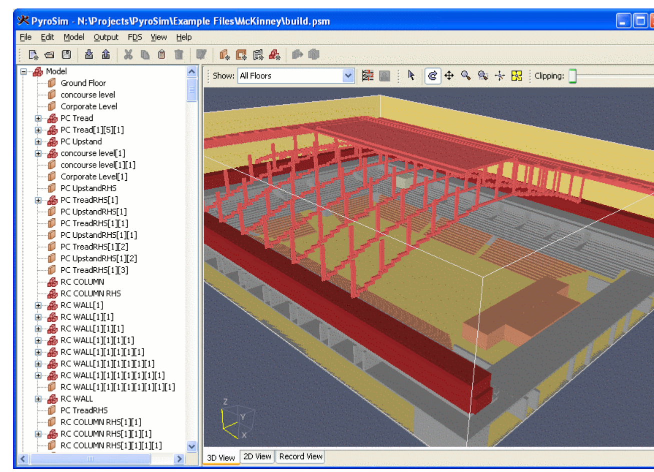
Turin, Italy, courtesy Arup



Courtesy, Schirmer Engineering



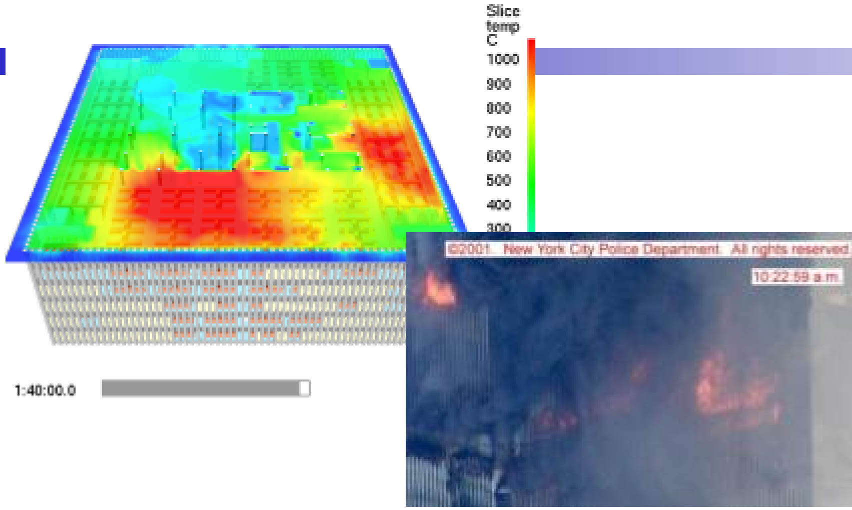
Parking Garage, courtesy VTT, Finland



PyroSim, courtesy Thunderhead

Engineering Consultants, Manhattan, Kansas

Fire Reconstructions



World Trade Center Investigation

NIST

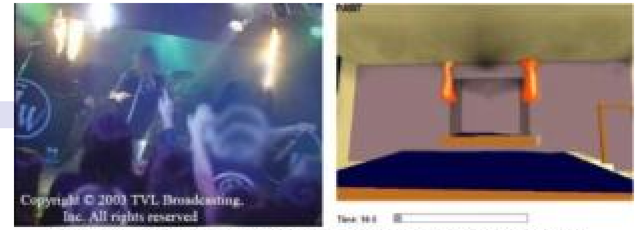


Figure 5-43. Initial growth of fire on foam at corner of the alcove (10 seconds)

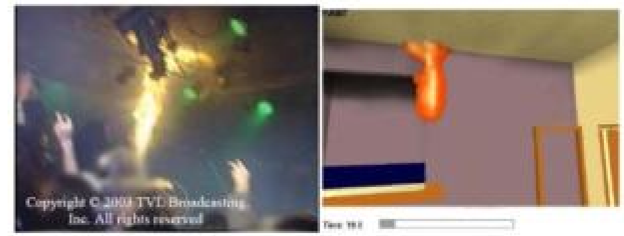
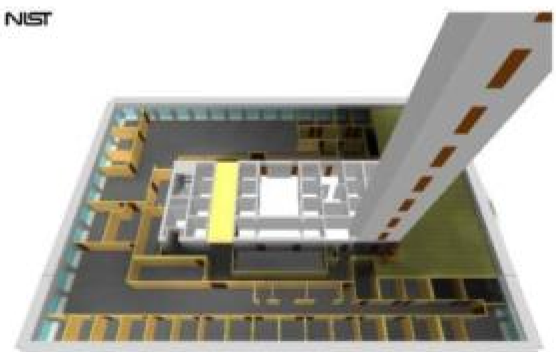
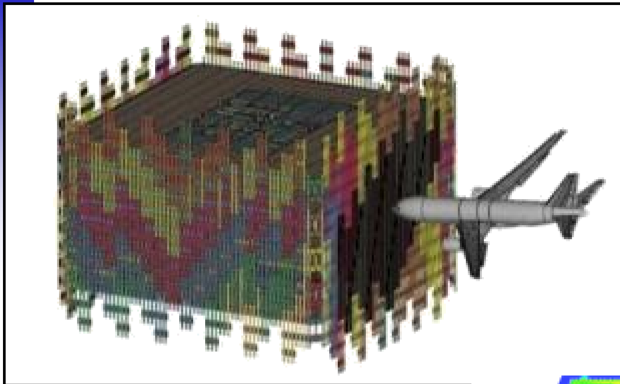


Figure 5-44. Flames impinging on ceiling (19 seconds)

The Station Nightclub Fire
Dan Madrzykowski and Steve Kerber



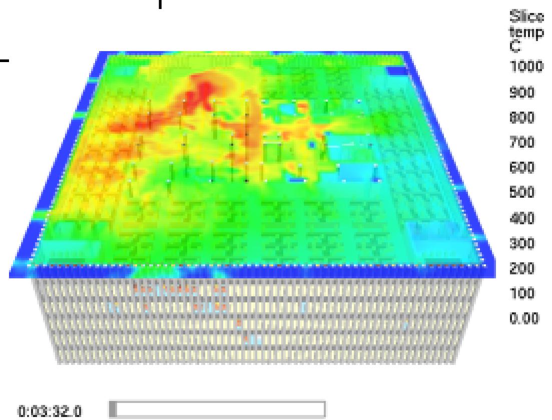
Cook County Administration Building Fire
69 West Washington, Chicago, Illinois, October 17, 2003
Doug Walton and Dan Madrzykowski



Aircraft Impact Analysis

Applied Research Associates

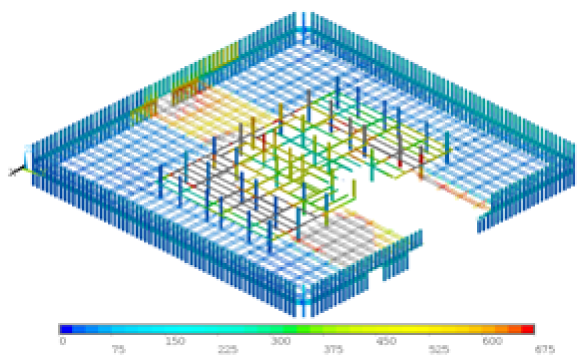
Program: LS-DYNA



Fire Analysis

NIST

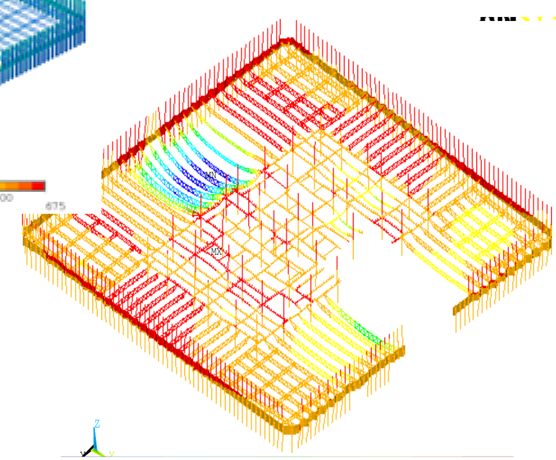
Program: Fire Dynamics Simulator



Thermal Analysis

NIST

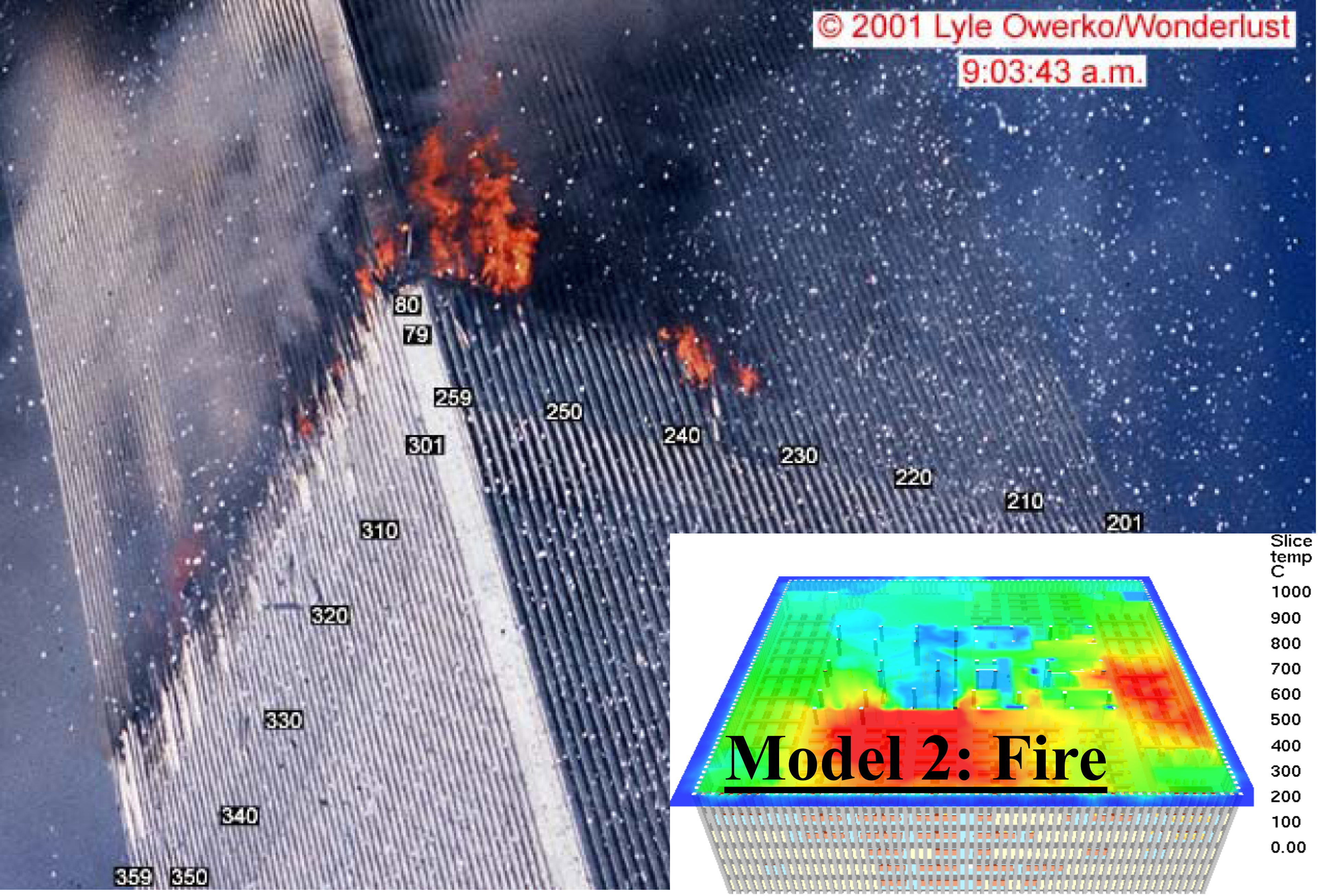
Program: ANSYS



Structural Analysis

Simpson Gumhertz & Heger

Program: ANSYS


© 2001 Lyle Owerko/Wonderlust
9:03:43 a.m.
80
79
259
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220
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Slice temp C
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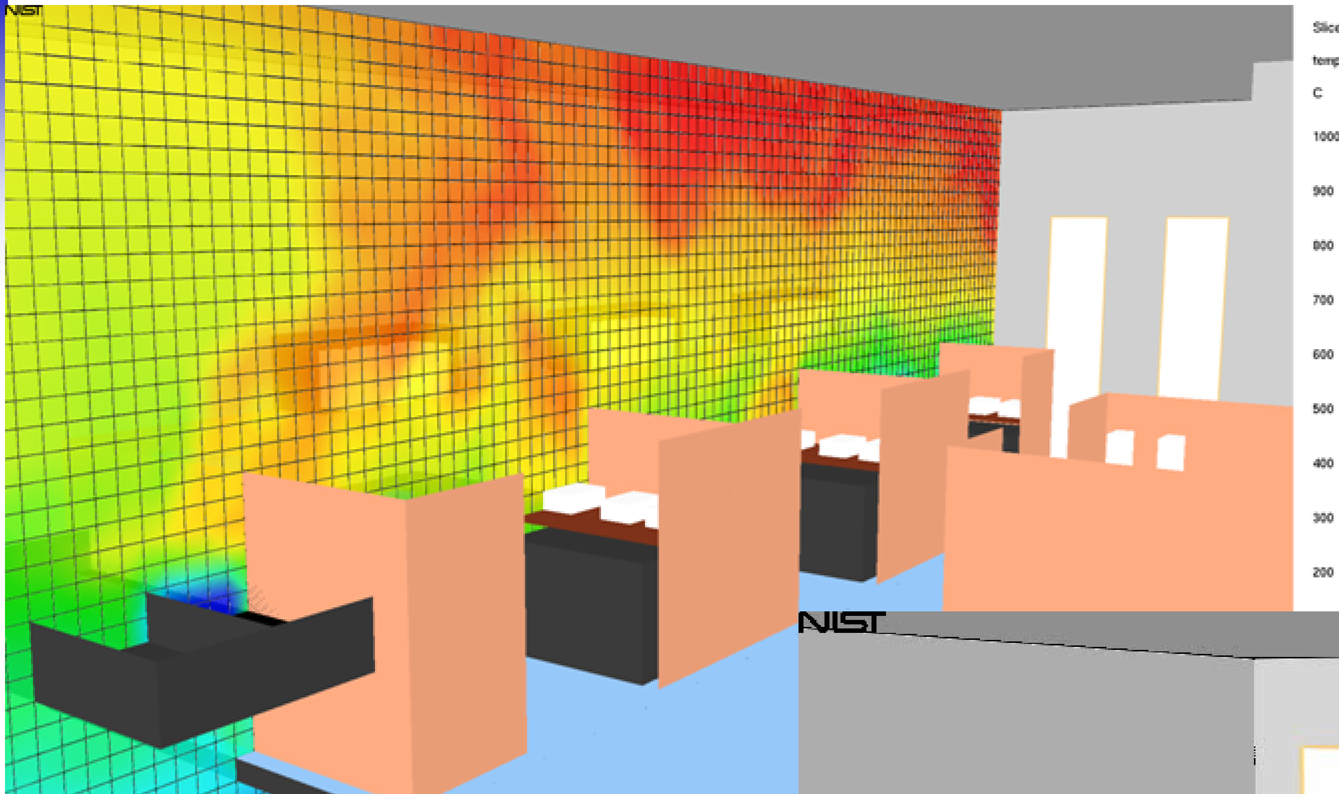
Model 2: Fire

Photos courtesy of the Port Authority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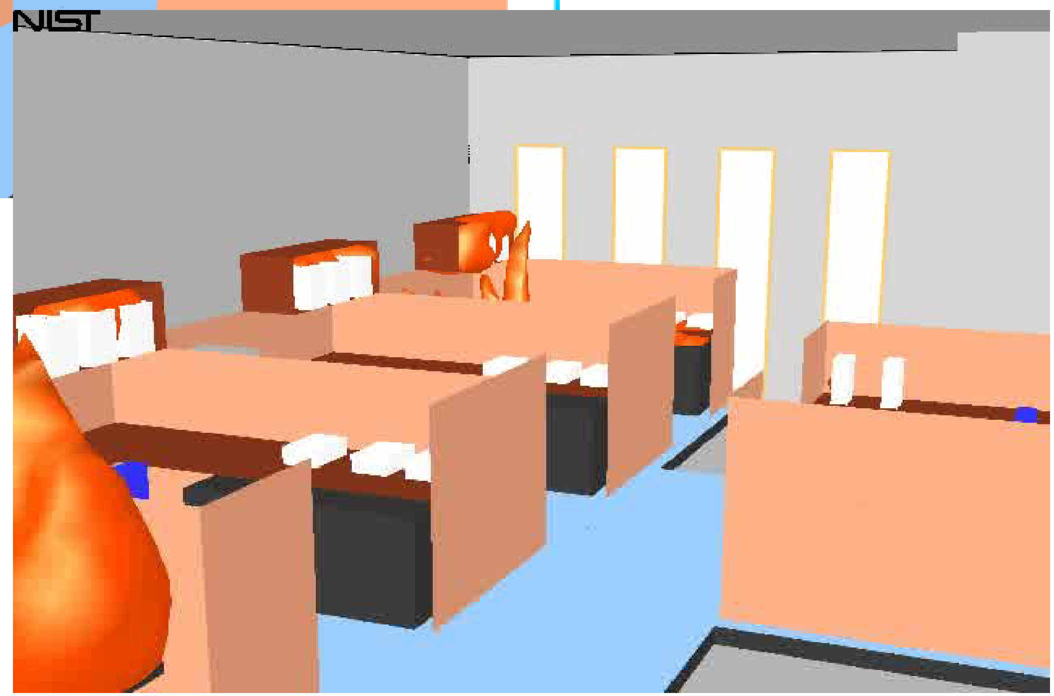
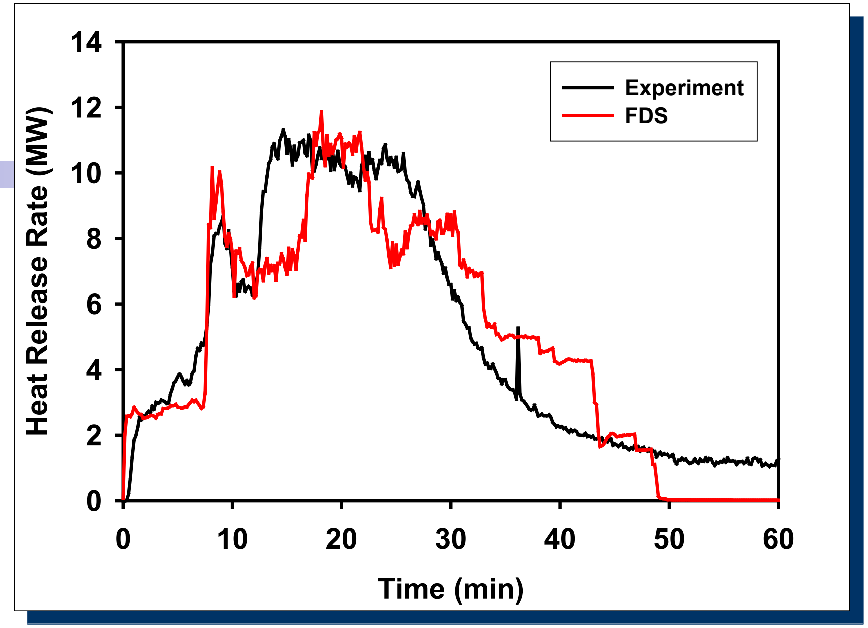
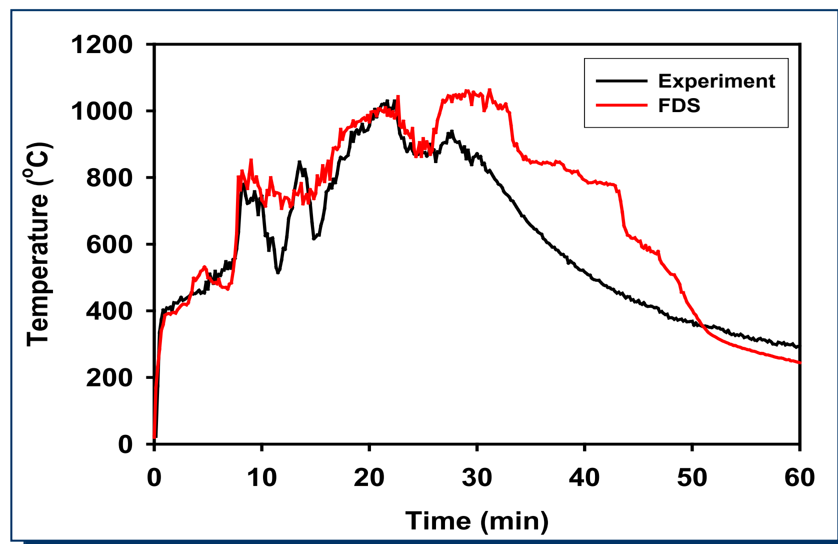

NIST

Video courtesy of Alex Maranghides, Anthony Hamins, NIST

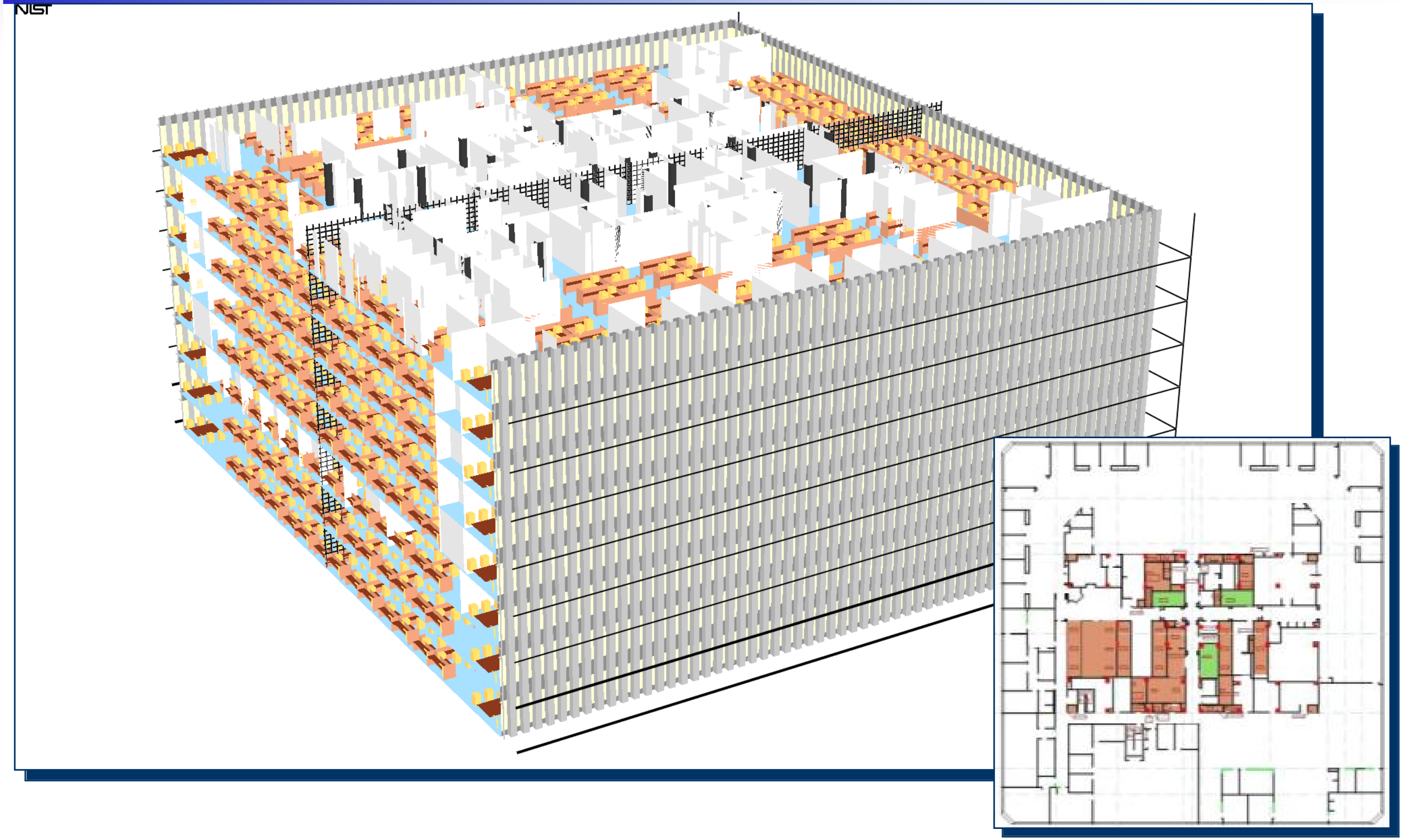
Heat Release Rate



Temperature

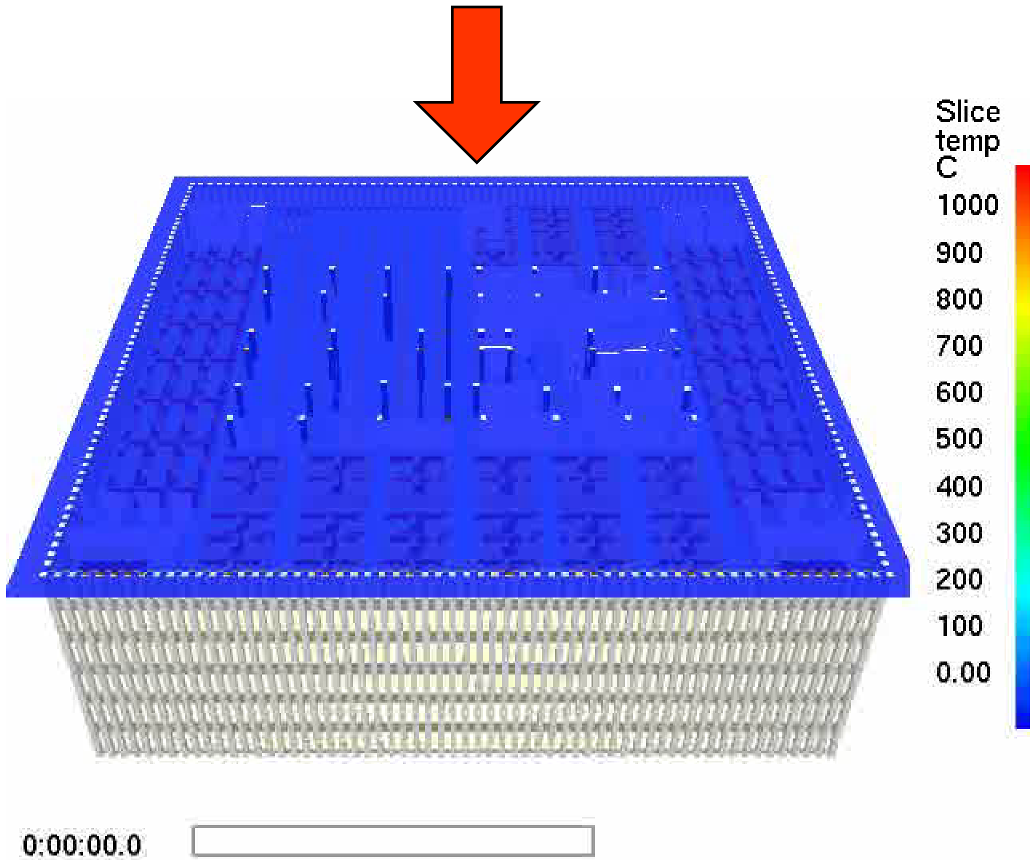


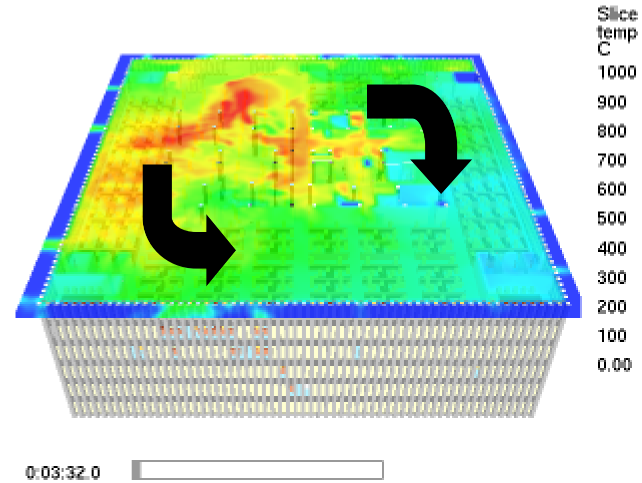
Multi-Floor WTC Geometry

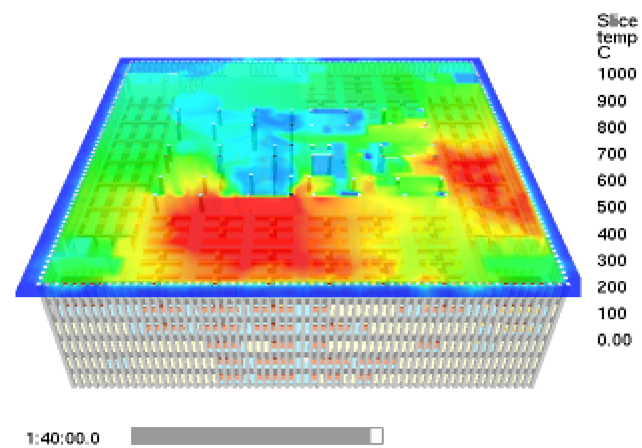


Upper Layer Gas Temperatures

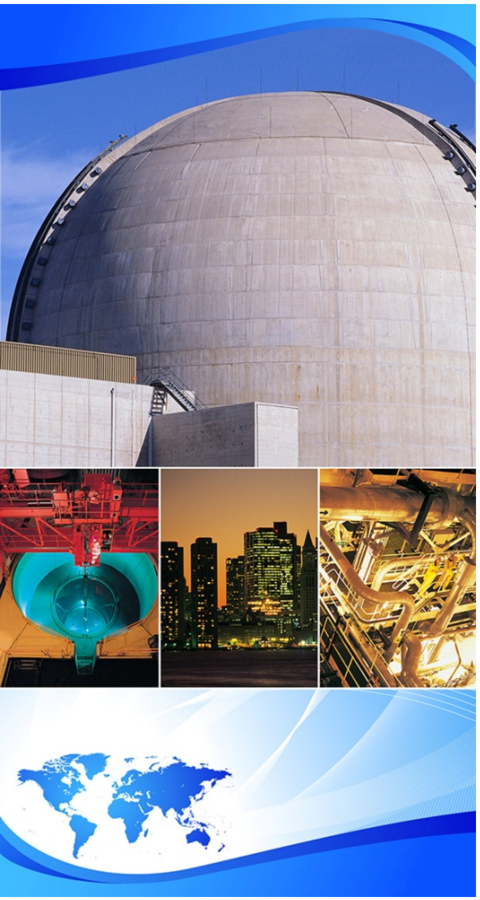
WTC 1 - Floor 97







Graphics courtesy of Glenn Forney, NIST



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5
Advanced Fire Modeling
Day 3 - AM Session
Example A: Control Room Fire
Example B: Switchgear Room Cabinet Fire

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

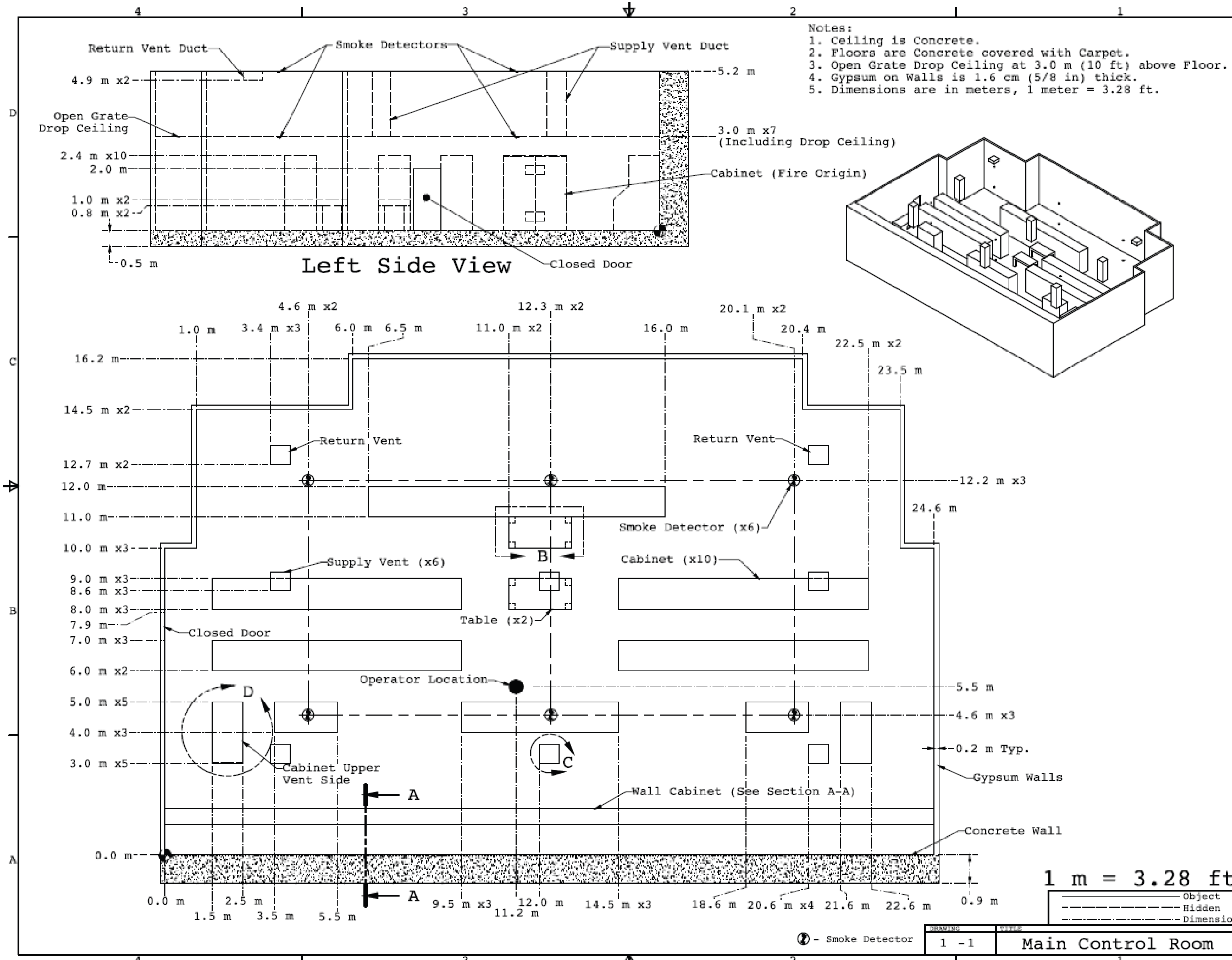
A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Step 1. Define Fire Modeling Goals

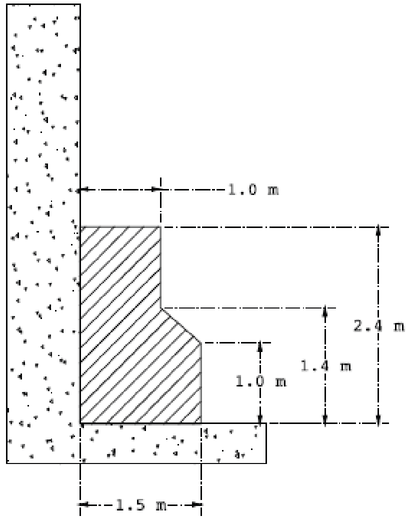
- Determine the length of time that the Main Control Room (MCR) remains habitable after the start of a fire within a low-voltage control cabinet.
- Follow guidance provided in Chapter 11 of NUREG/CR-6850 (EPRI 1011989), Volume 2, “Detailed Fire Modeling (Task 11).”
- Note that MCR fire scenarios are treated differently than fires within other compartments, mainly because it is necessary to consider and evaluate forced abandonment in addition to equipment damage.

Step 2. Characterize Fire Scenarios

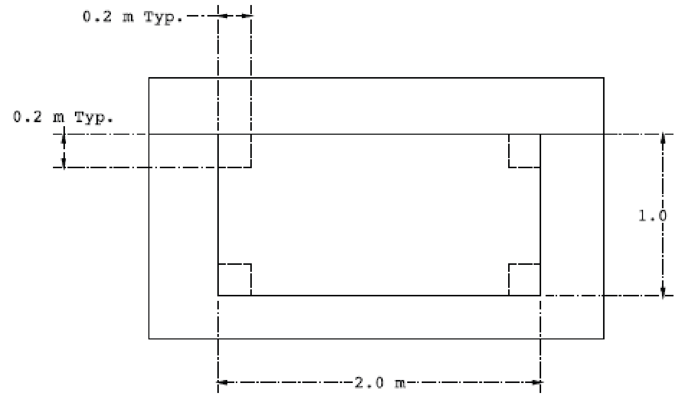
- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire
- Habitability and Human Factors


Notes:
1. Ceiling is Concrete.
2. Floors are Concrete covered with Carpet.
3. Open Grate Drop Ceiling at 3.0 m (10 ft) above Floor.
4. Gypsum on Walls is 1.6 cm (5/8 in) thick.
5. Dimensions are in meters, 1 meter = 3.28 ft.
Return Vent Duct
Smoke Detectors
Supply Vent Duct
4.9 m x2
5.2 m
Open Grate Drop Ceiling
3.0 m x7 (Including Drop Ceiling)
2.4 m x10
2.0 m
Cabinet (Fire Origin)
1.0 m x2
0.8 m x2
0.5 m
Left Side View
Closed Door
4.6 m x2
12.3 m x2
20.1 m x2
1.0 m
3.4 m x3
6.0 m
6.5 m
11.0 m x2
16.0 m
20.4 m
22.5 m x2
23.5 m
16.2 m
14.5 m x2
Return Vent
Return Vent
12.7 m x2
12.0 m
12.2 m x3
11.0 m
Smoke Detector (x6)
24.6 m
10.0 m x3
B
Cabinet (x10)
Supply Vent (x6)
9.0 m x3
8.6 m x3
8.0 m x3
7.9 m
Table (x2)
Closed Door
7.0 m x3
6.0 m x2
Operator Location
5.5 m
D
5.0 m x5
4.6 m x3
4.0 m x3
0.2 m Typ.
3.0 m x5
C
Cabinet Upper Vent Side
Gypsum Walls
A
Wall Cabinet (See Section A-A)
Concrete Wall
0.0 m
A
0.0 m
2.5 m
1.5 m
3.5 m
5.5 m
9.5 m x3
12.0 m
11.2 m
14.5 m x3
18.6 m
20.6 m x4
21.6 m
22.6 m
0.9 m
1 m = 3.28 ft
Object
Hidden
Dimension
- Smoke Detector
DRAWING
1 -1
TITLE
Main Control Room

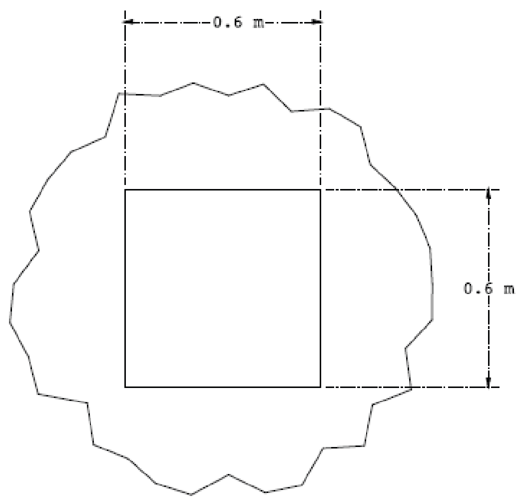
Typical “open grate” ceiling



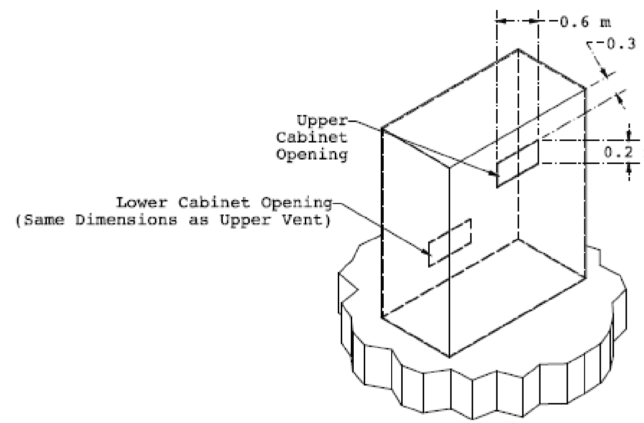
SECTION A-A



DETAIL B
TYPICAL



DETAIL C
(Supply or Return Vent, Typ.)



DETAIL D, ISO VIEW
(Fire Origin Cabinet)

Object
Hidden
Dimension

DRAWING	TITLE
1 -2	Main Control Room

Typical Control Room Cabinet

Material Properties

- For non-burning materials, the most important properties are thermal conductivity, k, density, ρ, and specific heat, c
- For specified burning rates, you need:
  - Heat Release Rate (HRR) or HRR Per Unit Area (HRRPUA)
  - Heat of Combustion – energy released per unit mass consumed
- For predicting the burning rate, you need:
  - Heat of Vaporization (liquids)
  - Heat of Gasification (solids)
  - Kinetic constants for reaction rates
  - (typically not used for NPP applications)

Table 3-1. Material Properties

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Source
Brick	0.8	2600	0.8	NUREG-1805, Table 2-3
Concrete	1.6	2400	0.75	NUREG-1805, Table 2-3
Copper	386	8954	0.38	SFPE Handbook, Table B.6
Gypsum	0.17	960	1.1	NUREG-1805, Table 2-3
Plywood	0.12	540	2.5	NUREG-1805, Table 2-3
PVC	0.192	1380	1.289	NUREG/CR-6850, Appendix R
Steel	54	7850	0.465	NUREG-1805, Table 2-3
XLP	0.235	1375	1.390	NUREG/CR-6850, Appendix R

Typical material properties for common construction and cable materials

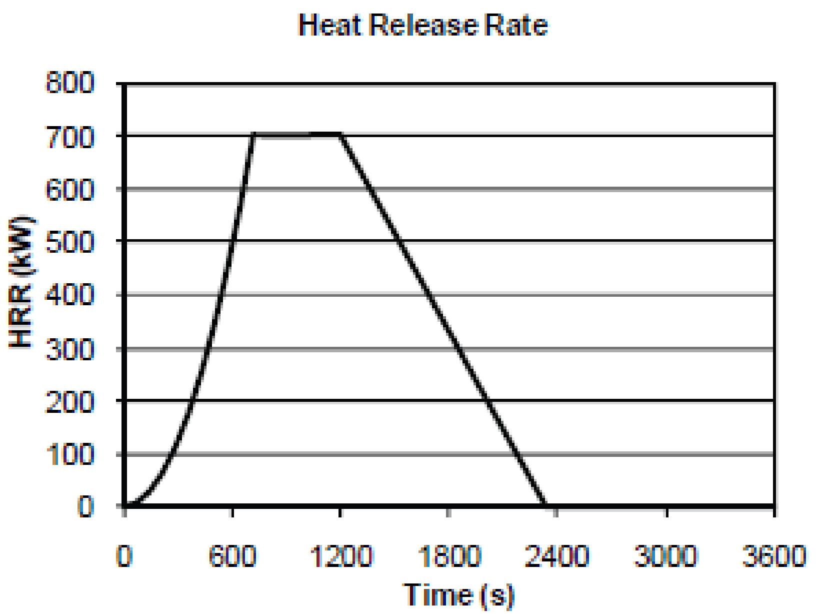
Ventilation

- 25 Air Changes Per Hour (ACH) for purge mode
- Two scenarios – purge mode or ventilation inoperative
- Leakage – often the “leakage area” is the area of the crack under the door
- Exact supply and exhaust location only important for CFD
- Zone models usually only consider height of mechanical ventilation injection and extraction grilles

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)

Fire

What is burning?

Cables made of polyethylene (C_2H_4) and neoprene (C_4H_5Cl)

Assume effective fuel: $C_3H_{4.5}Cl_{0.5}$

Table A-1. Data for MCR fire based on XPE/neoprene electrical cable.

Parameter	Value	Source
Effective Fuel Formula	$C_3H_{4.5}Cl_{0.5}$	Combination of polyethylene and neoprene
Peak HRR	702 kW	NUREG/CR-6850 (EPRI 1011989), App. G
Time to reach peak HRR	720 s	NUREG/CR-6850 (EPRI 1011989), App. G
Heat of Combustion	10,300 kJ/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
CO_2 Yield	0.63 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
Soot Yield	0.175 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
CO Yield	0.082 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
Radiative Fraction	0.53	*SFPE Handbook*, 4th ed., Table 3-4.16
Mass Extinction Coefficient	8700 m^2/kg	Mulholland and Croarkin (2000)

Habitability

Criteria for habitability (NUREG/CR-6850, Vol 2, Chap 11)

- Gas Temperature 2 m off the floor is 95 °C
- Heat Flux exceeds 1 kW/m^2
- Optical Density exceeds 3 m^{-1}

What is Optical Density?

$$D \equiv -\frac{1}{L}\log_{10}\left(\frac{I}{I_0}\right) = K\log_{10}e$$

Mass Extinction Coefficient (8700 m^2/kg)

$$K = K_m \rho Y_s$$

Smoke Concentration (kg/m^3)

Step 3. Select Fire Models

- Algebraic Models: FPA algorithm in FIVE and FDTs provides estimate of HGL temperature within a closed, ventilated compartment.
  - FDTs do not allow for time-dependent HRR
- Zone Models: CFAST includes smoke obscuration. MAGIC does not.
- CFD: Provides more detailed information at exact location of operators

Applicability of Validation

Table A-2. Normalized parameter calculations for the MCR fire scenario. See Table 2-5 for further details.

Quantity	Normalized Parameter Calculation		Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5} \sqrt{g}} = \frac{702 \text{ kW}}{(1.2 \text{ kg/m}^3)(1.0 \text{ kJ/kg/K})(293 \text{ K})(0.4^{2.5} \text{ m}^{2.5})\sqrt{9.8 \text{ m/s}^2}} \cong 6.2$		0.4 – 2.4	No
Fire Height, $H_f + L_f$, relative to the Ceiling Height, H_c	$\frac{H_f + L_f}{H_c} = \frac{2.1 \text{ m} + 2.7 \text{ m}}{5.2 \text{ m}} \cong 0.9$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 0.4 \text{ m}\,(3.7 \times 6.2^{0.4} - 1.02) \cong 2.7 \text{ m}$		0.2 – 1.0	Yes
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H_c	N/A – Ceiling jet targets are not included in simulation.		1.2 – 1.7	N/A
Equivalence Ratio, φ, of the room, based on Forced Ventilation of Purge Mode	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2} \dot{m}_{O_2}} = \frac{702 \text{ kW}}{13{,}100 \text{ kJ/kg} \times 3.7 \text{ kg/s}} \cong 0.014$ $\dot{m}_{O_2} = Y_{O_2}\,\rho_\infty \dot{V} = 0.23 \times 1.2 \text{ kg/m}^3 \times 13.4 \text{ m}^3/\text{s} \cong 3.7 \text{ kg/s}$		0.04 – 0.6	No
Compartment Aspect Ratio	$\frac{L}{H_c} = \frac{24.6 \text{ m}}{5.2 \text{ m}} \cong 4.7$	$\frac{W}{H_c} = \frac{16.2 \text{ m}}{5.2 \text{ m}} \cong 3.1$	0.6 – 5.7	Yes
Target Distance, r, relative to the Fire Diameter, D	$\frac{r}{D} = \frac{8.8 \text{ m}}{0.4 \text{ m}} \cong 22$		2.2 – 5.7	No

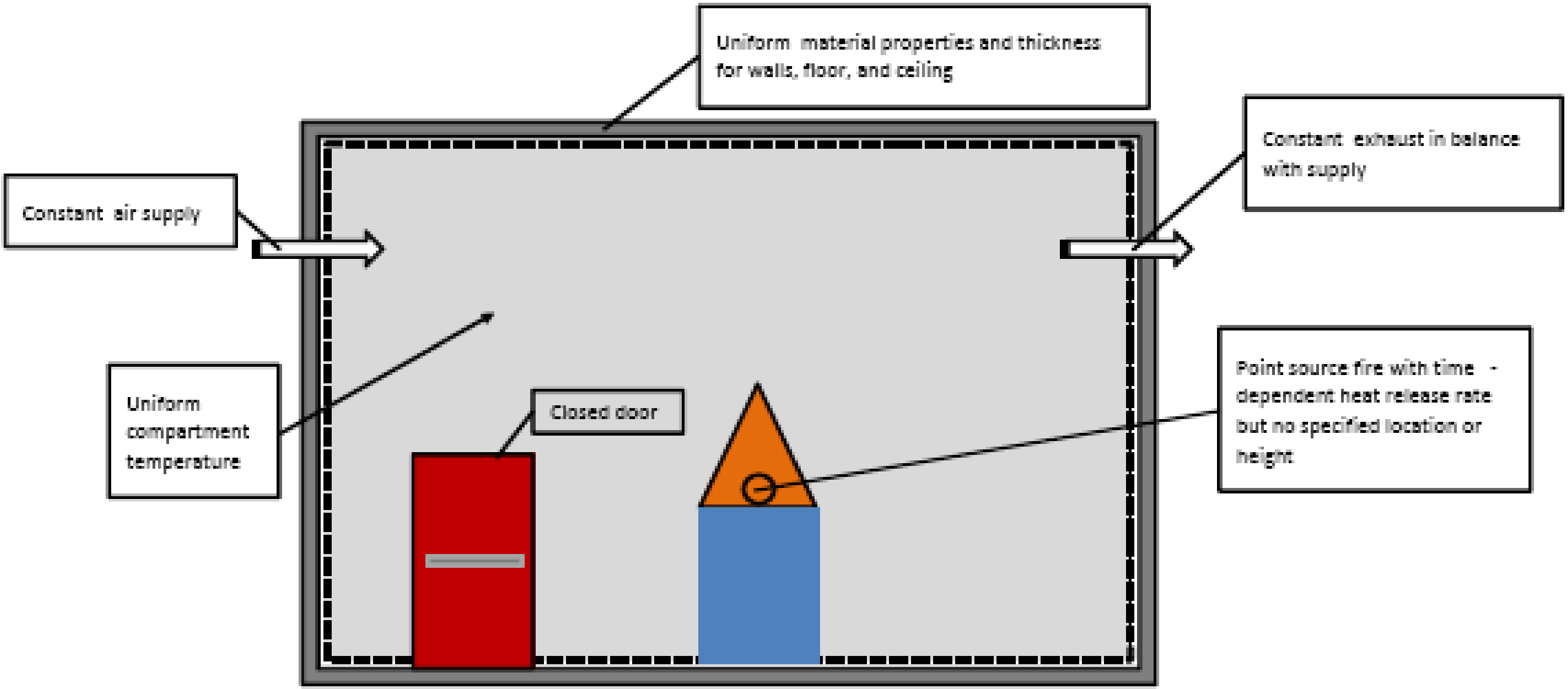
Applicability of Validation

- For the scenario with no ventilation, the classic definition of the Equivalence Ratio does not apply because there is no supply of oxygen in the room.
- However, it can be shown that there is sufficient oxygen in the room to sustain the specified fire.

$$m_{O_2,tot} = \rho V Y_{O_2} = 1.2\ \mathrm{kg/m^3} \times 1945\ \mathrm{m^3} \times 0.23 \cong 537\ \mathrm{kg}$$

$$m_{O_2,req} = \frac{Q}{\Delta H_{O_2}} \cong \frac{702\ \mathrm{kW} \times 60\ \mathrm{s/min} \times \left(\frac{12}{3} + 8 + \frac{19}{2}\right)\ \mathrm{min}}{13{,}100\ \mathrm{kJ/kg}} \cong 69\ \mathrm{kg}$$

Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions

- Temperature in smoke purge scenario
  - Use FPA correlation in FIVE-rev1 or FDTs
- Need equivalent length / width of non-rectangular rooms

$$A_{\mathrm{fl}} = L_e \times W_e \quad ; \quad P = 2 \times (L_e + W_e)$$

- Other input parameters

Table A-3. Summary of input parameters for the FPA calculation of the MCR.

