Evaluation of Fire Models for Nuclear Plant Fire Safety and Risk Analysis

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Objective of Presentation

- Present evaluation of fire models conducted as part of ICFMP
- Highlight current limitations of fire models
- Present results of blind, unbiased analysis to derive true model prediction errors
- Such analysis rare in literature

Reporting

- Detailed reports by Deytec, Inc., other participants of ICFMP, and panel reports available at www.deytecinc.com
- Summary report by Deytec, Inc. on "Fire Model Limitations" available at website by end of month
- Slides to be uploaded after meeting

International Collaborative Fire Model Project (ICFMP)

- Initiated in 1999 by NRC and SFPE
- I Led project from 1999 to 2006
- Evaluate fire models for NPP applications through 5 benchmark exercises (BE)
  - Code to Code
  - Code to experimental data
  - Simple to challenging scenarios

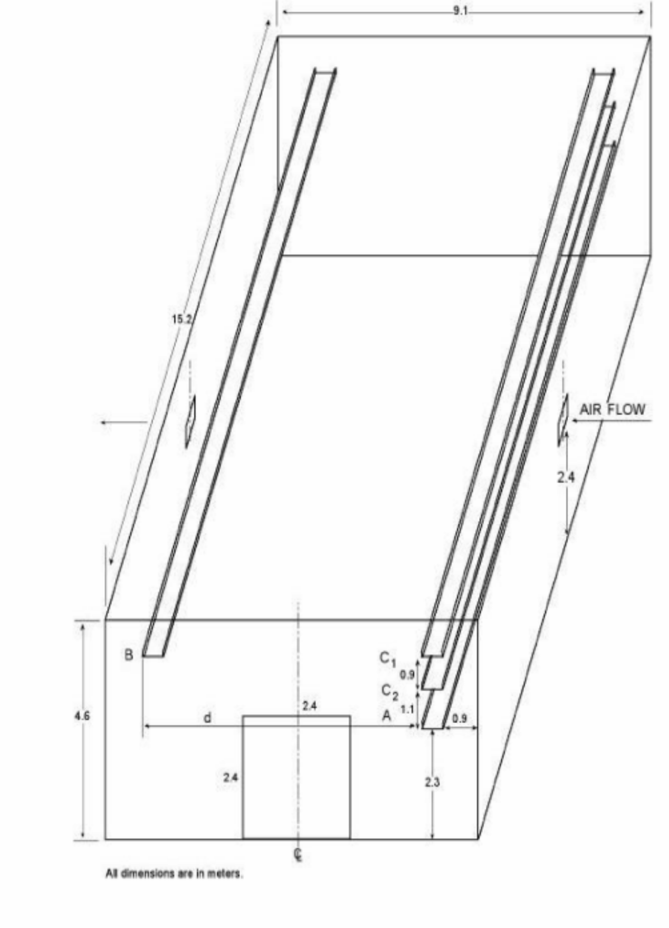
ICFMP Cont'd

- Five countries participated, typically 7 organizations exercised fire models
    - **Germany – GRS, iBMB (COCOSYS, FDS, CFX, CFAST)**
    - **France – IRSN, EdF, CTICM (FLAMME-S, MAGIC)**
    - **UK – BRE (JASMINE, CFAST)**
    - **USA – NRC, NIST (CFAST, FDS, FDTs)**
        - **Assigned as guest researcher at NIST**
        - **Analyst for NRC**
- 10 organizations participated in peer review
- 12 international workshops over 10 years
- 5 ICFMP benchmark reports and summary report

Challenges for Nuclear Plant Applications

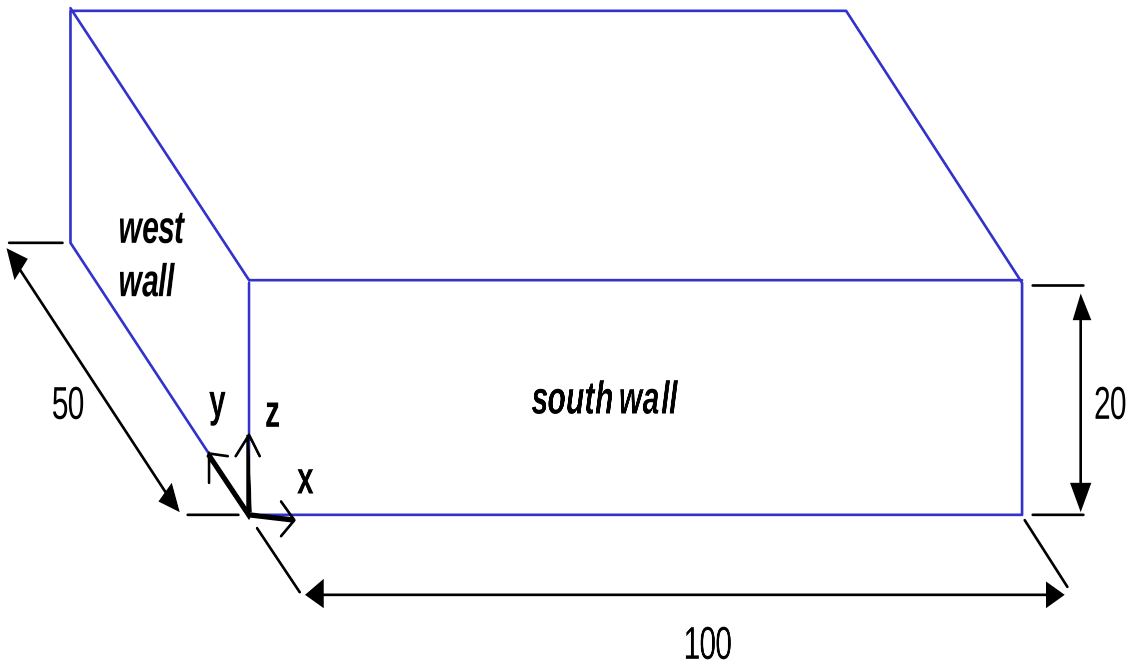
- Target heating, mainly cables
- Need to predict heat flux to targets
- Characterization of fire flame & plume important
  - Under-ventilated fires
  - Effects of geometry
- Multi-level buildings

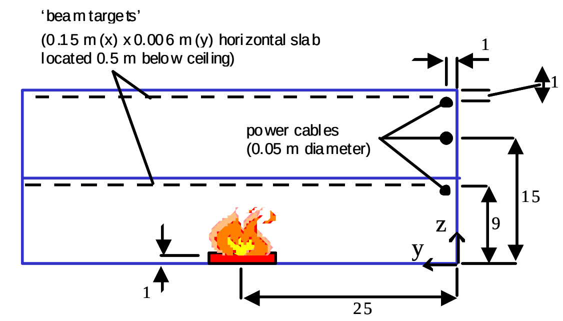
ICFMP Benchmark Exercise No. 1 – Cable Tray Fires



All dimensions are in meters.

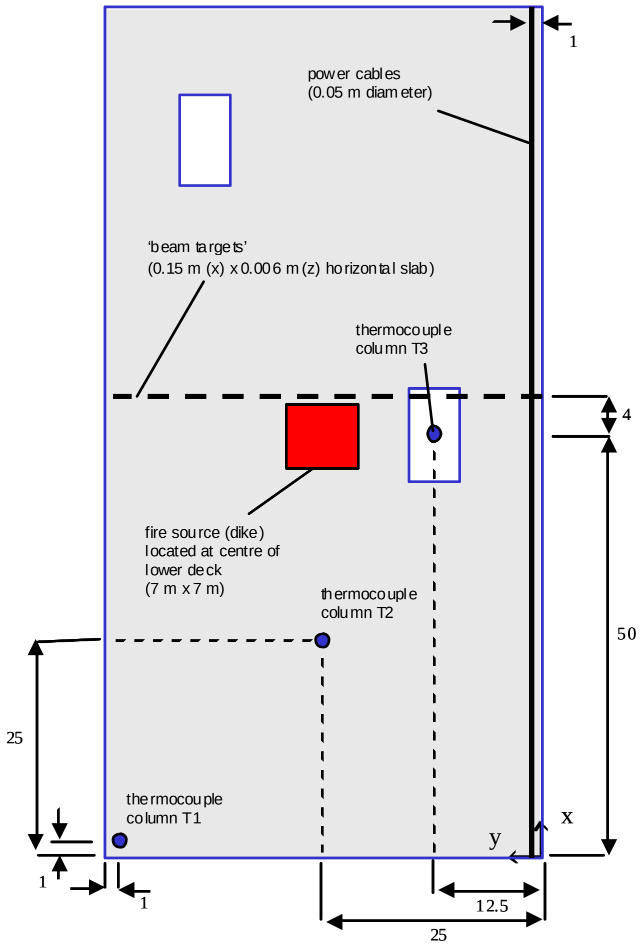
ICFMP Benchmark Exercise No. 2 – Pool Fires in Large Halls





