Validating Fire Models for Nuclear Power Plant Applications

Mark Henry Salley, P.E. USNRC

Kevin McGrattan, Ph.D. NIST

"Fire Safety in Nuclear Power Plants and Installations"
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Office of Nuclear Regulatory Research

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Introduction

- U.S. nuclear power industry is moving from prescriptive rules towards a risk-informed, performance-based (RI/PB) approach.
- In 2001, National Fire Protection Association issued NFPA Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants."
- In July 2004, the NRC amended its fire protection requirements in 10 CFR 50.48(c) to permit existing reactor licensees to voluntarily adopt NFPA 805.
- RI/PB fire protection utilizes modeling to determine the consequences of a fire. NFPA 805 requires that "fire models shall be verified and validated (V&V)."
- Office of Nuclear Regulatory Research (RES) and EPRI conducted a V&V study (draft NUREG 1824) comparing 5 fire models with measurements from 6 experimental configurations.

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.**

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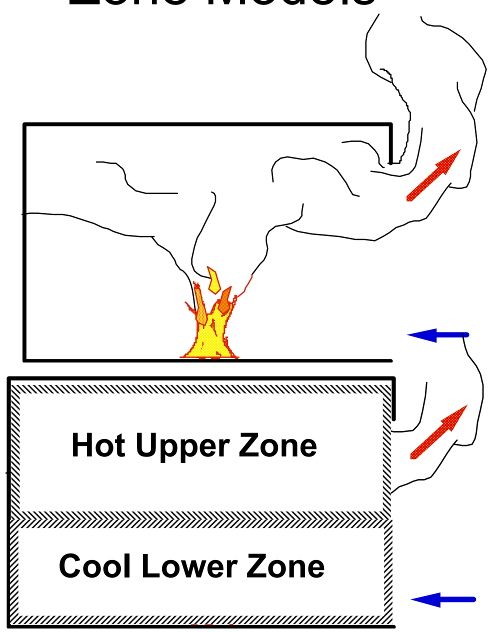
Models Selected

Fire Dynamics Tools (FDTs)	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

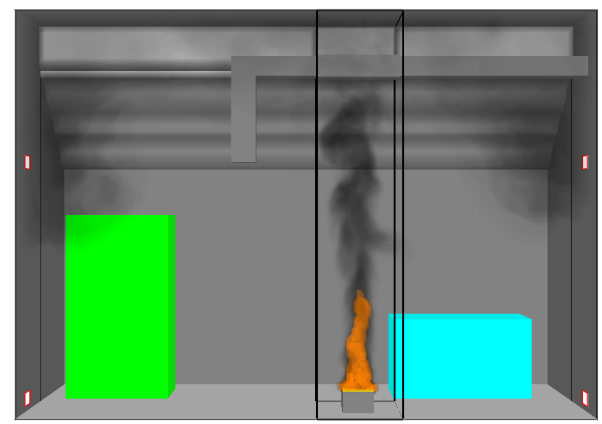
Hand Calculations

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

Zone Models



Field (CFD) Models



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How were the experiments selected?

Selection Criteria: High-Quality Experiments

- **Real-scale experiments**
- **Availability of data**
- **Directly applicable to nuclear power plant applications**
- **Accurate measurement of the fire heat release rate**
- **Complete documentation**
- **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**

Experiments Selected

Six sets of experiments selected (26 tests in all)

Series	Number of Tests	Q (kW)	*V* (m^3)	*H* (m)
FM/SNL	3	500	1400	6.1
NBS	3	100	15	2.4
ICFMP BE #2	3	1800-3600	5900	19
ICFMP BE #3	15	400-2300	580	3.8
ICFMP BE #4	1	3500	74	5.7
ICFMP BE #5	1	400	73	5.6

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Since 2000, the US Nuclear Regulatory Commission has participated in the International Collaborative Fire Model Project (ICFMP) to evaluate fire models for nuclear power plant applications. The participants include:

Électricité de France	**Magic**
Fire Research Station, UK	**JASMINE**
GRS, Germany	**COCOSYS, CFX**
iBMB, Germany	**Validation Experiments**
IRSN, France	**Flamme-S**
NRC/NIST, USA	**CFAST, FDS**
VTT, Finland	**Validation Experiments**

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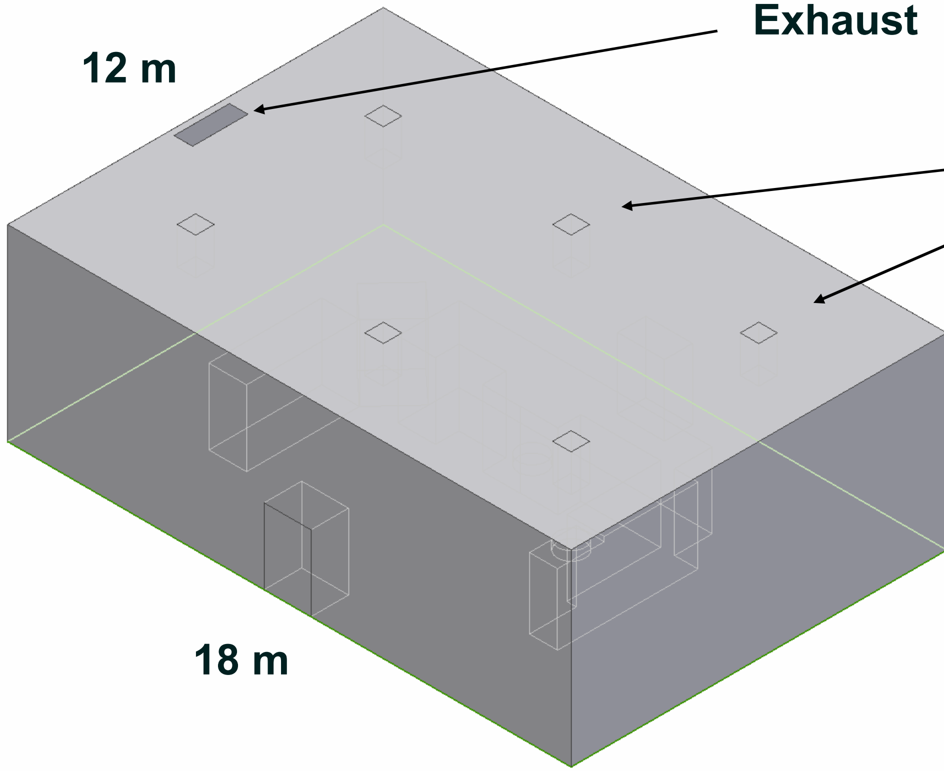
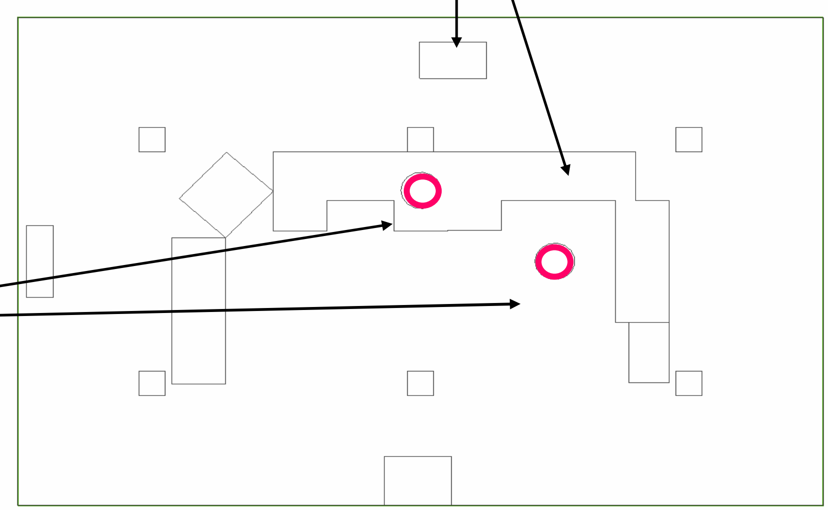
Factory Mutual / Sandia National Labs (1985)





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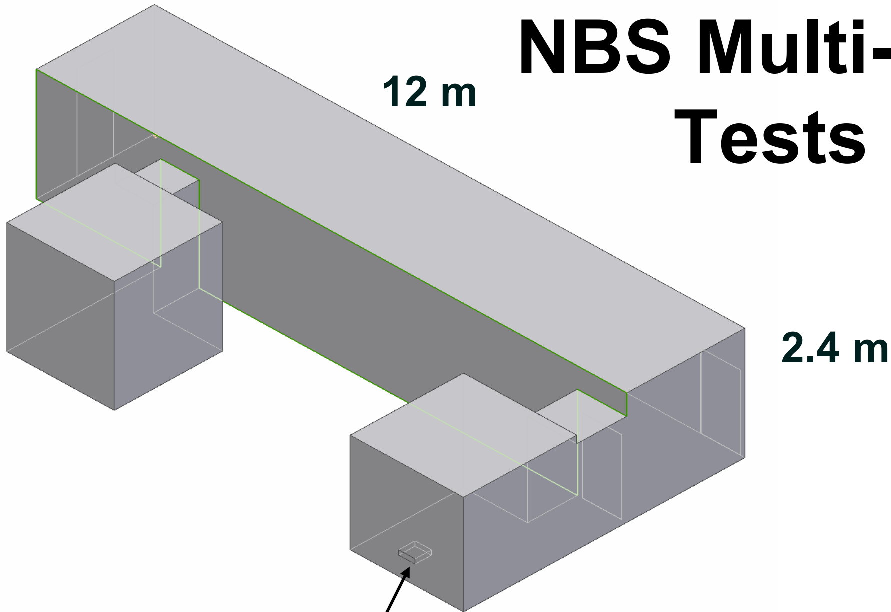
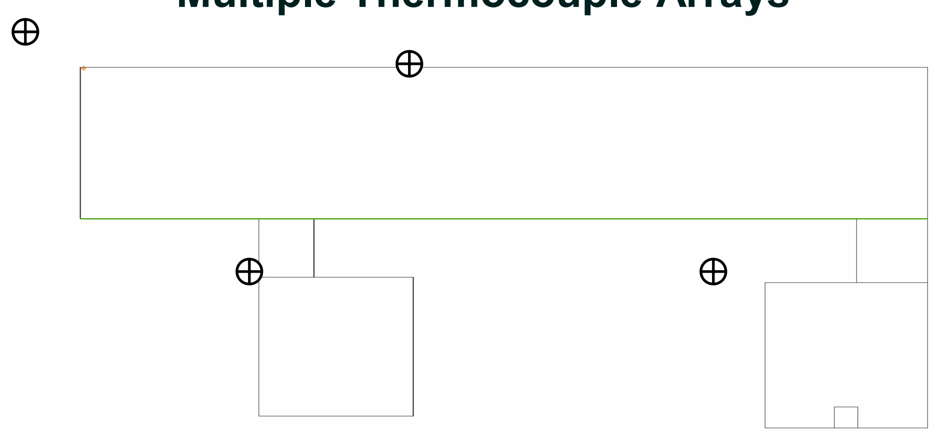
NBS Multi-Room Fire Tests (1985)