Parameter	Value	Source
Room height (H)	5.2 m	Figure A-1
Room effective length (L_e)	27.1 m	Equation (A-3)
Room effective width (W_e)	13.8 m	Equation (A-3)
Room boundary material	Gypsum board	Table 3-1
Mech. ventilation rate ($\dot{V}$)	13.4 m^3/s	Specified (25 ACH)
Ambient temperature (T_a)	20 °C	Specified
Fire parameters		Table A-1

Step 4. Calculate Fire-Generated Conditions

Heat Flux

The point source model is used to estimate the heat flux from the flames to the operator when the fire is at its peak HRR. The peak HRR, $\dot{Q}$, is 702 kW, the radiative fraction, χ_r, is 0.53, and the distance from the cabinet vent to the operator is approximately 8.8 m (29 ft). The heat flux is calculated:

$$\dot{q}'' = \frac{\chi_r \, \dot{Q}}{4\pi \, r^2} = \frac{0.53 \ \times 702 \text{ kW}}{4\pi \ \times \ 8.8^2 \text{ m}^2} \cong 0.38 \text{ kW/m}^2 \qquad \text{(A-4)}$$

While this heat flux prediction is well below the critical value of 1 kW/m^2, it does not account for the thermal radiation from the HGL. Thus, the point source method can be used as a screening tool, and further analysis can be performed by CFAST and FDS.

Smoke concentration and visibility

Neither the FDT[s] nor FIVE include methods to calculate smoke concentrations or visibility in mechanically ventilated enclosure fires, but calculation methods provided in Section 3, Chapter 9, of the *SFPE Handbook* are relatively simple to apply and are based on the same principles and concepts embodied in zone models. These hand calculations provide an estimate of the fire-generated smoke concentrations and visibility conditions for this scenario and will indicate if more detailed modeling is warranted.

The soot mass generation rate, $\dot{m}_s$, is the product of the soot yield, y_s, and the mass burning rate of fuel, $\dot{m}_f$. The latter quantity is obtained by dividing the HRR, $\dot{Q}$, by the heat of combustion, ΔH:

$$\dot{m}_s = y_s \dot{m}_f = y_s \frac{\dot{Q}}{\Delta H} = 0.175 \times \frac{702 \text{ kW}}{10{,}300 \text{ kJ/kg}} \cong 0.012 \text{ kg/s} \tag{A-5}$$

The soot mass fraction in the smoke layer, Y_s, is then calculated:

$$Y_s = \frac{\dot{m}_s}{\dot{m}_{\text{tot}}} \cong \frac{\dot{m}_s}{\dot{m}_a} = \frac{\dot{m}_s}{\rho \dot{V}} = \frac{0.012 \text{ kg/s}}{1.2 \text{ kg/m}^3 \times 13.4 \text{ m}^3\text{/s}} \cong 0.00075 \text{ kg/kg} \tag{A-6}$$

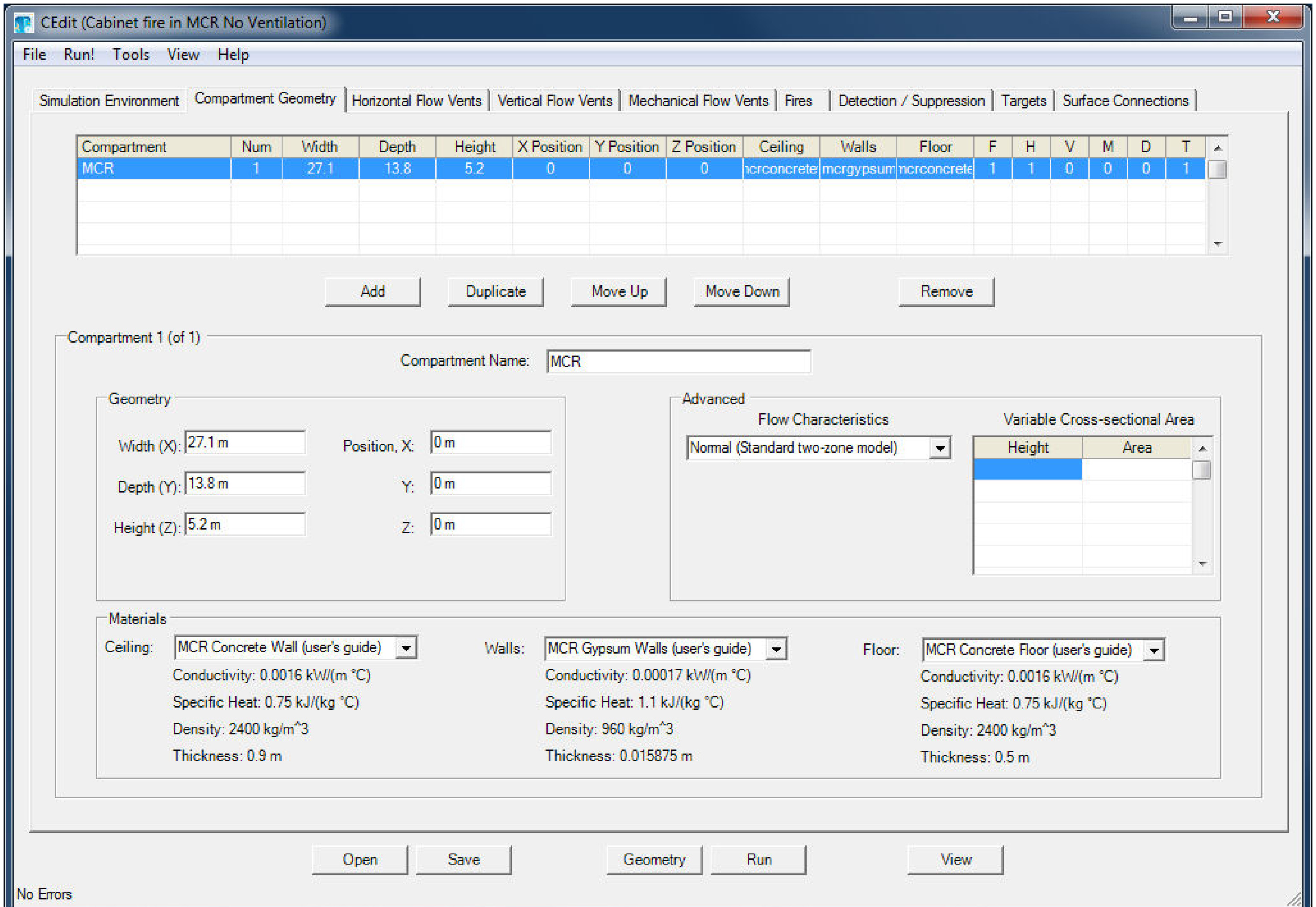
The extinction coefficient of the smoke, K, is calculated:

$$K = K_m \rho Y_s = 8700 \text{ m}^2\text{/kg} \times 1.2 \text{ kg/m}^3 \times 0.00075 \text{ kg/kg} \cong 7.8 \text{ m}^{-1} \tag{A-7}$$

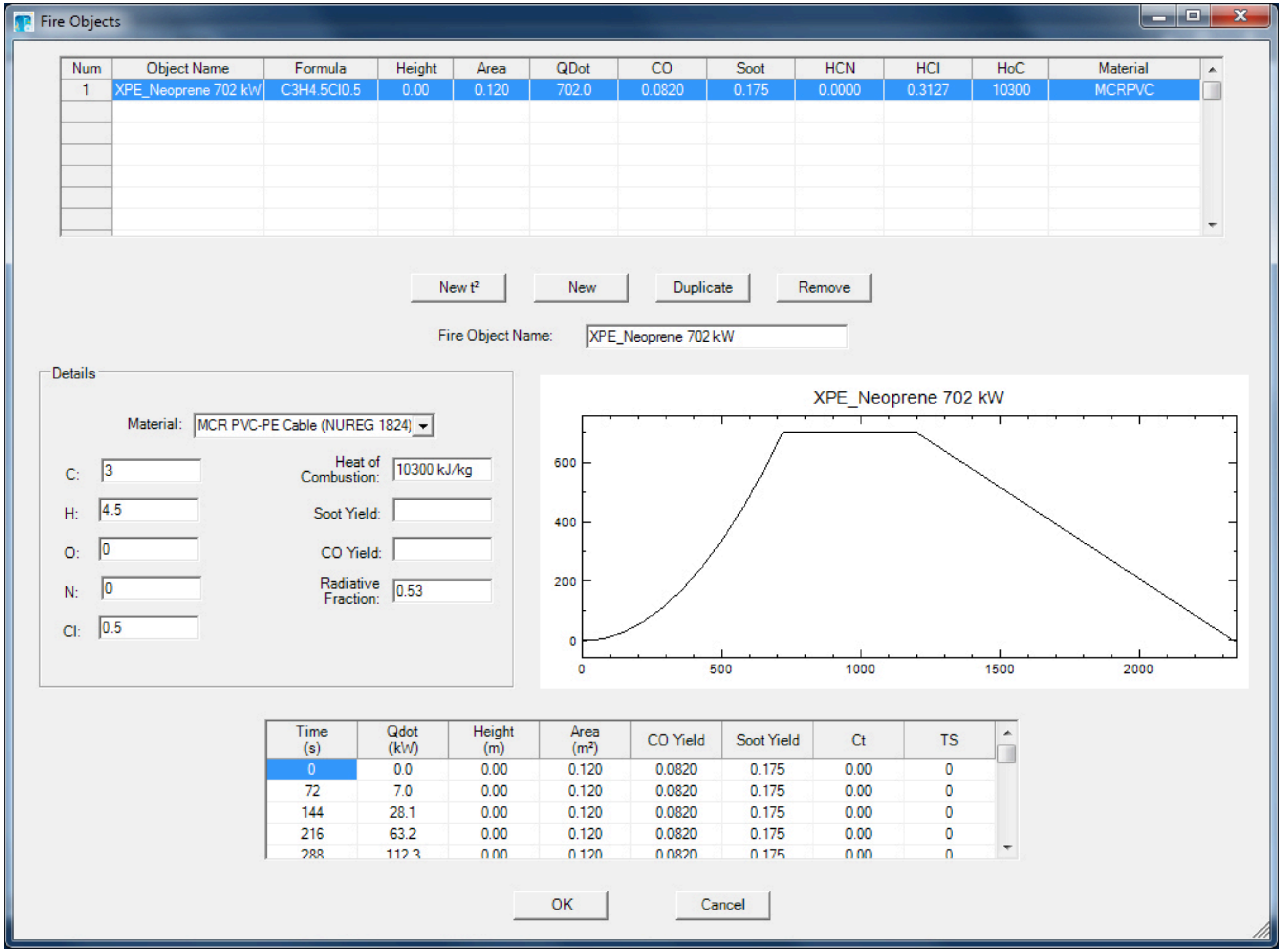
Here K_m is the mass specific extinction coefficient listed in Table A-1. By definition, the optical density of the smoke is related to the extinction coefficient via the expression:

$$D = \frac{K}{\ln 10} \cong \frac{7.8 \text{ m}^{-1}}{2.3} \cong 3.4 \text{ m}^{-1} \tag{A-8}$$

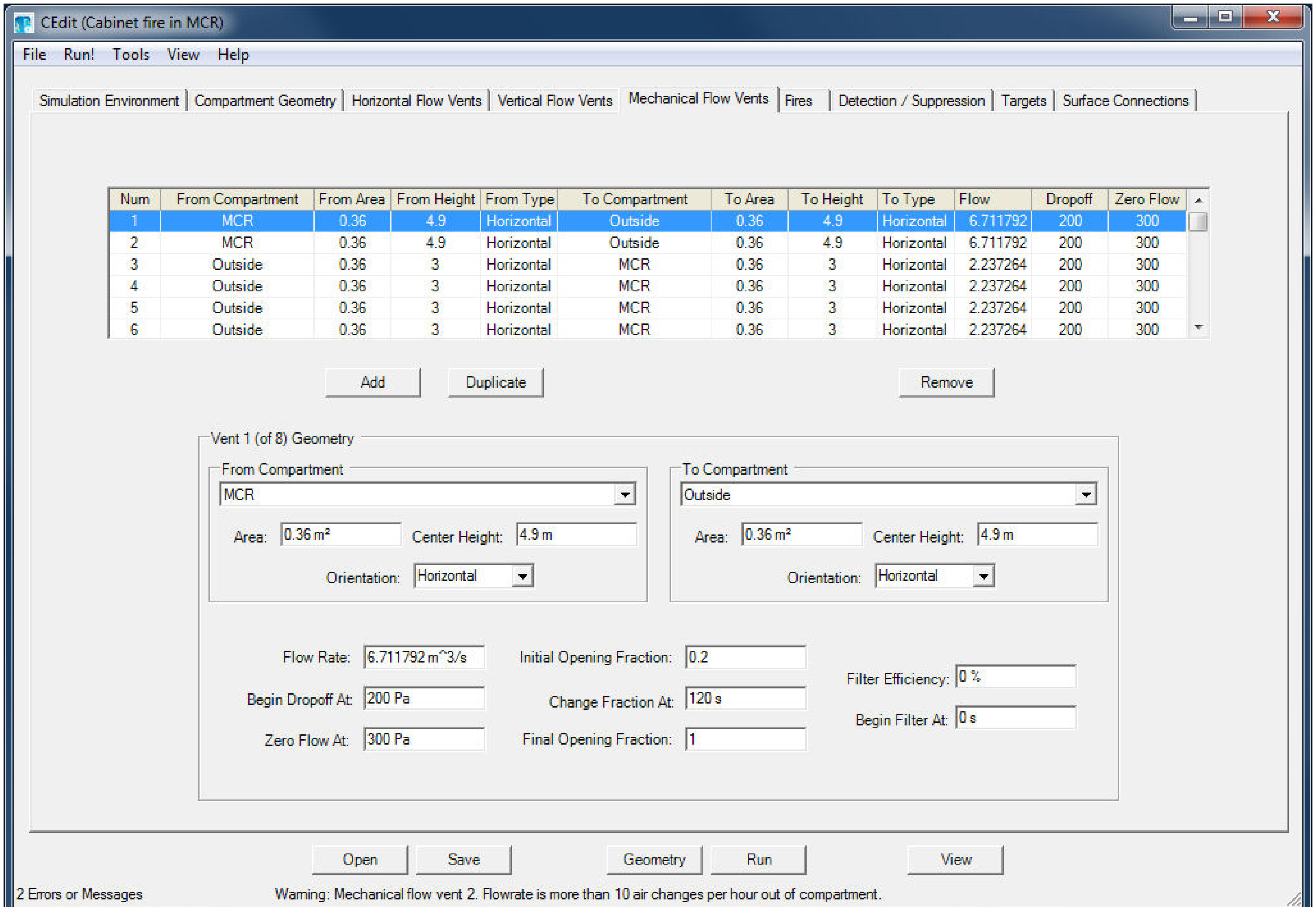
CFAST – geometry and material selection



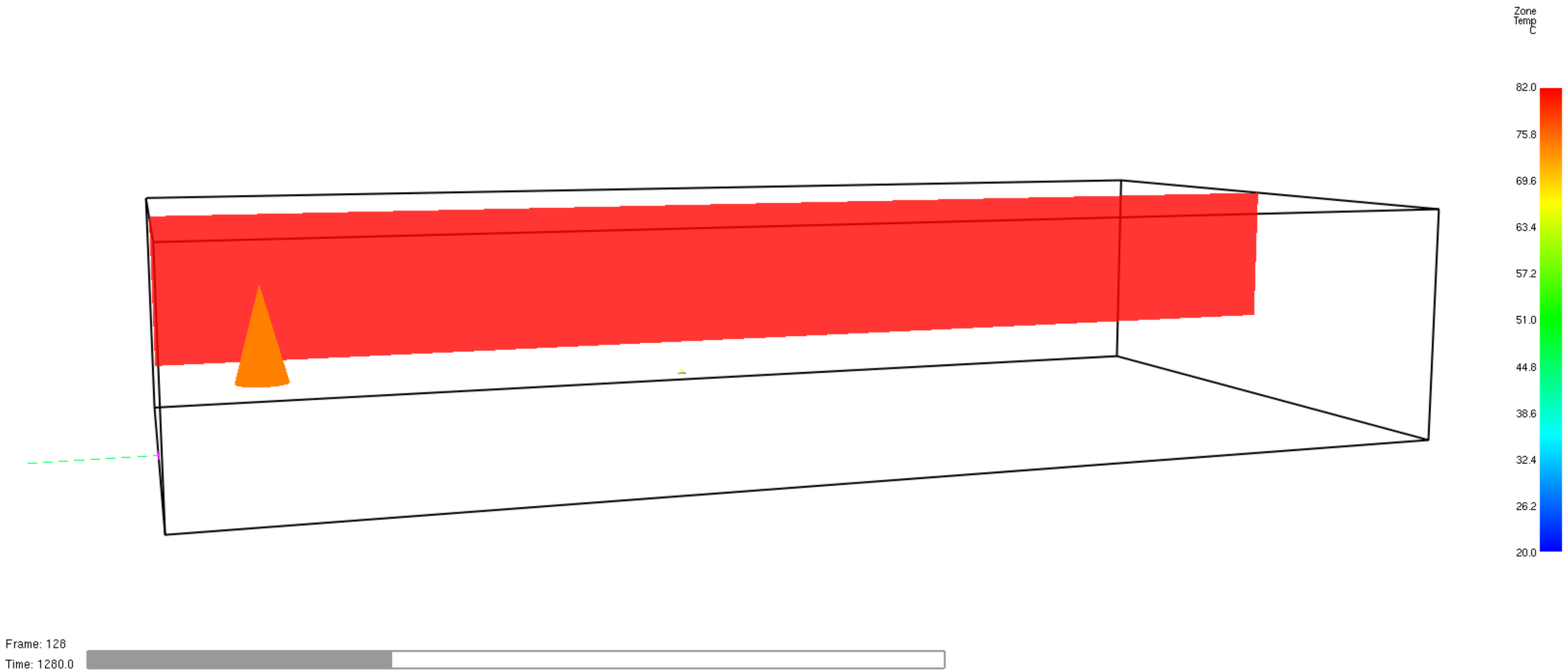
CFAST – fire specification



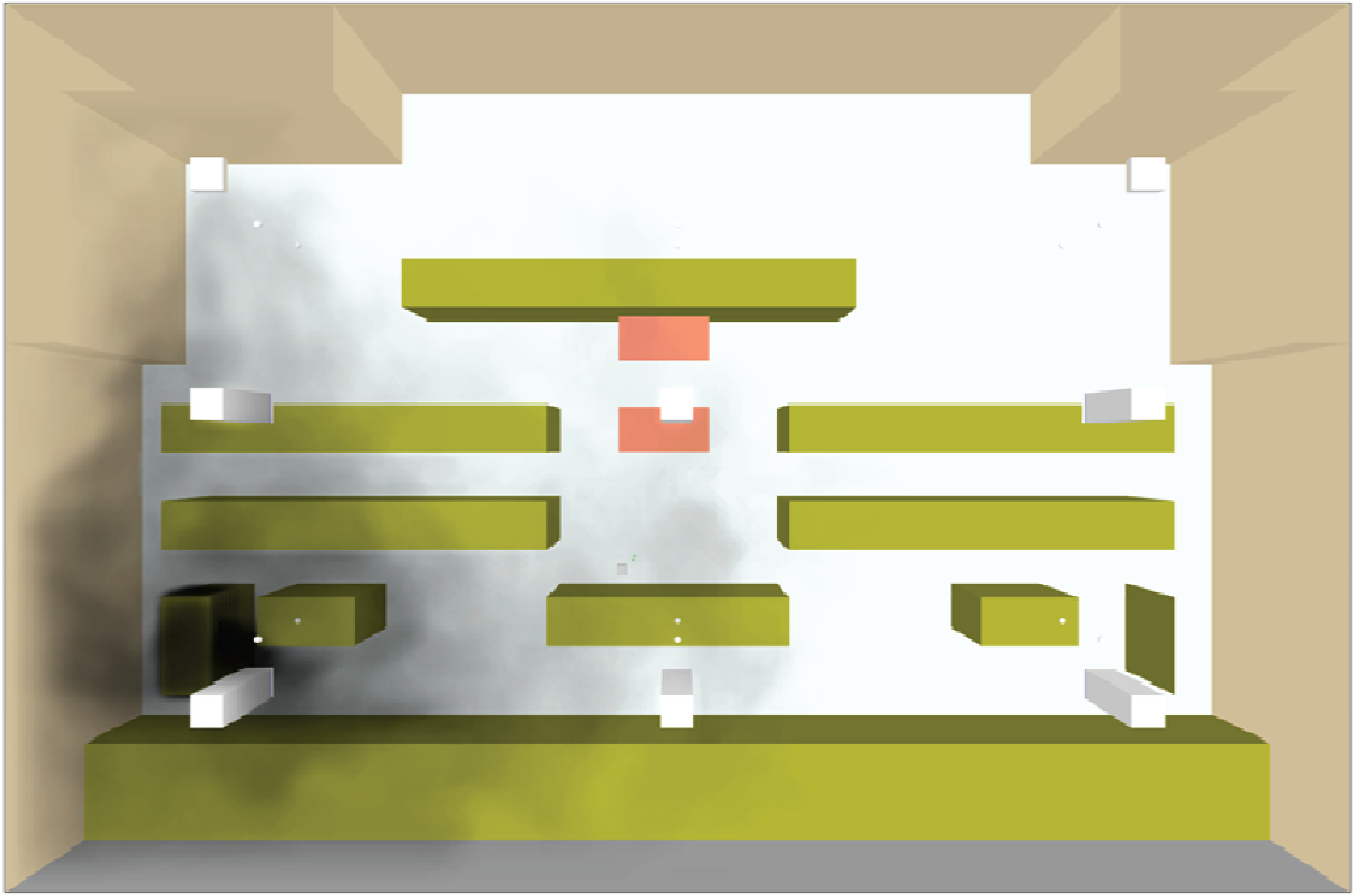
CFAST – mechanical ventilation



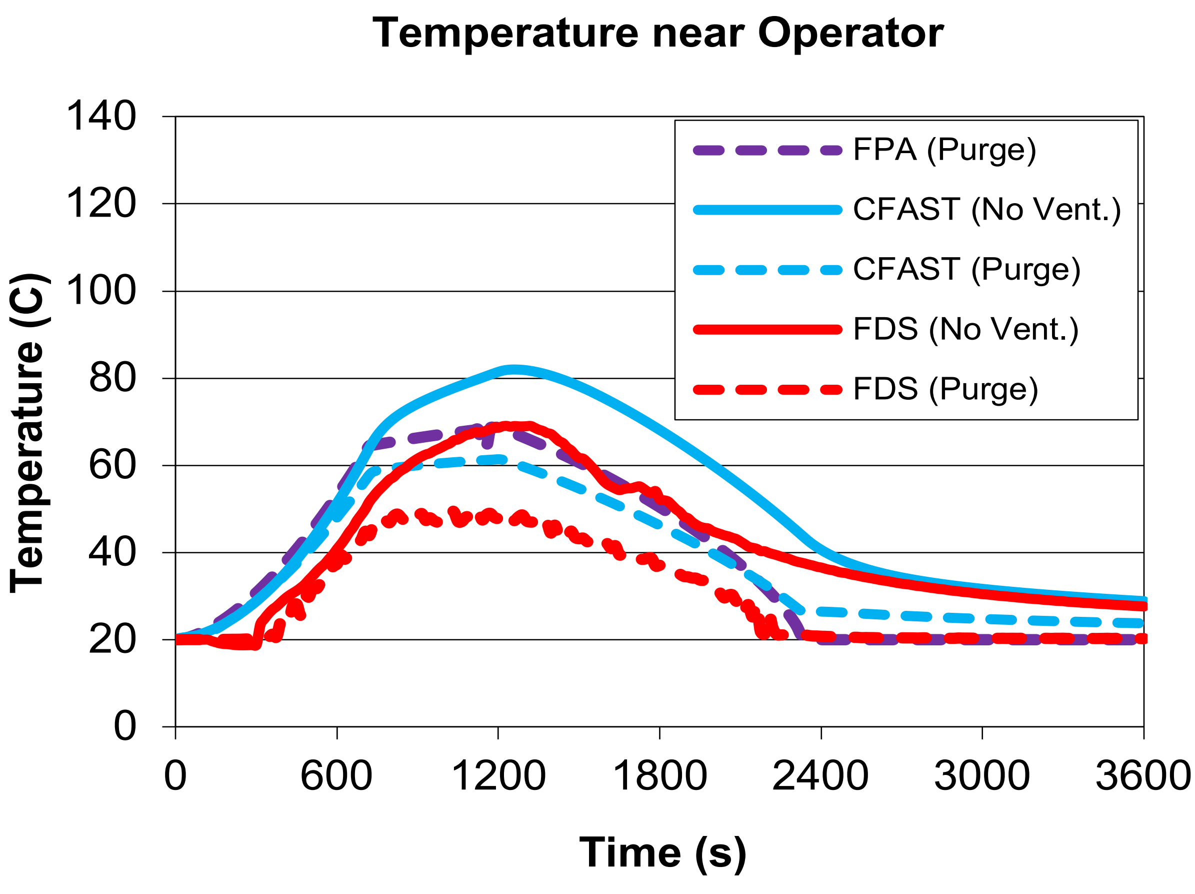
CFAST – Smokeview rendering of MCR fire



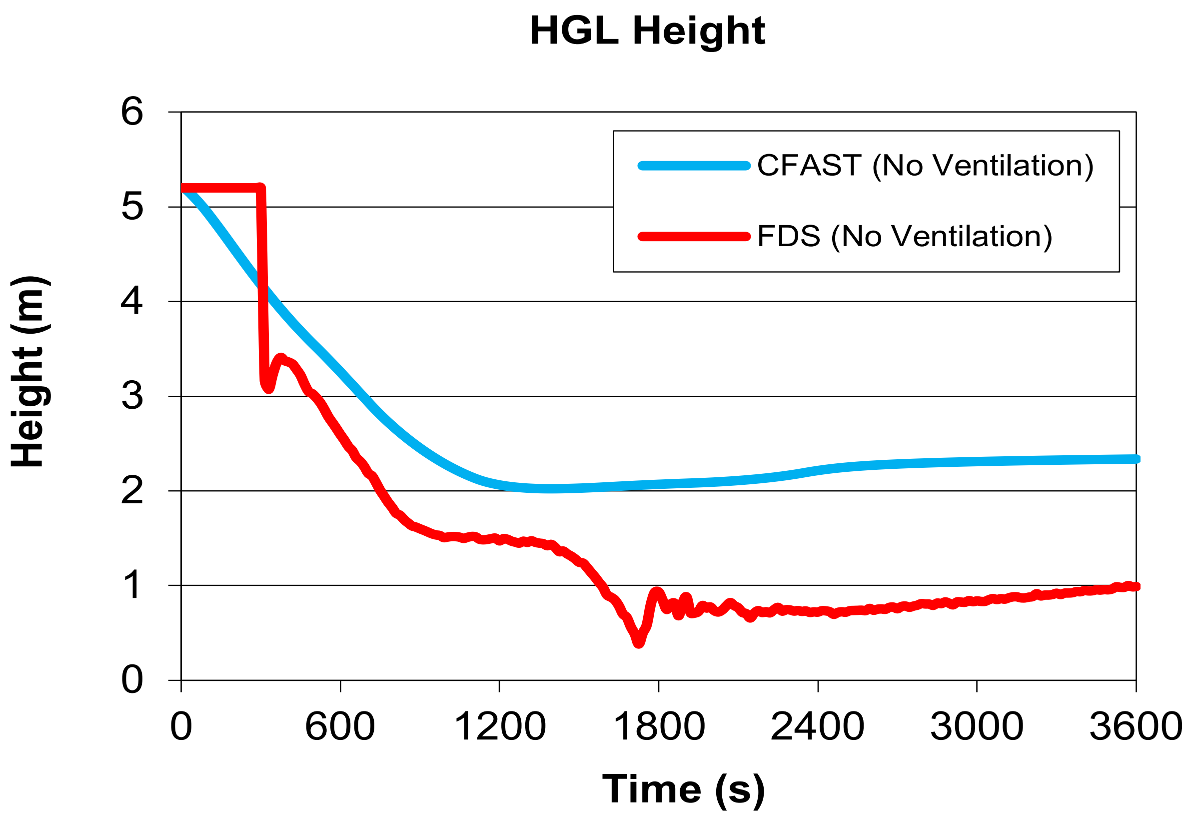
FDS – Smokeview rendering of MCR fire



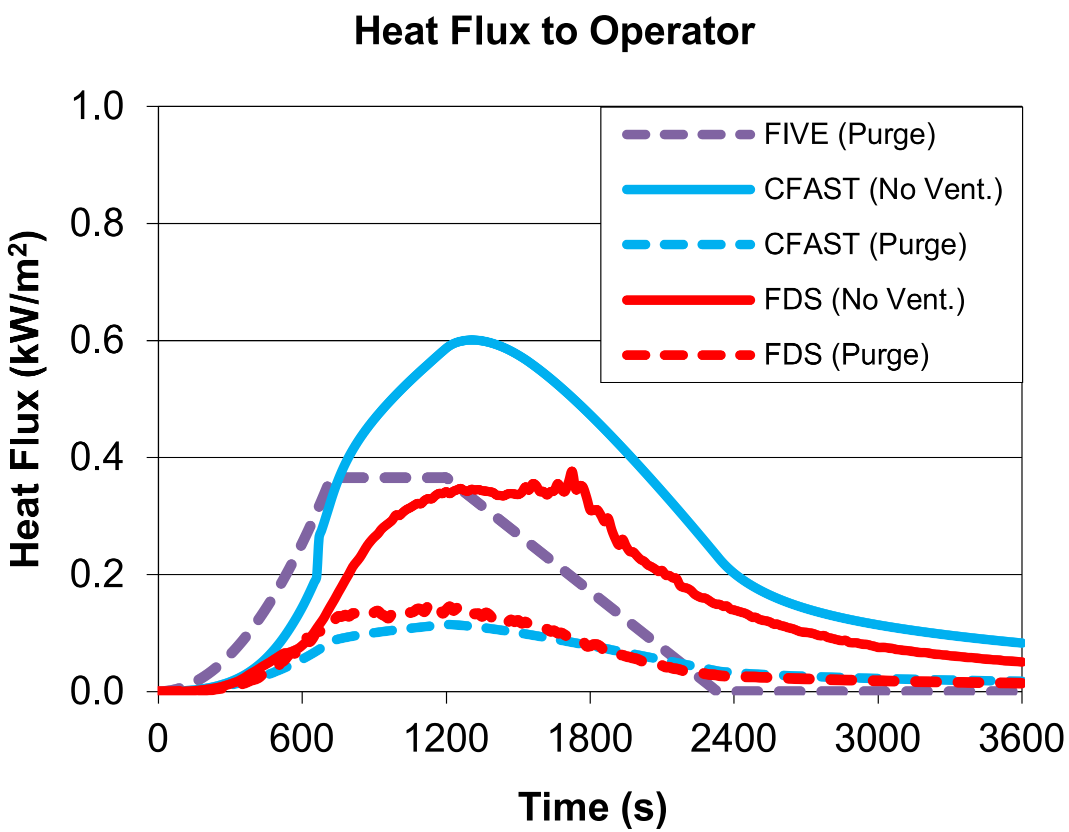
Step 4. Calculate Fire-Generated Conditions



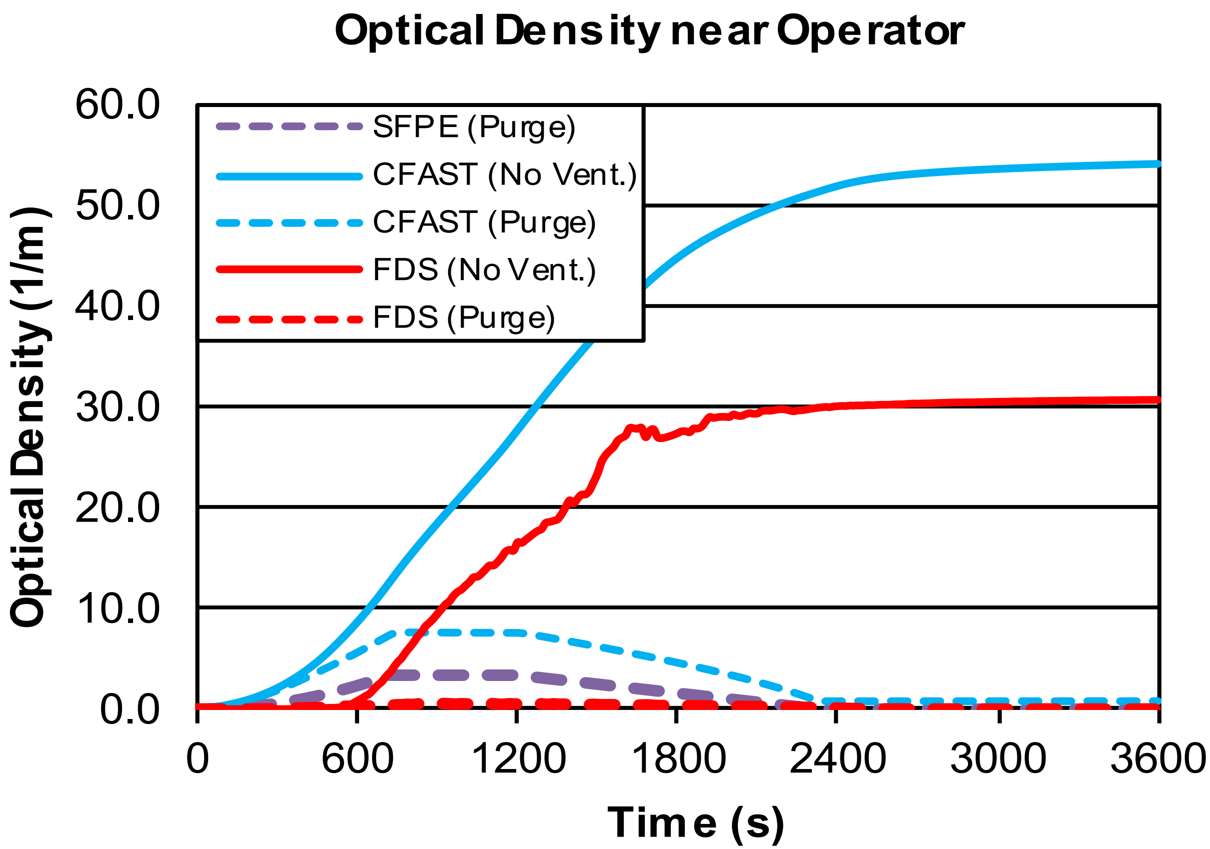
Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions

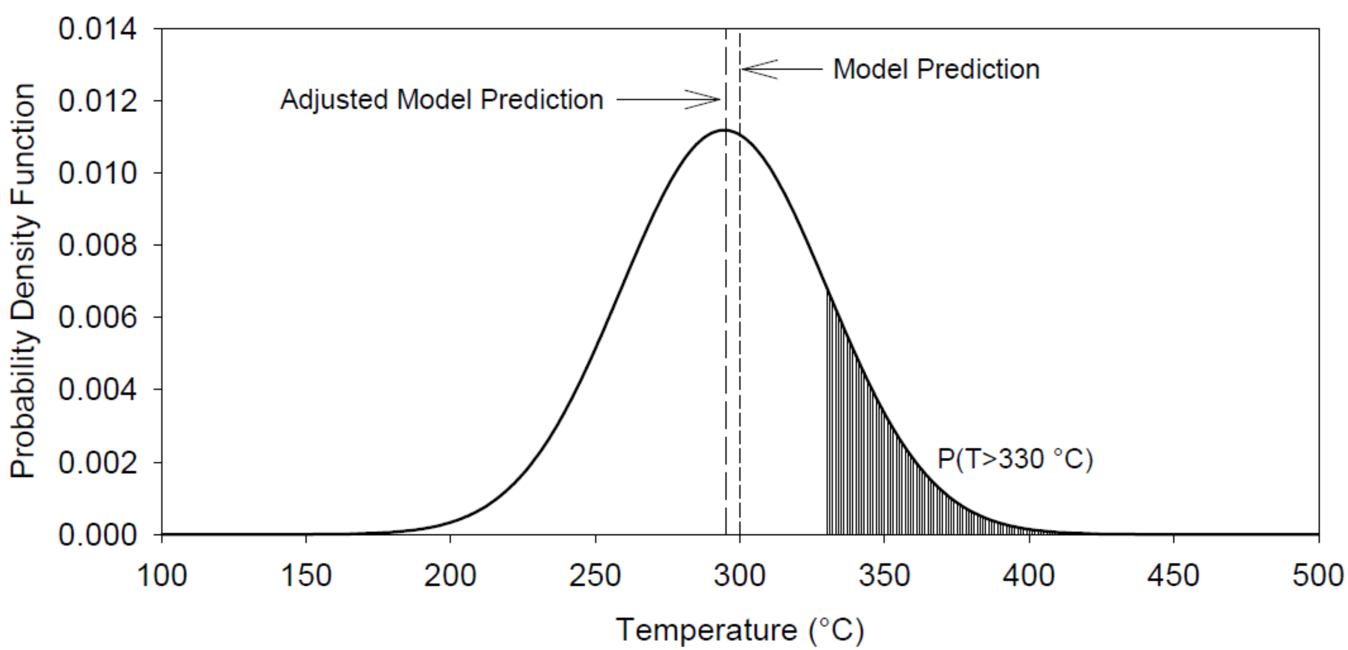


Step 4. Calculate Fire-Generated Conditions



Step 5. Sensitivity and Uncertainty Analysis

- Uncertainty Analysis quantifies the model uncertainty
  - List the predicted quantities and the critical values of these quantities
- Sensitivity Analysis can be used to assess parameter uncertainty



Step 5. Sensitivity and Uncertainty Analysis

Table A-4. Summary of the model predictions of the MCR scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Ventilation	Predicted Value	Critical Value	Probability of Exceeding
Temperature (°C), Initial Value = 20 °C						
FIVE-Rev1 (FPA)	1.56	0.32	Purge	70	95	0.000
CFAST	1.06	0.12		61	95	0.000
FDS	1.03	0.07		48	95	0.000
CFAST	1.06	0.12	No Vent.	82	95	0.009
FDS	1.03	0.07		70	95	0.000
Heat Flux (kW/m^2)						
FIVE-Rev1	1.42	0.55	Purge	0.4	1	0.000
CFAST	0.81	0.47		0.1	1	0.000
FDS	0.85	0.22		0.2	1	0.000
CFAST	0.81	0.47	No Vent.	0.6	1	0.228
FDS	0.85	0.22		0.4	1	0.000
Optical Density (m^{-1})						
CFAST	2.65	0.63	Purge	7.6	3	0.471
FDS	2.7	0.55		0.5	3	0.000
CFAST	2.65	0.63	No Vent.	54	3	0.912
FDS	2.7	0.55		31	3	0.909

Step 5. Sensitivity and Uncertainty Analysis

A.5.1 Temperature Criterion

The HGL temperature and height predictions are summarized in Table A-4 and are shown in detail in Figure A-12. None of the analyses imply that the temperature tenability limit would be exceeded by a fire of this type, regardless of the ventilation system. It is important to note that neither the FPA correlation nor CFAST estimate the temperature at the operator location specifically. For the purpose of assessing habitability, the HGL temperature is used to approximate the flux condition to which the operator would be exposed, regardless of whether the HGL descends to the operator's height. This means that the FPA and CFAST analyses have an extra level of conservatism built in for this particular case.

The FPA correlation predicts a peak HGL temperature of 70 °C (158 °F) when the smoke purge system is on, but, based on the CFAST calculation, it is expected that the layer height would not descend to the operator level if the purge system were in operation.

CFAST predicts that the HGL temperature reaches just above 80 °C (176 °F) in 20 min when the smoke purge system is off. The HGL descends to 2 m (6.6 ft) above the floor in approximately the same amount of time and thus remains above the head of the operator. When the smoke purge system is on, CFAST predicts that the peak HGL temperature reaches approximately 60 °C (140 °F), but that the smoke layer does not descend beyond a meter below the ceiling due to the operation of the smoke exhaust system. This is in contrast to the assumption that the enclosure is well-stirred when using the FPA model.

Step 5. Sensitivity and Uncertainty Analysis

The FDS predictions of HGL temperature are lower than those of the other models because FDS accounts for the mixing of heat and smoke with ambient air due to the high purging flow, since it models flow within the compartment in detail.

The HGL temperature is largely a function of the amount of energy from the fire that is carried aloft in the smoke plume. The model simulations have all assumed, based on data from the *SFPE Handbook, 4th edition*, that the convective fraction of the HRR is relatively low for the kind of cables under consideration. Typically, it is expected that approximately 65% of the fire's energy is lofted upwards in the plume, whereas in this case the models have all assumed a convective fraction of only 47% (one minus the radiative fraction). The consequence of this assumption is that the HGL temperature might be lower than one would expect from a typical fire because a higher percentage of its energy is assumed to be radiated away. Referring to Table 4-3, the HGL temperature rise is proportional to the HRR to the two-thirds power. For the purpose of this analysis, the HRR can be regarded as the convective HRR. If the convective HRR were increased by 38%, the HGL temperature rise would increase by approximately two-thirds of 38%, or 25%. This would have the effect of increasing the CFAST-predicted temperature rise from 60 °C (140 °F) to 75 °C (167 °F). Given an ambient temperature of 20 °C (68 °F), this means that if CFAST were to use the conventional 35% radiative fraction (65% convective fraction), its prediction[14] of the HGL in the no-ventilation case would be approximately 95 °C (203 °F), the critical value for abandonment. A similar argument can be made for the other HGL predictions.

Step 5. Sensitivity and Uncertainty Analysis

A.5.2 Heat Flux Criterion

In the fire scenario that includes the operation of the smoke purge system, none of the models predict that the heat flux to the operator exceeds the tenability criterion (see Figure A-13). In fact, CFAST and FDS estimate a peak flux of approximately 0.1 kW/m^2, a value that is one-tenth the critical value. With the smoke purge system turned off, FDS predicts a peak heat flux of 0.4 kW/m^2 and CFAST predicts 0.6 kW/m^2. However, as in the case of the HGL temperature criterion, it is important to consider the ramifications of the decision to use a radiative fraction of 53% rather than a value more typical of most fires, 35%. Table 4-3 suggests that the heat flux is proportional to the HRR to the four-thirds power. If the models were to use a radiative fraction of 35% rather than 53%, the convective HRR would be 38% greater, in which case the heat flux from the HGL layer onto the operator could increase by as much as 4/3 times 38%, or 50%. Referring to Figure A-13, this would have the effect of increasing the CFAST prediction from 0.6 kW/m^2 to 0.9 kW/m^2, close to the critical value of 1 kW/m^2. In fact, the validation study documented in NUREG-1824 (EPRI 1011999) indicates that CFAST tends to underpredict the total heat flux by 19%, on average. Given this fact and the discussion above on the HGL temperature, it should be noted that in the unventilated case, CFAST predicts that the HGL would descend to a level comparable in height to the operator (approximately 2 m), and it is reasonable to conclude that the operator would be exposed to a heat flux comparable to the habitability threshold.

Step 5. Sensitivity and Uncertainty Analysis

A.5.3 Visibility Criterion

The optical density results are shown in Figure A-14. As with temperature, the CFAST prediction is based on its upper layer smoke concentration calculation, whereas that of FDS is based on the actual operator location. The simple algebraic techniques described in A.4.1 and CFAST both predict that the optical density will exceed the critical threshold, even when the purge system is on. FDS, however, predicts a much lower optical density in the purge mode scenario for two reasons. First, FDS does not limit the transport of smoke to a descending layer like CFAST; and, second, FDS does not uniformly mix the smoke over the entire compartment volume like the simple algebraic model. As the operator stands relatively close to two supply vents, the supplied fresh air keeps this vicinity clearer than other areas.

When the smoke purge system is off, FDS predicts that the visibility tenability criterion will be exceeded at the operator position in about 12 min. Such conditions would force abandonment of the MCR. CFAST predicts that the visibility tenability criterion would be exceeded in the smoke layer in approximately 7 min, but it also predicts that the smoke layer remains above the operator's head throughout the fire simulation, which suggests that the MCR would not need to be abandoned. The fact that the HGL remains above 2 m (6.6 ft) is partially an artifact of the zone model. There is no mechanism in CFAST for the smoke layer to descend below the base of the fire; a fire with a lower base height could result in a lower HGL elevation.

Step 5. Sensitivity and Uncertainty Analysis

There is considerable uncertainty in the smoke yield of real fires, especially in cases where the fire might be under-ventilated inside of a cabinet. A value of 0.175 (kg soot per kg fuel consumed) was chosen for the smoke yield in the models, even though literature values range from 0.01 to 0.2 (kg soot per kg fuel consumed), depending on the fuel. In addition to the uncertainty in the specified input value of the smoke yield, the NRC/EPRI V&V study (NUREG-1824 (EPRI 1011999)) indicates that both CFAST and FDS overestimate measured smoke concentrations, on average, by factors of 2.65 and 2.70, respectively. In light of these uncertainties in both models and in the input parameters, it is prudent to consider the sensitivity of the simulation results to the selected value of the smoke yield. Table 4.3 indicates that the optical density is directly proportional to the smoke yield. This means that if the smoke yield is doubled, the predicted optical density is doubled as well. The curves in Figure A-14 can easily be adjusted to show the effect of a variation in the smoke yield, but the predicted abandonment times in the unventilated scenario do not change significantly with changes in the smoke yield.

Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

Step 6. Document the Analysis

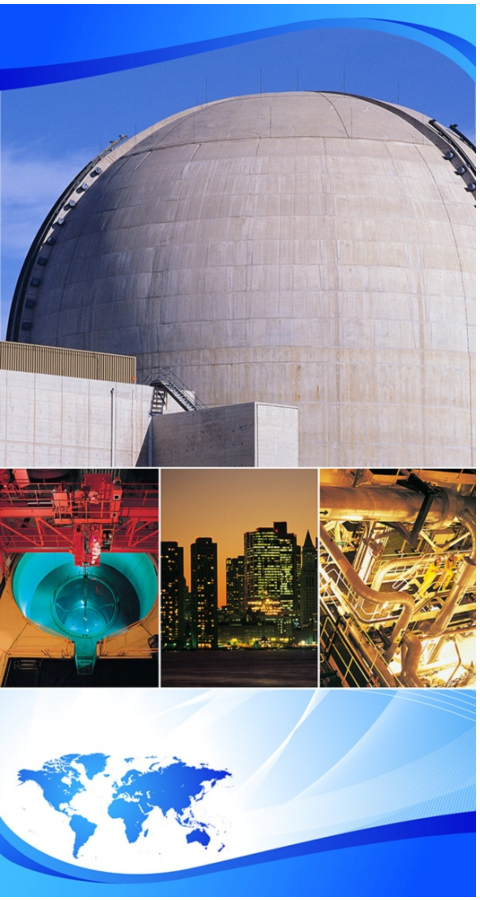
A.6 Conclusion

A fire modeling analysis has been performed to assess the habitability of the MCR in the event of a fire within an isolated electrical cabinet. The fire is not expected to spread to other cabinets. Of the three MCR abandonment criteria, it is most likely that the operators would be forced to abandon the MCR because the optical density would surpass 3 m^{-1} approximately 12 minutes after the fire ignites if the smoke purge system is not activated before this time, according to the FDS analysis. A simple analytical method and the zone model CFAST indicate that the optical density would exceed the critical value with the smoke purge system on and with the ventilation system turned off. However, these analyses are based on several important conservative assumptions. For the smoke purge case, the analytical method conservatively reports the optical density of the upper layer, but does not predict that the upper layer would descend to the level of the operator in either the purge or no-ventilation scenario based on the specified conservative assumptions, at least for a fire having a base height of 2 m (6.6 ft).

Step 6. Document the Analysis

A.7 References

1. NUREG-1805, *Fire Dynamics Tools*, 2004.
2. NUREG/CR-6850 (EPRI 1011989), *Fire PRA Methodology for Nuclear Power Facilities*, 2005.
3. NUREG-1824 (EPRI 1011999), *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*, 2007.
4. *SFPE Handbook of Fire Protection Engineering*, 4th edition, 2008.
5. NIST SP 1018-5, *Fire Dynamics Simulator (Version 5), Technical Reference Guide, Vol. 3, Experimental Validation*.
6. NIST SP 1030. *CFAST: An Engineering Tool for Estimating Fire Growth and Smoke Transport, Version 5 - Technical Reference Guide*, National Institute of Standards and Technology, Gaithersburg, Maryland, 2004.
7. G. W. Mulholland and C. Croarkin. "Specific Extinction Coefficient of Flame Generated Smoke." *Fire and Materials*, 24:227–230, 2000.