‘beam targets’
(0.15 m (x) x 0.006 m (y) horizontal slab
located 0.5 m below ceiling)

power cables
(0.05 m diameter)



power cables
(0.05 m diameter)

‘beam targets’
(0.15 m (x) x 0.006 m (z) horizontal slab)

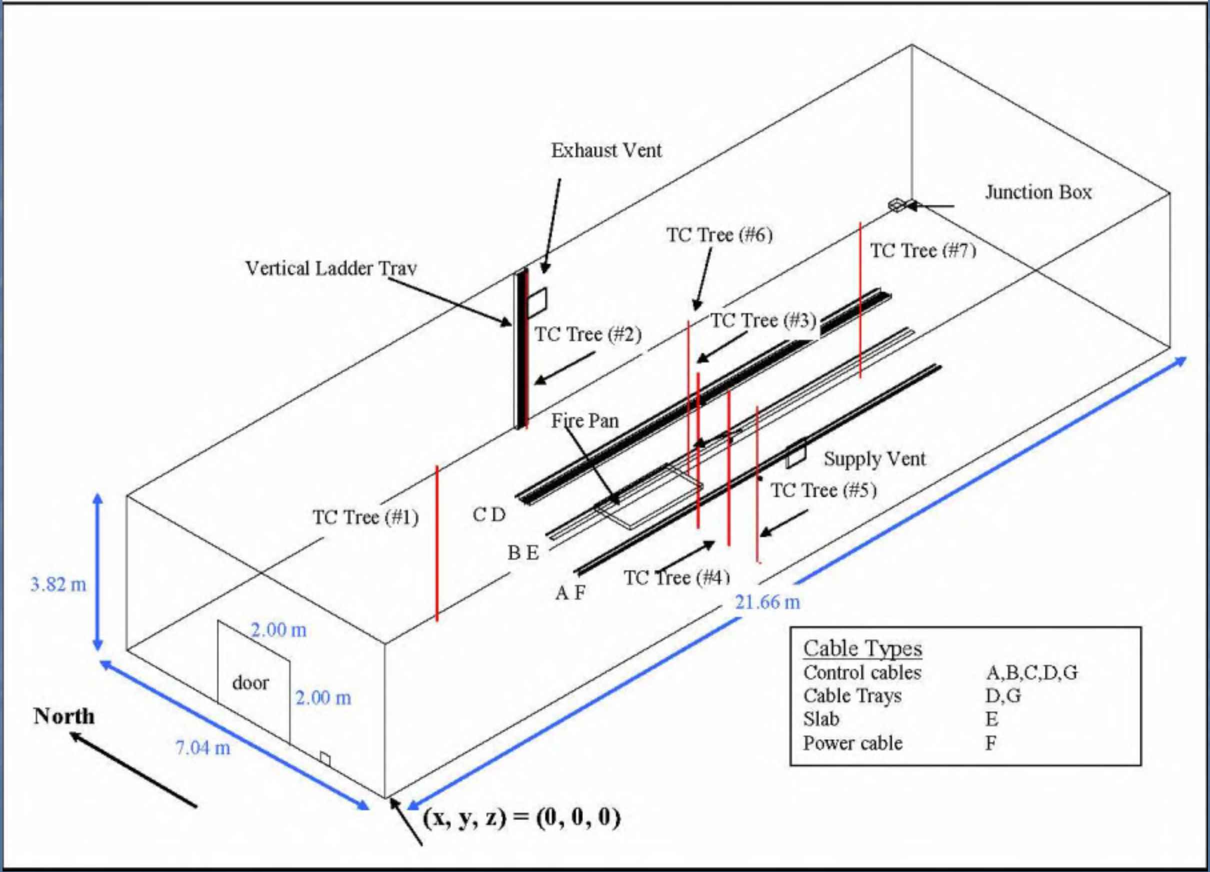
thermocouple
column T3

fire source (dike)
located at centre of
lower deck
(7 m x 7 m)

thermocouple
column T2

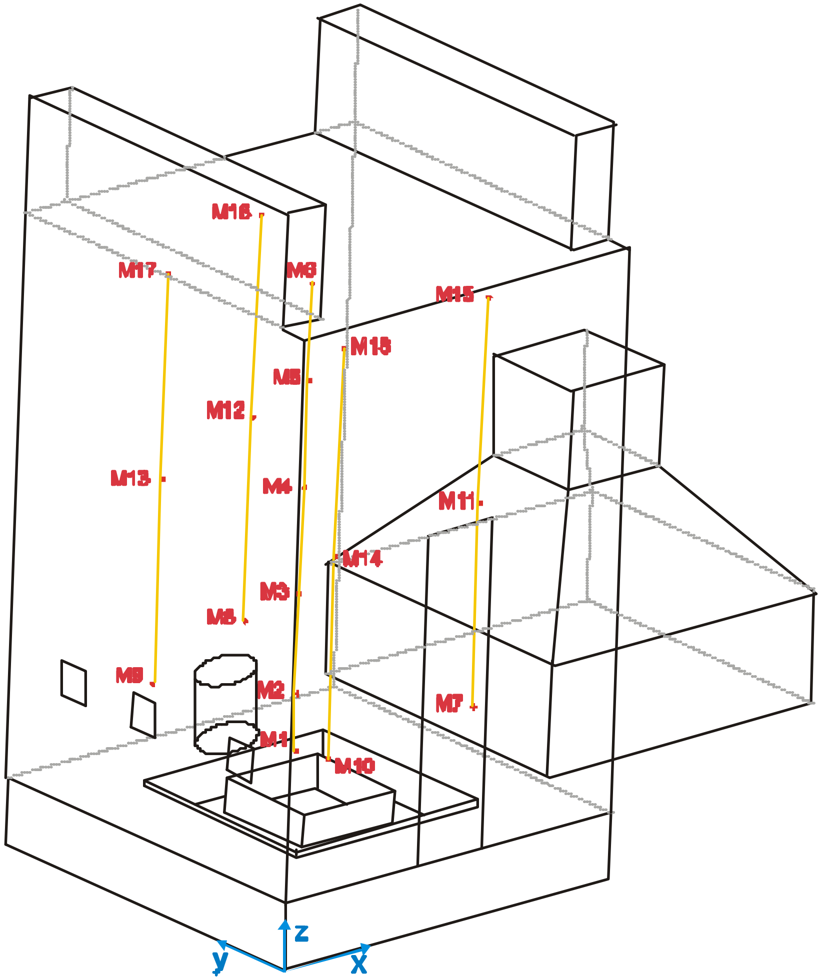
thermocouple
column T1

ICFMP Benchmark Exercise No. 3 – Full Scale Compartment Tests

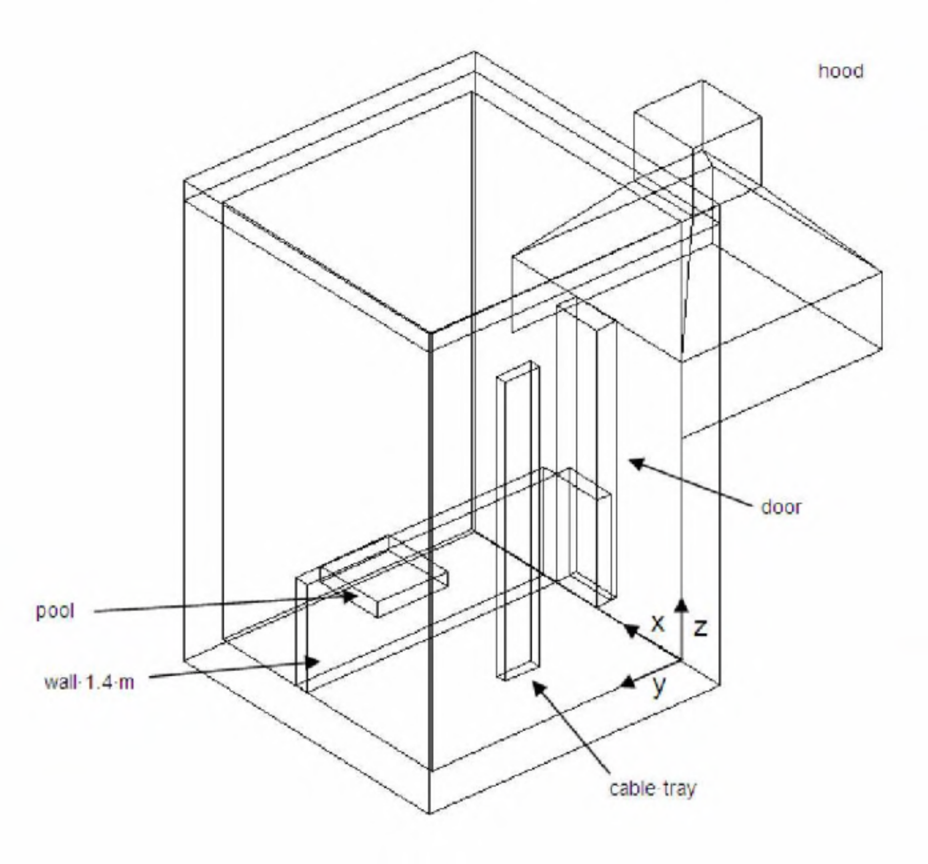


Cable Types	
Control cables	A,B,C,D,G
Cable Trays	D,G
Slab	E
Power cable	F

ICFMP Benchmark Exercise – No. 4 Large Fire Experiments



ICFMP Benchmark Exercise No. 5 – Pool Fires in a Trench



Capabilities

- Combustion chemistry (O2, CO2) for ventilated conditions
- Plume flows
- Mass & energy balances
- Door mass & heat flows
- Hot gas interface height
- Hot gas temperature
- Local gas temperatures from FDS