100 kW
Natural Gas

Multiple Thermocouple Arrays



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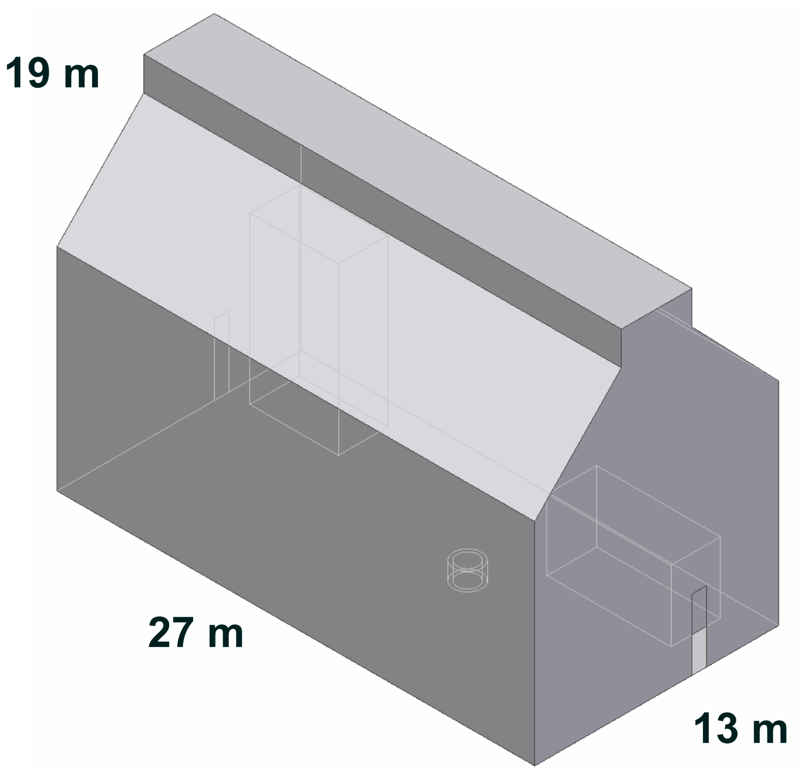
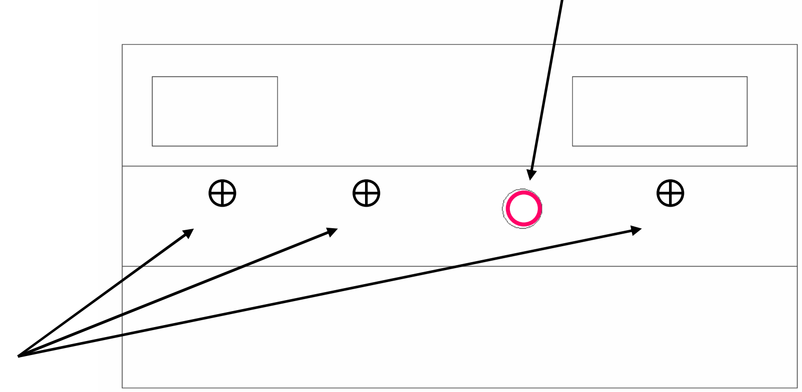
VTT (Finland) Large Hall Fire Tests (1998-1999)

ICFMP Benchmark Exercise #2





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NIST/NRC Fire in a Switch Gear Room (2003)

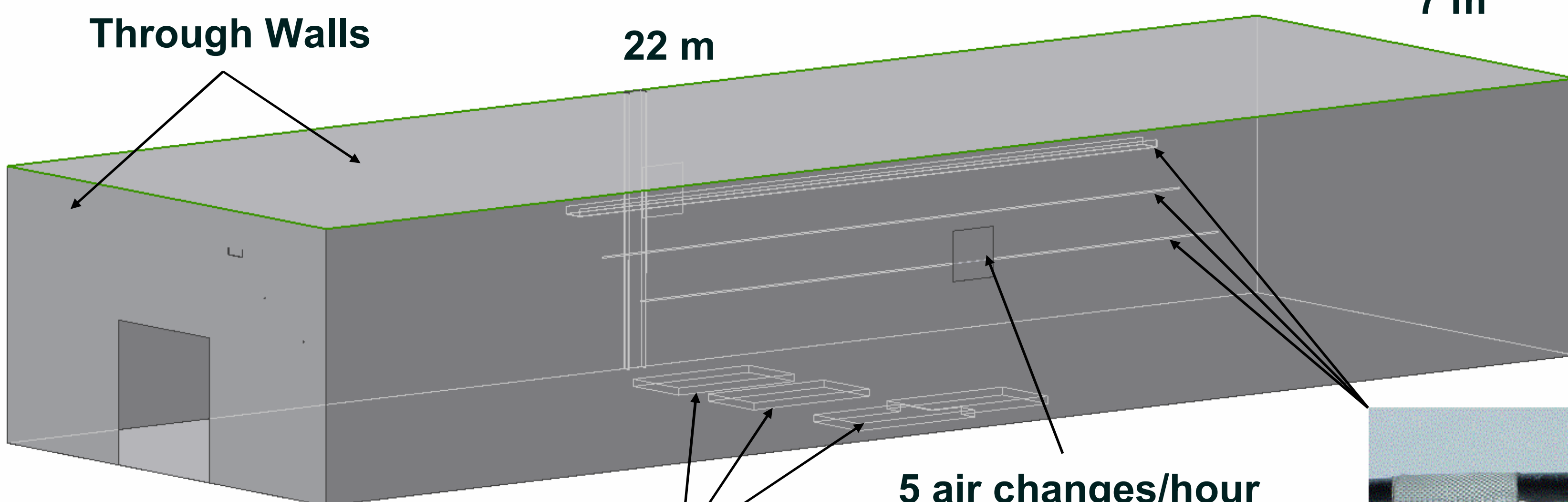
ICFMP Benchmark Exercise #3

Heat Flux Through Walls

22 m

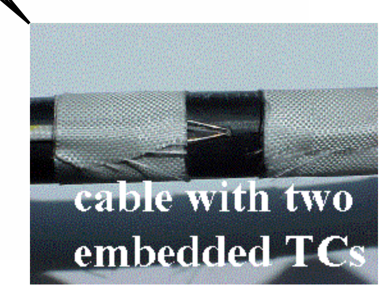
7 m

4 m

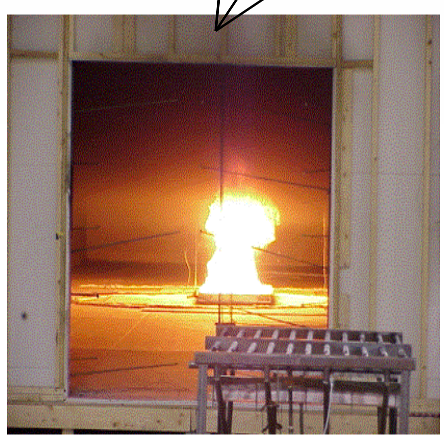


Mass/Energy Flow out Door

5 air changes/hour



400 to 2300 kW
Heptane Spray Fires



15 Tests
350 Measurements Per Test

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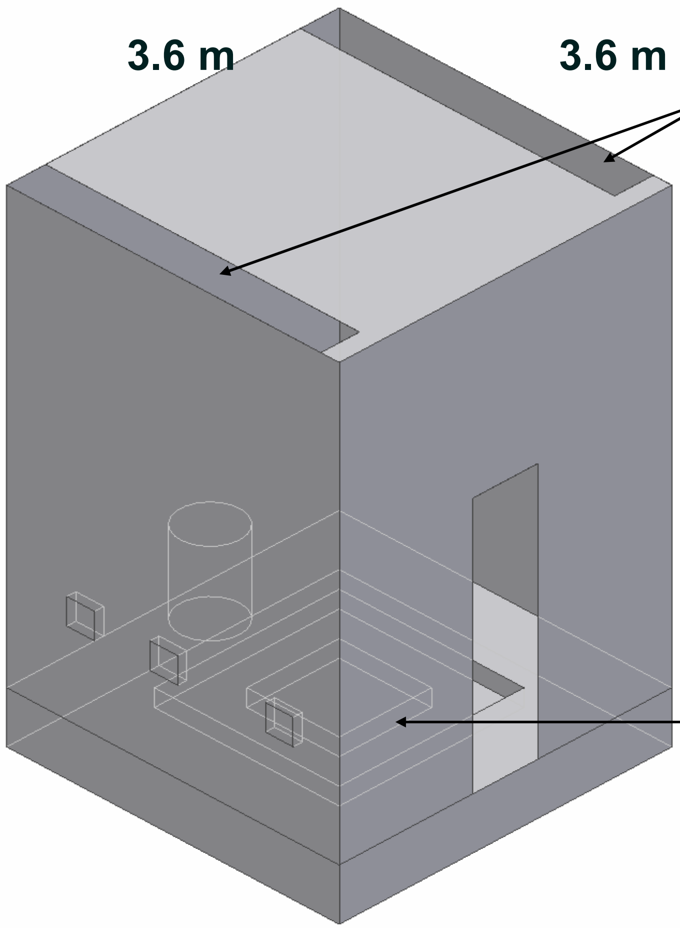
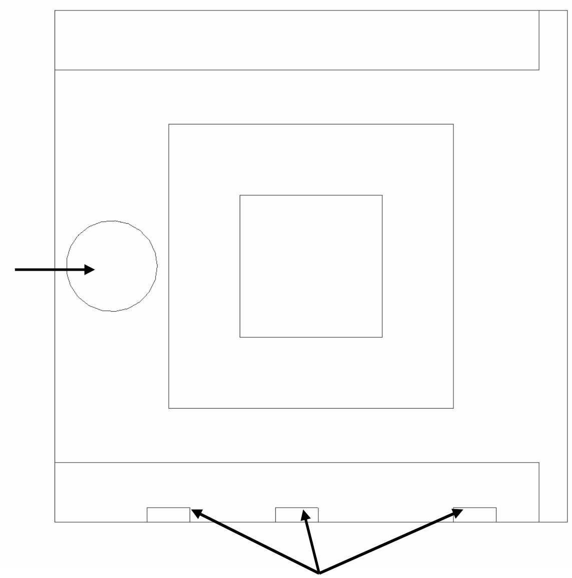
Institut für Baustoffe, Massivbau und Brandschutz (iBMB) Germany (2004) Pool Fire Inside a Compartment

