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

Deytec, Inc.

Nuclear Engineering Services

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1 Abstract

This report presents the results of an evaluation of fire models for nuclear plant fire safety and risk analysis conducted as part of the International Collaborative Fire Model Project (ICFMP) by the author. The main objective of this report, which follows several detailed technical reports by the author on benchmark exercises conducted in the ICFMP, is to highlight the current limitations of fire models for nuclear plant applications. This report presents the results of blind, unbiased analyses that were conducted to derive the true errors in model predictions. Such analyses and presentations are rare in the fire modeling literature. The analyses indicate that fire models at the present are severely limited in predicting parameters of major interest in nuclear plant fire safety and risk analysis. Erroneous decisions leading to unsafe nuclear plant conditions will result if the fire model limitations presented in this report are not considered in fire safety decision making. Bounding calculations with the fire models can still be conducted, as long as the limitations of the models are acknowledged, understood and taken into account. Research and improvement programs should be developed to overcome these limitations so that fire models become a reliable and more useful tool for nuclear plant fire safety analysis.

Table of Contents

2 List of Figures

3 List of Tables

4 Executive Summary

This report presents the results of an evaluation of fire models for nuclear plant fire safety and risk analysis conducted as part of the International Collaborative Fire Model Project (ICFMP) by the author. The main objective of this report, which follows several detailed technical reports by the author on benchmark exercises conducted in the ICFMP, is to highlight the current limitations of fire models for nuclear plant applications. This report presents the results of blind, unbiased analyses that were conducted for five international benchmark exercises in the ICFMP to derive the true errors in model predictions. Such analyses and presentations are rare in the fire modeling literature. The CFAST (Consolidated Fire and Smoke Transport) zone model, FDS (Fire Dynamic Simulator) computational fluid dynamic (CFD) model, and a collection of empirical fire correlations in FDTs (Fire Dynamic Tools) were used for the analysis presented in this report. The analyses indicate that fire models and empirical correlations at the present are severely limited in predicting parameters of major interest in nuclear plant fire safety and risk analysis. Erroneous decisions leading to unsafe nuclear plant conditions will result if the fire model limitations presented in this report are not considered in fire safety decision making. Bounding calculations with the fire models can still be conducted, as long as the limitations of the models are acknowledged, understood and taken into account. Research and improvement programs should be developed to overcome these limitations so that fire models become a reliable and useful tool for nuclear plant fire safety analysis.

The main goal of fire safety and risk analysis in nuclear plants is to predict damage to cables in various configurations as damage to power, control, or instrumentation cables could lead to the loss of reactor core cooling during accident conditions. Although the predictions of general compartment conditions, e.g. hot gas temperature and interface height, during a fire were reasonable (10-20 % errors) for most fire scenarios by the CFAST and FDS fire models, the prediction of parameters that are important for nuclear plant safety analysis proved much more difficult.

The compartment hot gas temperature is determined by plume flow and mass and energy balances which are robust in the fire models and thereby result in reliable predictions. The temperature distribution in the hot gas is also adequately captured by CFD codes like FDS over a wide range of conditions. The algorithms for predicting door heat and mass flows, and the oxygen and carbon dioxide concentrations for ventilated fires are simple and reliable. Carbon monoxide and smoke concentrations can also be reliably predicted for ventilated fires as long as correct yields are included for the combustion products in the models. The algorithms for predicting convective and/or radiative heat fluxes to the cables from the flaming region and hot gas is much more complex. The ability to predict heat flux, especially from the flaming region, was found to be particularly challenging (40 % to > 100 % errors) as the algorithms for calculating heat flux and fire flame characteristics involve phenomena that are presently not well understood. Although the correlations for FDTs are suitable for simple fire scenarios and parameters, they are severely limited for most fire scenarios in nuclear plants.

Limitations

The analysis of the five international benchmark exercises summarized in this report concluded that current models are severely limited in predicting the following:

1. Movement and location of the flaming region and fire plume
2. Under-ventilated conditions and fire extinction
3. Heat flux from the flaming region and hot gas
4. Cable target heating
5. Intense fire conditions
6. Fires in multi-level buildings
7. Mechanical ventilation

The prediction of the movement and location of the fire flame and plume is critical for nuclear plant fire safety analysis because the likelihood of cable failure will increase significantly if the cables are immersed in the flame or fire plume. The only models that have been formulated to predict the movement and location of the fire flame and plume are CFD models like FDS. CFAST utilizes a simple point source model for the fire and empirical correlations to determine plume flow and therefore does not predict flame and plume movement. Comparison of FDS predictions with experimental data over a wide range of fire scenarios presented in this report indicate that the code is unable to predict the movement and location of the fire flame and plume in under-ventilated conditions or where the fire flame and plume is affected by a solid boundary near the fire. The inability to adequately simulate the flame and the effects of under-ventilation on the fire, and certain flow phenomena, results in a lack of predictive capability to simulate the movement and location of the fire plume under a variety of conditions.

The combustion process is extremely complex with over a hundred combustion steps involved which are dependent on temperature. The knowledge of the combustion process is currently limited and evolving with research being conducted by the fire science community. The FDS model attempts to simulate the combustion process with a mixture fraction model. The analysis presented in this report confirmed the lack of current knowledge and the limitations of this simple approach for predicting under-ventilated conditions, combustion products, and extinction of the fire. Updates are ongoing to improve the FDS model to include the effects of temperature on combustion, and to simulate the production of soot and carbon monoxide. These models currently have several “dials” that have to be tuned in order to make predicted results match experimental data. Although these efforts are important steps to improve the model, they are in trial stages and not currently suitable for safety analysis for which the reliability of a model must be assured.

When a target cable is not directly in the fire flame and plume, it becomes important to calculate the heat flux to the target from the flaming region and hot gas. Analysis presented in this report shows that current algorithms used to predict the radiative heat flux from the fire, and the radiative and convective heat flux from the hot gas produce inaccurate results and are not reliable. The computation of the heat fluxes to the target poses a challenge beyond the fundamental limited ability to characterize the fire and the radiative heat from it.

Assuming that one is able to predict the heat flux to the cables, it is necessary to have a suitable model for a target cable to calculate its heating. A detailed heat transfer model for a cable tray will be fairly complex. Cable trays generally have a number of cables bundled together in layers, and most cables consist of several conductors. The CFAST or FDS codes currently do not include a target model for such complex cable configurations or cable compositions. The CFAST and FDS codes have a simple one-dimensional slab model of uniform composition for targets such as cables. Large uncertainties are noted in the prediction of cable and walls temperatures by CFAST and FDS in this study. The thermal inertia of the cables or walls tends to reduce the magnitude of the inaccuracies caused by the crude target models on the peak temperature predictions. However, the heat up of the cables, a parameter more important for safety analysis, predicted by the codes is much slower than observed in the experiments.

Analysis presented here of intense and severe fire conditions with the CFAST code produced erratic results due to the fundamental limitation of the model for scenarios with high heat fluxes. Modeling vertical flow through horizontal vents in CFAST (a zone model) also posed a challenge in a benchmark exercise which examined fires in multi-level buildings such as the turbine building. This was due to the lack of spatial treatment in the code to account for multiple hatches that separate levels in a building, and the simple criterion used to determine the direction of flow through a vertical opening which led to erratic results.

Although the trends of global parameters output from FDS for multi-level fire scenarios seem reasonable, there is no experimental data available to validate the output. Notably, there was wide variation in the prediction of hatch flow from various fire models used in the multi-level benchmark exercise. The variation in flow patterns through the hatches led to the wide spread in predicted hot gas temperature. A wide spread of values for the upper deck was observed where the gas temperatures predicted by different fire models *varied by a factor of about 5*. This was attributed to the fluid dynamic complexities of an upper deck connected to the lower deck by horizontal hatches. It was concluded that the physics of these flow phenomena are not well understood since there was such a large variation between the fire model predictions.

The analysis of scenarios with mechanical ventilation showed that errors in the prediction of fire extinction can result unless the fire model is coupled to the mechanical ventilation system, i.e. the pressure changes of the fire compartment can affect the flow rates of the mechanical ventilation system.

Finally, the results of this study indicate that the empirical correlations in FDTs are best suited for exploratory calculations where a rough estimate is sufficient, while acknowledging the answers may contain large inaccuracies.

Recommendation

Not withstanding the above limitations, bounding analysis with fire models is still possible as long as the limitations identified in this report, which are not all encompassing, are acknowledged, understood and taken into account. Bounding analysis can be conducted by initially examining whether the target will be impinged by the movement of the flame and fire plume. Calculations can then be conducted based on whether the cable target will be immersed in the flaming and plume region, or only exposed to radiative heating from the fire, and convective and radiative heating by the hot gases. Fire science and modeling is an evolving area. It is important to take time to understand the physics and performance of models when applying them. This document and others from the ICFMP project are good sources of information.

Research and improvement programs should be developed to overcome the limitations identified in this report so that fire models become a reliable and useful tool for nuclear plant fire safety analysis. This report and the more detailed reports of the ICFMP project provide some recommendations on approaches to improving the models to overcome the identified limitations. Phase II of the ICFMP project which was planned to conduct model improvements based on the findings of Phase I should be initiated.

5 Acronyms and Initialisms

BE	Benchmark Exercise
CFAST	Consolidated Fire and Smoke Transport
CFD	Computational Fluid Dynamics
FDS	Fire Dynamic Simulator
FDTs	Fire Dynamics Tools
C	Centigrade
CO2	Carbon Dioxide
CO	Carbon Monoxide
Expt.	Experiment
HGL	Hot Gas Layer
HRR	Heat Release Rate
iBMB	Institut für Baustoffe, Massivbau und Brandschutz
ICFMP	International Collaborative Fire Model Project
I&C	Instrumentation and Control
kg	Kilogram
kW	Kilowatt
LC	Lower compartment
LOL	Lower Oxygen Limit
m	Meter
m2	Square meter
m^{-2}	Square meter
m3	Cubic meter
max	Maximum
mg	Milligram
mu-gm	Microgram
NIST	National Institute of Standards and Technology
O2	Oxygen
Pa	Pascal
PVC	Polyvinyl Chloride
Rad	Radiation
s	Second
TC Tree	Thermocouple tree
UC	Upper compartment
USNRC	U.S. Nuclear Regulatory Commission
Vol.	Volume
w	Watt
XPE	Thermoset
Zf	Mixture fraction at flame surface

1 Introduction

The work presented in this report was initiated by the author when he was employed at the U.S. Nuclear Regulatory Commission (USNRC) and served as a guest researcher in the National Institute of Standards and Technology (NIST), U.S. Department of Commerce. The work, including reanalysis, was completed by the author after he left USNRC and established Deytec, Inc.

Efforts to review and establish performance-based fire safety analysis methods in the fire science community began in the mid-1990s. Several periodic conferences were initiated at that time to allow professionals and organizations to share their initiatives to establish performance-based fire safety analysis methods and regulations. These methods were reviewed by the author at that time (Dey, 1998) when the USNRC initiated an effort to evaluate risk-informed, performance-based methods for nuclear power plant fire protection analyses. This review led the USNRC to initiate the development of a risk-informed, performance-based regulation for fire protection at nuclear power plants (Dey, 1997).

The International Collaborative Fire Model Project was initiated in 1999 by the USNRC (Dey, 2000) to evaluate fire models for nuclear power plant applications. The author led the project from 1999 to 2006. The objective of the collaborative project was to share the knowledge and resources of various organizations to evaluate and improve the state of the art of fire models for use in nuclear power plant fire safety and fire hazard analysis. The project was divided into two phases. The objective of the first phase was to evaluate the capabilities of current fire models for fire safety analysis in nuclear power plants. The second phase was planned to implement beneficial improvements to current fire models that are identified in the first phase. Based on international workshops (Dey, 2001; Dey, 2003), five international benchmark exercises were formulated and conducted to evaluate the capabilities and limitations of fire models to predict parameters of interest in nuclear plant fire safety and risk analysis. Typically, seven organizations from five countries, Germany, UK, France, Finland, and USA, exercised their respective fire models in the benchmark exercises. The fire models exercised were zone, lumped-parameter, and computational fluid dynamic (CFD) fire models. Empirical fire correlations were also evaluated. At least ten other organizations participated in the ICFMP through peer review of project documents and attendance at twelve project workshops held over ten years.

This report presents a summary of the results of the analysis of the five benchmark exercises conducted with the CFAST (Consolidated Fire and Smoke Transport (Jones, 2009)) zone model, FDS (Fire Dynamic Simulator (McGrattan, 2009)) computational fluid dynamic model, and a collection of empirical fire correlations contained in FDTs (Fire Dynamic Tools (Iqbal, 2004)) by the author in the ICFMP project, and later updated for this report. The full reports of the analyses can be found in Dey, 2002; Dey, 2009a; Dey, 2009b; Dey, 2009c; and Dey, 2009d. Reports that documented a synthesis of the results of analysis by the various organizations using their respective fire models were also developed in the ICFMP for each benchmark exercise (Dey, 2002; Miles, 2004; McGrattan, 2007; Klien-Hessling, 2006; and Riese, 2006). A summary of the work done for Benchmark Exercises 1-5 is contained the ICFMP Summary Report (Rowekamp, 2008). This report only discusses the analysis conducted by the author. A separate paper will be published by the author that will discuss the technical and programmatic "lessons learned" in the ICFMP project.

Chapter 2 provides a summary of the five international benchmark exercises conducted in the ICFMP. Chapter 3 presents a discussion of the limitations of CFAST and FDS fire models, and the FDTs empirical fire correlations, based on analysis of the fire scenarios in the five benchmark exercises.

2 International Benchmark Exercises

2.1 Benchmark Exercise No. 1 – Cable Tray Fires

This benchmark exercise was designed to evaluate the capability of fire models to analyze cable tray fires of redundant safety systems in nuclear power plants. Safety systems in nuclear power plants are required to safely shutdown the reactor during abnormal and emergency events to prevent a reactor meltdown. By regulation in the US, a specified distance separates cable trays of redundant safety systems if they are located in the same compartment in which a single fire could potentially damage both systems. Therefore, the analysis of fires that could damage redundant safety trains is an important part of nuclear power plant fire hazard analysis.

This benchmark exercise was a hypothetical exercise without any experimental data. The results of the different models can be analyzed and compared against each another, but it was not possible to derive errors in the model predictions since there was no experimental data. The benchmark exercise was developed for a simple scenario defined in sufficient detail to allow the evaluation of the physics modeled in the fire computer codes. The comparisons between codes can be used to understand the modeling of the physics in them, i.e. if all the codes produce similar results over a range of cases for a scenario, then the physics modeled in the codes is most likely understood and adequate for the scenario. If the results from the codes are widely different, then one can suspect that the physics of the phenomena is not understood well and modeled adequately in any of the codes.

A representative emergency switchgear room in a nuclear plant was selected for this benchmark exercise. The room is 15.2 m (50 ft) deep x 9.1 m (30 ft) wide and 4.6 m (15 ft) high. The room contains the power and instrumentation cables for the pumps and valves associated with redundant safety systems. The power and instrument cable trays run the entire depth of the room, and are separated horizontally by a distance, d. The cable trays are 0.6 m (~24 in.) wide and 0.08 m (~3 in.) deep. A simplified schematic of the room, illustrating critical cable tray locations, is shown in Figure 2-1. The room has a door, 2.4 m x 2.4 m (8 ft x 8 ft), and a mechanical ventilation system with a flow rate of 5 volume changes per hour in and out of the room.

There were two parts to the exercise. The objective of Part I was to determine the maximum horizontal distance between a specified transient (trash bag) fire and tray A that results in the ignition of tray A. Part II examined whether the target cable tray B will be damaged for several heat release rates of the cable tray stack (A, C2, and C1), and horizontal distance, d. The effects of the fire door being open or closed, and the mechanical ventilation on or off, were examined in both parts of the benchmark exercise.

The full specification for the benchmark exercise can be found in Dey, 2002.

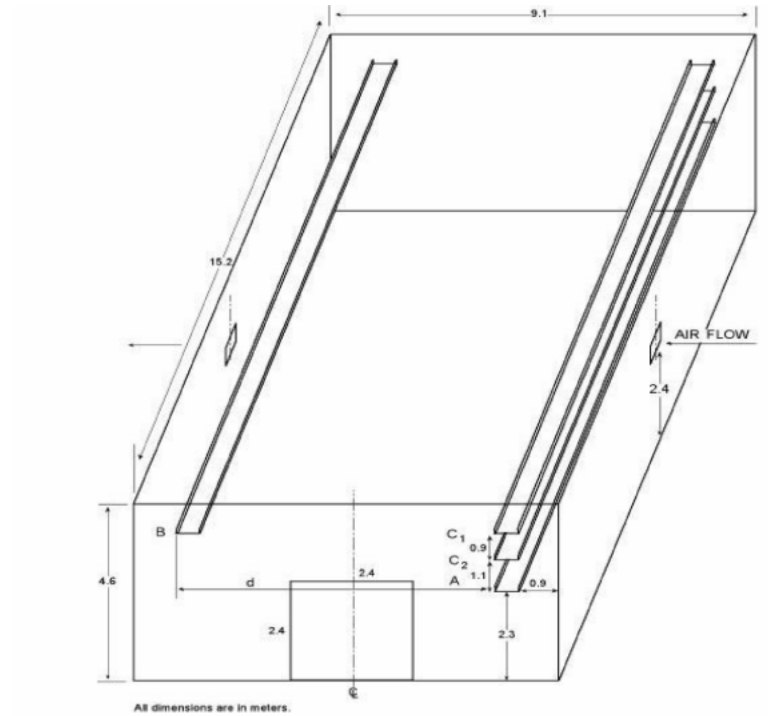

Figure 2-1 Simplified Schematic of Emergency Switchgear Room for BE No. 1

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

The analysis presented in this report was conducted for Benchmark Exercise # 2, Part II. The objective of Part II of the second benchmark exercise was to examine scenarios that are more challenging for zone models, in particular to fire spread in a multi-level larger volumes. The issues to be examined are a subset of those that will be faced by modelers simulating fires in turbine halls in nuclear power plants. The following provides some key elements of the specification of the problem.

Presently, there is no experimental data that would be representative of turbine hall fires. Therefore, Part II of Benchmark Exercise # 2 included three hypothetical cases to examine the effect of a bigger fire and larger floor area representative of a hydrocarbon pool fire in a real turbine hall. Three scenario cases set inside a rectangular building with dimensions comparable to those of a real turbine hall were analyzed. Cable and beam targets were added to allow the onset of damage to be studied. The fire size was chosen to produce temperatures that may be capable of damaging equipment or cables. Again, the comparisons between codes can be used to understand the modeling of the physics in them, i.e. if all the codes produce similar results over a range of cases for the scenario, then the physics modeled in the codes is most likely understood and adequate for the scenario. If the results from the codes are widely different, then one can suspect that the physics of the phenomena is not understood well and modeled adequately in any of the codes.

Figures 2-2 and 2-3 show the dimensions and geometry of the building. The building is divided into two levels (decks) connected by two permanent openings (hatches). Although many turbine halls contain three decks, it was decided that modeling two decks is sufficient for the benchmark exercise to examine the physics of these scenarios. Figure 2-3 shows the exact location of the internal ceiling and the two open hatches (each 10 m by 5 m in size).