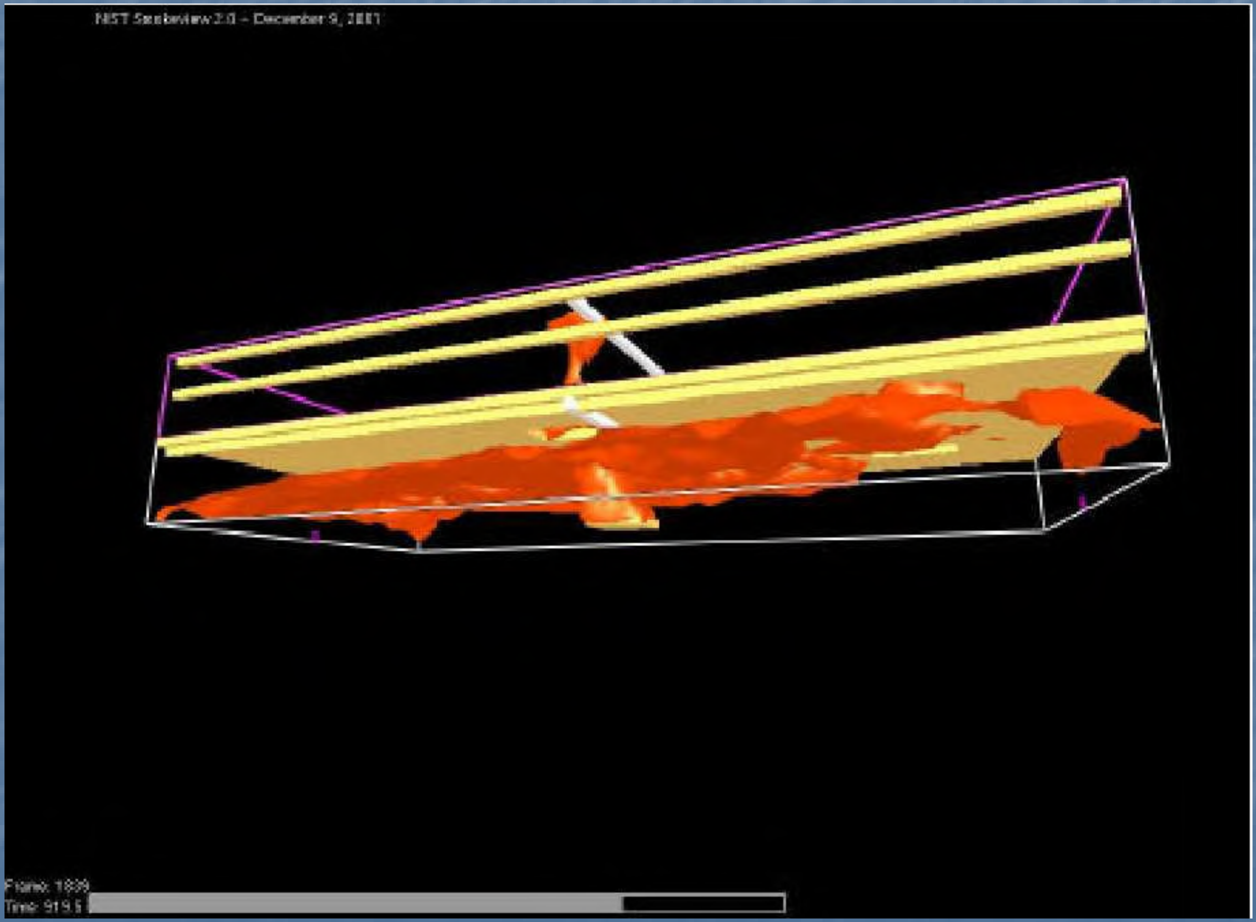
Limitations

- Movement & location of fire plume
- Under-ventilated conditions and fire extinction
- Heat flux from flame & hot gas
- Cable target modeling
- Intense fire conditions
- Fires in multi-level buildings
- Mechanical ventilation

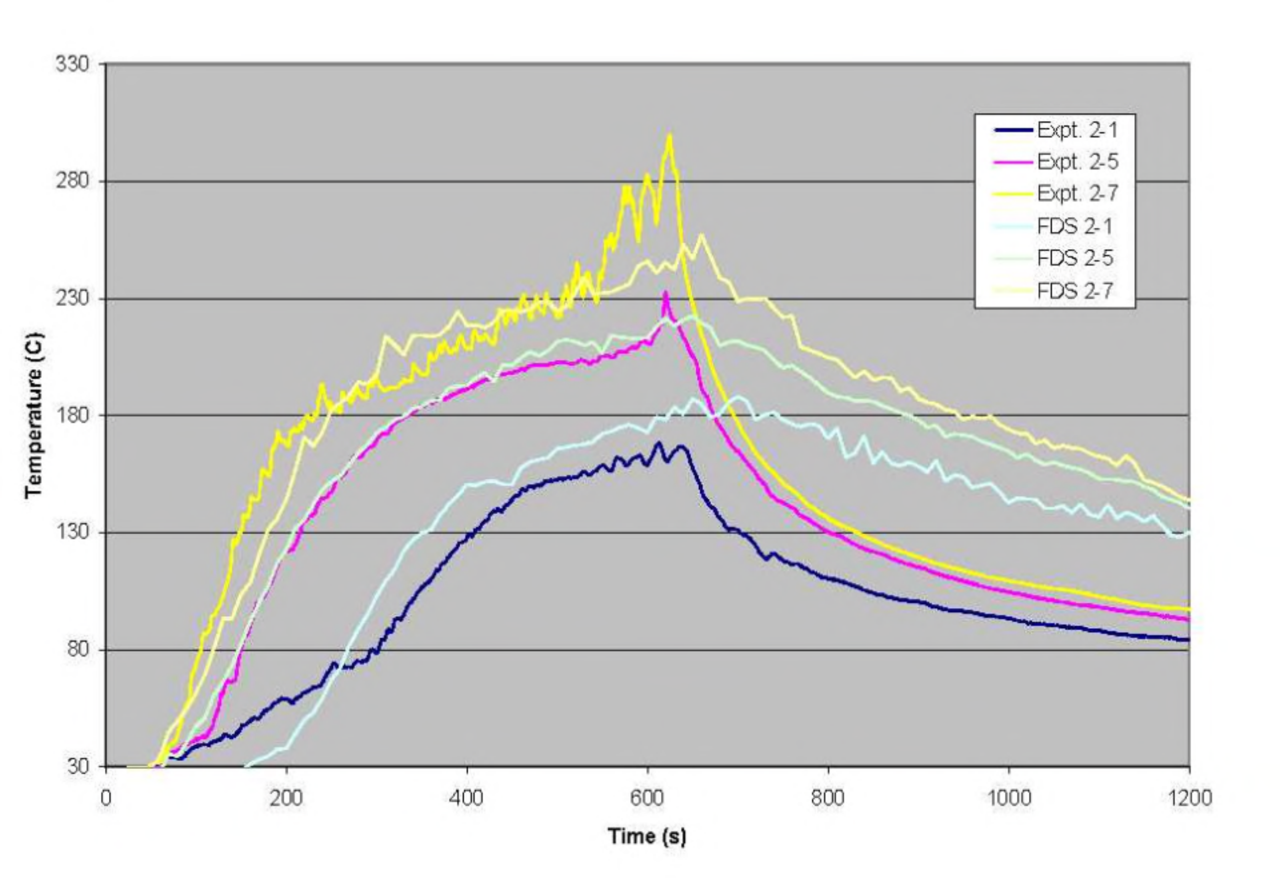
Movement & Location of Fire Plume

- Zone & correlations not capable
- CFD models attempt to simulate phenomena
  - Combustion chemistry – mixture fraction
  - Approximate treatment of extinction
  - Fluid dynamics