ICFMP Benchmark Exercise (BE) #4





3.5 MW
Jet Fuel Fire

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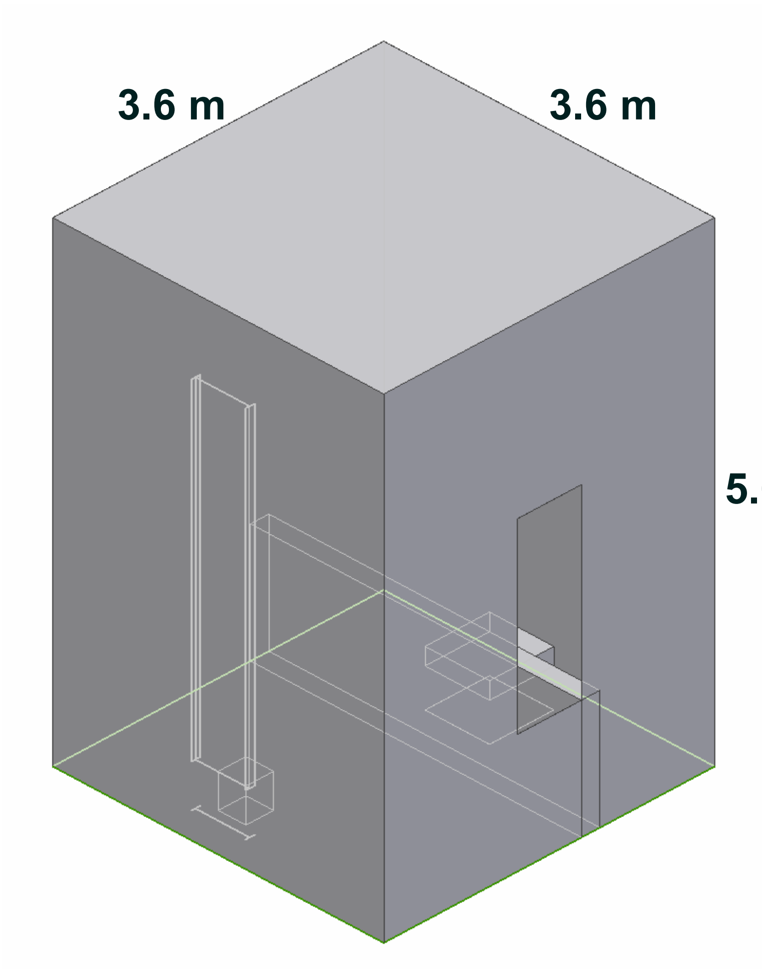
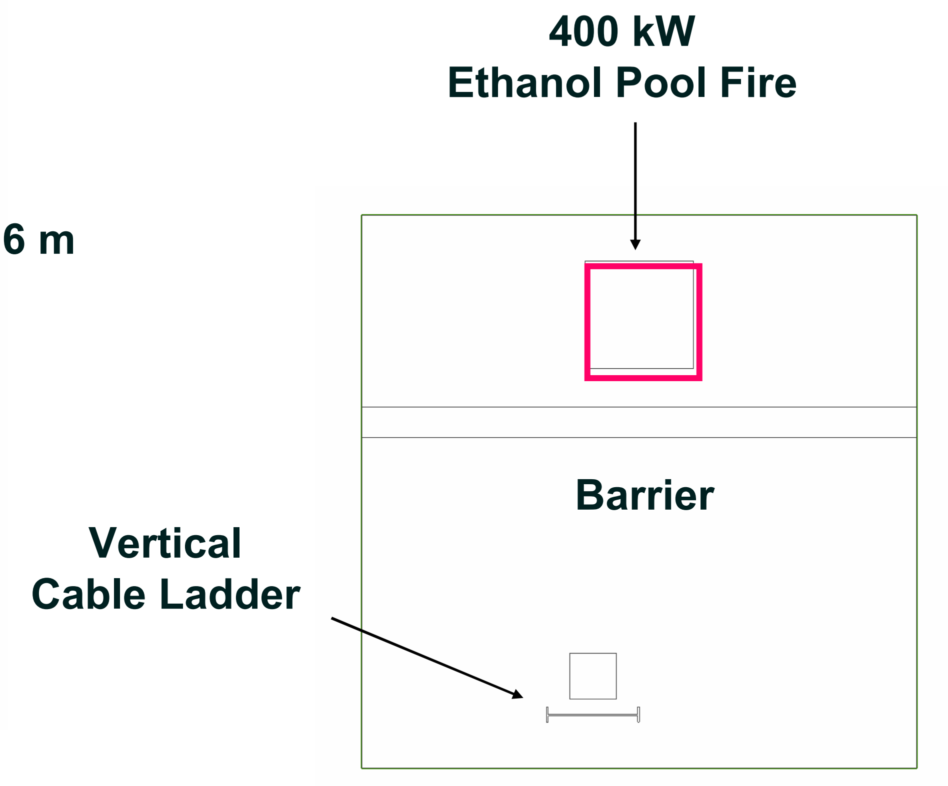
Institut für Baustoffe, Massivbau und Brandschutz (iBMB) Germany (2004) Flame Spread in Cable Trays

ICFMP Benchmark Exercise #5





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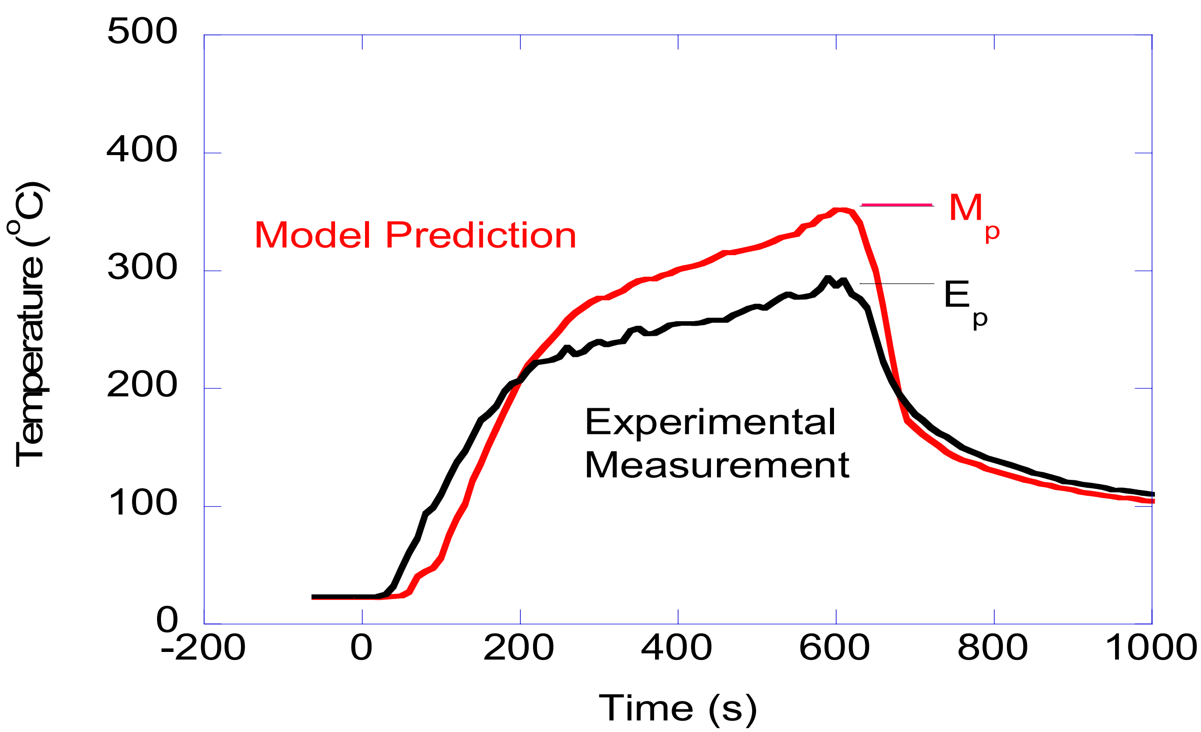
List of quantities

- Hot gas layer temperature
- Hot gas layer height
- Ceiling jet temperature
- Plume temperature
- Flame height
- Oxygen concentration
- Smoke concentration
- Compartment pressure
- Radiated heat flux to target
- Total heat flux to target
- Target temperature
- Total heat flux to walls
- Wall temperature

Comparison of Models with Actual Measurements

What is “The degree of accuracy required for each quantity?” NFPA 805 and ASTM E 1355 don’t say.

Big Idea – Use experimental uncertainty as a yardstick.



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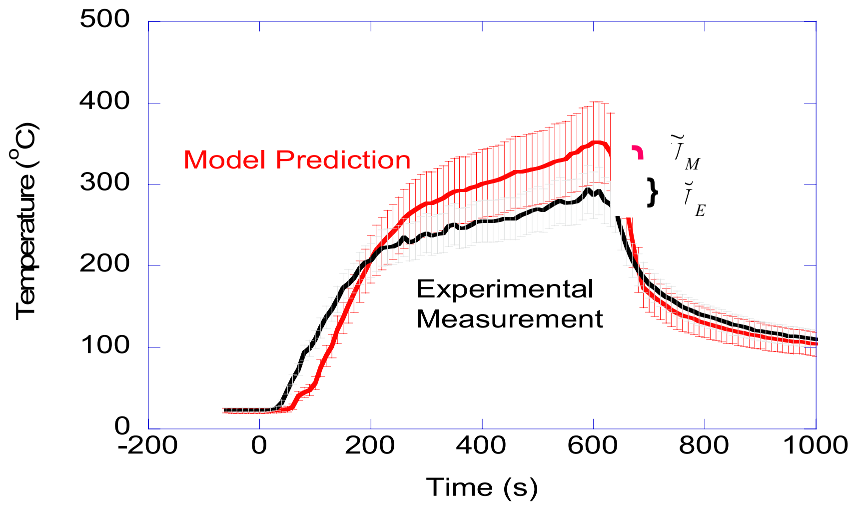
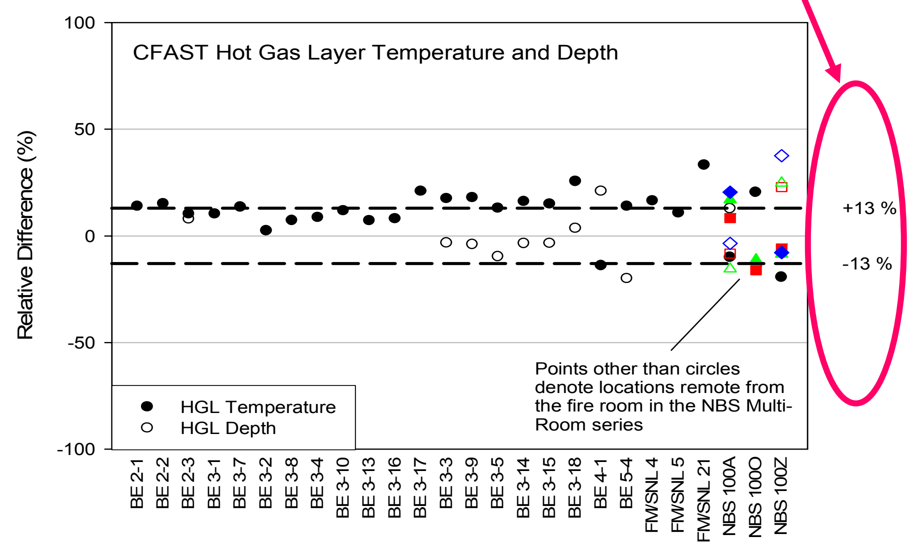
Model Evaluation Approach

$$\varepsilon = \frac{M_p - E_p}{E_p}$$ **Define relative difference**

$$U_C = \left(\widetilde{U}_M^2 + \widetilde{U}_E^2\right)^{1/2}$$ **Combine measurement and model uncertainty**

$$|\varepsilon| < U_C$$ **Assessment**





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Model Input Uncertainty

Experimental heat release rate, $\dot{Q}$ drives fire effects, and its uncertainty dominates model uncertainty.

