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

Deytec, Inc.

Nuclear Engineering Services

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ABSTRACT

This paper 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 paper, 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 paper presents the results of blind, unbiased analyses that were conducted to derive the true errors in fire model predictions. Such analyses and presentations are rare in the fire modeling literature. The analyses indicate that fire models at the present are limited in predicting parameters of interest in nuclear plant fire safety and risk analysis. Erroneous decisions leading to unsafe nuclear plant conditions will result if the fire model limitations and predictive errors 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 and true predictive errors of the models are acknowledged, understood, and taken into account. Research and improvement programs should be developed to overcome these limitations and improve model predictive errors so that fire models become a reliable and more useful tool for nuclear plant fire safety and risk analysis.

1. INTRODUCTION

This paper provides a summary of the author's work conducted as part of the International Collaborative Fire Model Project (ICFMP). The author led the ICFMP project from 1999 to 2006 while he was at the U.S. Nuclear Regulatory Commission (USNRC) and at the same time a guest researcher at the National Institute of Standards and Technology (NIST). The analyses conducted by the author to evaluate select fire models are presented here, along with conclusions on their reliability and applicability for nuclear plant fire safety and risk analysis. The work, including reanalysis, was completed by the author after he left USNRC and established Deytec, Inc.

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

2. INTERNATIONAL BENCHMARK EXERCISES

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. Therefore, the benchmark exercises were focused to study the ability of models to simulate cable heating. The 1st and 2nd international benchmark exercises included hypothetical exercises for fire scenarios in nuclear plants for which experimental data did not exist. A representative emergency switchgear room, 15.2 m deep x 9.1 m wide and 4.6 m high, in a nuclear plant was selected for the 1st benchmark exercise. The room contained the power and instrumentation cables for the pumps and valves associated with redundant emergency core cooling systems. The prediction of cable heating and damage from various fire sources was examined, including fires affecting cable trays carrying cables for redundant safety systems. A full description of the specification of Benchmark Exercise No. 1 can be found in Dey, 2002. The 2nd benchmark exercise examined scenarios that are more challenging for zone models, in particular to fire spread in multi-level larger volumes. The issues examined were a subset of those that will be faced by modelers simulating fires in turbine halls in nuclear power plants. The heating of cables and structural beams was examined in a two-level large volume (50 m x 100 m x 20 m), with the two levels connected by equipment hatch openings as in a turbine building. The ability of the fire models to simulate the flow of hot gases through the hatch openings and subsequent heating of targets was examined. A full description of the specification of Benchmark Exercise No. 2 can be found in Miles, 2004.

The 3rd, 4th, and 5th international benchmark exercises consisted of tests conducted specifically for the ICFMP. Full-scale compartment fire experiments were conducted by the USNRC at NIST for ICFMP Benchmark Exercise No. 3 to simulate a cable room of similar size as in the 1st benchmark exercise with various types of cables in different configurations. Figure 1 shows a schematic of the compartment constructed for Benchmark Exercise No. 3. The compartment had typical features of a compartment in a nuclear plant, including a door and forced ventilation system.