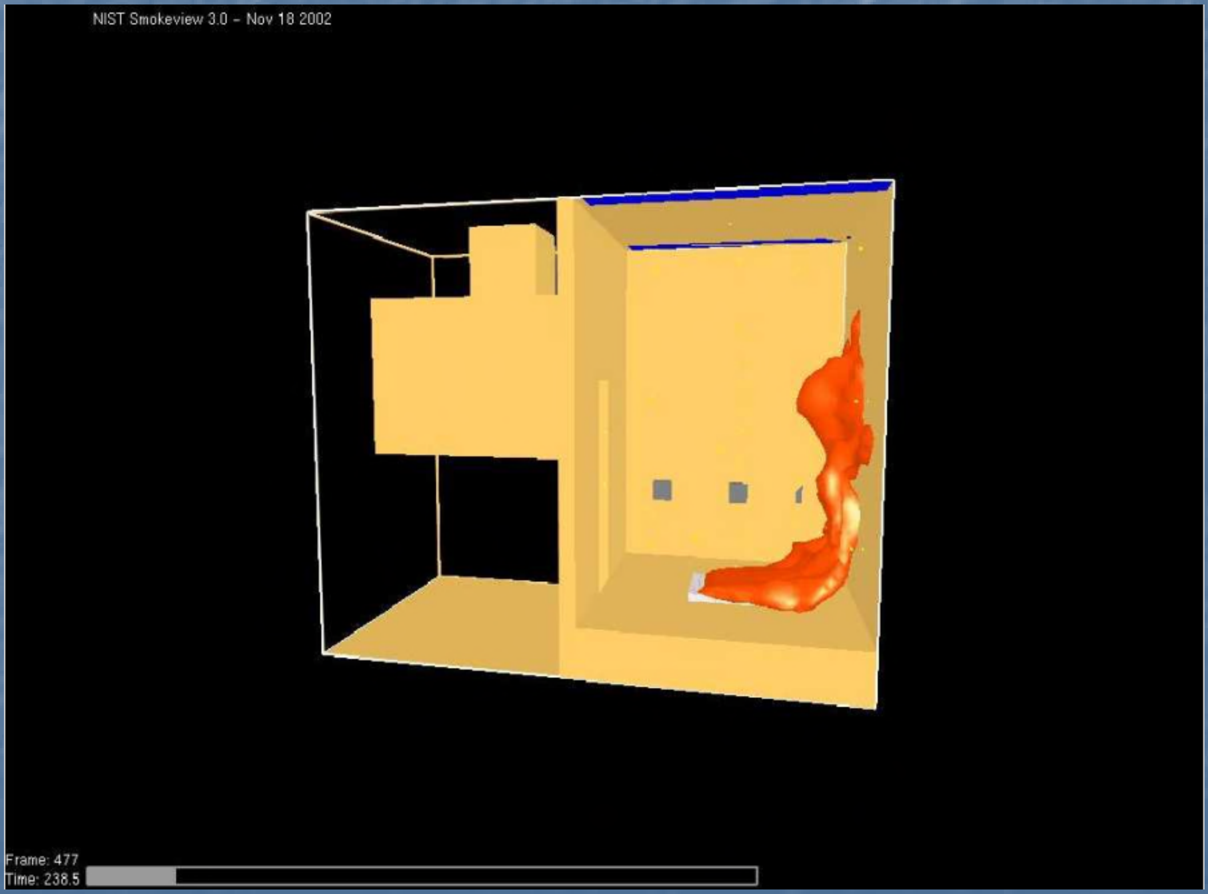
FDS Prediction of Flame - BE 2



Observed Flame Oscillations - BE 3 T2

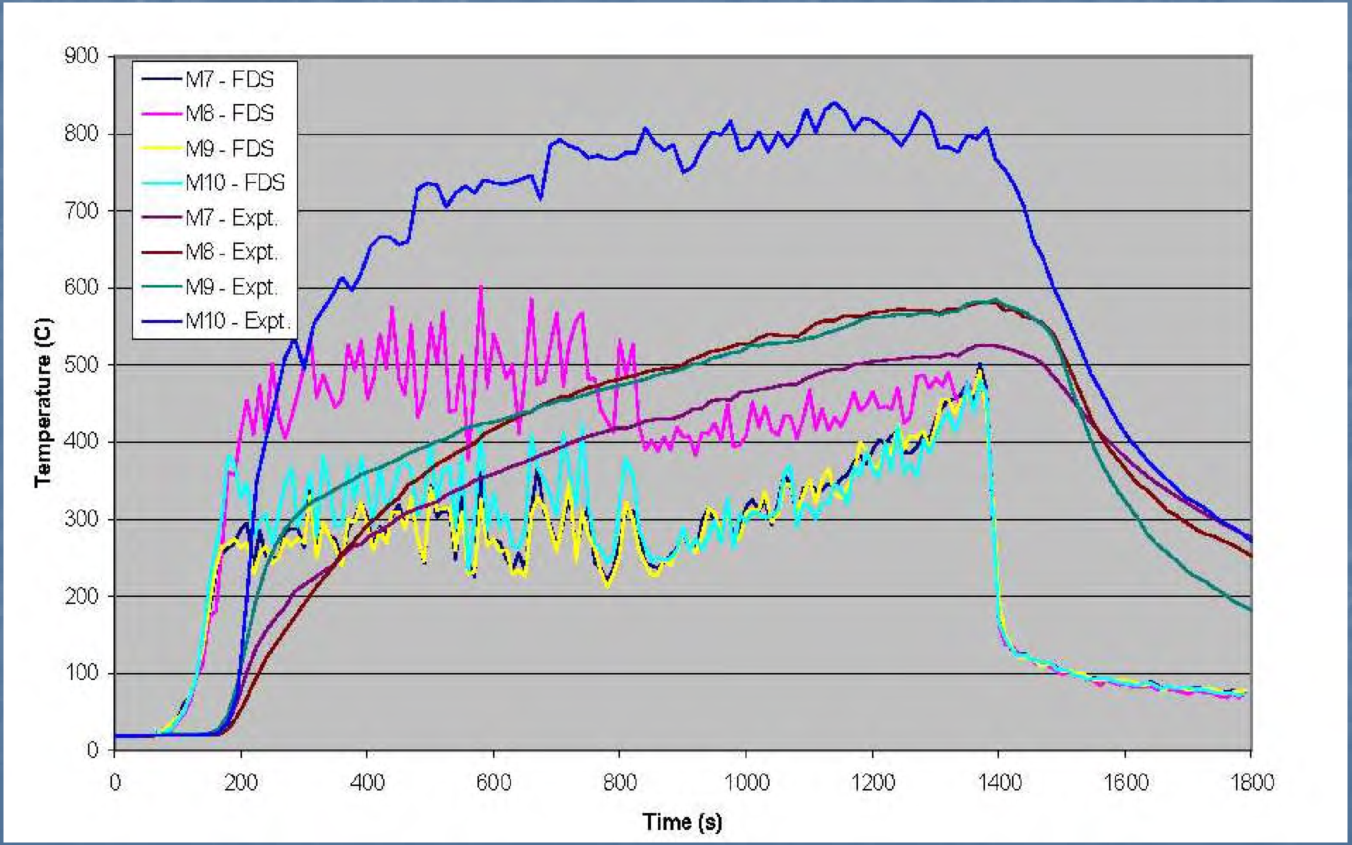


FDS Prediction of Flame – BE 4



Observed Flame – BE 4

Temperature Profiles Near Flame – BE 4 T1



Observed Flame - BE 5

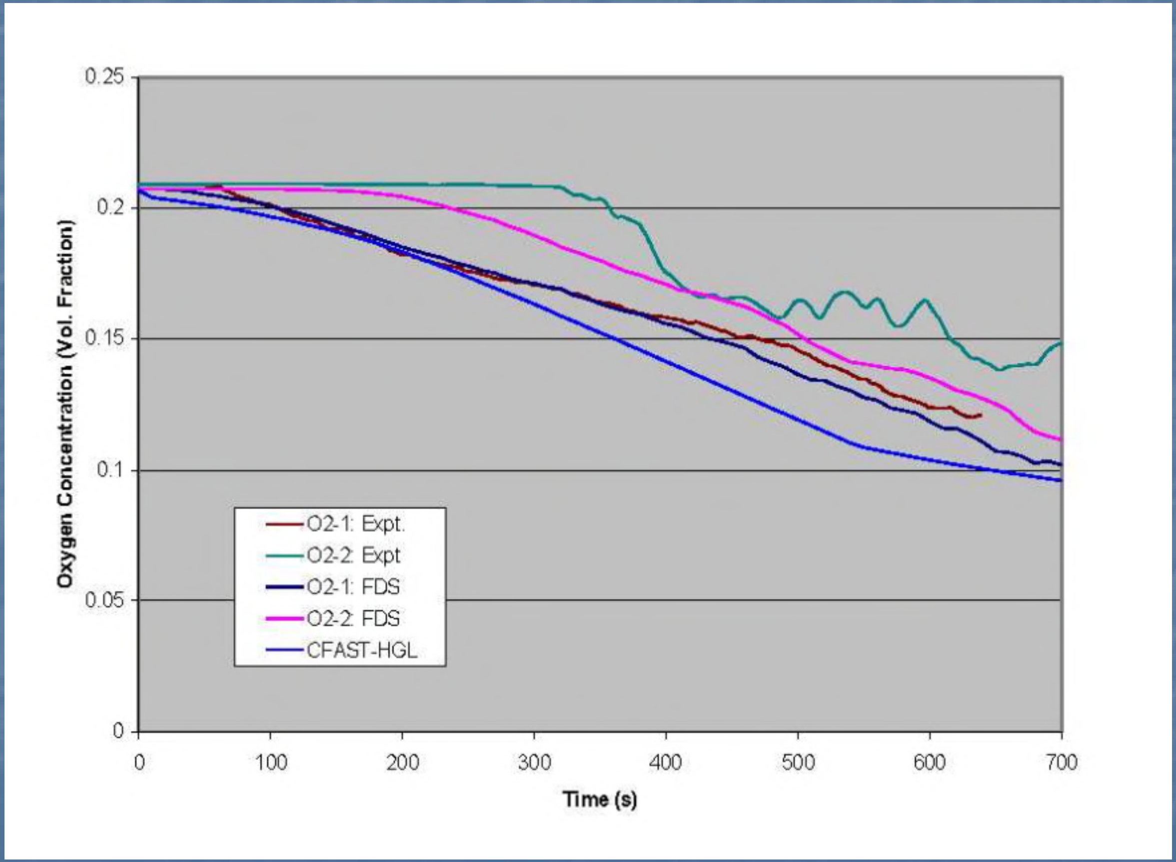
Observed Flame – BE 5

Observed Flame – BE 5

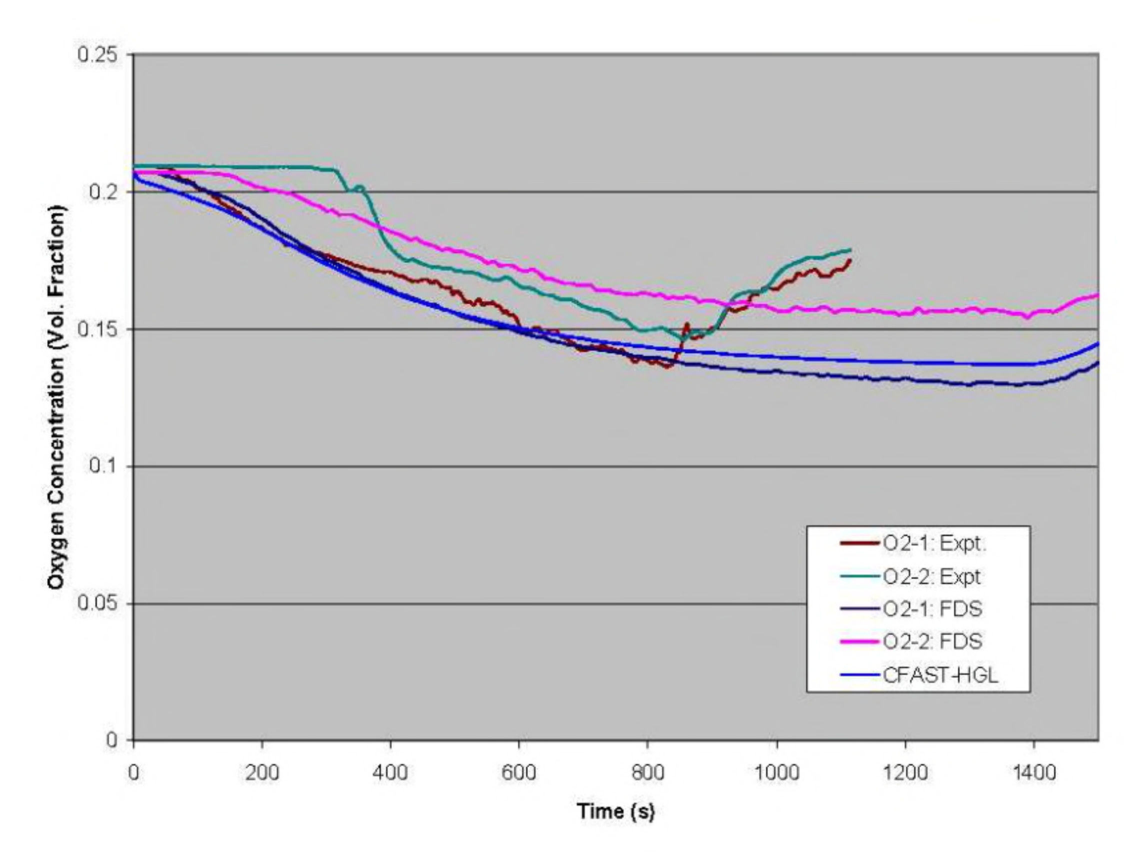
Under-Ventilated Conditions & Fire Extinction

- Effect on flame movement discussed
- Limited knowledge & ability to model combustion process
- Limited capability to predict O2 concentration in some cases