$$\dot{Q} = \chi_a \cdot \dot{m} \cdot H_c$$

$\dot{Q} = heat\ release\ rate\ (kW)$

$\dot{m} = mass\ burning\ rate\ (g/s)$

$\chi_a = combustion\ \ efficiency$

$H_c = heat\ of\ \ combustion\ \ (kJ/g)$

Example: Hot Gas Layer (HGL) Temperature

According to an empirical correlation substantiated by hundreds of measurements:

$$T_g - T_\infty = 6.85 \left(\frac{\dot{Q}^2}{A_0 \sqrt{H_0} h_k A_T} \right)^{1/3} \propto \dot{Q}^{2/3}$$

$$\frac{\delta T}{\mathrm{T}} = (2/3) \frac{\delta \dot{Q}}{\dot{Q}}$$

Uncertainty in HRR measurements is roughly 15 %

Uncertainty in the HGL temperature prediction varies by 2/3 x 15 % = 10 %

Combined Uncertainty

$$U_C = \left(\widetilde{U}_M^2 + \widetilde{U}_E^2\right)^{1/2}$$

Summary of the Relative Expanded Uncertainties
Associated with the HGL Layer Depth and Temperature Rise

Series	HGL Depth			HGL Temperature Rise		
	$\widetilde{U}_E$ (%)	$\widetilde{U}_M$ (%)	U_c (%)	$\widetilde{U}_E$ (%)	$\widetilde{U}_M$ (%)	U_c (%)
NBS	6	2	6	6	10	12
FM/SNL	23	2	23	10	13	16
BE #2	8	2	8	9	10	13
BE #3	6	2	6	6	11	12
BE #4	22	2	22	6	17	18
BE #5	9	2	9	7	10	12

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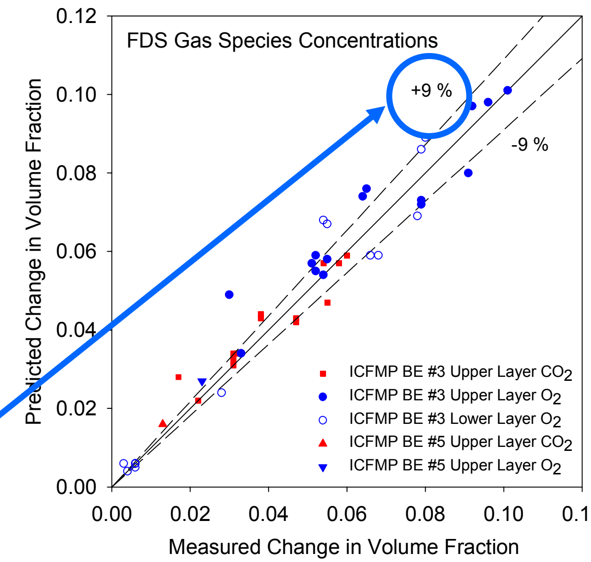
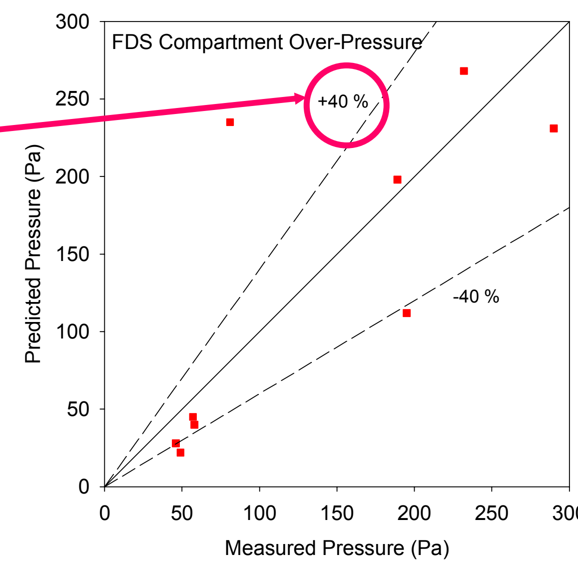
Representative Uncertainties

Parameter	Number of Tests	Weighted Combined Uncertainty (%)
HGL Temperature Rise	26	13
HGL Depth	26	9
Ceiling Jet Temperature	18	16
Plume Temperature	6	14
Gas Concentration	16	9
Smoke Concentration	15	33
Pressure	15	40 (no forced ventilation)
		80 (with forced ventilation)
Heat Flux	17	20
Surface / Target Temperature	17	14





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NUREG-1824
Draft for Comment

EPRI 1011999
Preliminary Report

Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications

Volume 1: Main Report

December 2005

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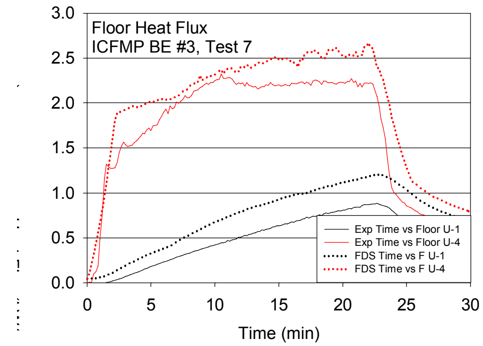
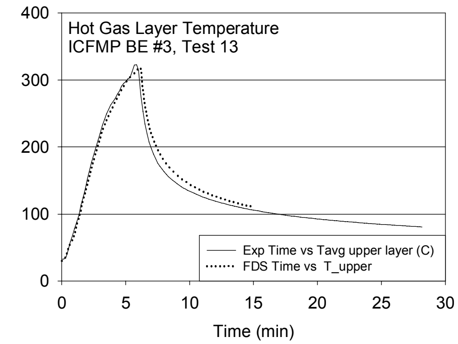
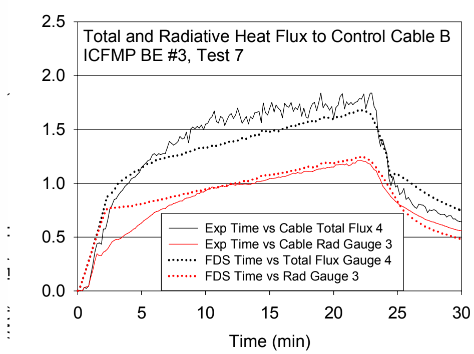
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

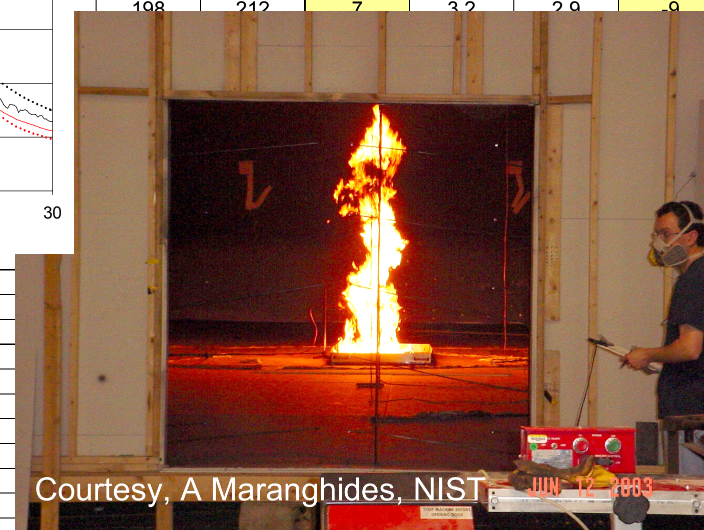
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

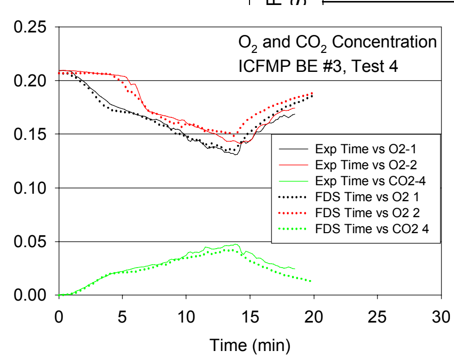




		HGL Temperature Rise			HGL Depth		
		Exp. (°C)	FDS (°C)	Rel. Diff. (%)	Exp. (m)	FDS (m)	Rel. Diff. (%)
BE #2	Case1	55	66	21	14.6	14.9	3
	Case2	86	102	18	14.8	15.3	4
	Case3	83	101	23	13.9	14.1	2
	Test 1	123	125	2	3.0	3.0	-1
		117	122	5	3.1	3.0	-1
		229	220	-4	3.0	2.9	-3
		218	220	1	3.0	2.9	-2
		204	214	5	3.0	2.9	-2
		198	212	7	3.2	2.9	-9
	BE #4 Test 1						
	BE #5 Test 4						
FM/SNL	Test 4						
	Test 5						
	21						
	EXI	--	92	--	2.2	2.1	-4
	BR	260	234	-10	1.2	1.1	-2
	18	65	75	16	1.2	1.2	-1
	38	67	68	2	1.2	1.4	13
	TR	35	40	14	1.5	1.5	-1




Courtesy, A Maranghides, NIST




Courtesy, S Hostikka, VTT

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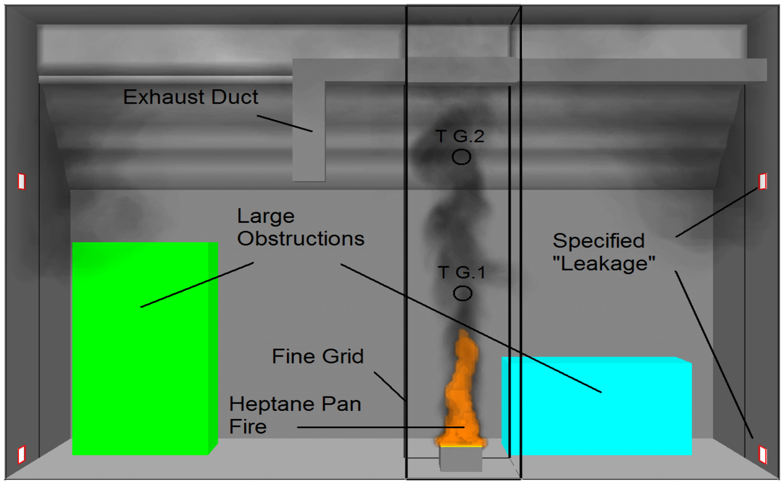
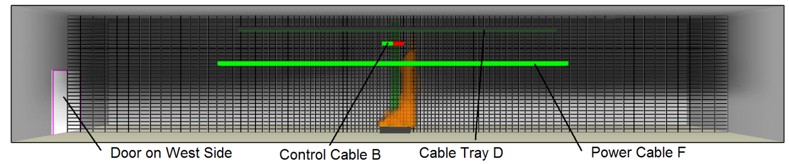
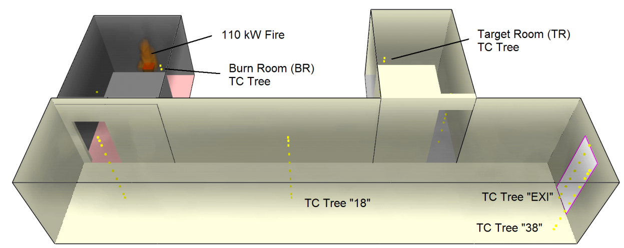