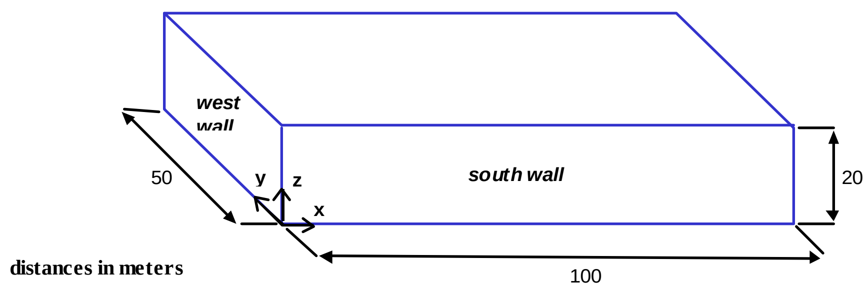

Figure 2-2 Building Geometry for BE No. 2, Part II – External Dimensions

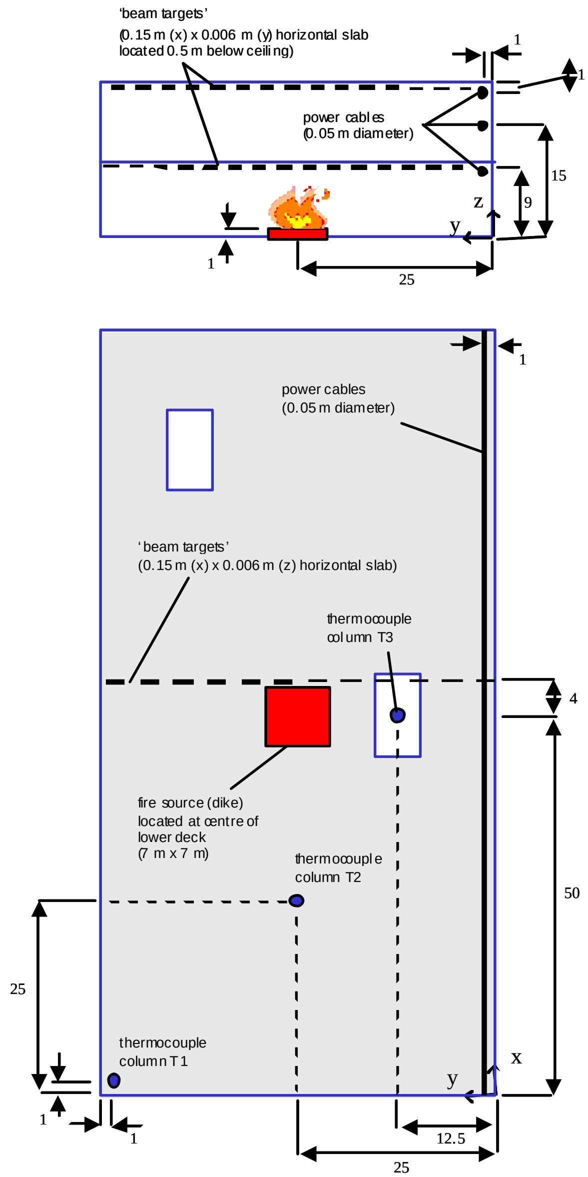

Figure 2-3 Location of Fire Source, Hatches and Targets for BE No. 2, Part II

The three cases had different ventilation conditions, covering nearly-sealed conditions, natural ventilation conditions, and a combination of natural and mechanical ventilation. For natural ventilation conditions, a complete set of smoke exhaust vents at roof level and a complimentary set of make-up vents in the side walls were assumed to be open for the full duration of the scenario. For natural and mechanical ventilation conditions, it was assumed there are mechanical vents at roof level and that the make-up air is supplied by natural ventilation openings in the side walls. For all three cases, the fire source is assumed to be lube oil burning in a dike (tray) with dimension 7 m by 7 m, located at the centre of the lower deck. To make Benchmark Exercise No. 2, Part II relevant to practical applications, three cable targets were introduced, similar to the first benchmark exercise. Two structural beam targets were also included to examine issues related to the structural integrity of the building. Additionally, a 'human target' was located 1.5 m above floor level (the internal ceiling) at the centre of the upper deck.

The full specification of the benchmark exercise can be found in Miles, 2004.

2.3 Benchmark Exercise No. 3 – Full-Scale Nuclear Power Plant Compartment Fire Experiments

The results of Benchmark Exercise No. 1 indicated large discrepancies between code predictions which resulted from inadequacies in the sub model for the target, and the prediction of heat flux incident on it. Benchmark Exercise No. 3 was specifically designed to examine the predictive capability fire models to calculate heat flux to a target and the resulting heating, specifically to cables. The data from the tests can also be used to improve target models.

Figure 2.4 is a schematic of the compartment designed and used for Benchmark Exercise No. 3 which is similar to that analyzed in Benchmark Exercise No. 1. The compartment was 7.04 m x 21.66 m x 3.82 m in dimension and designed to represent a realistic-scale cable room in a nuclear power plant. The total compartment volume was 582 m3.

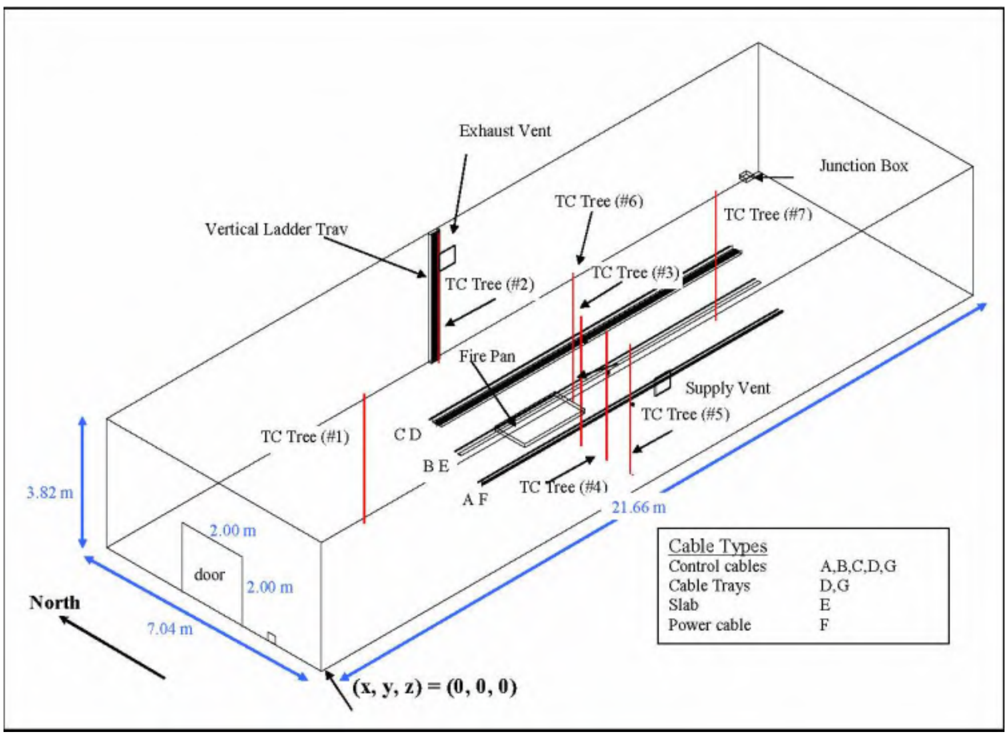

Figure 2-4 Schematic of Compartment for Benchmark Exercise No. 3

Walls and ceiling were covered with two layers of 25 mm marinate boards, while the floor was covered with two layers of 25 mm gypsum boards. The supply duct and horizontal cables are on the right side of the compartment as shown in Fig. 2.4, while the vertical cable tray and exhaust duct are on the left. The location of some of the compartment features are also shown in Figure 2-4, including the targets (A-F), thermocouple trees, junction box, fire pan, and the door. The compartment contained three control cables (A, B, C), a horizontal (Target D) and a vertical cable tray (Target G) with control cables, a solid polyvinyl chloride (PVC) slab "target" (E), a single power cable (F), and a junction box. Both PVC and thermo set (XPE) cables were used in the experiments. A picture of some of the cables in the compartment is shown in Figure 2-5.

Figure 2-5 Cables in Compartment for Benchmark Exercise No. 3

The targets were arranged to examine the following effects:

- Modeling one cable versus cables bundled in a cable tray
- Modeling a cable as composed of a slab with uniform material versus a real cable geometry and composition
- Heating characteristics of cables with a large diameter versus smaller cables
- Elevation of the target in the hot gas layer
- Distance of target from the fire
- Vertical versus horizontal cable target
- Heating of a junction box on the ceiling

One goal of the target selections and locations was to develop data that could be used in establishing the degree of conservatism and margin in cable damage criteria that are presently used in the field. Several thermocouples were placed along the lengths of the cables in all the targets to examine the effect of elevation and distance from the fire on cable heating.

The test configuration and fire scenarios were selected to examine the following effects:

1. Heat release rate
2. Natural ventilation with open door
3. Mechanical ventilation system operation
4. Combination of mechanical and natural ventilation
5. Distance between fire and target
6. Target heating directly in the plume region

Fifteen tests were conducted in total for Benchmark Exercise No. 3 which resulted in a vast amount of data for model evaluation and improvement. A picture of a partially under-ventilated fire in Test 13 is shown in Figure 2-6. A full specification of Benchmark Exercise No. 3 can be found in Dey, 2009a and Hamins, 2006. Videos of the fires in the tests can be found in Dey, 2009e; and the experimental data from the tests can be found in Dey, 2009f and Hamins, 2006.

Figure 2-6 Under-Ventilated Fire in Test 13 of Benchmark Exercise No. 3

2.4 Benchmark Exercise No. 4 – Large Fire Experiments in a Compartment

Benchmark Exercise No. 4 was chosen to challenge fire models and test their ability to model intense fires relative to the size of the compartment. The prediction of heat flux to targets was also again examined. Experiments with large pool fires in a compartment conducted at iBMB (Institut für Baustoffe, Massivbau und Brandschutz) of the Braunschweig University of Technology, Germany were used for this benchmark exercise. The experimental room (see Figure 2-7) had a floor area of 3.6 m x 3.6 m and a height of 5.7 m. The room was made of concrete and is naturally and mechanically ventilated.

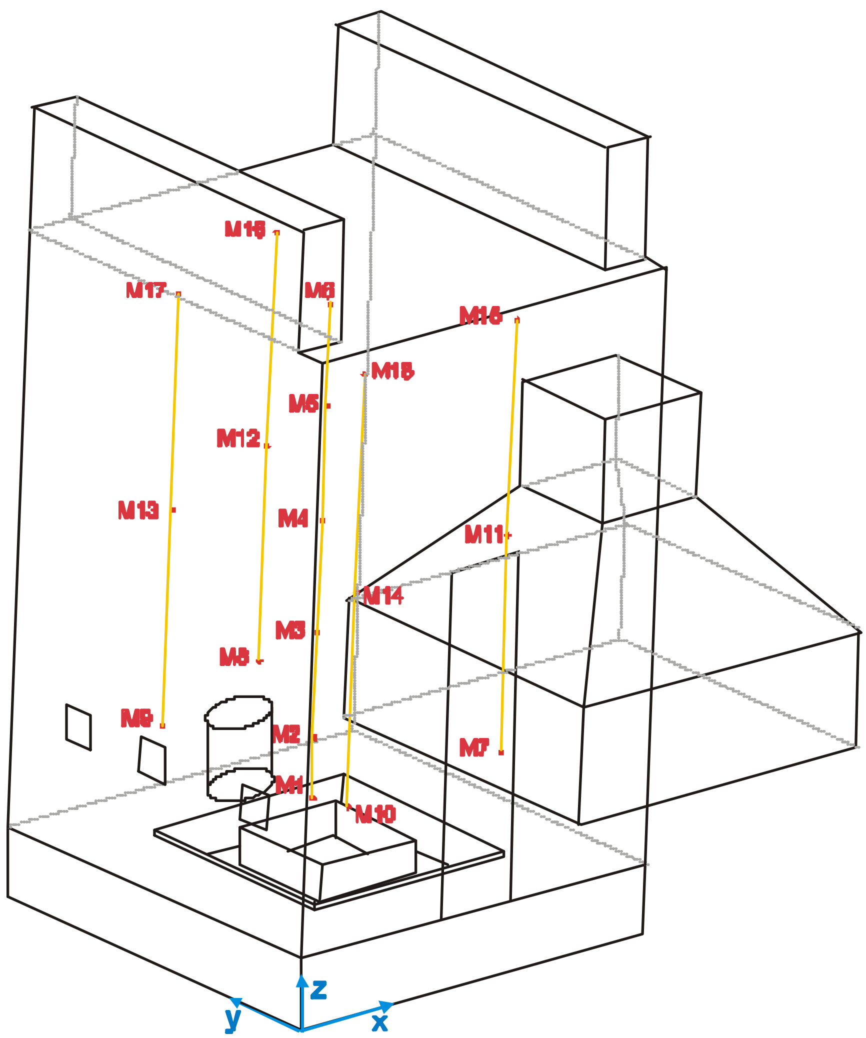

Figure 2-7 iBMB Oskar Compartment Used for Benchmark Exercise No. 4

Figure 2-8 View of the Targets in Benchmark Exercise No. 4

Two tests in the test series conducted were used for ICFMP Benchmark Exercise No. 4. Test 1 had an open door (see Fig. 2-7) which was located at the center of the front wall. The door had an area of 0.7 m x 3.0 m. In Test 3, the door opening was partly closed by reducing the free cross section to 0.7 m x m. Although the mechanical ventilation was not in operation, there was some flow which was measured. A 4 m x 4 m fire pan was located in the center of the floor area on a weight scale. Three different types of targets were positioned on the left side of the fire compartment. The materials were "aerated concrete ", concrete, and steel. The targets were 0.3 m x 0.3 m in size and are shown in Figure 2-8.

The full specification of Benchmark Exercise No. 4 can be found in Klein-Hessling, 2006. Figure 2-9 is a picture of the fire in Test 1.

Figure 2-9 Fire in Test 1 of Benchmark Exercise No. 4

2.5 Benchmark Exercise No. 5 - Cable Exposure to Pool Fires in a Trench

The experiments for Benchmark Exercise No. 5 were also conducted at iBMB (Institut für Baustoffe, Massivbau und Brandschutz) of the Braunschweig University of Technology, Germany. The fire scenarios in Benchmark Exercise # 5 were designed to evaluate the capability of fire models to predict the effects of pool fires in complex geometries, cable heating, and flame spread in vertical cable trays. The analysis presented in the next chapter examines the ability of fire models to predict the effects of pool fires in complex geometries, and cable heating. An analysis of the capability of fire models to predict flame spread in cable trays is presented in Riese, 2006.

The experimental room (see Figure 2-10), which is the same as for Benchmark Exercise No. 4, has a floor area of 3.6 m x 3.6 m and a height of 5.6 m. The room is made of concrete and is naturally and mechanically ventilated.

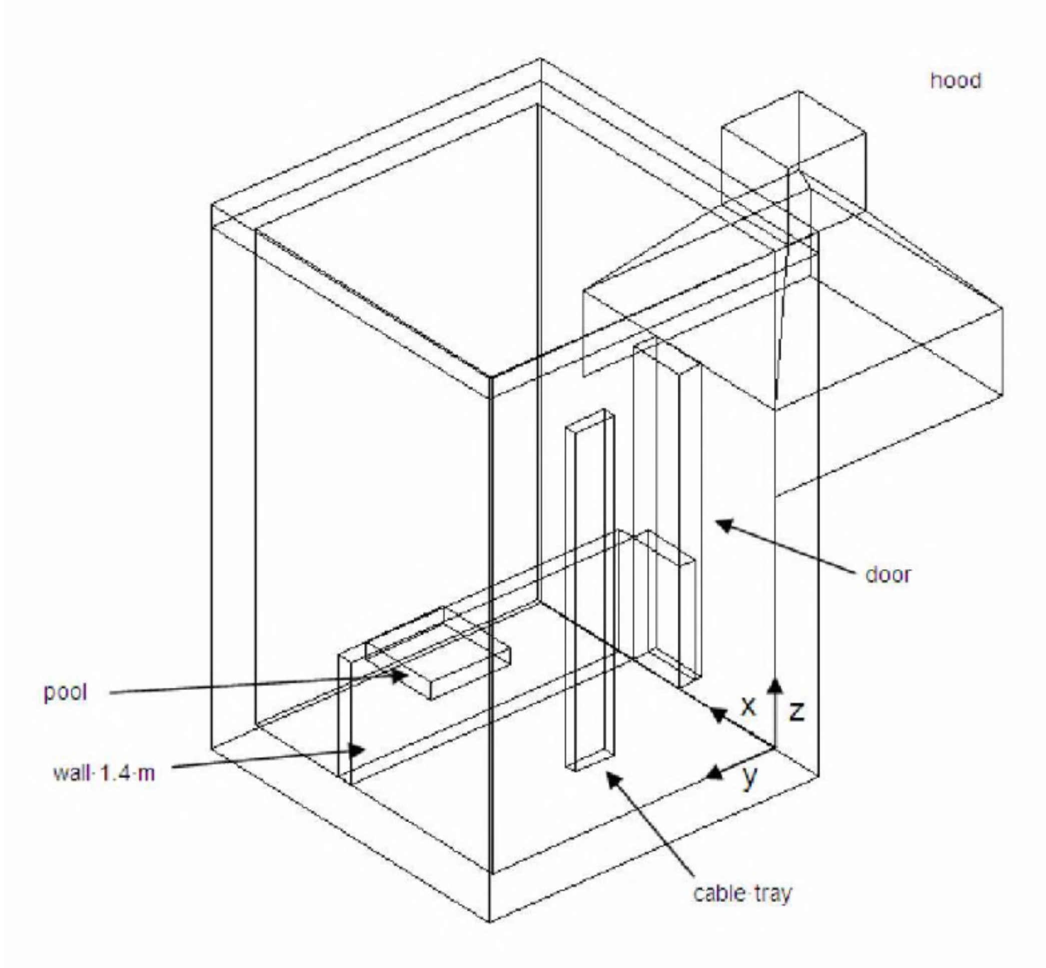

Figure 2-10 Schematic of Compartment for Benchmark Exercise No. 5

Natural ventilation takes place through an opening of 0.7 m width and 3.6 m height, which is reduced by a wall of 1.4 m height to an area of approx. 1.5 m². The selected test compartment was not mechanically ventilated. The first part of the selected test consisted of preheating the cable trays in the room. A pool 1 m² floor area filled with ethanol (ethylene alcohol) located in a trench is used as a pre-heating source. This 1st part of the experiment is utilized for analysis in this study. A hood was installed above the front door (See Figure 2-10). The energy release can be estimated using the hot gases flowing into the hood and the oxygen consumption method.

Two vertical cable trays were located along the height of the compartment on the opposite side of the pool fire enclosed by a 1.4 m wall. The two cable trays were filled with power cables and instrumentation and control (I&C) cables, respectively. For Test 4 in the series, which is used in this report, the cables were composed of PVC material.

The full specification of the benchmark exercise can be found in Riese, 2006. Figure 2-11 is a picture of the pool fire analyzed here for Benchmark Exercise No. 5.

