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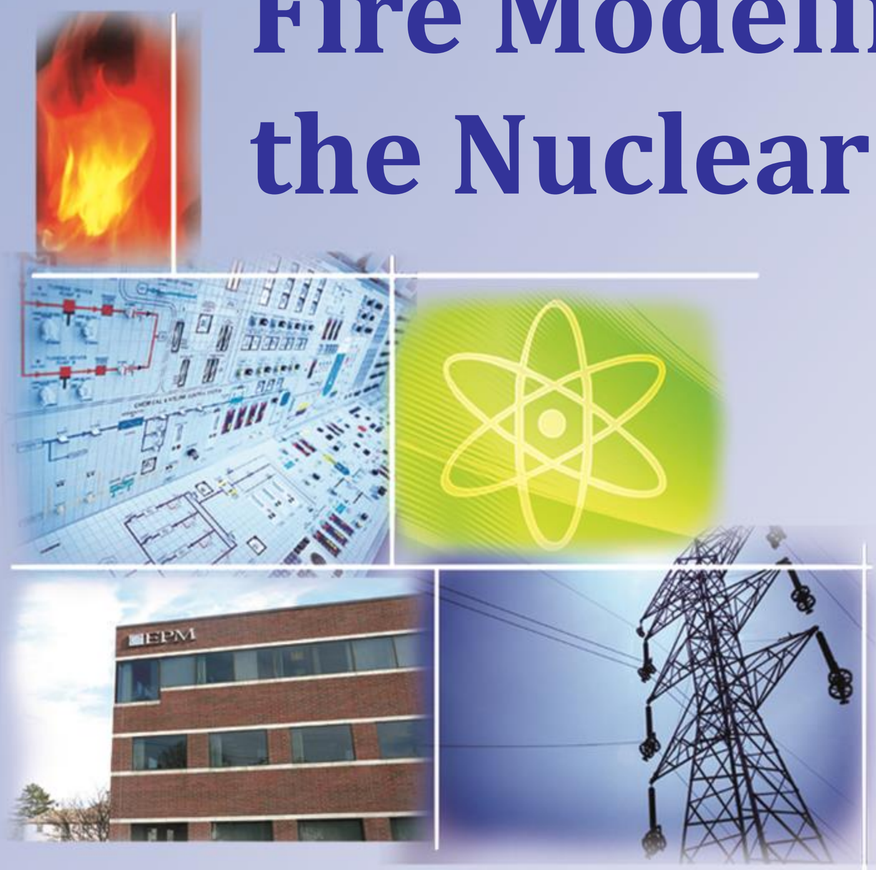
Fire Modeling Examples From the Nuclear Power Industry



DOE Nuclear Facility Safety Programs Workshop 2014

Las Vegas, Nevada

Presented by: Mark Schairer, P.E.

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Nuclear Power and Fire Protection

- US Nuclear Power Plants were licensed to deterministic fire protection rules (i.e., Appendix R-Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979)
- In July 2004, NRC amended 10 CFR 50.48 to allow licensees to voluntarily adopt NFPA 805 as a risk-informed performance based alternative to the deterministic fire protection requirements.
- Approx. 50% of US NPPs elected to transition to NFPA 805

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Why is Fire Modeling Used?

- Fire Modeling can be used to support performance-based fire protection and risk analyses including:
  - NFPA 805 Transition Projects
    - Assess Variances from Deterministic Nuclear Safety Criteria
      - i.e., separation issues, degraded fire protection systems
  - Fire Probabilistic Risk Assessments (FPRA)
    - Estimate Plant CDF/LERF
    - Evaluate Risk Impact of Modifications and Recovery Actions
  - NRC Significance Determination Process (SDP)

Fire Modeling

- *Benefits* of Fire Modeling
  - Focused analysis to determine fire compartments/scenarios that have most risk
  - Allows for plant specific scenarios to be analyzed
  - Reduces unnecessarily high levels of conservatism
  - Allows for unique, less expensive solutions when compared to prescriptive requirements (i.e., mods) – without decreasing safety levels
  - Provides quantitative results and an adjustable model to aid in decision-making

Why use a risk-based approach?

Traditional Engineering Failure Analysis	Risk Approach (Fire Modeling)
• Deterministic assumption that a consequence will result in the loss of capability of a component to perform its function • Assumes component is failed/succeeds (1.0) • No Common Cause Failures • Limited Human Actions	• Evaluates the likelihood of consequences of the failure of all components • Assumes a best estimate failure rate for each component • Analysis of Common Cause Failures • Significant Human Actions

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Available Fire Modeling Tools

- Nuclear Regulatory Commision requires V&V of fire modeling tools
- Available models for use via NUREG-1824:
  - Closed Form Correlations
    - NUREG-1805 FDTs
    - FIVE
  - Zone Models
    - CFAST
    - MAGIC
  - Field Model (CFD)
    - FDS

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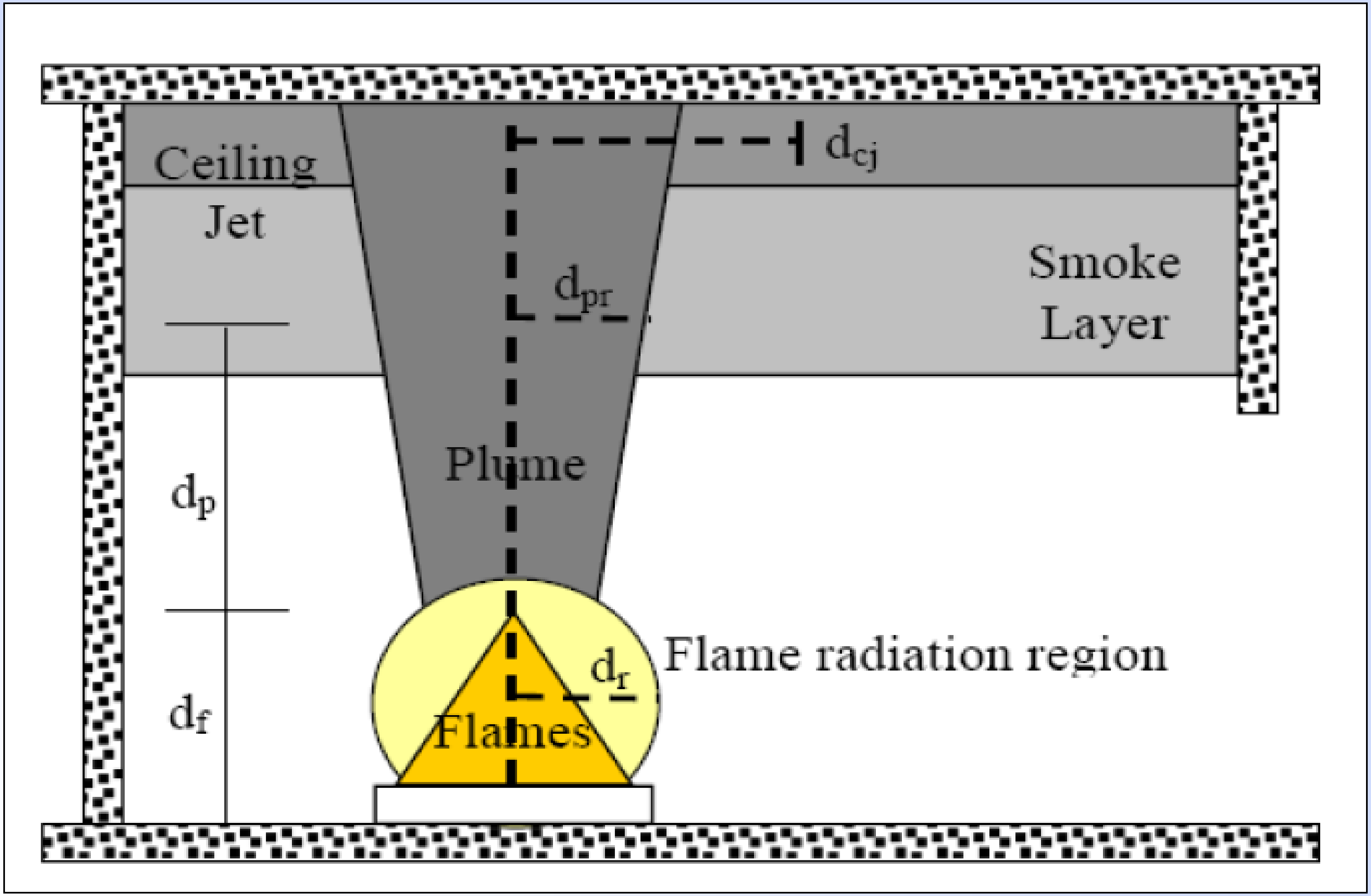
Zone of Influence (ZOI)