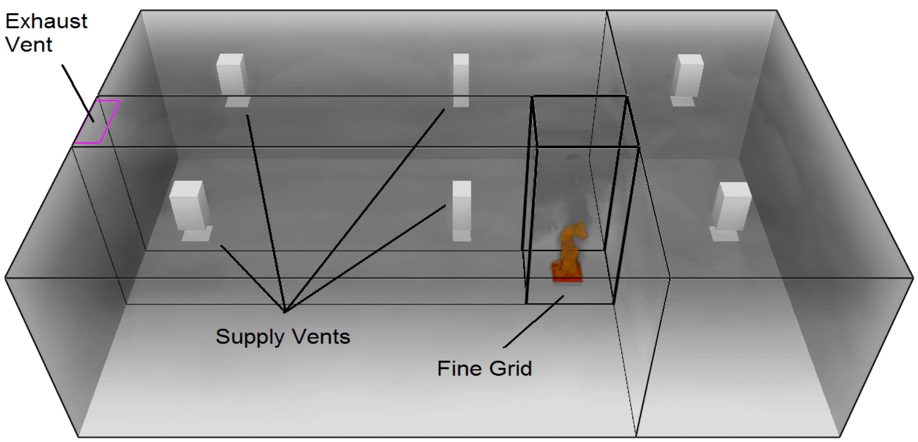
VTT, Finland



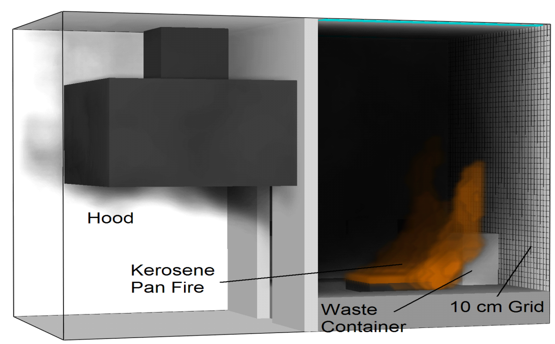
NIST, USA



NBS, USA



Sandia/FM (USA)



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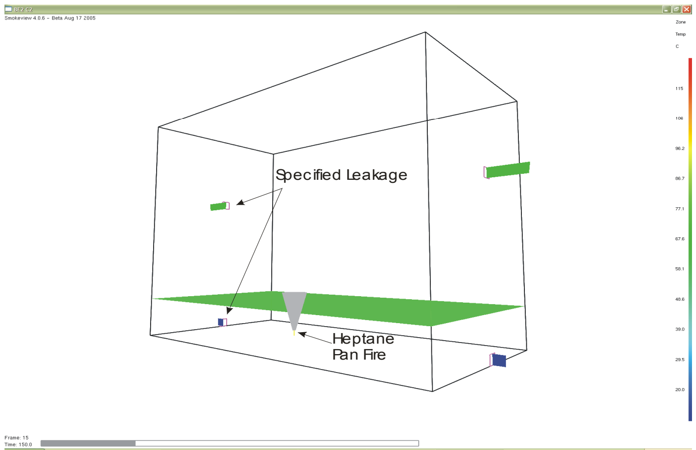

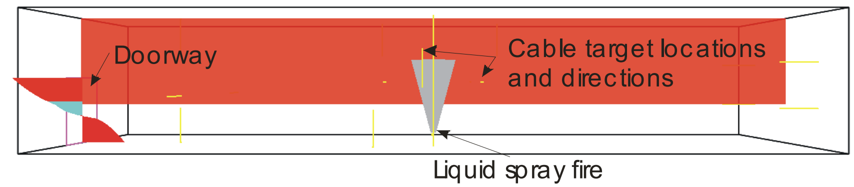

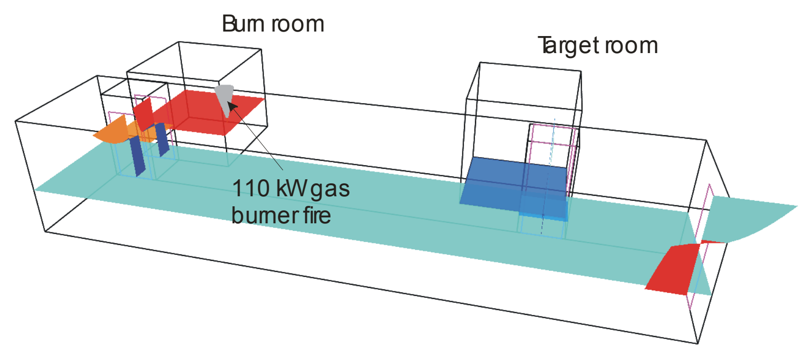

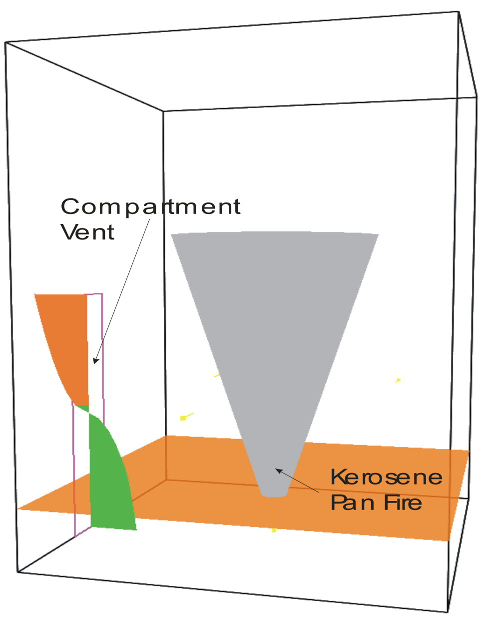

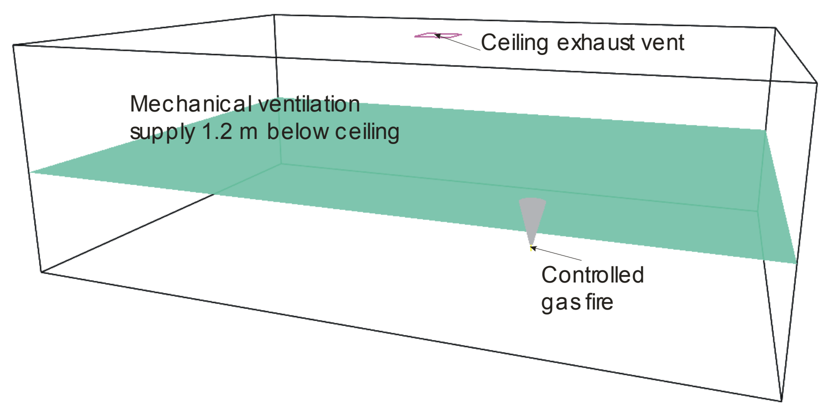

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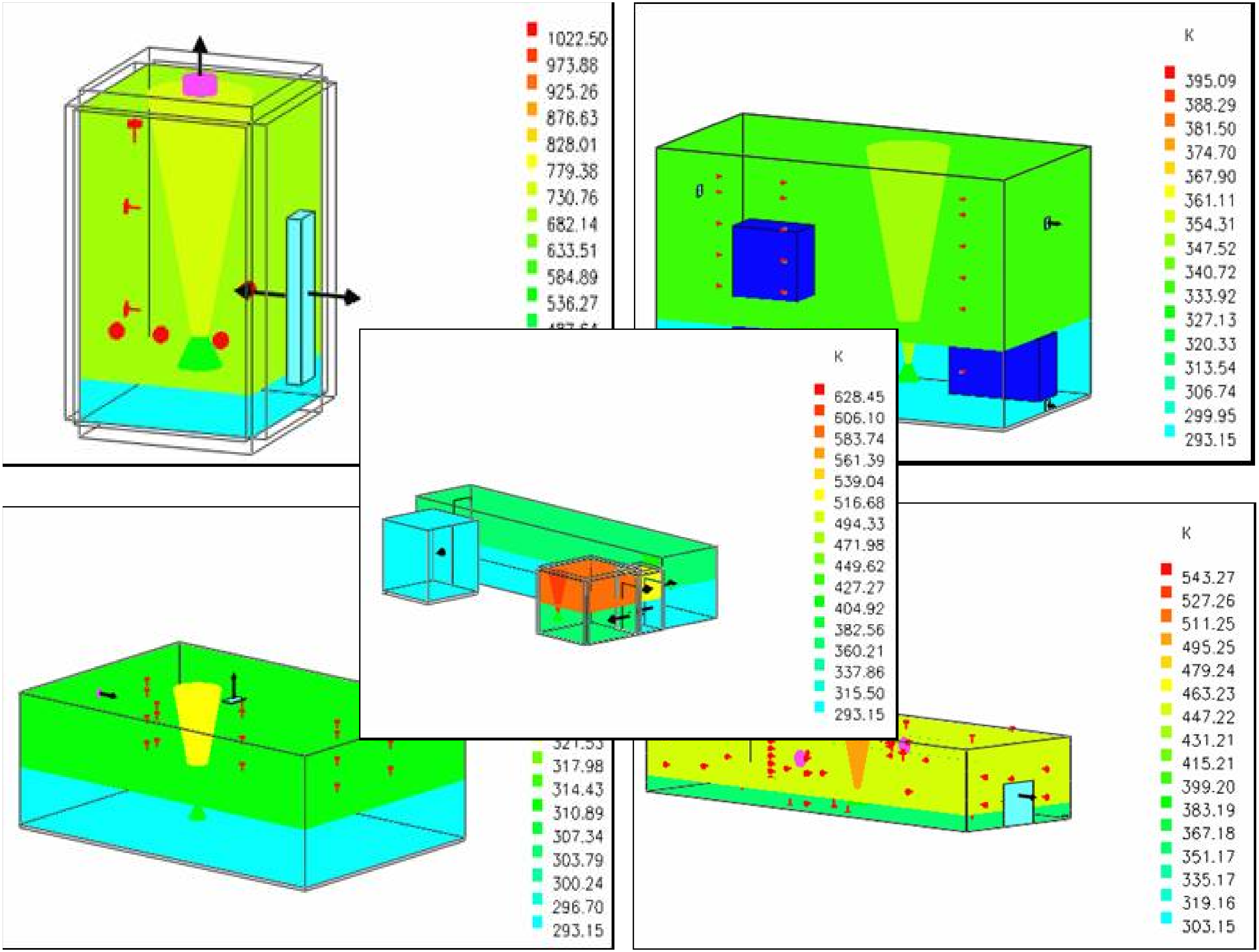