Figure 2-11 Pool Fire in Trench in Benchmark Exercise No. 5

3 Fire Model Limitations

This chapter discusses the limitations of the CFAST and FDS fire models, and empirical fire correlations contained in FDTs for nuclear plant fire safety and risk analysis. The limitations presented here were derived based on analysis conducted in the five international benchmark exercises described in Chapter 2. The full analysis for the benchmark exercises are contained in Dey, 2002; Dey, 2009a; Dey, 2009b; Dey, 2009c; and Dey, 2009d. The results of blind, unbiased analyses were used to derive the true errors in model predictions which are presented. The analyses indicate that fire models and empirical correlations at the present are severely limited in predicting parameters of major interest in nuclear plant fire safety and risk analysis.

As discussed earlier, the main goal of fire safety and risk analysis in nuclear plants is to predict damage to cables in various configurations as damage to power, control, or instrument cables could lead to the loss of reactor core cooling during accident conditions. Although the predictions of general compartment conditions, e.g. hot gas temperature and interface height, during a fire were reasonable (10-20 % errors) for most fire scenarios by the CFAST and FDS fire models, the prediction of the heat flux to and heat up of cable targets proved much more difficult.

The compartment hot gas temperature and interface height are determined by mass and energy balances and plume flow which are robust in the fire models and thereby result in reliable predictions. The temperature distribution in the hot gas is also adequately captured by CFD codes like FDS. The algorithms for predicting door heat and mass flows, and the oxygen and carbon dioxide concentrations for ventilated fires are simple and reliable. Carbon monoxide and smoke concentrations can also be reliably predicted for ventilated fires as long as correct yields are included for the combustion products in the models. The algorithms for predicting convective and/or radiative heat fluxes to the cables from the flaming region and hot gas is much more complex. The ability to predict heat flux, especially when targets are close to the fire flame, was found to be particularly challenging (40 % to > 100 % errors) as the algorithms for calculating heat flux and fire flame characteristics involve phenomena that are presently not well understood. Although the correlations for FDTs are suitable for simple fire scenarios and parameters, they are severely limited for most fire scenarios in nuclear plants. Fire models can be reliably used by first examining the flame characteristics in the fire scenario, and then making bounding calculations based on whether the cable target will be exposed to the flame or only to hot gases.

3.1 Movement and Location of the Fire Flame

The prediction of the movement and location of the fire flame and plume is critical for nuclear plant fire safety analysis because the likelihood of cable failure will increase significantly if the cables are immersed in the flame or fire plume. The only models that have been formulated to predict the movement and location of the fire flame and plume are CFD models like FDS. CFAST utilizes a simple point source model for the fire and empirical correlations to determine plume flow, and therefore does not predict flame and plume movement.

The combustion process is extremely complex with over a hundred combustion steps involved which are dependent on temperature. The knowledge of the combustion process is currently limited and evolving with research being conducted in the fire science community. The FDS model attempts to simulate the combustion process with a mixture fraction chemistry model. The model is based on the assumption that large-scale convective and radiative transport phenomena can be simulated directly, but physical processes occurring at small length and time scales must be represented in an approximate manner. All species of interest are described in terms of a scalar quantity, the mixture fraction Z(x, t). The form of the state relations between the species of interest and the mixture fraction, based on classical laminar diffusion theory, lead to a "flame sheet' model where the flame is a two dimensional surface embedded in a three dimensional space. Oxygen and fuel diffuse from areas of higher to lower concentrations and meet at the flame sheet where there is instantaneous and complete combustion. Multiple flames are approximated by a single diffusion flame. The local heat release rate is computed from the local oxygen consumption rate at the flame surface, assuming that the heat release rate is directly proportional to the oxygen consumption rate, independent of the fuel involved. The mixture fraction at the flame surface, Zf, is defined where the fuel and oxidizer simultaneously vanish. Zf is around 0.05 for most hydrocarbon fuels. In the numerical algorithm, the local heat release rate is computed by first locating the flame sheet, then computing the local heat release rate per unit area, and finally distributing this energy to the grid cells cut by the flame sheet.

One assumption inherent in the mixture fraction model is that the combustion process is temperature independent, i.e. the state relations between the mass fraction of each species and mixture fraction is fixed. FDS includes some approximate techniques to account for this assumption when the oxygen concentration or temperature is too low to sustain combustion. For scenarios where the fire is under-ventilated, the flame sheet will be extended to regions where the fuel and oxygen are at the ideal stochiometric ratios input to the model. This is shown in Figure 3-1 for Benchmark Exercise (BE) No. 2. However, this does not indicate the presence of combustion in those regions because the temperatures may not be high enough to sustain combustion.

FDS version 5 included a mixture fraction vector through which oxygen and fuel can coexist, thereby attempting to model extinction. Attempts are also being made to include an eddy dissipation model and two-step combustion chemistry to simulate the production of soot and carbon monoxide. These models currently have several "dials" that have to be tuned in order to make predicted results match experimental data. Although these efforts are important steps to improve the model, they are in trial stages and not currently suitable for safety analysis for which the reliability of a model must be assured.

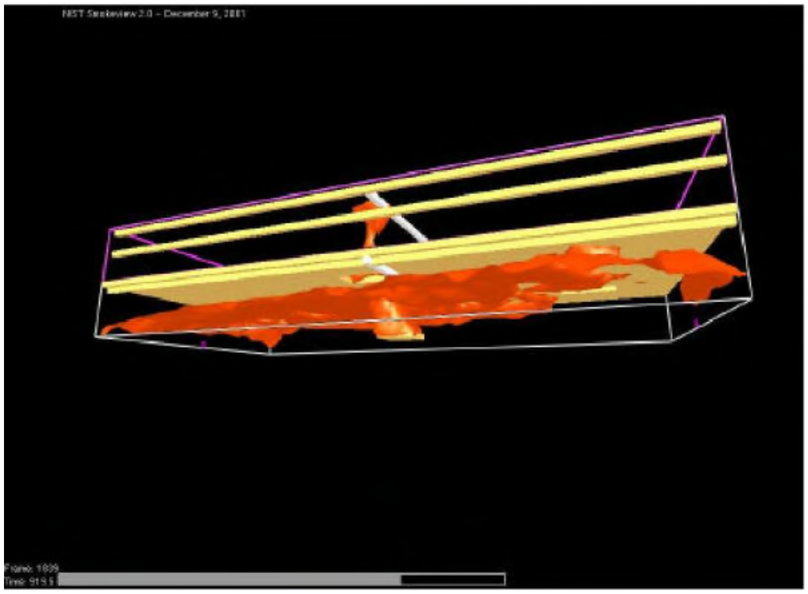

Figure 3-1 Isosurface of Mixture Fraction (920 s) from FDS - BE 2, Part II, Case 1

The inability to adequately simulate the flame and the effects of under-ventilation on the fire results in a lack of predictive capability to simulate the movement and location of the fire plume under a variety of conditions.

Figure 3-2 compares the gas temperatures in thermocouple Tree 2 predicted by FDS with measurement for Test 2 of Benchmark Exercise No. 3. The fire in this closed-door test was extinguished due to under-ventilation at 630 s. The experimental observation indicates a large increase and oscillations in gas temperature at Tree 2-7 starting at 540 s (and some increase at Tree 2-5) due to the lateral movement of the fire plume due to under-ventilation at the end of the transient. This flame and plume movement was also observed in the fire videos available for Benchmark Exercise No. 3 (Dey, 2009e). This movement of the fire plume due to under-ventilation is not simulated by FDS. Similar oscillations at Tree 2-7 were also noted for Test 4 and Test 13 of Benchmark Exercise No. 3. The measured surface temperature of the control cable at D-TS-12 also showed an 30 C increase and oscillation starting at ~ 580 s caused by the lateral movement of the flaming region and plume due to under-ventilation. None of these observations were predicted by FDS.

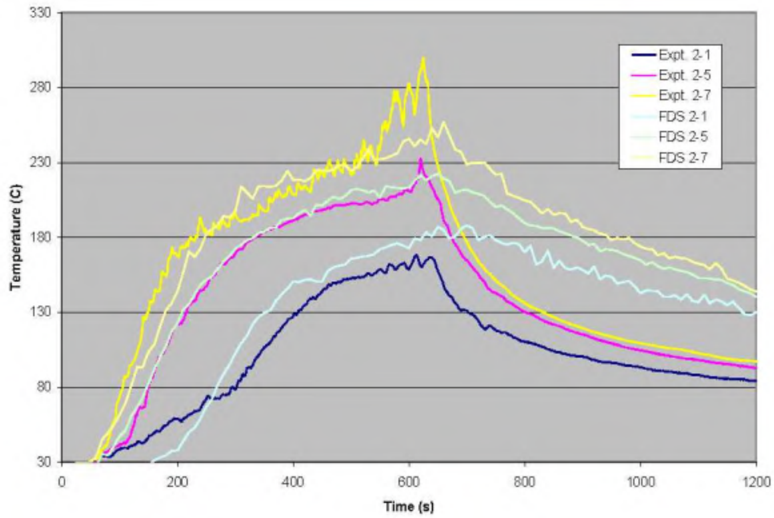

Figure 3-2 Compartment Temperature (Tree 2) - BE 3 Test 2

The movement of the fire plume in this test is also observed through both radiative and total measured fluxes shown in Figure 3-3 that indicate peaks starting at 536 s. These peaks in radiative or total heat flux are not predicted by FDS. These heat flux gauges were located at the other side of the room and fire compared to thermocouple Tree 2 indicating lateral movement of the flame in both directions. This was observed in the video recording of the fire.

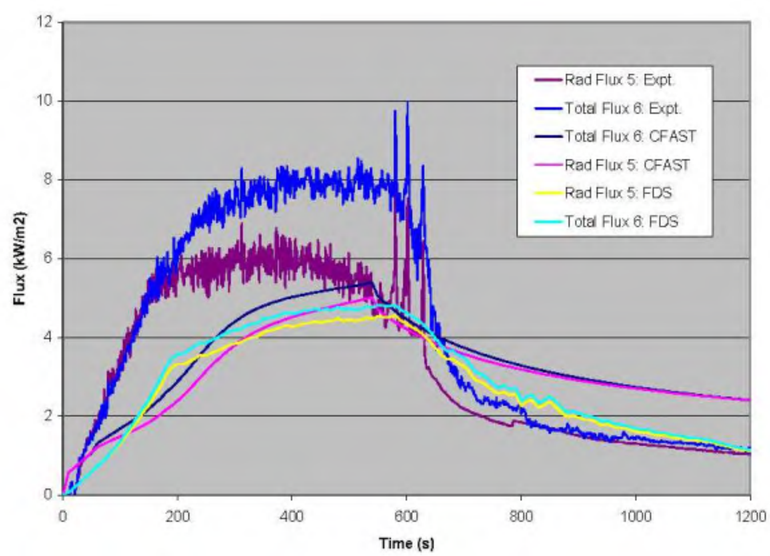

Figure 3-3 Heat Flux to Cables - BE 3 Test 2

The movement of the fire flame and plume is also observed through oscillations shown in Figure 3-4 in the measured temperature at Tree 5-6 for Test 15 of Benchmark Exercise No. 3. This oscillation indicates the movement of the flame in and out of that region. In Test 15, the fire pan was moved from the center of the room (the location for most tests) and located 1.25 m from the south wall. Tree 5 was on the south side of the fire pan while Tree 3 was in the north side. The vicinity of the fire to the south wall results in the movement of the flame due to boundary effects on the flow. These large oscillations and movement of the flame are not predicted by FDS as shown in Figure 3-3.

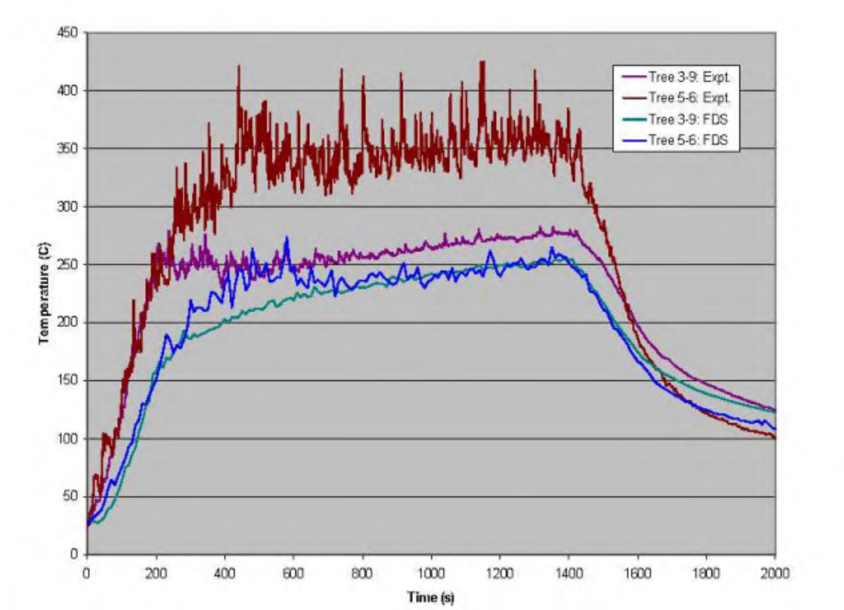

Figure 3-4 Hot Gas Temperature - BE 3 Test 15

The oscillations and movement of the flame toward the south wall is again evident through the measurements of hot gas temperatures at thermocouple Tree 3 and Tree 5 shown in Figure 3-5 and Figure 3-6, respectively. The figures show that the fire plume is tilted toward Tree 5 where the temperatures are higher and grouped together. The temperatures recorded by Tree 3 are what one would expect when a flame is not present while the grouping of the recorded temperatures at Tree 5 indicates the presence of the fire plume at the point of measurement.

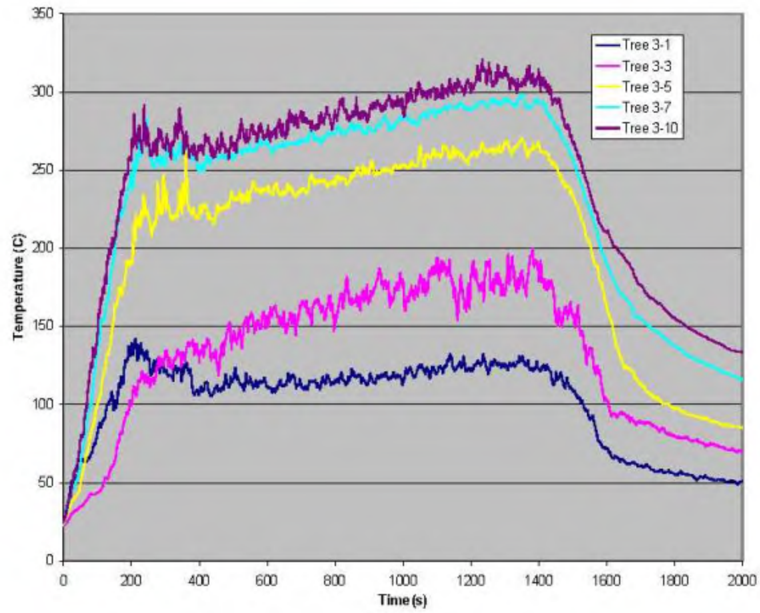

Figure 3-5 Measured Hot Gas Temperature at Tree 3 - BE 3 Test 15

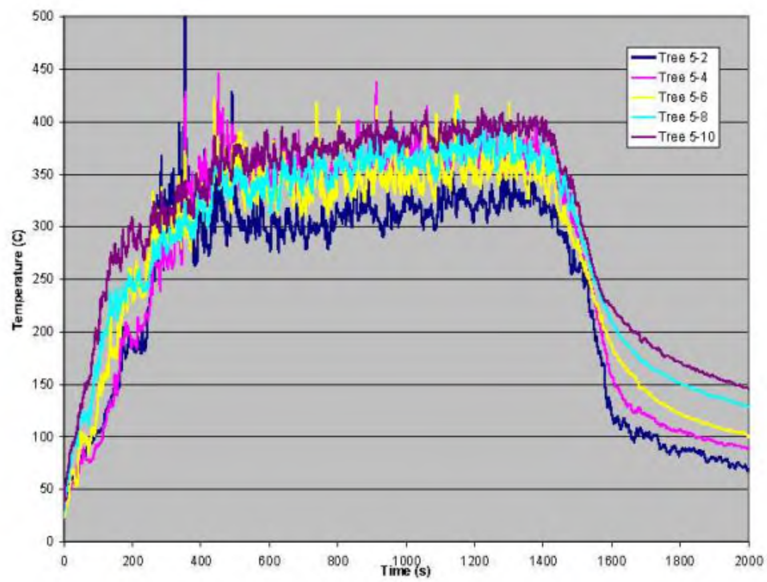

Figure 3-6 Measured Hot Gas Temperature at Tree 5 - BE 3 Test 15

The inability of the FDS model to simulate fire movement and location was also observed in Benchmark Exercise No. 4. The fire was located at the center of the compartment in the experiments conducted for Benchmark Exercise No. 4. FDS computations of the plume predict a larger tilt due to inflow from the door, whereas, the plumes in the experiments are observed to be stiffer and influenced less by the inflow. This inaccuracy in FDS again limits the reliability of using FDS to evaluate targets near the plume.

Figure 3-7 shows an isosurface of the mixture fraction (at a value of 0.062) at 238 s from FDS for Test 1 of Benchmark Exercise No. 4. The isosurface represents the flame sheet created by FDS at that point. Figure 3-7 shows that FDS simulates the flame sheet to be significantly pushed toward the rear wall by the flow of ambient air into the compartment through the door. Figure 3-8 shows a picture (view from door) of the fire flame in Test 1 of Benchmark Exercise No. 4. The flame is evidently not moved significantly.

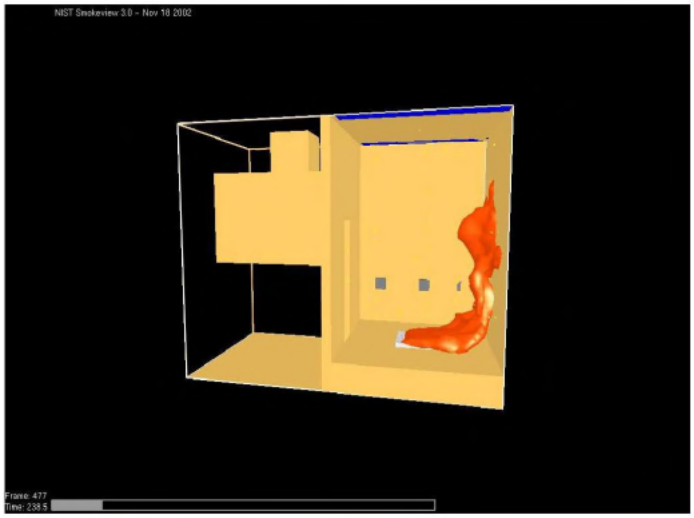

Figure 3-7 View of Flame sheet from FDS - BE 4 Test 1

Figure 3-8 Fire in Benchmark Exercise No. 4, Test 1

Figure 3-9 shows a slice profile (at x = 1.8 m) of the gas temperature in the compartment predicted by FDS for the same test. Figure 3-9 again shows that FDS simulates that the plume is pushed significantly toward the rear wall.