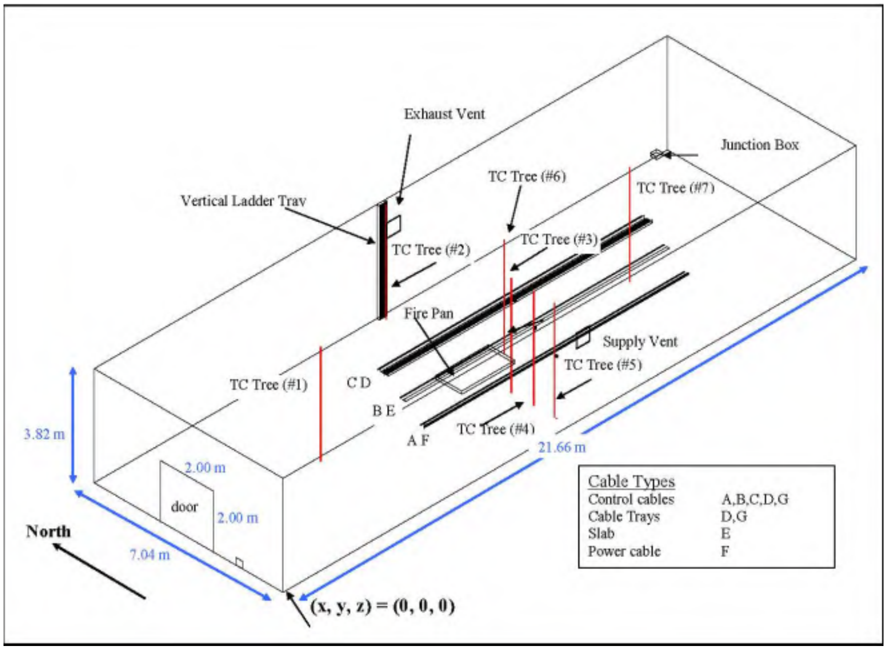

Figure 1 Schematic of Compartment for Benchmark Exercise No. 3

Cable targets and trays were arranged to examine various effects, including the modeling of one cable versus cables bundled in a cable tray, and a cable composed of a slab with uniform material versus one with real cable geometry and composition. The effects of diameter, elevation in the hot gas layer, and distance from the fire on the heating of cables were examined. The ability to predict the heating of vertical versus horizontal cable targets by models was also examined. Fifteen tests were conducted with various fire sizes and types, and location of the fire relative to the cables. The ventilation conditions were also varied in the test series. This resulted in a vast amount of data for model evaluation and improvement. A picture of a partially under-ventilated fire in Test 13 of the test series 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 and experimental data from the tests are available from the author.

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

Gesellschaft fur Anlagenund Reaktorsicherheit (GRS) in Germany conducted tests for ICFMP Benchmark Exercise No. 4 to simulate intense fire scenarios in a compartment, including heating of various targets; and ICFMP Benchmark Exercise No. 5 to simulate pool fires, and cable heating, ignition and flame spread. A full description of the specifications of Benchmark Exercise Nos. 4 and 5 can be found in Klein-Hessling, 2006, and Riese, 2006, respectively.

3. RESULTS

This section 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 by the author in the five international benchmark exercises described earlier. The full analysis for the benchmark exercises are contained in Dey, 2002; Miles, 2004; Dey, 2009a; Klein-Hessling, 2006; and Riese, 2006. A more detailed discussion of the capabilities and limitations is contained in Dey, 2009b.

3.1 Capabilities

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 compartment hot gas temperature and interface height are determined by mass and energy balances and models for plume flow which are robust in the fire models and thereby result in reliable predictions. The temperature distribution in the hot gas was also adequately captured by FDS (< 15 % error) for a wide range of fire scenarios, including intense fires. The algorithms and equations for predicting door heat and mass flows, and the oxygen and carbon dioxide concentrations for *ventilated* fires are reliable in the codes (< 20 % error). Carbon monoxide and smoke concentrations can also be reliably predicted (< 20 % error) for *ventilated* fires as long as correct yields are included for the combustion products in the models.

3.2 Limitations

Although the predictions of general compartment conditions were reasonable, the prediction of parameters that are important for nuclear plant safety analysis proved much more difficult. The results presented here are based on blind predictions made with the CFAST and FDS fire models, and fire correlations in FDTs before the experiments were conducted. This was an important aspect of the benchmark exercises in order to determine the true predictive errors, and thereby the real limitations and capabilities of these fire models. The analyses indicate that the fire models, and especially empirical correlations, at the present are limited in predicting the following parameters of interest in nuclear plant fire safety and risk analysis:

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, and
7. Mechanical ventilation

3.2.1 Movement and Location of the Flaming Region and Fire Plume

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 indicated that the code is unable to predict the movement and location of the fire flame and plume in under-ventilated conditions and when the fire flame and plume is near a solid boundary. The inability to adequately simulate 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 some 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 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.