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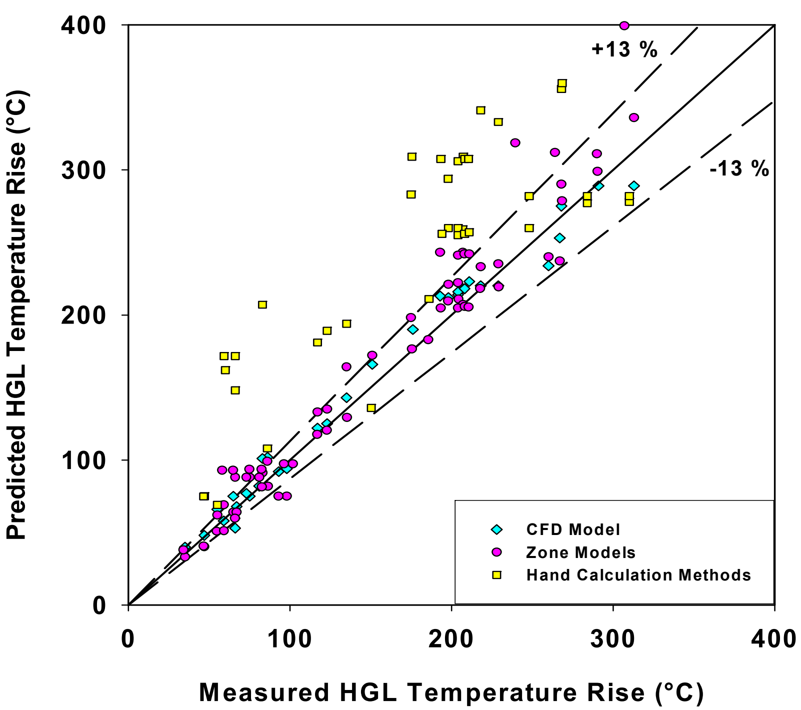
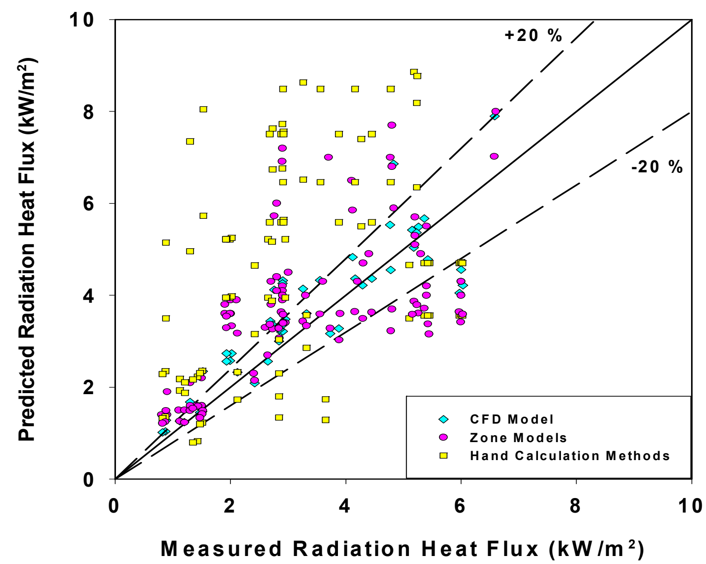
Results of NRC V&V (NUREG 1824)





From _Fire Protection Engineering_, Spring 2007

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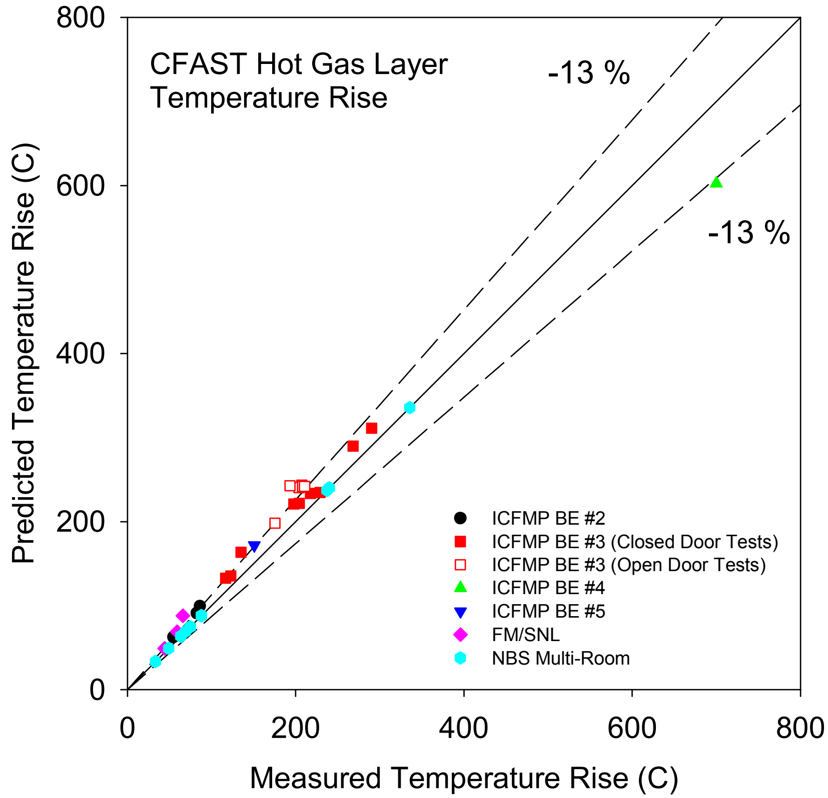
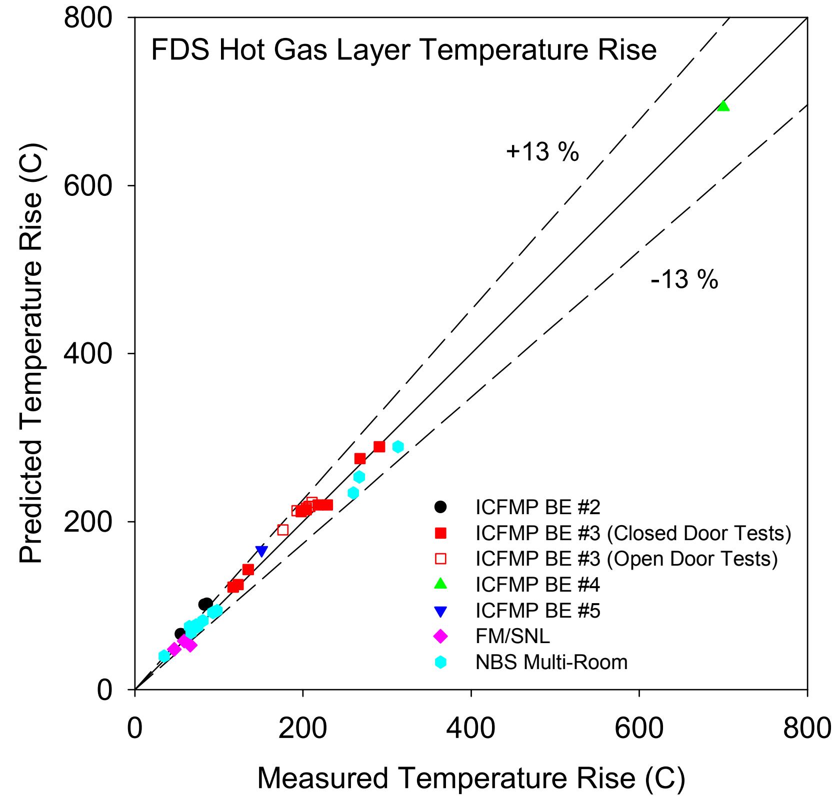
Hot Gas Layer Temperature





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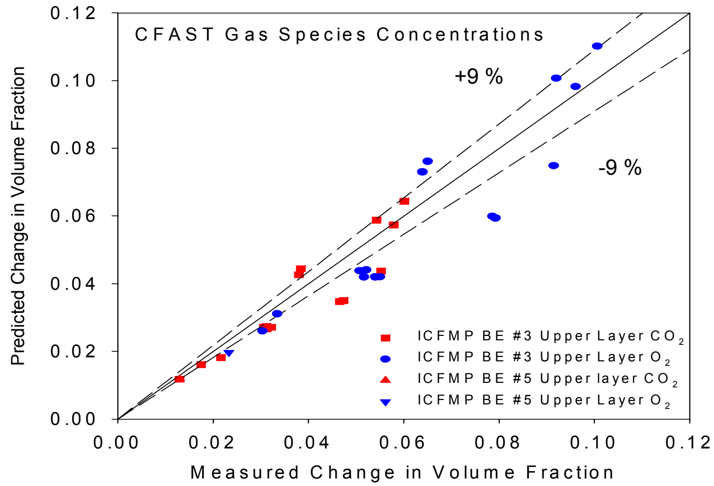
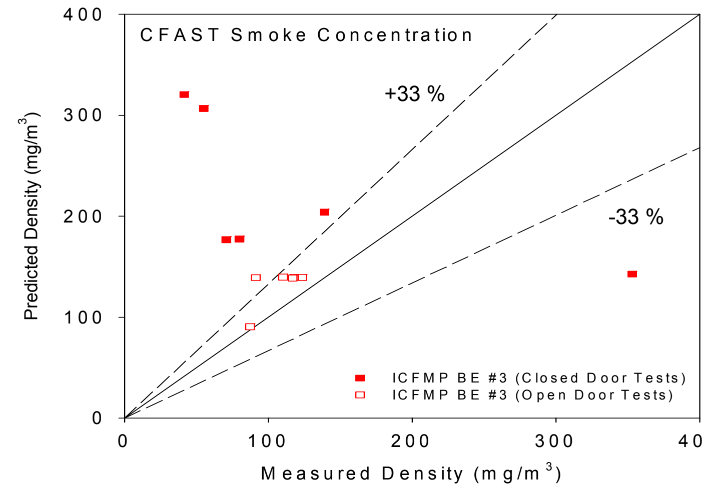
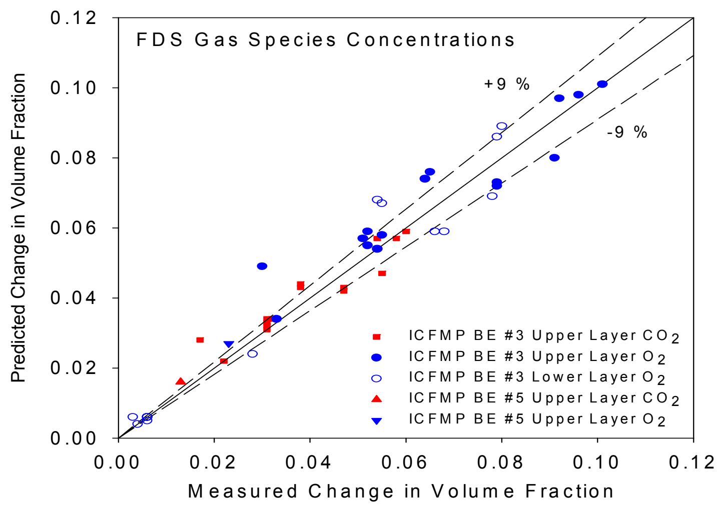
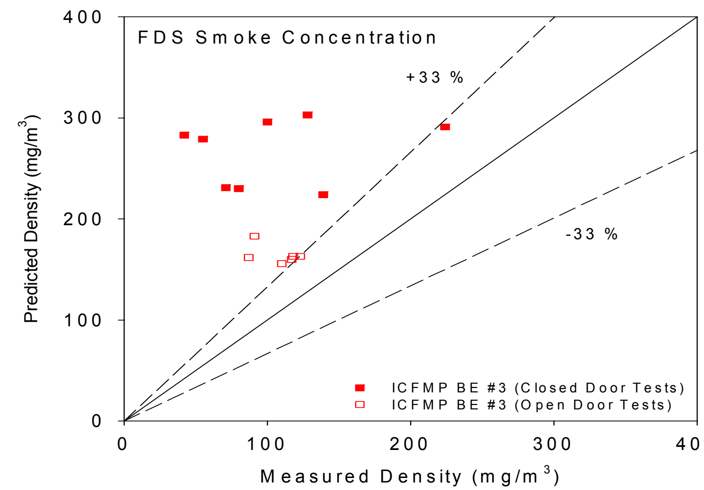
CFAST
Gas Species and Smoke