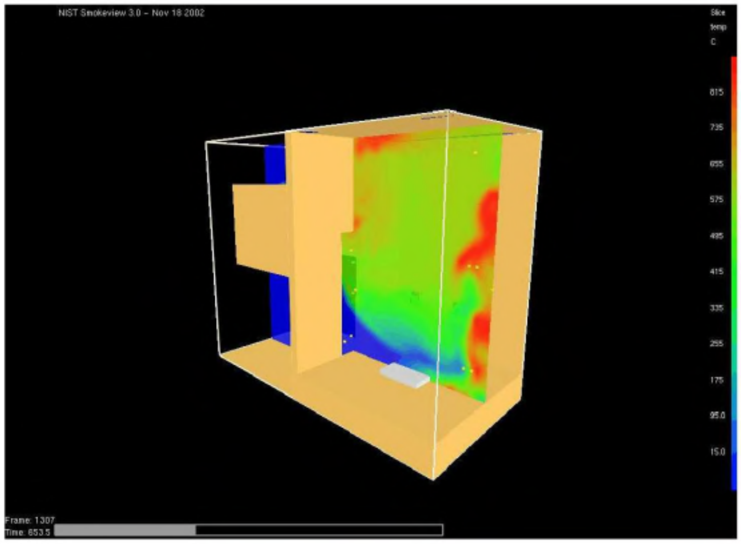

Figure 3-9 Temperature Predicted by FDS , BE 4 Test 1

Figure 3-10 shows the comparison of measured plume temperatures at M2, M4, and M6 with that predicted by FDS. As shown in Figure 3-10, FDS predicts peaks in the plume temperature at ~ 50 s. These peaks are explained by the plume development predicted by FDS. Observations of the plume predicted by FDS through Smokeview (the graphical interface for FDS) indicates a steady vertical plume until ~ 50 s when the plume is pushed to the rear wall by air flow into the compartment through the door. This causes peaks at ~ 50 s in the thermocouples, M2, M4, and M6 which are located directly above the fuel pan. The experimental measurements do not indicate this extensive movement of the fire plume. The measured data shows the plume to be fully developed at ~ 105 s after which the plume temperatures increase to ~ 1000 C without any intermediate peaks.

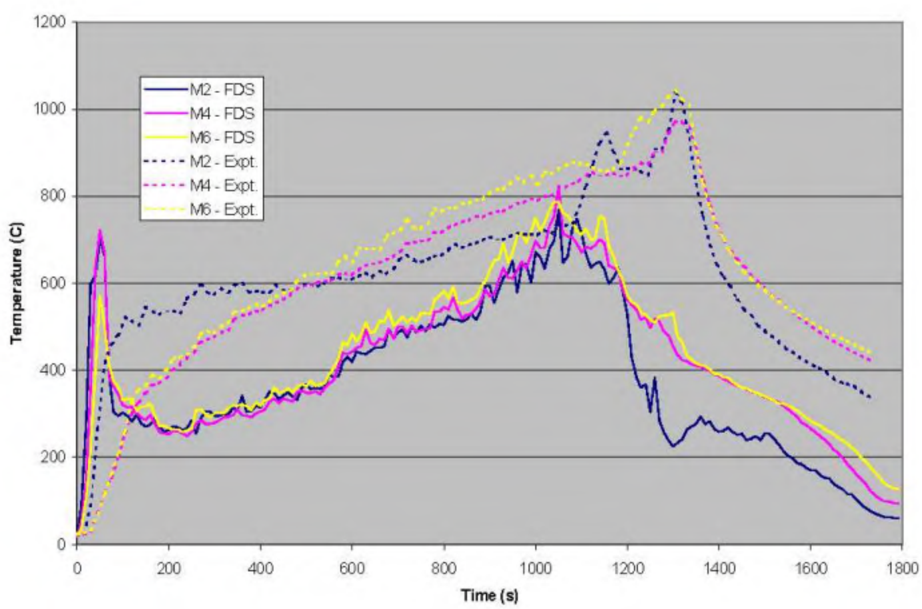

Figure 3-10 Plume Temperature - BE 4, Test 1

Finally, Figure 3-11 shows the local gas temperatures in the compartment at Level 1 for M7, M8, M9, and M10. The measured temperatures show a rapid increase in temperature followed by a more gradual increase until the end of the transient. The temperature measured at M10 is much higher than that measured at M7, M8, and M9. This is due to the tilting of the fire plume toward M10. FDS also shows a rapid increase in temperature followed by large oscillations and unexpected trends. These oscillations may be caused by oscillations in the flow through the door predicted by FDS. The temperature predicted at M8 (closer to the wall than M10) by FDS is highest since the code predicts the fire plume is pushed more toward the rear wall than observed, as discussed above.

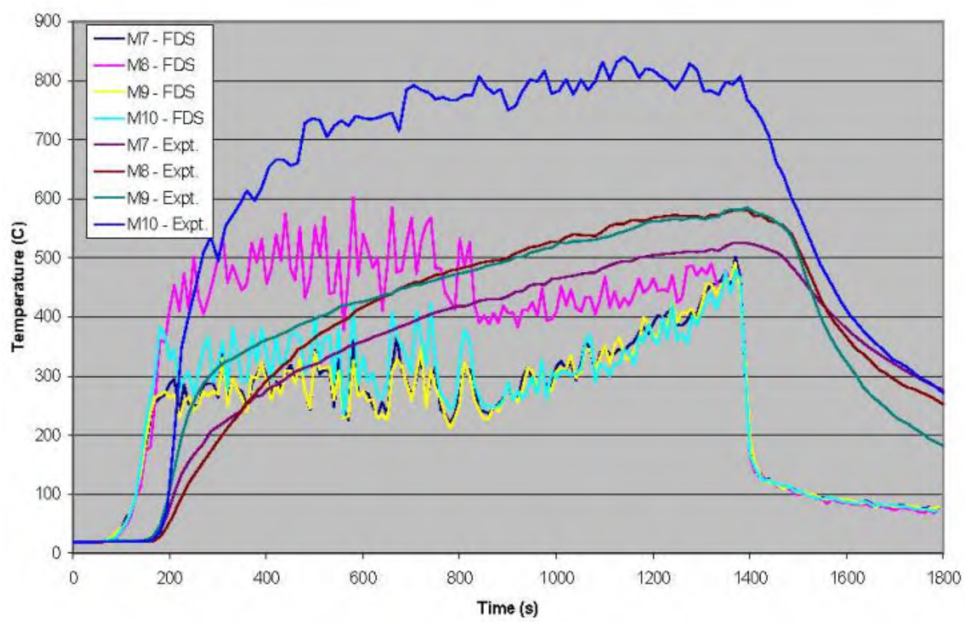

Figure 3-11 Gas Temperature - BE 4, Test 1

Finally in Benchmark Exercise No. 5, the experiments with a pool fire in the trench shows the importance of accurate modeling of the plume development in CFD codes so that fire phenomena in complex geometries is adequately captured. This is important in order to accurately evaluate target heating and ignition near the plume. The experiments showed that FDS predictions can be erroneous and lead to large under predictions of plume and target temperatures for pool fires in complex geometries such as in a dike that would contain lube oil in a nuclear plant.

Figure 3-12 shows photographs of the fire within a 1-minute time frame and illustrates the random nature of the flame in the trench that was observed in Benchmark Exercise No. 5.

Figure 3-12 Photographs of Pool Fires in a Trench - BE 5, Test 4

Figure 3-13 shows the comparison of measured plume temperatures at TP2 - TP7 with that predicted by FDS. As shown in Figure 3-13, FDS predicts peaks in the plume temperature at ~ 120 s which are absent in the measured data. The measured data shows the plume to be fully developed at ~ 60 s after which the plume temperatures at TP2 increases to ~ 450 C without any intermediate peaks. FDS predicts the plume temperature at TP2 to reach only ~ 180 C at the end of the transient indicating the predicted temperature in the plume region is the same as in the HGL.

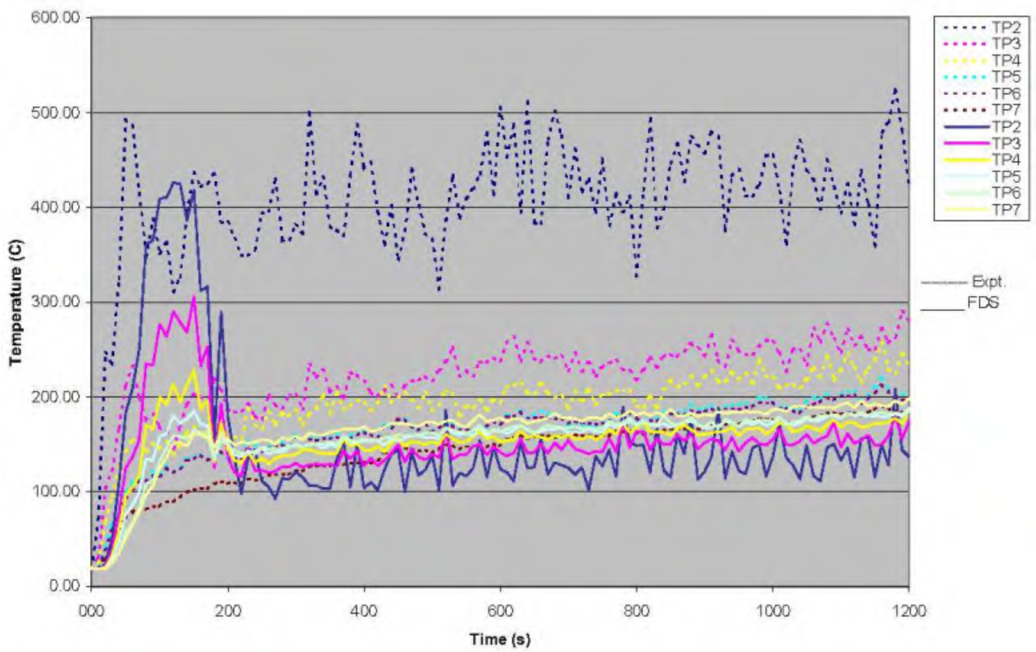

Figure 3-13 Plume Temperature - BE 5, Test 4

The above observations show that FDS predictions can be erroneous and lead to large under predictions of plume and target temperatures for pool fires in complex geometries.

3.2 Under-ventilated Conditions and Fire Extinction

3.2.1 Fire Extinction

The analysis of the scenarios in Part II of Benchmark Exercise No. 1 demonstrated the complexity in modeling an elevated fire source that can be affected by a limited oxygen environment. The extinction sub-models utilized in CFAST is an approximation of the interaction of the complex combustion process with a limited oxygen environment. Therefore, the result from the extinction sub-model represented an approximation of the conditions expected for the fire scenarios. The assumption for the Lower Oxygen Limit (LOL) in CFAST significantly affected the predicted peak target temperature.

One assumption inherent in the mixture fraction model in FDS is that the combustion process is temperature independent, i.e. the state relations between the mass fraction of each species and mixture fraction is fixed. FDS currently includes some approximate techniques to account for this assumption when the oxygen concentration or temperature is too low to sustain combustion. As stated earlier, for scenarios where the fire is under-ventilated, the flame sheet will be extended to regions where the fuel and oxygen are at the ideal stochiometric ratios input to the code. However, this does not indicate the presence of combustion in those regions because the temperatures may not be high enough to sustain combustion.

Both CFAST and FDS employ simple algorithms for predicting fire behavior in under ventilated conditions. The models also had difficulty predicting the mixing of and local concentrations of oxygen, especially for forced ventilation conditions, in the tests for Benchmark Exercise No. 3. The lack of ability to model the coupling of the compartment with the mechanical ventilation system resulted in errors in the predicted compartment pressure, ventilation flow rates, and O2 concentration, as is discussed later.

Figure 3-14 shows a comparison of the O2 concentration predicted by CFAST and FDS with experimental measurement for Test 1 of Benchmark Exercise No. 3 which was closed-door experiment without forced ventilation. The measurements show oscillations in the O2 concentration near the fire that are not predicted by CFAST or FDS. These oscillations are possibly due to the lack of complete mixing of the hot gas that results in pockets of the gas containing higher levels of O2. CFAST and FDS predictions are both - 55 %[1], which is quite high.

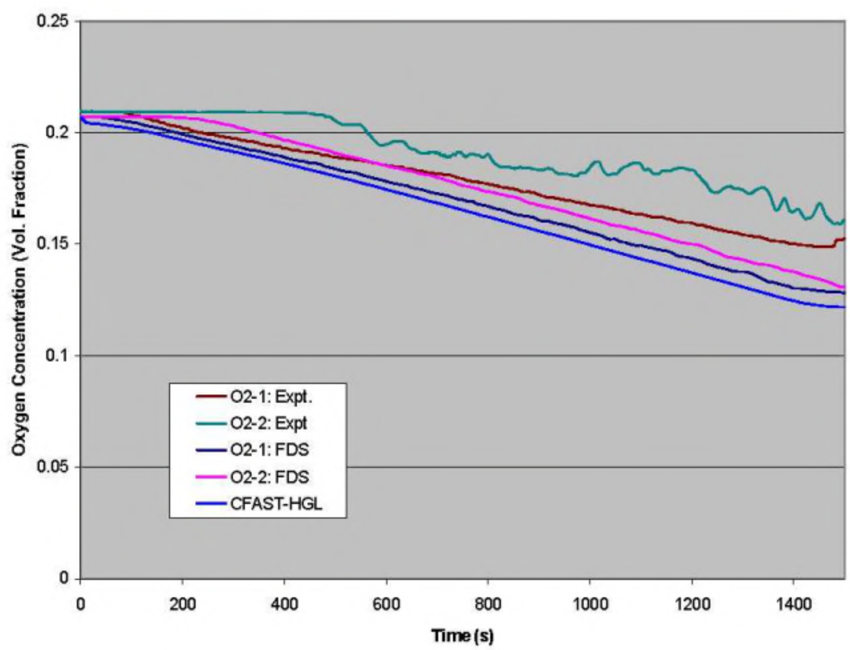

Figure 3-14 Oxygen Depletion - BE 3, Test 1

Again, Figure 3-15 shows comparisons of the O2 concentration predicted by CFAST and FDS with experimental measurement for Test 2 of Benchmark Exercise No. 3, also a closed-door test but with a larger fire. Large oscillations in the oxygen concentration

[1] Model errors presented in this report have utilized the following formula: model error = (model prediction at peak- measured value at peak) / (measured value at peak - initial measured value). A + sign before the error value indicates that the model prediction was greater than the measured value, and a - sign indicates that the model prediction was less than measured value.

near the fire are not predicted by CFAST or FDS. These oscillations occur after the HGL has reached the floor and incomplete mixing of the hot gas.

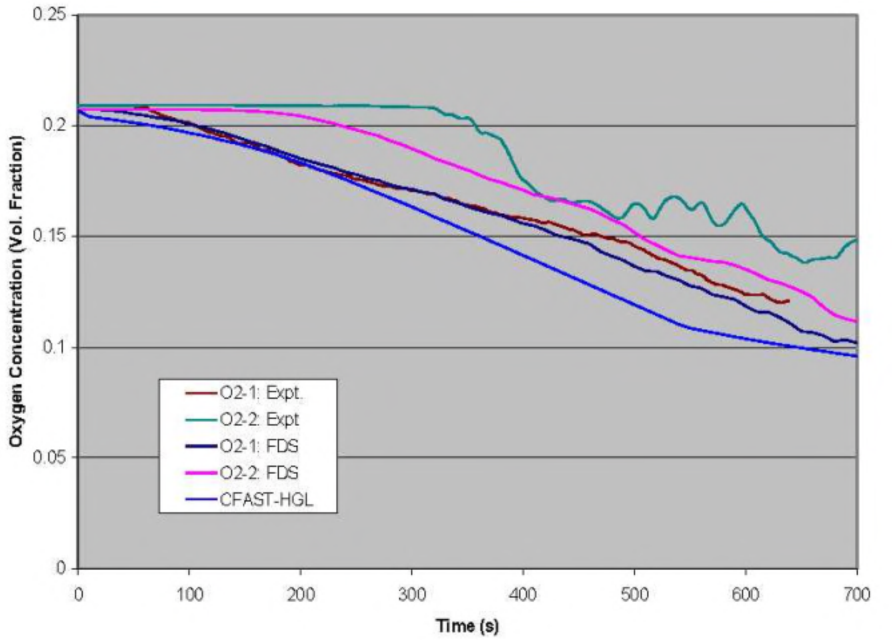

Figure 3-15 Oxygen Depletion - BE 3, Test 2

Figure 3-16 shows a comparison of the O2 concentration predicted by CFAST and FDS with experimental values for Benchmark Exercise No. 3, Test 4 with forced ventilation and closed-door conditions. A more rapid decrease in oxygen concentration is observed in the experiment than predicted by both codes. In fact, the FDS predicted concentration at O2-2 near the fire does not reach 15 %, the point at which the test was terminated. Although the fire was terminated at 838 s due to under ventilation, the LOLs used in CFAST and FDS did not terminate the fire during the 26-minute transient. This comparison indicates the importance of the prediction of local oxygen concentrations, and sensitivity of predictions of under-ventilated conditions and fire extinction to the LOL used.

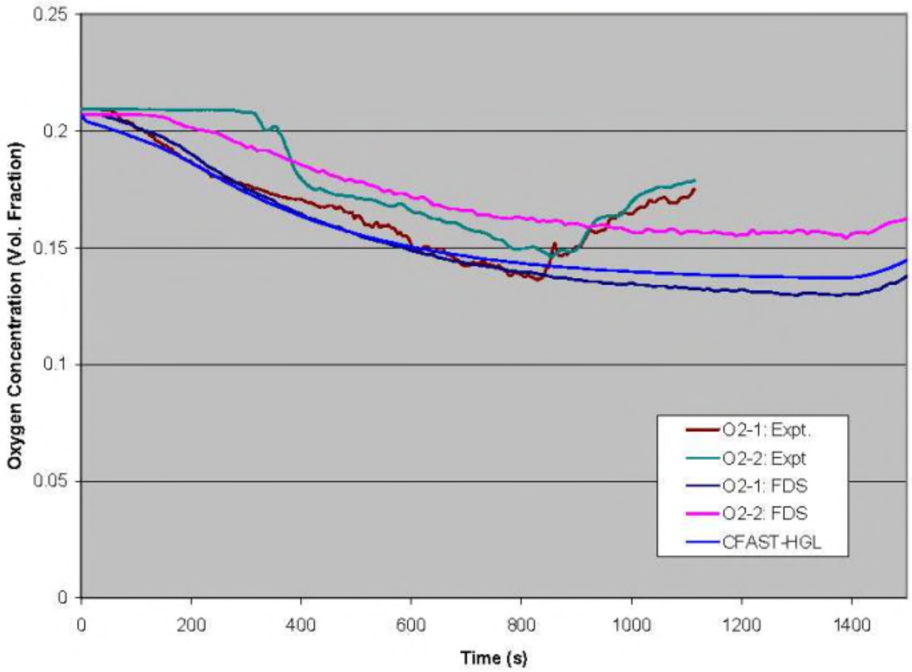

Figure 3-16 Oxygen Concentration - BE 3, Test 4

The codes have difficulty predicting the mixing and local oxygen concentrations, especially for forced ventilation conditions. Since both codes employ simple algorithms for fire behavior in under ventilated conditions, this leads to errors in the prediction of fire extinction.