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5
Advanced Fire Modeling
Day 3 – AM Session
Example B: Switchgear Room Cabinet Fire

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

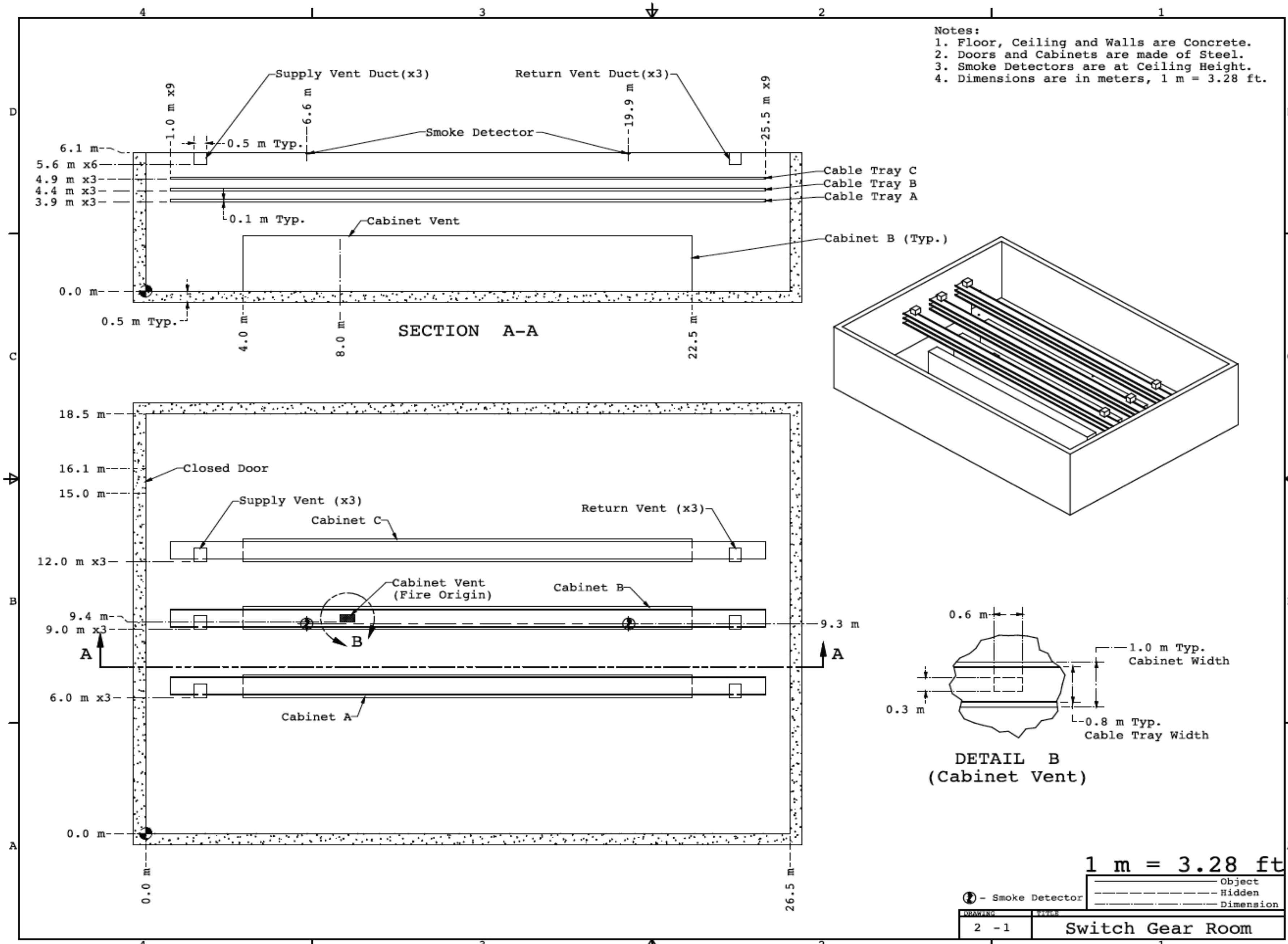
A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Step 1. Define Fire Modeling Goals

- Estimate the effects of fire in a cabinet in a Switchgear Room on nearby cable and cabinet targets.
- Switchgear Room contains safety-related equipment for both Train A and Train B that are not separated as required by Appendix R.
- The purpose of the calculation is to analyze this condition and determine whether these targets fail, and, if so, at what time failure occurs.
- Follow guidance provided in Chapter 11 of NUREG/CR-6850 (EPRI 1011989), Volume 2, "Detailed Fire Modeling (Task 11)."

Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Ventilation
- Fire
- Fire Protection Systems
  - None credited for this scenario


Notes:
1. Floor, Ceiling and Walls are Concrete.
2. Doors and Cabinets are made of Steel.
3. Smoke Detectors are at Ceiling Height.
4. Dimensions are in meters, 1 m = 3.28 ft.
Supply Vent Duct(x3)
Return Vent Duct(x3)
Smoke Detector
1.0 m x9
6.6 m
19.9 m
25.5 m x9
0.5 m Typ.
6.1 m
5.6 m x6
4.9 m x3
4.4 m x3
3.9 m x3
Cable Tray C
Cable Tray B
Cable Tray A
0.1 m Typ.
Cabinet Vent
Cabinet B (Typ.)
0.0 m
0.5 m Typ.
4.0 m
8.0 m
22.5 m
SECTION A-A
18.5 m
16.1 m
Closed Door
15.0 m
Supply Vent (x3)
Cabinet C
Return Vent (x3)
12.0 m x3
Cabinet Vent
(Fire Origin)
Cabinet B
9.4 m
9.0 m x3
9.3 m
B
A
A
6.0 m x3
Cabinet A
0.0 m
0.0 m
26.5 m
0.6 m
1.0 m Typ.
Cabinet Width
0.3 m
0.8 m Typ.
Cable Tray Width
DETAIL B
(Cabinet Vent)
1 m = 3.28 ft
Smoke Detector
Object
Hidden
Dimension
2 -1
Switch Gear Room

Material Properties

Table 3-1. Material properties.

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Source
Brick	0.8	2600	0.8	NUREG-1805, Table 2-3
Concrete	1.6	2400	0.75	NUREG-1805, Table 2-3
Copper	386	8954	0.38	SFPE Handbook, Table B.6
Gypsum	0.17	960	1.1	NUREG-1805, Table 2-3
Plywood	0.12	540	2.5	NUREG-1805, Table 2-3
PVC	0.192	1380	1.289	NUREG/CR-6850, Appendix R
Steel	54	7850	0.465	NUREG-1805, Table 2-3
XLP	0.235	1375	1.390	NUREG/CR-6850, Appendix R

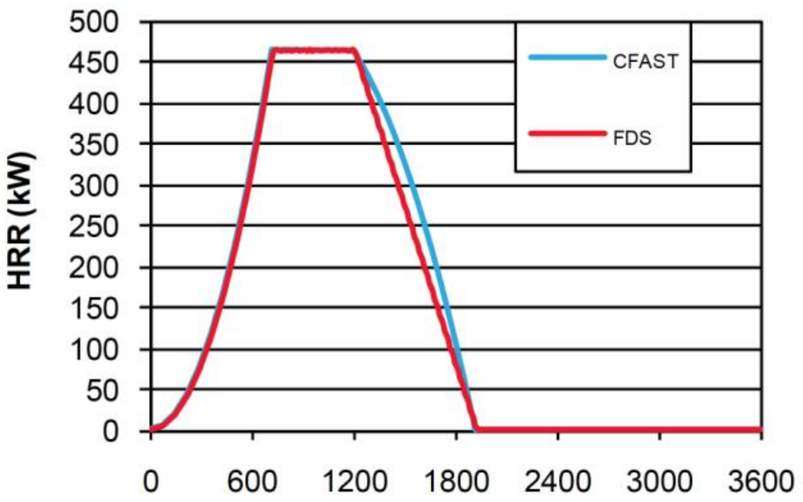
Ventilation

- Design flowrate specified for each of three supply and return registers.
- Normal operation continues during the fire.
- Leakage – often the "leakage area" is the area of the crack under the door.
- Exact supply and exhaust location only important for CFD.
- Zone models usually only consider height of ducts off floor and orientation of the vent.

Fire

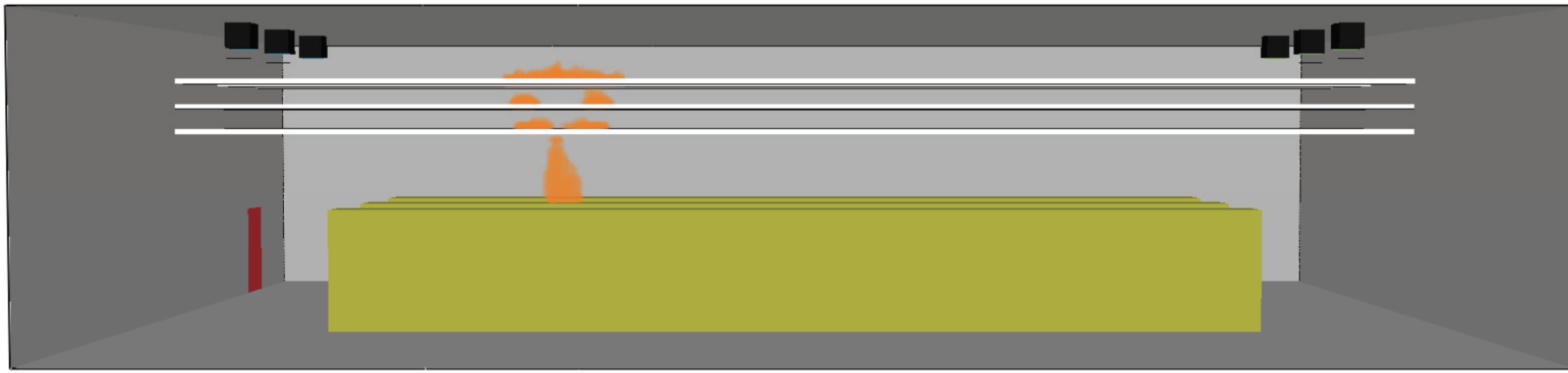
Table G-1
Recommended HRR Values for Electrical Fires

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)

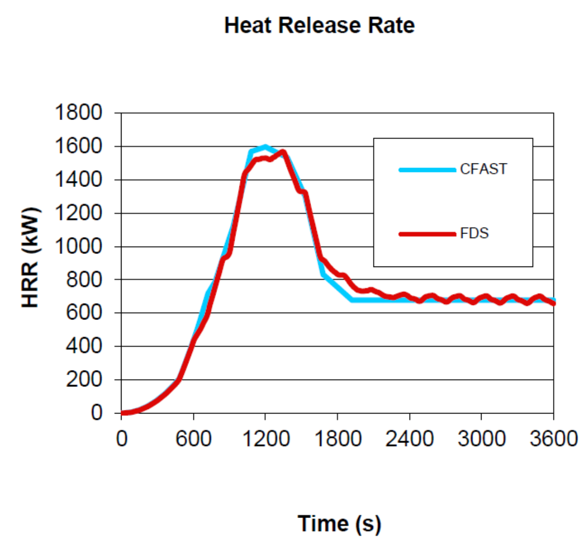


HRR taken from Appendix G, NUREG/CR 6850 (EPRI 1011989)

Fire



- Original fire source is specified atop the central cabinet.
- FLASH-CAT model (NUREG/CR-7010, Volume 1) is used to determine the ignition, flame spread and extinction of the cables above the original fire source.



Fire

What is burning?

Cables made of polyethylene (C_2H_4) and polyvinylchloride (C_2H_3Cl).

Assume effective fuel: $C_2H_{3.5}Cl_{0.5}$

Table B-1. Products of combustion for switchgear room cabinet and cable fire.

Parameter	Value	Source
Effective Fuel Formula	$C_2H_{3.5}Cl_{0.5}$	Combination of polyethylene and PVC
Peak HRR	464 kW	NUREG/CR-6850 (EPRI 1011989), App. G
Heat of Combustion	20,900 kJ/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
CO_2 Yield	1.29 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
Soot Yield	0.136 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
CO Yield	0.147 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
Radiative Fraction	0.49	*SFPE Handbook*, 4th Ed., Table 3-4.16

Step 3. Select Fire Models

- Algebraic Models: FPA algorithm in FIVE provides estimate of HGL temperature within a closed, ventilated compartment. FDTs do not allow for time-dependent HRR. Both FIVE and FDTs can estimate heat flux from a fire to a target.
- Zone Models: Both CFAST and MAGIC include algorithms to estimate the heat flux to and temperature of cable targets.
- CFD: Typical application of FDS. The primary advantage of a CFD model for this fire scenario is that the CFD model can predict local conditions at the specific location of the target cables and adjacent cabinet.

Applicability of Validation

Table B-2. Key parameters and their ranges of applicability to NUREG-1824 (EPRI 1011999).

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{464\ \text{kW}}{(1.2\ \text{kg/m}^3)(1.0\ \text{kJ/kg/K})(293\ \text{K})(0.48^{2.5}\ \text{m}^{2.5})\sqrt{9.8\ \text{m/s}^2}} \cong 2.6$ $\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{1600\ \text{kW}}{(1.2\ \text{kg/m}^3)(1.0\ \text{kJ/kg/K})(293\ \text{K})(1^{2.5}\ \text{m}^{2.5})\sqrt{9.8\ \text{m/s}^2}} \cong 1.4$	0.4 – 2.4	No
Flame Length, L_f, relative to the Ceiling Height, H_c	$\frac{H_f + L_f}{H_c} = \frac{2.4\ \text{m} + 2.1\ \text{m}}{6.1\ \text{m}} \cong 0.7$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 0.48\ \text{m}\,(3.7 \times 2.6^{0.4} - 1.02) \cong 2.1\ \text{m}$	0.2 – 1.0	Yes
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H_c	N/A – Ceiling jet targets are not included in simulation.	1.2 – 1.7	N/A
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\,\dot{m}_{O_2}} = \frac{1{,}600\ \text{kW}}{13{,}100\ \text{kJ/kg} \times 0.4\ \text{kg/s}} \cong 0.31$ (based on peak fire size) $\dot{m}_{O_2} = 0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2\ \text{kg/m}^3 \times 1.4\ \text{m}^3/\text{s} \cong 0.4\ \text{kg/s}$	0.04 – 0.6	Yes
Compartment Aspect Ratio	$\frac{L}{H_c} = \frac{26.5\ \text{m}}{6.1\ \text{m}} \cong 4.3$ $\quad \frac{W}{H_c} = \frac{18.5\ \text{m}}{6.1\ \text{m}} \cong 3.0$	0.6 – 5.7	Yes
Target Distance, r, relative to the Fire Diameter, D	$\frac{r}{D} = \frac{1.5\ \text{m}}{0.48\ \text{m}} \cong 3.1$	2.2 – 5.7	Yes

Step 4. Calculate Fire-Generated Conditions

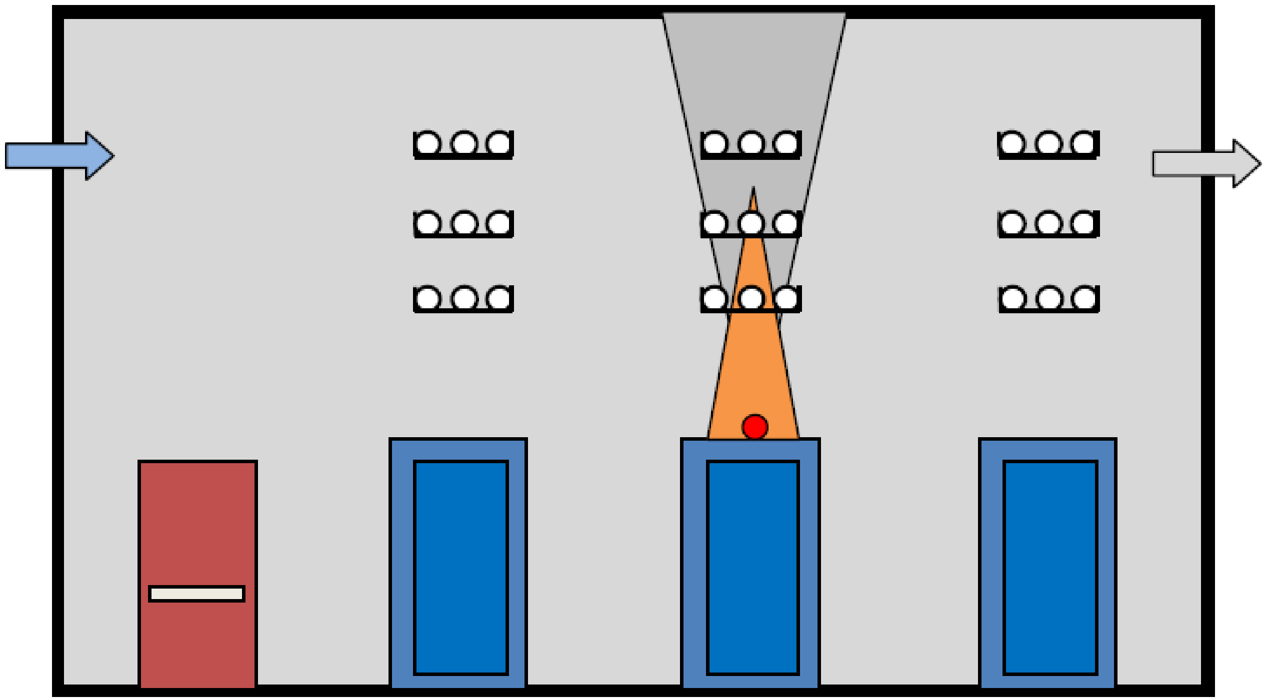


Figure B-2. Schematic diagram of cabinet fire in switchgear room.

Step 4. Calculate Fire-Generated Conditions

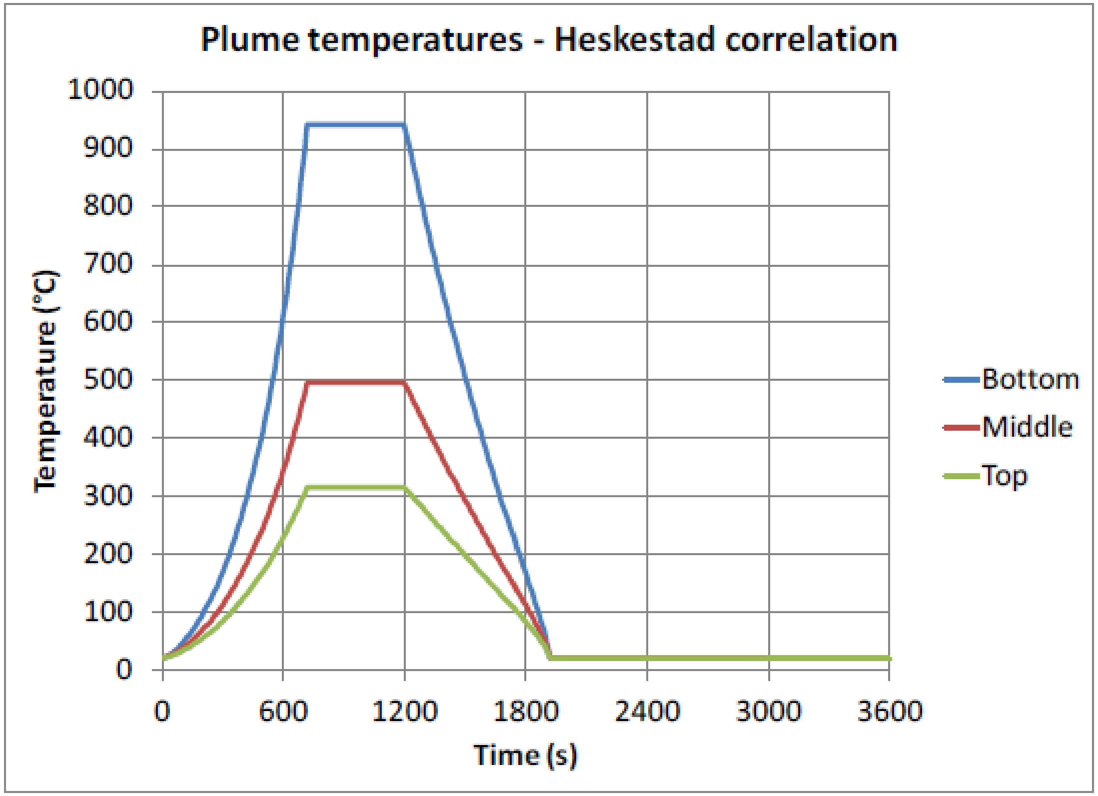


Figure B-3. Plume temperatures at cable trays located above cabinet fire.

Step 4. Calculate Fire-Generated Conditions

Table B-3. Summary of input parameters for FPA analysis of switchgear room scenario.

Parameter	Value	Source
Room height (H)	~~5.2 m~~	Figure B-1 Should be 6.1 m
Room length (L)	26.5 m	Figure B-1
Room effective width (W_e)	18.5 m	Calculation
Room boundary material	Concrete	Figure B-1. See Table 3-1 for properties.
Mech. Ventilation rate ($\dot{V}$)	1.42 m^3/s	From scenario description
Fire elevation (H_f)	2.4 m	From scenario description of cabinet height and vent location.
Ambient temperature (T_a)	20°C	Specified
Fire parameters	See Table B-1	

Temperature: The FPA HGL temperature correlation for mechanically ventilated spaces is expressed in non-dimensional terms as:

$$\frac{\Delta T_g}{T_\infty} = 0.63\left(\frac{\dot{Q}}{\dot{m}c_pT_\infty}\right)^{0.72}\left(\frac{h_kA_T}{\dot{m}c_p}\right)^{-0.36} \quad \text{(B-4)}$$

Step 4. Calculate Fire-Generated Conditions

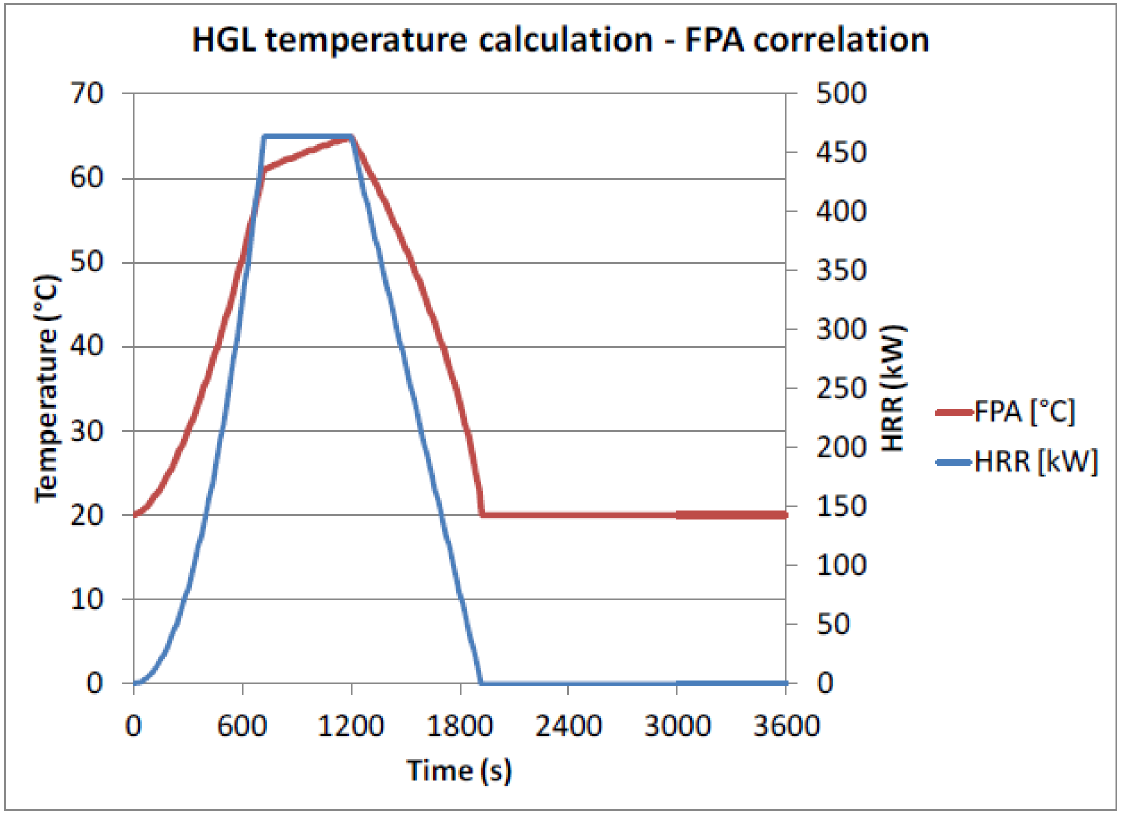


Figure B-4. Average HGL temperature from FPA correlation for switchgear room cabinet fire scenario.

CFAST – Geometry and material selection

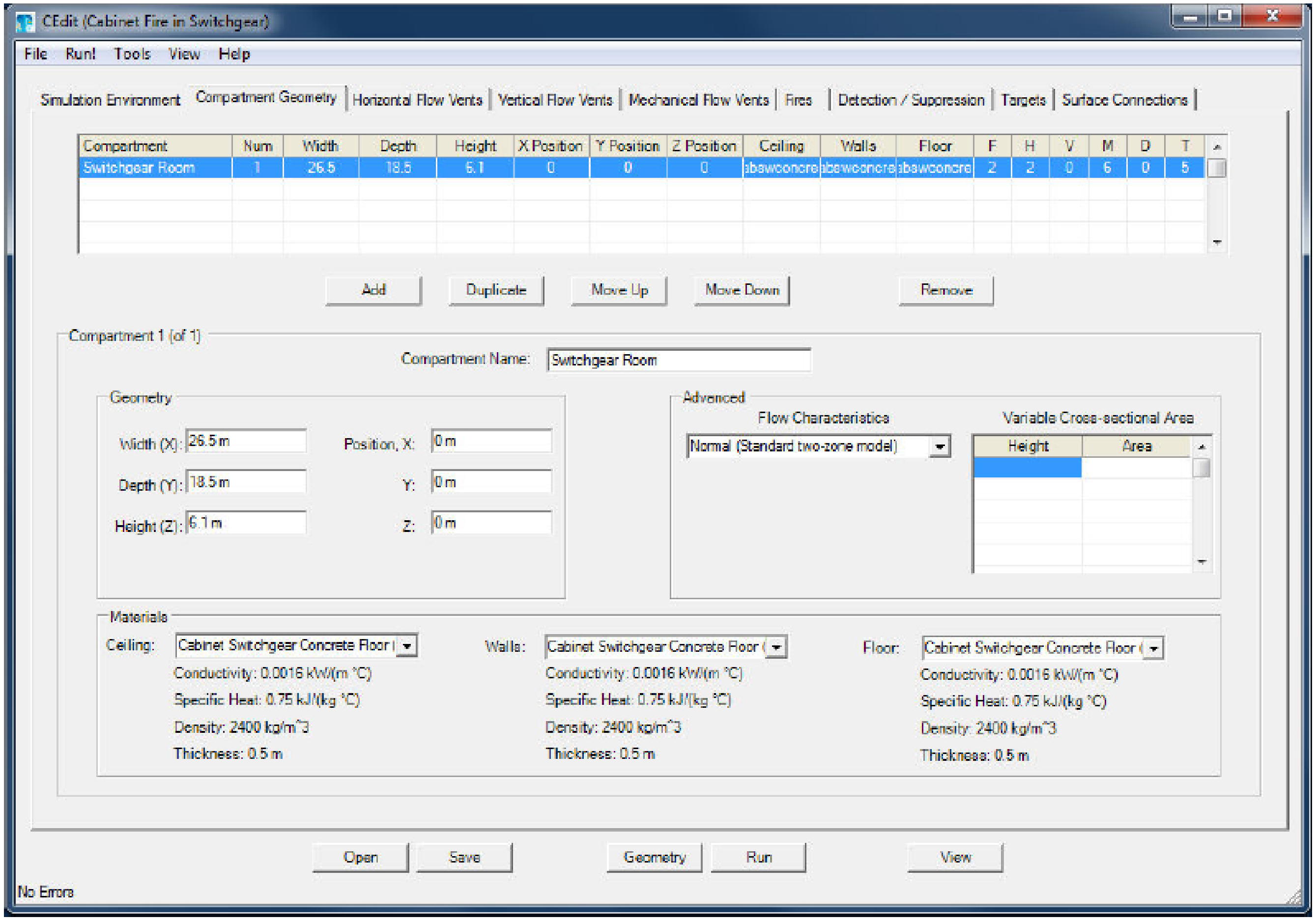
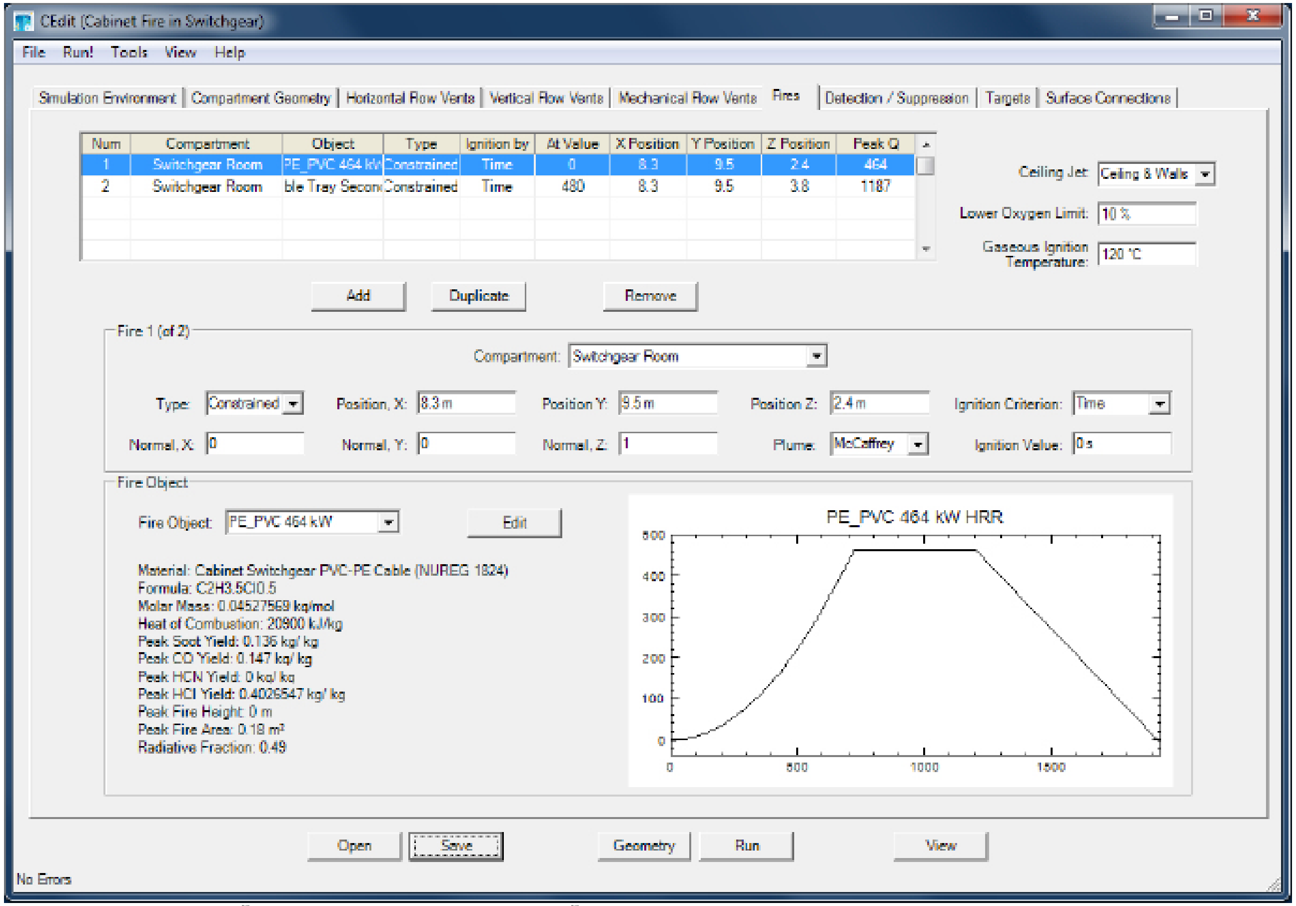


Figure B-6. CFAST inputs for compartment geometry in SWGR scenario.

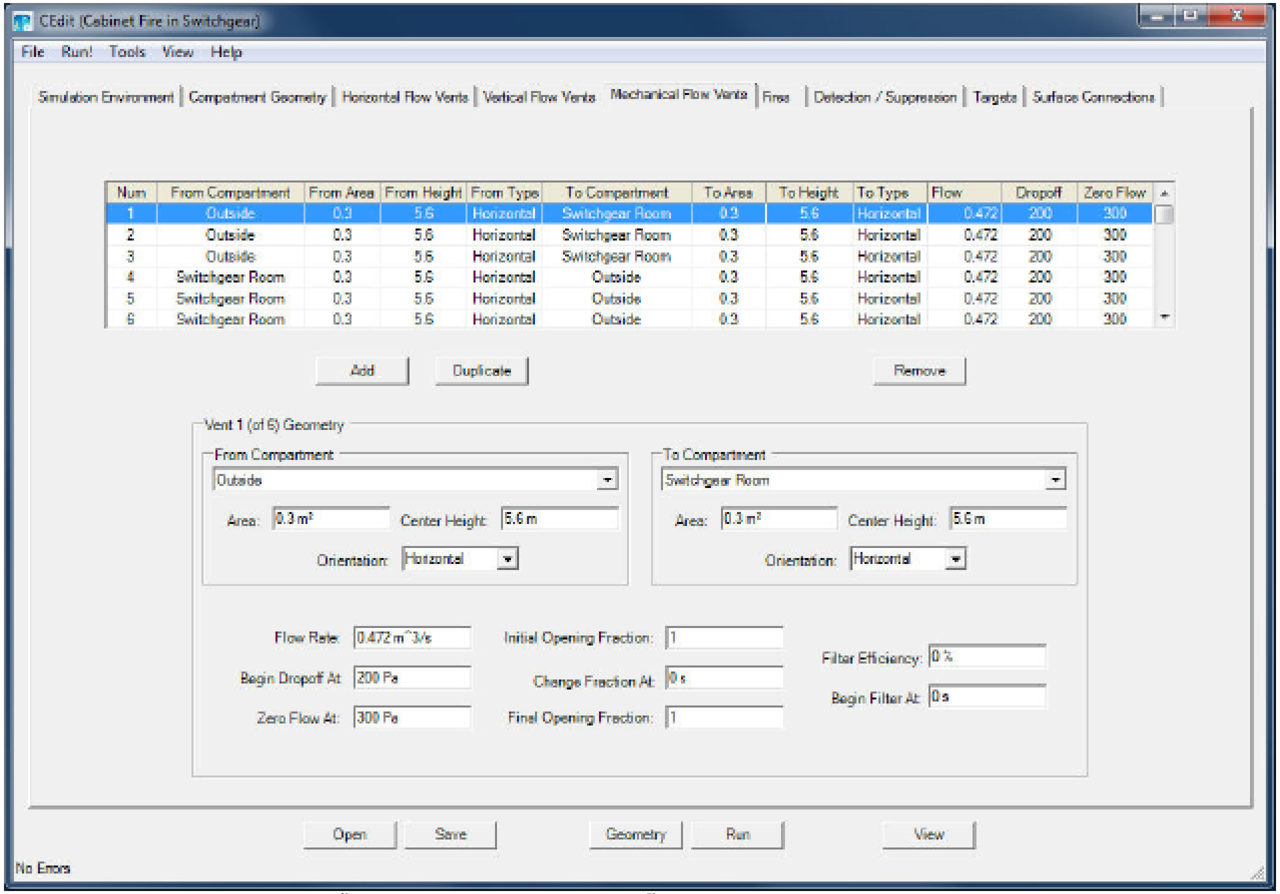
CFAST – Fire specification



Note: Values for "Lower Oxygen Limit" and "Gaseous Ignition Temperature are set at default values.

Figure B-7. CFAST fire specification inputs for the SWGR scenario.

CFAST – Mechanical ventilation



Note: Values for “Begin Dropoff At” and “Zero Flow At” are set at default values.

Figure B-8. CFAST mechanical ventilation inputs for the SWGR scenario.

CFAST – Cabinet and cable targets

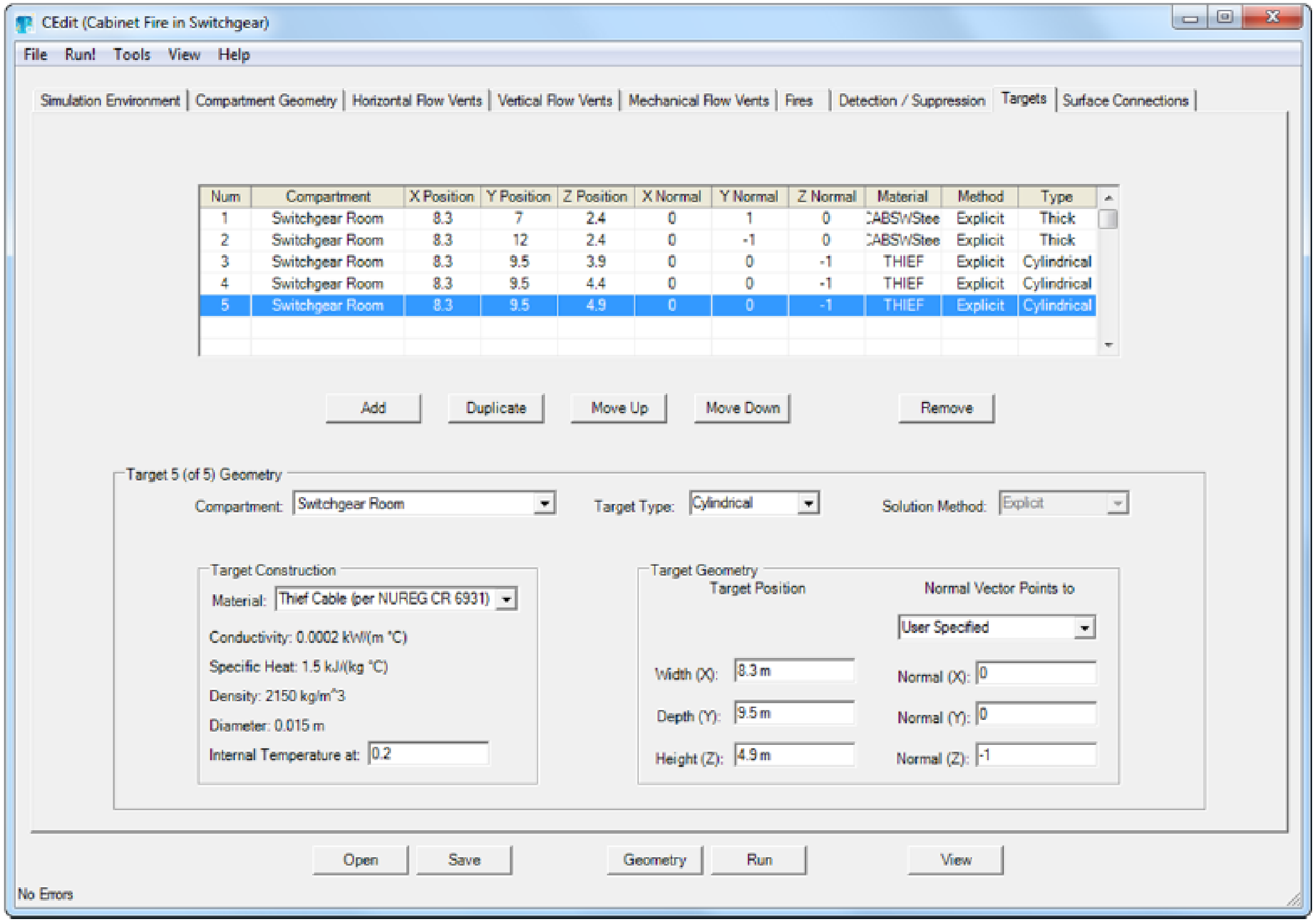


Figure B-9. CFAST inputs for cabinet and cable targets for the SWGR scenario.

CFAST – Smokeview rendering of SWGR fire

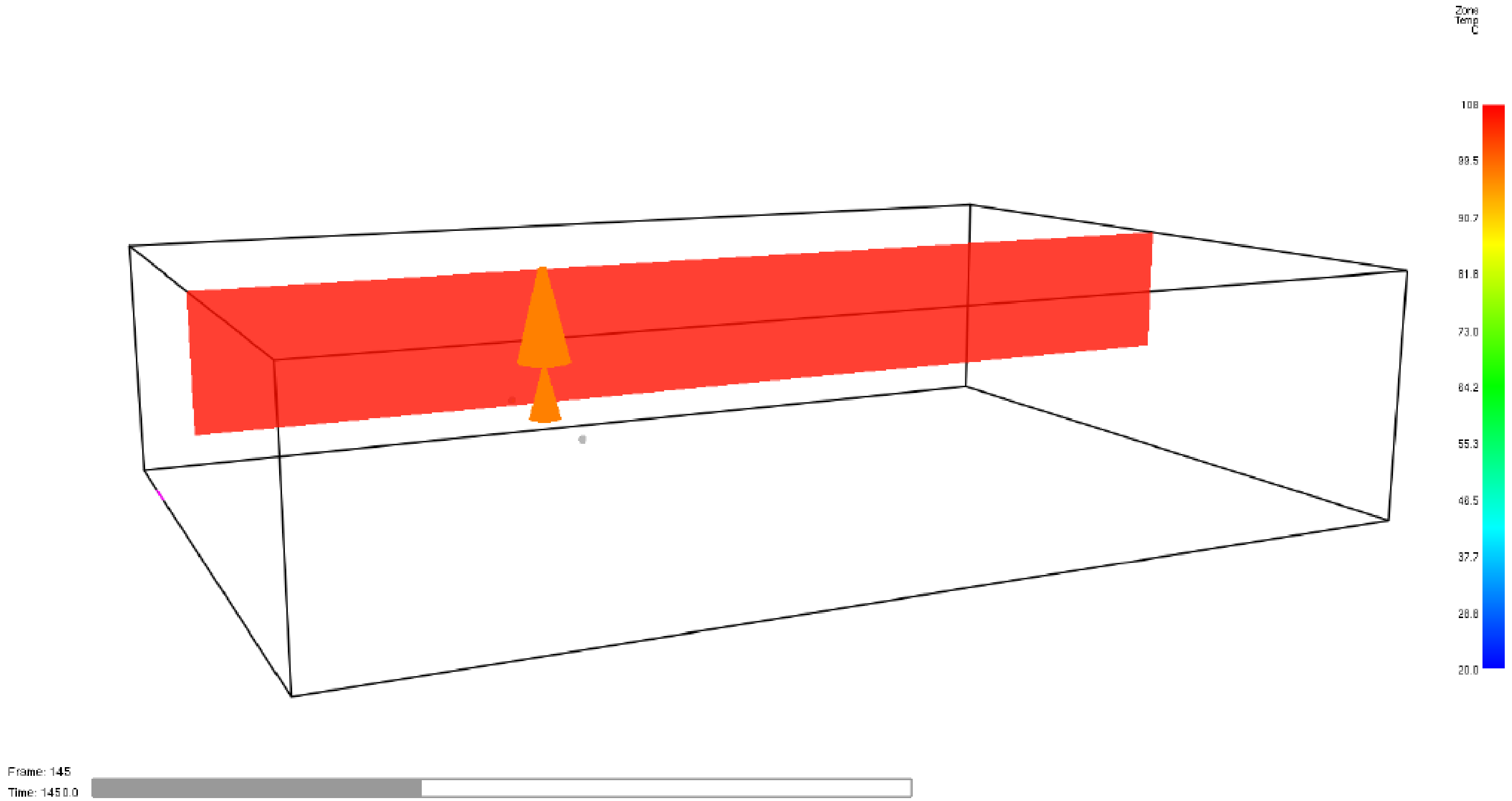
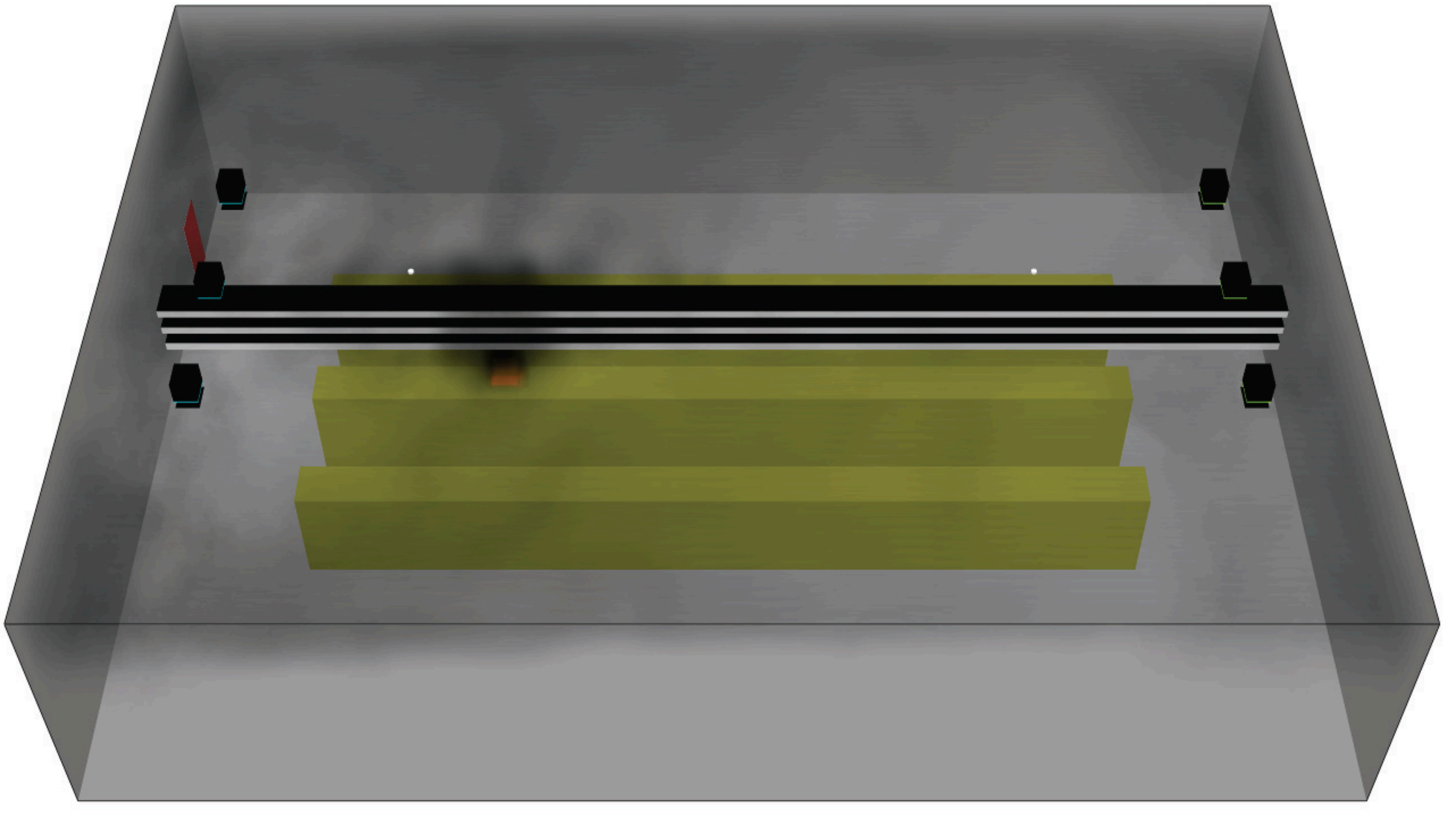


Figure B-5. Average CFAST/Smokeview rendering of Switchgear Room.

FDS – Smokeview rendering of SWGR fire



FDS – Smokeview rendering of SWGR fire

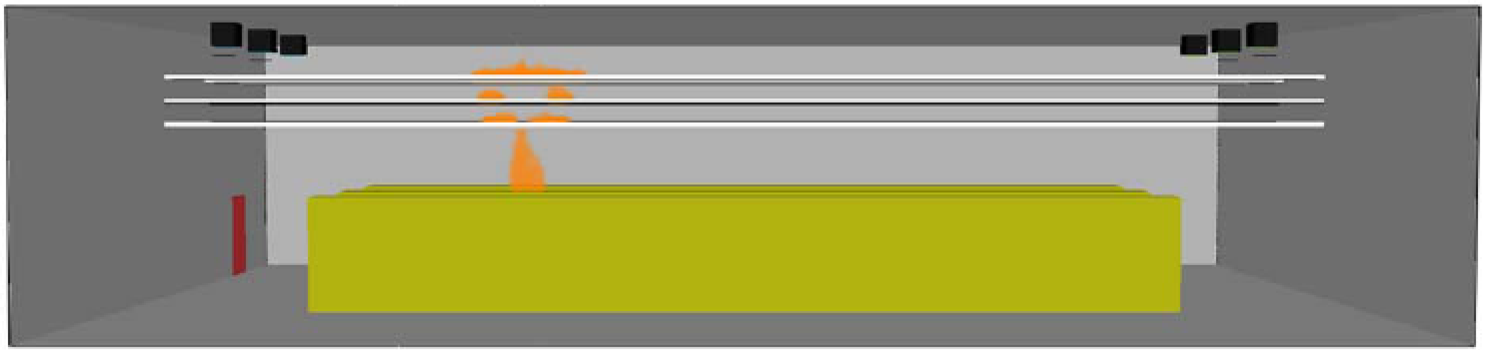
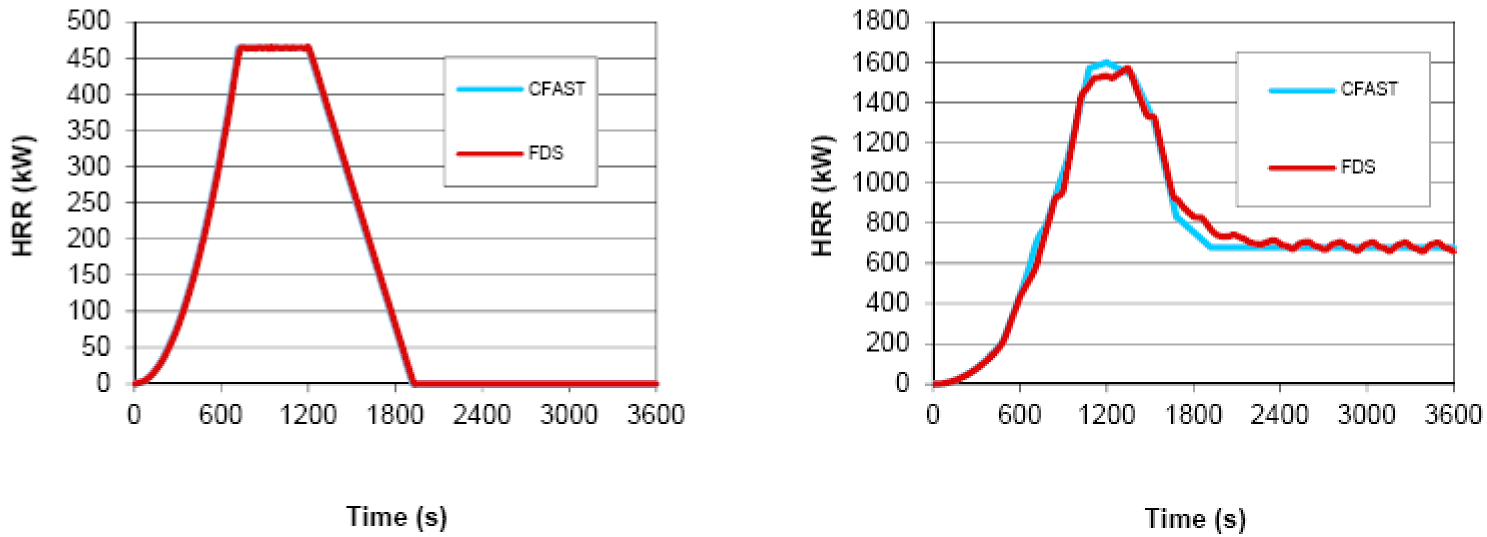


Figure B-11. FDS/Smokeview rendering of the SWGR fire showing localized ignition of extinction of secondary cable fires resulting from initial cabinet fire.

Fire: The initial fire source is modeled as a 0.6 m (2 ft) x 0.3 m (1 ft) "gas burner" atop the central cabinet with the specified HRR. This is meant to represent a fire that burns near the top of the cabinet and exhausts through the vent. The ignition and growth of the cable fire is based on the empirical FLASH-CAT model described above. Figure B-11 shows a snapshot of the burning cable during the simulation.

Step 4. Calculate Fire-Generated Conditions



(a) Initial cabinet fire only

(b) Initial cabinet fire and ignited cables

Figure B-12. Heat release rate inputs to CFAST and FDS for a SWGR cabinet fire scenario.