An example of analysis showing the inability of the FDS code to model plume movement in under-ventilated conditions is shown in Figure 3 which 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 thermocouple 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 taken for Benchmark Exercise No. 3 (available from author). 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 the closed-door tests in Test 4 and Test 13 of Benchmark Exercise No. 3. The measured surface temperature of the control cable at D-TS-12 also showed a 30 C increase and oscillation starting at ~ 580 s caused by the lateral movement of the flaming region and plume due to under-ventilation. These observations were not captured by FDS. Measurements with radiative and total heat flux gauges during this same test also confirmed the presence of oscillations due to the lateral movement of the plume that is not captured by FDS.

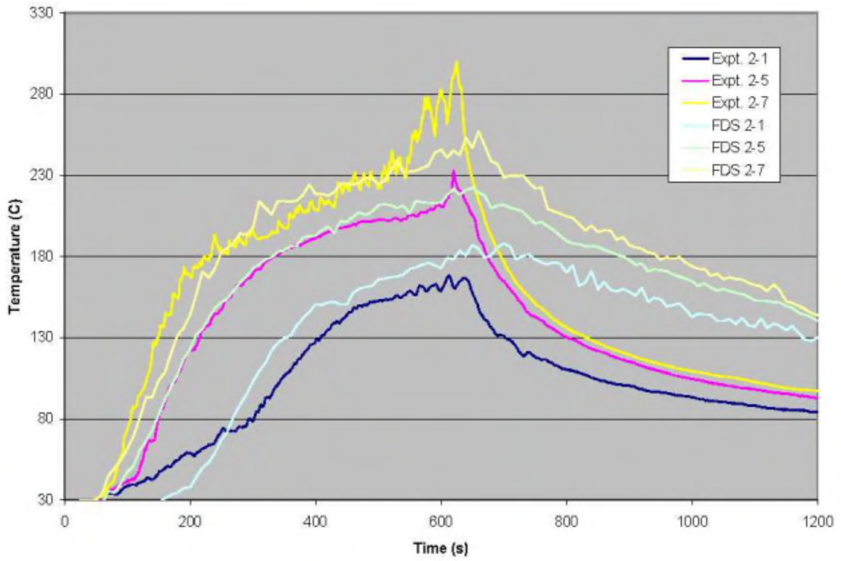

Figure 3 Compartment Temperature (Tree 2) – Benchmark Exercise No. 3, Test 2

Analysis of Test 15 in Benchmark Exercise No. 3 where the fire pan was moved closed to a wall showed large discrepancies in compartment temperatures between measurement and FDS predictions, indicating the difficulty of the FDS code to accurately predict plume movement when the fire is near a boundary. The inability of the FDS model to simulate the fire plume was also observed in Benchmark Exercise No. 4. The fire was located at the center of a relatively small 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, verified by many thermocouple measurements, again shows the limited reliability of using FDS to evaluate targets near the plume under certain conditions.

Comparison of measurements and FDS predictions of plume temperatures for an erratic pool fire in a dike in Benchmark Exercise No. 5 also showed that FDS did not accurately predict plume movement. Dey, 2009b, and the more detailed reports of the author's analysis, discuss in much more detail the analysis that demonstrated the difficulty of the FDS code for modeling plume movement in under-ventilated conditions and when the fire is near a boundary or subject to certain flow conditions.

3.2.2 Under-ventilated Conditions and Fire Extinction

The extinction sub-models utilized in CFAST is a crude approximation of the interaction of the complex combustion process with a limited oxygen environment. The assumption for the Lower Oxygen Limit (LOL) in CFAST significantly affected the predicted peak target temperature in the test scenarios. 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. Both CFAST and FDS employ simple algorithms for predicting fire behavior in under ventilated conditions which lead to large errors in the prediction of fire extinction. 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 which affected prediction of fire extinction.

Figure 4 shows comparisons of the O2 concentration predicted by CFAST and FDS with experimental measurement for Test 2 of Benchmark Exercise No. 3, a closed-door test with a large 1-MW fire. Large oscillations in the oxygen concentration near the fire are not predicted by CFAST or FDS. These oscillations occur after the hot gas layer has reached the floor and are due to incomplete mixing of the hot gas. Similar oscillations were observed in Test 1 and other closed-door tests in Benchmark Exercise No. 3.