Benchmark Exercise No. 4 involved severe conditions and flow dynamics. The simple extinction model in FDS decreased the heat output from the fire in the more severe scenario in Test 4 when in reality combustion was fully sustained. Pulsating flow through the door provides sufficient oxygen to the fire and prevents it from being under ventilated. Although fluid dynamics of the scenario is simulated well by FDS, the simple extinction model in FDS (LOL) decreases the heat output from the fire when combustion is fully sustained. The discrepancy in the HRR from FDS and measured is shown in Figure 3-17. The algorithm in FDS for accounting for the under ventilation of the fire is too simplistic for complex scenarios as in Benchmark Exercise No.4.

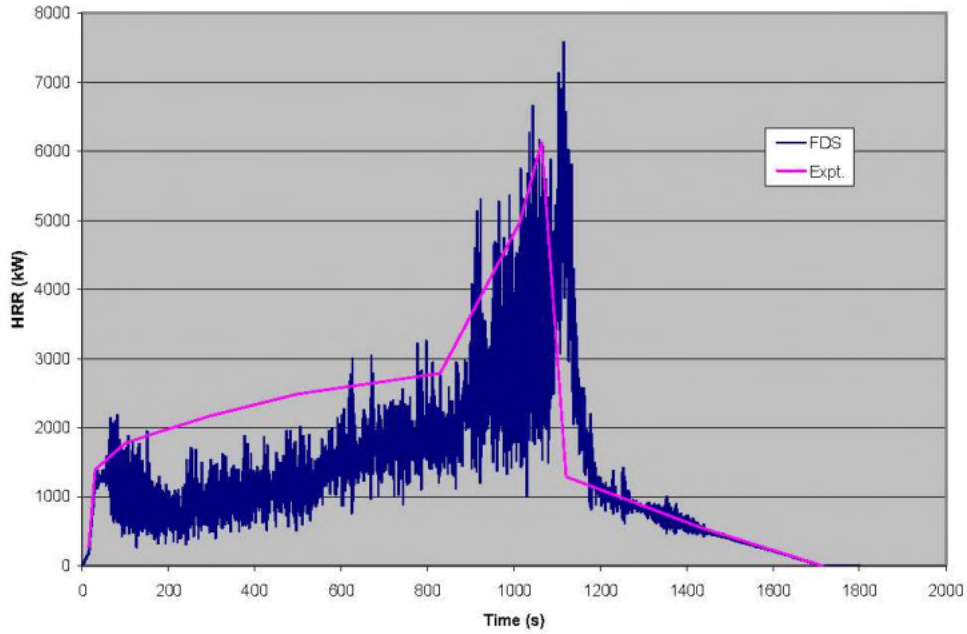

Figure 3-17 Heat Release Rate - BE 4, Test 3

3.2.2 Combustion Products

The prediction of carbon monoxide and smoke, products of incomplete combustion, posed a challenge for the closed door experiments in Benchmark Exercise No. 3 in which the fire became under ventilated. Both, CFAST and FDS do not account for the effects of under ventilation on carbon monoxide or smoke production. A constant yield for the quantities is used by the codes through out the transient, whereas in reality the prediction of these species changes with the availability of oxygen during the combustion process. The smoke yield used in the calculations is also dependent on the size of the fire.

Figure 3-18 compares the concentration of CO predicted by CFAST and FDS in the HGL with experimental observation for Test 13 of Benchmark Exercise No. 3 which was a 2-MW nominal, closed-door experiment. In Figure 3-18, the trends of the predicted values are similar to experimental observation until ~ 236 s when measurement indicates a higher rate of increase in CO concentration. The CFAST and FDS combustion models are simple and do not include the effect of O2 concentrations on the CO production. The codes use a constant CO yield through the transient. Therefore, both codes show an increase in the CO level at the same rate through the transient. However, the fire becomes under ventilated at ~ 236 s at which point the yield of CO production increases as the measurement shows. The CFAST and FDS codes cannot predict the effects of under ventilation of a fire on the CO produced.

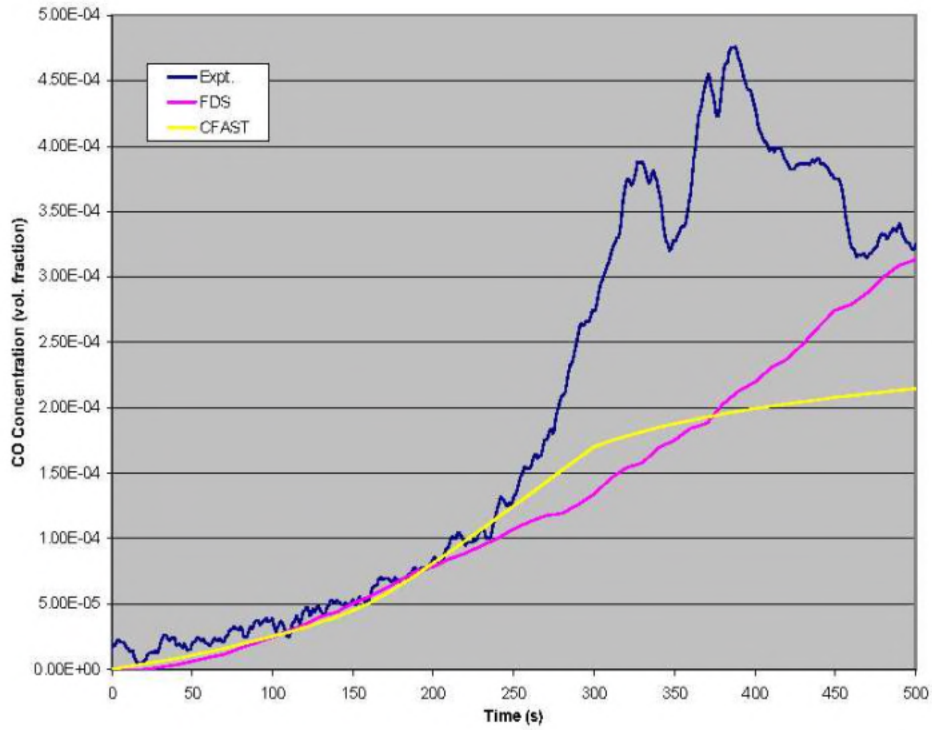

Figure 3-18 CO Concentration - BE 3, Test 13

Figure 3-19 and Figure 3-20 compare the concentration of smoke predicted by CFAST and FDS in the HGL with experimental observation for Test 2 at 1 MW nominal, and Test 13 at 2 MW nominal. For example, the experimental observation in Figure 3-19 for Test 2 indicates the smoke concentration increases to its peak value at ~465 s and decreases by about 30 % to the point when the fuel is shut off at ~ 630 s. This peak and similar other peaks in smoke production for the other tests in Benchmark Exercise No. 3 early in the transient are due to under ventilation and decrease in the HRR of the fire. The simple combustion models in CFAST and FDS do not predict this observed trend. Also a comparison of the Figure 3-19 and Figure 3-20 shows that the smoke yield used is more accurate for the large fire in Test 13, as opposed to the smaller fire in Test 2.

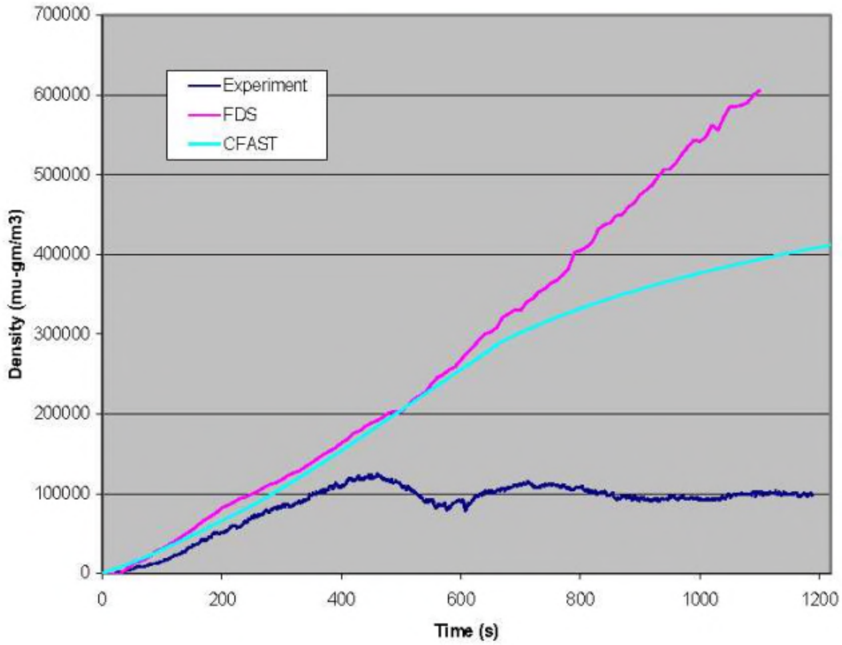

Figure 3-19 Smoke Concentration - BE 3, Test 2

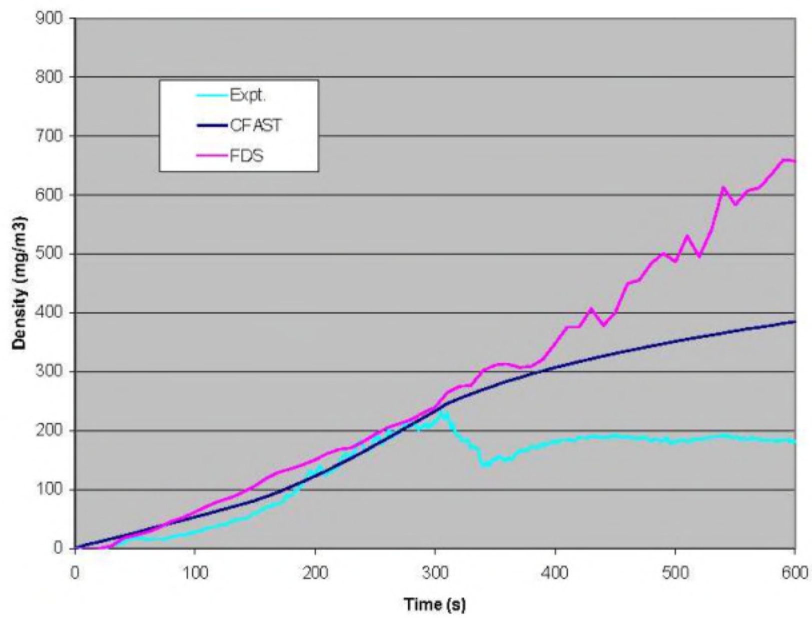

Figure 3-20 Smoke Concentration - BE 3, Test 13

CFAST and FDS do not account for the effects of under ventilation on carbon monoxide or smoke production. The constant yield for the quantities used by the codes through the transient leads to large inaccuracies in the prediction of these combustion products for under ventilated fires. Also, the amount of smoke produced as a function of the size of the fire is not modeled in the codes.

As noted earlier, attempts are being made to include an eddy dissipation model and two-step combustion chemistry in FDS to simulate the production of soot and carbon monoxide. Although these efforts are important steps to improve the model, they are in trial stages and not currently suitable for safety analysis for which the reliability of a model must be assured.

3.3 Heat Flux from the Fire Flame and Hot Gas

The first indication that the prediction of heat flux from the flaming region and hot gas was a challenge to fire models arose in Benchmark Exercise No.1. Although Benchmark Exercise No. 1 included only code-to-code comparisons, the results from the different codes were used to understand the modeling of the physics in them, i.e. if all the codes produced similar results over a range of cases for a scenario then it was concluded that the physics modeled in the codes is most likely understood and adequate for the scenario. If the results from the codes were widely different, then one can suspect that the physics of the phenomena is not understood well and modeled adequately in any of the codes. The predictions of heat flux in Benchmark Exercise No. 1 were widely different from the fire models used in the exercise, as shown in Table 3-1 taken for the ICFMP report for Benchmark Exercise No. 1 (Dey, 2002).

Table 3-1 Predictions of Heat Flux on Cable for Benchmark Exercise No. 1, Part I

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

Therefore, the prediction of heat flux was identified as an issue early in the ICFMP.

Subsequently, a wide variation in predicted heat fluxes was also observed in Benchmark Exercise No. 2 Part II, as shown in Table 3-2 taken from the ICFMP report for Benchmark Exercise No. 2 (Miles, 2004). This exercise for code-to-code comparisons indicated that heat flux predictions are even more difficult for such scenarios. The variation in computed fluxes was large, both between different types of model and different models of the same type. Incident flux calculations were strongly influenced by the radiation treatment.

Table 3-2 Predictions of Heat Flux on Cable and Beam for BE No 2, Part II

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)

In Benchmark Exercise No. 3, the author noted large uncertainties in the prediction of heat fluxes to targets and walls, and the thermal response of the targets. Results of the exercise showed that FDS consistently under predicted the convective and radiative heat fluxes to targets and walls. The CFAST predictions varied, and were sometimes much larger than measured values. The errors of the flux predictions by the codes were much larger than the expected uncertainty of the heat flux due to measurement uncertainties. Experimental observation consistently indicated a larger convective heat flux (total heat flux - radiative heat flux) than that predicted by both CFAST and FDS for all the experiments. The prediction of the spatial temperature distribution in vertical cable trays when fires source was in its immediate vicinity was challenging, even for FDS. The prediction of heat fluxes in or near a fire plume was also difficult, even for CFD codes.

CFAST utilizes a point source model and predicts unrealistically high fluxes for gauge locations near and pointing toward the floor. The predictions from CFAST of both components of heat flux, radiative and convective, have large errors depending on the location and orientation of the gauges, and the convective heat flux is under predicted in many of the transients.

Figure 3-21 and Figure 3-22 compare the radiative and total heat flux predicted by CFAST and FDS with experimental observations for Benchmark Exercise No. 3, Test 3 and Test 2, respectively. As noted in these two figures, a large convective flux (total - radiative) is measured but not predicted by the codes. Both models under predict the heat flux. This similar observation can be noted by examining similar plots for many other gauges and tests. The errors in the flux predictions for CFAST and FDS can be a high as 150 % and 47 %, respectively. The errors in the FDS predictions are generally larger for gauges that point toward the fire, indicating larger errors in the predictions of radiative heat flux from the fire. The error in the prediction of the convective heat flux also seems to have a directional trend, a smaller error is noted for gauges pointing toward the floor in a horizontal direction.

Also note that Figure 3-22 shows a decrease in the measured radiative flux after ~ 400 s due to decrease in the intensity and size of the fire from under-ventilation. The CFAST and FDS do not model or predict these changes in the size of the fire.

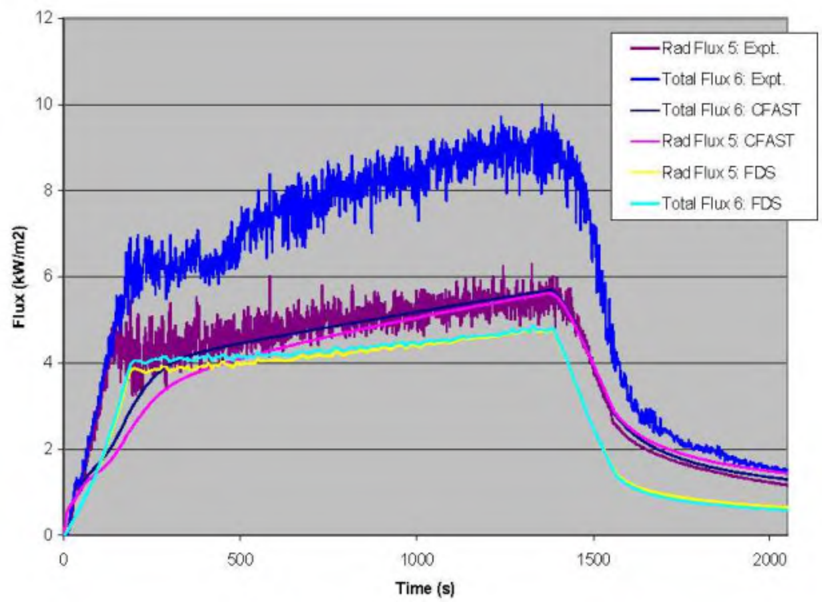

Figure 3-21 Heat Flux to Cables - BE 3, Test 3

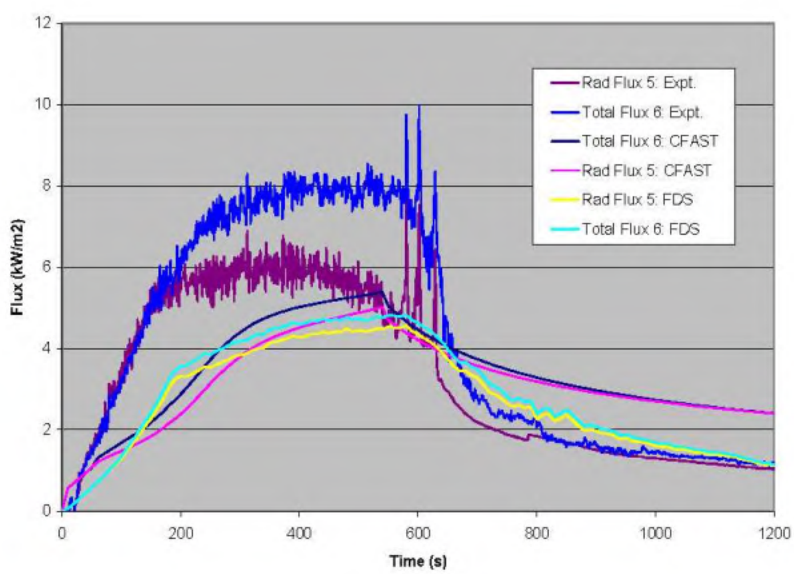

Figure 3-22 Heat Flux to Cables - BE 3, Test 2

Figure 3-23 and Figure 3-24 show the measurements and FDS predictions of the cable temperature in the vertical cable tray for Benchmark Exercise No. 3, Test 14 where the fire was near the vertical cable tray (see Figure 3-25). Measurements indicate that the peak cable temperature is highest at TS 32, which is at 0.7 m from the floor under the HGL interface; however, FDS predicts the peak cable temperature to increase with height in the cable tray. Again, this is due to the under prediction of the radiative flux from the fire to the cables by FDS. The prediction of the spatial flux and temperature distribution in vertical cable trays when fires sources are in its immediate vicinity is challenging and can be erroneous, even for FDS.