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Detailed Fire Modeling Tiered Approach

- 1st Level: Conservative fire modeling
  - Broad brush, "quick and dirty"
  - Closed form correlations
    - Detailed Fire Modeling Workbook
- 2nd Level: Less conservative, more realistic
  - Refine conservatisms, requires additional time
- 3rd Level: Use of zone and field models
  - Most realistic, most time consuming
    - CFAST and FDS

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1^{st} Level: Closed Form Correlations

- Examples of closed form correlations
  - Detailed Fire Modeling Workbooks
  - FIVE (Fire Induced Vulnerability Evaluation)
  - NUREG-1805 – Fire Dynamics Tools (FDTs)
- When to use:
  - Generally used as a scoping tool
  - Cost/schedule/budget limitations
  - Resource limitations
  - Conservative inputs required to stay within bounds of V&V
  - Yields conservative bounding results with safety margin

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Closed-Form Correlations

NUREG-1805 FDT 9: Plume Temperature Calculations

The following calculations estimate the centerline plume temperature in a compartment fire.

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).

The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

Heat Release Rate of the Fire (Q)	18.00	kW		
Elevation Above the Fire Source (z)	1.50	ft	0.46	m
Area of Combustible Fuel (A_c)	2.78	ft^2	0.26	m^2
Ambient Air Temperature (T_a)	72.00	°F	22.22	°C
	Calculate		295.22	K

AMBIENT CONDITIONS

Specific Heat of Air (c_p)	1.00	kJ/kg-K
Ambient Air Density (ρ_a)	1.20	kg/m^3
Acceleration of Gravity (g)	9.81	m/sec^2
Convective Heat Release Fraction (χ_c)	0.70	

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

ESTIMATING PLUME CENTERLINE TEMPERATURE

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 2-6.*

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2^{nd} Level: Modeling Refinements

- Revisit and refine conservative assumptions and modeling inputs:
  - Reduce the zone of influence and subsequent target impacts
    - Reduce assumed heat release rates based on specific ignition source characteristics
    - Credit administrative controls (i.e. transient combustible controlled areas)
  - Refine target set to focus on risk significant target impacts
  - Incorporate possible modifications to limit or prevent target failures (i.e. passive fire protection features)
  - Delay time to target damage to improve suppression probabilities

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FMWB Fire Growth and Propagation

escription of Fire Scenario

fire starts at REAC-TR-SWGR-1A and spreads to its adjacent vertical section (1B) in 10 minutes

e propagates to ITK154N (approx. 12 inches vert.) and ITX526N (approx. 28" horiz.)

ble trays are located 12 inches vertically and 28 inches horizontally resulting in a 1 minute and 12 minute ignition time respectively (per 6850 table H-7)

e spreads along trays approximately 1 foot and ignites unmarked tray at 15 minutes, assuming 3.54ft/hour spread rate.

tection: The fire will be detected by a smoke detector with alarm at MCR within 1 minute. The fire will be manually detected within 15 minutes.

ppression: There is no automatic suppression system in this fire area. The first fire brigade will respond 0 minutes after detection

ne to Damage Calculation

Source	
Name	HRR [kW]
SWGR-1A	211

Target	
Name	Dist [in]
1TK154N	12
1TX526N	28

FDT Inputs	1TK154N	1TX526N
HRR [kW]	211	211
Area [ft²]	2.78	2.78
Dist [in]	12	28
χ_r	0.4	0.4
Tamb [°F]	77	77

Results	1TK154N	1TX526N
Tp Centerline [°C]	N/A	N/A
Heat Flux [kW/m²]	72	13
Time To Damage [min] per 6850 Appendix H	1	12

e Elevation [in]	90
ble Fire Spread Rate [in/min]	0.71
cation Factor	1

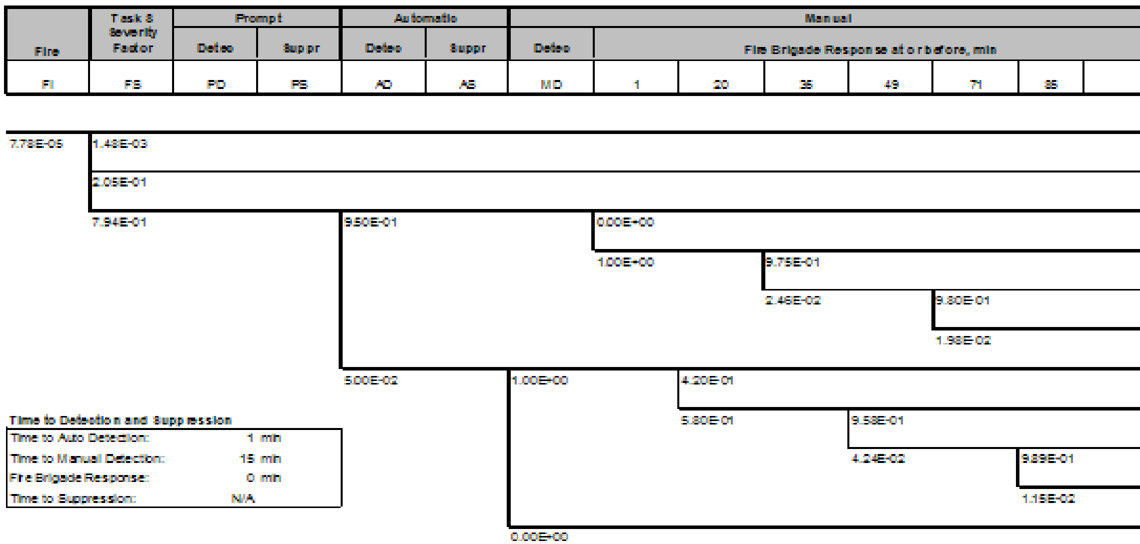
											Time (minutes)												
											FDS1	FDS2/3/4/6/7/8											
urce Type	Source	HRR per Unit [kW]	Unit	Vertical Separation of Tray [in]	Tray Width [in]	Tray Length [in]	Directions of Spread	Number of Units	Ignition Time	Duration	0	1	12	15	20	30	40	50	60	65	70	7
Cabinet	SWGR-1A	211	Cabinet	n/a	n/a	n/a	n/a	1	0	20	24	211	211	211	211	0	0	0	0	0	0	0
1st Tray	1TK154N	20	ft²	n/a	24	24	2	4.00	1	75	0	80	132	146	170	217	265	312	359	383	407	43
2nd Tray	ITX526N	20	ft²	n/a	12	12	2	1.00	12	75	0	0	20	27	39	63	86	110	134	145	157	16
3rd Tray	Unmarked	20	ft²	n/a	12	12	1	1.00	15	75	0	0	0	20	26	38	50	61	73	79	85	9
											0	0	0	0	0	0	0	0	0	0	0	0
											0	0	0	0	0	0	0	0	0	0	0	0
										Total HRR:	24	291	363	404	446	318	400	483	566	608	649	69

Zone of Influence	Flames (ft)	0.83	5.54	6.23	6.59	6.93	5.80	6.55	7.22	7.81	8.09	8.36	8.
	Plume (ft)	1.33	6.90	7.72	8.14	8.54	7.22	8.10	8.89	9.59	9.92	10.24	10.
	Plume Radius (ft)	0.50	1.35	1.47	1.54	1.60	1.40	1.53	1.65	1.76	1.81	1.86	1.
	Ceiling Jet (ft)	0.12	1.42	1.77	1.97	2.18	1.55	1.95	2.36	2.76	2.97	3.17	3.
	Flame Radiation (ft)	0.86	3.01	3.36	3.55	3.73	3.14	3.53	3.88	4.20	4.35	4.49	4.
HGL	Hot Gas Layer Temperature (°C)		73	109	119	130	114	134	154	172	182	191	20

EPM FMWB Fire Event Tree

Ignition Source READ-TR-SWGR-1A/1B

Fire Event Tree



Time to Detection and Suppression

Time to Auto Detection:	1 min
Time to Manual Detection:	15 min
Fire Brigade Response:	0 min
Time to Suppression:	N/A

Freq	End State	Description of End State
1.15E-07	FDS0	Fire is not severe enough to damage targets.
1.59E-05	FDS1	Fire is severe enough to damage (non-propagating) targets, but is not severe enough to damage secondary combustibles
0.00E+00	FDS2	Prior to 1 minutes, there is not enough time available for manual suppression. Suppression probability is zero.
5.72E-05	FDS3	The manual suppression was successful at 35 min with available time for the manual suppression of 19 minutes.
1.41E-06	FDS4	Manual suppression was ultimately successful with sufficient time (i.e., >45 min) available.
2.85E-08	FDS5	Even with sufficient manual suppression time, assume a small but finite non-suppression probability and total room damage.
1.30E-06	FDS6	Auto detection failed. However prior to 30 minutes, there is no time available for suppression. Suppression probability is zero.
1.71E-06	FDS7	The manual suppression was successful at 49 min with available time for the manual suppression of 19 minutes.
7.50E-08	FDS8	Manual suppression was ultimately successful with sufficient time (i.e., >45 min) available.
8.69E-10	FDS9	Even with sufficient manual suppression time, assume a small but finite non-suppression probability and total room damage.
0.00E+00	FDS10	Failure of manual detection and manual suppression leads to total room damage.