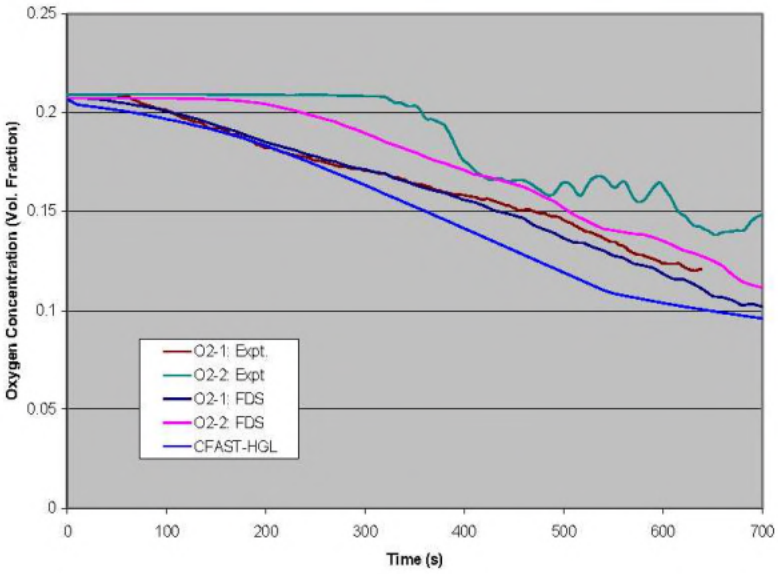

Figure 4 Oxygen Depletion in Benchmark Exercise No. 3, Test 2

Test 4 in Benchmark Exercise No. 3 with forced ventilation and closed-door conditions showed a more rapid decrease in oxygen concentration observed in the experiment than predicted by both codes. In fact, the FDS prediction of oxygen concentration at O2-2 near the fire does not reach 15 %, the point at which the test was terminated. Although the fire was extinguished 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.

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. 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 with many “dials” that have to be tuned, and not currently suitable for safety analysis for which the reliability of a model must be assured.

3.2.3 Heat Flux from the Flaming Region and Hot Gas

When a target cable is not directly in the fire flame or plume, it becomes important to calculate the heat flux to the target from the flaming region and hot gas. Analysis conducted by the author shows that current algorithms in CFAST and FDS 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.

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. The predictions of heat flux in Benchmark Exercise No. 1 were widely different from the various fire models used in the exercise (Dey, 2002). 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 (Miles, 2004) for multi-level fire scenarios. 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 models, and different models of the same type. Incident flux calculations were strongly influenced by the radiation treatment (Miles, 2004).

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 (up to 40 % - 50 % under predictions). The CFAST predictions varied, and were sometimes much larger than measured values. 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 cable temperature distribution in vertical cable trays when the fires source is in its immediate vicinity was challenging, even for FDS. The prediction of heat fluxes in or near a fire plume was also difficult for FDS.

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 (up to 150 %) depending on the location and orientation of the gauges, and the convective heat flux is under predicted in many of the transients.

Figure 3-5 compares the radiative and total heat flux predicted by CFAST and FDS with experimental observations for Benchmark Exercise No. 3, Test 3. As noted in this figure, a large convective flux (total - radiative) is measured but not predicted by the codes. Both models under predict the total heat flux in this case. This similar observation can be noted by examining various plots for many other gauges and tests. The errors in the flux predictions for CFAST and FDS can be a high as 150 % and 50 %, 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.