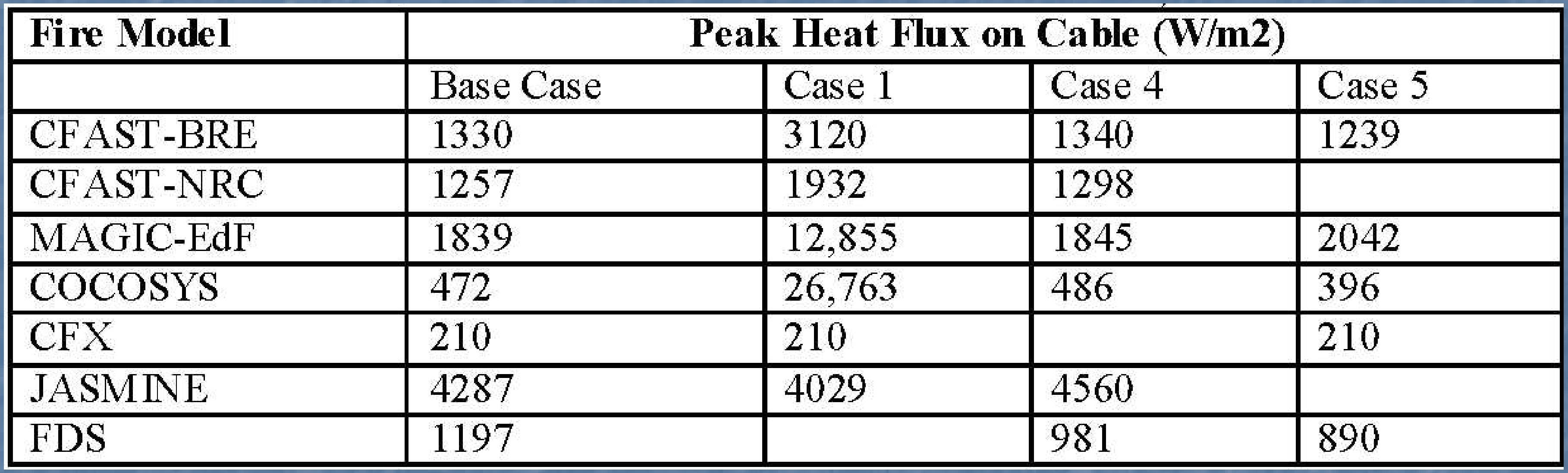
Oxygen Concentration – BE 3 T2



Oxygen Concentration BE 3 T4

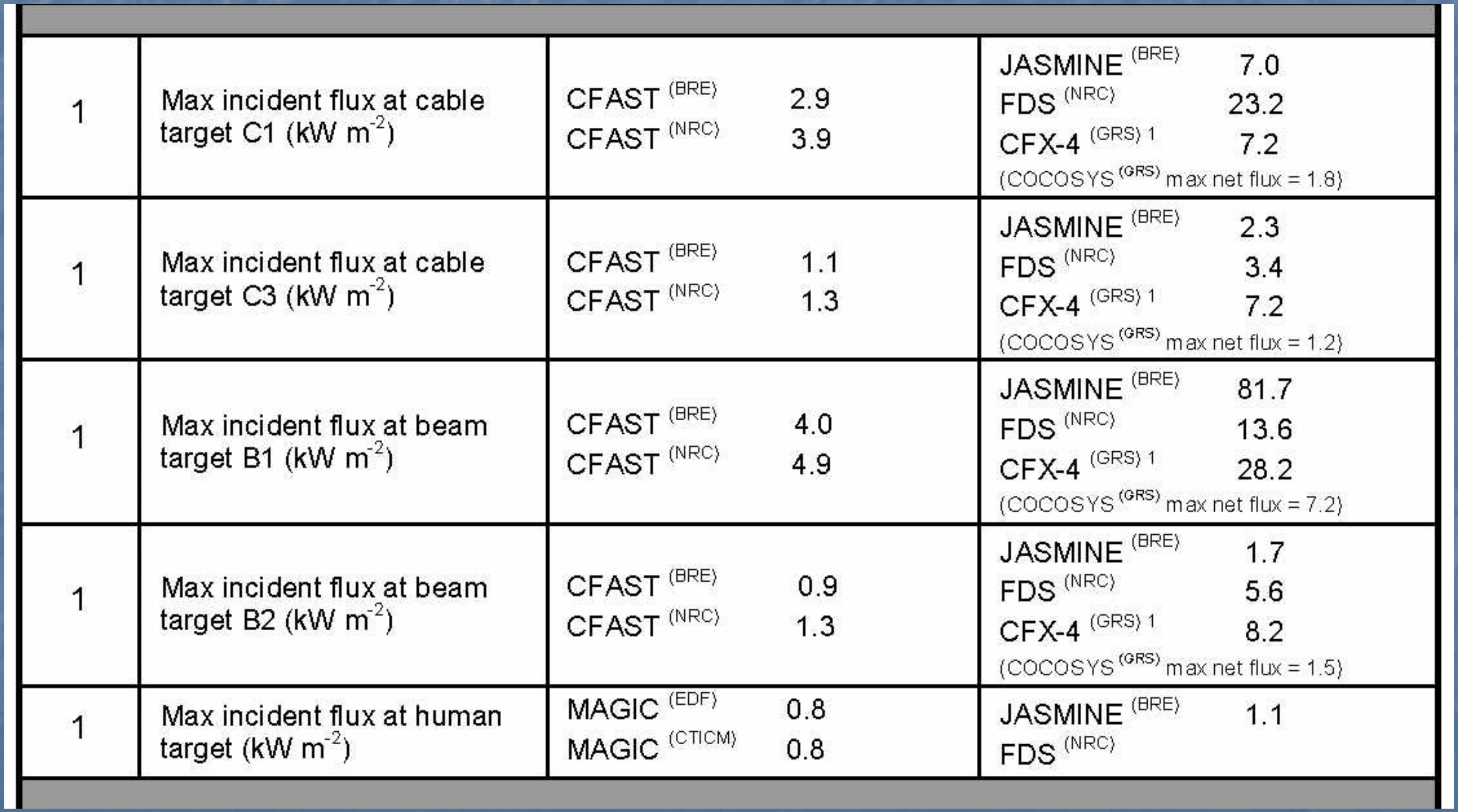


Heat Flux from Flame & Hot Gas Predictions – ICFMP BE 1



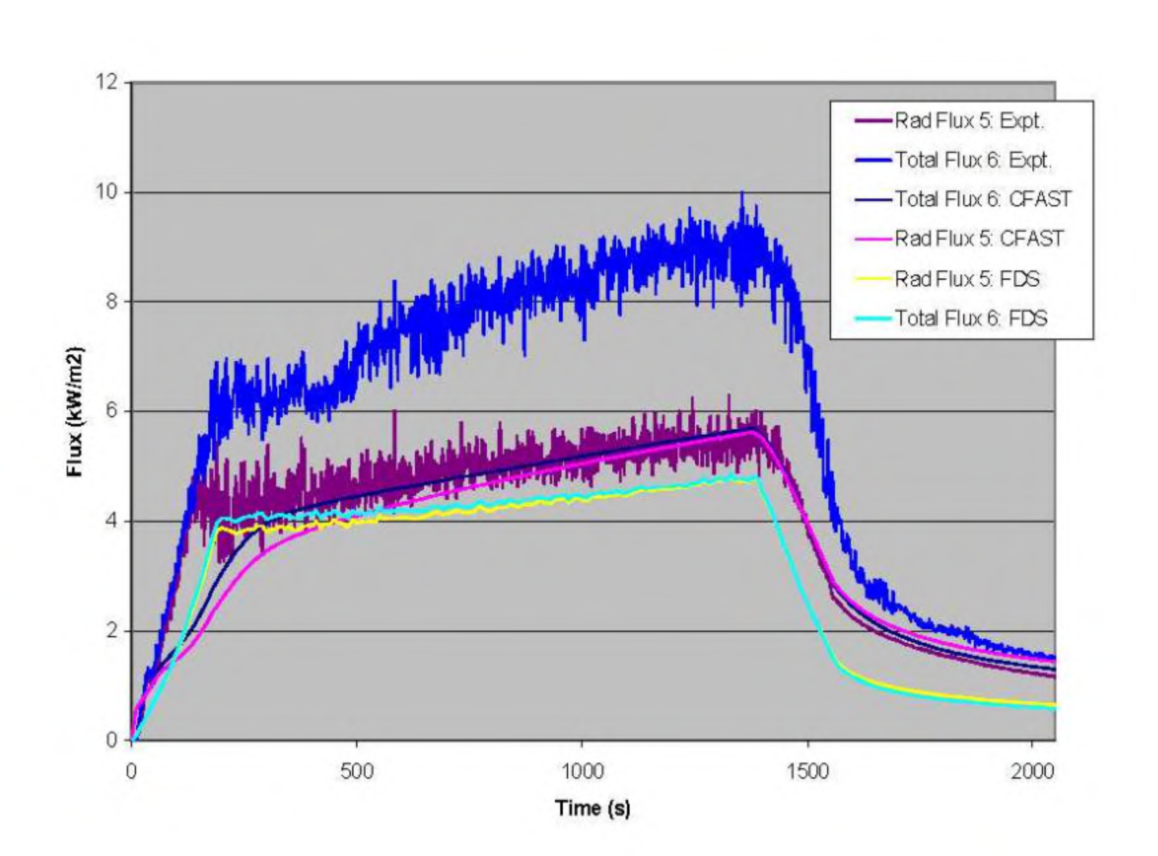
Fire Model	Peak Heat Flux on Cable (W/m2)			
	Base Case	Case 1	Case 4	Case 5
CFAST-BRE	1330	3120	1340	1239
CFAST-NRC	1257	1932	1298	
MAGIC-EdF	1839	12,855	1845	2042
COCOSYS	472	26,763	486	396
CFX	210	210		210
JASMINE	4287	4029	4560	
FDS	1197		981	890

Heat Flux Predictions – ICFMP BE 2



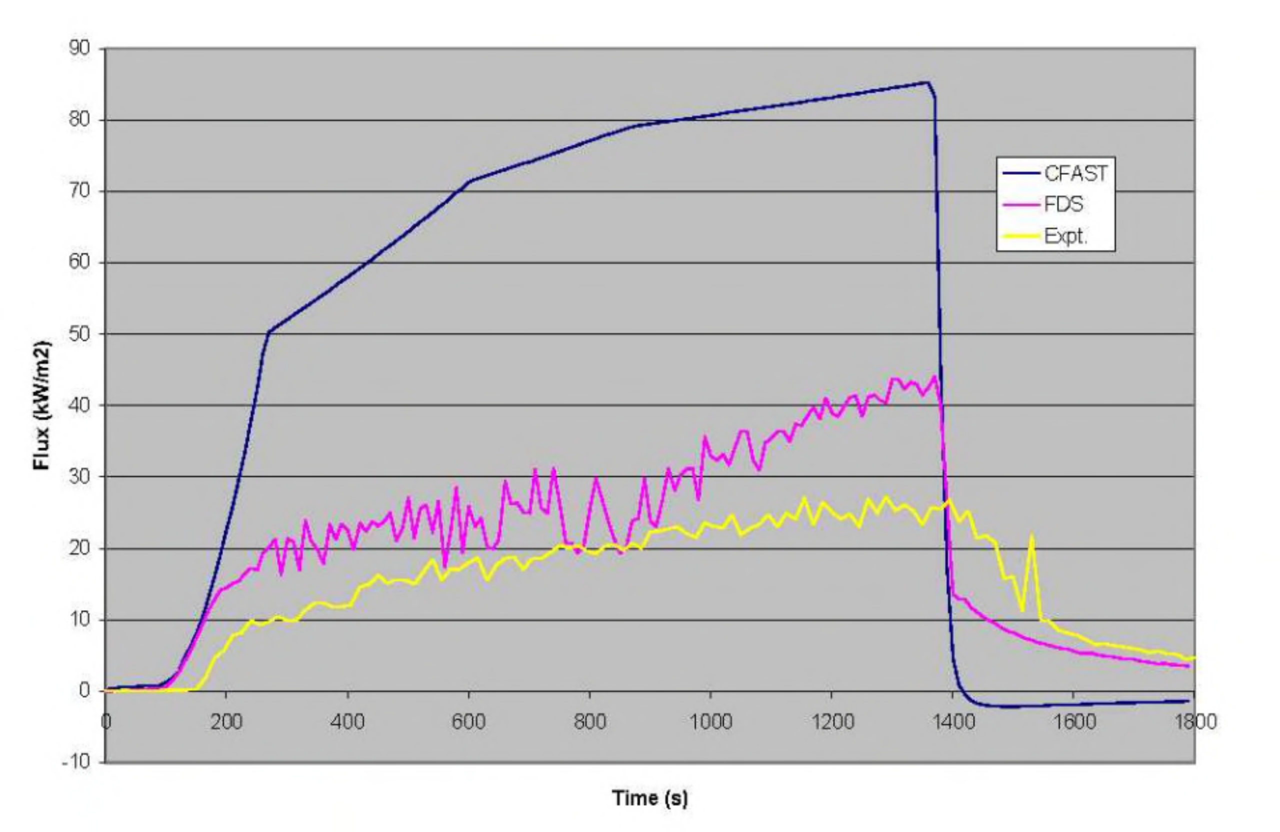
1	Max incident flux at cable target C1 (kW m^{-2})	CFAST $^{(BRE)}$ 2.9 CFAST $^{(NRC)}$ 3.9	JASMINE $^{(BRE)}$ 7.0 FDS $^{(NRC)}$ 23.2 CFX-4 $^{(GRS)\ 1}$ 7.2 (COCOSYS $^{(GRS)}$ max net flux = 1.8)