Step 4. Calculate Fire-Generated Conditions

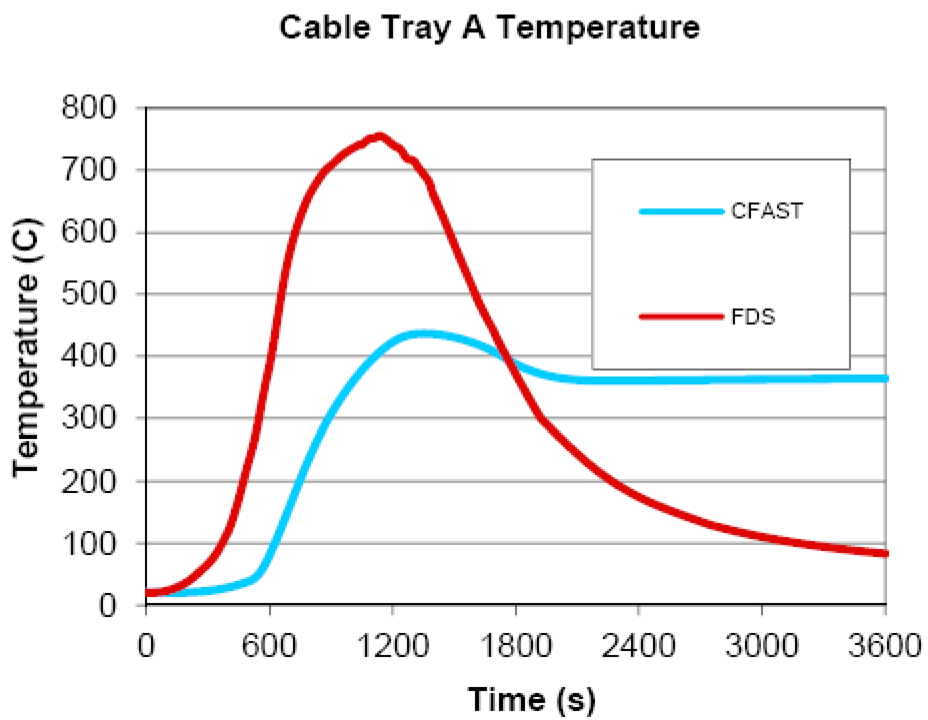


Figure B-13. Estimated temperatures for Cable Tray A directly above the fire source for a SWGR cabinet fire scenario.

Step 4. Calculate Fire-Generated Conditions

Table B-5. Estimated time to ignition of lowest cable tray by CFAST for the SWGR cabinet fire.

Ignition Criterion	Time
Gas temperature ≥ 205 °C	270 s
Cable temperature ≥ 205 °C	860 s
Heat flux ≥ 6 kW/m^2	490 s
Heat flux ≥ 15 kW/m^2	740 s
Flame impingement	490 s

Step 4. Calculate Fire-Generated Conditions

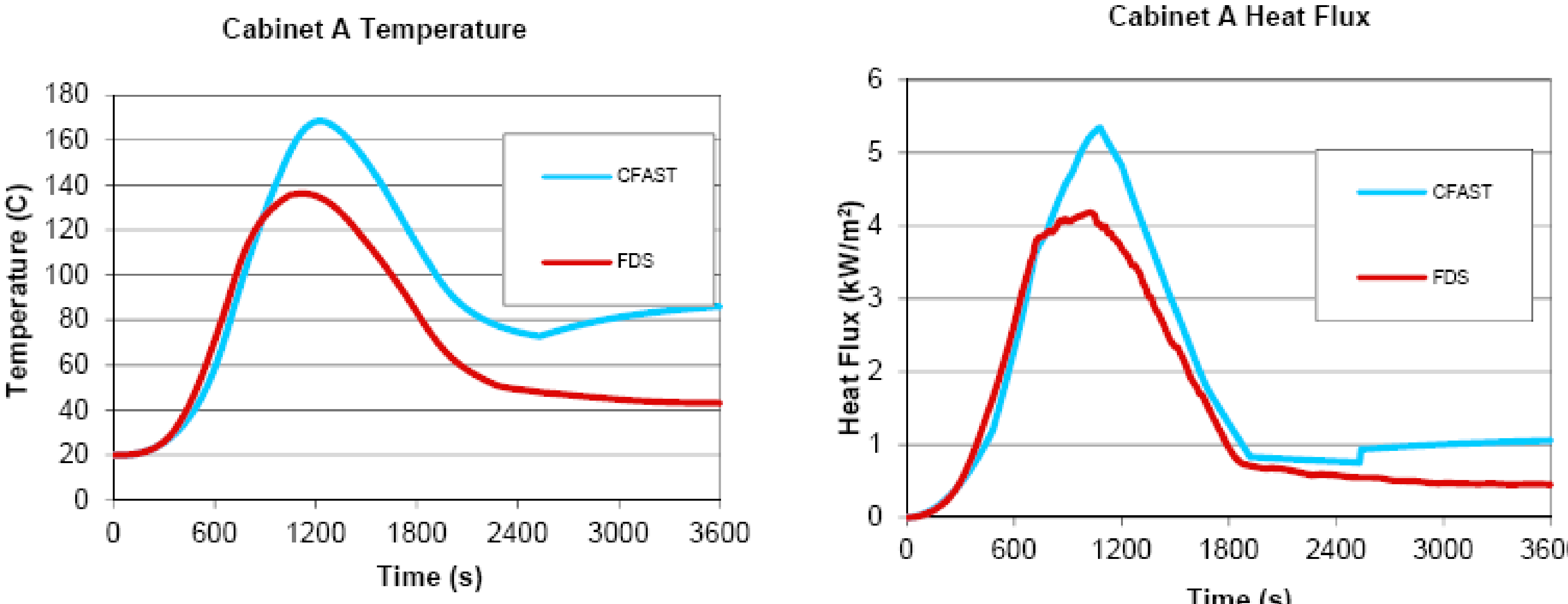


Figure B-14. Estimated temperature and heat flux to a cabinet adjacent to the fire source in a SWGR cabinet fire scenario.

Step 5. Sensitivity and Uncertainty Analysis

Table B-4. Summary of the model predictions of the cabinet fire scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Location	Predicted Value	Critical Value	Probability of Exceeding
Temperature (°C), Initial Value = 20 °C						
CFAST	1.00	0.27	Cable Tray A	335	205	0.937
FDS	1.02	0.13		755	205	1.000
CFAST	1.00	0.27	Cabinet A	168	205	0.177
FDS	1.02	0.13		136	205	0.000
Heat Flux (kW/m^2)						
CFAST	0.81	0.47	Cabinet A	5.3	6	0.576
FDS	0.85	0.22		4.2	6	0.159

Step 5. Sensitivity and Uncertainty Analysis

B.5.3 Parameter Uncertainty Propagation

The analysis above has shown that a 98th percentile cabinet fire is likely to damage cables in the tray above the cabinet but unlikely to damage adjacent cabinets. However, for some PRA applications, it may be necessary to calculate the probability of cable damage for *any* fire within the cabinet, not just the 98th percentile fire.

Figure B-15 displays the distribution[17] of peak heat release rates for cabinets with more than one bundle of unqualified cable (NUREG/CR-6850, Appendix G). The analysis described above made use of the 98th percentile fire from this distribution, whose peak is 464 kW.

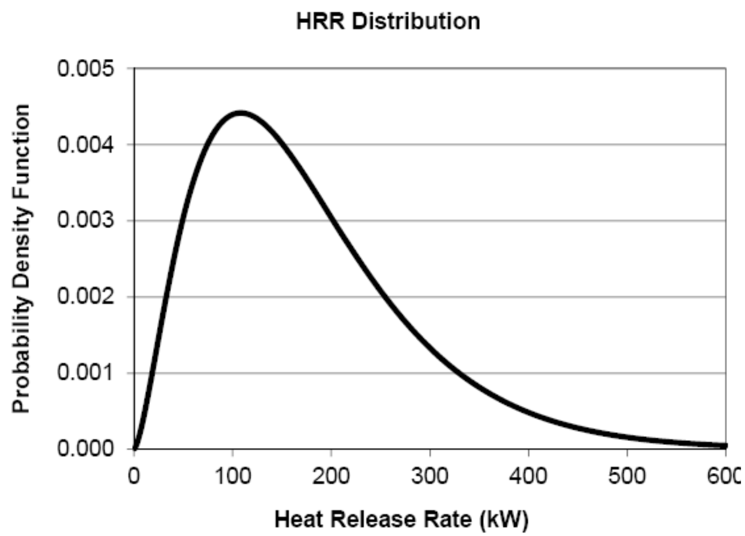


Figure B-15. Distribution of HRR for an electrical cabinet fire.

Step 5. Sensitivity and Uncertainty Analysis

Applying Heskestad's flame height correlation to the entire range of HRR, now taken as a random variable, leads to a distribution of flame height shown in Figure B-16.

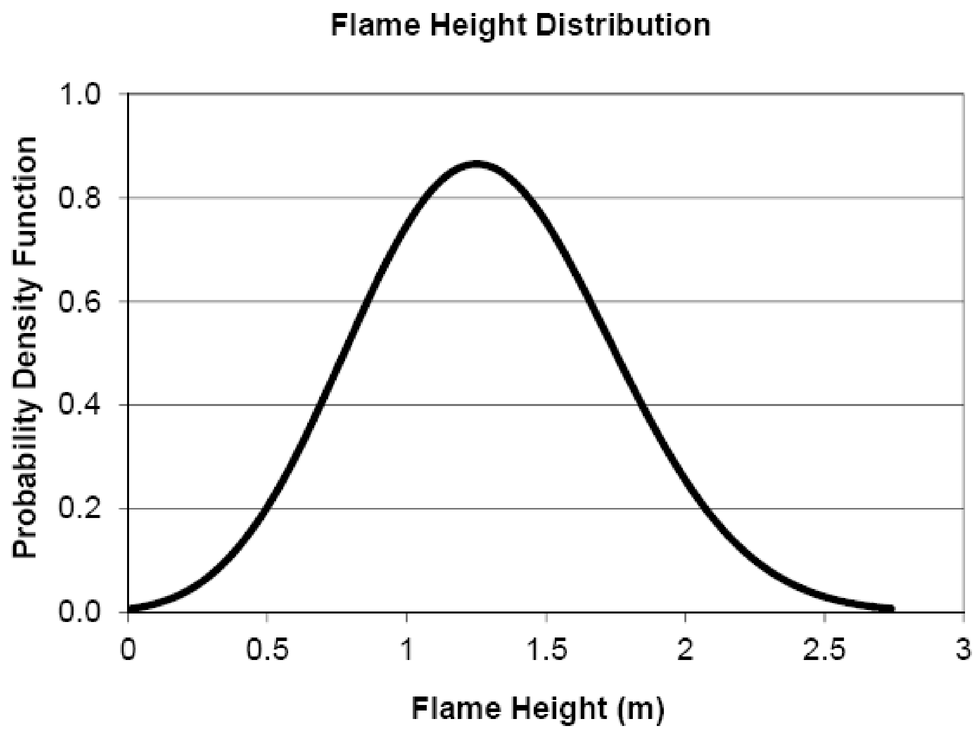


Figure B-16 Distribution of flame heights for the entire range of cabinet fires.

Step 5. Sensitivity and Uncertainty Analysis

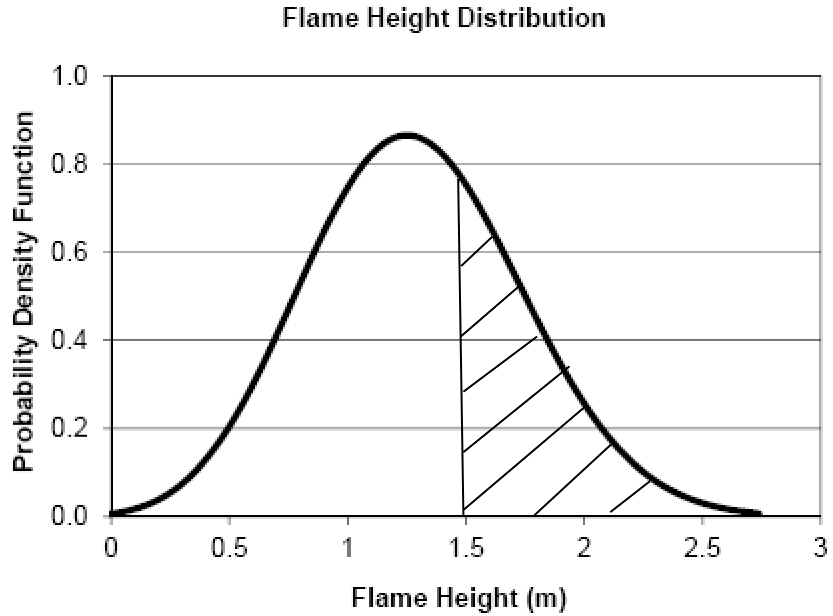


Figure B-16 Distribution of flame heights for the entire range of cabinet fires.

The cable tray is 1.5 m (4.9 ft) above the top of the cabinet. The probability that the flames from a randomly chosen fire will reach the cables is equal to the area beneath the curve in Figure B-16 for flame heights greater than 1.5 m (4.9 ft), or approximately 0.31. Consistent with the guidance in NUREG/CR-6850, this resulting probability can be used as the "severity factor" for the quantification of corresponding fire ignition frequencies.

Step 6. Document the Analysis

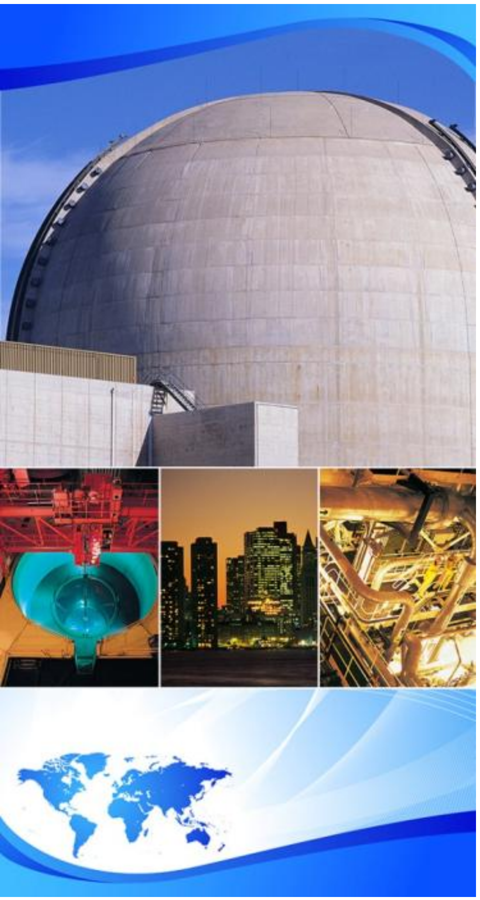
- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

Step 6. Document the Analysis

B.6 Conclusion

This analysis has considered the potential that a fire in an electrical cabinet in a 4160 V SWGR will damage overhead cables and adjacent electrical cabinets. Algebraic equations from the FDTs and FIVE-Rev1, including the Heskestad flame height correlation and the Heskestad plume temperature correlation, were used for screening purposes, to evaluate the potential for damage as well as to determine whether more detailed analysis with CFAST and FDS was warranted. The algebraic equations demonstrate that the calculated flame height from the cabinet fire would be high enough to potentially ignite the lowest of the three horizontal cable trays located directly above the cabinet fire. They also demonstrate that the calculated fire plume temperatures are high enough at all three horizontal cable trays located directly above the cabinet fire to potentially damage cables in all three trays. As applied in this scenario, the algebraic equations demonstrate that a more detailed analysis with CFAST and FDS is warranted.

The more detailed analyses with CFAST and FDS demonstrate that the cabinet fire is likely to fail the electrical cables in the lowest cable tray directly above the cabinet fire in approximately 10 min. The additional cable trays directly above the lowest tray ignite in turn. However, based on analyses of both CFAST and FDS, it is unlikely that the fire would damage the adjacent cabinets because the incident heat flux and smoke temperature are too low.



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5
Advanced Fire Modeling
Day 3 - PM Session
Example C: Lubricating Oil Fire in Pump Compartment
Example D: MCC Fire in Switchgear Room

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

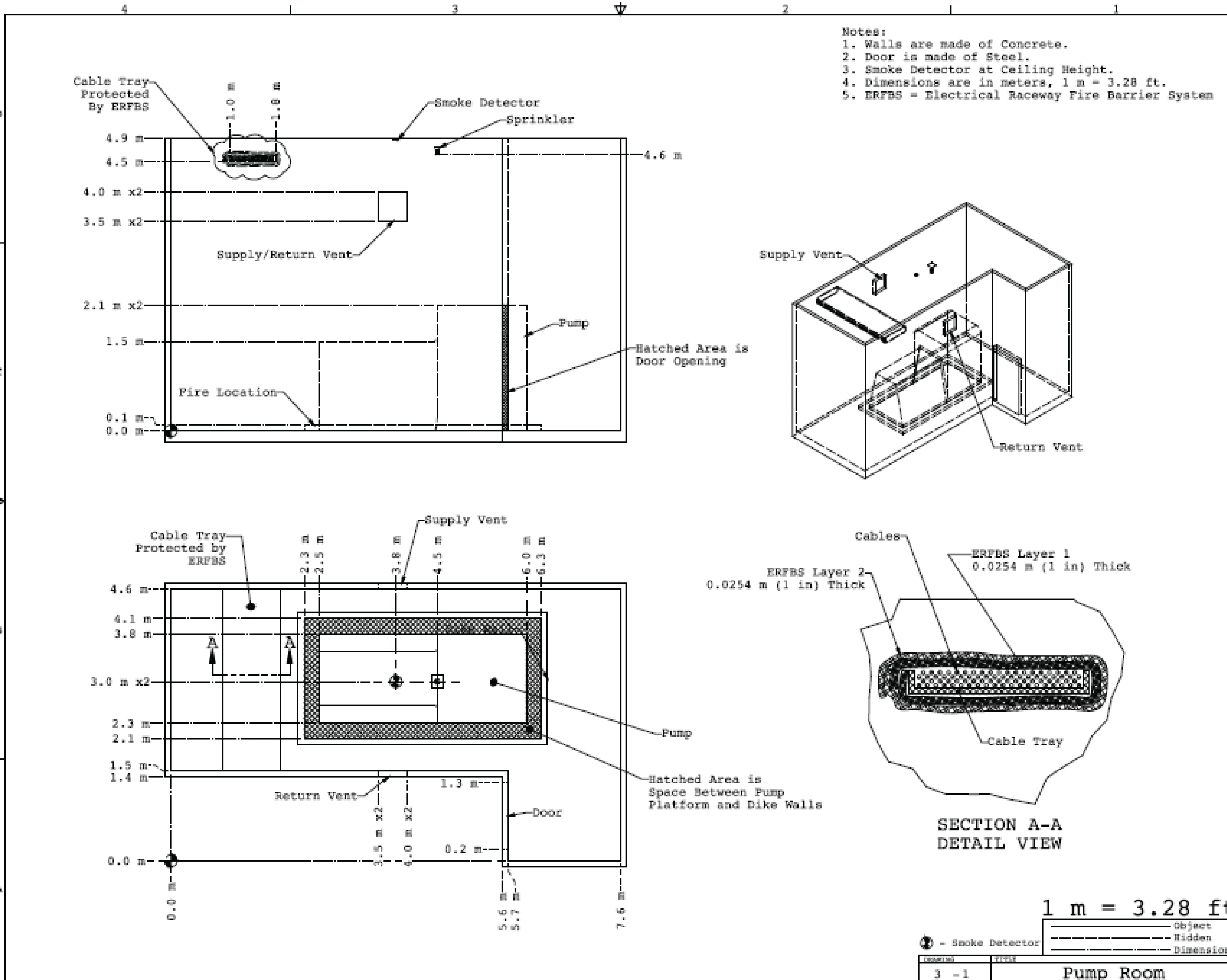
A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Step 1. Define Fire Modeling Goals

- Determine whether important safe-shutdown equipment within a pump room will fail, and at what time failure occurs
- Cables in pump room are protected by an Electrical Raceway Fire Barrier System (ERFBS), but there is concern that existing ERFBS will not provide required protection
- Impact of opening door to pump room during fire is also investigated

Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
  - Detection / suppression not credited for analyzed scenario
- Ventilation
- Fire


Notes:
1. Walls are made of Concrete.
2. Door is made of Steel.
3. Smoke Detector at Ceiling Height.
4. Dimensions are in meters, 1 m = 3.28 ft.
5. ERFBS = Electrical Raceway Fire Barrier System
Cable Tray Protected By ERFBS
1.0 m
1.0 m
Smoke Detector
Sprinkler
4.9 m
4.5 m
4.6 m
4.0 m x2
3.5 m x2
Supply/Return Vent
2.1 m x2
1.5 m
Pump
Hatched Area is Door Opening
Fire Location
0.1 m
0.0 m
Supply Vent
Return Vent
Cable Tray Protected by ERFBS
Supply Vent
2.3 m
2.5 m
3.8 m
4.5 m
6.0 m
6.3 m
4.6 m
4.1 m
3.8 m
A
A
3.0 m x2
2.3 m
2.1 m
1.5 m
1.4 m
Pump
Hatched Area is Space Between Pump Platform and Dike Walls
Return Vent
1.3 m
Door
3.5 m x2
4.0 m x2
0.2 m
0.0 m
0.0 m
5.6 m
5.7 m
7.6 m
Cables
ERFBS Layer 1 0.0254 m (1 in) Thick
ERFBS Layer 2 0.0254 m (1 in) Thick
Cable Tray
SECTION A-A DETAIL VIEW
1 m = 3.28 ft
Object
Hidden
Dimension
- Smoke Detector
3 -1
Pump Room

ERFBS and cable insulation data

Table C-1. Data for ERFBS and cable insulation.

Material	Parameter	Value*
Ceramic Fiber Insulation	Thickness (2 layers)	5 cm
	Thermal conductivity	0.06 W/m/K
	Density	128 kg/m^3
	Specific heat	1.07 kJ/kg/K
	Emissivity	0.9
Cable	Diameter	15 mm
	Jacket thickness	2 mm
	Insulation/jacket conductivity	0.192 W/m/K
	Insulation/jacket density	1380 kg/m^3
	Insulation/jacket specific heat	1.289 kJ/kg/K
	Mass per unit length	0.4 kg/m
	Conductor mass fractions	33% PE/PVC, 67% copper

*Source: Product literature (ERFBS) and NUREG/CR-6850 (EPRI 1011989), Volume 2, Appendix R (PVC cable insulation).

Fire

Fire: The fire starts following an accidental release of 190 L (50 gal) of lubricating oil. The spill is contained by the dike. Lubricating oil is a mixture of hydrocarbons, mostly alkanes, which have the chemical formula C_nH_{2n+2} (with *n* ranging from 12 to 15). For the purpose of modeling, the fuel is specified to be $C_{14}H_{30}$. Fuel properties for the lubricating oil are summarized in Table C-2. The properties obtained from NUREG-1805 correspond to those for transformer oil, based on the statement in Table 3-4 in NUREG-1805 that lubricating and transformer oils are similar.

Table C-2. Data for lubricating oil fire.

Parameter	Value	Source
Effective Fuel Formula	C_nH_{2n+2}	Specified as $C_{14}H_{30}$
Mass burning rate	0.039 kg/s.m^2	NUREG-1805 Table 3-4
Fuel volume	190 L	Specified
Fuel density	760 kg/m^3	NUREG-1805 Table 3-4
Heat of Combustion	46,000 kJ/kg	NUREG-1805 Table 3-4
Heat of Combustion per unit mass of oxygen consumed	13,100 kJ/kg	Huggett 1980, Average value
CO_2 Yield	2.64 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16*
Soot Yield	0.059 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16*
CO Yield	0.019 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16*
Radiative Fraction	0.34	*SFPE Handbook*, 4th ed., Table 3-4.16*
Mass Extinction Coefficient	8700 m^2/kg	Mulholland and Croarkin (2000)

*Material identified as "Hydrocarbon" in SFPE Handbook was used to derive the properties.

Ventilation

- One supply and one return, each 0.5 m^2
- Flow rate is 0.25 m^3/s
- One closed door, 1.1 m by 2.1 m
  - Leakage – 1.3 cm (1/2 in) gap under door
- Door opens after 10 min

Step 3. Select Fire Models

- Algebraic Models: Nothing to estimate HGL temperature in a flashed over compartment. Hand calculation used to evaluate oxygen availability in closed ventilated room
- Zone Models: In flashover situation, zone models transition from 2 zones to 1.
- CFD: Challenging scenario because of under-ventilated conditions

Table C-3. Normalized parameter calculations for the pump room fire scenario.

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}}$ $= \frac{4934 \text{ kW}}{(1.2 \text{ kg/m}^3)(1.0 \text{ kJ/kg/K})(293 \text{ K})(1.9^{2.5} \text{ m}^{2.5})\sqrt{9.8 \text{ m/s}^2}} \cong 0.9$	0.4 – 2.4	Yes
Flame Length, L_f, relative to the Ceiling Height, H_c	$\frac{L_f}{H_c} = \frac{4.8 \text{ m}}{4.9 \text{ m}} \cong 0.99$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 1.9 \text{ m}\,(3.7 \times 0.93^{0.4} - 1.02) \cong 4.8 \text{ m}$	0.2 – 1.0	Yes
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H_c	N/A	1.2 – 1.7	N/A
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\,\dot{m}_{O_2}} = \frac{4934 \text{ kW}}{13{,}100 \text{ kJ/kg} \times 0.07 \text{ kg/s}} \cong 5.5$ $\dot{m}_{O_2} = 0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2 \text{ kg/m}^3 \times 0.25 \text{ m}^3\text{/s} \cong 0.07 \text{ kg/s}$	0.04 – 0.6	No
Equivalence Ratio, φ, as an indicator of the Opening Ventilation	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\,\dot{m}_{O_2}} = \frac{4934 \text{ kW}}{13{,}100 \text{ kJ/kg} \times 0.38 \text{ kg/s}} \cong 0.99$ $\dot{m}_{O_2} = 0.23 \cdot 0.5 A_o \sqrt{h_o} = 0.23 \times 0.5 \times 2.31 \text{ m}^2 \sqrt{2.1 \text{ m}} \cong 0.38 \text{ kg/s}$	0.04 – 0.6	No
Compartment Aspect Ratios	$\frac{L}{H_c} = \frac{9.4 \text{ m}}{4.9 \text{ m}} \cong 1.9$ $\frac{W}{H_c} = \frac{2.8 \text{ m}}{4.9 \text{ m}} \cong 0.6$	0.6 – 5.7	Yes
Target Distance, r, relative to the Fire Diameter, D	N/A	2.2 – 5.7	N/A

Notes:

(1) The non-dimensional parameters are explained in Table 2-5.

(2) The equivalent fire diameter, $D = \sqrt{4A/\pi}$, where A is the area of the spilled lubricating oil.

C.4.1 Calculation of Oxygen Availability

At the start of the scenario, the mechanical ventilation is operational, the door is closed, and the fire output immediately jumps to the peak heat release rate (HRR) with a total spill area of approximately 2.75 m^2 (29.6 ft^2), as shown in the hatched area of Figure C-1. The peak HRR, $\dot{Q}$, is computed from the fuel mass burning rate, $\dot{m}''$, the heat of combustion, ΔH, and the specified area of the spill, A:

$$\dot{Q} = \dot{m}''\,\Delta H\,A = 0.039\,\mathrm{kg/m^2/s} \times 46{,}000\,\mathrm{kJ/kg} \times 2.75\,\mathrm{m^2} \cong 4{,}934\,\mathrm{kW} \quad \text{(C-1)}$$

The oxygen needed to sustain the fire is calculated from the following equation:

$$\frac{\dot{Q}}{\Delta H_{\mathrm{O_2}}} = \frac{4934\,\mathrm{kW}}{13{,}100\,\mathrm{kJ/kg}} = 0.377\,\mathrm{kg/s} \quad \text{(C-2)}$$

where ΔH_{O_2} is the heat of combustion per unit mass of oxygen consumed. The quantity of oxygen provided by the ventilation system is calculated by multiplying the oxygen content (0.23) by the density and the ventilation rate of the air:

$$0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2\,\mathrm{kg/m^3} \times 0.25\,\mathrm{m^3/s} = 0.069\,\mathrm{kg/s} \quad \text{(C-3)}$$

The oxygen provided by the ventilation system is much lower than the amount needed to sustain the fire. The oxygen initially in the room can provide the additional oxygen needed for combustion for a short time. The available oxygen in the room, calculated from the room dimensions (Table C-4), is:

$$0.23\,\rho_\infty LWH_c = 0.23 \times 1.2\ \mathrm{kg/m^3} \times (2.81 \times 9.39 \times 4.9)\ \mathrm{m^3} = 35.7\ \mathrm{kg} \quad \text{(C-4)}$$

The oxygen initially in the room can sustain the fire for an amount of time equal to the oxygen quantity in the room divided by the consumption rate minus the ventilation supply rate, as shown below:

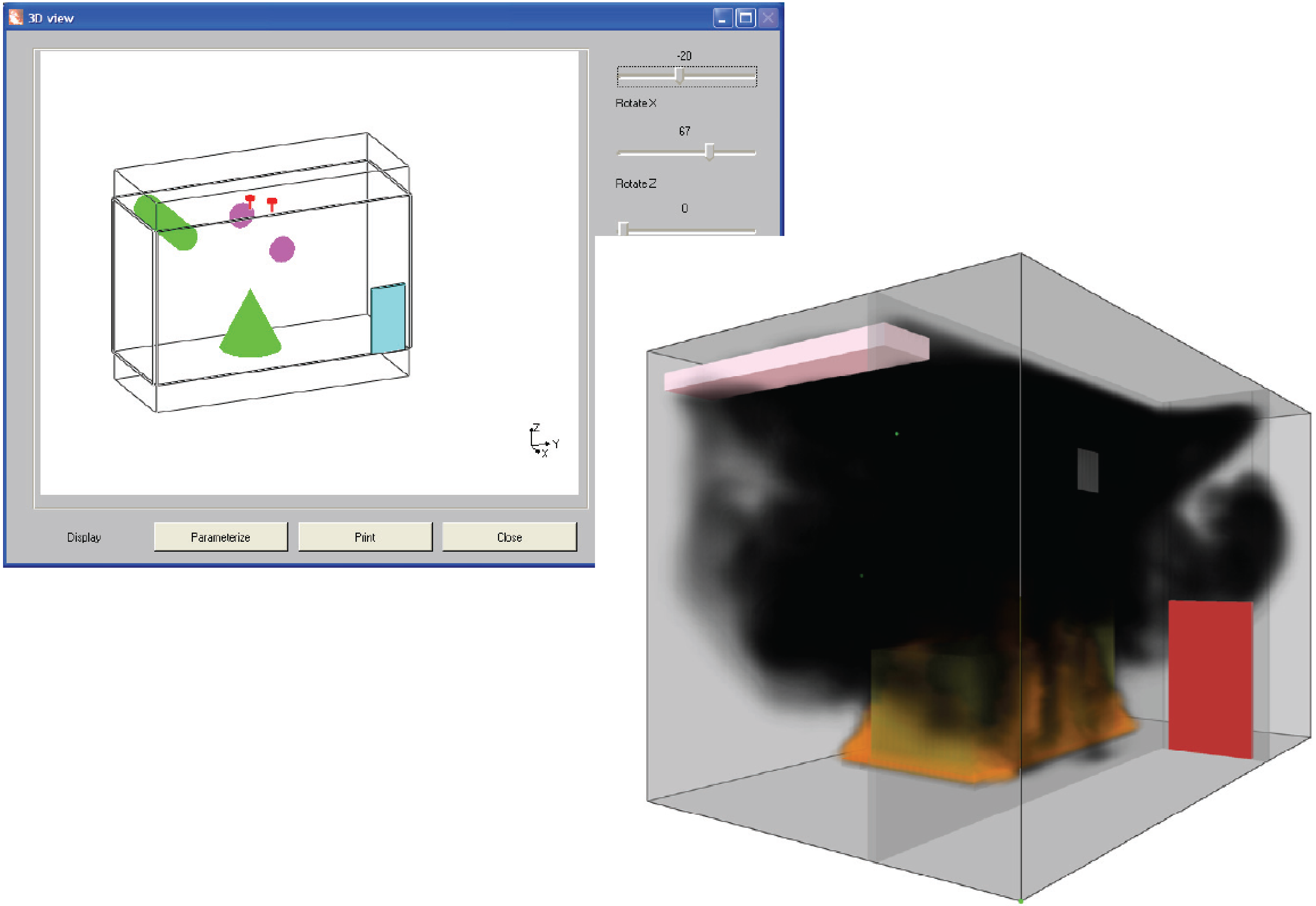
$$\frac{35.7\ \mathrm{kg}}{(0.377\ \mathrm{kg/s} - 0.069\ \mathrm{kg/s})} = 116\ \mathrm{s} \quad \text{(C-5)}$$

Equation C-4 assumes that all the oxygen within the room can be consumed by the fire. This establishes an upper limit to the burning duration before the fire becomes ventilation-limited. After 116 s, the size of the fire is maintained only by the ventilation system and is limited to:

$$0.069\ \mathrm{kg/s} \times 13{,}100\ \mathrm{kJ/kg} = 904\ \mathrm{kW} \quad \text{(C-6)}$$

These results show that the oxygen supply available to the room will only allow a fire of reduced size to burn until the door is opened (under-ventilated condition).

Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions

Fire: It is assumed that the lubricating oil is preheated prior to the spill, such that the HRR reaches the peak immediately upon fire initiation, as shown in the HRR curve plotted in Figure C-3. The lower oxygen level is assumed to be 10%. Using the specified spill area and volume, the spill depth is calculated as 0.069 m (0.23 ft).

The fire is modeled as a single circular area of equivalent diameter. The actual entrainment for the pool fire is proportional to the perimeter of the fire, which is significantly greater than the perimeter of the assumed circular area. However, the enclosure is small and the smoke filling rates are expected to be short regardless of the assumed fire shape.

The fire duration, Δt, is determined from the pool depth, δ, density, ρ, and burning rate, $\dot{m}''$:

$$\Delta t = \frac{\delta\,\rho}{\dot{m}''} = \frac{0.069\ \mathrm{m} \times 760\ \mathrm{kg/m^3}}{0.039\ \mathrm{kg/m^2/s}} \cong 1345\ \mathrm{s}\quad (22.4\ \mathrm{min}) \qquad \text{(C-7)}$$

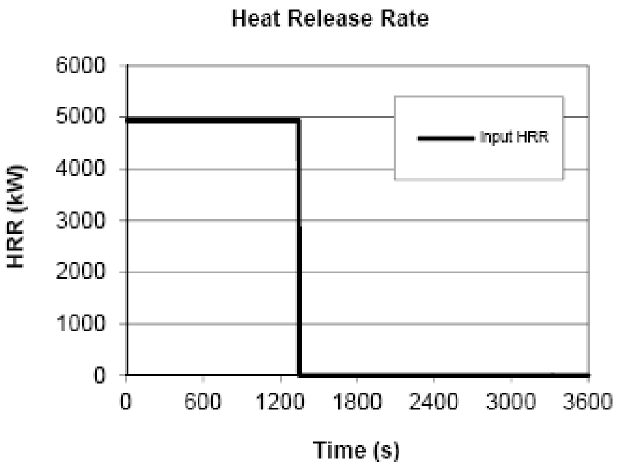


Figure C-3. Heat release rate curve for lubricating oil fire.

Step 4. Calculate Fire-Generated Conditions

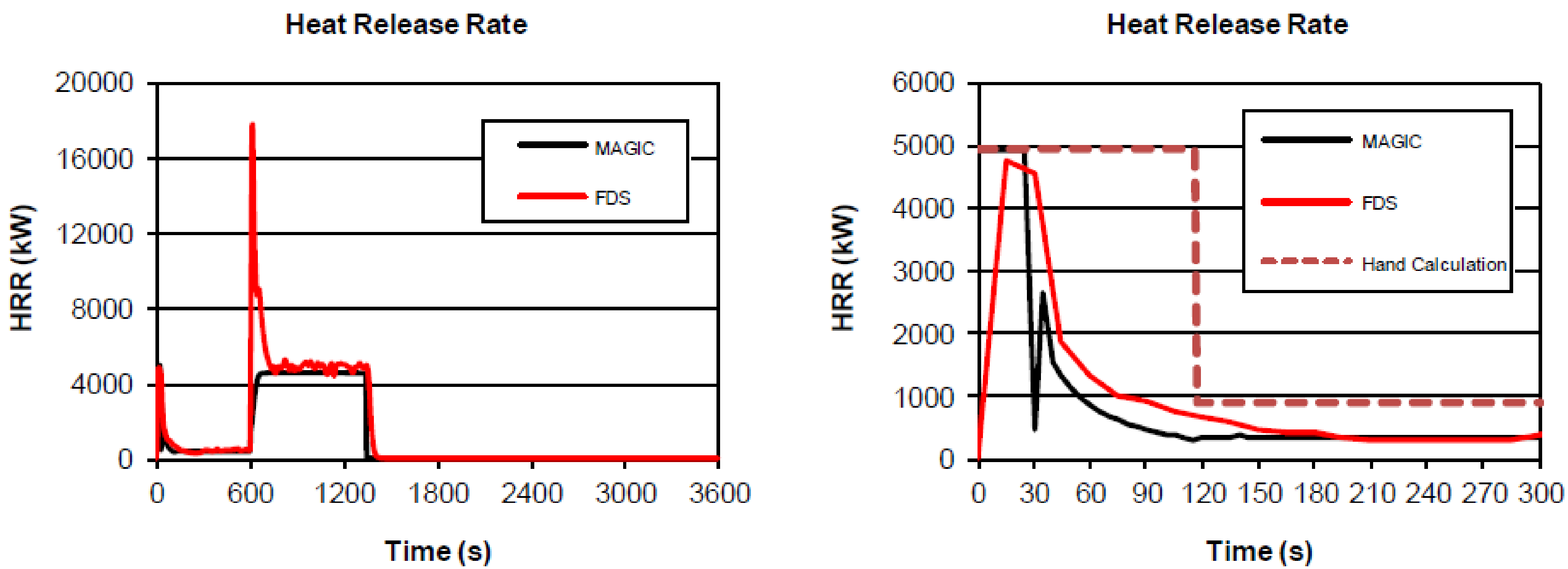
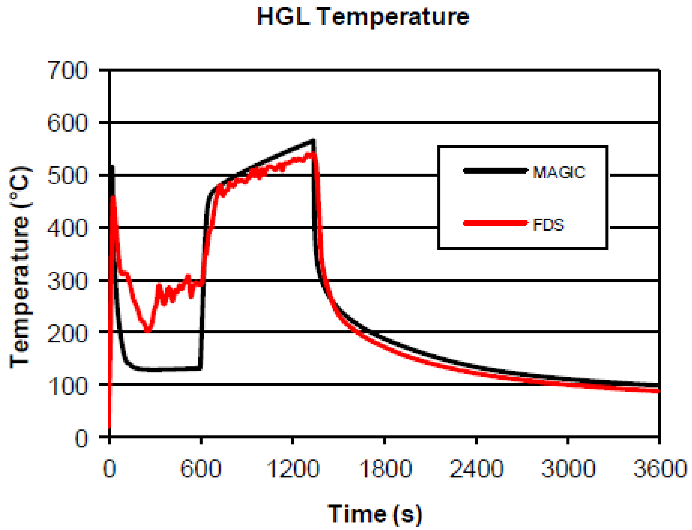
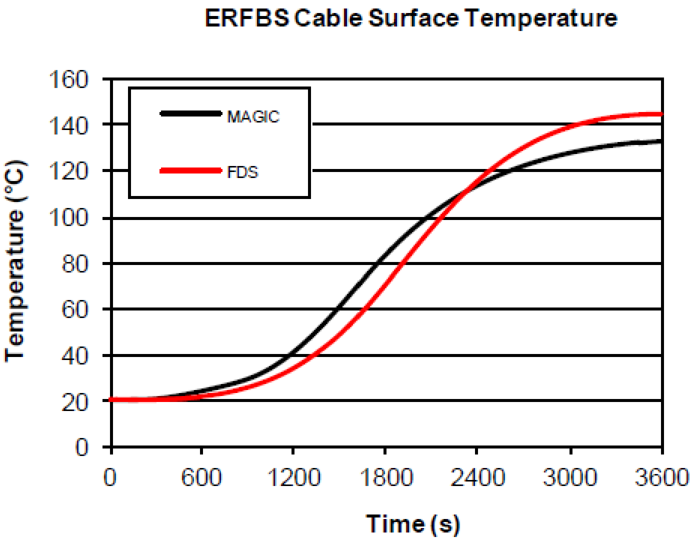
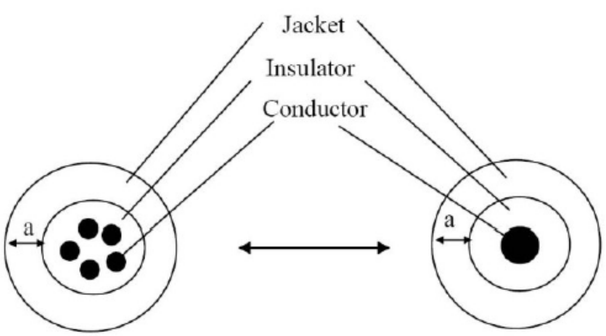


Figure C-9. Heat Release Rate Predicted by Hand Calculations, MAGIC, and FDS for the Pump Room Fire Scenario.

Step 4. Calculate Fire-Generated Conditions

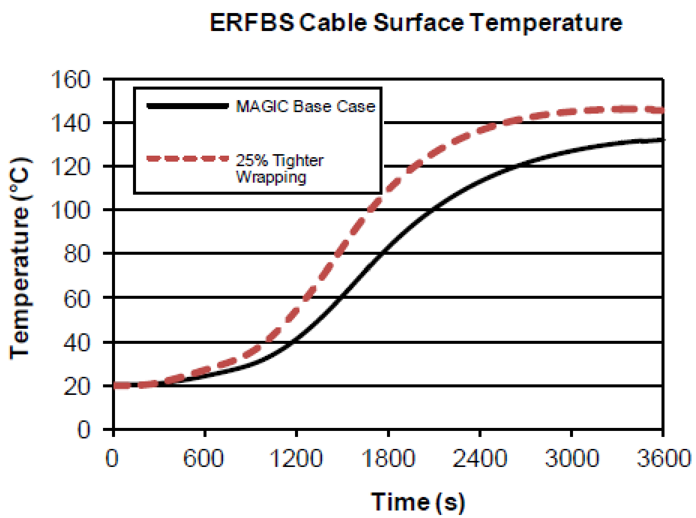






Source: NUREG-1824 (EPRI 1011999), Volume 6, Figure 3-3

Figure C-5. Modeling Multi-Conductor Cables in MAGIC



Step 4. Calculate Fire-Generated Conditions

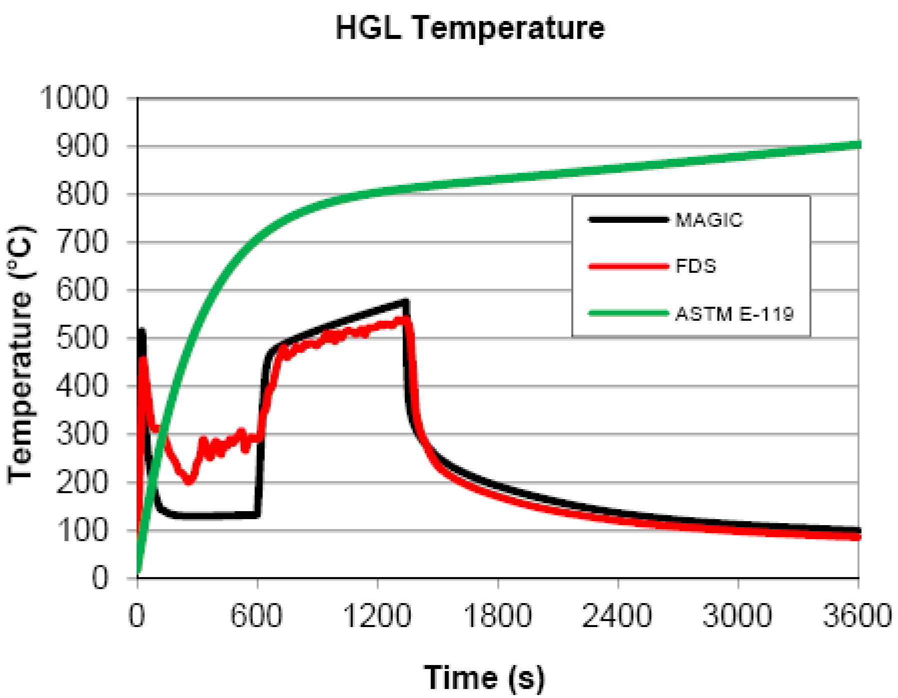


Figure C-11. HGL Temperature Predicted by MAGIC and FDS for the pump room fire scenario.

Step 4. Calculate Fire-Generated Conditions

Comparison to the Standard Fire Endurance Temperature Curve

Figure C-11 includes the standard ASTM E119 temperature curve to which the ERFBS was subjected during its qualification test. The predicted HGL temperatures of both MAGIC and FDS fall below this curve during most of the hour-long simulation, but there is a period near the beginning of the fire where the models' predicted temperatures exceed the standard curve. In order to compare the relative exposure of the ERFBS, it is necessary to consider the integrated incident heat flux corresponding to the model HGL predictions and the ASTM E 119 temperature curve. The integrated heat flux is given by the following formula:

$$q'' = \int_{t_0}^{t_1} \dot{q}''(t)\, dt = \int_{0}^{3600} \sigma(T^4 - T_0^4) + h(T - T_0)\ dt \qquad \text{(C-11)}$$

Applying Eq. (C-11) to each of the HGL temperature curves in Figure C-11 yields values of 346 MJ/m^2 for the ASTM E119 curve and approximately 40 MJ/m^2 for both FDS and MAGIC. This 40 MJ/m^2 exposure corresponds to an approximately 14 min exposure within the standard test furnace. Table C-6 lists the thermal exposure as a function of time in the standard test furnace. It is also significant to note that the maximum predicted exposure temperature remains lower than the maximum exposure temperature that the ERFBS protected raceway was exposed to during the ASTM E119 fire test.

Step 4. Calculate Fire-Generated Conditions

Table C-6. Integrated thermal exposure of an object subjected to the ASTM E119 temperature curve.

Time (min)	Thermal Exposure (MJ/m^2)
5	6
10	23
15	47
20	75
25	104
30	135
35	167
40	200
45	235
50	270
55	307
60	346

Step 5. Sensitivity and Uncertainty Analysis

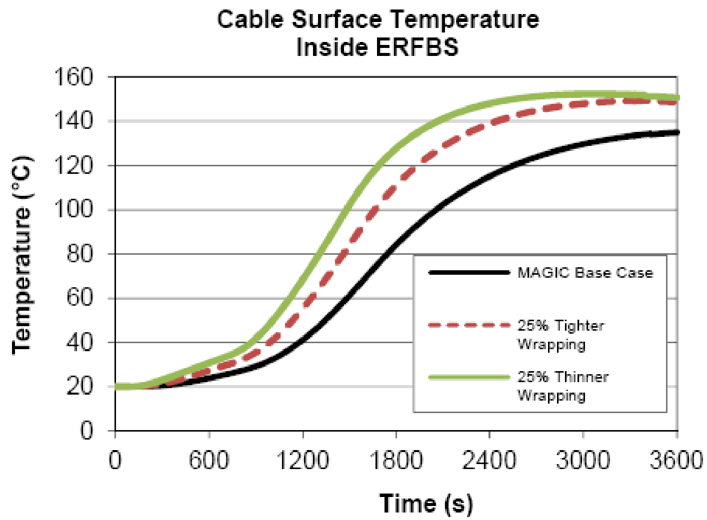
Table C-5. Summary of the model predictions of the pump room scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Predicted Value	Critical Value	Probability of Exceeding
Cable Temperature (°C)					
MAGIC	1.19	0.27	135	205	0.000
FDS	1.02	0.13	145	205	0.000

Step 5. Sensitivity and Uncertainty Analysis

Sensitivity of the ERFBS Construction

Comparing Figures C-11 and C-12 shows that the ERFBS has a large impact on the temperature of the target cable. To determine the sensitivity of the target cable temperature to the insulation installation technique, two additional MAGIC cases are run. In the first case (file: Pump_Room_thinner_wrapping.cas.), the thickness of the ceramic insulation blanket is reduced by 25% to 0.0375 m. In the second case (file: Pump_Room_tighter_wrapping.cas.), the thickness of the ceramic insulation blanket is reduced by 25% while the density is increased to 171 kg/m^3, such that the mass per area remains constant, which simulates a tighter installation of the insulation. The results, plotted in Figure C-13, show that both cases led to a higher cable temperature.



Step 5. Sensitivity and Uncertainty Analysis

Sensitivity of the Door Size

As mentioned in Section C.3.3, the equivalence ratio for the pump room scenario falls outside of the validation range. As a sensitivity test, MAGIC was run with the door area doubled, such that the equivalence ratio falls within the applicable validation range (0.04 – 0.6) for the portion of the simulation when the doors are open (file: Pump_Room_2Doors.cas), as calculated below:

$$\dot{m}_{O_2} = 0.23 \cdot 0.5 A_o \sqrt{h_o} = 0.23 \times 0.5 \times 4.62\ \mathrm{m}^2\ \sqrt{2.1\ \mathrm{m}} \cong 0.77\ \mathrm{kg/s} \qquad \text{(C-12)}$$

$$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\ \dot{m}_{O_2}} = \frac{4934\ \mathrm{kW}}{13{,}100\ \mathrm{kJ/kg} \times 0.77\ \mathrm{kg/s}} \cong 0.5 \qquad \text{(C-13)}$$

Figure C-14 shows the temperature comparison for the HGL and the cable surface temperature (measured inside the ERFBS) for the base case and for the case with double doors. The plots show that the results for both cases are very similar, indicating that the door size does not significantly affect the results. Nevertheless, it is consistent with experimental data that the scenario with the equivalence ratio closest to unity produces the highest enclosure temperature.