Total FI 7.78E-05

FDS	Time (m)	Damaged Targets and Associated Components
FDS0	0	Damage to fire source only
FDS1	0	Damage to fire source plus targets in ZOI out to closest combustible
FDS2/3/4/6/7/8	1	All targets within ZOI
FDS5/9/10	75	Room Damage, Refer to "Targets" for complete list of components affected.

FDS	Frequency	CCDP	CDF	CLERP	LERF
FDS0	1.15E-07	1.18E-05	1.36E-12	3.95E-08	4.56E-15
FDS1	1.59E-05	7.87E-03	1.25E-07	2.17E-06	3.47E-11
FDS2/3/4/6/7/8	6.17E-05	6.00E-02	3.71E-06	1.67E-05	1.03E-09
FDS5/9/10	2.94E-08	7.12E-02	2.09E-09	2.25E-04	6.60E-12
Total	7.78E-05		3.83E-06		1.07E-09

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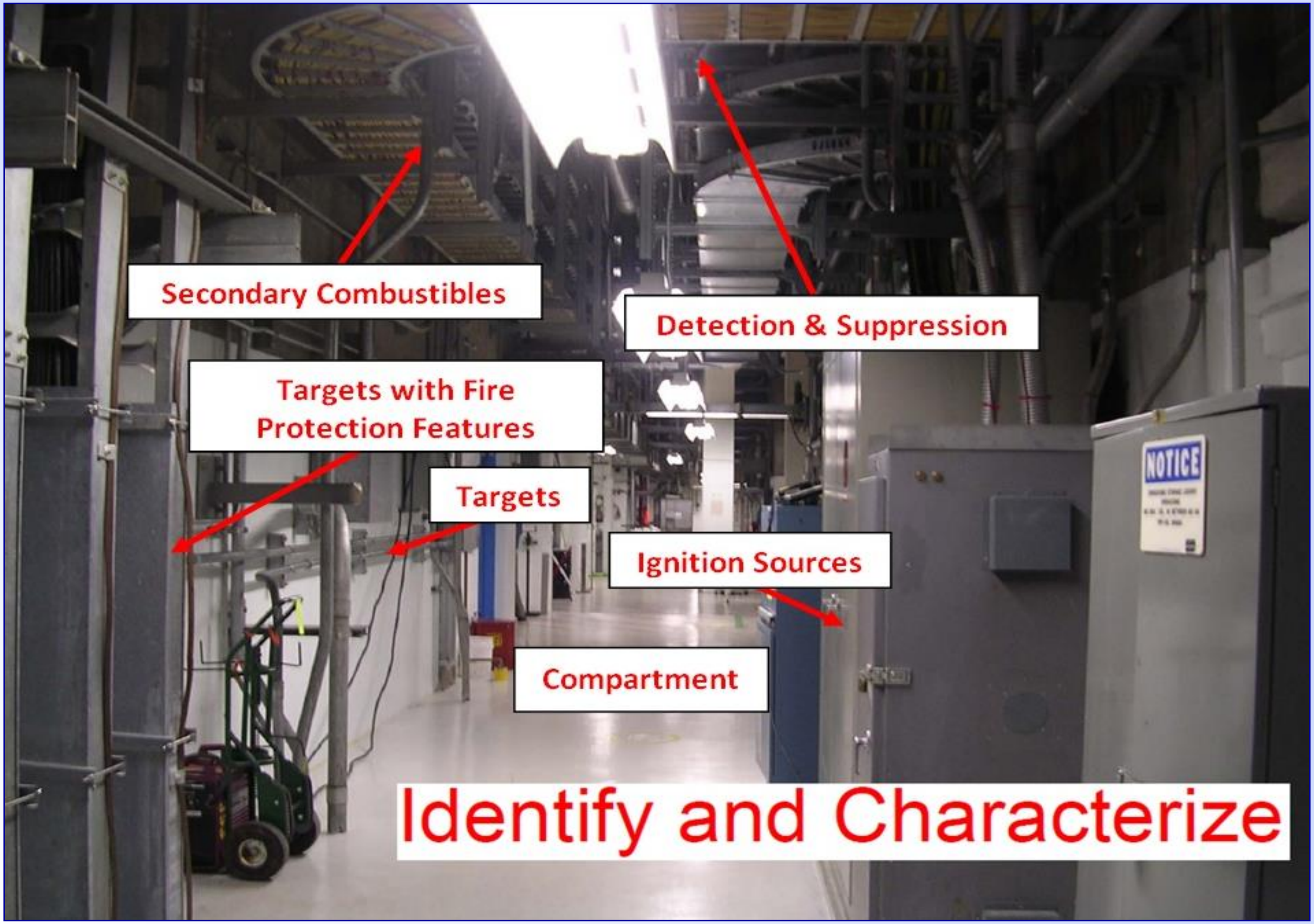
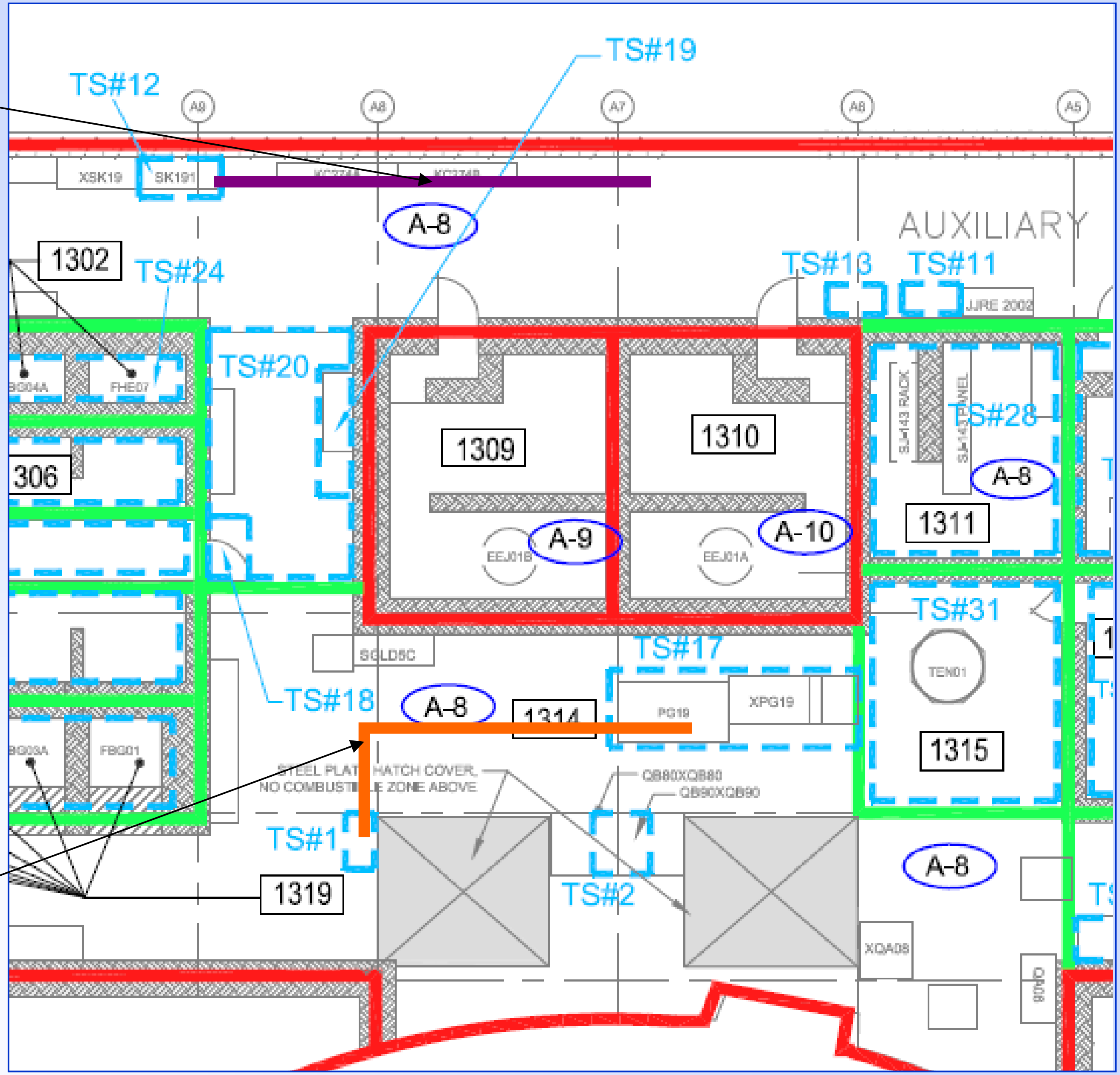
Single Compartment Fire Modeling