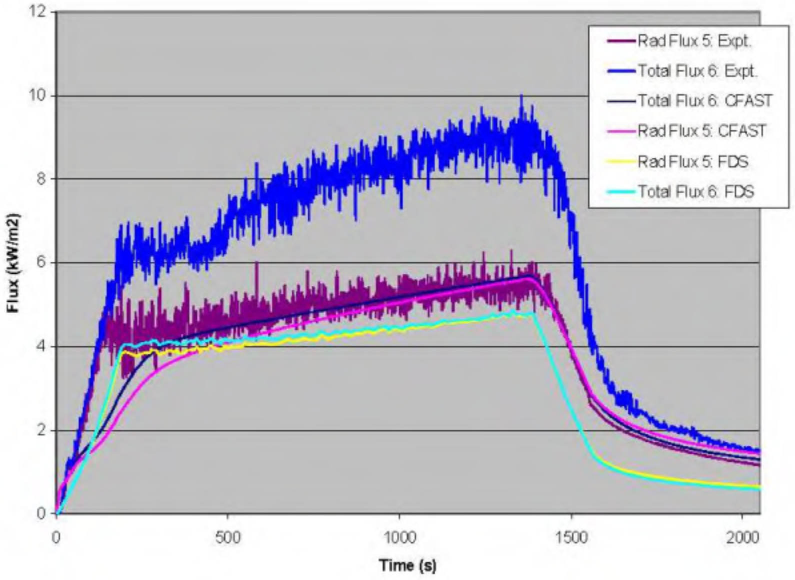

Figure 5 Heat Flux to Cables – Benchmark Exercise No. 3, Test 3

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 indicate that the peak cable temperature observed 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. 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.

Large discrepancies in the total heat flux predictions of the FDS and CFAST codes with experiment were also noted in many measurements in Benchmark Exercise Nos. 4 and 5 (Dey, 2009b). Again, the errors in the peak values ranged from ~ 50 % to as much as 150 %.

2.2.4 Fires in Multi-Level Buildings

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.

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 for Case 1 of Benchmark Exercise No. 2, Part II, are shown in Figure 5. 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.

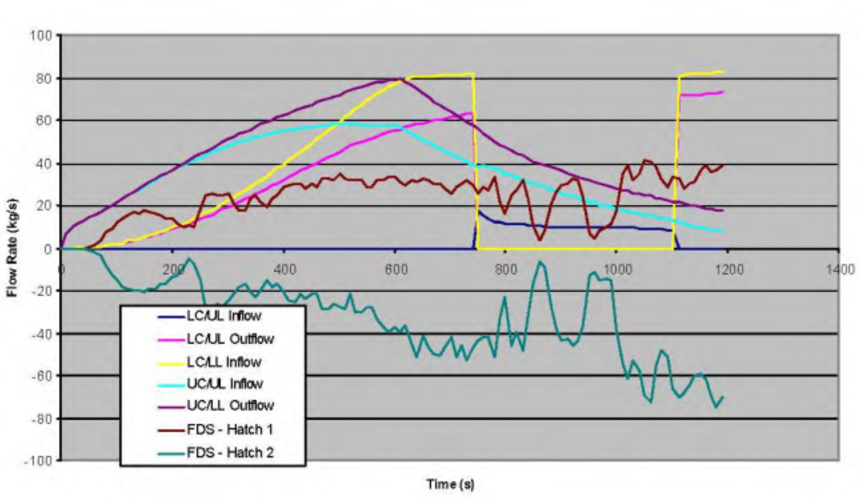

Figure 6 Hatch Mass Fow Prediction in BE No. 2, Part II, Case 2

Although the trends of parameters such as flow and temperature 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 led to the wide spread in predicted hot gas temperatures (Miles, 2004). The predicted gas temperatures for the upper deck *vary by a factor of about 5* between the different fire models. 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.

3.2.5 Other Limitations of the CFAST and FDS Fire Models

Other limitations of the models that should be noted and only briefly discussed here are the prediction of: (1) Cable target heating; (2) Intense fire conditions; and (3) Mechanical ventilation. 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 of severe fire conditions with the CFAST code produced erratic results due to the fundamental limitation of the model for scenarios with high heat fluxes. 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. The bases for these other limitations are presented in Dey, 2009b.

3.2.6 Limitations of the 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 (-60 %) 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. CONCLUSION AND RECOMMENDATION

Not withstanding the above limitations, bounding analysis with fire models is still possible as long as the limitations, 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. The work presented here and done by others in the ICFMP project, are good sources of information.

Research and improvement programs should be developed to overcome the limitations identified here so that fire models become a reliable and useful tool for nuclear plant fire safety analysis. This paper 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.

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