1	Max incident flux at cable target C3 (kW m^{-2})	CFAST $^{(BRE)}$ 1.1 CFAST $^{(NRC)}$ 1.3	JASMINE $^{(BRE)}$ 2.3 FDS $^{(NRC)}$ 3.4 CFX-4 $^{(GRS)\ 1}$ 7.2 (COCOSYS $^{(GRS)}$ max net flux = 1.2)
1	Max incident flux at beam target B1 (kW m^{-2})	CFAST $^{(BRE)}$ 4.0 CFAST $^{(NRC)}$ 4.9	JASMINE $^{(BRE)}$ 81.7 FDS $^{(NRC)}$ 13.6 CFX-4 $^{(GRS)\ 1}$ 28.2 (COCOSYS $^{(GRS)}$ max net flux = 7.2)
1	Max incident flux at beam target B2 (kW m^{-2})	CFAST $^{(BRE)}$ 0.9 CFAST $^{(NRC)}$ 1.3	JASMINE $^{(BRE)}$ 1.7 FDS $^{(NRC)}$ 5.6 CFX-4 $^{(GRS)\ 1}$ 8.2 (COCOSYS $^{(GRS)}$ max net flux = 1.5)
1	Max incident flux at human target (kW m^{-2})	MAGIC $^{(EDF)}$ 0.8 MAGIC $^{(CTICM)}$ 0.8	JASMINE $^{(BRE)}$ 1.1 FDS $^{(NRC)}$