FDS
Gas Species and Smoke





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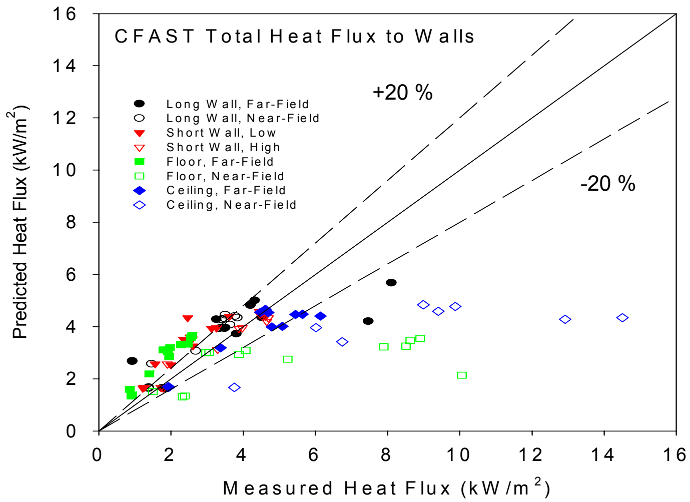
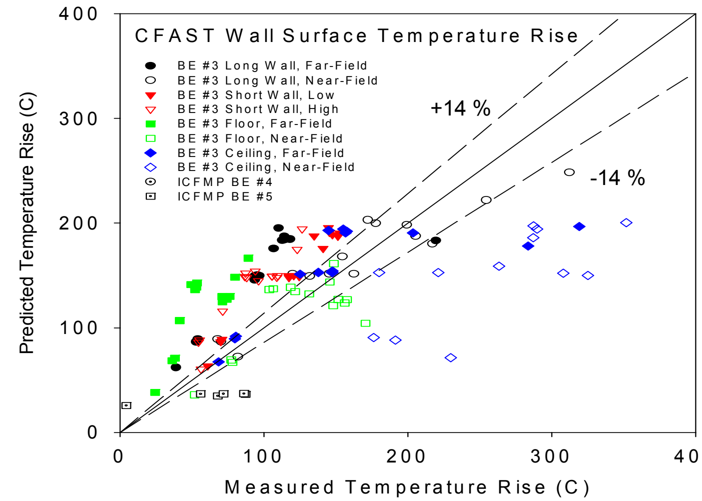
CFAST
Heat Flux and
Wall Temperature





FDS
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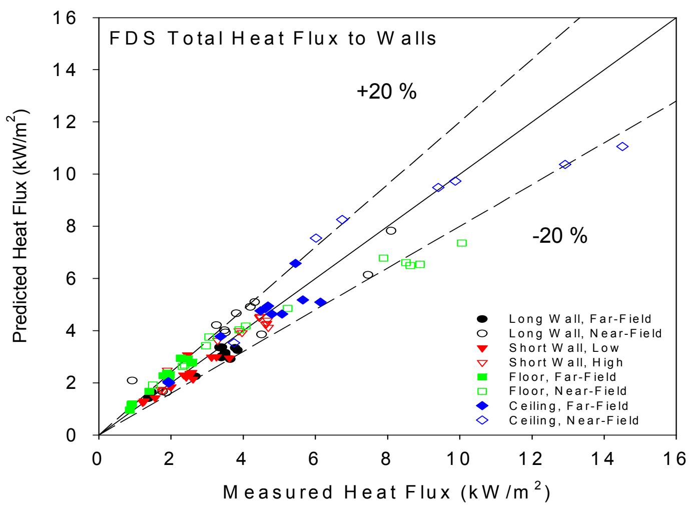

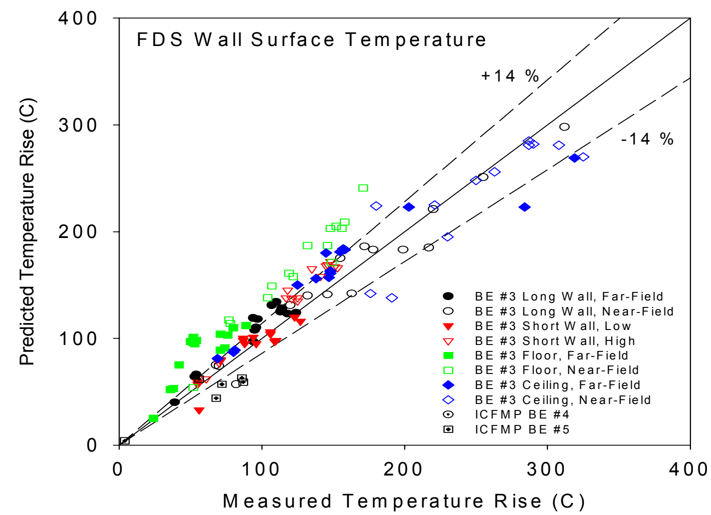

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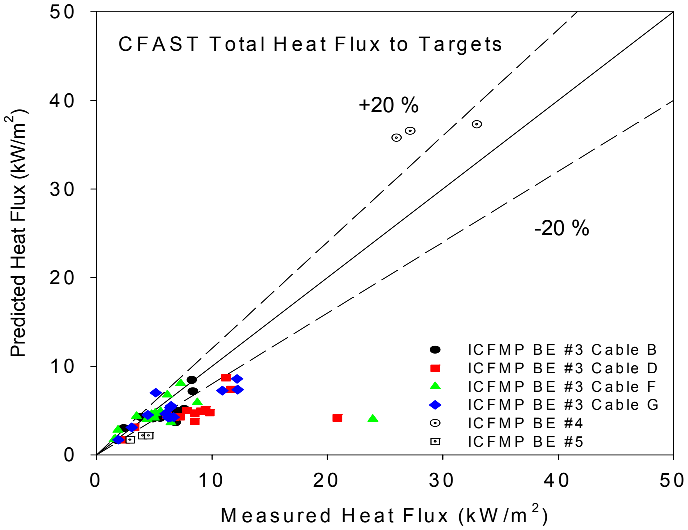
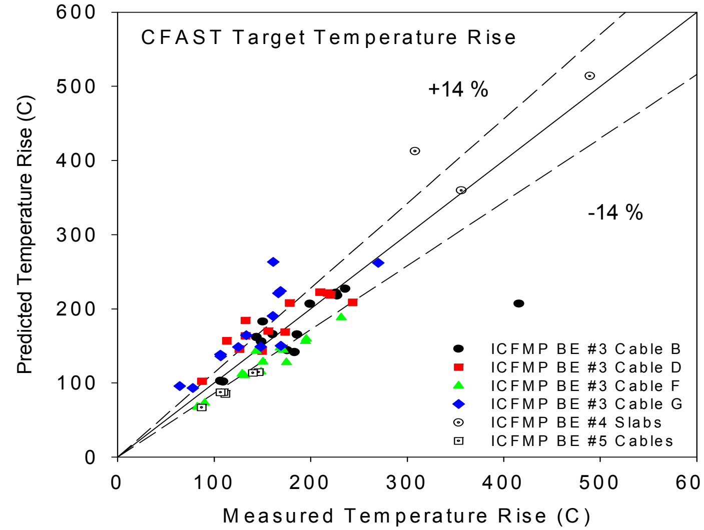
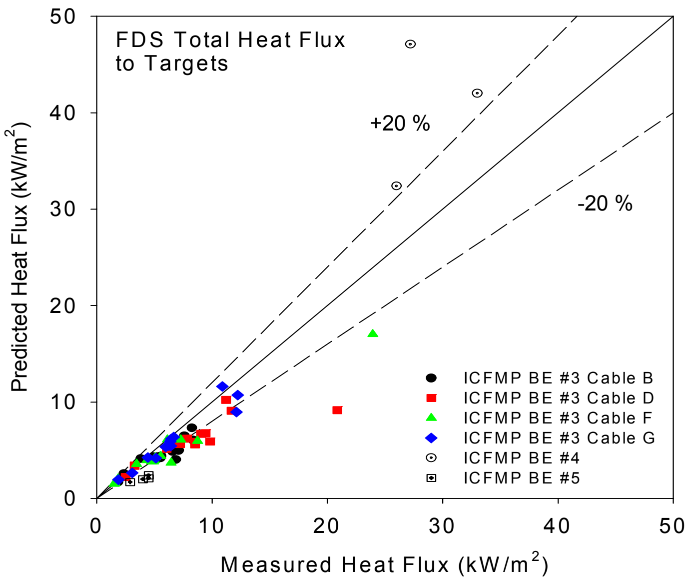
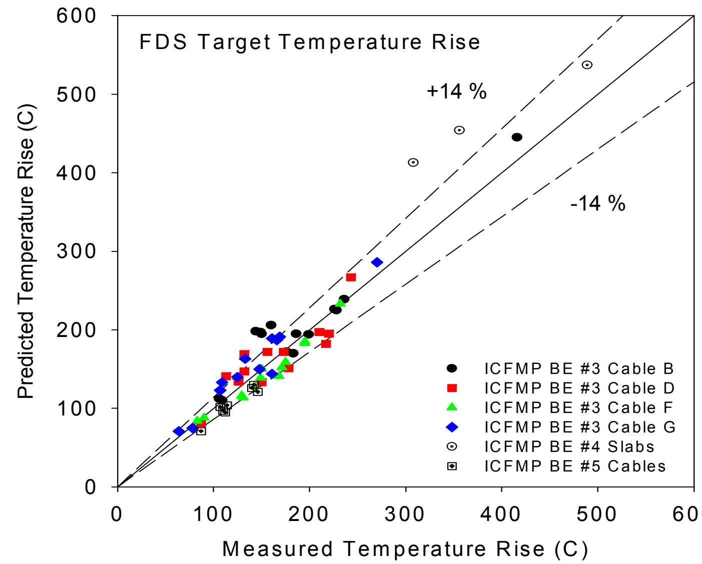
CFAST
Heat Flux and Target Temperature