Target Conduit A

Example where <u>simple</u> fire modeling was successful



Target Conduit B

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Target Tray A

Example where fire modeling suppression was successful

Ignition Source

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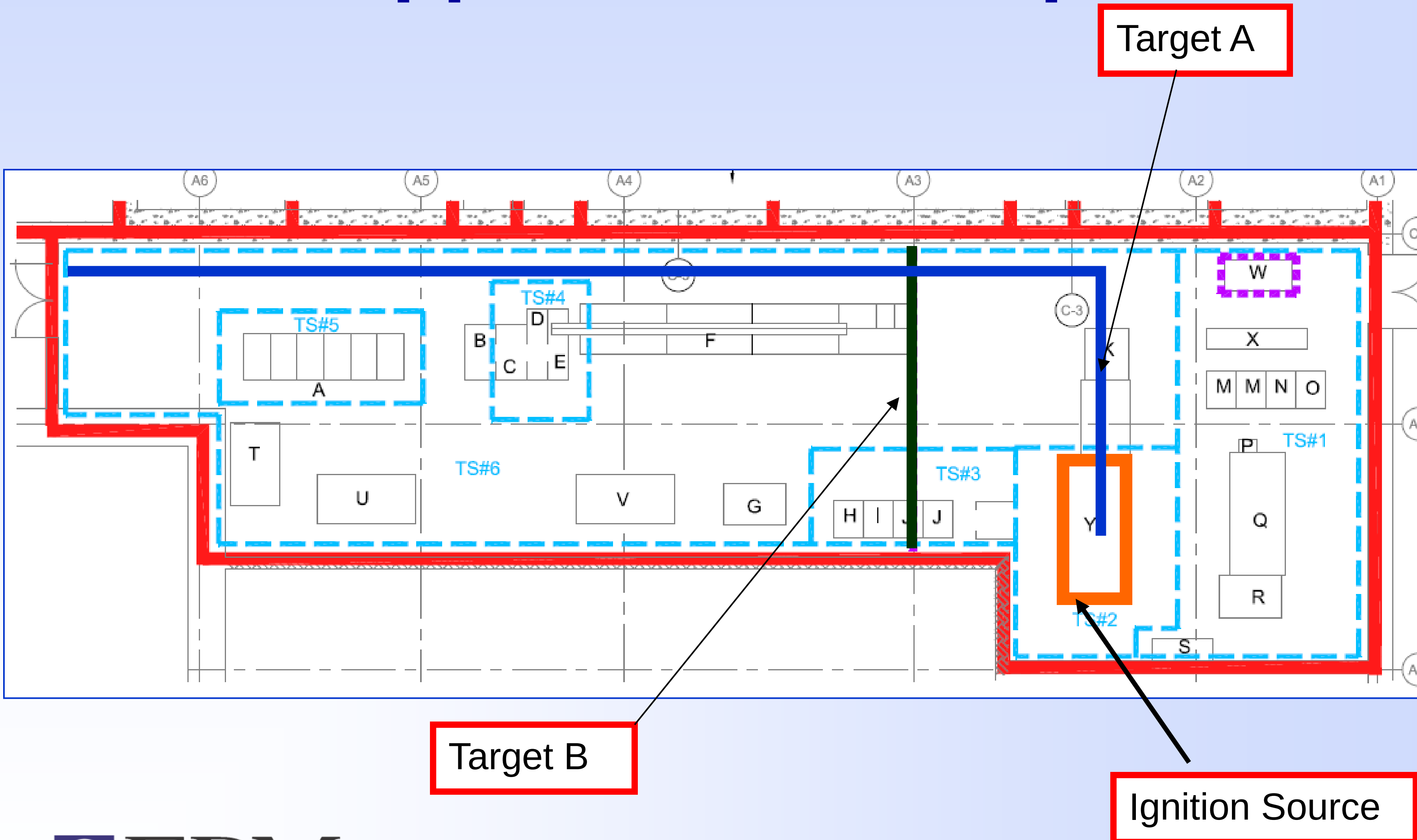
Suppression Example



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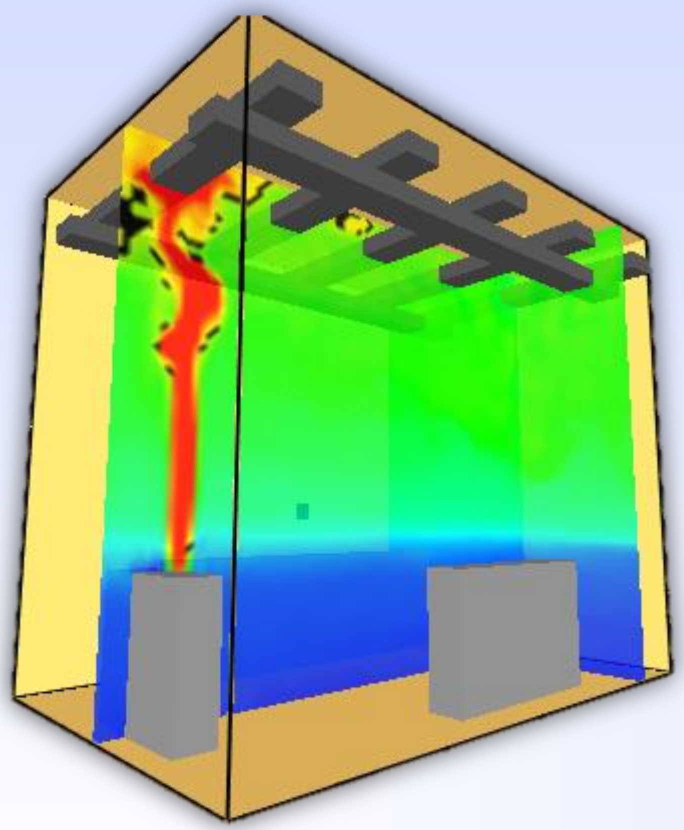
3^{rd} Level: Zone and Field Models

- Can provide greater detail for model analysis using differential equations instead of algebraic correlations.
  - Increased cost due time and preparation
  - May require dedicated computational resources
- When to use:
  - For refined analysis or complicated configurations/building features
  - When closed form correlations do not provide enough detail or accuracy for model analysis
  - High value or risk significant areas need analysis
  - Detailed input information is available within the bounds of V&V
  - Detailed, realistic inputs will yield more realistic results and can still be within the safety margin

Single Compartment Fire Modeling



Smokeview screenshot of FDS simulation

- Comprised of fire scenarios damaging target sets located within the *same compartment*,
- Does not include scenarios within or impacting the MCR
- The majority of fire scenarios analyzed generally fall into this category