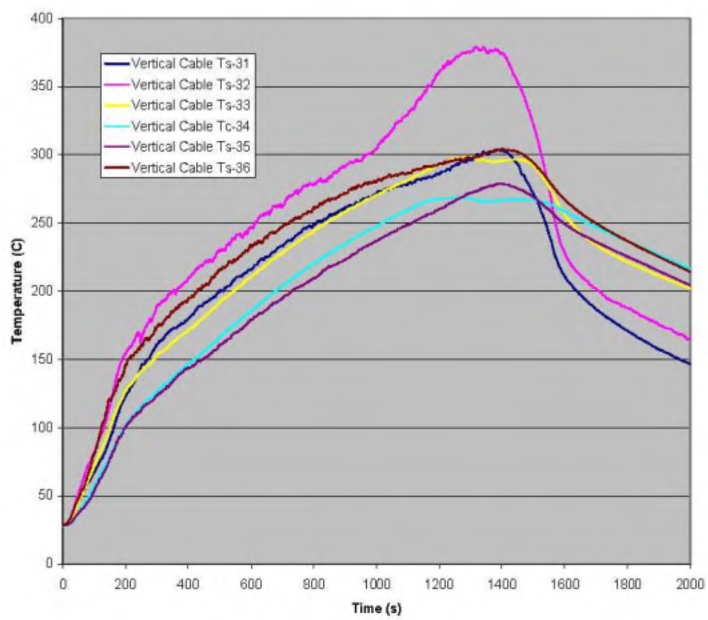

Figure 3-23 Vertical Cable Tray Temperature (Expt.) - BE 3 Test 14

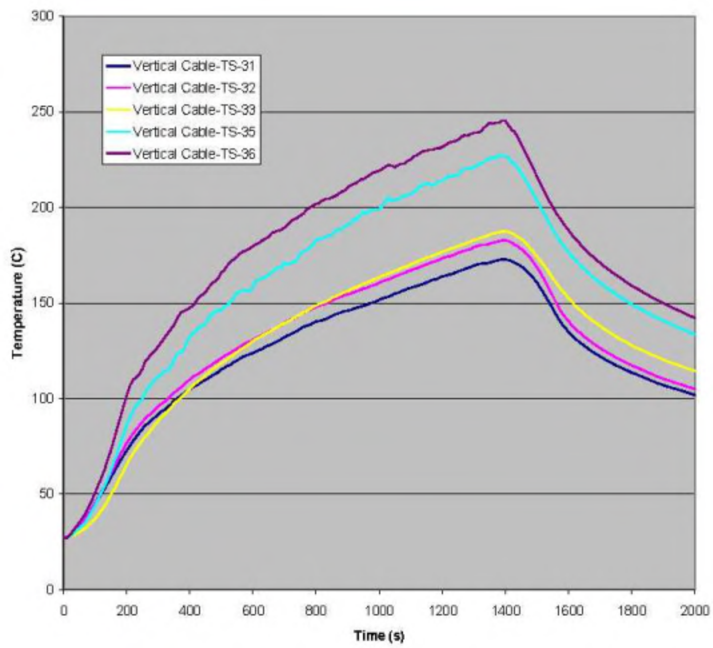

Figure 3-24 Vertical Cable Tray Temperature (FDS) - BE 3 Test 14

Figure 3-25 Fire in Benchmark Exercise No. 3, Test 14

The limitations of the heat flux models in CFAST were discussed above making the model unsuitable for simulating fire scenarios with intense fire sources as in Benchmark Exercise No. 4. Figure 3-26 shows a comparison of the total heat flux predicted by FDS with measurements at WS2 on the steel plate for Benchmark Exercise No. 4, Test 1. The uncertainty in the FDS prediction is + 59 %. Figure 3-27 shows a comparison of the heat flux on the wall predicted by FDS with experiment for the same test. FDS under predicts the heat flux by 45 %.

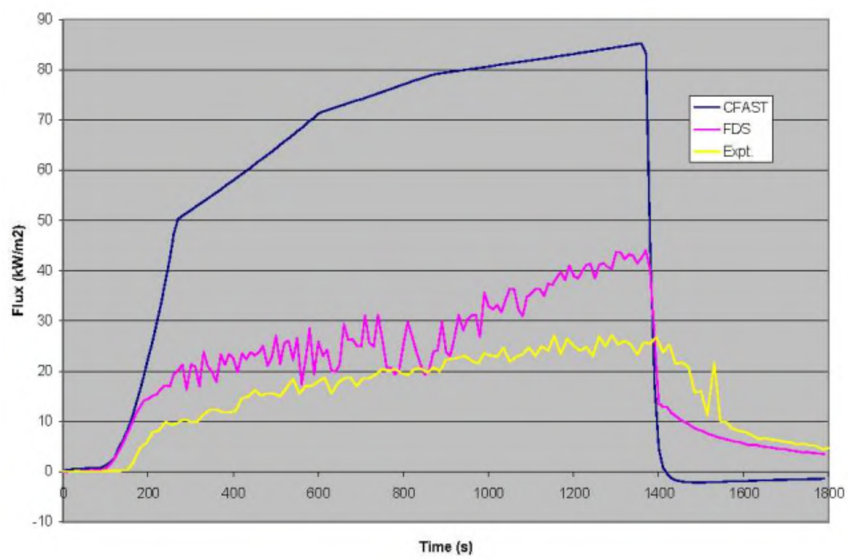

Figure 3-26 Heat Flux on Steel Plate - BE 4, Test 1

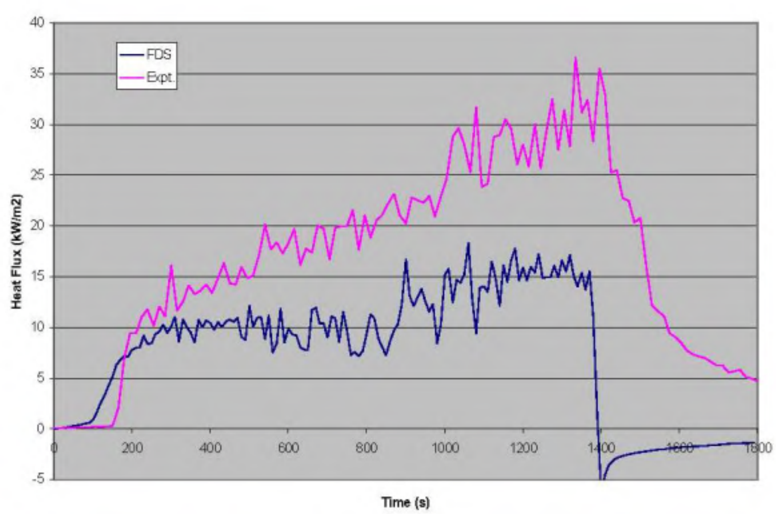

Figure 3-27 Heat Flux on Wall - BE 4, Test 1

Figure 3-28 shows a comparison of the total heat flux predicted by FDS with measurement at WS4 on the aerated concrete block for Test 3 in Benchmark Exercise No. 4. There is a large increase in the measured heat flux at ~ 1155 s when the HRR reaches its peak at 6000 kW. The uncertainty of the FDS prediction at WS4 at ~ 71 kW/m2 is - 53 %.

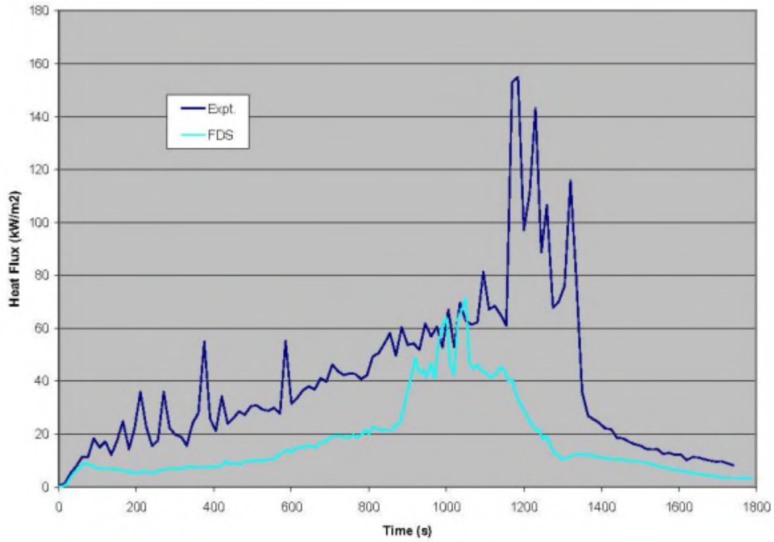

Figure 3-28 Heat Flux on Aerated Concrete Block - BE 4, Test 3

Generally, the errors of the heat flux predictions by FDS are large, up to 59 %. There are specific weaknesses in the heat flux models in FDS which make it unreliable for predicting heat fluxes to NPP targets.

In Benchmark Exercise No. 5, the heat flux to the cables predicted by CFAST and FDS also had large inaccuracies and deviated by as much as + 49 % and - 49 % from experimental observation, respectively.

Figure 3-29 shows a comparison of the total heat flux on the cables predicted by CFAST and experiment. The measured fluxes at WS2, WS3, and WS4 are increasingly higher due to the temperature gradient in the HGL. The heat fluxes predicted by CFAST for WS2, WS3, and WS4 are of similar magnitude since only the average HGL temperature is predicted in a zone model, and temperature gradients in the hot gas are not simulated in such a model. Figure 3-30 shows a comparison of the total heat flux on the cables predicted by FDS and experiment. FDS does not predict the variation and gradient in the heat flux versus elevation, as measured. The uncertainties of the peak predicted heat fluxes for WS2, WS3, and WS4 for FDS are high as + 49 %.

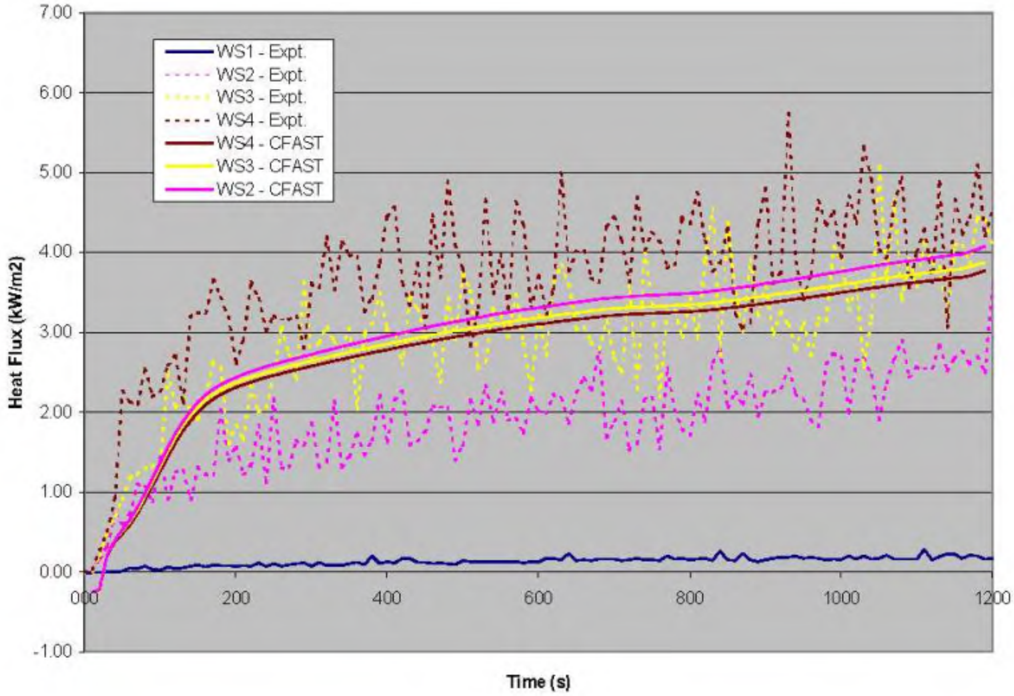

Figure 3-29 Heat Flux on Cables (CFAST) - BE 5, Test 4

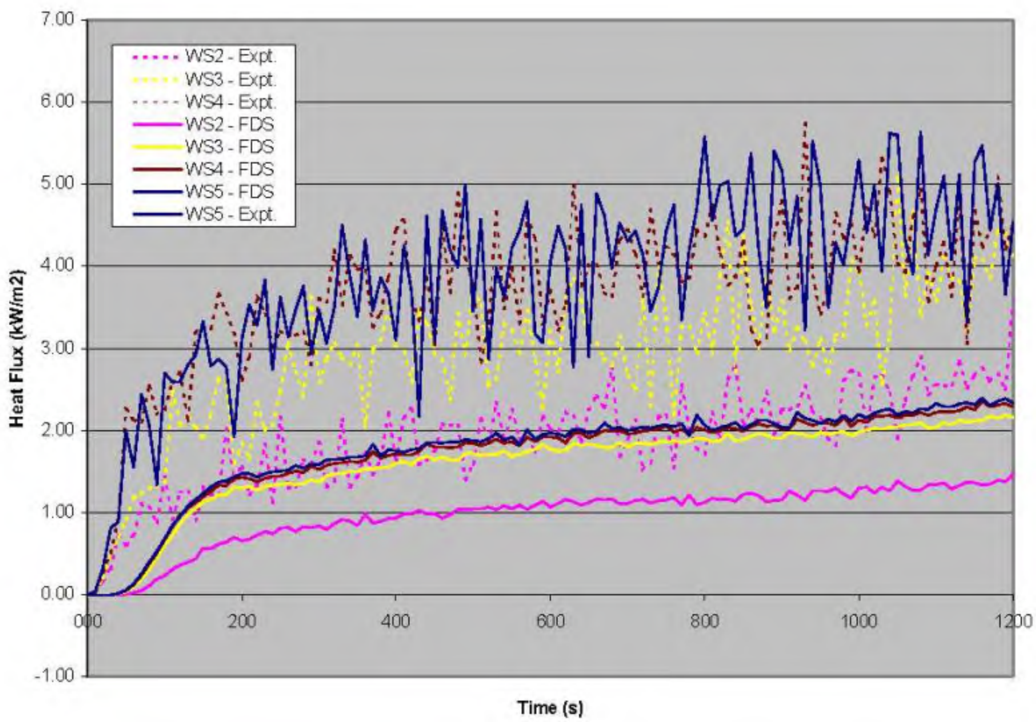

Figure 3-30 Heat Flux on Cables (FDS) - BE 5, Test 4

There are specific weaknesses in the heat flux models in CFAST and FDS which make them inaccurate for predicting heat fluxes to targets.

3.4 Cable Target Modeling

A detailed heat transfer model for a cable tray will be fairly complex. Cable trays generally have a number of cables bundled together in layers, and most cables consist of several conductors. Cables configured in a single layer will get damaged and ignite at a lower flux than cables in a multilayer configuration because the flux to a single layer will not be shielded by cables above that layer. The CFAST or FDS codes currently do not include a target model for such complex cable configurations or cable compositions. The CFAST and FDS codes have a simple one-dimensional slab model of uniform composition for targets such as cables. The slabs in the calculations for the benchmark exercises were assumed to be of the same thickness as the cables and composed of the jacket material.

Large uncertainties are noted in the prediction of cable and walls temperatures by CFAST and FDS. The thermal inertia of the cables or walls tends to reduce the magnitude of the inaccuracies caused by the crude target models on the peak temperature predictions. However, the heat up of the cables predicted by the codes, a parameter most important for safety analysis, is much slower than observed in the experiments.

Figure 3-31 shows a comparison of the control cable surface temperature at B-TS-14 predicted by CFAST and FDS with measurement for Test 3 of Benchmark Exercise No. 3. The Figure shows that the heat up of the cable predicted by the models is slower than experimental observation, as well as under predicting the peak temperature. Also, note that the cable temperature is higher than the temperature of the gas (Tree 4-8) near it due to radiative heating from the fire.

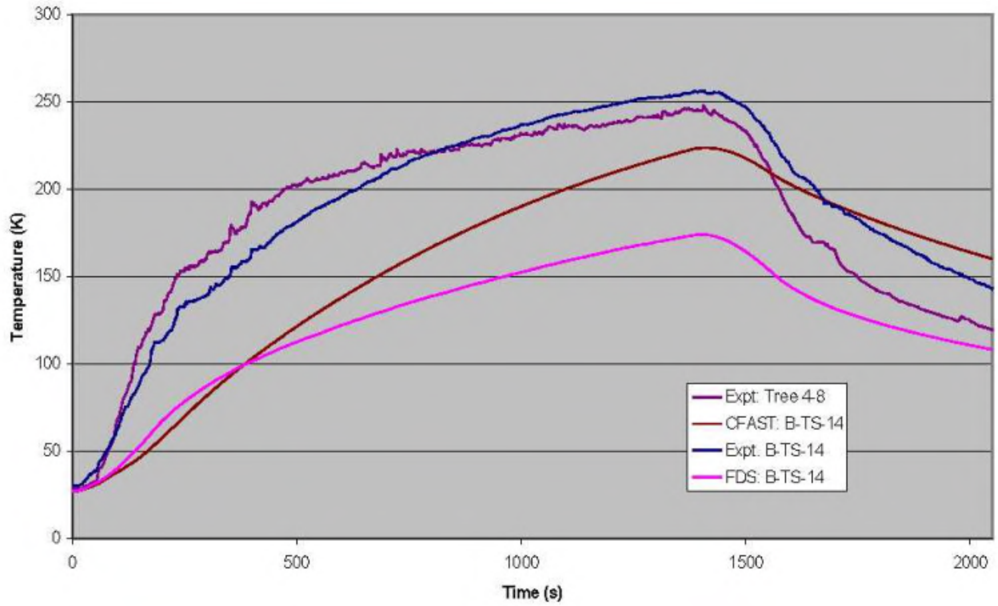

Figure 3-31 Control Cable Temperature (B-TS-14) - BE 3, Test 3

Figure 3-32 shows a comparison of the control cable surface temperature at C-TS-10 predicted by CFAST and FDS with measurement for Test 3 of Benchmark Exercise No. 3. The figure shows that the heat up of the cable predicted by the models is slower than experimental observation, as well as under predicting the peak temperature. Measurements indicate that the peak cable surface temperature at C-TS-10 is 20 C more than the peak gas temperature (Tree 3-9) near it due to the heating of the cable by radiation from the fire. Figure 3-32 also shows measurements indicating that the cable surface temperature at C-TS-10 (single cable) is ~ 60 C higher than the control cable surface temperature at D-TS-12 because of the bundling of the cable at D-TS-12 in a tray.