Step 5. Sensitivity and Uncertainty Analysis

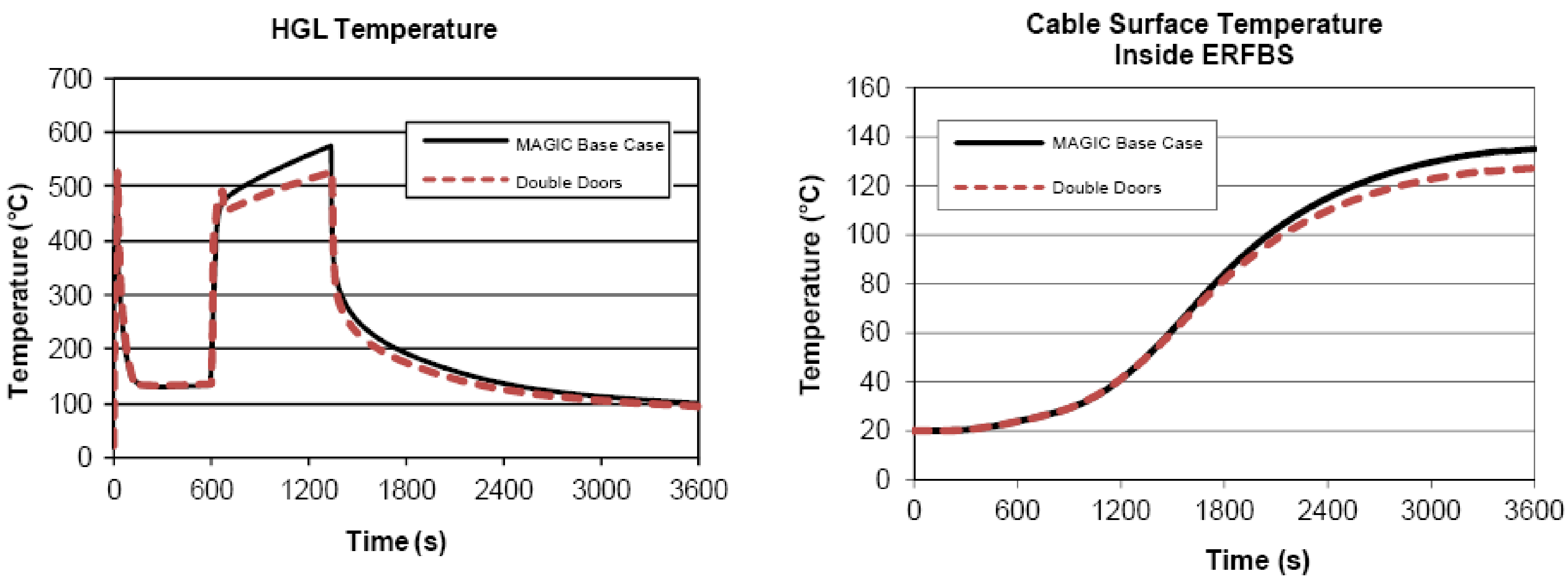


Figure C-14. Temperature predicted by MAGIC for increased door size.

Step 5. Sensitivity and Uncertainty Analysis

The sensitivity case shows that (1) based on comparison to the ASTM E119 temperature curve, the ERFBS system is not expected to fail under the predicted exposure temperatures, and (2) based on the predicted cable surface temperature, further validation of the thermal properties of the ERFBS is warranted as the surface temperature of the cable is close to the damage criteria.

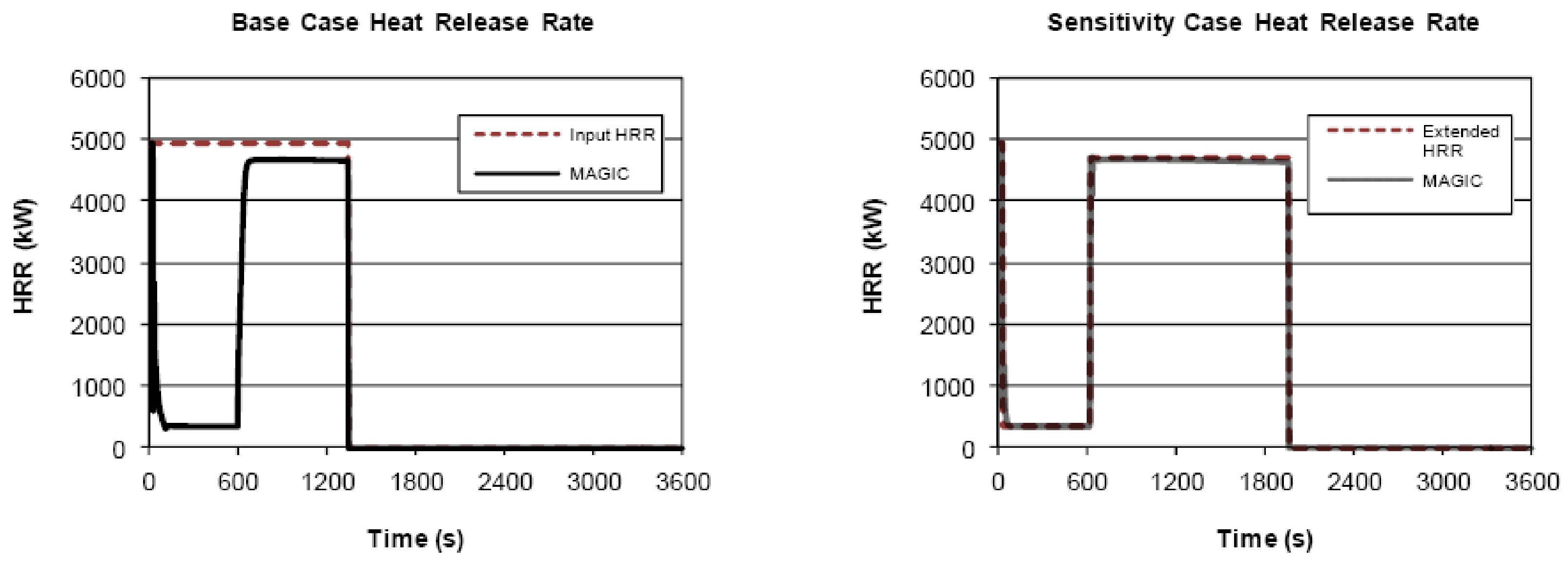


Figure C-15. HRR for base case and HRR sensitivity case.

Step 5. Sensitivity and Uncertainty Analysis

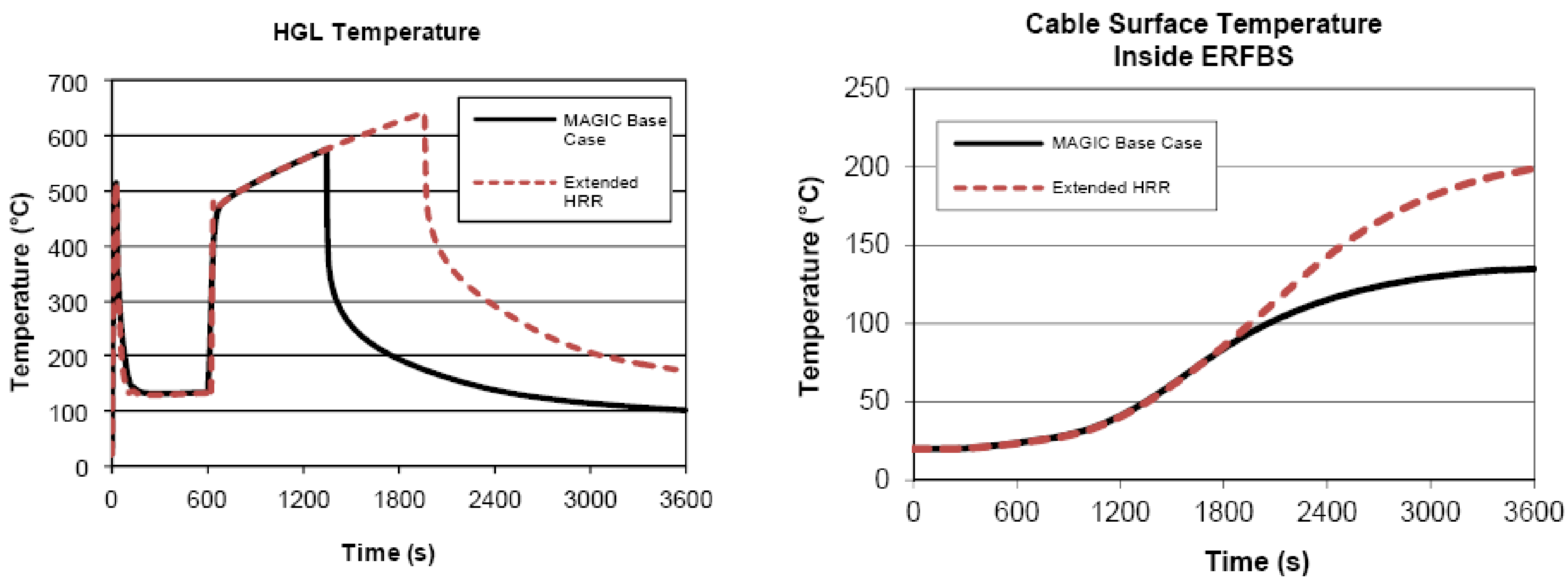


Figure C-16. Temperature for base case and HRR sensitivity case.

Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

Step 6. Document the Analysis

C.6 Conclusion

This analysis has considered the potential for a relatively large lubricating oil spill fire in a relatively small enclosure to damage a cable tray protected by an ERFBS. Algebraic calculations, the zone model MAGIC, and the CFD model FDS were all used to evaluate the fire conditions within the enclosure. MAGIC and FDS were used to calculate the thermal response of the cables to these calculated fire conditions.

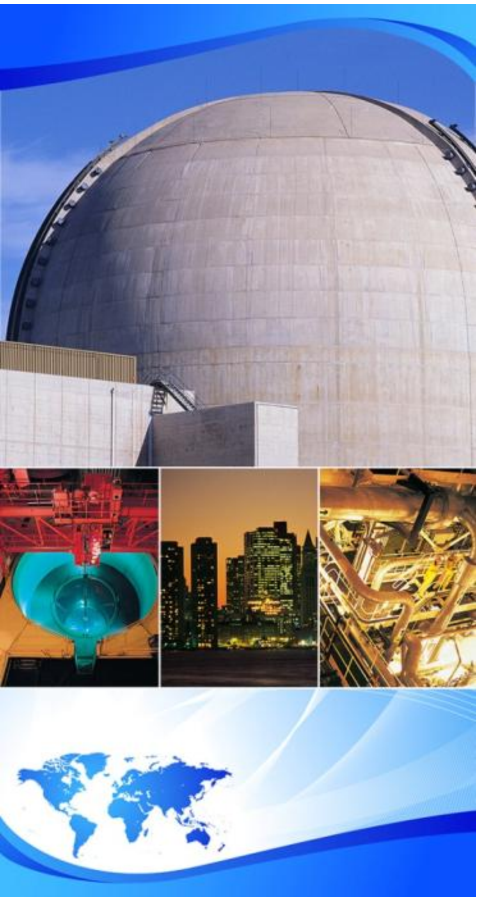
Based on the assumed lubricating oil spill area and burning characteristics, a fire of approximately 5 MW is expected. However, after the rapid consumption of the limited quantity of air in the room, the mechanical ventilation to the enclosure could only support a HRR of less than 1 MW before the door to the enclosure opens after 10 min. This analysis suggests that to avoid rapid fire escalation, doors to such rooms should not be opened until firefighters are prepared to suppress the fire, and, even then, the potential for rapid fire escalation should be considered.

Step 6. Document the Analysis

Two different strategies were applied to assess the integrity of the ERFBS. Because the thermal and chemical properties of the insulating material are only partially known, it is practical to implement an alternative technical approach of comparing the predicted HGL temperatures from the models with the standard temperature curve under which the ERFBS received an hour rating. Because the predicted HGL temperatures do not lie completely within the standard curve, a simple integrated heat flux calculation was performed to demonstrate that the ERFBS received approximately 10 times the thermal exposure in the standard fire endurance test than is predicted by the two models.

A second strategy for assessing the integrity of the ERFBS was to directly calculate the heat penetration through the insulating blankets using the thermal material properties of the cables and the ERFBS. Both models predicted cable temperatures below the reported critical values.

Based on the two approaches to determine its performance, the ERFBS is expected to prevent the cables from reaching temperatures that would limit their functionality in the event of a fire involving burning spilled lubricating oil. This conclusion is based on certain assumptions regarding the burning behavior of the lubricating oil during the under-ventilated stages. A sensitivity study on the burning behavior of the lubricating oil concluded that the results could change if the burning rate decreases during the under-ventilated stage. The results are also shown to be sensitive to the thermal properties of the ERFBS material. Further research or testing of the ERFBS thermal properties may be necessary to confirm the initial conclusion.



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5
Advanced Fire Modeling
Day 3 - PM Session
Example D: MCC Fire in Switchgear Room

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

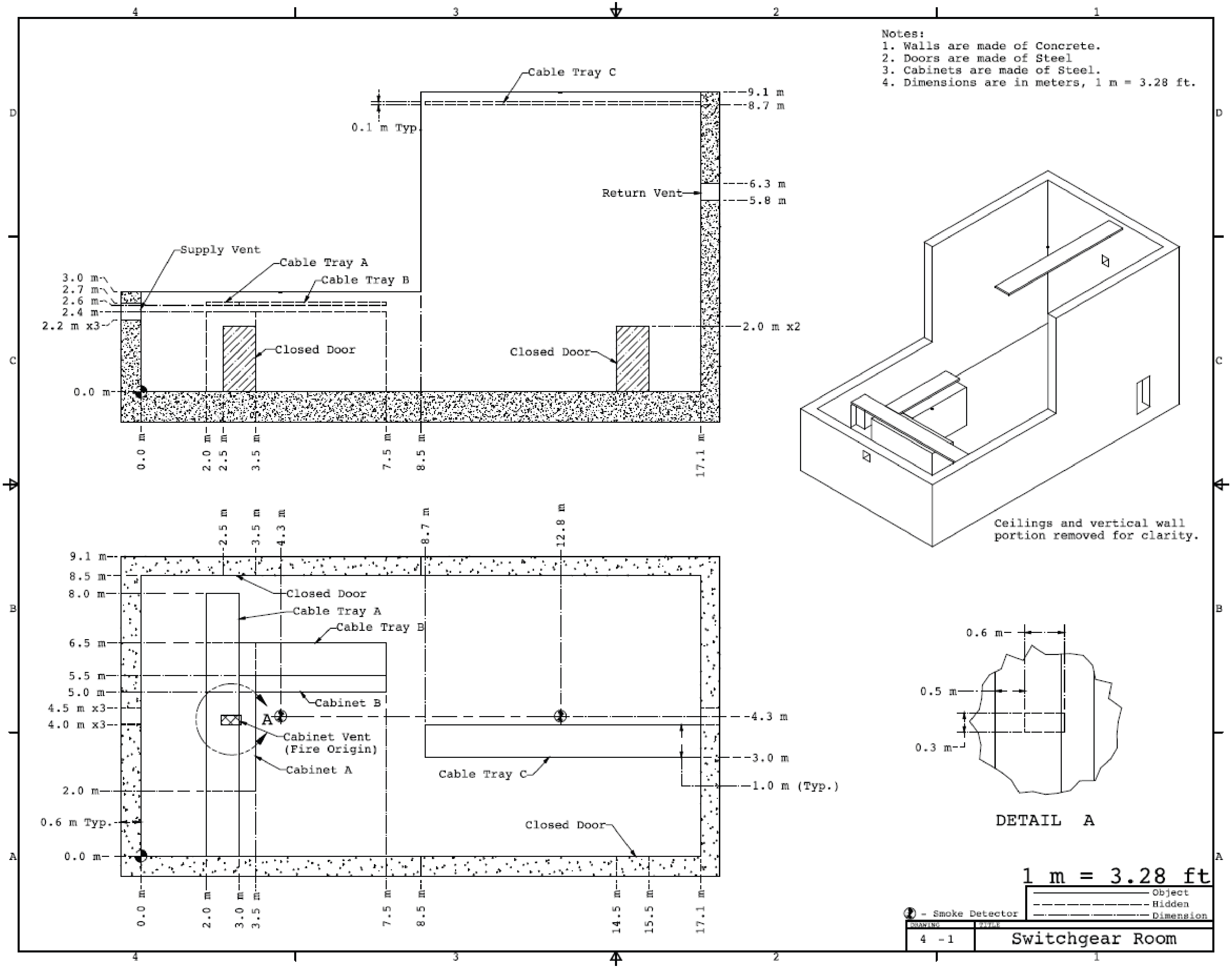
A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

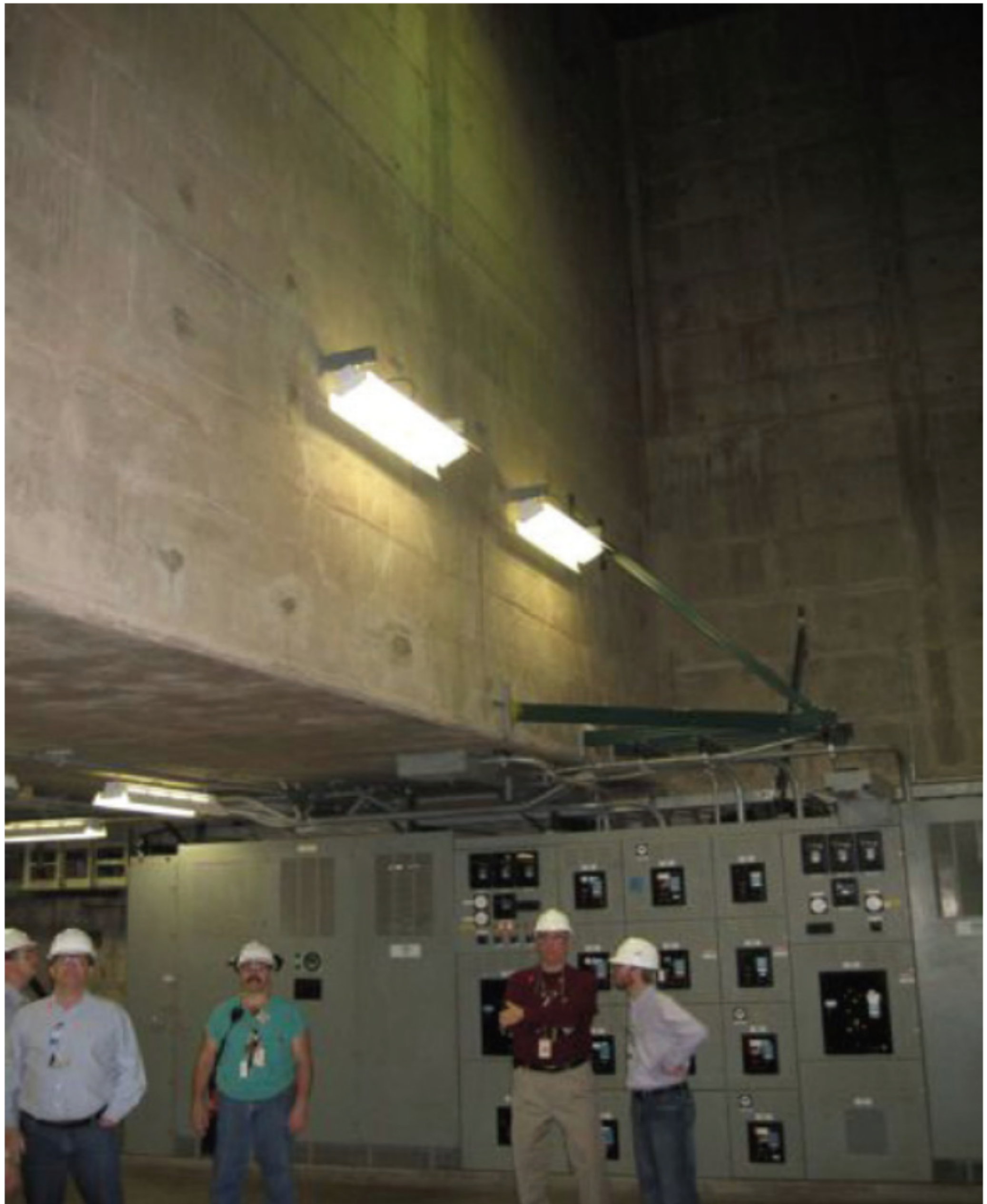
Step 1. Define Fire Modeling Goals

- Determine if a fire in the Motor Control Center damages nearby cables and cabinets in a switchgear room
- Define damage to both cables and cabinets as a surface temperature of 400 ºC

Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire


Notes:
1. Walls are made of Concrete.
2. Doors are made of Steel
3. Cabinets are made of Steel.
4. Dimensions are in meters, 1 m = 3.28 ft.
Cable Tray C
9.1 m
8.7 m
0.1 m Typ.
Return Vent
6.3 m
5.8 m
Supply Vent
Cable Tray A
Cable Tray B
3.0 m
2.7 m
2.6 m
2.4 m
2.2 m x3
Closed Door
Closed Door
2.0 m x2
0.0 m
0.0 m
2.0 m
2.5 m
3.5 m
7.5 m
8.5 m
17.1 m
Ceilings and vertical wall portion removed for clarity.
2.5 m
3.5 m
4.3 m
8.7 m
12.8 m
9.1 m
8.5 m
8.0 m
6.5 m
5.5 m
5.0 m
4.5 m x3
4.0 m x3
2.0 m
0.6 m Typ.
0.0 m
Closed Door
Cable Tray A
Cable Tray B
Cabinet B
A
Cabinet Vent (Fire Origin)
Cabinet A
Cable Tray C
Closed Door
4.3 m
3.0 m
1.0 m (Typ.)
0.0 m
2.0 m
3.0 m
3.5 m
7.5 m
8.5 m
14.5 m
15.5 m
17.1 m
0.6 m
0.5 m
0.3 m
DETAIL A
1 m = 3.28 ft
Object
Hidden
Dimension
- Smoke Detector
4 -1
Switchgear Room



Material Properties

Table 3-1. Material Properties

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Source
Brick	0.8	2600	0.8	NUREG-1805, Table 2-3
Concrete	1.6	2400	0.75	NUREG-1805, Table 2-3
Copper	386	8954	0.38	SFPE Handbook, Table B.6
Gypsum	0.17	960	1.1	NUREG-1805, Table 2-3
Plywood	0.12	540	2.5	NUREG-1805, Table 2-3
PVC	0.192	1380	1.289	NUREG/CR-6850, Appendix R
Steel	54	7850	0.465	NUREG-1805, Table 2-3
XLP	0.235	1375	1.390	NUREG/CR-6850, Appendix R

Material Properties

Cables: The cable trays are filled with cross-linked polyethylene (XPE or XLPE) insulated cables with a neoprene jacket. These are considered thermoset (TS) materials. These cables have a diameter of approximately 1.5 cm (0.6 in), a jacket thickness of approximately 2 mm (0.79 in), 3 conductors, and a mass per unit length of 0.4 kg/m. Tray locations are shown in the compartment drawing. These particular cables have been shown to fail when the temperature just underneath the jacket reaches approximately 400 °C (750 °F) (NUREG/CR-6931, Vol. 2, Table 5.10[18]). A second criterion for damage is exposure to a heat flux that exceeds 11 kW/m^2 (NUREG-1805, Appendix A, Section A.5.4). Damage criteria for the adjacent cabinet are the same as for the cable trays because the cables within the cabinet are subjected to similar thermal exposure conditions as the steel cabinet housing.

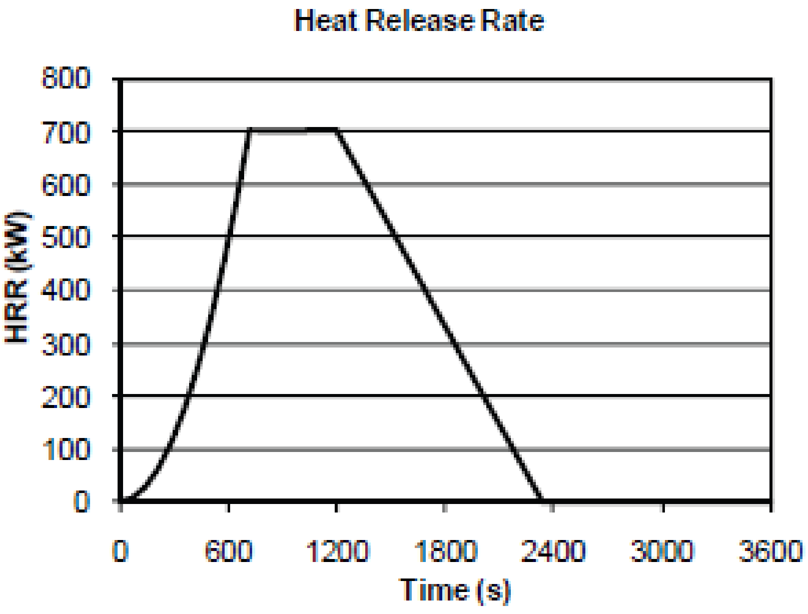
Ventilation

- 3 Air Changes Per Hour (ACH)
- Doors closed
- Compartment volume is 882 m^3
- Volume flow rate is 0.735 m^3/s

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)

Fire

What is burning?

Cables made of polyethylene (C_2H_4) and neoprene (C_4H_5Cl)

Assume effective fuel: $C_3H_{4.5}Cl_{0.5}$

Table D-1. Products of combustion for the MCC fire.

Parameter	Value	Source
Effective Fuel Formula	$C_3H_{4.5}Cl_{0.5}$	Combination of polyethylene and neoprene
Peak HRR	702 kW	NUREG/CR-6850 (EPRI 1011989), App. G
Time to reach peak HRR	720 s	NUREG/CR-6850 (EPRI 1011989), App. G
Heat of Combustion	10,300 kJ/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
CO_2 Yield	0.63 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
Soot Yield	0.175 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
CO Yield	0.082 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
Radiative Fraction	0.53	*SFPE Handbook*, 4th Ed., Table 3-4.16

Step 3. Select Fire Models

- Algebraic Models: FDTs can be used for the heat flux calculation. Non-uniform ceiling height a problem for HGL calculations in both FDTs and FIVE-rev1.
- Zone Models: Non-uniform ceiling is a problem. However, CFAST can model the ceiling in terms of a non-uniform cross-section or as adjacent compartments
- CFD: No particular issues for FDS. Two level ceiling is not a problem. May want to use multiple grids.

Applicability of Validation

Table D-2. Normalized parameter calculations for the MCC fire scenario.

Quantity	Normalized Parameter Calculation		Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}}$ $= \frac{702\text{ kW}}{(1.2\text{ kg/m}^3)(1.0\text{ kJ/kg/K})(293\text{ K})(0.5^{2.5}\text{ m}^{2.5})\sqrt{9.8\text{ m/s}^2}} \cong 3.6$		0.4 – 2.4	No
Fire Height, $H_f + L_f$, relative to the Ceiling Height, H_c	$\frac{H_f + L_f}{H_c} = \frac{2.4\text{ m} + 2.5\text{ m}}{3.0\text{ m}} \cong 1.6$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 0.48\text{ m}\,(3.7 \times 3.6^{0.4} - 1.02) \cong 2.5\text{ m}$		0.2 – 1.0	No
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H_c	N/A – There are no targets like sprinklers or smoke detectors under consideration in this example.		1.2 – 1.7	N/A
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\,\dot{m}_{O_2}} = \frac{702\text{ kW}}{13{,}100\text{ kJ/kg} \times 0.2\text{ kg/s}} \cong 0.3$ $\dot{m}_{O_2} = 0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2\text{ kg/m}^3 \times 0.735\text{ m}^3\text{/s} \cong 0.2\text{ kg/s}$		0.04 – 0.6	Yes
Compartment Aspect Ratio (Lower | Upper)	$\frac{L}{H_c} = \frac{8.5\text{ m}}{3.0\text{ m}} \cong 2.8$; $\frac{W}{H_c} = \frac{8.5\text{ m}}{3.0\text{ m}} \cong 2.8$	$\frac{L}{H_c} = \frac{8.6\text{ m}}{9.1\text{ m}} \cong 0.9$; $\frac{W}{H_c} = \frac{8.5\text{ m}}{9.1\text{ m}} \cong 0.9$	0.6 – 5.7	Yes
Target Distance, r, relative to the Fire Diameter, D	$\frac{r}{D} = \frac{1.1\text{ m}}{0.5\text{ m}} \cong 2.2$		2.2 – 5.7	Yes

Step 4. Calculate Fire-Generated Conditions

D.4.1 Algebraic Models (FDT^s)

Fire: The FDT^s use a steady-state HRR in both the flame height and radiation heat flux calculation. A constant HRR of 702 kW is used for both. A fire diameter of 0.48 m (1.6 ft) is calculated from the effective vent area atop the cabinet of 0.18 m^2 (2 ft^2). Table D-2 indicates that the Heskestad flame height correlation yields a calculated flame height of 2.5 m (8.2 ft). Consequently, the cables located directly above the cabinet would be engulfed in flame and therefore would be expected to fail. This flame height calculation also shows that there would be significant flame extension beneath the ceiling, which is located just 0.6 m (2 ft) above the base of the assumed fire.

The point source radiation model predicts the peak heat flux to the side of the adjacent cabinet that is approximately 1.1 m (3.6 ft) from the center of the vent on top of the burning cabinet:

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi r^2} = \frac{0.53 \times 702\ \mathrm{kW}}{4\pi \times 1.1^2} \cong 24.5\ \mathrm{kW/m^2} \qquad \text{(D-1)}$$

This estimate does not include the contribution to the heat flux from the HGL or from the flame extension beneath the ceiling. However, this estimate does indicate that the heat flux to the adjacent cabinet could exceed the critical heat flux by a relatively large margin. Consequently, this scenario would warrant more detailed analysis with either a zone model or a CFD model.

CFAST – Geometry and materials

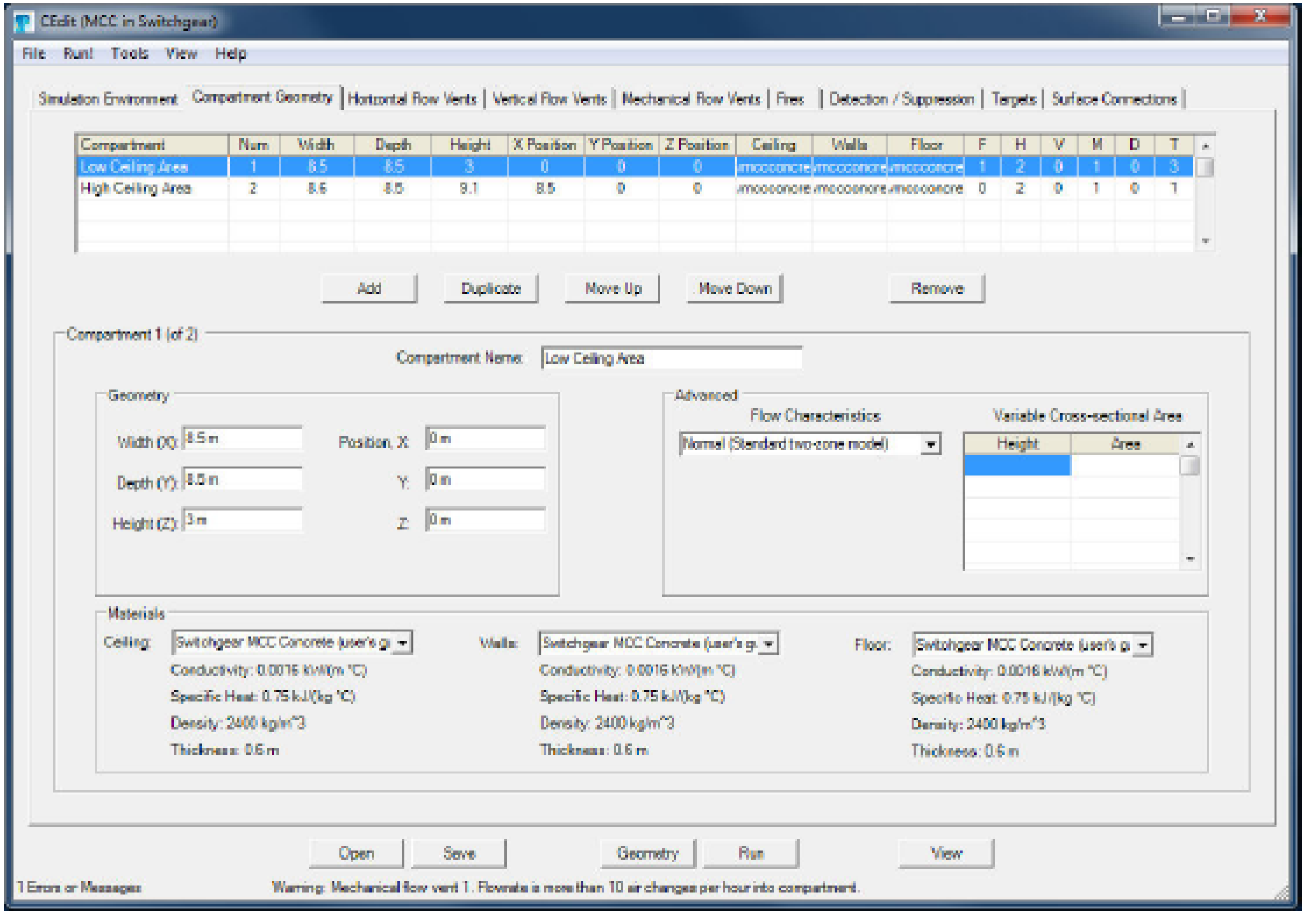


Figure D-5. CFAST inputs for compartment geometry for SWGR.

CFAST – Fire specification

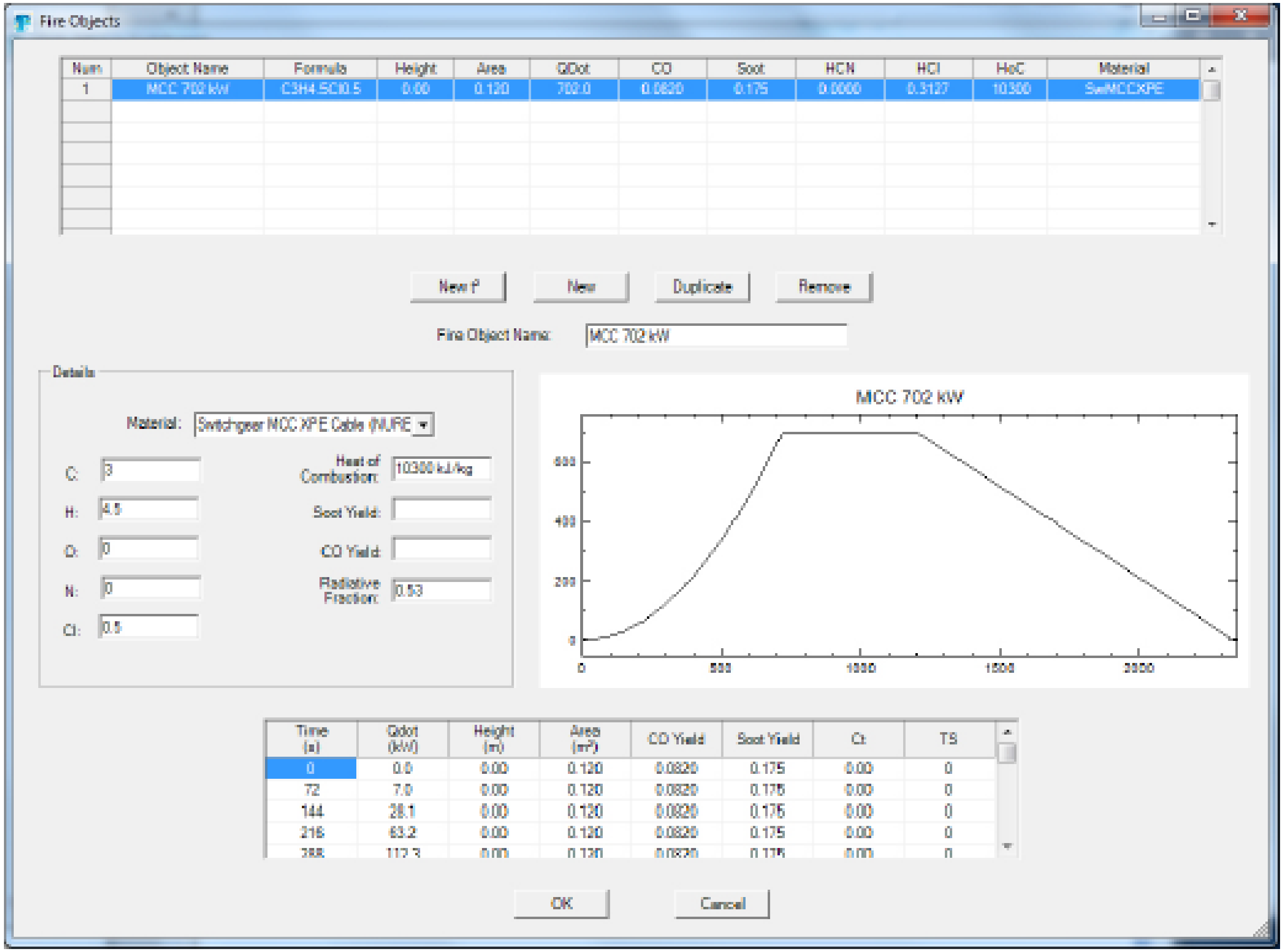


Figure D-6. CFAST fire inputs for two-height ceiling SWGR scenario.

CFAST – Target specification

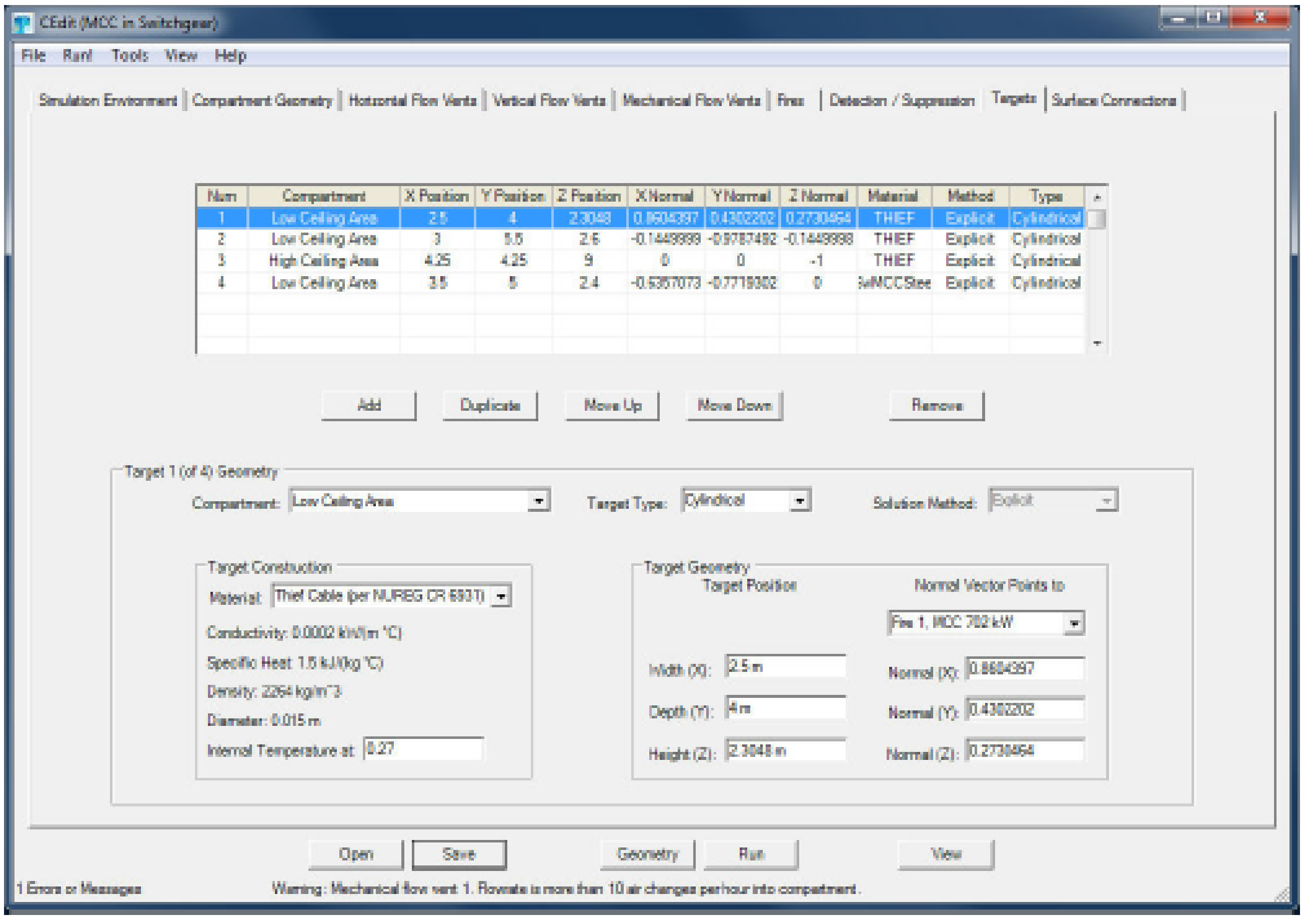


Figure D-7. CFAST target inputs for two-height ceiling SWGR scenario.

CFAST – Mechanical ventilation

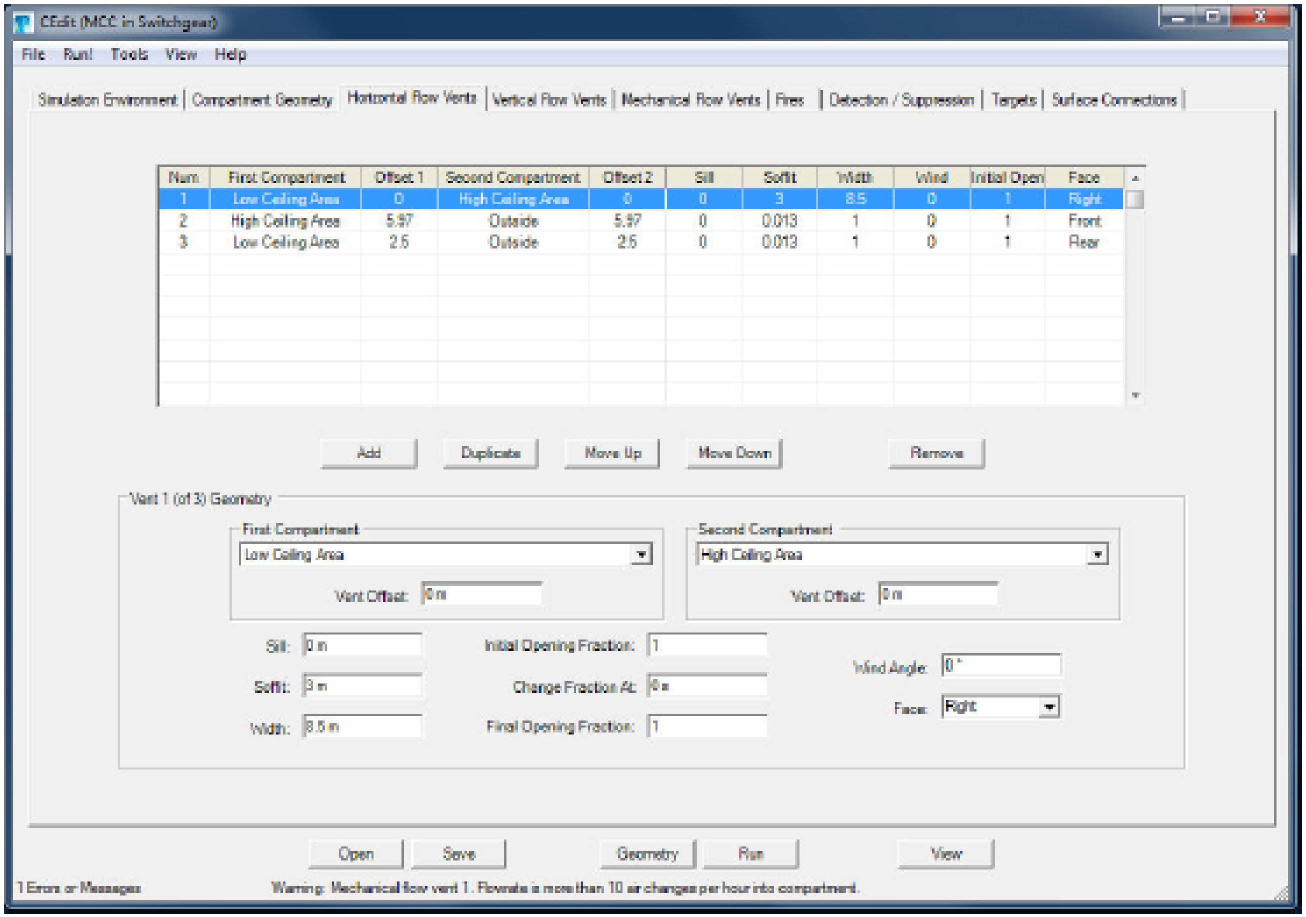


Figure D-8. CFAST inputs for vents connections in two-height ceiling SWGR scenario.

CFAST – Smokeview rendering of SWGR fire

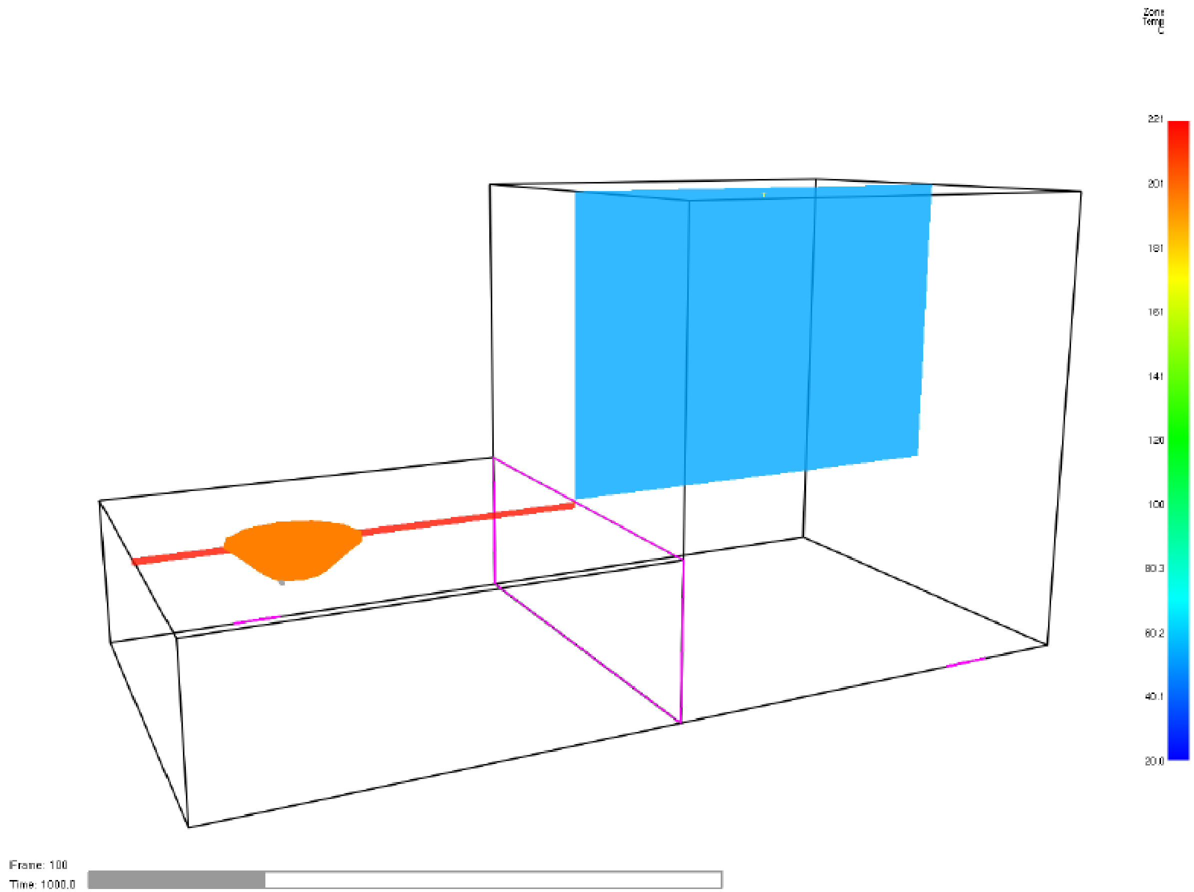


Figure D-4. Geometry of two-height ceiling Switchgear Room as modeled in CFAST.

FDS – Smokeview rendering of SWGR fire

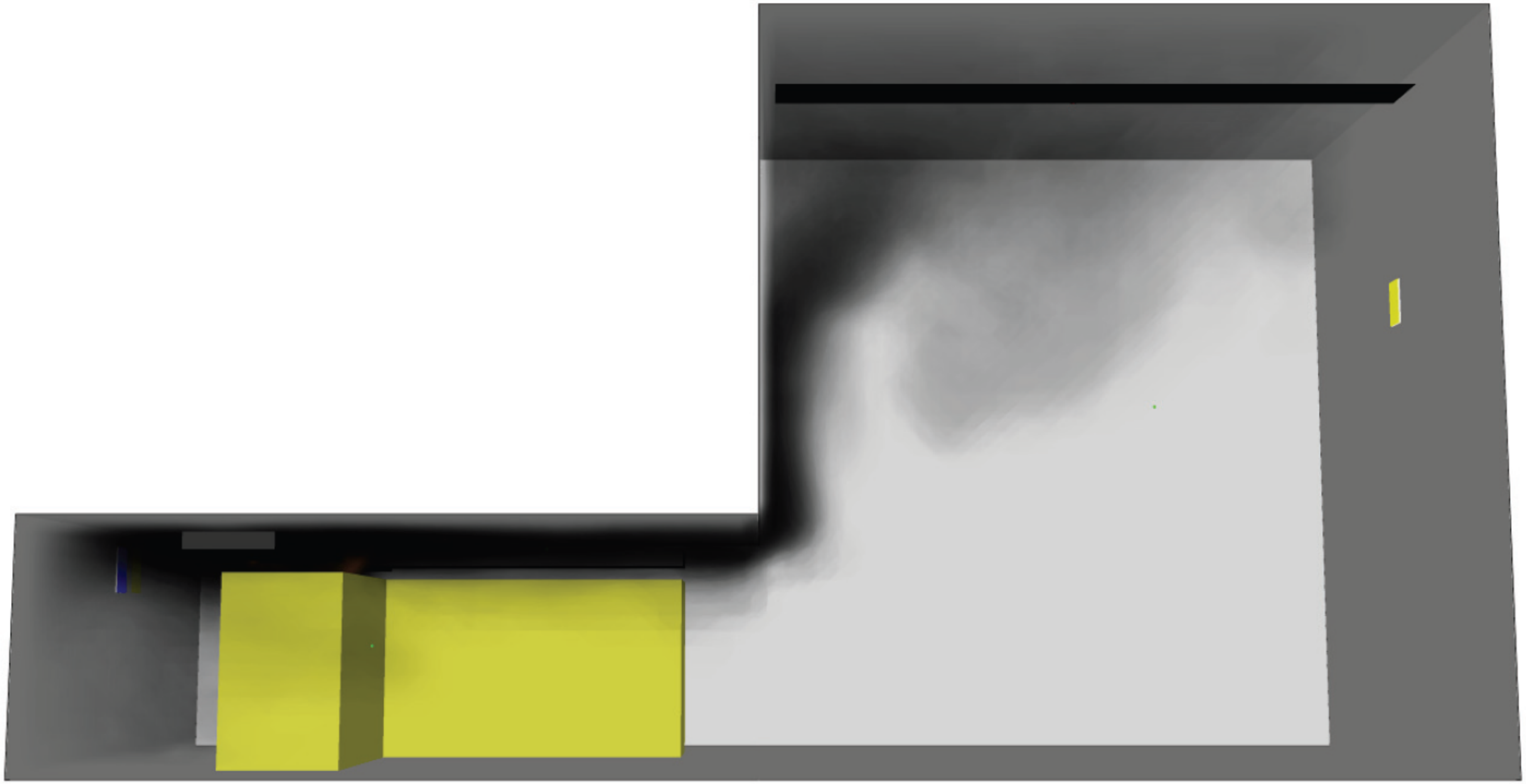


Figure D-5. FDS/Smokeview representation of the MCC/Switchgear Room scenario.