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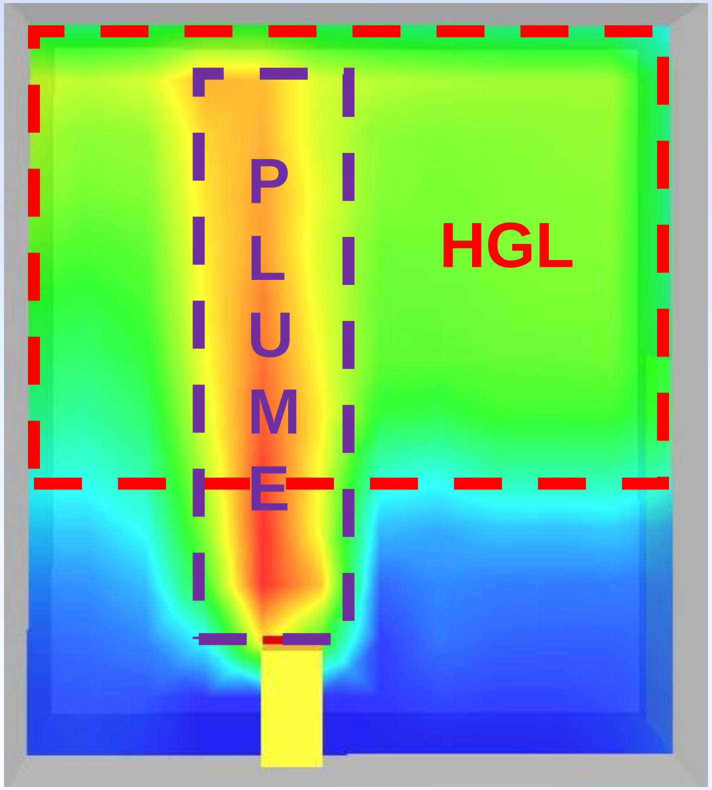
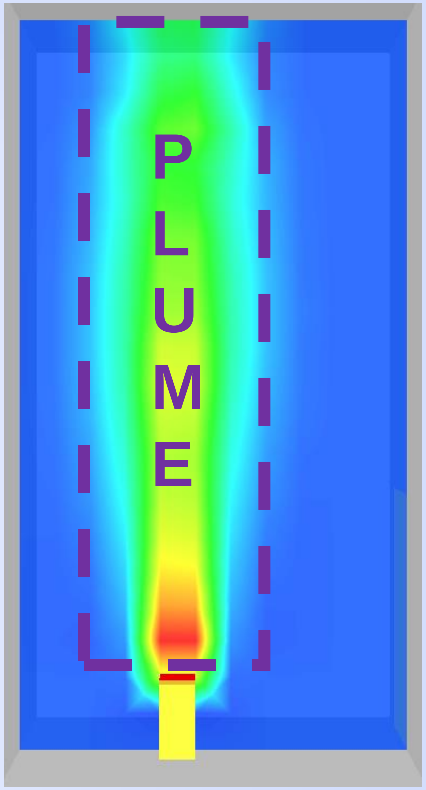
HGL/Plume Interaction Study

- In some cases the HGL/Plume interaction can cause increased plume temperatures



HGL/Plume Interaction



No HGL/Plume Interaction

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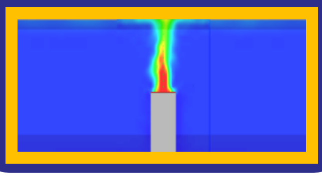
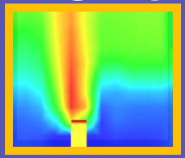
HGL/Plume Interaction Study

Category I:



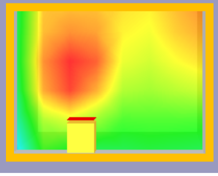
- Room dimensions preclude HGL/plume interaction because HGL is unlikely to form
- Room volume > 25,000 cubic ft, ceiling height > 15ft

Category II:



- Room dimensions require HGL/plume interaction analysis
- FDT may underestimate plume temperatures
- Room volume < 25,000 cubic ft, ceiling height > 10ft

Category III:



- HGL/plume interaction bounded by plume calculations in FDT9
- Ceiling height < 10 ft

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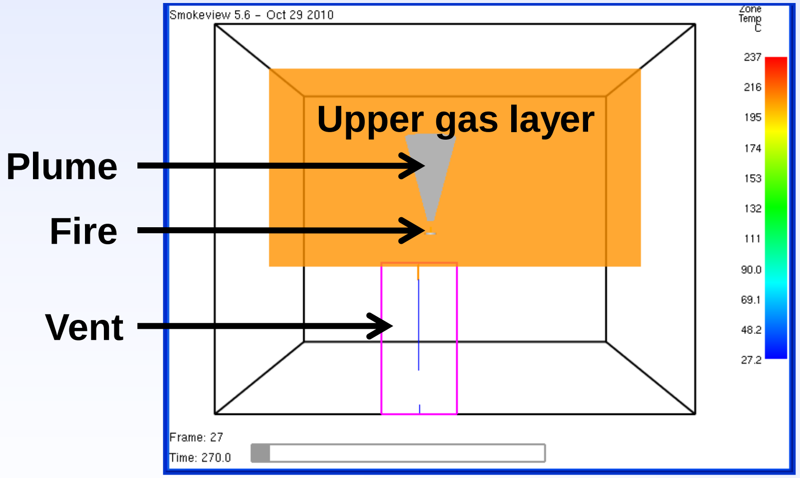
Damage Time Calculations

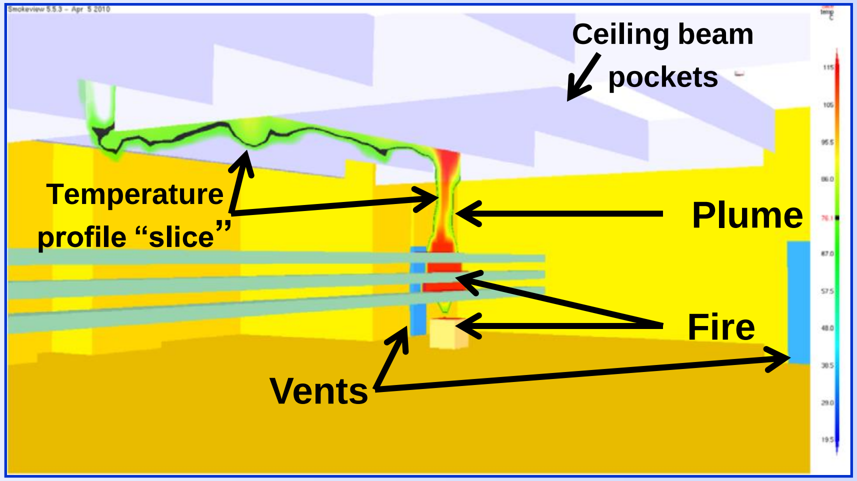
Computer Fire Modeling:

- **Consolidated Model of Fire Growth and Smoke Transport (CFAST)**
  - 2-zone model approximation

- **Fire Dynamics Simulator (FDS)**
  - 3-D computational fluid dynamics (CFD) model
  - Numerically solves a form of the Navier-Stokes equations associated with low –speed, thermally driven flow
  - Allows for results which show an approximation of the temperature (or other parameter) at any location in the simulation
  - Allows more complex scenarios to be modeled



Smokeview screenshot of CFAST fire model results (Electrical Cabinet Fire)



Smokeview screenshot of FDS fire model results (transient fire spreading to cable trays)