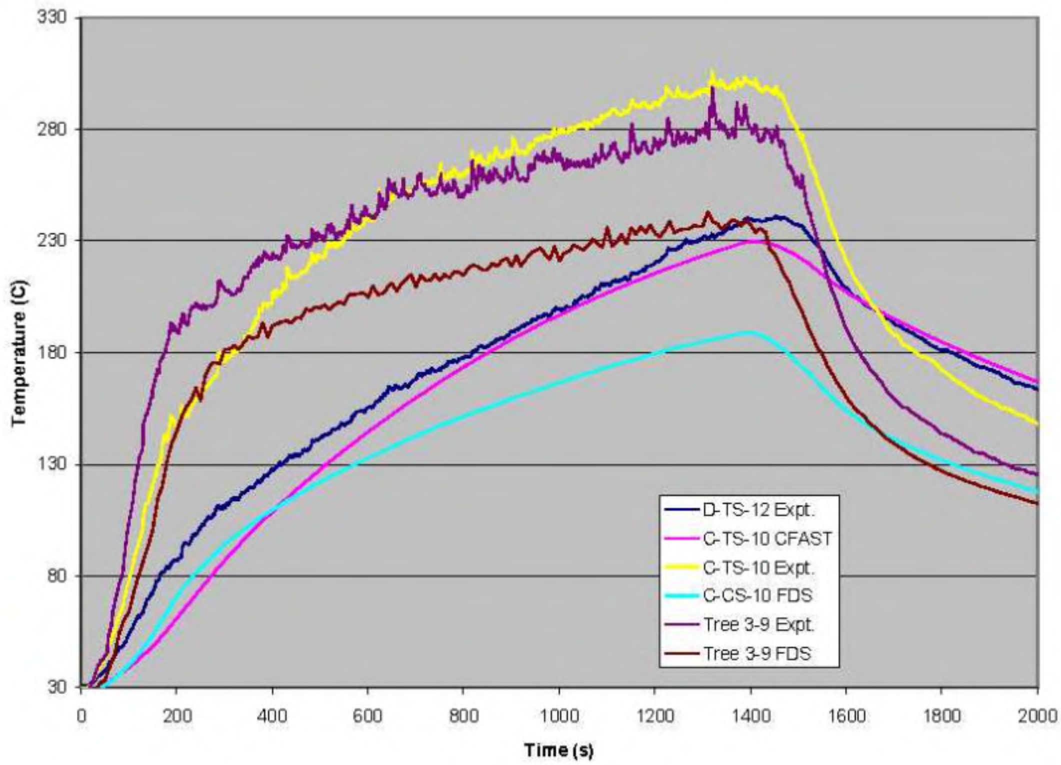

Figure 3-32 Cable Temperature (C-TS-10) - BE 3, Test 3

Figure 3-33 shows a comparison of the power cable surface temperature at F-TS-20 predicted by CFAST and FDS with measurement. The figure shows that the heat up of the power cable predicted by the models is slower than experimental observation, as well as under predicting the peak temperature. Figure 3-33 also shows measurements indicating that the power cable surface temperature at F-TS-20 is ~ 15 C less than the control cable surface temperature at A-TS-18 near it due to the larger thermal inertia of the power cable. Measurements indicate that the peak control cable surface temperature (A-TS-18) is ~ 5 C more, and the peak power cable surface temperature (F-TS-20) is ~ 11 C less than the peak gas temperature (Tree 5-6) near the cables illustrating the varying degrees of heating of the cables by radiation from the fire.

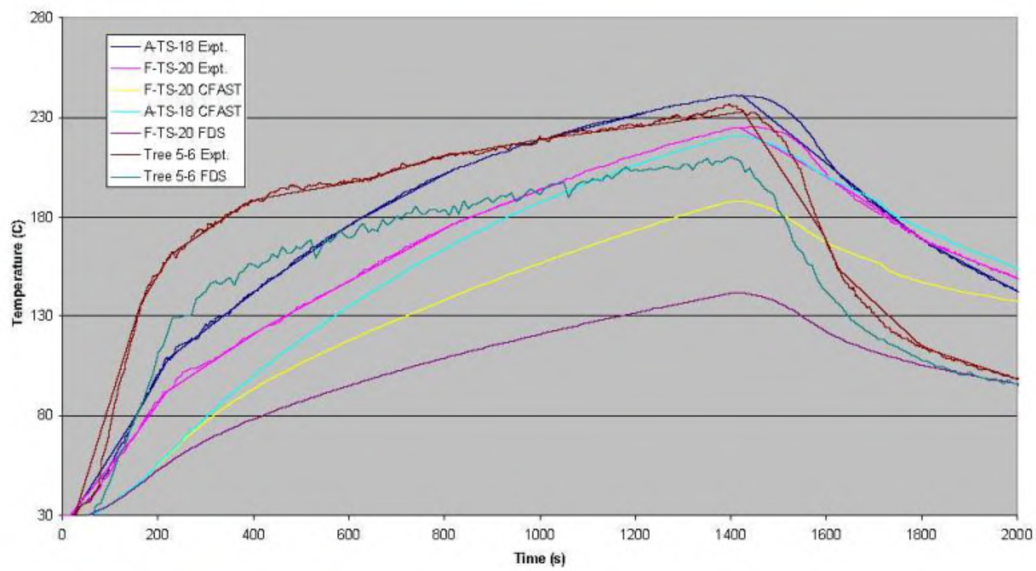

Figure 3-33 Power Cable Temperature (F-TS-20) - BE 3, Test 3

Figure 3-34 shows a comparison of the surface temperature of the power cable predicted by CFAST and FDS with experiment for Test 4 of Benchmark Exercise No. 5. The measured cable surface temperature at different elevations shows gradient similar to that observed for the heat flux measurements at those locations. The predictions of cable temperature by CFAST at the different elevations are the same magnitude because CFAST uses the average HGL temperature to compute the heat fluxes to the cables, thereby making its predictions unreliable. FDS under predicts the cable temperatures by up to 41 %.

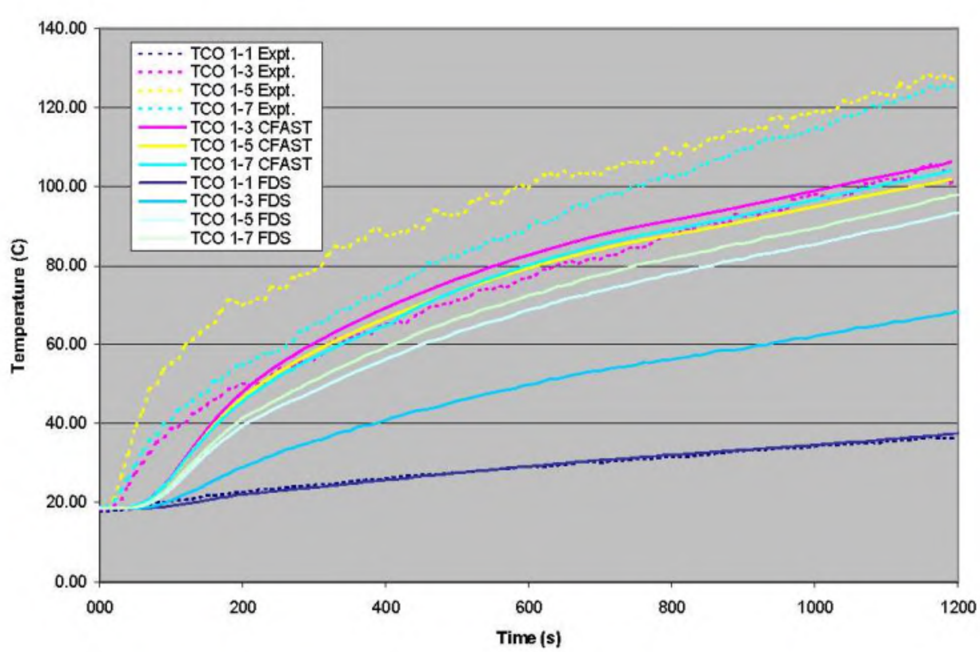

Figure 3-34 Power Cable Temperature - BE 5, Test 4

Figure 3-35 shows a comparison of the surface temperature of the instrumentation and Control (I&C) cable predicted by CFAST and FDS with experiment. Again, the predictions of cable temperature by CFAST at the different elevations are the same magnitude because CFAST uses the average HGL temperature to compute the heat fluxes to the cables. FDS under predicts the cable temperatures by up to 55 %.

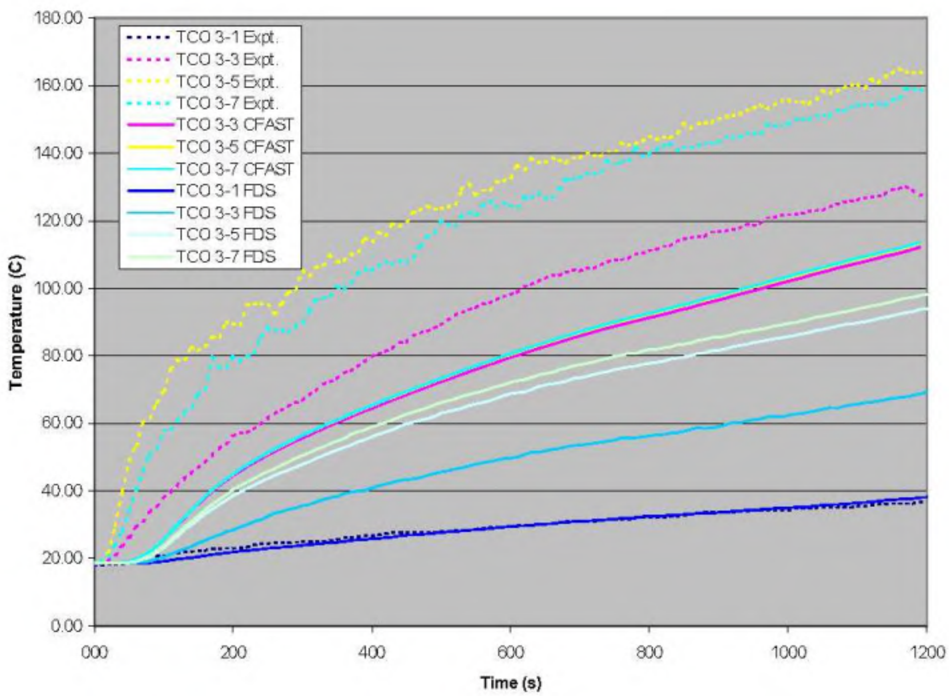

Figure 3-35 Instrumentation & Control Cable - BE 5, Test 4

The large uncertainties in the predictions of heat up and peak temperatures of cables by CFAST and FDS are due to the limitations of the heat flux models and the target models, making the predictions unreliable for nuclear plant safety analysis. Development of suitable sub-models for predicting the thermal damage to target elements, in particular cables, cable bundles and cable trays is necessary. The calculation of incident fluxes is particularly important in predicting cable damage, and highlights the need to address the radiative heat transfer, both from the flaming region and the smoke layer, more carefully. This conclusion is derived from the results of all the ICFMP benchmark exercises. To some extent target damage sub-models can be considered separately to the gas phase in a zone or CFD model in that a particular target sub-model could be coupled to either a zone or CFD fire model, or used as part of a separate 'post-processing' calculation. In the latter case it would be assumed that the targets have only a minor influence on the fluid dynamics and heat transfer processes within the compartment so that during the gas phase (zone or CFD) simulation only the incident fluxes will be recorded, and the solid phase calculations are then performed later.

3.5 Intense Fire Conditions

Several difficulties were encountered with the CFAST code, including instabilities, in the computation of several parameters in Benchmark Exercise No. 4 which included scenarios with intense fire conditions. Test conditions included temperatures up to 800 C and heat fluxes up to 100 kW/m2. Although the CFAST prediction of global parameters (HGL temperature, interface height) was reasonable for the less severe Test 1, CFAST predicted unrealistic values for heat flux to the targets and walls, and the corresponding target and wall temperatures.

There were convergence issues in the CFAST simulation of the more severe test. The simulation halted before completion. CFAST is sensitive in cases with a high heat flux. The penetration of the thermal wave in the compartment floor and in less dense materials with low thermal conductivity poses numerical challenges for the CFAST code causing the simulation to halt before the end of the transient.

Figure 3-36 shows a comparison of the total heat flux predicted by CFAST with measurements at WS4 on the aerated concrete block for Test 1 of Benchmark Exercise No. 4. Oscillations are noted in the flux predicted by CFAST because the computations in the code are sensitive in cases with a high heat flux. Figure 3-37 shows a comparison of the total heat flux predicted by CFAST with measurements at WS3 on the concrete block for the same test. Although the oscillations are absent, CFAST significantly over-predicts the heat flux with an uncertainty of + 146 %. A similar gross over prediction by CFAST was noted for heat flux to the steel plate.

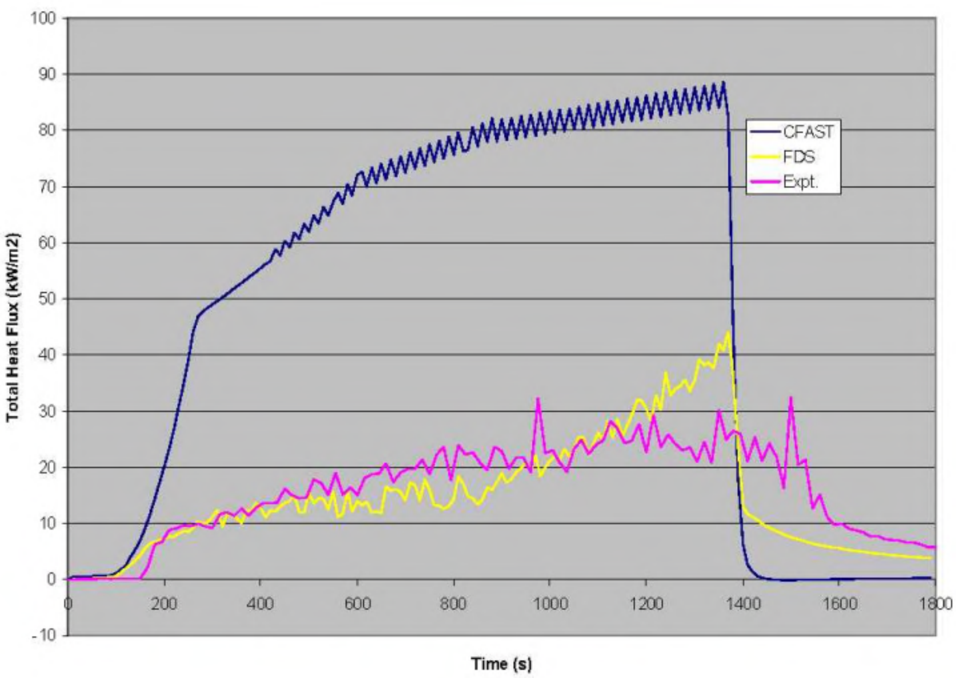

Figure 3-36 Heat Flux on Aerated Concrete Block (WS4) - BE 4, Test 1

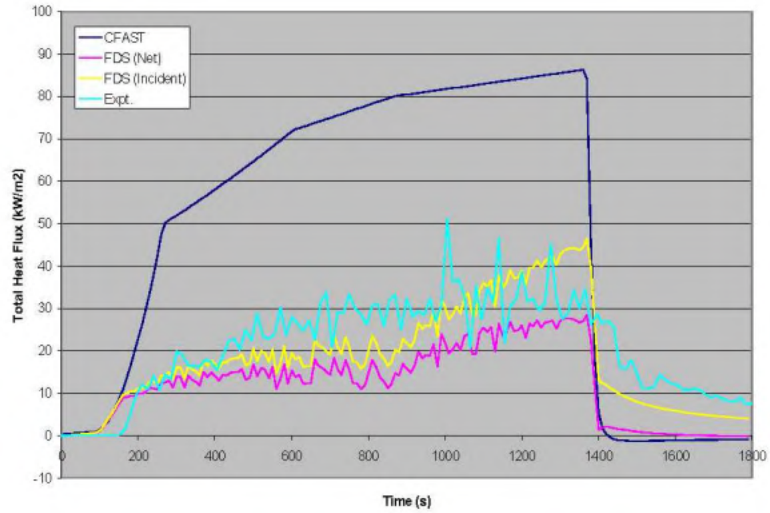

Figure 3-37 Heat Flux on Concrete Block (WS3) - BE 4, Test 1

Large oscillations were noted in the predicted surface temperature of the aerated concrete block by CFAST due to the oscillations in the CFAST prediction of the heat flux to the aerated concrete block, as discussed above. Figure 3-38 shows a comparison of the surface temperature of the concrete block predicted by CFAST and measurement. Although oscillations are absent, CFAST significantly over predicts the temperature 128 %. Again, a similar gross over prediction was noted for the front surface temperature of the steel plate.

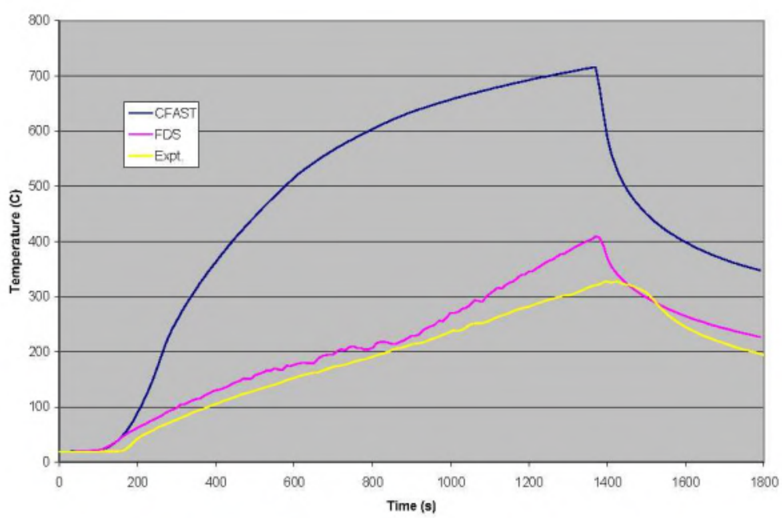

Figure 3-38 Concrete Block Temperature - BE 4, Test 1

Although the CFAST model could be used to compute global parameters for the less severe scenario in this benchmark exercise, its use is limited and not recommended for computing heat fluxes and target responses due to the limitations noted above. For more severe scenarios, the two zone approximation and inherent weaknesses in the code limit its applications. The CFAST model is unsuitable for these scenarios with intense fire sources.

The CFAST model requires major fundamental improvements if it is to be used for fire scenarios with intense fire sources such as those examined in this benchmark exercise. The computation of thermal propagation through materials with low density and conductivity should be reviewed to determine if this limitation can be solved and eliminated. Further, an examination should be conducted to determine whether the computational limitation for simulating Test 3 is inherent in the code, or whether it can be addressed with improvements to the numeric in the code.

FDS performed well for global parameters like hot gas temperature considering the intense fire conditions, but its accuracy was limited for predicting the plume and heat flux.

3.6 Fires in Multi-Level Buildings

3.6.1 Modeling Vertical Flow in CFAST

Modeling vertical flow through horizontal vents in CFAST (a zone model) posed a challenge in Benchmark Exercise No. 2 which examined fires in multi-level buildings such as the turbine building. Firstly, since a zone model is a lumped model for each compartment, it is not possible to represent horizontal vents at different locations in the compartment. All horizontal vents have to be combined and represented by one vent, or a specific vent needs to be chosen for analysis while ignoring others that may not have an effect on compartment conditions. This is a significant limitation because there are important flow phenomena which differ when more than one vertical vent is present. The prediction of the flow of hot gases through the hatches, and the heat transport between the lower and upper compartments are critical to the prediction of the thermal environment and target responses in the compartments.

The modeling of vertical flow through a horizontal vent is complex and difficult. A non-zero cross vent pressure difference will lead to unidirectional flow from the higher to the lower pressure side. However, an unstable configuration develops when the fluid densities are reversed, i.e., the hotter gas in the lower compartment is underneath the cooler gas in the upper compartment. This will lead to flow from the lower compartment to the upper compartment. This phenomenon is difficult to model.

In CFAST, Cooper’s algorithm is used for computing mass flow through ceiling and floor vents. There are two components to the flow. The first is net flow dictated by a pressure difference. The second is an exchange flow based on the relative densities of gas. CFAST also attempts to model flow shedding for the bidirectional flow, i.e., flow from the hot gas layer (HGL) in the lower compartment to the HGL in the upper compartment will shed in the upper compartment lower layer; flow from the upper compartment lower layer to the lower compartment lower layer will shed in the HGL in the lower compartment. Selection criteria are established in CFAST based on the pressure and density differences that determine the direction of the flows. The various combinations of flows through the hatch from the upper and lower compartment upper and lower layers predicted by CFAST and FDS for Case 1 of Benchmark Exercise No. 2, Part II, are shown in Figure 3-39. The figure illustrates the difficulty of implementing this type of model with selection criteria. The selection criteria which determine the direction of the flows result in discontinuities (shown in figure) that are not realistic.