FDS
Heat Flux and Target Temperature





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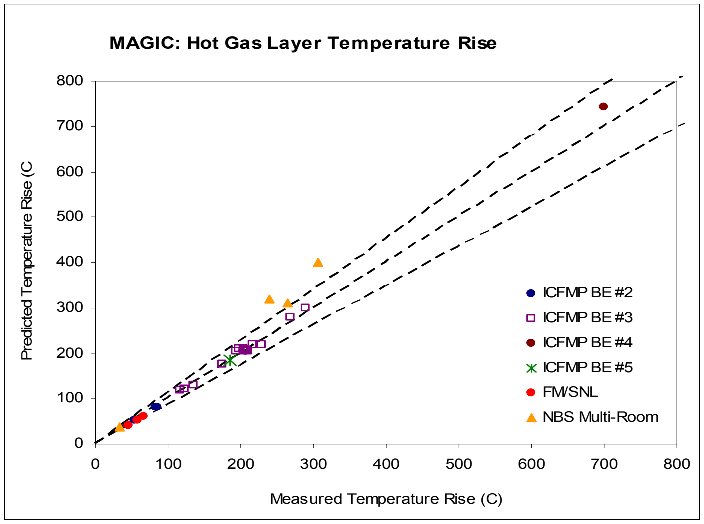
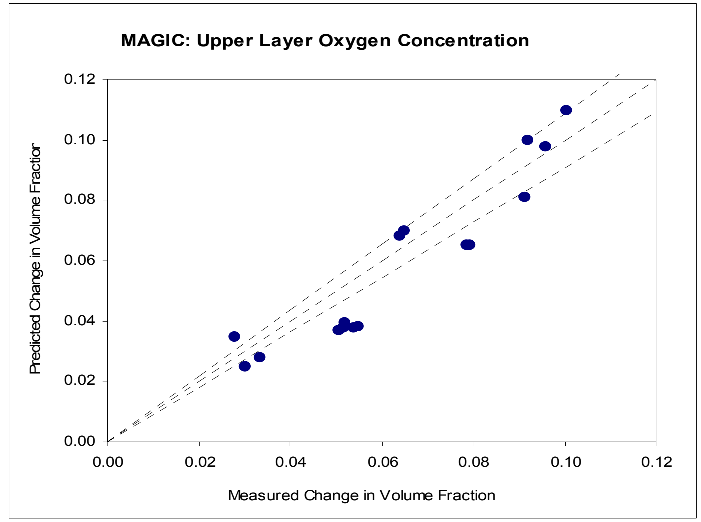
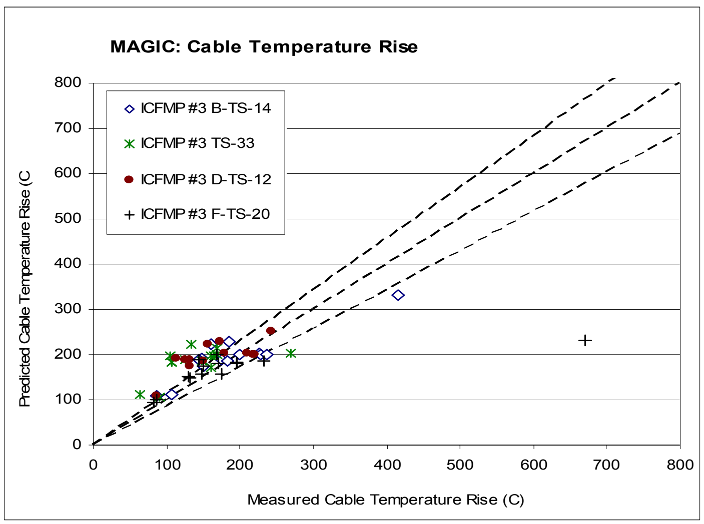
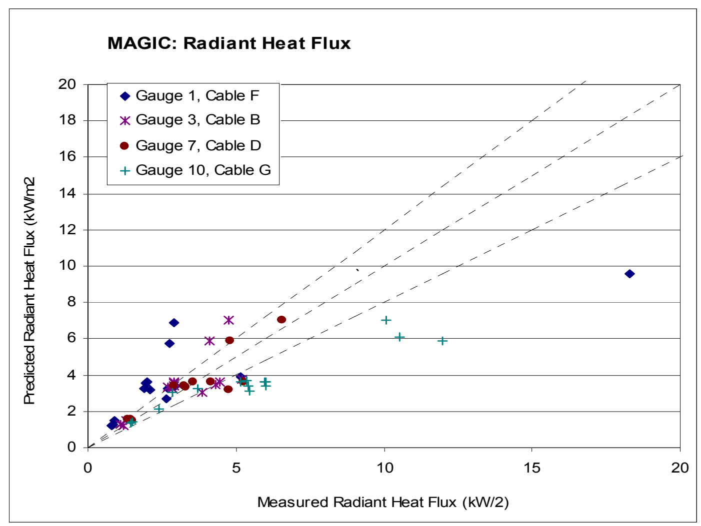
V&V Results for MAGIC









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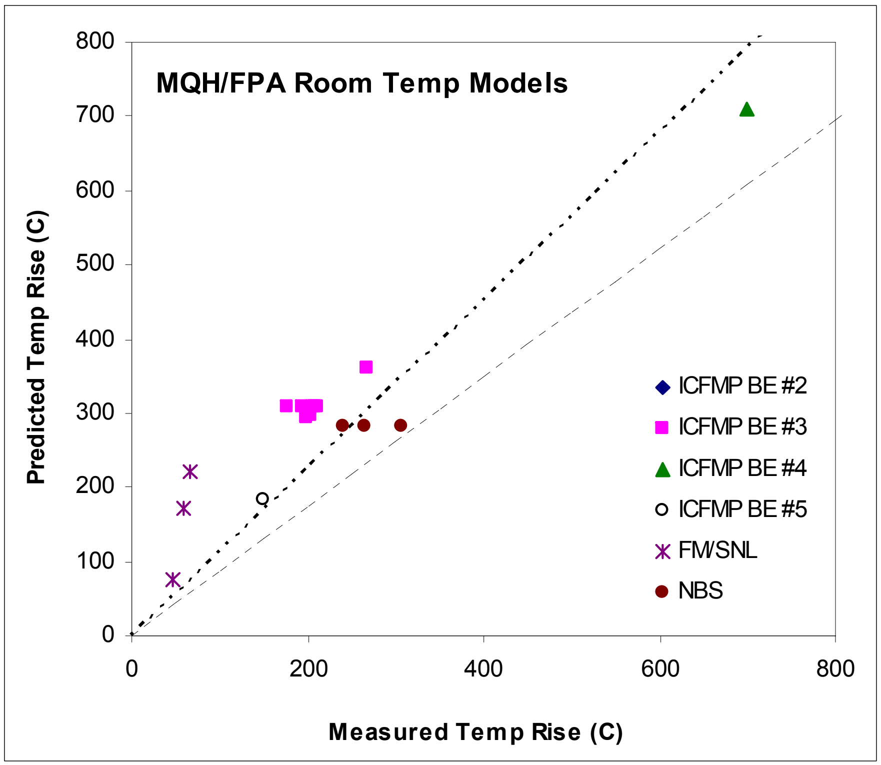
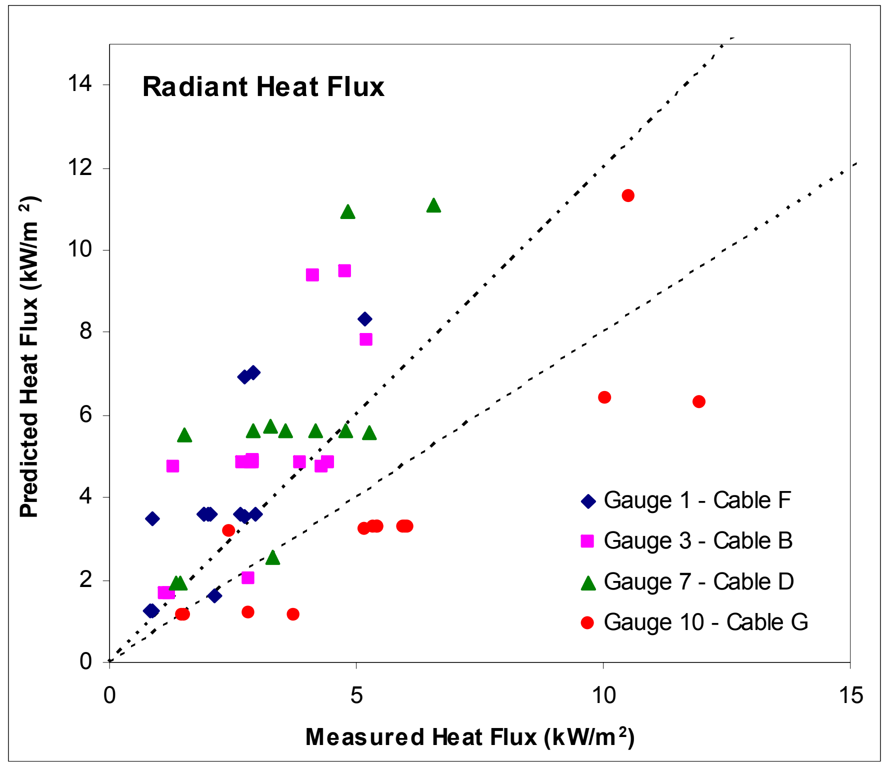
V&V Results for Hand Calculations





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General Findings of NUREG 1824

The use of fire models to support fire protection decision-making requires understanding of their limitations and confidence in their predictive capabilities.

A collection of hand calculations, two zone models and one CFD models were evaluated in the V&V project. Each of these tools have strengths and limitations in evaluating the different fire scenarios present in commercial nuclear power plants.

<u>Hand calculations</u>

Very useful for large number of calculations intended for screening purposes

<u>Zone models</u>

Very useful for detailed evaluation of fire conditions in simple geometry rooms or fire scenarios

<u>CFD</u>

Only marginally more accurate for average quantities in experiments conforming to classic 2 zone stratification, even though it demands about 1000 times the CPU time (minutes vs days).

Very powerful, but may be unnecessary for design fire applications in non-cluttere compartments with flat ceilings. Obstructions/geometric complexity should impact selection of model type.