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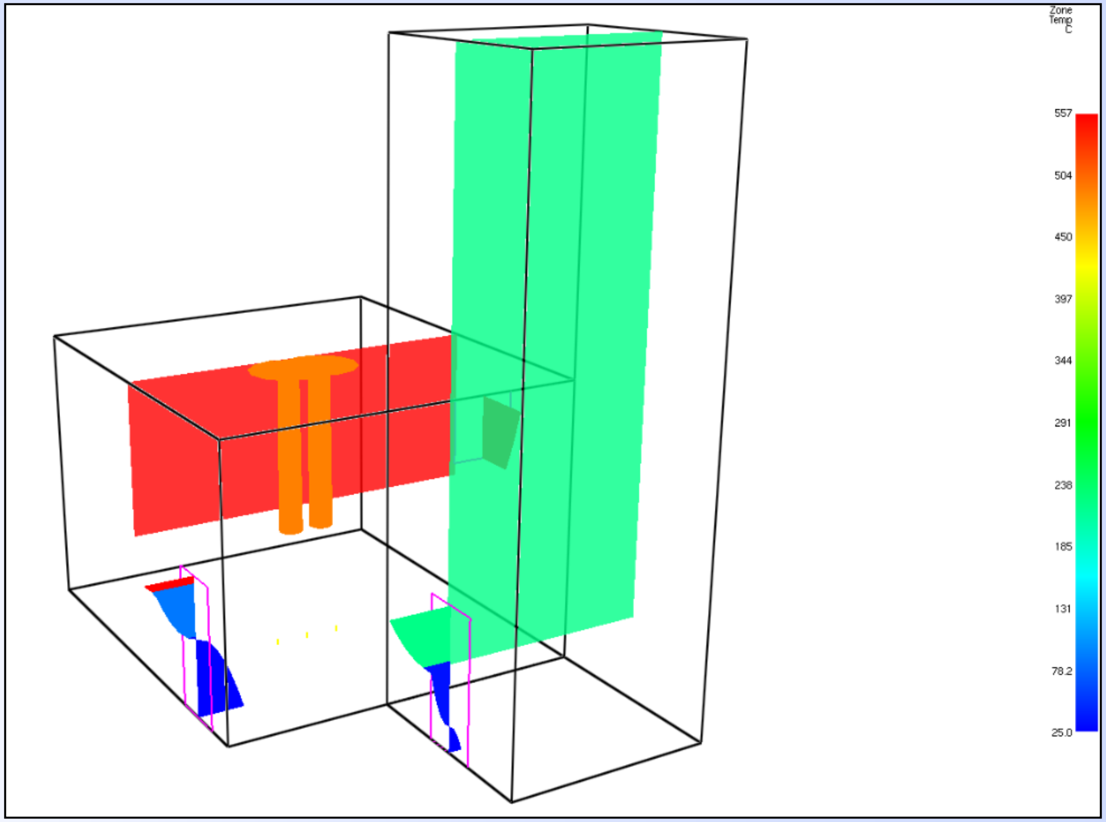
Multi Compartment Analysis

- Model the spread of hot gases and smoke from one compartment to another.
- Analysis predicts the flow of gases through open doors and failed penetrations.
- Results determine if smoke and hot gases can accumulate and cause damage to targets in adjacent compartments.



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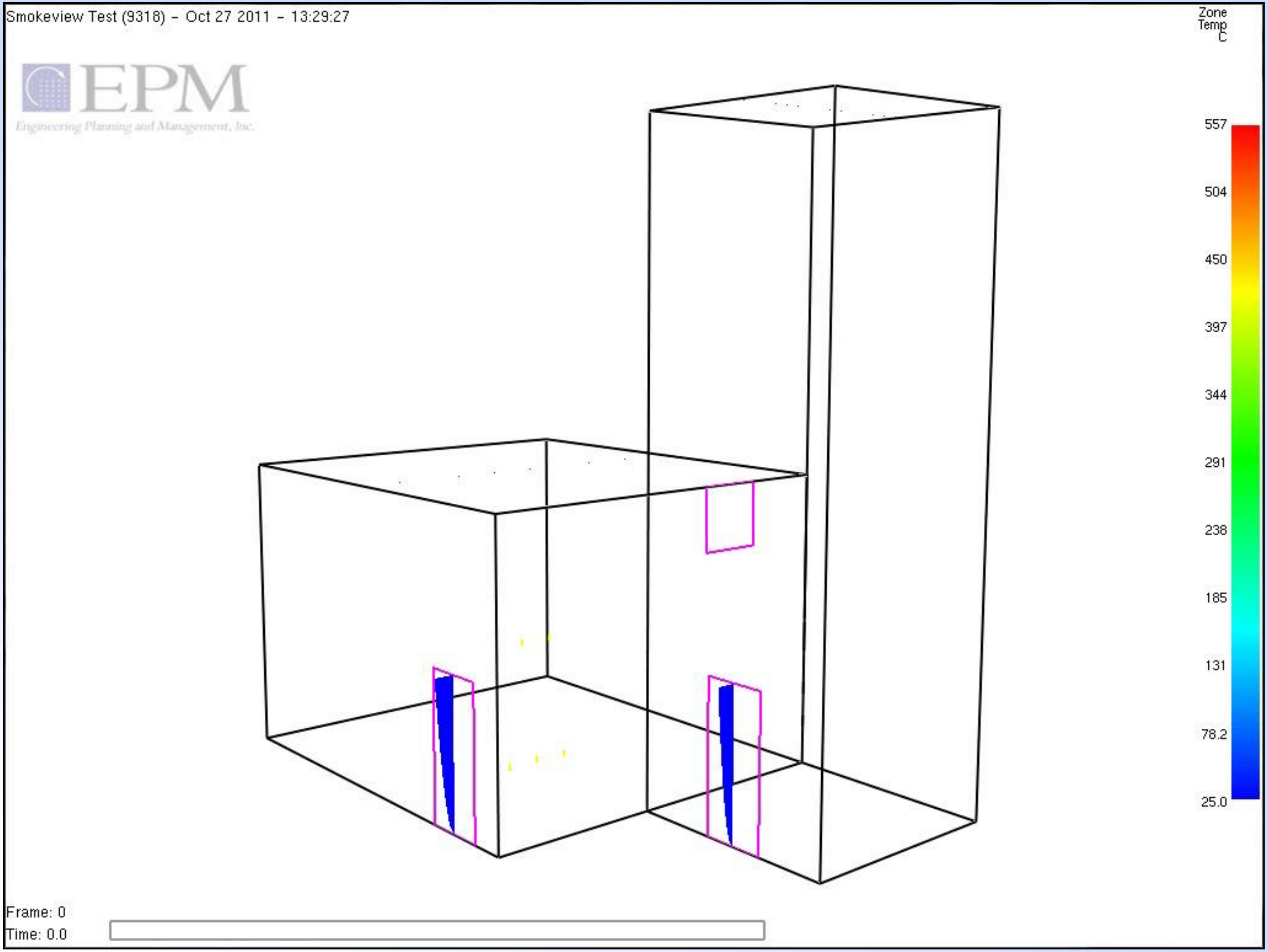

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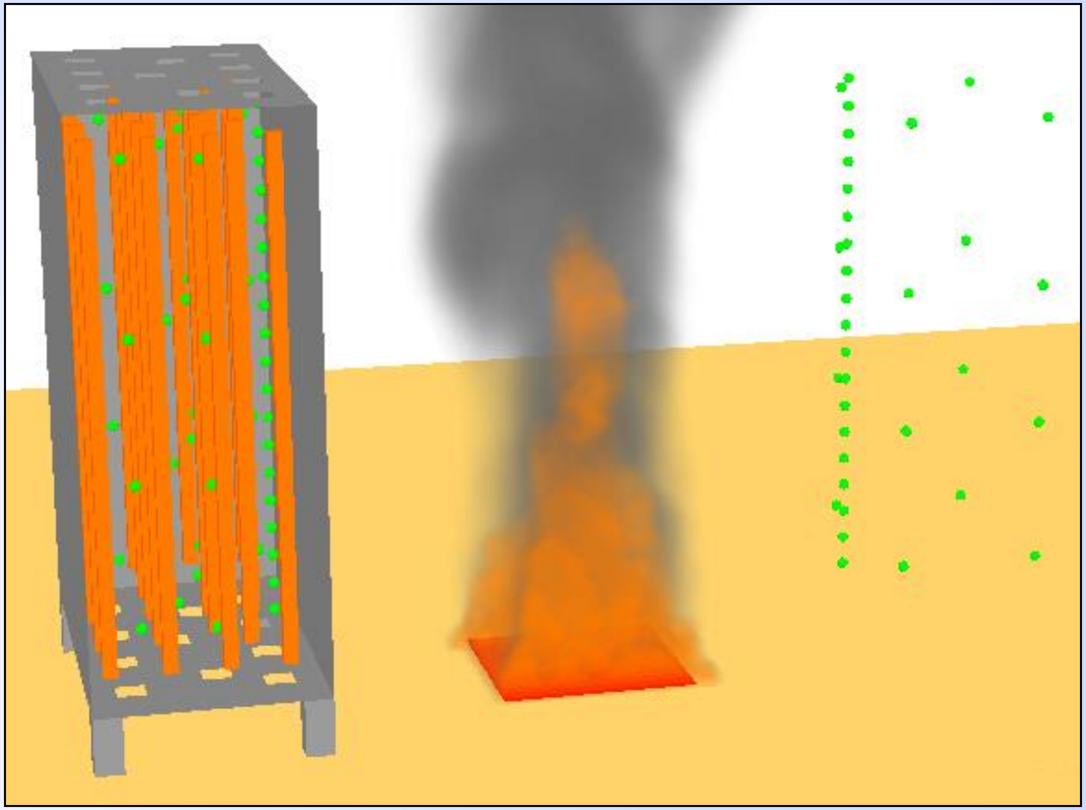
Temperature Sensitive Equipment Zone of Influence (ZOI) Study

- Subject of NFPA 805 Task Force FAQ 13-0004

- Evaluated the shielding effects of the electrical cabinet housing on the temperature sensitive components inside.