Step 4. Calculate Fire-Generated Conditions

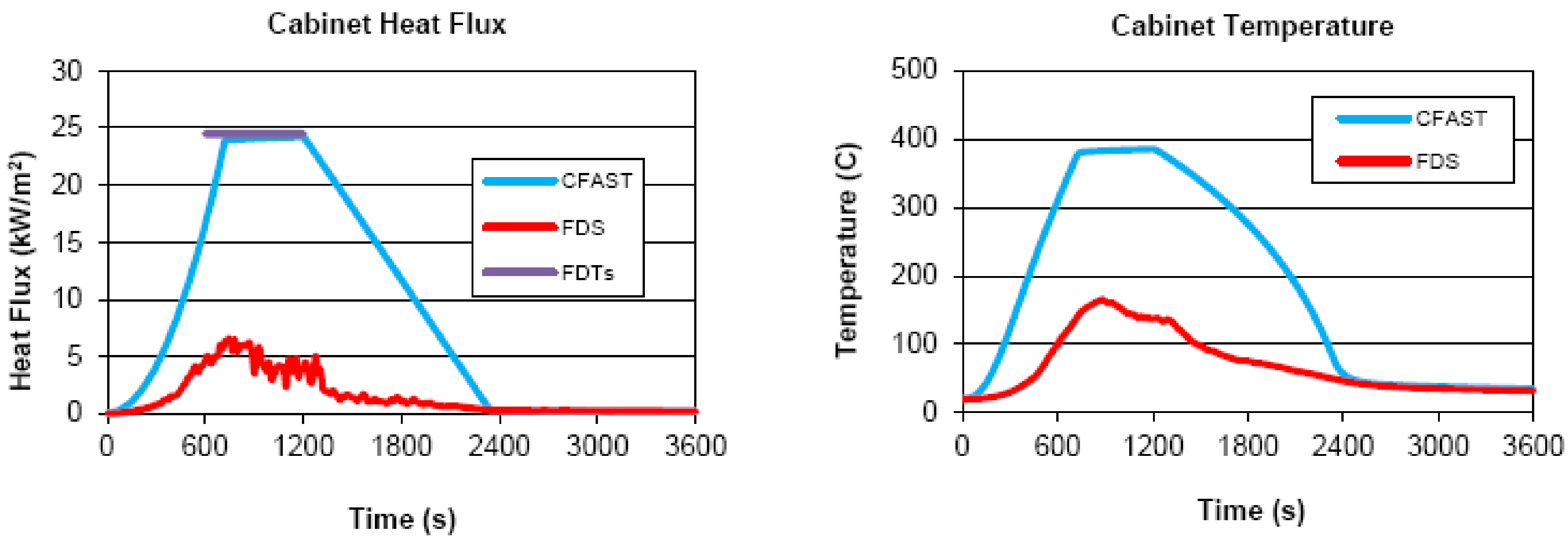
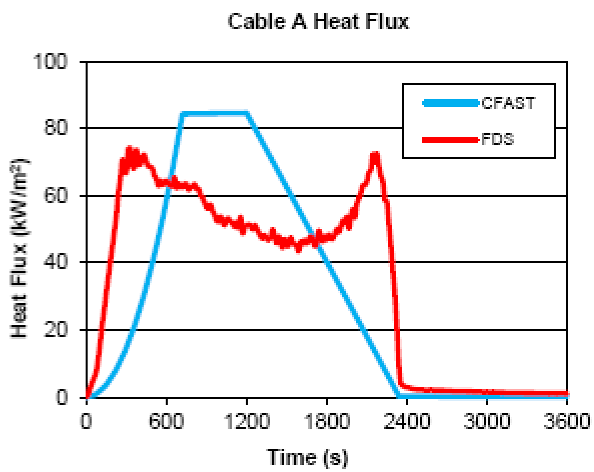
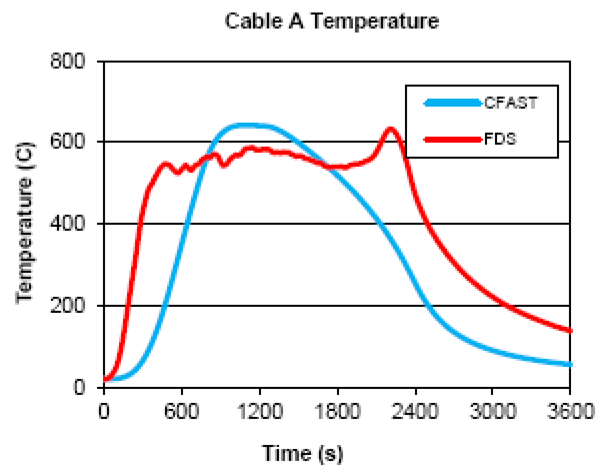
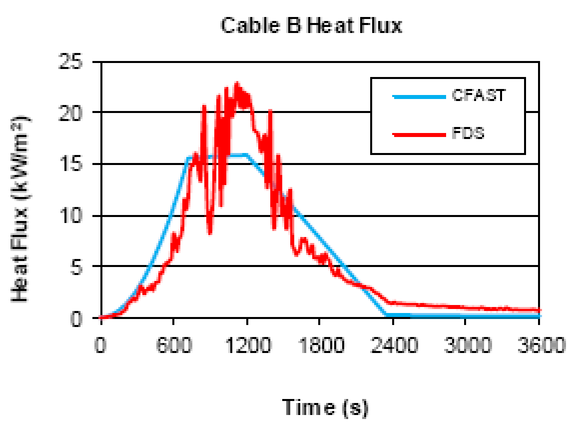


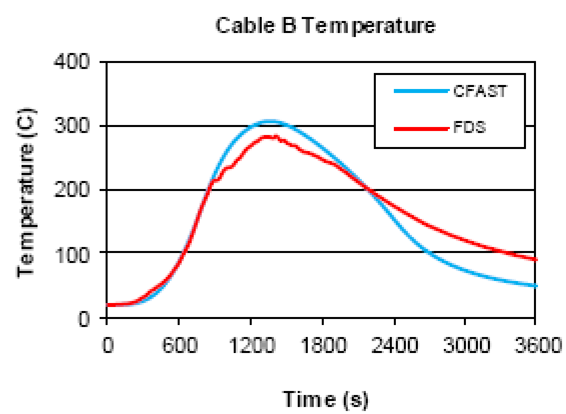
Figure D-10. Heat flux and temperature predictions for the adjacent cabinet.

Step 4. Calculate Fire-Generated Conditions









Step 4. Calculate Fire-Generated Conditions

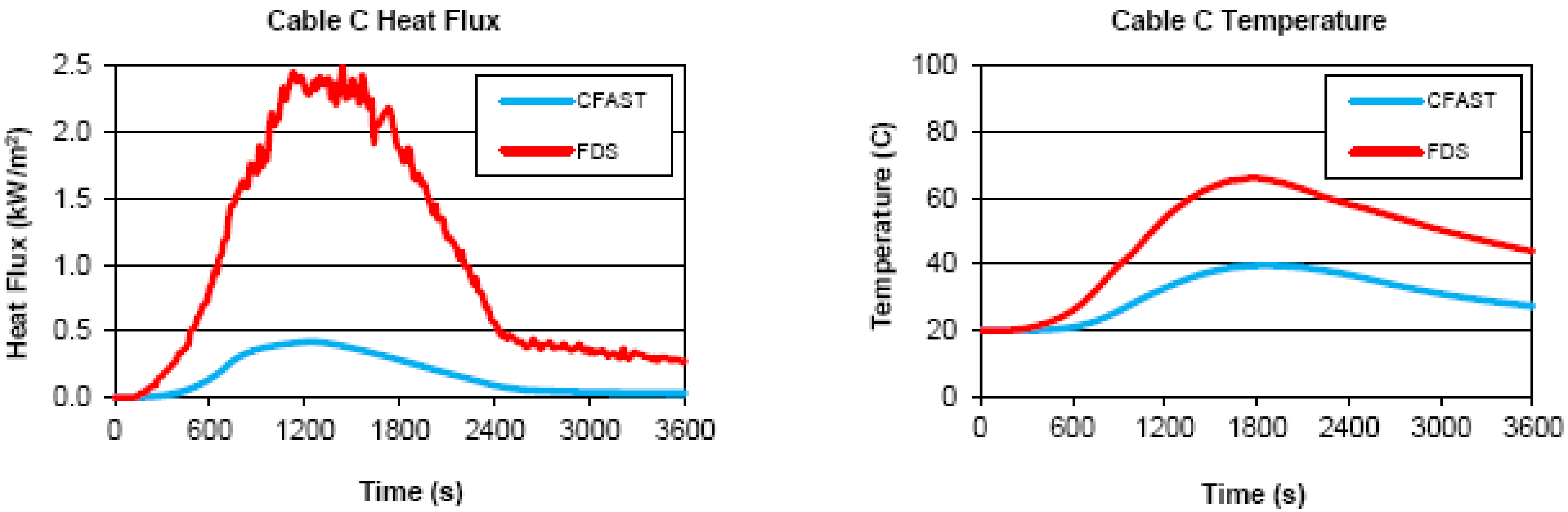


Figure D-11. Summary of the cable predictions for the MCC/Switchgear Room.

Step 5. Sensitivity and Uncertainty Analysis

Table D-3. Summary of the model predictions of the MCC fire scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Target	Predicted Value	Critical Value	Probability of Exceeding
Surface Temperature (°C), Initial Value = 20 °C						
CFAST	1	0.27	Cabinet	390	400	0.460
FDS	1.02	0.13		170	400	0.000*
CFAST	1	0.27	Cable A	705	400	0.950
FDS	1.02	0.13		620	400	0.997
CFAST	1	0.27	Cable B	305	400	0.112
FDS	1.02	0.13		280	400	0.000
CFAST	1	0.27	Cable C	40	400	0.000
FDS	1.02	0.13		65	400	0.000
Heat Flux (kW/m^2)						
CFAST	0.81	0.47	Cabinet	24.3	11	0.911
FDS	0.85	0.22		6.0	11	0.006*
CFAST	0.81	0.47	Cable A	104	11	0.974
FDS	0.85	0.22		75.0	11	1.000
CFAST	0.81	0.47	Cable B	15.8	11	0.823
FDS	0.85	0.22		23.0	11	0.997
CFAST	0.81	0.47	Cable C	0.2	11	0.000
FDS	0.85	0.22		2.5	11	0.000

* These results require closer scrutiny. See discussion below.

Step 5. Sensitivity and Uncertainty Analysis

D.5.1 Damage to Cabinet

The predicted heat flux to and temperatures of the cabinet adjacent to the MCC are shown in Figure D-10. The cabinet is located approximately 1.1 m (3.6 ft) from the center of the flaming vent. The point source radiation calculation included in CFAST and the FDT[s] predicts a peak heat flux of 24.5 kW/m^2 to the nearest point on the cabinet. FDS predicts the peak heat flux (and resulting surface temperature) to be significantly lower because the fire is partially obscured by the overhead cable tray and the burning MCC. FDS also accounts for the orientation of the adjacent cabinet top and side relative to the fire's location. However, the heat flux to the top of the MCC near the adjacent cabinet is substantially greater than the critical value, and a small change in the position of the fire could result in a much higher heat flux to the target. Given the sensitivity of the predicted heat flux and surface temperature to a minor change in the fire dynamics, the FDS prediction for the cabinet ought to be discounted in this case.

Step 5. Sensitivity and Uncertainty Analysis

D.5.2 Cable Damage Based on Temperature Alone

The predicted cable temperatures for the three trays are shown in Figure D-11. CFAST and FDS estimate cable temperatures using the THIEF methodology (NUREG/CR-6931, Vol. 3). Both models predict that the cables in Tray A are likely to fail.

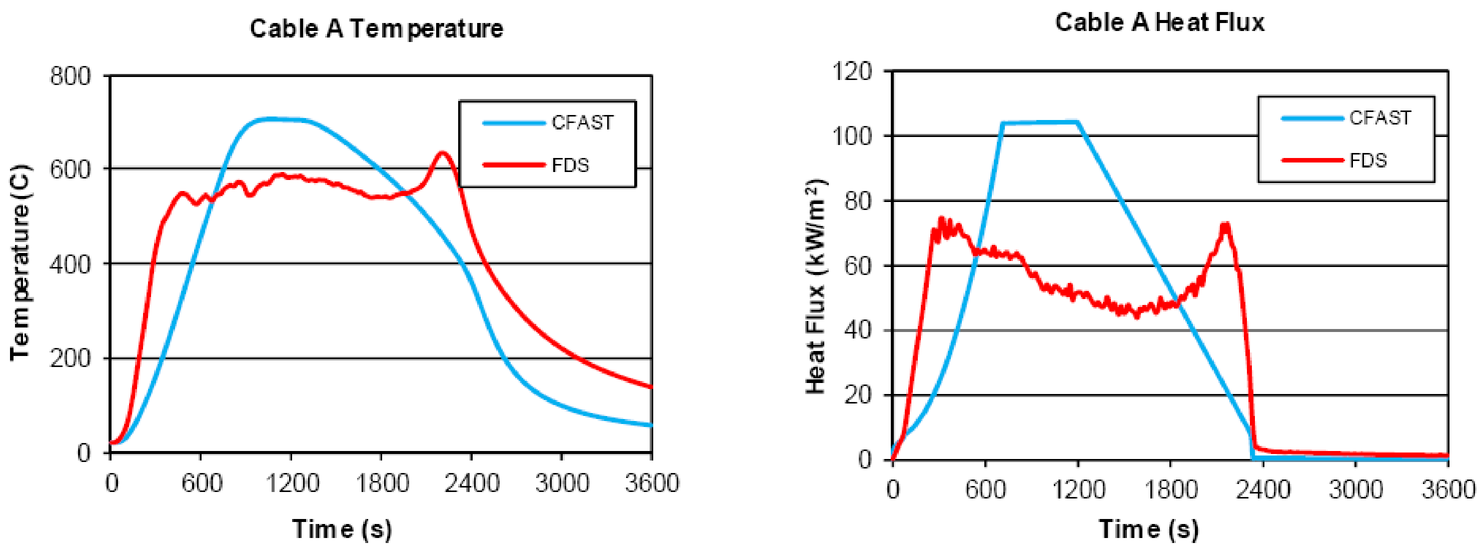
Neither model predicts that the cables in Tray B will reach the failure temperature of 400 °C (750 °F), but the CFAST prediction of 300 °C (572 °F) suggests that there is a 9% probability that the cable temperature could be as high as the critical value. Note that these predictions are sensitive to the exact location of the target cable within the tray, its view of the fire, and the HGL temperature. In this case, the cables in Tray B are heated primarily by convection and radiation from the HGL. Given that the HRR is the most important parameter controlling the temperature of the HGL, how much would the HRR have to increase to increase the CFAST prediction from 300 °C (572 °F) to 400 °C (752 °F)? Table 4-3 indicates that the rise in the HGL temperature is proportional to the HRR to the 2/3 power. Following the methodology in Section 4.4.1, in order to increase the predicted HGL temperature by 100 °C (212 °F), the peak HRR, $\dot{Q}$, must increase by approximately:

$$\Delta\dot{Q} = \frac{3}{2}\dot{Q}\frac{\Delta T}{T - T_0} = \frac{3}{2}\,702\text{ kW} \times \frac{100\text{ °C}}{300\text{ °C} - 20\text{ °C}} \cong 376\text{ kW} \qquad \text{(D-3)}$$

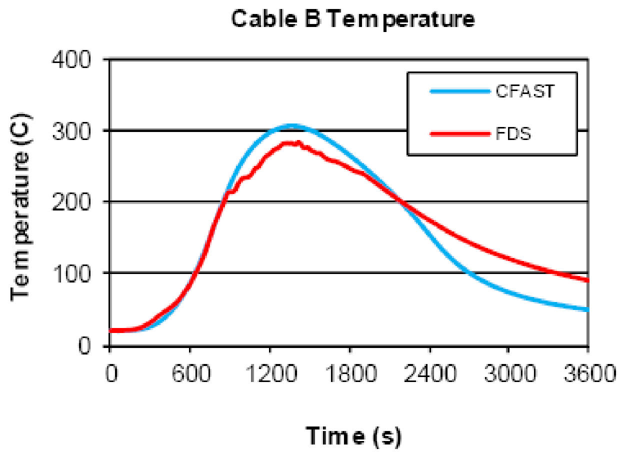
Step 5. Sensitivity and Uncertainty Analysis

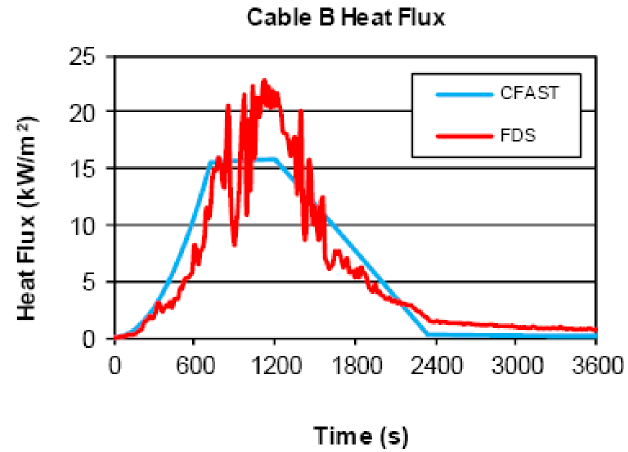
D.5.3 Cable Damage Based on Incident Heat Flux

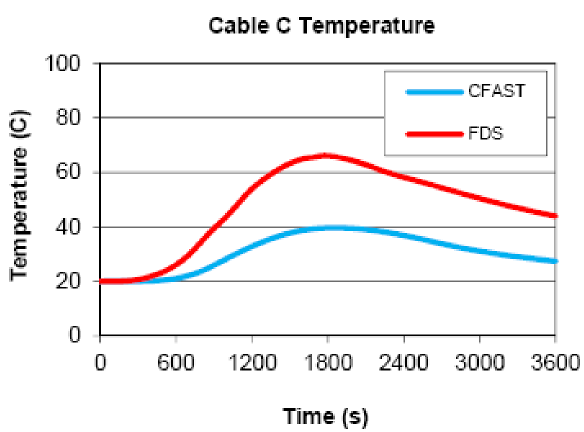
The predictions of heat flux to the cables in the three trays are shown in Figure D-11. The critical value is 11 kW/m^2. Flame height correlations predict that the fire will impinge on Tray A, and both CFAST and FDS indicate that the heat flux to these cables would be well in excess of the critical value.

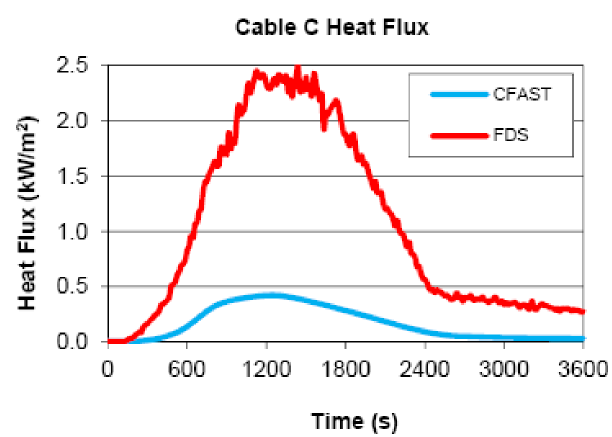


Step 5. Sensitivity and Uncertainty Analysis









Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

Step 6. Document the Analysis

D.6 Conclusion

The purpose of the calculations in this example is to predict if and when various components within a compartment will become damaged due to a fire in the MCC. The fire model analyses performed for this scenario indicate that the fire would damage the cables in Tray A because all the models (FDT[s], CFAST, FDS) predict that the flames would directly impinge on the cables themselves.

- CFAST and FDS predict that the cables in Tray B are likely to be damaged based on the heat flux criterion. However, neither model predicts that the interior cable temperatures are likely to be high enough to cause failure.
- Neither FDS nor CFAST predicts that the cables in Tray C would be damaged.
- A point source heat flux analysis indicates that the adjacent cabinet housing would be exposed to a heat flux that would cause damage. Even though FDS does not predict damage, its predictions of heat flux to surfaces very near the adjacent cabinet are sufficiently high to cast doubt on the conclusion that the cabinet would not be damaged. Small changes in the positions of various obstructions could easily change the predicted heat flux by an order of magnitude. Even though the point source method tends to over-predict the heat flux to targets close to the fire, there is too much uncertainty in the geometric configuration to accept the validity of the more detailed calculation.

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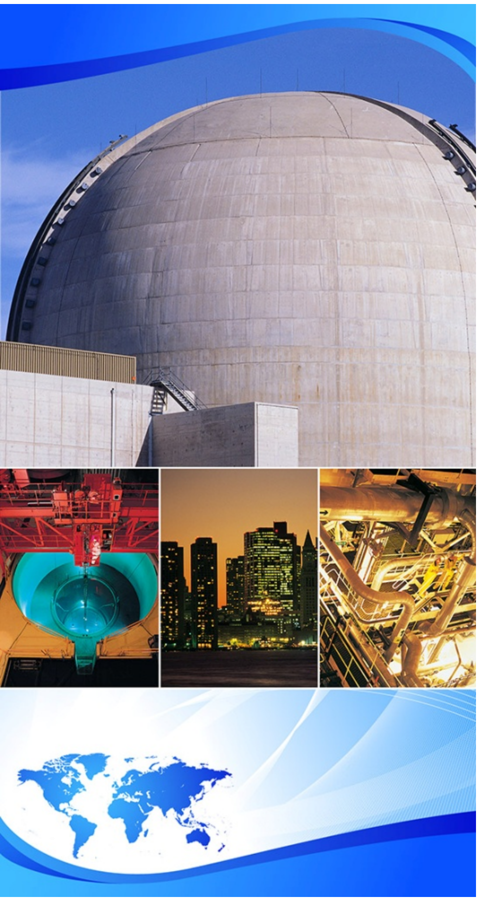


EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5

Advanced Fire Modeling
Day 4 - AM Session
Example E: Transient Fire in Cable Spreading Room

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

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

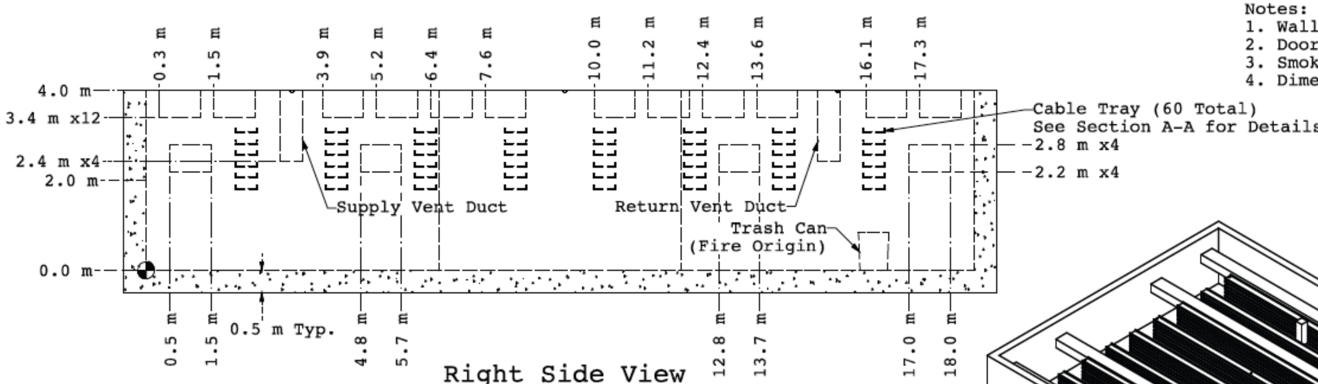
Step 1. Define Fire Modeling Goals

- Estimate the impact on safe-shutdown cables due to a fire in a trash bin inside a Cable Spreading Room.
- Transient combustibles have been identified as a possible source of fire that may impact the cables. The purpose of the calculation is to analyze this condition and determine whether the cable targets will fail, and, if so, at what time failure occurs.
  - Bottom cable tray has a solid steel bottom
- Follow guidance provided in Chapter 11 of NUREG/CR-6850 (EPRI 1011989), Volume 2, "Detailed Fire Modeling (Task 11)."

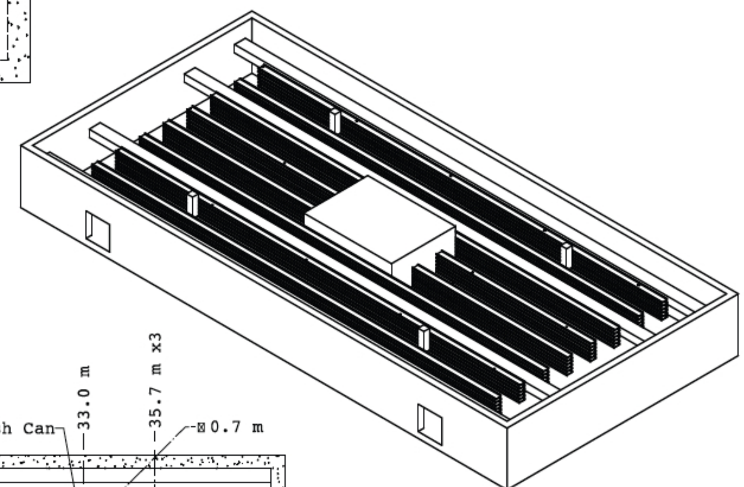
Step 2. Characterize Fire Scenarios

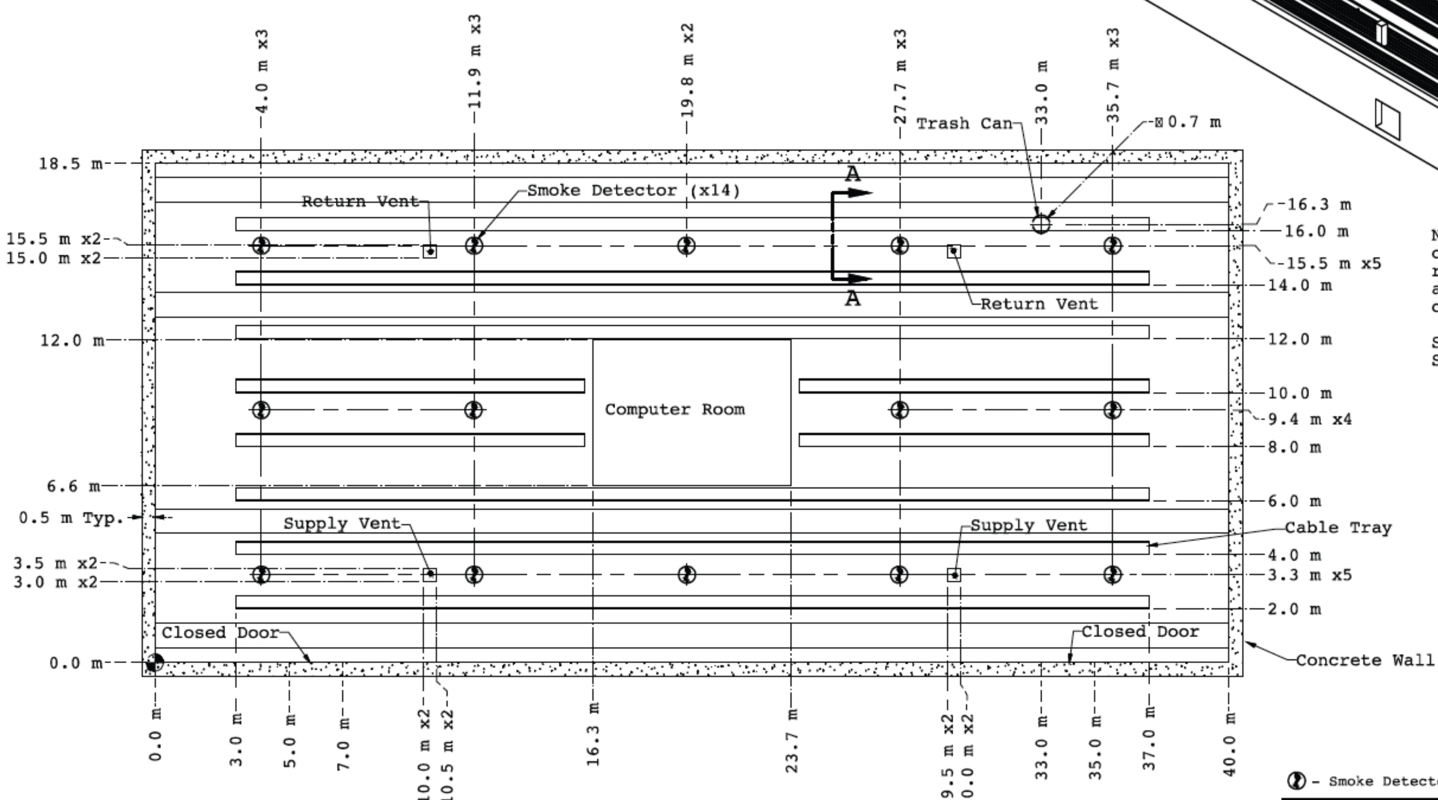
- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire

Notes:
1. Walls are made of Concrete.
2. Doors are made of Steel.
3. Smoke Detectors are at Ceiling Height.
4. Dimensions are in meters, 1 m = 3.28 ft.



Right Side View





NOTE: Obstructions at celing height are removed from Top View and Isometric View for clarity.

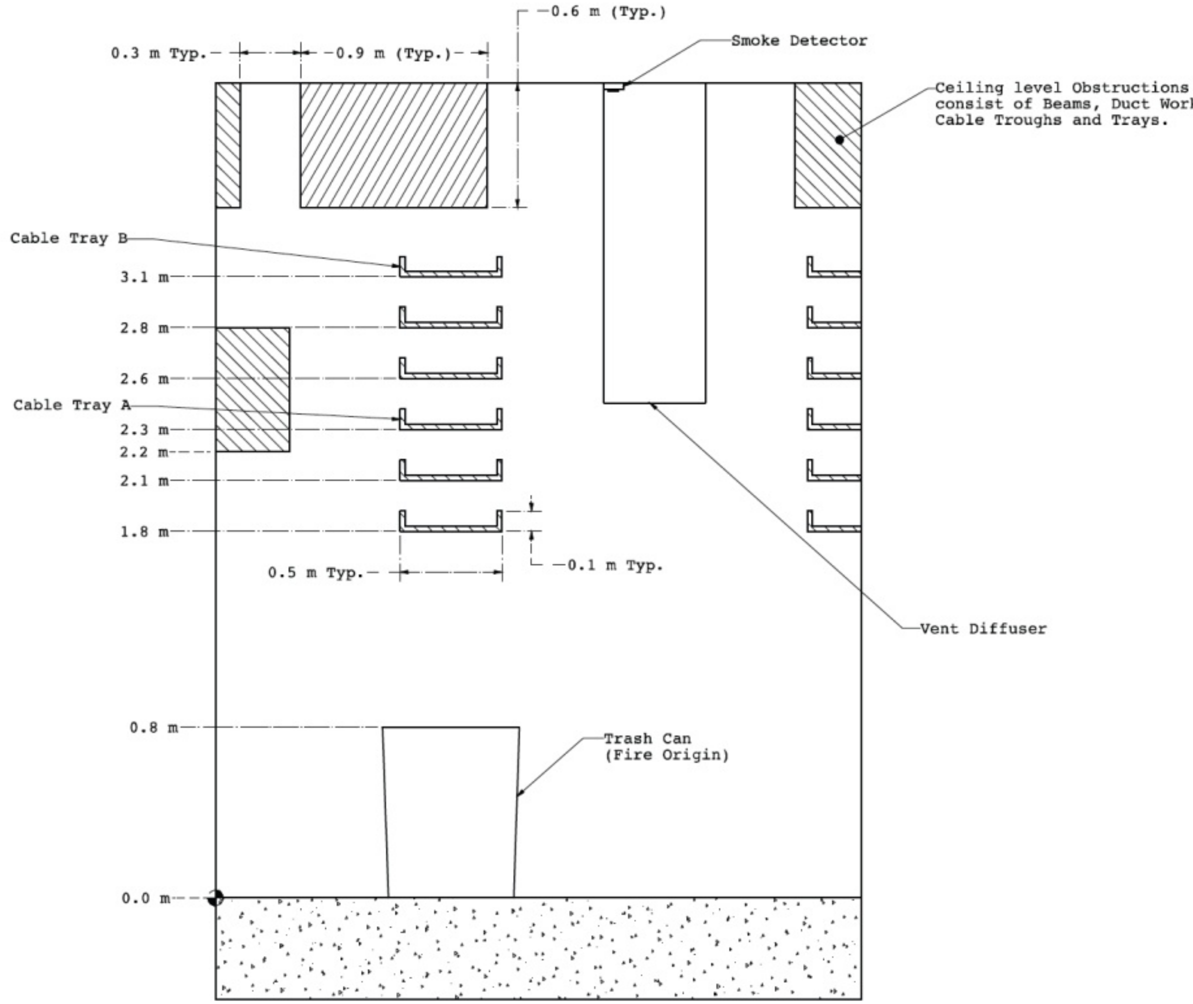
See Right Side View and Sheet 2 for details.

1 m = 3.28 ft

- Smoke Detector

Object
Hidden
Dimension

DRAWING	TITLE
5 -1	Cable Spreading Room



0.6 m (Typ.)
Smoke Detector
0.3 m Typ.
0.9 m (Typ.)
Ceiling level Obstructions consist of Beams, Duct Work, Cable Troughs and Trays.
Cable Tray B
3.1 m
2.8 m
2.6 m
Cable Tray A
2.3 m
2.2 m
2.1 m
1.8 m
0.5 m Typ.
0.1 m Typ.
Vent Diffuser
0.8 m
Trash Can (Fire Origin)
0.0 m

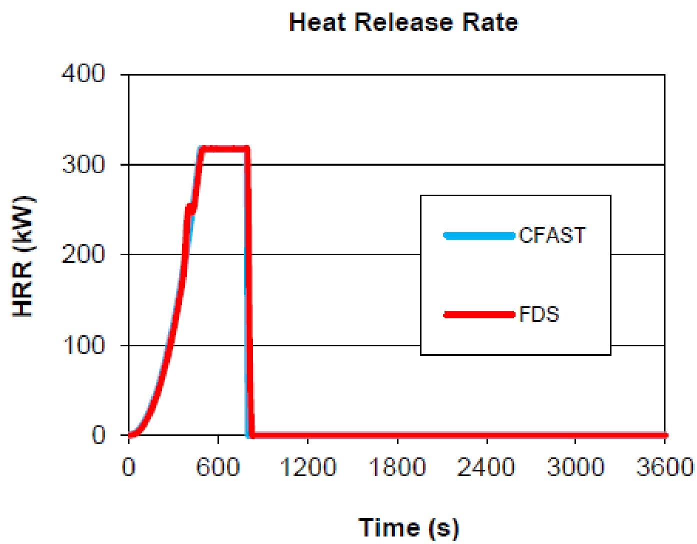
Ventilation

- The CSR has two doors on the east wall that are normally closed.
- Standard procedure calls for an operator to investigate the fire within 600 s (10 min) of an alarm condition.
- Two supply vents and two return vents. 1.4 m^3/s for each.
- Leakage – often the "leakage area" is the area of the crack under the door.
- Exact supply and exhaust location only important for CFD.
- Zone models usually only consider height of ducts off floor and orientation of the vent.

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)

What is burning?

A trash fire ignites within a cylindrical steel waste bin 0.8 m (2.6 ft) high and 0.6 m (2.0 ft) in diameter, containing 5 kg of trash.

Duration of Fire

Total energy released is 5 kg x 30,400 kJ/kg = 152,000 kJ

$$Q \equiv 152{,}000\ \mathrm{kJ} = \int_0^{480} \dot{Q}_p \left(\frac{t}{480}\right)^2 dt + \int_{480}^{t_f} \dot{Q}_p\, dt = 317\ \mathrm{kW}\left(\frac{480\ \mathrm{s}}{3} + \left(t_f - 480\ \mathrm{s}\right)\right) \qquad \text{(E-1)}$$

Solving for t_f yields a total burning time of 800 s.

Table E-1. Products of combustion for CSR fire.

Parameter	Value	Source
Effective Fuel Formula	$C_4H_7O_{2.5}$	Assumption
Peak HRR	317 kW	NUREG/CR-6850 (EPRI 1011989), App. G
Time to reach peak HRR	480 s	NUREG/CR-6850 (EPRI 1011989), App. G
Heat of Combustion	30,400 kJ/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
CO_2 Yield	2.0 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
Soot Yield	0.038 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
CO Yield	0.014 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
Radiative Fraction	0.40	*SFPE Handbook*, 4th ed., Table 3-4.16

Step 3. Select Fire Models

- <u>Algebraic Models</u>: FPA algorithm in FIVE provides estimate of HGL temperature within a closed, ventilated compartment. FDTs do not allow for time-dependent HRR. Both FIVE and FDTs can estimate smoke detector activation time.
- <u>Zone Models</u>: Both CFAST and MAGIC include algorithms to estimate the temperature of cable targets.
- <u>CFD</u>: Typical application of FDS. The primary advantage of a CFD model for this fire scenario is that the CFD model can predict local conditions at the specific location of the target cables and includes more complete radiation calculations from the fire to the cable targets.

Applicability of Validation

Table E-2. Key parameters and their ranges of applicability to NUREG-1824.

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{317\ \text{kW}}{(1.2\ \text{kg/m}^3)(1.0\ \text{kJ/kg/K})(293\ \text{K})(0.6^{2.5}\ \text{m}^{2.5})\sqrt{9.8\ \text{m/s}^2}} \cong 1.0$	0.4 – 2.4	Yes
Flame Length, L_f, relative to the Ceiling Height, H	$\frac{H_f + L_f}{H} = \frac{0.8\ \text{m} + 1.6\ \text{m}}{4.0\ \text{m}} = 0.6$ $L_f = D\left(3.7\ \dot{Q}^{*2/5} - 1.02\right) = 0.6\ \text{m}\ (3.7 \times 1.0^{0.4} - 1.02) \cong 1.6\ \text{m}$	0.2 – 1.0	Yes
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H	N/A – Ceiling jet targets are not included in simulation.	1.2 – 1.7	N/A
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\ \dot{m}_{O_2}} = \frac{317\ \text{kW}}{13{,}100\ \text{kJ/kg} \times 0.4\ \text{kg/s}} \cong 0.06$ $\dot{m}_{O_2} = 0.23\ \rho_\infty \dot{V} = 0.23 \times 1.2\ \text{kg/m}^3 \times 1.4\ \text{m}^3/\text{s} \cong 0.4\ \text{kg/s}$	0.04 – 0.6	Yes
Compartment Aspect Ratio	$\frac{L}{H} = \frac{40\ \text{m}}{4.0\ \text{m}} = 10 \qquad \frac{W}{H} = \frac{18.5\ \text{m}}{4.0\ \text{m}} \cong 4.6$	0.6 – 5.7	No
Target Distance, r, relative to the Fire Diameter, D	$\frac{r}{D} = \frac{2.3\ \text{m}}{0.6\ \text{m}} \cong 3.8$	2.2 – 5.7	Yes

Notes: (1) The "Fire Height", $H_f + L_f$, is the sum of the height of the fire off the floor plus the fire's flame length.

Step 4. Calculate Fire-Generated Conditions

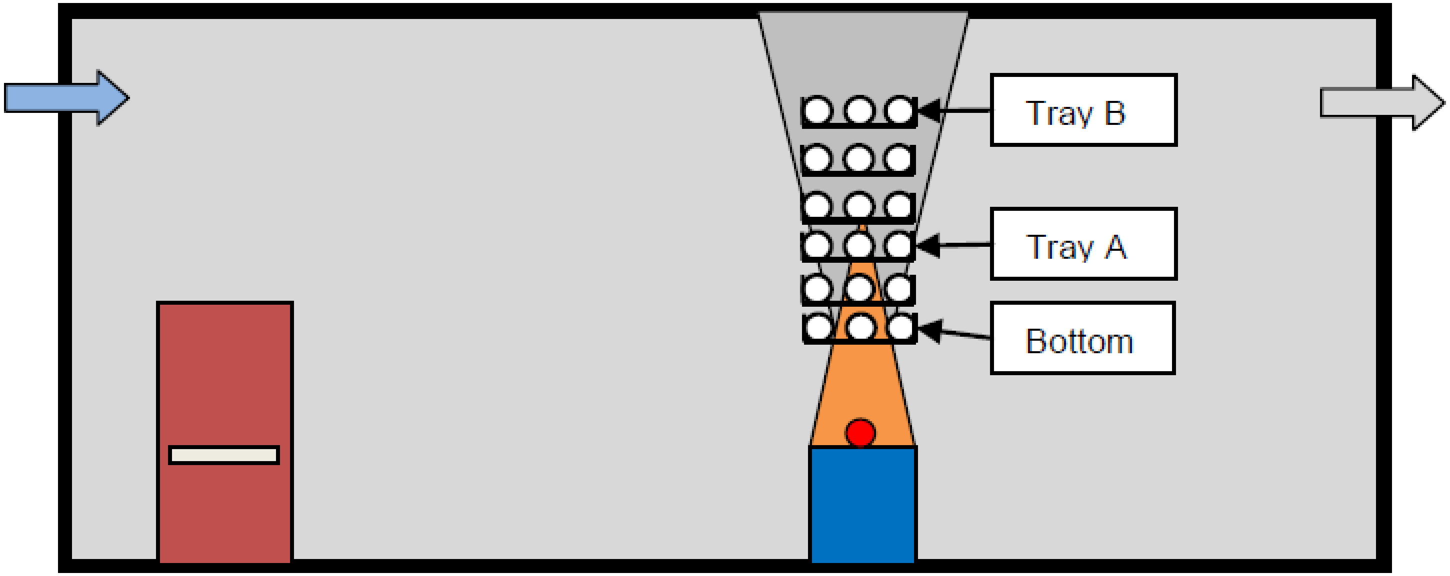


Figure E-4. Schematic diagram of transient trash fire in cable spreading room.

Step 4. Calculate Fire-Generated Conditions

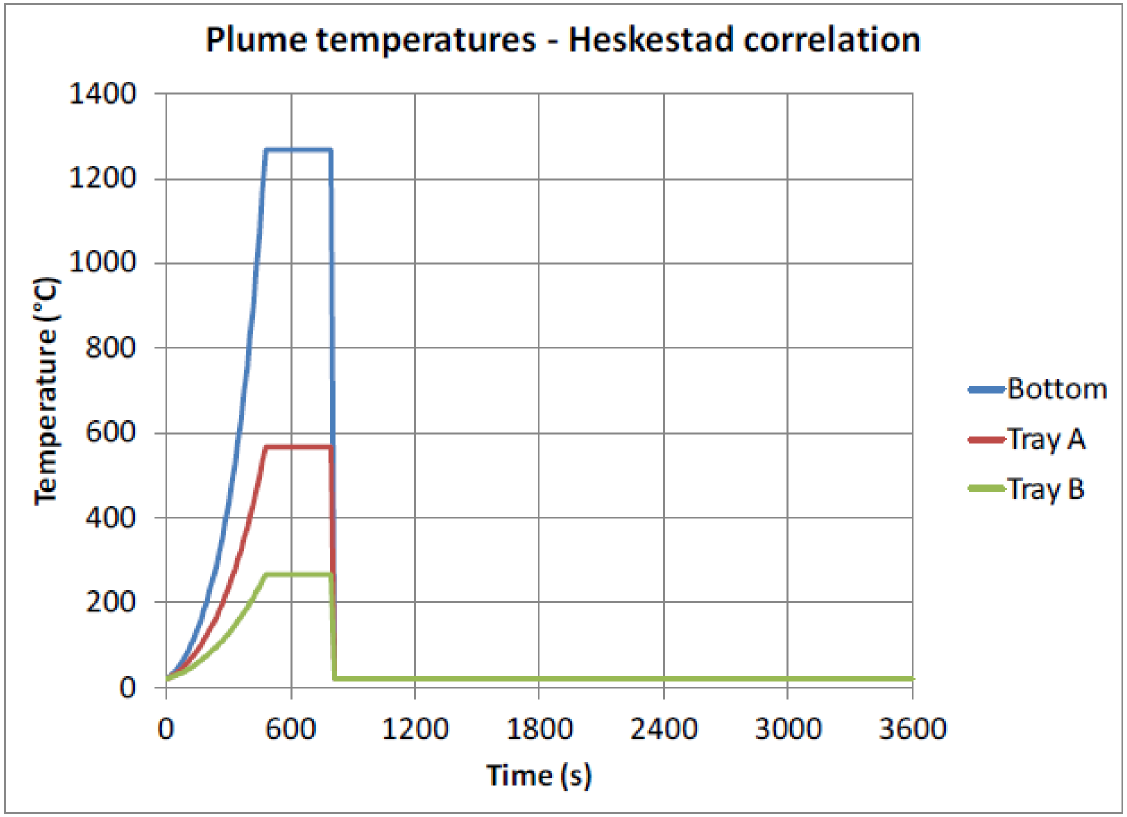


Figure E-5. Plume temperatures at cable trays located above transient trash fire.

Step 4. Calculate Fire-Generated Conditions

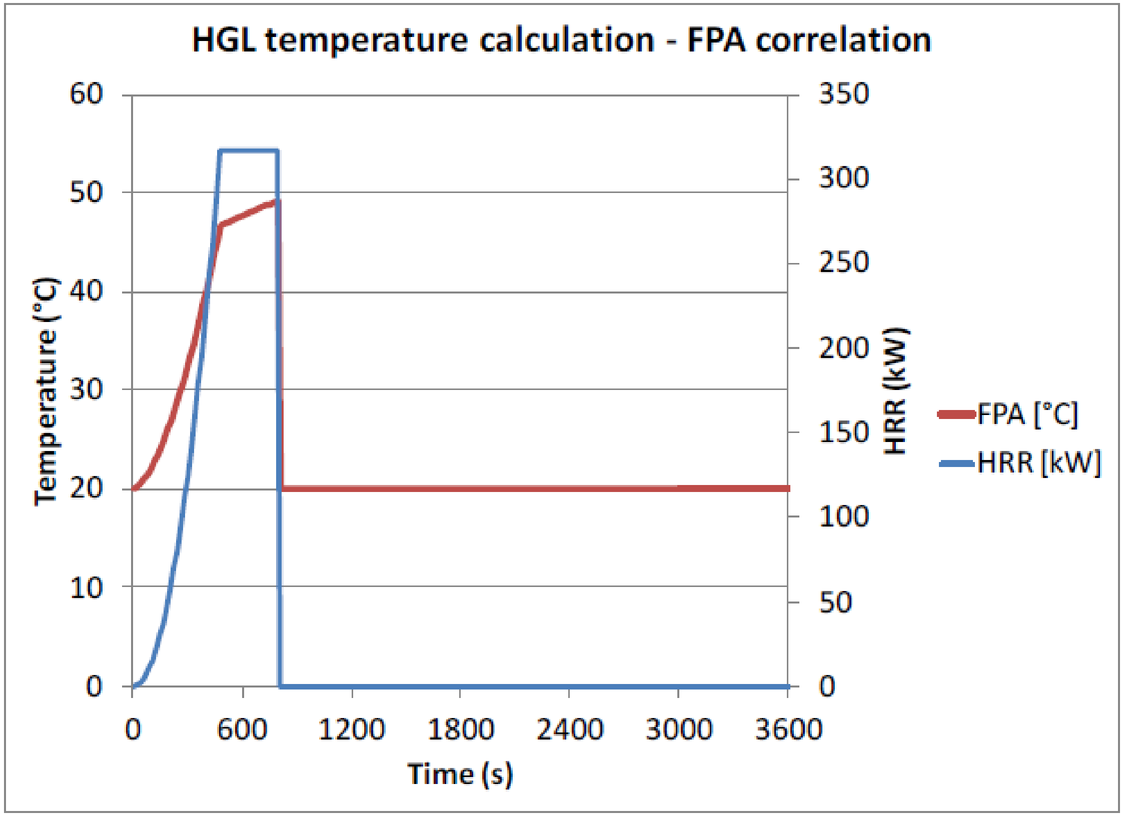


Figure E-6. Average HGL temperature from FPA correlation for CSR trash fire scenario.

Step 4. Calculate Fire-Generated Conditions

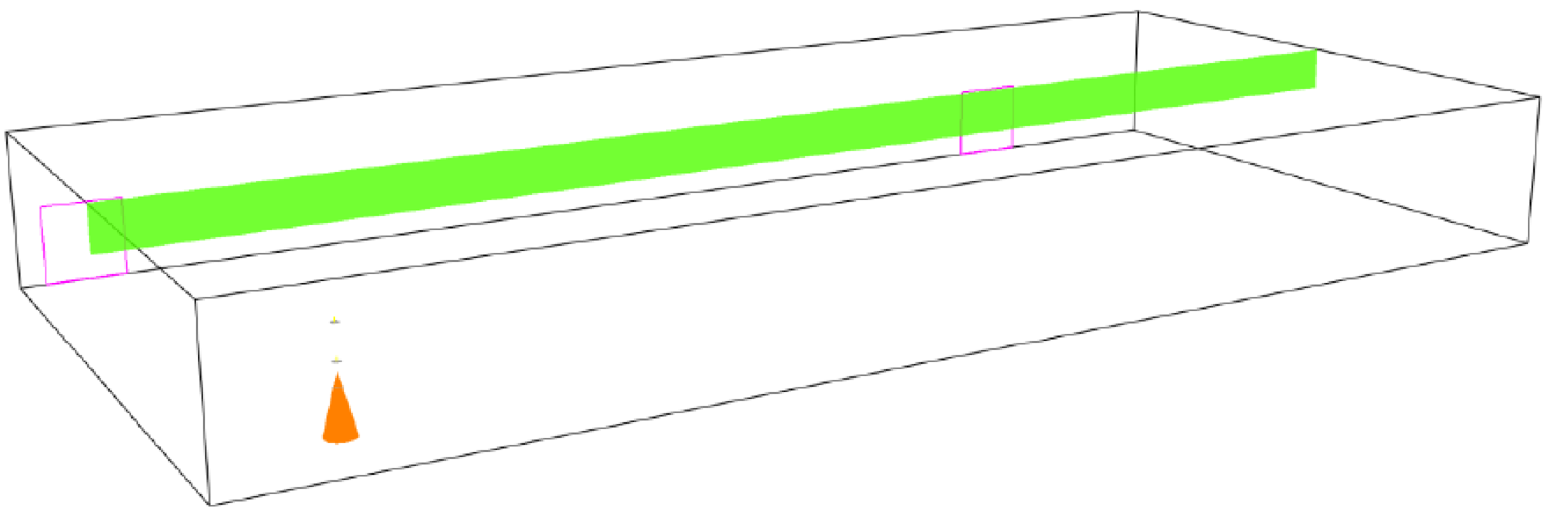
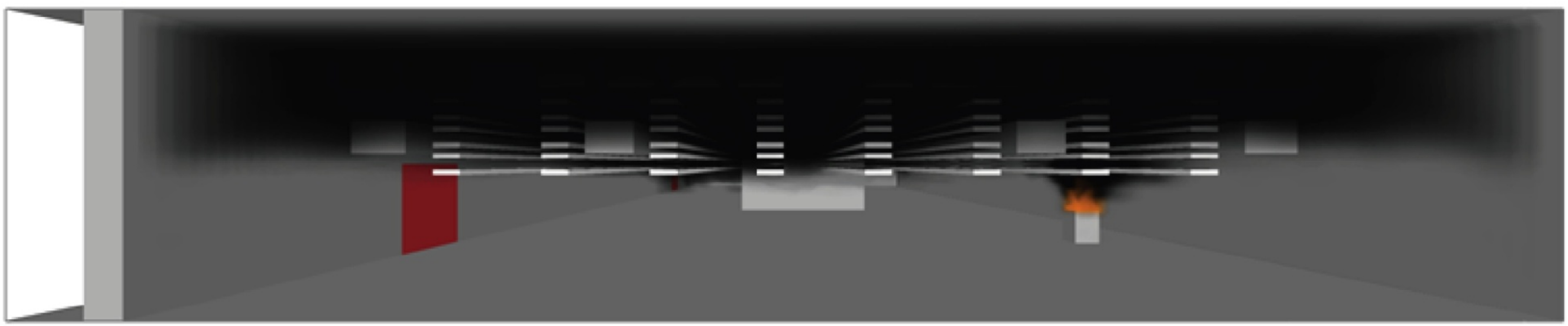


Figure E-7. CFAST rendering of the Cable Spreading Room scenario.