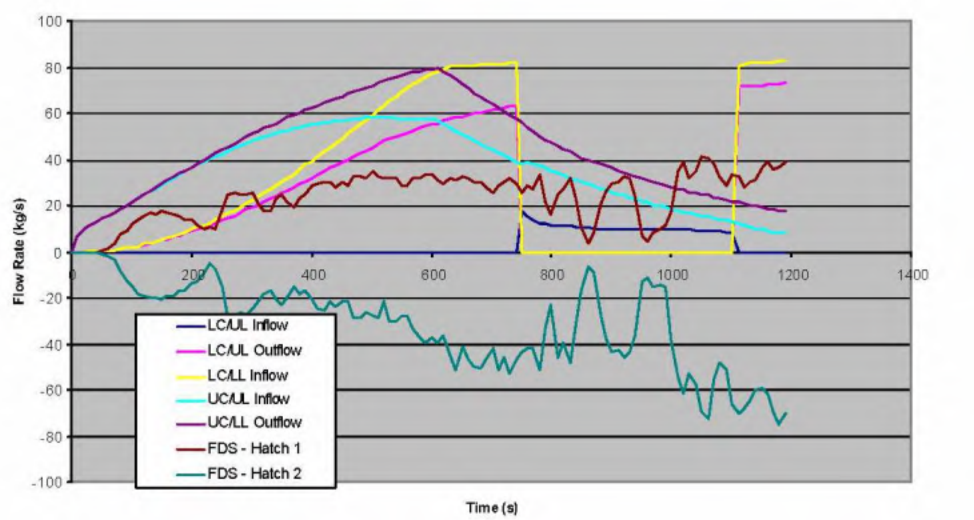

Figure 3-39 Hatch Mass Flow Predictions in BE No. 2, Part II, Case 1

Figure 3-40 shows the compartment vent flows for the same case. The vent flows predicted by CFAST instantly reach high values which are not realistic and is caused by the instant changes in hatch flow that instantly change the pressure in the compartment. The hatch and vent flows predicted by FDS are more realistic but need to be validated for these types of configurations.

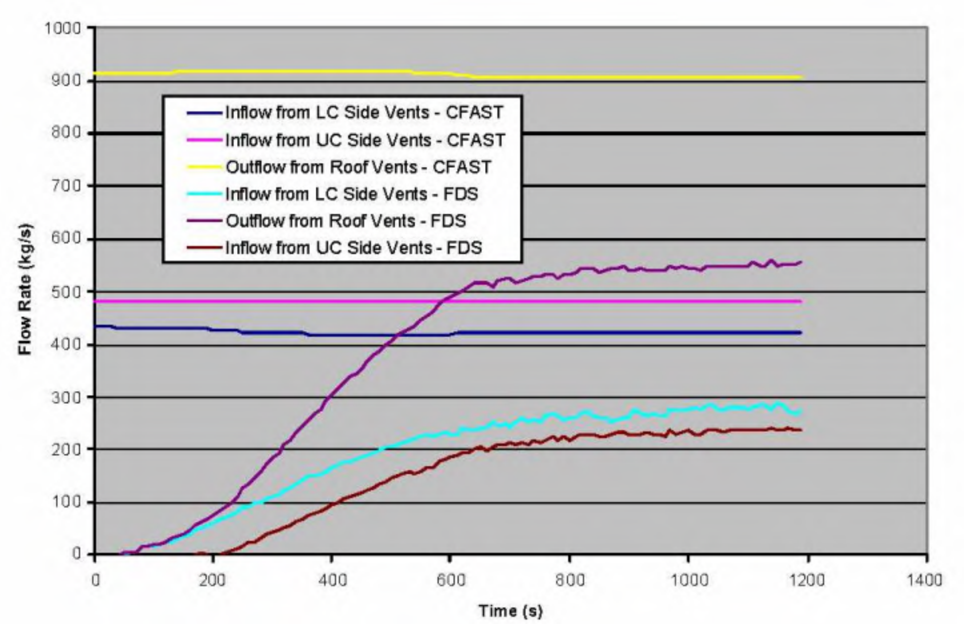

Figure 3-40 Compartment Vent Flows in Benchmark Exercise No. 2, Part II, Case 2

The limitation of a zone model in being able to simulate only one vertical opening negates its validity for analyzing fire scenarios such as in Benchmark Exercise No. 2. As described earlier, the flow through the hatches predicted by FDS is unidirectional throughout the transient because the two hatches are inter-connected in the flow dynamics. The high velocity of the fire plume gases causes an upward flow through Hatch 1 which pressurizes the upper compartment. The pressurization of the upper compartment then causes the flow through Hatch 2 to be downward.

3.6.2 Needed Validation for FDS

The CFAST and FDS fire models used in this benchmark analysis have had limited validation for the types of scenarios examined, specifically for flow through hatches. Cooper's correlation that is used in CFAST for predicting vertical flow through horizontal vents has not been verified or validated. Further development, and verification and validation of the sub-model for vertical flow in horizontal vents in CFAST are necessary before it can reliably used in safety analysis. Although FDS has been validated (i.e. compared with experimental data) for several experiments conducted in large facilities, it is necessary to validate FDS for the specific types of scenarios examined here before it can be reliably used for safety analysis. Specific parameters that need to be compared with experimental data are pressure in the compartments; and flow through the hatches, side vents in the lower and upper compartments, and roof vents. It is necessary to conduct tests for fire scenarios like those analyzed in Benchmark Exercise No. 2 to provide data for the validation of these parameters.

Although the trends of parameters such as velocity, temperature, soot concentration output from FDS seem reasonable, there is no experimental data available for the types of scenarios examined in Benchmark Exercise No. 2 to confirm the accuracy of the predictions. Notably, there was wide variation in the predictions from various fire models used in Benchmark Exercise No. 2 for the flow through hatches. Examination of individual reports in the ICFMP report for Benchmark Exercise No. 2 (Miles, 2004) reveals contradictory flow patterns in the hatches. For example, for Case 1 whereas FDS predicts upward flow through hatch 1 and downward flow through hatch 2 throughout the simulation, other CFD models (JASMINE and CFX) predicted flow reversal. This variation in flow patterns through the hatches leads to the wide spread in predicted hot gas temperatures shown in Figure 3-41 taken from the ICFMP report for Benchmark Exercise No. 2 (Miles, 2004). The predicted gas temperatures for the upper deck *vary by a factor of about 5* between the different fire models. As suggested above, this is attributed to the fluid dynamic complexities of an upper deck connected to the lower deck by horizontal hatches. It can be concluded that the physics of these flow phenomena are not well understood since there is such a large variation between the fire model predictions. Further experiments and model validation is necessary before predictions of such parameters and their effects can be reliably used in fire safety analysis.

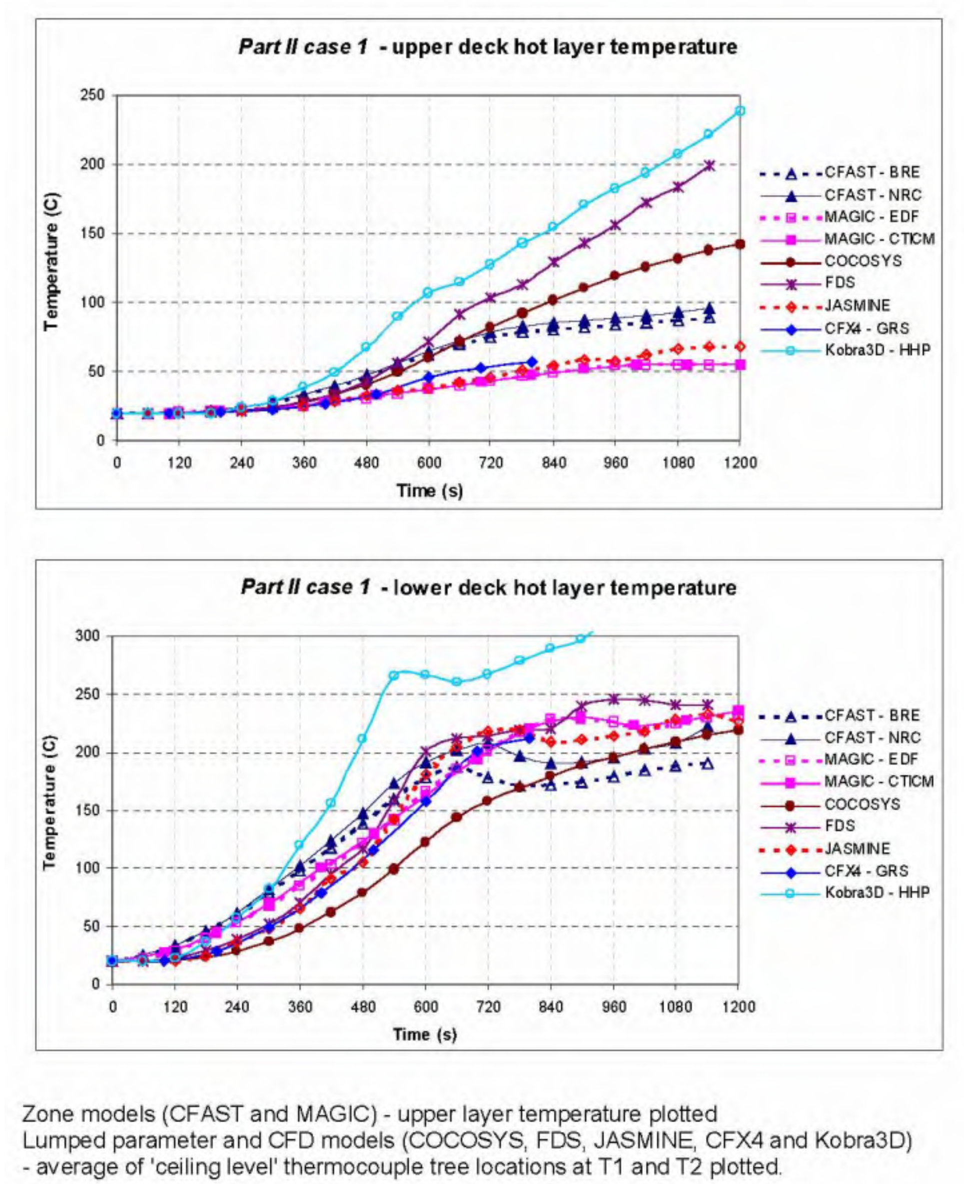

Figure 3-41 Predicted Hot Gas Temperatures for BE No. 2, Part II, Case 1

3.7 Mechanical Ventilation

Figure 3-42 compares the compartment pressure predicted by CFAST and FDS with measurement in Test 4 of Benchmark Exercise No. 3, a test with a closed door and forced ventilation. The CFAST and FDS calculations were conducted with the leakage for a closed compartment and does not account for the vents of the mechanical ventilation system. CFAST and FDS do not have the capability to model the details of a mechanical ventilation system and its feedback on compartment pressure during the build up of the fire. Therefore, as shown in Figure 3-42, the CFAST and FDS prediction of compartment pressure is much higher than observed in the experiment.

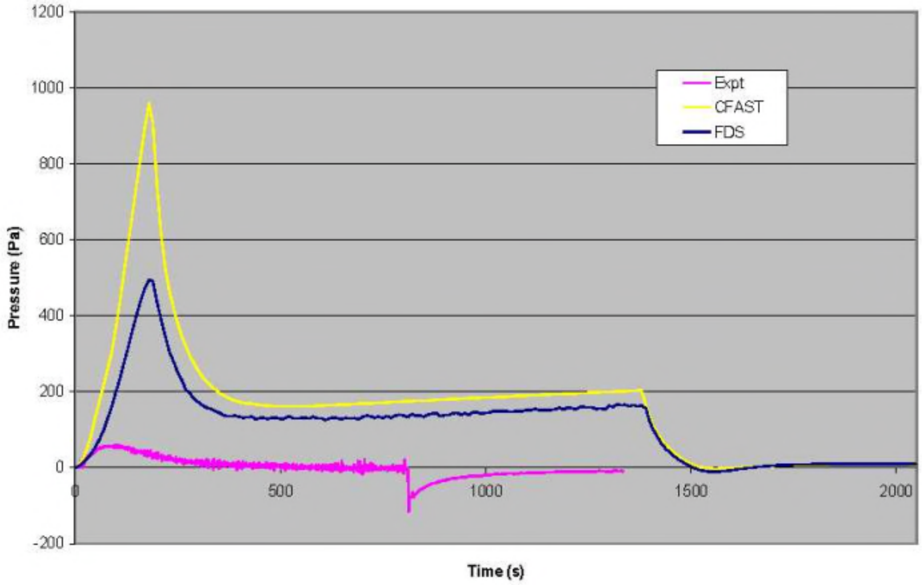

Figure 3-42 Compartment Pressure - BE 3, Test 4

Figure 3-43 shows a comparison of the vent flows predicted by CFAST and FDS with experimental observation for Test 4 in Benchmark Exercise No.3. The supply mass flow predicted by CFAST and FDS remain constant through the transient since the codes do not simulate the feedback from the ventilation system. The exhaust mass flow from CFAST and FDS decreases with time only due to the increase in the temperature of the hot gas. The mechanical ventilation is specified as volumetric flows in CFAST and FDS. The temperature of the gas going out is more than that of the ambient air coming in resulting in a mass imbalance.

However, as shown in the Figure 3-43, the supply flow rate observed in the experiment quickly decreases at the beginning of the transient due to the pressure build up in the compartment. On the other hand, the measured exhaust flow rate is seen to increase at the beginning of the transient due to the pressurization of the compartment and then decreasing to a steady level. This figure illustrates the impact of the lack of the ability of the codes to include the coupling between the compartment and the mechanical ventilation system. Test 5 of Benchmark Exercise No. 3, an open door test with mechanical ventilation, also showed similar trends and issues with the code predictions. It is difficult to realistically model the compartment fire scenario with mechanical ventilation without including a model of the coupling between the two. This limitation is also tied to the prediction of fire extinction, as discussed earlier.

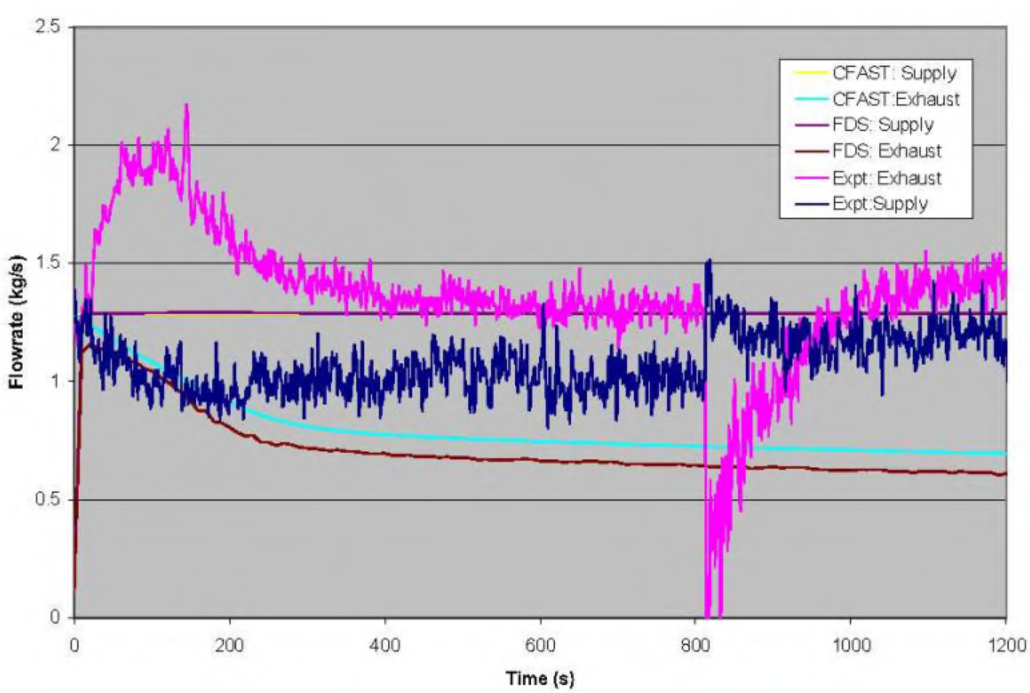

Figure 3-43 Vent Flows - BE 3, Test 4

3.8 Limitations of Empirical Correlations in FDTs

The empirical correlations in FDTs provide a method to quickly calculate global parameters (such as HGL temperature and interface height), as well as radiative fluxes to targets for exploratory analysis. However, it is important to note that the results obtained may have large errors.

A large deviation (626 C predicted versus 288 C measured) was noted for the HGL temperature for Test 13 of Benchmark Exercise No. 3 with a 2 MW fire. There was large error (18.1 kW/m2 predicted versus 7 kW/m2 measured) in the prediction of radiative flux in Test 14 of the same exercise in which the fire was close to the flux gauge. Very large deviations for compartment pressure, and large deviations for smoke concentrations were noted. The correlation for compartment over pressure does not appear to predict realistic values. As discussed earlier, the prediction of smoke concentrations in closed compartment scenarios which become under ventilated is difficult, even for CFD codes. Therefore, the smoke concentrations predicted by FDTs which do not account for under ventilation are not realistic.

In Benchmark Exercise No. 4, some large deviations for heat fluxes (-66 %) and plume temperature at M6 (-66 %) were noted. The heat flux correlations used may not have had a large fire, such as the one in Test 1 of Benchmark Exercise No. 4, included in the experimental database used to develop the correlation. Also, the plume correlation is for erect plumes and not when the fire plume is tilted, as was evident in Benchmark Exercise No. 4.

Some large deviations for plume temperature were also noted in Benchmark Exercise No. 5. The plume correlation is for fires in an open environment and does not include the complex effects of the surrounding walls. There also were large errors (62 %) in the predicted heat fluxes in Benchmark Exercise No. 5.

Since the range of validity of the correlations in FDTs is narrow, the results are best suited for exploratory calculations where a rough estimate is sufficient, while acknowledging the answers may contain large inaccuracies.

4 Conclusions and Recommendations

This study concludes that fire models at present are severely limited in predicting parameters of major interest in nuclear plant fire safety. Bounding calculations with the fire models can still be conducted, as long as the limitations of the models are acknowledged, understood and taken into account. This study determined that the fire models examined are presently limited in predicting: (1) the movement and location of the flaming region and fire plume; (2) under-ventilated conditions and fire extinction; (3) heat flux from the flaming region and hot gas; (4) cable target heating; (5) intense fire conditions; (6) fires in multi-level buildings; and (7) mechanical ventilation.

Erroneous decisions leading to unsafe nuclear plant conditions will result if these limitations are not considered in nuclear plant fire safety decision making. Fire science and modeling is an evolving area. It is necessary to take time to understand the physics and performance of models when applying them. This and other ICFMP documents are a good source of information.

It is recommended that research and improvement programs be developed to overcome the limitations identified in this report so that fire models become a reliable and useful tool.

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