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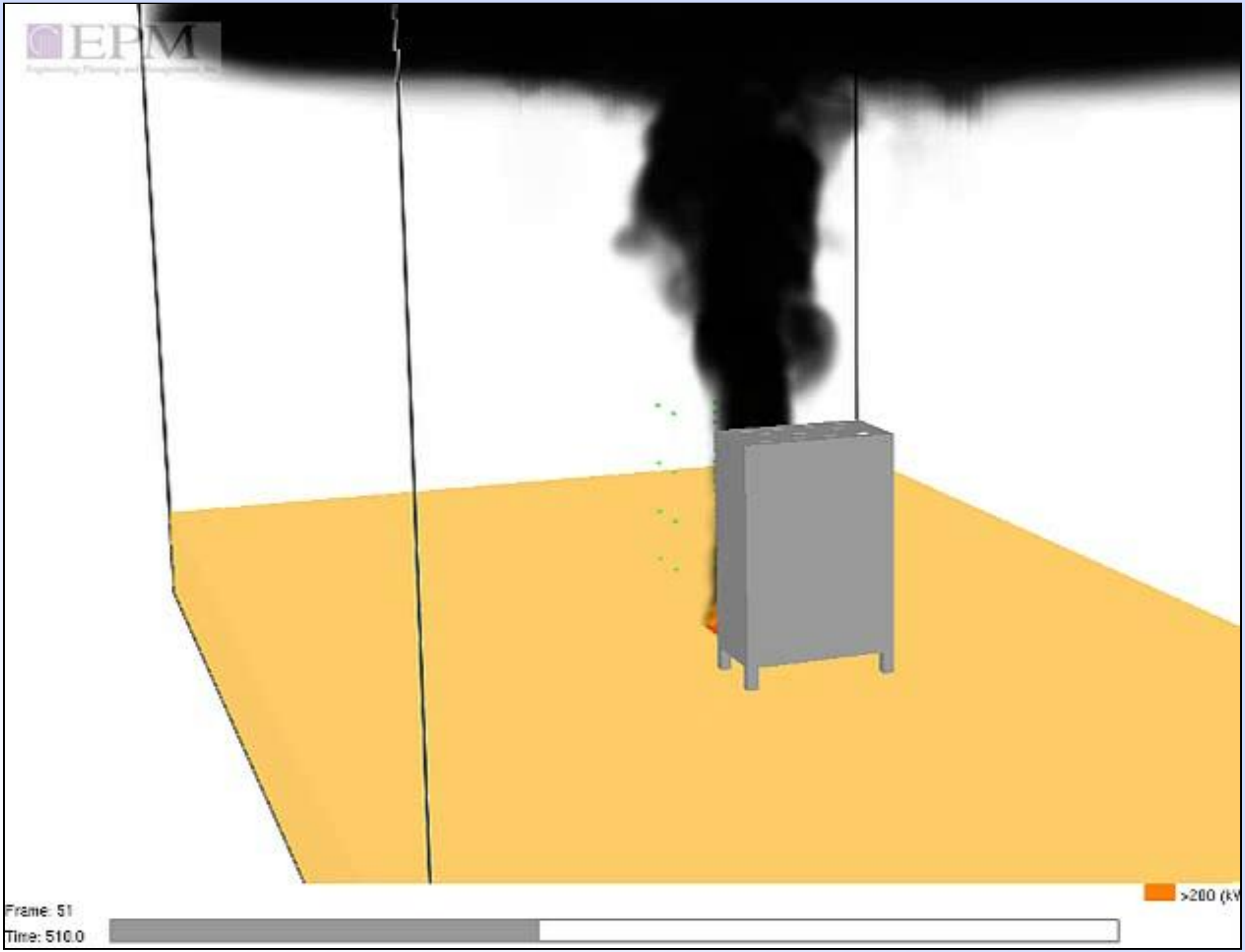

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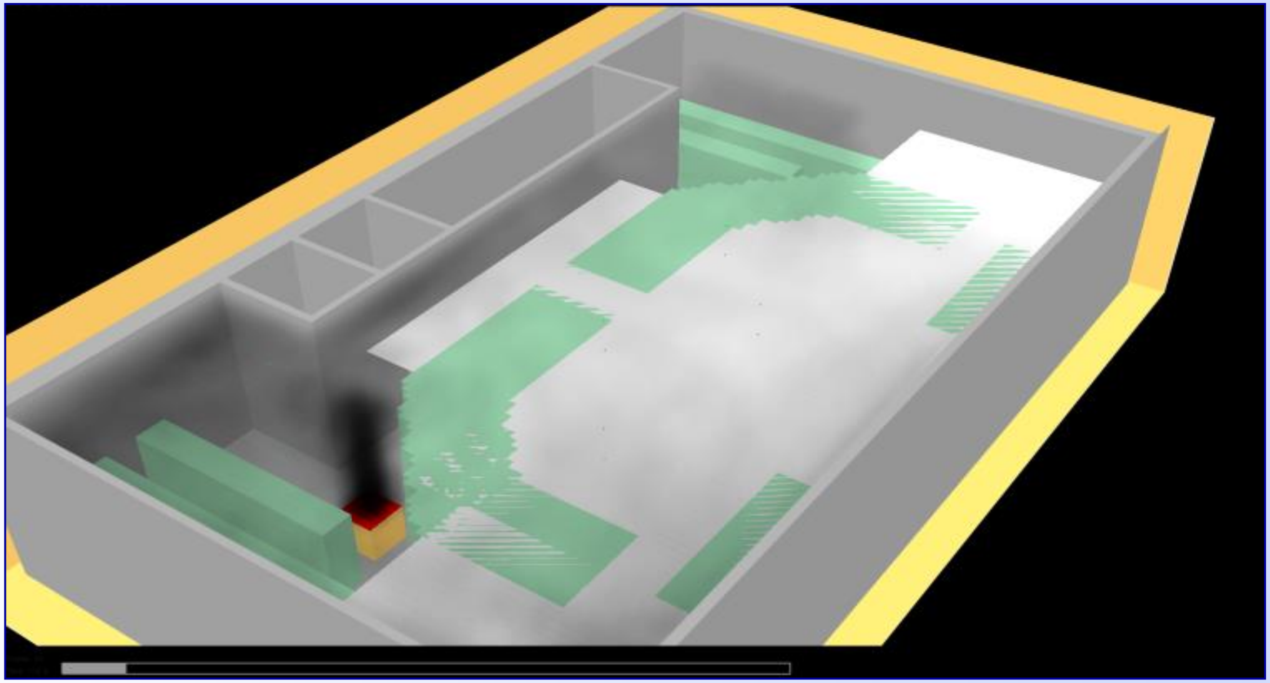
Main Control Room Fire Modeling

- This analysis considers fires that could occur within the MCR. Also considers scenarios from fires in other compartments that may force MCR abandonment