Step 4. Calculate Fire-Generated Conditions



FDS simulation, elevation view.

Step 4. Calculate Fire-Generated Conditions

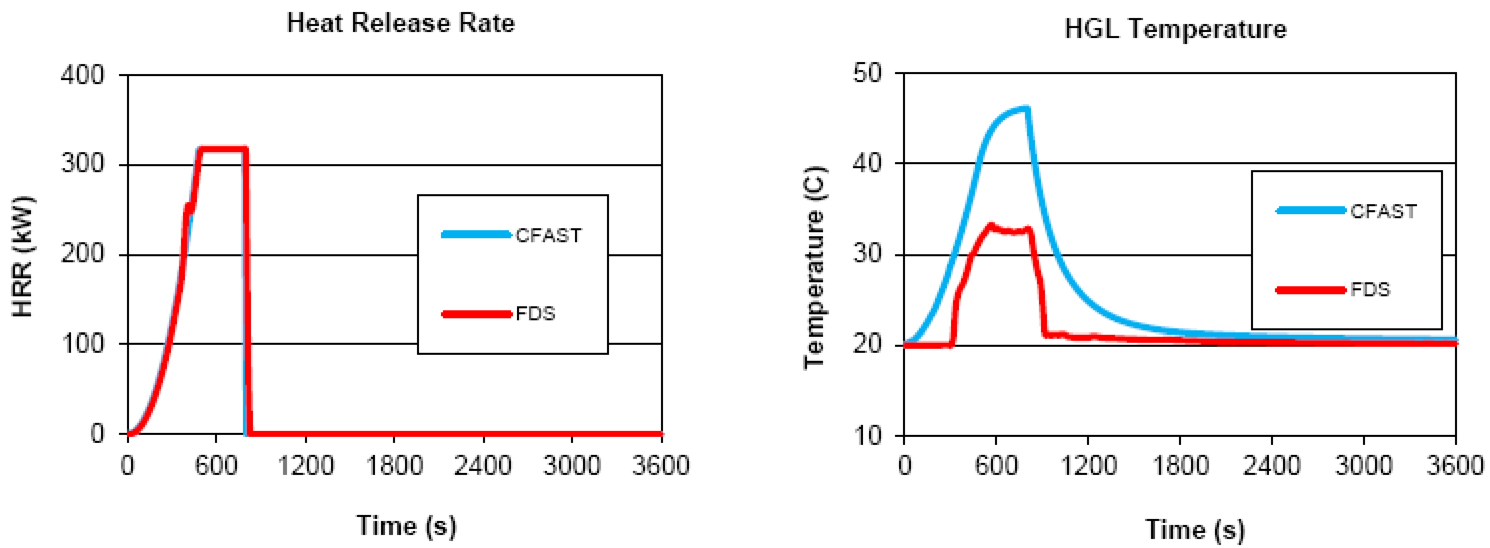


Figure E-14. Heat release rate and estimated HGL temperature for Cable Spreading Room scenario.

Step 4. Calculate Fire-Generated Conditions

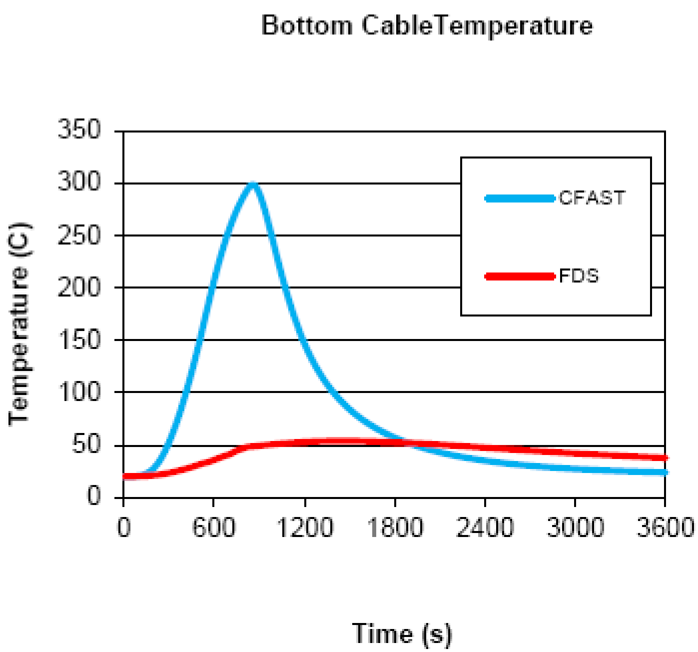
E.5.1 Smoke Detection

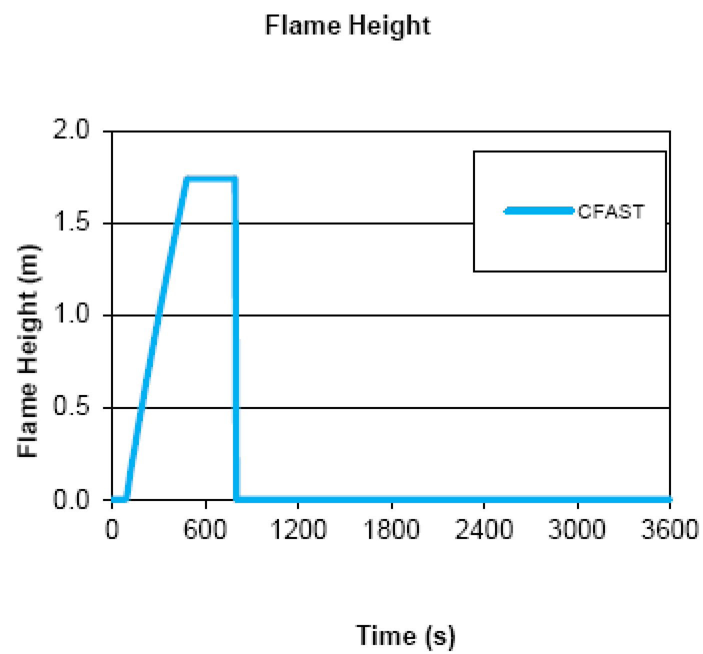
Table E-6 shows the results for smoke detection activation for the models. The models provide similar estimates of the detector activation time. CFAST models smoke detector actuation as a heat detector with a relatively low thermal inertia and activation temperature. However, there is no consensus in the fire literature for the appropriate RTI (Response Time Index) value and activation temperature. Given the presence of beam pockets and obstructions, even a CFD model like FDS, which uses actual smoke concentration rather than temperature in its detector algorithm, is subject to significant uncertainty.

Table E-6. Smoke detector activation times, Cable Spreading Room.

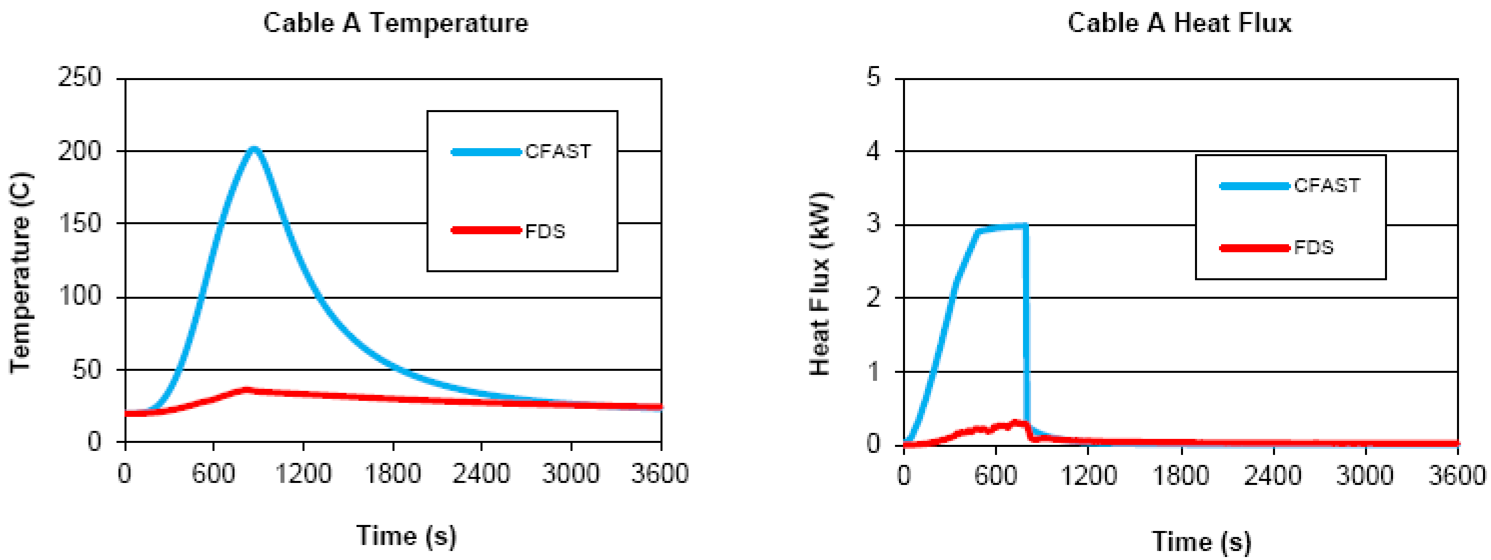
Model	Time (s)
CFAST	170 s
FDS	160 s

Step 4. Calculate Fire-Generated Conditions





Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions

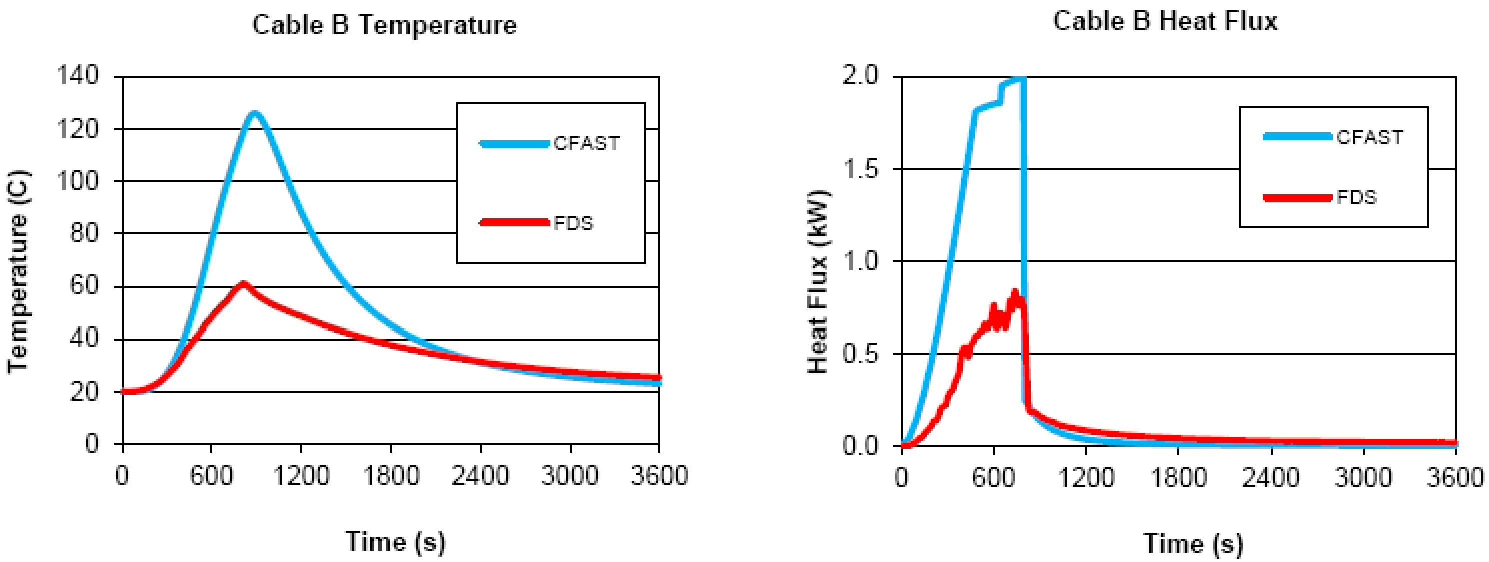


Figure E-15. Estimated cable conditions for the Cable Spreading Room.

Step 5. Sensitivity and Uncertainty Analysis

Table E-5. Summary of the model predictions of the CSR scenario.

Model	Bias Factor, δ	Standard Deviation, σ_M	Location	Predicted Value	Critical Value	Probability of Exceeding
Temperature (°C), Initial Value = 20 °C						
CFAST	1	0.27	Bottom Cable	298	205	0.893
FDS	1.02	0.13		54	205	0.000
CFAST	1	0.27	Cable A	202	205	0.472
FDS	1.02	0.13		36	205	0.000
CFAST	1	0.27	Cable B	126	205	0.003
FDS	1.02	0.13		61	205	0.000
Heat Flux (kW/m^2)						
CFAST	0.81	0.47	Bottom Cable	4.2	6	0.367
FDS						
CFAST	0.81	0.47	Cable A	3.0	6	0.091
FDS	0.85	0.22		0.3	6	0.000
CFAST	0.81	0.47	Cable B	2.0	6	0.000
FDS	0.85	0.22		0.8	6	0.001

Alternative Analysis – Parameter Propagation

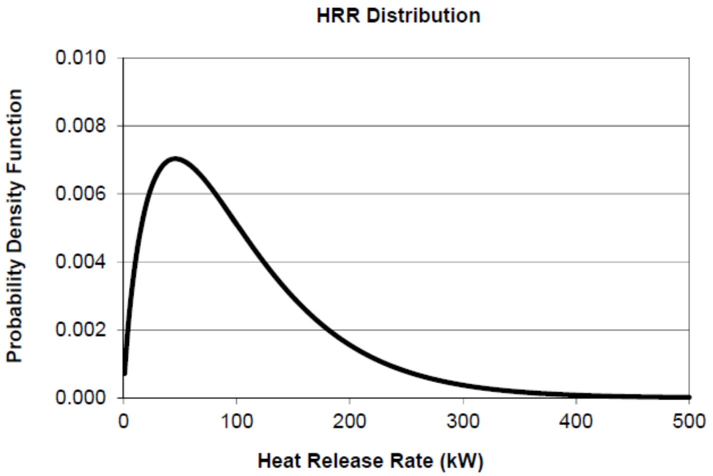


Figure E-16. Distribution of HRR for a trash fire.

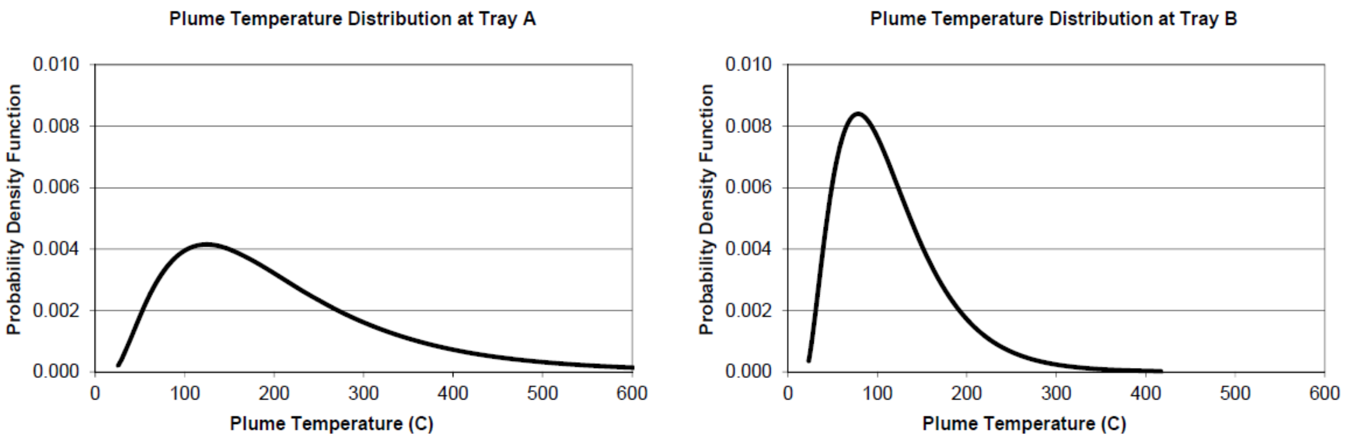


Figure E-17. Distribution of plume temperatures at Trays 3 and 6, respectively.

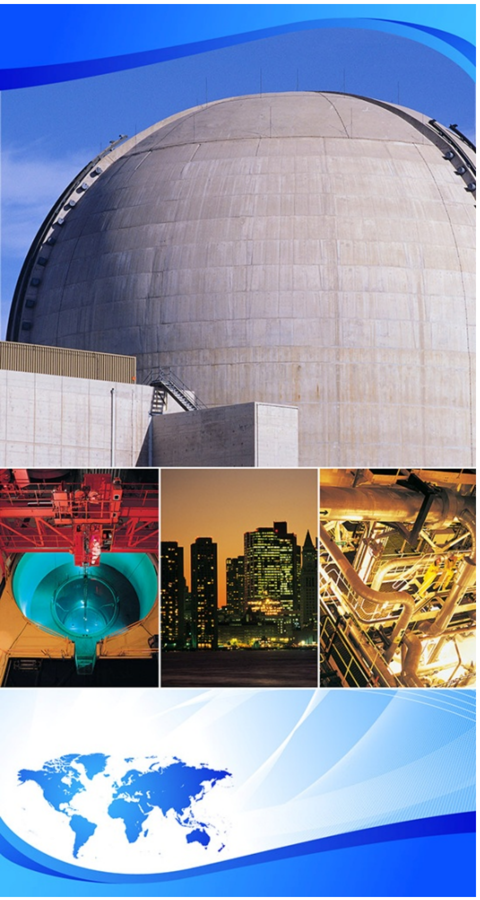
Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

Step 6. Document the Analysis

E.6 Conclusion

The analysis shows that a 317 kW waste bin fire beneath a vertical array of cable trays is unlikely to damage cables in the trays three and six levels above the fire. Both CFAST and FDS estimate peak temperatures and heat fluxes below the failure criteria for cables in the third tray from the bottom. From FDS calculations, temperatures and heat fluxes on the protected lowest cable tray are well below critical values. Estimates from CFAST for unprotected cables demonstrate the importance of the protection afforded by the solid metal lower surface of the cable trays.



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5

Advanced Fire Modeling

Day 4 - AM Session

Example F: Lube Oil Fire in Turbine Building

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

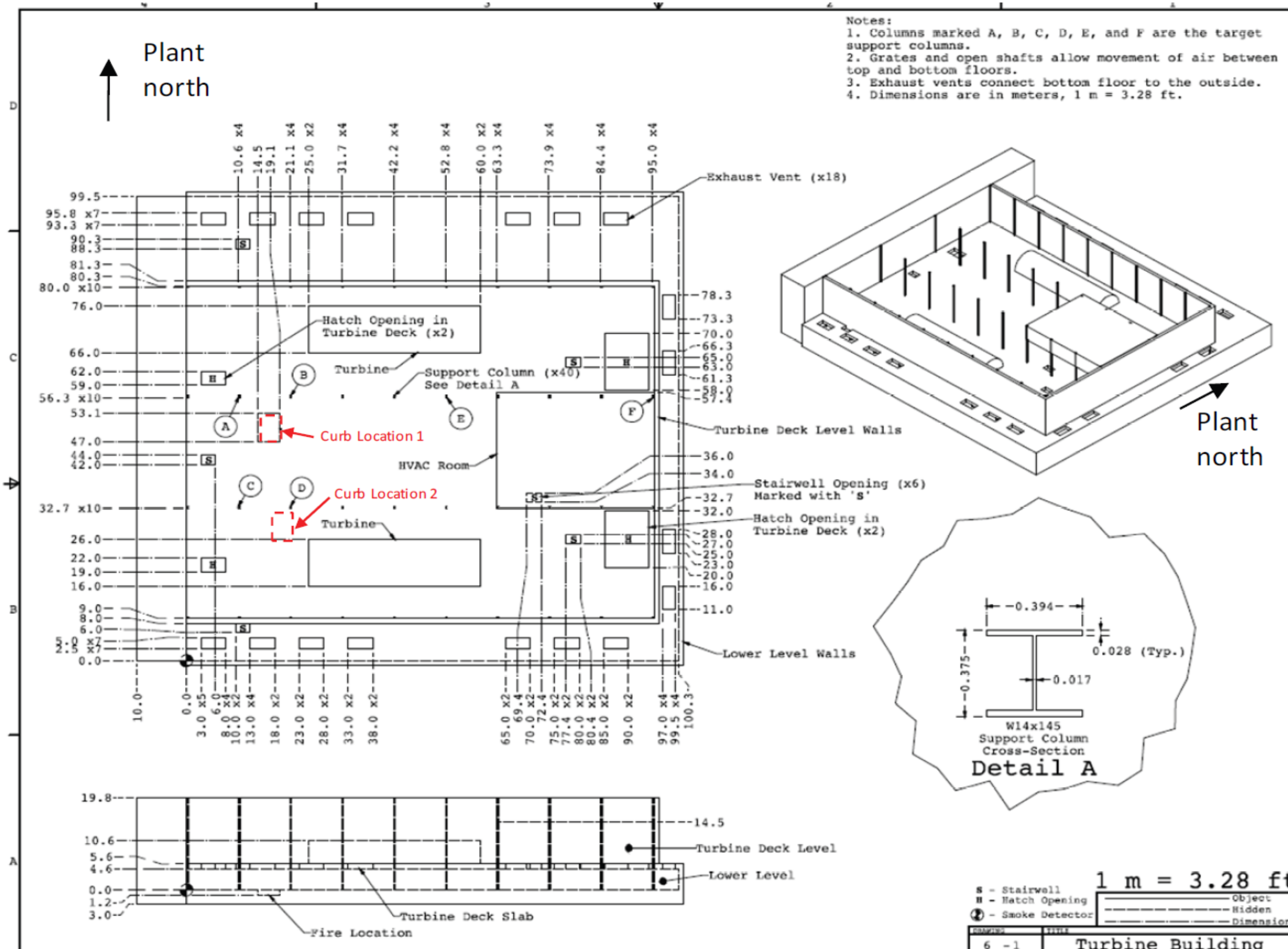
A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Step 1. Define Fire Modeling Goals

- Determine the heat flux to and temperature of structural steel columns in a turbine hall due to a lube oil fire.
- Evaluate structural steel response for two potential curb locations.
- This type of analysis may arise when addressing ASME/ANS RA-Sa-2009 supporting requirement FSS-F1

Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire



Notes:
1. Columns marked A, B, C, D, E, and F are the target support columns.
2. Grates and open shafts allow movement of air between top and bottom floors.
3. Exhaust vents connect bottom floor to the outside.
4. Dimensions are in meters, 1 m = 3.28 ft.
Plant north
Exhaust Vent (x18)
Hatch Opening in Turbine Deck (x2)
Turbine
Support Column (x40) See Detail A
Curb Location 1
Curb Location 2
HVAC Room
Turbine Deck Level Walls
Stairwell Opening (x6) Marked with 'S'
Lower Level Walls
W14x145 Support Column Cross-Section
Detail A
Turbine Deck Level
Lower Level
Turbine Deck Slab
Fire Location
S - Stairwell
H - Hatch Opening
Smoke Detector
Object
Hidden
Dimension
1 m = 3.28 ft
6 -1
Turbine Building

Figure F-2. Structural Steel Column in the Turbine Building.

Figure F-3. Main Turbine Lubricating Oil Tanks in the Turbine Building.

Material Properties

Table 3-1. Material Properties

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Source
Brick	0.8	2600	0.8	NUREG-1805, Table 2-3
Concrete	1.6	2400	0.75	NUREG-1805, Table 2-3
Copper	386	8954	0.38	SFPE Handbook, Table B.6
Gypsum	0.17	960	1.1	NUREG-1805, Table 2-3
Plywood	0.12	540	2.5	NUREG-1805, Table 2-3
PVC	0.192	1380	1.289	NUREG/CR-6850, Appendix R
Steel	54	7850	0.465	NUREG-1805, Table 2-3
XLP	0.235	1375	1.390	NUREG/CR-6850, Appendix R

Table F-2. Structural Steel Failure Criteria (ASTM E119-10a)

Member	Maximum Cross-Section Temperature (°C)	Maximum Cross-Section Average Temperature (°C)
Beam	704	593
Column	649	538

Ventilation

- Large, open area
- Forced ventilation intentionally shut down at start of fire
- 18 exhaust vents to the outside around the perimeter

Fire

Table F-2. Data for lube oil fire.

Parameter	Value	Source
Effective Fuel Formula	C_nH_{2n+2}	Assumption (n in range of 12-15)
Mass burning rate	0.039 kg/s.m^2	NUREG-1805 Table 3-4
Density	760 kg/m^3	NUREG-1805 Table 3-4
Heat of Combustion	46,000 kJ/kg	NUREG-1805 Table 3-4
CO_2 Yield	2.64 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16*
Soot Yield	0.059 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16*
CO Yield	0.019 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16*
Radiative Fraction	0.33	*SFPE Handbook,* 4th ed., Table 3-4.16*
Mass Extinction Coefficient	8700 m^2/kg	Mulholland and Croarkin (2000)

*Material identified as "Hydrocarbon" in SFPE Handbook used to derive properties.

The peak heat release rate, $\dot{Q}$, is computed from the fuel mass burning rate, $\dot{m}''$, the heat of combustion, ΔH, and the specified area of the spill, A:

$$\dot{Q} = \dot{m}'' \, \Delta H \, A = 0.039 \, \mathrm{kg/m^2/s} \times 46{,}000 \, \mathrm{kJ/kg} \times 28.1 \, \mathrm{m^2} \cong 50{,}400 \, \mathrm{kW} \qquad \text{(F-1)}$$

The fire duration, Δt, is determined from the pool depth, δ, density, ρ, and burning rate, $\dot{m}''$:

$$\Delta t = \frac{\delta \, \rho}{\dot{m}''} = \frac{0.11 \, \mathrm{m} \times 760 \, \mathrm{kg/m^3}}{0.039 \, \mathrm{kg/m^2/s}} \cong 2144 \, \mathrm{s} \quad (35.7 \, \mathrm{min}) \qquad \text{(F-2)}$$

Step 3. Select Fire Models

- Algebraic Models: Fire resistance calculations typically use a pre-defined time-temperature curve, like ASTM E 119, but such an exposure history is not appropriate here. However, heat flux calculations are valid and are used to evaluate structural steel response.
- Zone Models: Challenging case – too many assumptions violated, in particular the ratio of flame height to ceiling height. Zone models not used.
- CFD: Near-field or engulfing fire heat flux is a challenge for any model, but FDS used for comparison with algebraic models.

Applicability of Validation

Table F-3. Normalized Parameter Calculations for the Turbine Building Fire Scenario.

Quantity	Normalized Parameter Calculation						Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{50{,}400 \text{ kW}}{(1.1 \text{ kg/m}^3)(1.0 \text{ kJ/kg/K})(309 \text{ K})(6.0^{2.5} \text{ m}^{2.5})\sqrt{9.8 \text{ m/s}^2}} \cong 0.52$						0.4 – 2.4	Yes
Flame length to ceiling height ratio	$\frac{L_f}{H} = \frac{11.0 \text{ m}}{4.6 \text{ m}} \cong 2.4$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 6.0 \text{ m}\,(3.7 \times 0.52^{0.4} - 1.02) \cong 11.0 \text{ m}$						0.2 – 1.0	No
Ceiling jet radius relative to the ceiling height	N/A						1.2 – 1.7	N/A
Equivalence ratio based on opening area	See Section F.3.3 for discussion of this parameter.						0.04 – 0.6	Yes
Compartment aspect ratios	$\frac{L}{H} = \frac{100.3 \text{ m}}{4.6 \text{ m}} \cong 21.8$; $\frac{W}{H} = \frac{99.5 \text{ m}}{4.6 \text{ m}} \cong 21.6$						0.6 – 5.7	No
Target distance to fire diameter (Columns A,B,C,D,E,F)	$\frac{8.5 \text{ m}}{6.0 \text{ m}} \cong 1.4$	$\frac{7.2 \text{ m}}{6.0 \text{ m}} \cong 1.2$	$\frac{18.8 \text{ m}}{6.0 \text{ m}} \cong 3.1$	$\frac{18.3 \text{ m}}{6.0 \text{ m}} \cong 3.1$	$\frac{36.5 \text{ m}}{6.0 \text{ m}} \cong 6.1$	$\frac{78. \text{ m}}{6.0 \text{ m}} \cong 13.1$	2.2 – 5.7	Yes/No
	$\frac{28.0 \text{ m}}{6.0 \text{ m}} \cong 4.7$	$\frac{26.9 \text{ m}}{6.0 \text{ m}} \cong 4.5$	$\frac{8.8 \text{ m}}{6.0 \text{ m}} \cong 1.5$	$\frac{3.9 \text{ m}}{6.0 \text{ m}} \cong 0.7$	$\frac{43.3 \text{ m}}{6.0 \text{ m}} \cong 7.2$	$\frac{80. \text{ m}}{6.0 \text{ m}} \cong 13.5$		

Notes: (1) The effective area of the fire is determined from the formula, $D = \sqrt{4A/\pi}$, where A is the area of the dike.

To estimate the quantity of oxygen available in the turbine hall, the volume of the turbine hall is calculated to be 209,577 m^3 based on the overall dimensions of 100.3 m by 99.5 m by 21.0 m. The volume occupied by solid obstructions is ignored for this calculation. The total mass of oxygen within the turbine building is then calculated as:

$$m_{O_2,\mathrm{tot}} = \rho V Y_{O_2} = 1.1\ \mathrm{kg/m^3} \times 209{,}577\ \mathrm{m^3} \times 0.23 \cong 53{,}023\ \mathrm{kg} \qquad \text{(F-3)}$$

The quantity of oxygen consumed by the specified lube oil fire is calculated as:

$$m_{O_2,\mathrm{req}} = \frac{\dot{Q}\,\Delta t}{\Delta H_{O_2}} = \frac{50{,}400\ \mathrm{kW} \times 2{,}144\ \mathrm{s}}{13{,}100\ \mathrm{kJ/kg}} = 8{,}249\ \mathrm{kg} \qquad \text{(F-4)}$$

Thus, the specified fire would consume less than 16 % of the oxygen available within the turbine building. Consequently, the fire would not be expected to be ventilation limited, on a global basis, even without ventilation with the outside environment through the roof vents.

Step 4. Calculate Fire-Generated Conditions

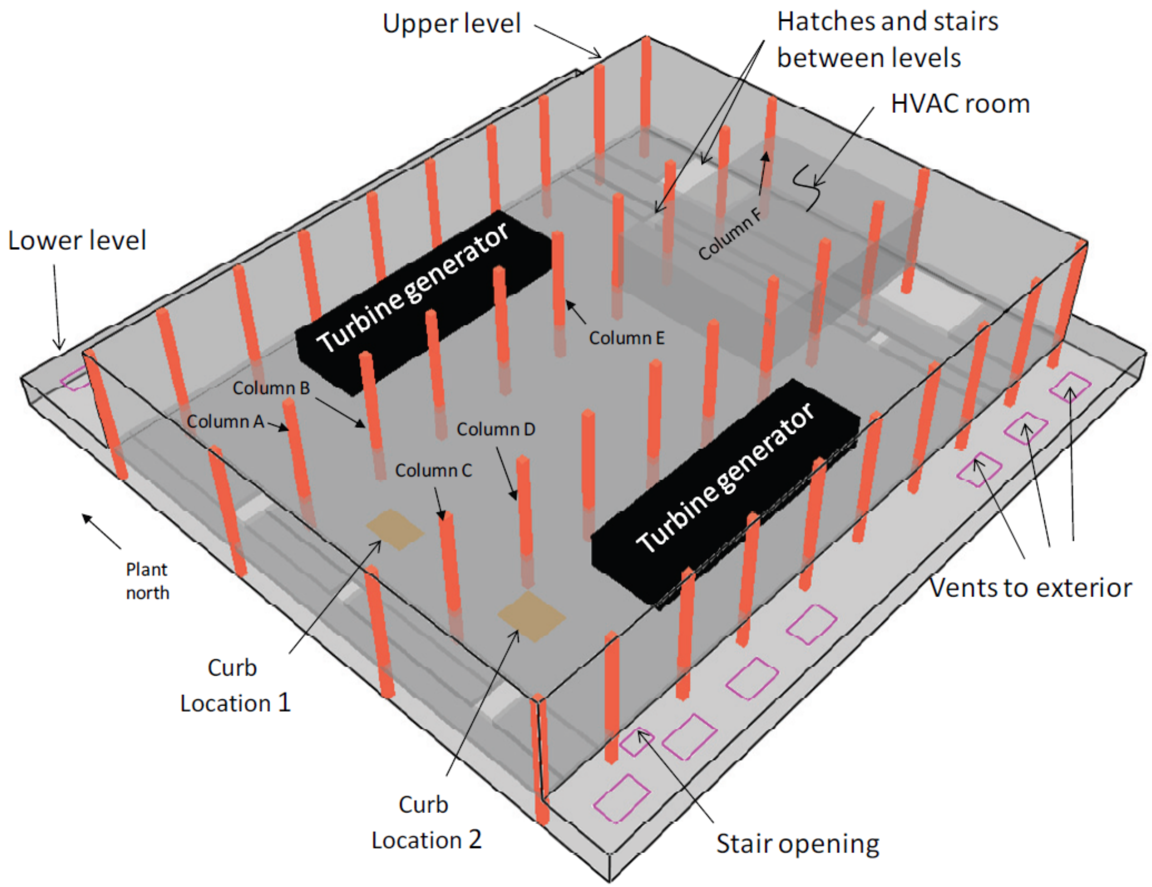


Figure F-5. FDS Geometry for the Turbine Building Fire Scenario.

Flame extension beneath turbine deck

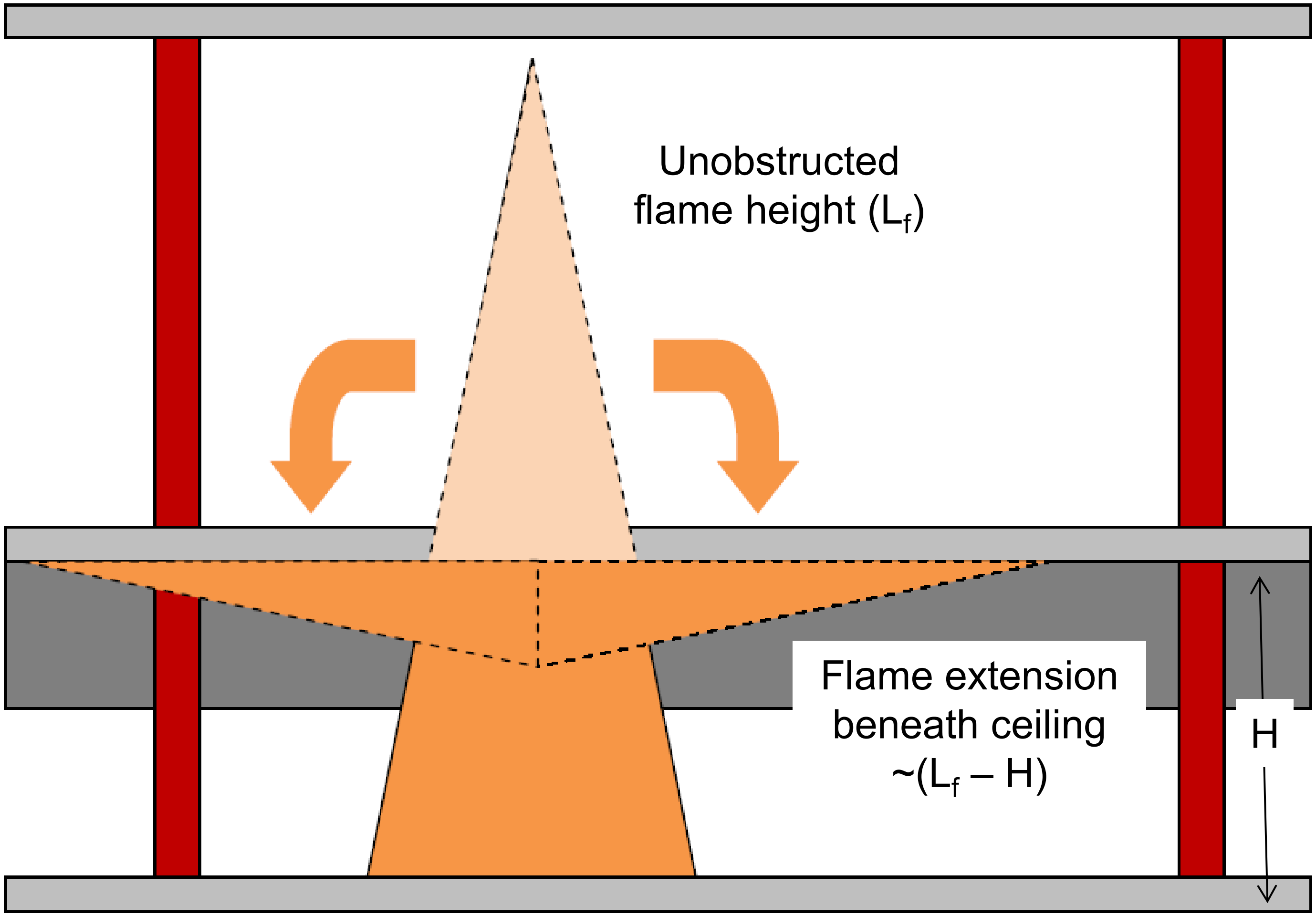


Figure F-4. Schematic diagram of the fire impinging on the ceiling.

Flame extension beneath turbine deck

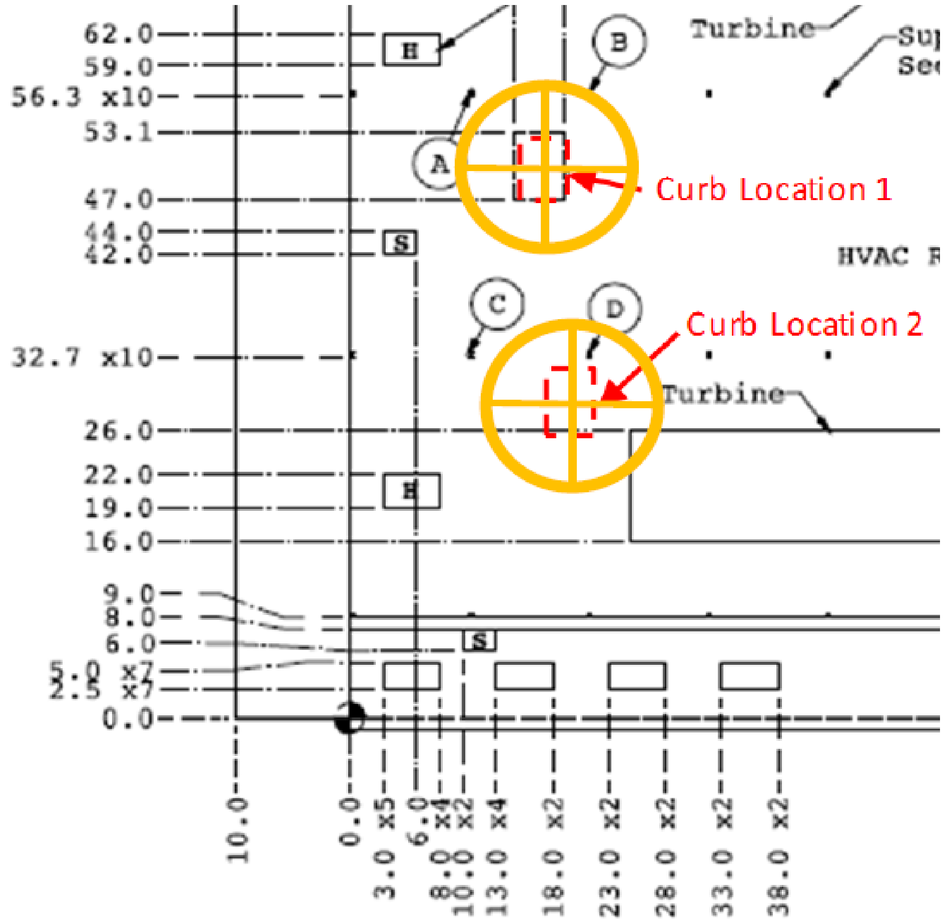


Figure F-5. Detail from Figure F-1 with estimated flame extension beneath ceiling superimposed.

Column heating – hand calculation

In order to estimate an approximate time for a column to reach the specified failure temperature of 538 °C when subjected to different radiant heat fluxes, a simple energy balance is used to calculate the rate of temperature rise of the steel in response to this imposed heat flux:

$$\rho_s c_s V_s \frac{dT_s}{dt} = \dot{q}_r'' \, A_s \qquad \text{(F-6)}$$

The subscript s refers to steel. For a constant heat flux, this differential equation can be readily integrated to yield the steel temperature as a function of time:

$$T_s - T_0 = \frac{\dot{q}_r'' \, t}{\rho_s c_s (V_s/A_s)} \qquad \text{(F-7)}$$

To calculate the time, t_{crit} , when the steel failure temperature is reached, this equation is rearranged, with the critical steel temperature, T_{crit}, inserted for the steel temperature.

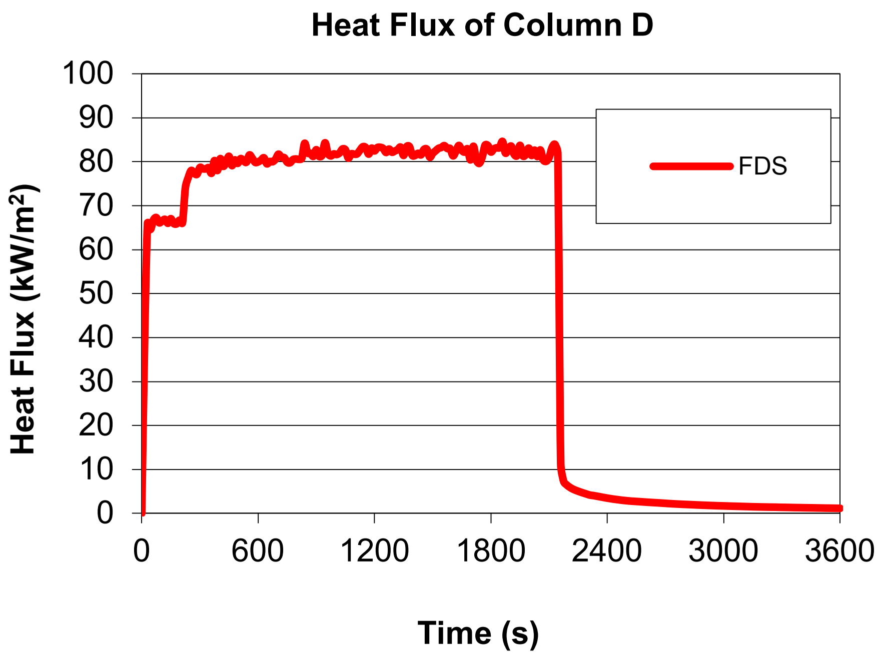
$$t_{\mathrm{crit}} = \frac{\rho_s c_s (V_s/A_s)(T_{\mathrm{crit}} - T_0)}{\dot{q}_r''} = \frac{c_s (W/D)(T_{\mathrm{crit}} - T_0)}{\dot{q}_r''} \qquad \text{(F-8)}$$

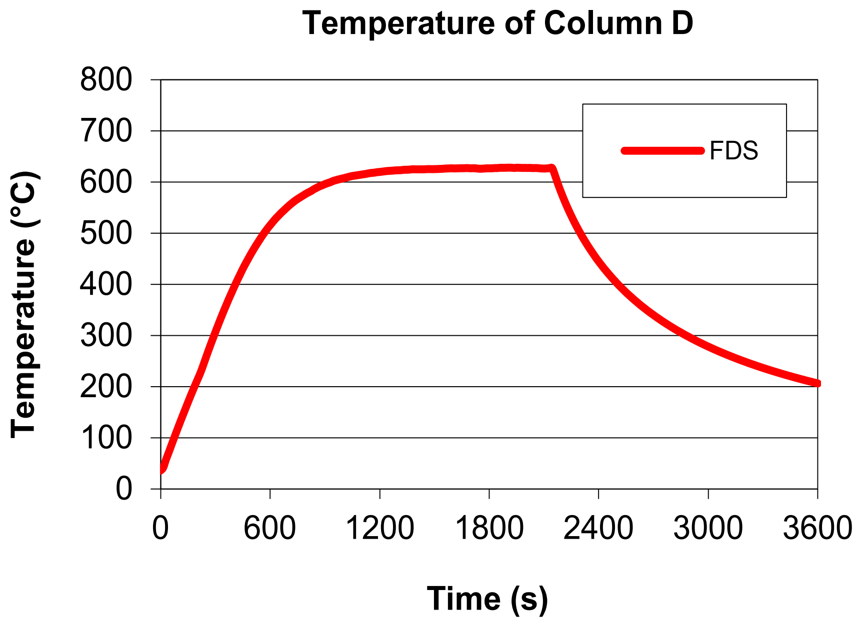
The term V_s/A_s is sometimes called the section factor and is the effective thickness of the steel member; it is calculated as the cross-sectional area of a steel member divided by the heated perimeter of the member. In the US, it is more common to use a parameter referred to as the W/D ratio, which is simply the section factor multiplied by the steel density. For a W14x145 steel column, the W/D ratio has a value of approximately 96.2 kg/m^2 (1.64 lb/ft/in). With this value used for the W/D ratio, the time to reach the critical steel temperature for the column can be estimated, based on the radiant heat flux estimated in equation F-5, as:

$$t_{\mathrm{crit}} = \frac{(0.465 \text{ kJ/kg/°C})(96.2 \text{ kg/m}^2)(538 \text{ °C} - 36 \text{ °C})}{75.0 \text{ kW/m}^2} \cong 300 \text{ s} \qquad \text{(F-9)}$$

Column heating – FDS calculation

FDS Results, Curb Location 2





Step 5. Sensitivity and Uncertainty Analysis

Table F-4. Summary of results for the Turbine Building fire scenarios.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Target	Predicted Value	Critical Value	Probability of Exceeding
Surface Temperature (°C), Initial Value = 36 °C						
Curb Location 1						
FDS	1.02	0.13	Column A	270	538	0.000
FDS	1.02	0.13	Column B	260	538	0.000
FDS	1.02	0.13	Column C	170	538	0.000
FDS	1.02	0.13	Column D	150	538	0.000
FDS	1.02	0.13	Column E	90	538	0.000
FDS	1.02	0.13	Column F	50	538	0.000
Curb Location 2						
FDS	1.02	0.13	Column A	130	538	0.000
FDS	1.02	0.13	Column B	120	538	0.000
FDS	1.02	0.13	Column C	400	538	0.001
FDS	1.02	0.13	Column D	620	538	0.828
FDS	1.02	0.13	Column E	75	538	0.000
FDS	1.02	0.13	Column F	50	538	0.000

Step 6. Document the Analysis

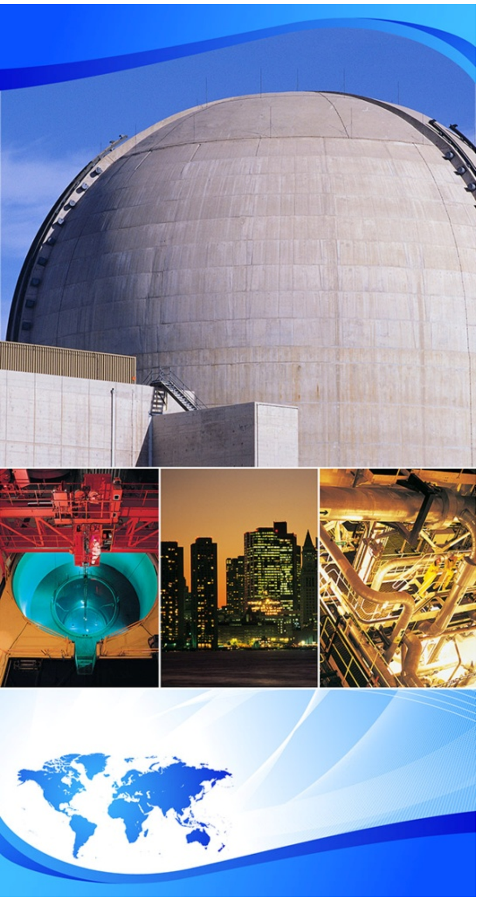
- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

Step 6. Document the Analysis

F.6 Conclusion

Based on the FDS simulation of this scenario, a 50 MW lube oil fire in Curb Location 1, which is the curbed area located between Columns A, B, C, and D, is not predicted to cause the structural steel to exceed a temperature of 538 °C (1,000 °F). This is not the case for the proposed Curb Location 2, which is located closer to Column D and is predicted to cause the structural steel to exceed a temperature of 538 °C (1,000 °F). Consequently, the recommendation for the design package is to install the curbed area at Curb Location 1.

Overall, given the large volume of lubricant involved, it is significant that structural failure is not predicted by the CFD fire model for Curb Location 1. Although it may seem counterintuitive, this is a direct result of the relatively small area in which the lubricant is confined. The curbing restricts the surface area of the lubricant spill, and, correspondingly, the heat release rate of the fire.