Heat Flux to Cables – BE 3 T3



BE 3 T14

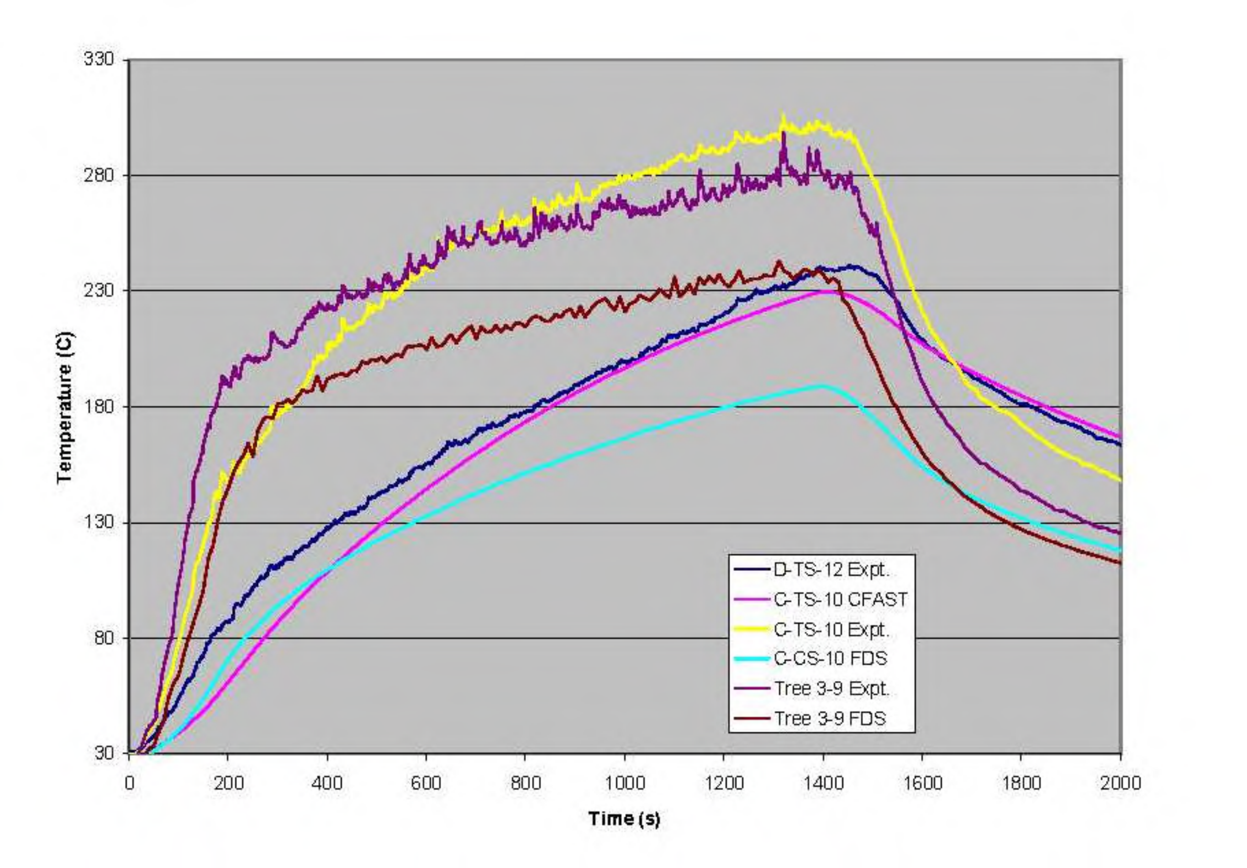
Heat Flux to Steel Plate BE 4 T1



Cable Target Modeling

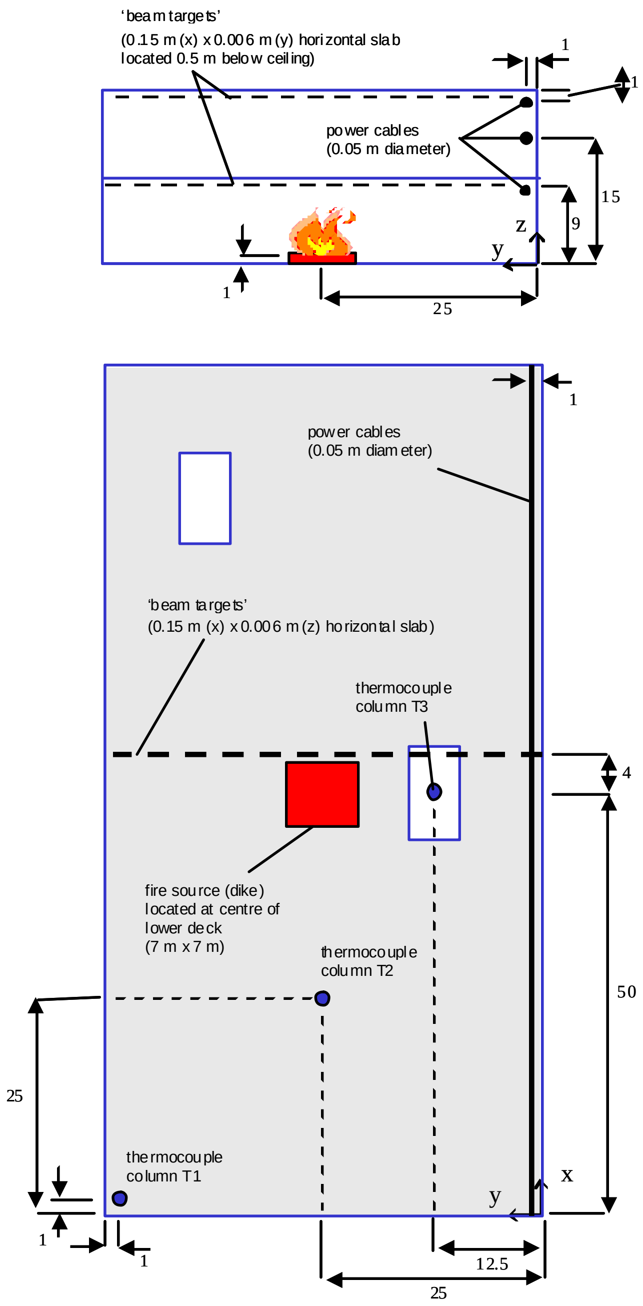
- Cable tray is a complex geometry
- Cables bundled with several conductors
- Heat transfer model complex and not available
- Heating depends on many factors
- Most models have 1-D heat transfer in slab geometry