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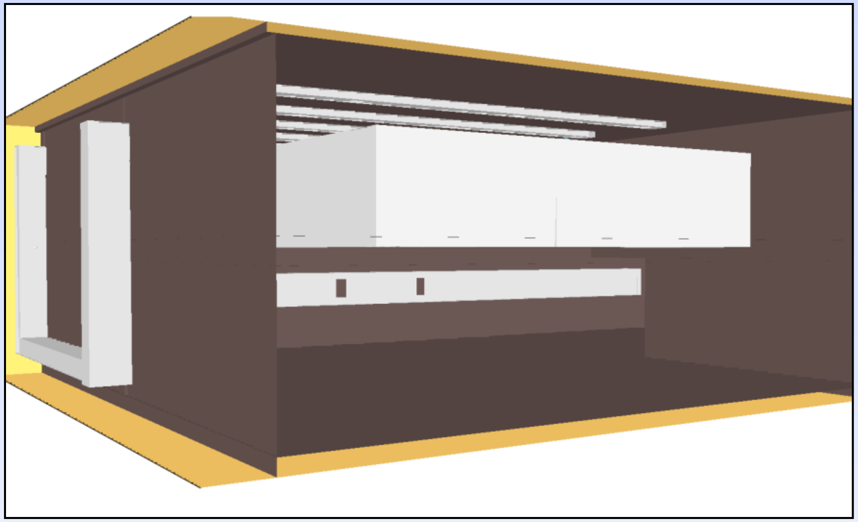
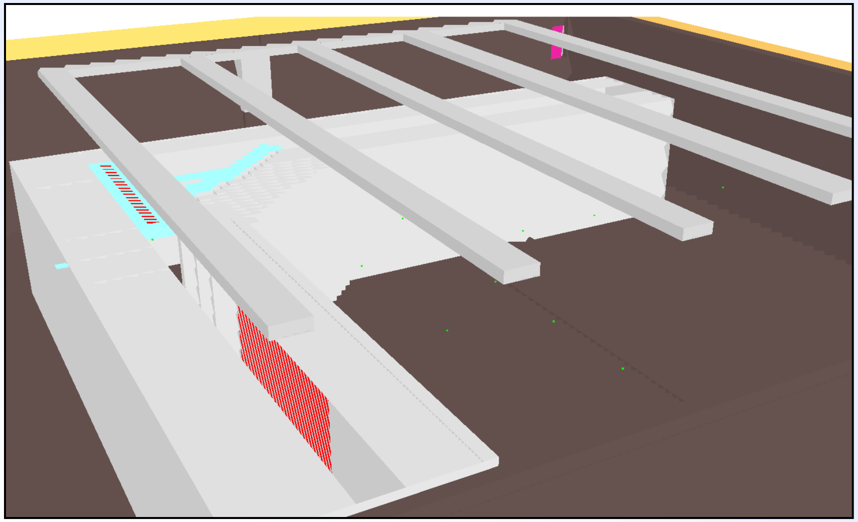
Main Control Room (MCR) Forced Abandonment Example

- Problem: The shared ventilation system between the subject MCR and Cable Spreading Room (CSR) allows air flows to be recycled between the two compartments.
- Openings in the floor of the MCR to the CSR below, protected via fire dampers
- MCR habitability impacted by a fire in the MCR and in the CSR below

MCR and CSR Shared HVAC System





- A smoke-purge mode was not provided for the MCR
  - Normal HVAC system could only be credited until shutdown
  - Duct smoke detection interlock provided in the CSR
  - Upon activation of the smoke detector HVAC stops

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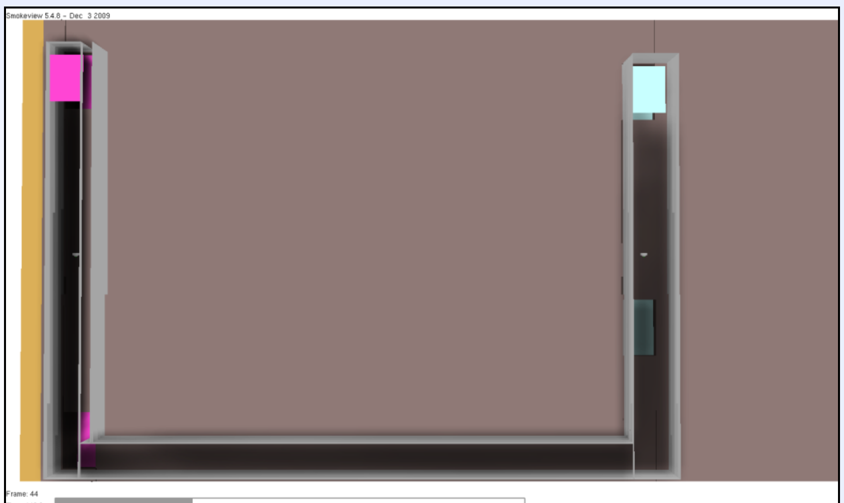
Modeling the HVAC System in FDS



- HVAC ducts modeled as hollow obstructions
- Recycled air flows modeled using fans within the ductwork which induced flows between the compartments
- Fresh ambient air was introduced into the HVAC system via volume fluxes flowing in and out of the computational domain
- Interlock smoke detector modeled in the CSR to shutdown flows at set obscuration point

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Benefits of Using FDS for the MCR Analysis

- Able to predict the effects of a fire in either compartment on the adjacent volume
- Allowed the actual duct configurations and HVAC flows to be modeled
- Simultaneously able to evaluate the impact of recycled air flows between the compartments as well as the introduction of fresh ambient air into the HVAC system
- Allowed normal HVAC flows until interlock activation and system shutdown

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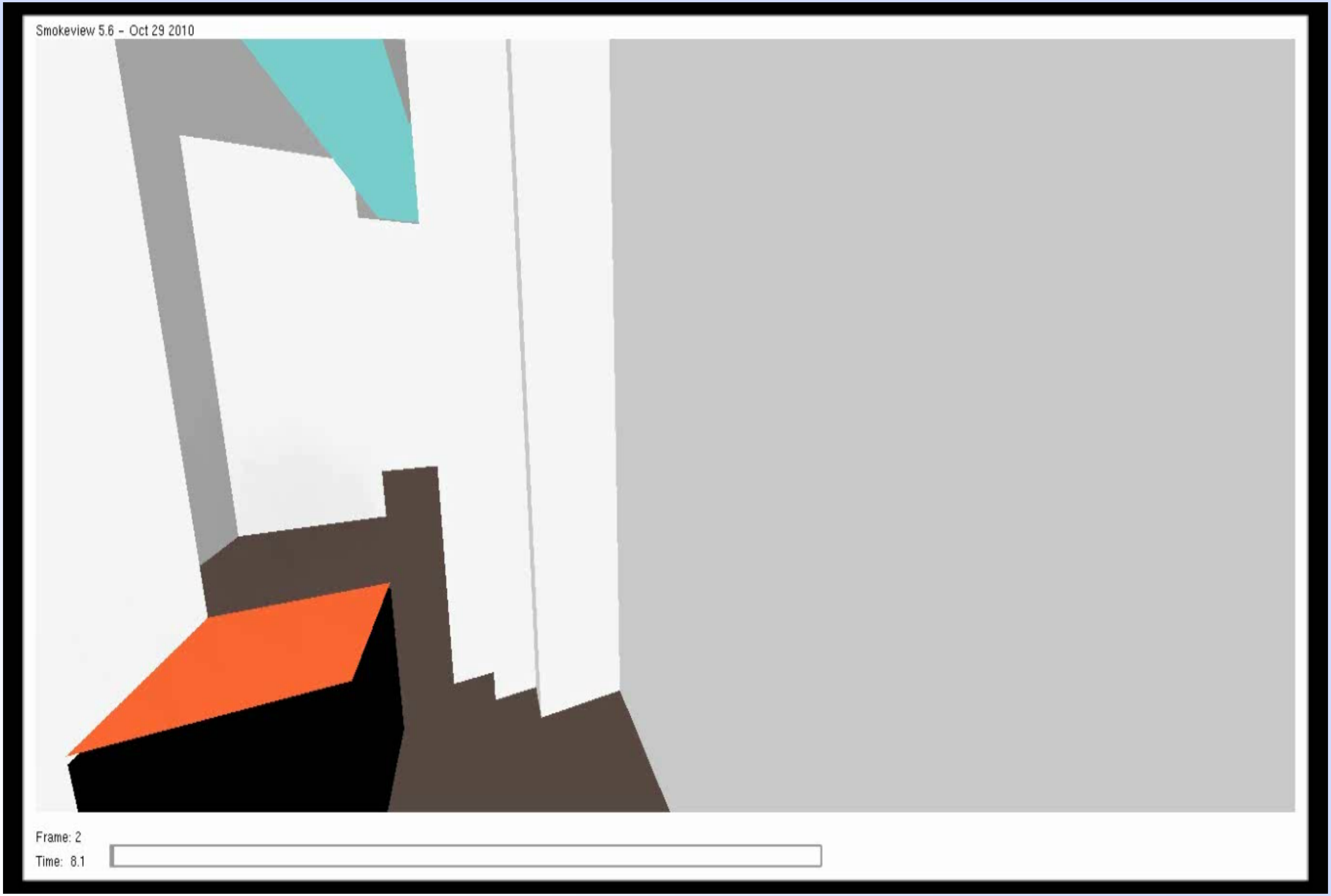

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Summary

- Models vary by complexity directly in relation to the level of detail and accuracy they provide.
  - Closed form correlations are limited to the applications they were developed for, but are the most cost effective.
  - CFAST allows for additional accuracy and detail with moderate resources.
  - FDS serves as a versatile, refined tool to accurately model complex fire modeling scenarios.
- Documented success using fire models in the nuclear power industry within the regulatory process to reduce plant risk and cost.

Questions?

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