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5

Advanced Fire Modeling
Day 4 - PM Session
Example G: Transient Fire in a Corridor

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

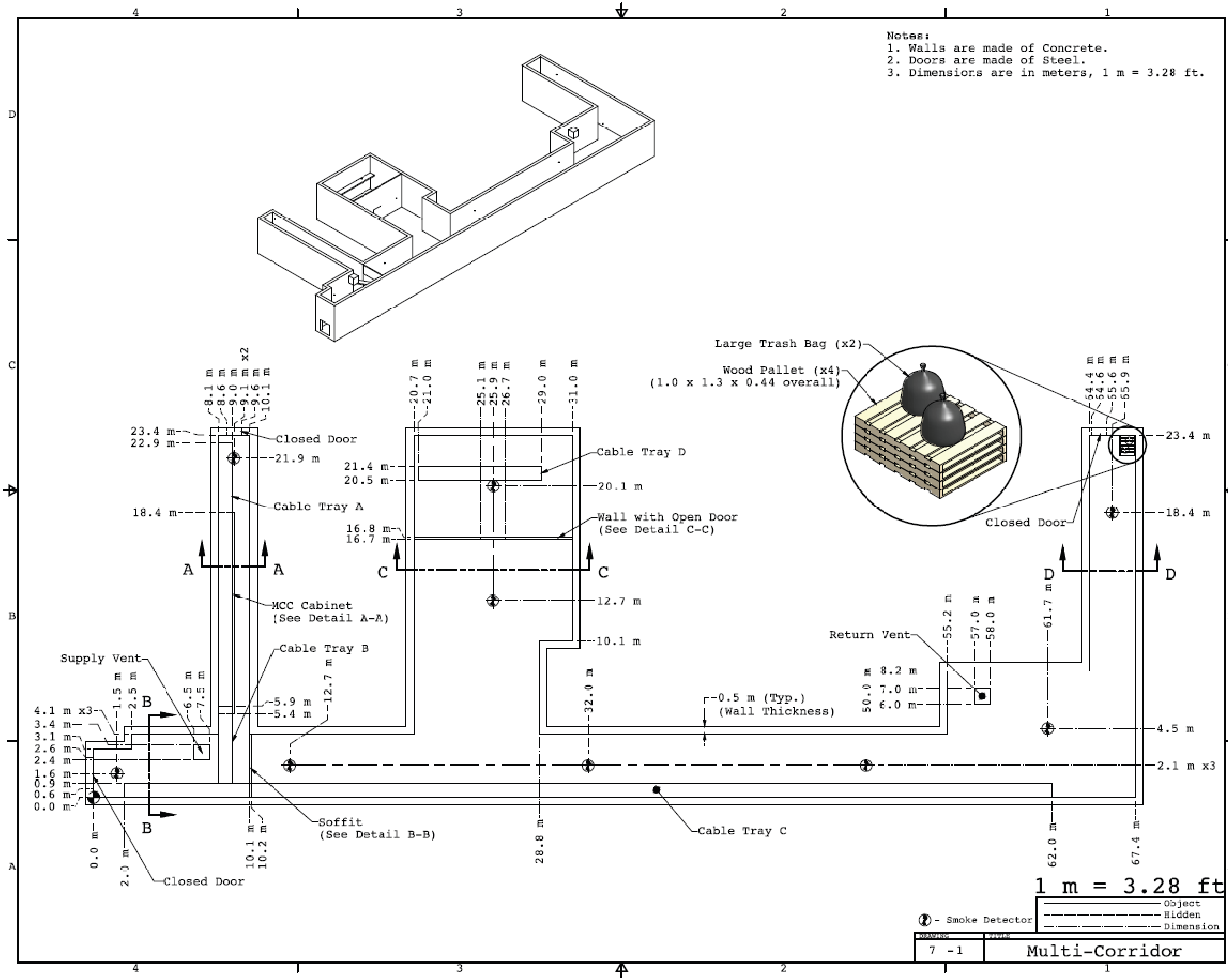
A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

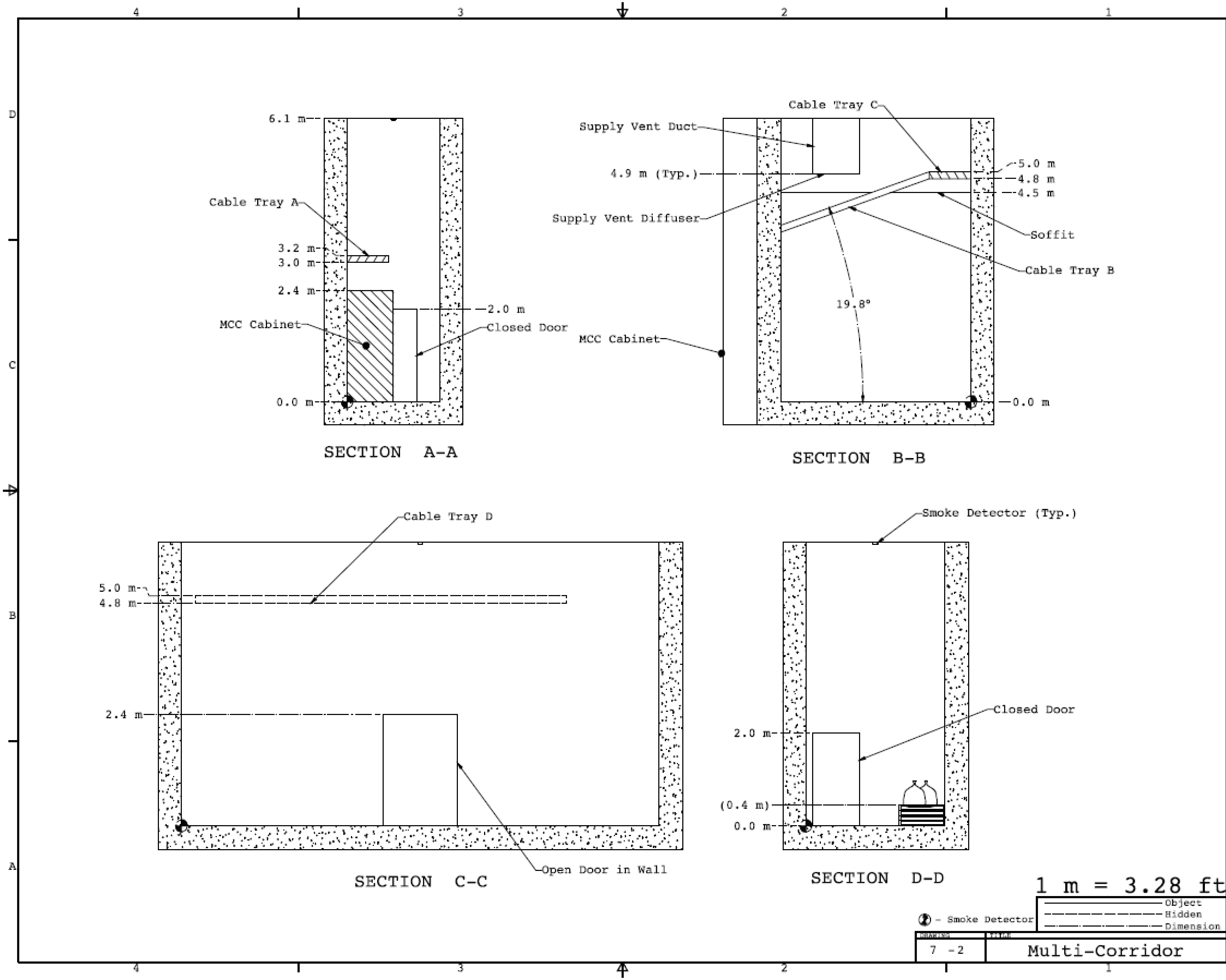
Step 1. Define Fire Modeling Goals

- Determine if important safe-shutdown equipment will fail due to a fire involving a stack of pallets in a hallway
- Also determine time to smoke detector activation

Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire


Notes:
1. Walls are made of Concrete.
2. Doors are made of Steel.
3. Dimensions are in meters, 1 m = 3.28 ft.
Large Trash Bag (x2)
Wood Pallet (x4)
(1.0 x 1.3 x 0.44 overall)
Closed Door
Cable Tray A
Cable Tray B
Cable Tray C
Cable Tray D
MCC Cabinet
(See Detail A-A)
Wall with Open Door
(See Detail C-C)
Supply Vent
Return Vent
Soffit
(See Detail B-B)
-0.5 m (Typ.)
(Wall Thickness)
Closed Door
Closed Door
1 m = 3.28 ft
- Smoke Detector
Object
Hidden
Dimension
7 -1
Multi-Corridor



6.1 m
Cable Tray A
3.2 m
3.0 m
2.4 m
2.0 m
MCC Cabinet
Closed Door
0.0 m
SECTION A-A
Cable Tray C
Supply Vent Duct
4.9 m (Typ.)
5.0 m
4.8 m
4.5 m
Supply Vent Diffuser
Soffit
Cable Tray B
19.8°
MCC Cabinet
0.0 m
SECTION B-B
Cable Tray D
5.0 m
4.8 m
2.4 m
Open Door in Wall
SECTION C-C
Smoke Detector (Typ.)
Closed Door
2.0 m
(0.4 m)
0.0 m
SECTION D-D
1 m = 3.28 ft
Object
Hidden
Dimension
- Smoke Detector
7 -2
Multi-Corridor

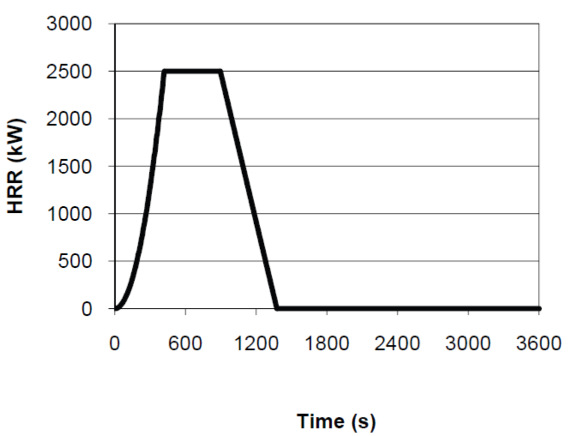
Ventilation and Detection

- 1.67 m^3/s air flow
- All doors closed
- 9 smoke detectors with a sensitivity of 4.9 %/m
- No suppression system

Fire

Table G-1. Products of combustion for a wood pallet fire.

Parameter	Value	Source
Effective Fuel Formula	$C_6H_{10}O_5$	Assumption, Cellulose
Peak HRR	2500 kW	*SFPE Handbook*, 4th Ed., Figs. 3-1.65, 3-1.100
Time to reach peak HRR	420 s	*SFPE Handbook*, 4th Ed., Figs. 3-1.64
Heat of Combustion	17,100 kJ/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
Heat of Combustion per unit mass of oxygen consumed	13.2 kJ/g	*SFPE Handbook*, 4th Ed., Table 3-4.15
CO_2 Yield	1.27 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
Soot Yield	0.015 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
CO Yield	0.004 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
Radiative Fraction	0.37	*SFPE Handbook*, 4th Ed., Table 3-4.16



Step 3. Select Fire Models

- Algebraic Models: Not designed for multiple compartment scenarios, but can be used to assess room of origin or in this case, the corridor containing the pallets
- Zone Models: Scenario consistent with physical assumptions
- CFD: No need in this case. All questions answered satisfactorily with simpler models.

Applicability of Validation

Table G-2. Normalized parameter calculations for the Multi-Compartment Corridor fire scenario.

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{2500\text{ kW}}{(1.2\text{ kg/m}^3)(1.0\text{ kJ/kg/K})(293\text{ K})(1.3^{2.5}\text{ m}^{2.5})\sqrt{9.8\text{ m/s}^2}} = 1.2$	0.4 – 2.4	Yes
Flame Length, L_f, relative to the Ceiling Height, H	$\frac{H_f + L_f}{H} = \frac{0.44\text{ m} + 3.8\text{ m}}{6.1\text{ m}} = 0.7$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 1.3\text{ m}\,(3.7 \times 1.2^{0.4} - 1.02) = 3.8\text{ m}$	0.2 – 1.0	Yes
Ceiling Jet Horizontal Radial Distance, r_{cj}, relative to the Ceiling Height, H	$\frac{r_{cj}}{H - H_f} = \frac{4.46\text{ m}}{6.1\text{ m} - 0.44\text{ m}} = 0.8$	1.2 – 1.7	No
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\dot{m}_{O_2}} = \frac{2500\text{ kW}}{13{,}100\text{ kJ/kg} \times 0.46\text{ kg/s}} = 0.4$ $\dot{m}_{O_2} = 0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2\text{ kg/m}^3 \times 1.67\text{ m}^3\text{/s} \cong 0.46\text{ kg/s}$	0.04 – 0.6	Yes
Compartment Aspect Ratios	$\frac{L}{H} = \frac{15.2\text{ m}}{6.1\text{ m}} = 2.49\ ;\ \frac{W}{H} = \frac{3.0\text{ m}}{6.1\text{ m}} = 0.49$	0.6 – 5.7	No
Target Distance, r, relative to the Fire Diameter, D	N/A	2.2 – 5.7	N/A

Notes: (1) The effective diameter of the base of the fire, D, is calculated using $D = \sqrt{4A/\pi}$, where A is the area of the pallets.
(2) The "Fire Height", $H_f + L_f$,, is the sum of the height of the fire off the floor plus the fire's flame length.

Step 4. Calculate Fire-Generated Conditions

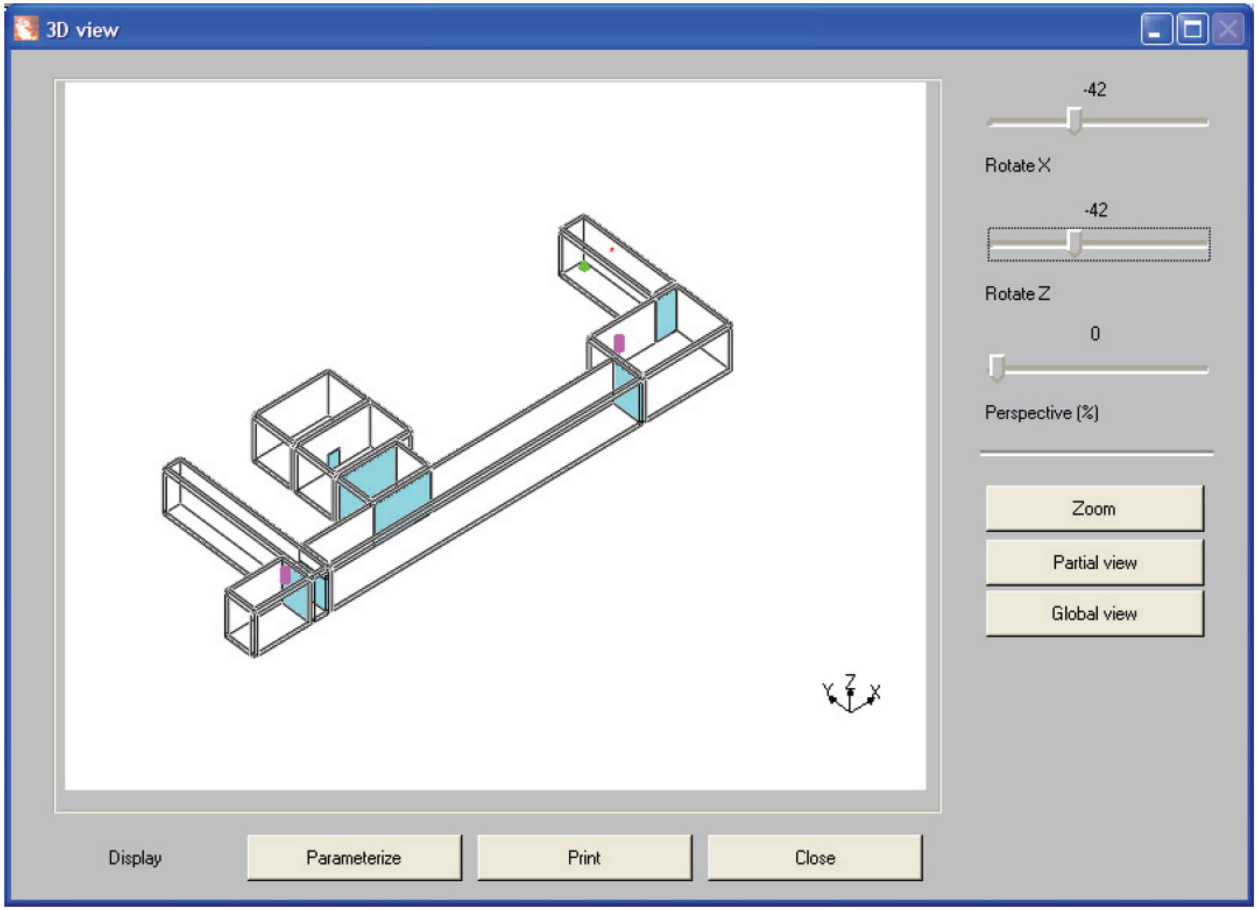


Figure G-4. MAGIC rendering of the Corridor scenario.

Step 4. Calculate Fire-Generated Conditions

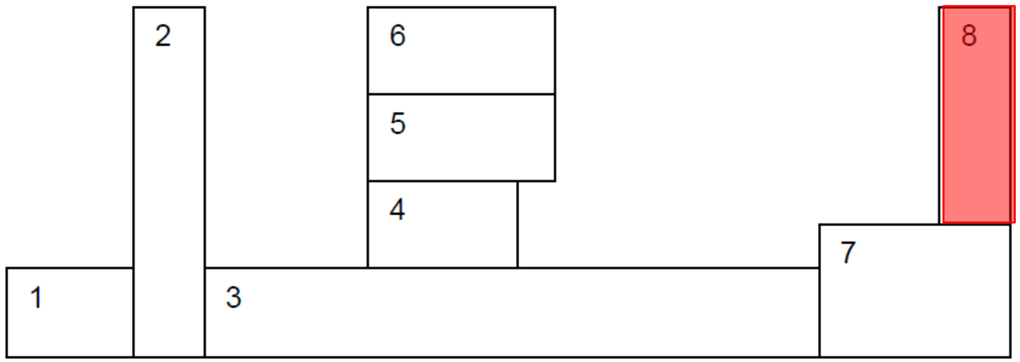


Figure G-3. Effective corridor layout for implementation in zone models (not to scale).

Table G-3. Compartment dimensions for Corridor scenario.

Comp.	Length (m)	Width (m)	Area (m^2)
1	8.1	4.1	33.2
2	2.0	23.4	46.8
3	45.1	4.1	184.9
4	8.1	6.0	48.6
5	10.3	6.6	68.0
6	10.3	6.6	68.0
7	12.2	8.2	100.0
8	3	15.2	45.6

Step 4. Calculate Fire-Generated Conditions

G.4.1 Algebraic Models

This scenario concerns the prediction of cable damage at a location outside the compartment of fire origin. The temperature of the hot gas layer in the compartment of fire origin can be modeled as a potential screening tool. If the HGL temperature within the compartment of origin is not likely to cause damage to cables in that compartment, damage to cables outside the fire compartment is even more unlikely. As part of this approach, it is conservatively assumed that the cable surface temperature will match the HGL temperature (i.e., heat-up of the cable is assumed to be immediate).

FIVE was used for the MQH room temperature analysis. The inputs to the model are found in Table 3-1, Table G-1, and Table G-3. The calculation is applied to the fire room only, with the opening to the next compartment treated as an opening with an area (height × width) equal to $6.1 \times 3 = 18.3\ m^2$. To correct the MQH temperature correlation for a fire in the corner, a factor of 1.7 is multiplied by the results in FIVE, as suggested by Karlsson and Quintiere 2000 (Equation 6.23).

For the time to detection, the Alpert Ceiling jet temperature calculation is used. The approach is to calculate the time at which the ceiling jet temperature at the heat detector is 30°C. The additional inputs for this correlation are the horizontal radial distance from the centerline of the fire plume to the detector, which is 4.5 m, and the fire location factor of 4, due to fire in the corner. Because the fire room is a corridor shape, the flow is likely to be confined; therefore, the confined flow correlation by Delichatsios is also used. The additional input is the corridor half-width of 1.5 m.

Step 4. Calculate Fire-Generated Conditions

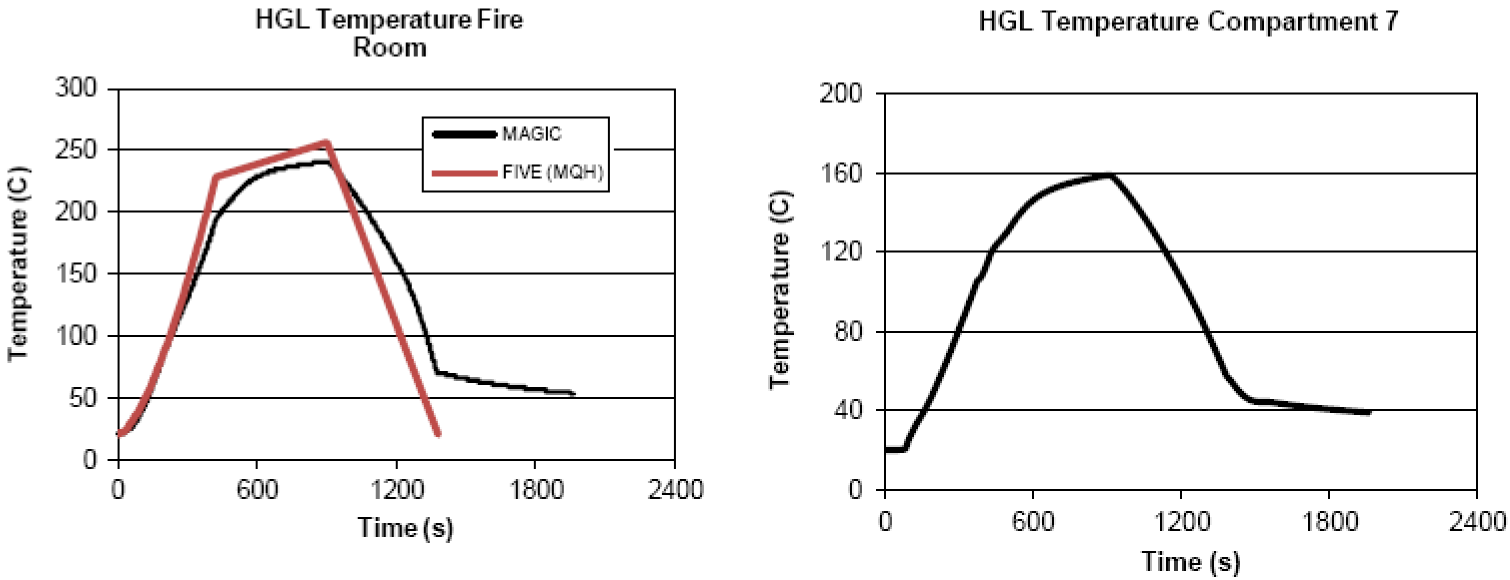


Figure G-9. Hot Gas Layer Temperature Predictions by MAGIC for the Corridor Scenario.

Step 4. Calculate Fire-Generated Conditions

G.5.2 Smoke Detection

The smoke detector activation time in the corridor containing the fire is based on the time for the ceiling jet temperature to reach 30°C at the detector location. The results, plotted in Figure G-11, show that the two correlations from FIVE produce identical results of 50 s. MAGIC predicts 40 s.

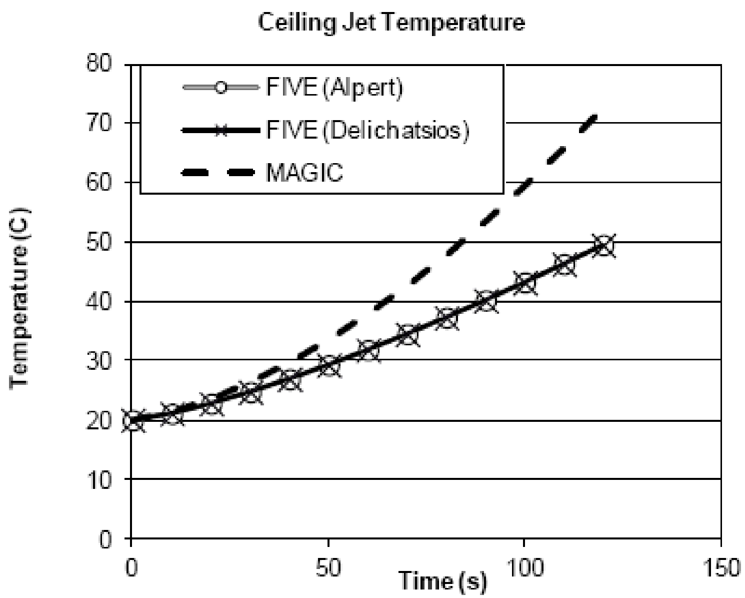


Figure G-11. Detector temperature prediction by MAGIC for fire corridor.

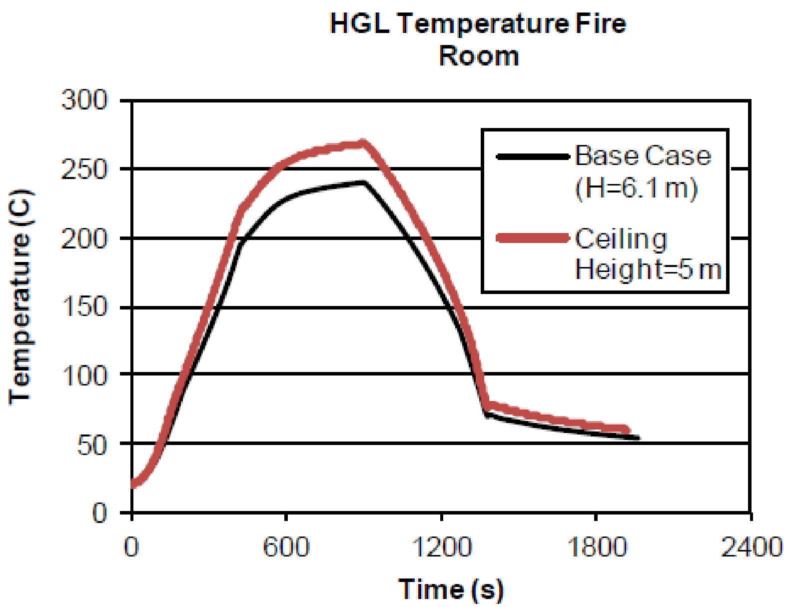
Step 5. Sensitivity and Uncertainty Analysis

Table G-2. Summary of the model predictions of the Corridor scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Ventilation	Predicted Value	Critical Value	Probability of Exceeding
HGL Temperature (°C), Initial Value = 20 °C						
FIVE (MQH)	1.56	0.32	Natural	256	330	0.001
MAGIC	1.01	0.07	Mechanical	240	330	0.000

Step 5. Sensitivity and Uncertainty Analysis

What happens if the room height is reduced?



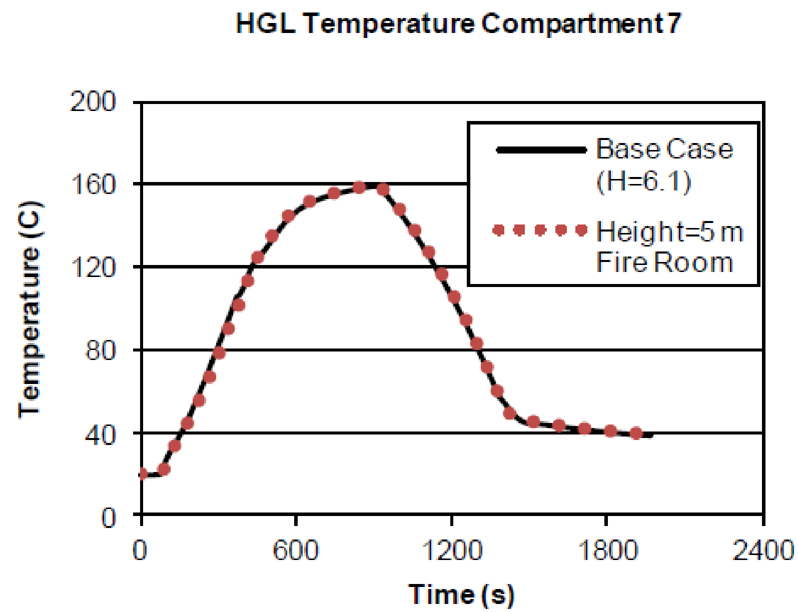


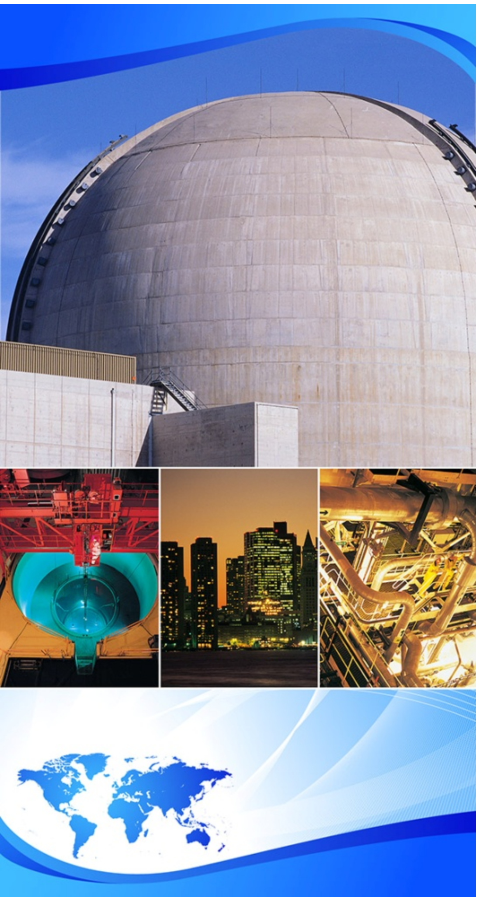
Figure G-10. Hot Gas Layer Temperature for Reduced Ceiling Height by MAGIC.

Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

G.6 Conclusion

Both FIVE and the zone model MAGIC predict that HGL temperatures will not reach high enough to cause cable damage in any compartment or corridor, including the corridor containing the burning pallets, while accounting for uncertainty in the temperature predictions of MAGIC and the sensitivity of the predictions to variations in the heat release rate. Based on a simplified method for smoke detector activation, smoke detector operation occurs at 40 to 50 seconds.



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5

Advanced Fire Modeling

Day 4 - PM Session

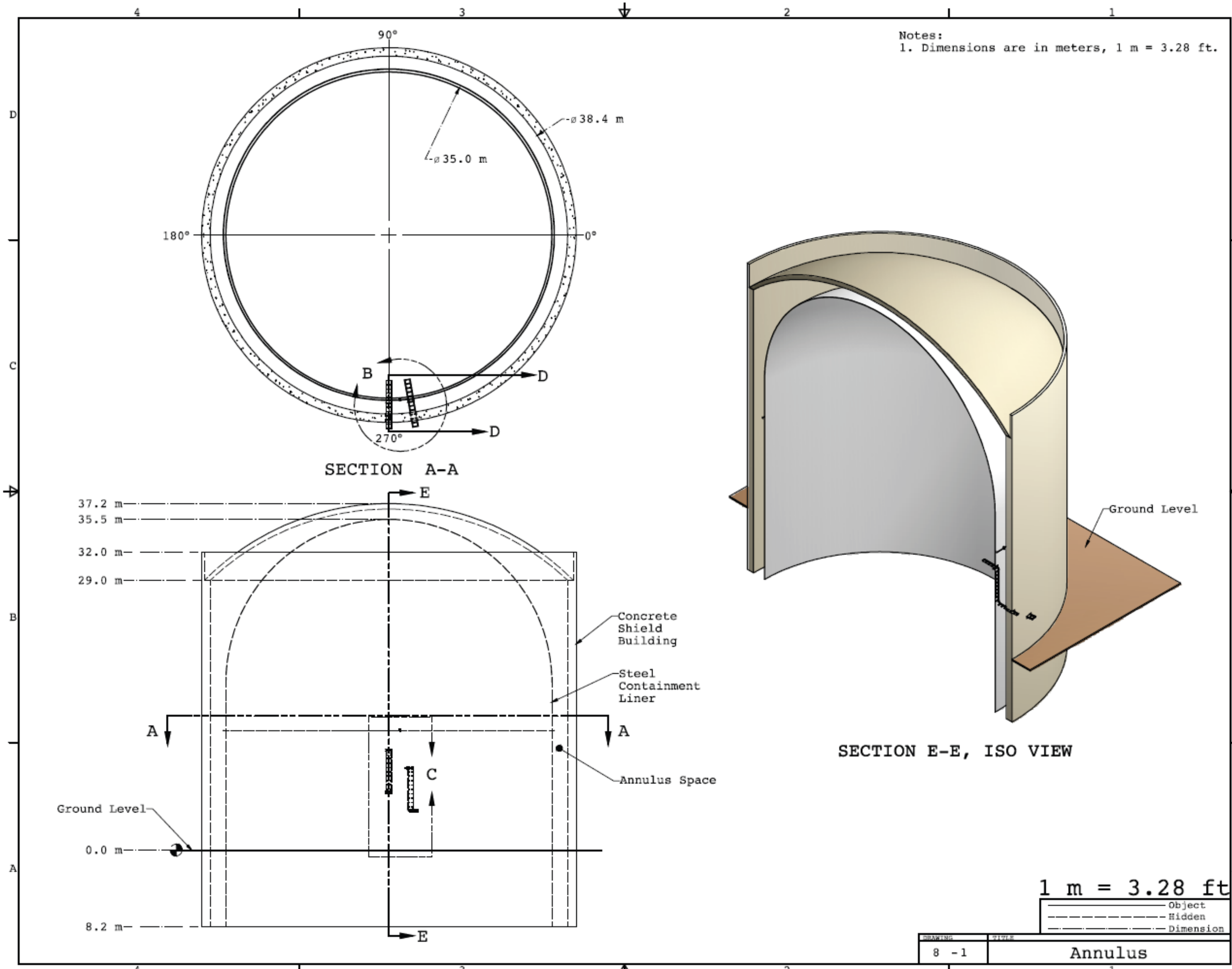
Example H: Cable Tray Fire in Annulus

Joint RES/EPRI Fire PRA Workshop
July and October 2013
Charlotte, NC

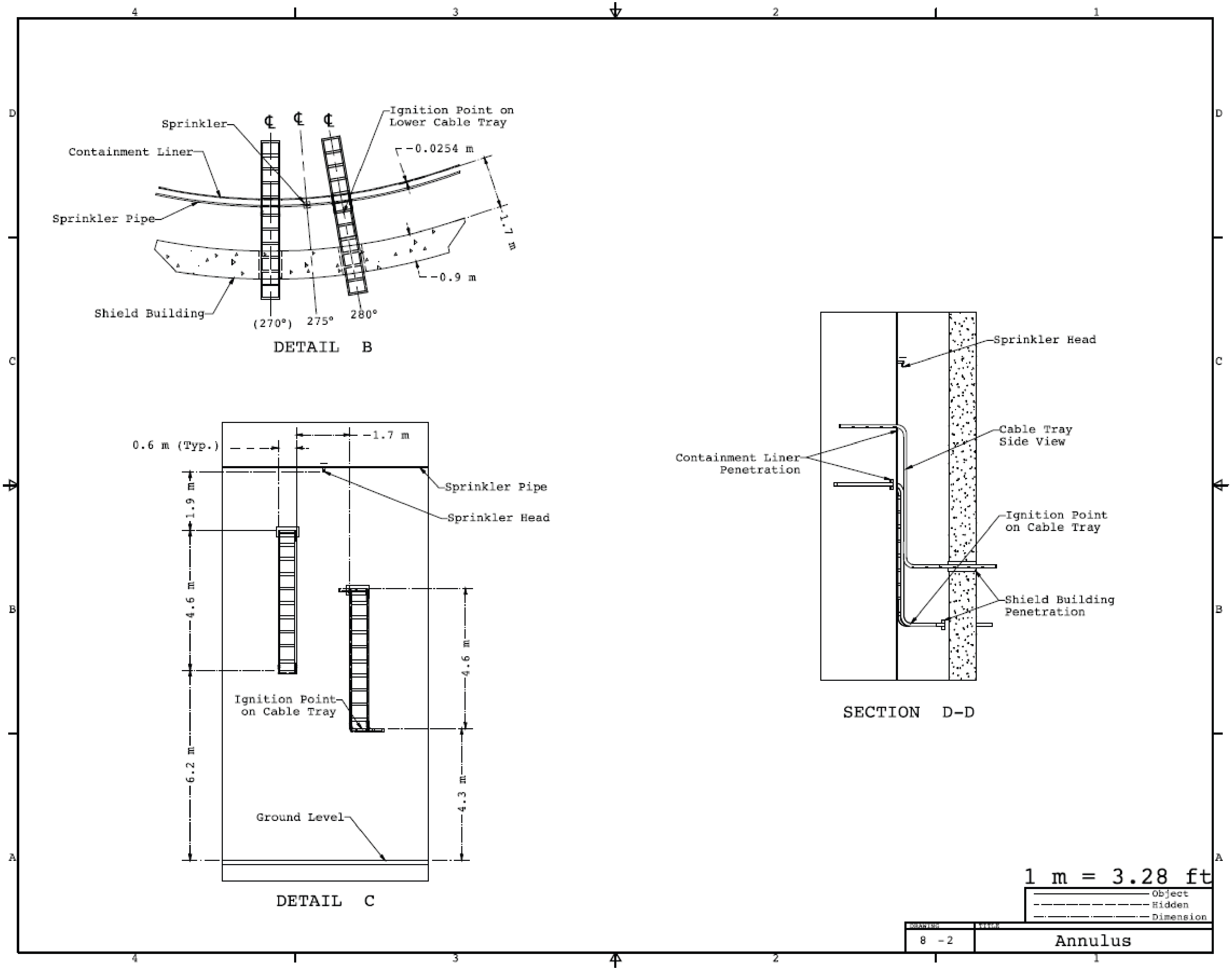
A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Step 1. Define Fire Modeling Goals

- Determine potential for damage to redundant safe-shutdown cables due to a fire in an adjacent tray in annulus region of the containment building.
- Follow guidance provided in Chapter 11 and Appendix R (Cable Fires) of NUREG/CR-6850 (EPRI 1011989), Volume 2.



Notes:
1. Dimensions are in meters, 1 m = 3.28 ft.
90°
180°
0°
270°
ø 38.4 m
ø 35.0 m
B
D
D
SECTION A-A
37.2 m
35.5 m
32.0 m
29.0 m
0.0 m
8.2 m
E
E
A
A
C
Concrete Shield Building
Steel Containment Liner
Annulus Space
Ground Level
Ground Level
SECTION E-E, ISO VIEW
1 m = 3.28 ft
Object
Hidden
Dimension
DRAWING
8 -1
TITLE
Annulus


Sprinkler
Containment Liner
Sprinkler Pipe
Shield Building
Ignition Point on Lower Cable Tray
0.0254 m
1.7 m
0.9 m
(270°)
275°
280°
DETAIL B
0.6 m (Typ.)
1.7 m
Sprinkler Pipe
Sprinkler Head
1.9 m
4.6 m
6.2 m
4.6 m
4.3 m
Ignition Point on Cable Tray
Ground Level
DETAIL C
Sprinkler Head
Cable Tray Side View
Containment Liner Penetration
Ignition Point on Cable Tray
Shield Building Penetration
SECTION D-D
1 m = 3.28 ft
Object
Hidden
Dimension
8 -2
Annulus

Fire

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

R.4.1.2 Recommended Values for Flame Spread in Horizontal Cable Trays

Consider a single vertical cable tray ignited at the bottom. Assume a heating distance of 2 mm and an incident heat flux of 70 kW/m^2.

- Flame spread for PVC cable = 0.9 mm/sec
- Flame spread for XPLE cable = 0.3 mm/sec

Table R-4
Flame Spread Estimates for PVC Cable

Material	Bench Scale HRR [kW/m^2]	Flame Spread Rate [mm/s]
PE/PVC	395	156
PE/PVC	359	137
PE/PVC	312	112
PE/PVC	589	258

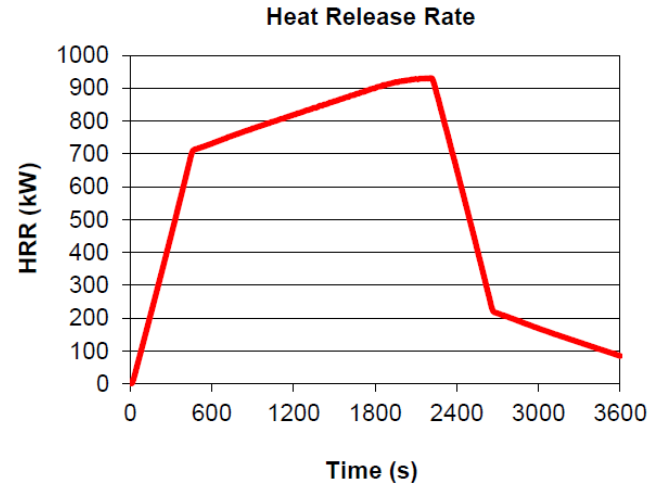


Figure H-1. Heat release rate for a cable fire in the annulus.

What is burning?

Cables made of polyethylene (C_2H_4) and polyvinylchloride (C_2H_3Cl).

Assume effective fuel: $C_2H_{3.5}Cl_{0.5}$

Table H-1. Products of combustion for a PE/PVC cable fire.

Parameter	Value	Source
Heat of Combustion	20,900 kJ/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
CO_2 Yield	1.29 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
Soot Yield	0.136 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
CO Yield	0.147 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
Radiative Fraction	0.49	*SFPE Handbook,* 4th ed., Table 3-4.16

Material Properties

Cables: The cable trays are filled with PE-insulated, PVC-jacketed control cables. These cables have a diameter of approximately 1.5 cm (0.6 in), a jacket thickness of approximately 1.5 mm (0.06 in), and 7 conductors. There are approximately 120 cables in each tray. The mass of each cable is 0.4 kg/m. The mass fraction of copper is 0.67. These cables fail when the internal temperature just underneath the jacket reaches approximately 205 °C (400 °F) or the exposure heat flux exceeds 6 kW/m^2 (NUREG-1805, Appendix A).

$$m_c'' = \frac{n\,Y_p\,(1-\nu)m'}{W} = \frac{120 \times 0.33 \times (1-0) \times 0.4\ \mathrm{kg/m}}{0.6\ \mathrm{m}} \cong 26.4\ \mathrm{kg/m^2} \qquad \text{(H-1)}$$

$$\Delta t = \frac{m_c''\,\Delta H}{5\,\dot{q}_{avg}''/6} = \frac{26.4\ \mathrm{kg/m^2} \times 20{,}900\ \mathrm{kJ/kg}}{5/6 \times 250\ \mathrm{kW/m^2}} \cong 2648\ \mathrm{s} \qquad \text{(H-2)}$$

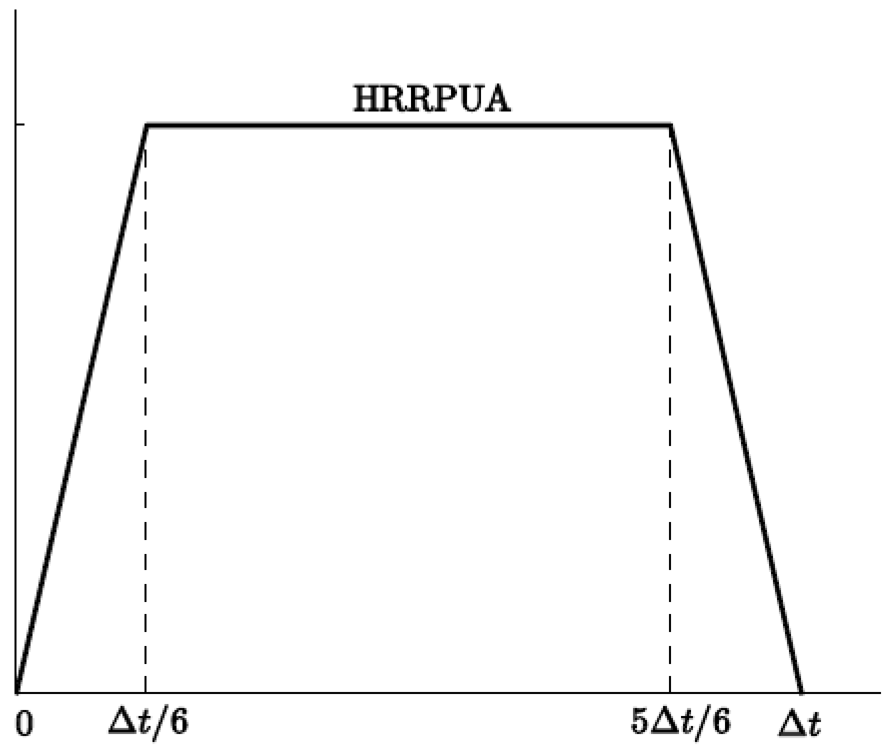


Figure 9-1. Idealized time history of the local heat release rate per unit area.

NUREG/CR-7010

Step 3. Select Fire Models

- <u>Algebraic Models</u>: Point source heat flux
- <u>Zone Models</u>: Typically not used outside of a compartment.
- <u>CFD</u>: FDS assumes rectangular geometry, but it can approximate the curved wall using a series of “stair steps”

Applicability of Validation

- Diameter of the fire is not well-defined
- Compartment parameters not appropriate

CHRISTIFIRE 2, Vertical Tests

Two trays of PVC Instrument Cable separated by 6 inches

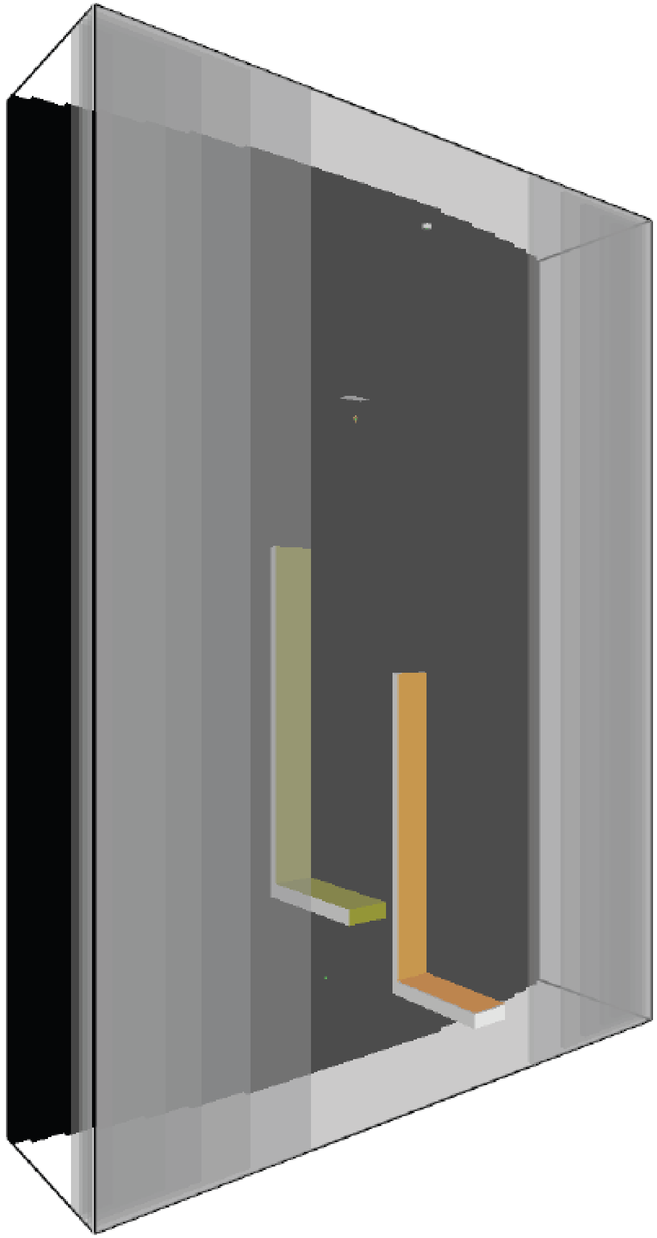
October 2011, NIST Large Fire Lab

Step 4. Calculate Fire-Generated Conditions

Two forms of the point source radiation model

$$\dot{q}''_{\text{ps}} = \frac{\chi_r\,\dot{Q}}{4\pi\,r^2} = \frac{0.49\ \times 945\ \text{kW}}{4\pi\ \times\ 2.0^2\ \text{m}^2} \cong 9.2\ \text{kW/m}^2 \qquad \text{(H-3)}$$

$$\dot{q}''_{\text{dps}} = \frac{\chi_r}{4\pi}\sum_i \frac{\dot{Q}_i}{{r_i}^2} = \frac{0.49}{4\pi}\left(\frac{255}{2.9^2} + \frac{172.5}{2.4^2} + \frac{172.5}{2.0^2} + \frac{172.5}{2.2^2} + \frac{172.5}{2.9^2}\right)\frac{\text{kW}}{\text{m}^2} \cong 6.2\ \text{kW/m}^2 \qquad \text{(H-4)}$$



FDS simulation.

Step 5. Sensitivity and Uncertainty Analysis

Table H-2. Summary of model predictions for the annulus fire scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Target	Predicted Value	Critical Value	Probability of Exceeding
Heat Flux (kW/m^2)						
Point Source	1.42	0.55	Cables	9.2	6.0	0.553
Distributed Point Source	1.42	0.55		6.2	6.0	0.248
FDS	1.10	0.17		2.5	6.0	0.000
Target Temperature (°C)						
FDS	1.02	0.13	Cables	120.0	205.0	0.000
Plume Temperature (°C)						
FDS	1.15	0.11	Sprinkler	90.0	100.0	0.001

Sensitivity Analysis – how do changes in the input parameters affect the outcome?

$$\text{Output Quantity} = \text{Constant} \times (\text{Input Parameter})^{\text{Power}}$$

(Relative Change in Output) = Power x (Relative Change in Input)

Relative Change in Plume Temperature= 2/3 x Relative Change in HRR

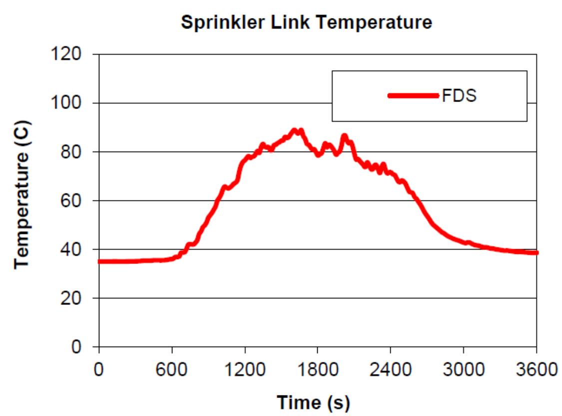


Figure H-6. Predicted sprinkler link temperature for the annulus fire scenario.

$$\Delta\dot{Q} = \frac{3}{2}\dot{Q}\frac{\Delta T}{T - T_0} = \frac{3}{2}945\ \text{kW} \times \frac{10\ °\text{C}}{90\ °\text{C} - 35\ °\text{C}} \cong 258\ \text{kW}$$

Table 4-3. Sensitivity of model outputs from Volume 2 of NUREG-1824 (EPRI 1011999).

Output Quantity	Important Input Parameters	Power Dependence
HGL Temperature	HRR Surface Area Wall Conductivity Ventilation Rate Door Height	2/3 -1/3 -1/3 -1/3 -1/6
HGL Depth	Door Height	1
Gas Concentration	HRR Production Rate	1/2 1
Smoke Concentration	HRR Soot Yield	1 1
Pressure	HRR Leakage Rate Ventilation Rate	2 2 2
Heat Flux	HRR	4/3
Surface/Target Temperature	HRR	2/3

Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

H.6 Conclusion

Simple point source heat flux calculations indicate that a fire in one of the cable trays within the annulus region of the containment building might damage the cables in an adjacent tray. However, an additional analysis using FDS indicates that cable damage is unlikely due to the orientation of the target cables and the blockage of thermal radiation by the cable tray itself. This suggests that the details of the cable tray location, orientation, and configuration can significantly impact potential for damage.

FDS predicts that sprinkler activation above the fire is unlikely. However, its prediction is sensitive to the exact location of the sprinkler relative to a fire plume that may be subject to unpredictable air movements throughout the entire facility. Alternative protection strategies, such as shielding between trays or other thermal barriers, should be considered to ensure the protection of the redundant cables.