Cable Temperature BE 3 T3



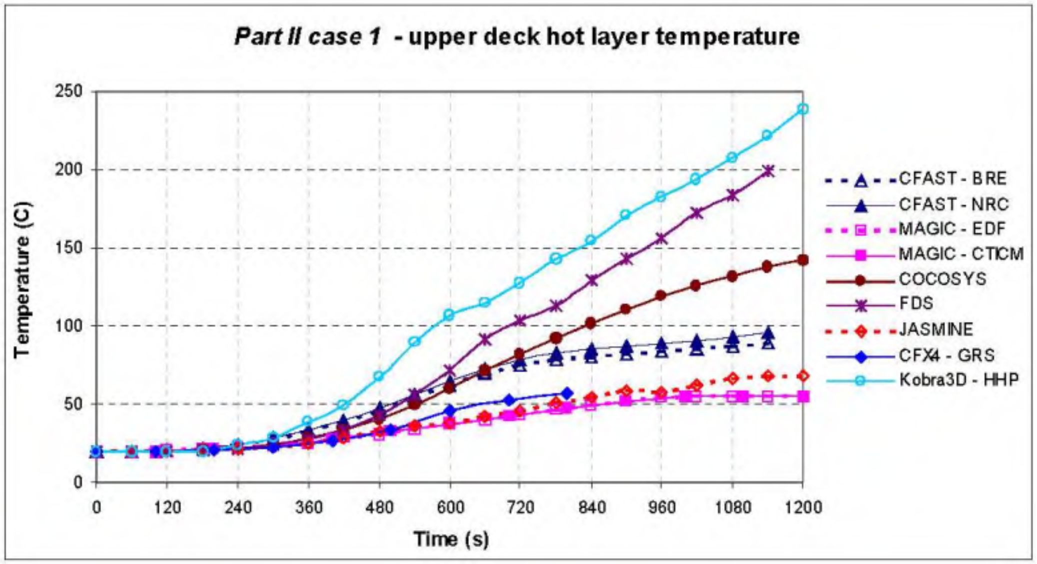
Intense Fire Conditions - BE 4

- Temperatures up to 800 C
- Heat flux up to 100 kW/m2
- Significant challenges for CFAST
- FDS performs well for global parameters, limited for predicting plume and heat flux

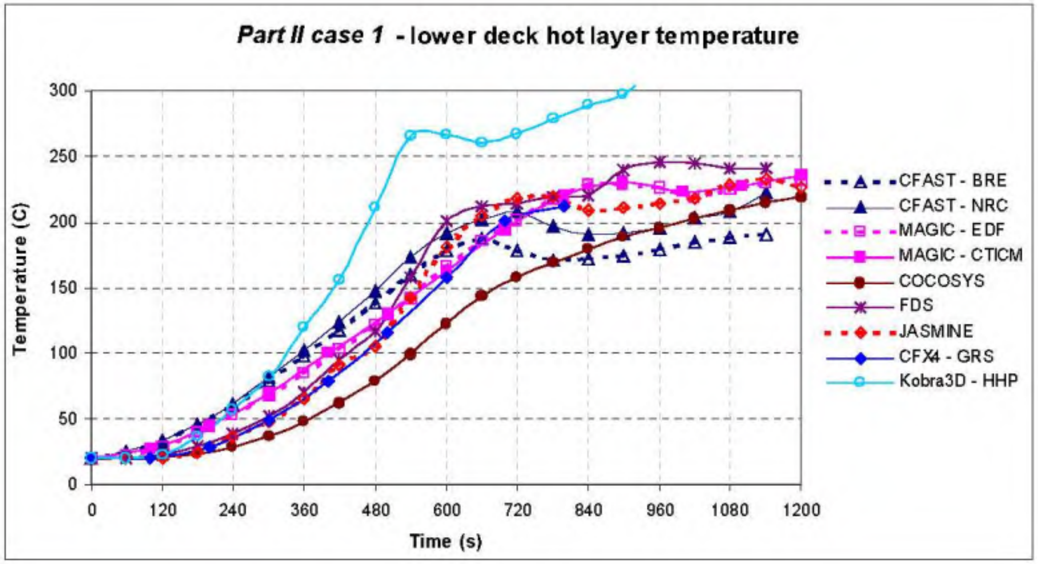

‘beam targets’
(0.15 m (x) x 0.006 m (y) horizontal slab
located 0.5 m below ceiling)
1
1
power cables
(0.05 m diameter)
15
9
z
y
1
25
1
power cables
(0.05 m diameter)
‘beam targets’
(0.15 m (x) x 0.006 m (z) horizontal slab)
thermocouple
column T3
4
fire source (dike)
located at centre of
lower deck
(7 m x 7 m)
thermocouple
column T2
50
25
thermocouple
column T1
x
y
1
1
12.5
25

Fires in Multi-Level Buildings

- Zone model assumptions limit application
- Fluid dynamics of vertical flow through hatches challenged CFD models
- CFD models predicted different flow patterns – phenomena not understood
- Need to examine phenomena and validate before use

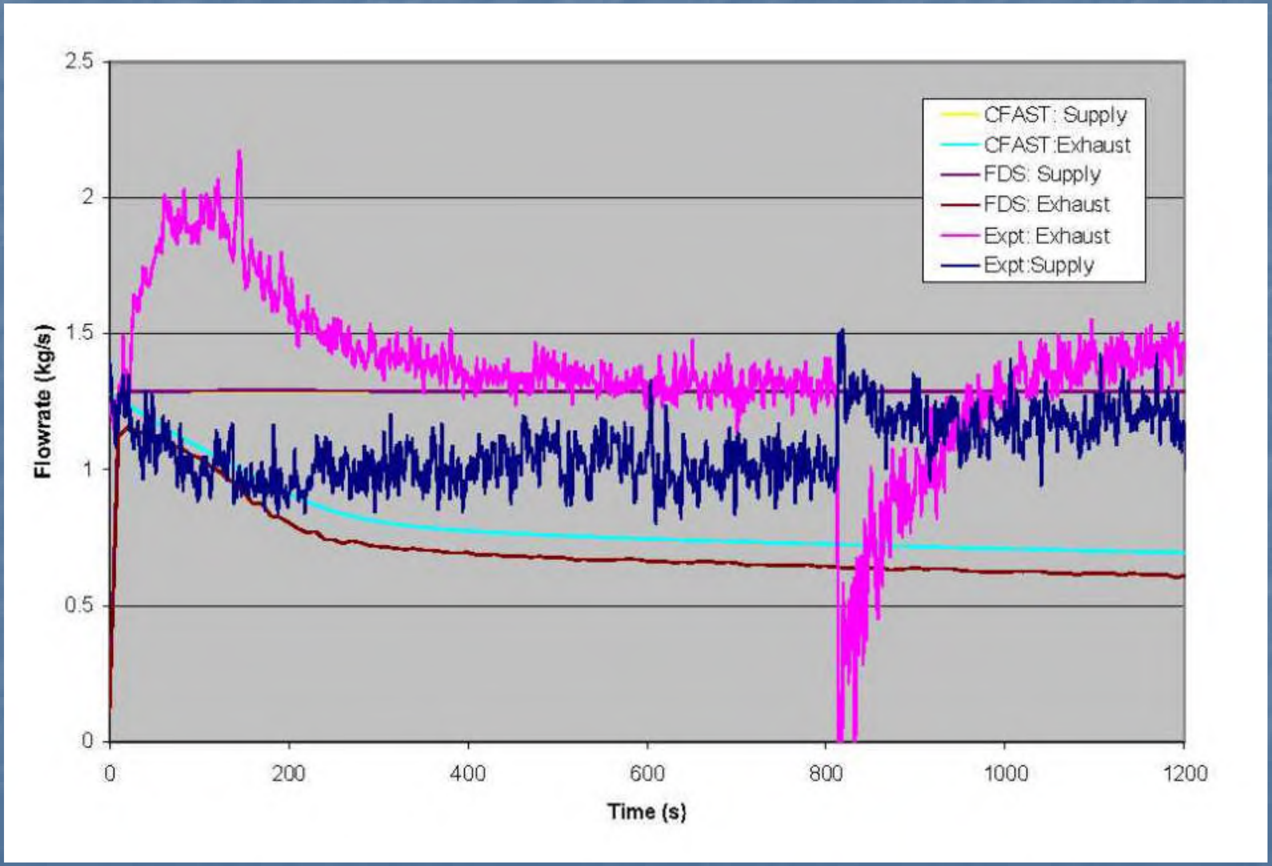


Part II case 1 - upper deck hot layer temperature



Part II case 1 - lower deck hot layer temperature

Mechanical Ventilation: Vent Flow Predictions - BE 3 T4



Limitations of FDTs

- Limited to simple scenarios within range of empirical correlation data base
- Radiative heat flux and hot gas temperature predictions off by factor of two for some cases
- Plume temperature errors up to 66 %
- Can only be used as screening tool

Conclusions

- Fire models at present severely limited in predicting parameters of major interest in nuclear plant fire safety
- Bounding calculations acknowledging limitations possible
- Erroneous decisions leading to unsafe nuclear plant conditions will result if limitations not considered
- Research and improvement programs should be developed to overcome these limitations so that fire models become a reliable and useful tool

Recommendation

- Fire science & modeling is an evolving area
- Take time to understand the physics and performance of models
- ICFMP documents good source of information
- Ensure safety by bounding analysis in areas of uncertainty