Lessons Learned in ICFMP Project for Verification and Validation of Computer Models for Nuclear Plant Fire Safety Analysis

Dr. Monideep K. Dey

Deytec, Inc., HC 64 Box 100-27, Yellow Spring, WV 26865, USA, mdey@deytecinc.com

INTRODUCTION

This paper presents the "lessons learned" from the verification and validation (V&V) exercises of computer fire models conducted as part of the International Collaborative Fire Model Project (ICFMP). An earlier paper presented the author's work conducted in the ICFMP [1]. The V&V process in the ICFMP project was developed with two objectives:

1. To examine the modeling of the physics involved in several nuclear power plant (NPP) scenarios by current state-of-the-art fire models, and to develop the capabilities and limitations of these models for simulating such scenarios;
2. To determine the predictive accuracy of the models (model error) of important parameters for nuclear plant fire safety analysis.

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 synthesis of the ICFMP results was conducted as a project of Deytec, Inc. in 2010 to benefit the scientific community [2]. The successes and difficulties faced in the ICFMP project in the verification and validation of computer fire models for reliable use in nuclear plant safety analysis is presented here.

INTERNATIONAL BENCHMARK EXERCISES

The ICFMP project consisted of five international benchmark exercises in which nuclear safety research organizations from five countries (Germany, UK, France, Finland, and USA) attempted to verify and validate fire models developed in their respective countries to standard problems developed by the ICFMP. The 1st international benchmark exercise included a hypothetical exercise for fire scenarios in nuclear plants for which experimental data did not exist. The 2nd, 3rd, 4th, and 5th international benchmark exercises consisted of tests simulating NPP fire scenarios. Full-scale compartment fire experiments were conducted by the USNRC at NIST for ICFMP Benchmark Exercise No. 3 to simulate a cable room with various types of cables in different configurations [3]. Gesellschaft fur Anlagenund Reaktorsicherheit (GRS) in Germany conducted tests for ICFMP Benchmark Exercise No. 4 to simulate intense fire scenarios in a compartment [4], and ICFMP Benchmark Exercise No. 5 to simulate pool fires and cable flame spread [5]. The ICFMP project consisted of 11 international meetings of project participants over a decade where the benchmark exercises were developed, and results and "lessons learned" discussed to formulate project reports. Details of the experiments, fire model calculations, and the results of each international benchmark exercise are discussed in References 3, 4, and 5.

RESULTS

Capabilities and Limitations

The V&V process in the ICFMP project was very beneficial in many respects. The benchmark exercises allowed different models to be analyzed and compared against each another and experimental data for a wide range of fire scenarios in nuclear power plants. The comparisons of the trends between codes and experimental data allowed an examination of the modeling of the physics of the scenarios. The capabilities and limitations were derived from such comparisons and analysis. The V&V process in the ICFMP facilitated a very valuable exchange of information, analyses, and ideas among participants regarding the physics of fire phenomena, and successes and challenges in modeling such phenomena.

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 (10-20 % errors). The temperature distribution in the hot gas is also adequately captured by computational fluid dynamic (CFD) computer codes like the Fire Dynamics Simulator (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. These topics continue to be researched by the fire science community.

Determination of Model Predictive Errors

In order to determine model predictive errors that would be widely accepted, the ICFMP project was established by the parties to conduct blind (a priori) benchmark exercises, i.e. participants would conduct and submit results of their respective fire model calculations based on a specification of the exercise prior to the release of experimental data and learning of the results from other participants. Great efforts were expended to develop the specification of the benchmark exercises in sufficient detail to minimize the variance in the input parameter values used to conduct the blind calculations. The goal of blind exercises was to provide participants a process in which they could establish the true predictive errors of their models in an international forum. These results could then be used by the respective organizations for application.

The differences between blind and open results have been studied and documented [6]. Studies have shown that it is possible to conduct open fire simulations that reproduce the general fire behavior to a satisfactory level. This is achieved due to the availability of experimental data of the real behavior for reference, allowing for iterations until an adequate input file is found. Only blind simulations are free of the possible bias that could be introduced by prior knowledge of how the event developed. These studies have concluded that most fire model validations in fire safety engineering have been conducted a posteriori (open). The degree and importance of the bias introduced in open calculations in fire safety engineering is currently under study by different research groups.

The ICFMP attempted to conduct blind exercises but faced two categories of issues in the process:

1. Lack of agreement among participants on the measurements and data needed as input to the fire models being exercised;
2. Lack of an established formal procedure for the submission and collection of blind calculations from the participants.

The main three input parameters that were issues in the ICFMP V&V process were: (1) Heat release rate (HRR); (2) Radiative fraction of heat from fire; and (3) thermal parameters of compartment boundary. These input parameters also have the greatest effect on output parameters of interest in NPP fire safety analysis. Although attempts were made at measuring and specifying these parameters for the benchmark exercises, there was disagreement among participants as to the correct values to be used as input for the fire models. For example, Table 1 shows the evolution of the heat release rate specified by the experimentalists for Test 3 of Benchmark Exercise No. 3 that resulted from considerable discussion by ICFMP participants of the appropriate analysis method for the measured data. The heat release rates in the Table vary by more than 20 %. In the end, ICFMP participants utilized the HRR values for the benchmark exercise that they determined to be correct and justified based on their respective analyses of the data. There was also disagreement on the radiative fraction of heat from the fire and the thermal properties of the compartment boundary. Values for these parameters used by participants in the benchmark exercises varied from 15 % to 45 % for the radiative fraction, and were different by up to 50 % for the thermal properties of the compartment boundaries. Extensive discussion of the data issues is provided in the full ICFMP reports and Reference 2.

Table 1 Evolution of Heat Release Rate for Benchmark Exercise No. 3, Test 3

Release Date	July 2, 2003**	July 21, 2003	Sept. 9, 2003	April 4, 2004	June 2005
HRR - from Fuel Flow	1050*	1050	1150	1150	1150
HRR - from Calorimetry	1150	1260	1260	1260	1190

*HRR specified in kW.
**Prior to release of experimental data.

Since there was no agreement on these inputs to the models, participants changed their calculations based on modified values of model input parameters they believed to be correct after the experimental results were released to participants. Blind fire model predictions had been submitted to a central contact, but the submission and collection of blind calculations was informal due to the lack of an international standard and the collegial nature of the collaborative project. In the end, it was up to participants to declare which calculations were open or blind. There was also some confusion on the definition of a blind exercise used in the ICFMP because other definitions exist in the literature.

The model errors derived for output parameters was significantly different (up to 55% differences in model error) among participant calculations using the same fire model, or using models with the same degree of sophistication. Therefore, it is concluded that the ICFMP benchmark exercises were not successful as blind validation exercises. However, the development of the V&V process provided experience in the conduct of such blind exercises and the issues that provided a challenge. These issues could be addressed and the V&V process can be improved.

RECOMMENDATIONS

It is recommended that current fire models be improved in their ability to predict heat flux and cable heat up, especially when cables are close to the fire flame, as such applications are critical in NPP fire safety analysis. Research is recommended on the measurements that are needed to provide the input values to fire models as documented in this study and the full ICFMP reports of the benchmark exercises. It should be noted that uncertainty quantification of the input variables does not solve the issue posed in this paper as the issue is to prevent the variation of input parameters for a desired result, i.e. to better match experimental measurement in a blind exercise.

It is further recommended that an international standard be developed to:

1. Establish a consensus on the measurement methods for parameters that are needed as input to fire models;
2. Develop to the extent possible a consensus on the values, or the methods to obtain values, for parameters that are needed as input to fire models;
3. Establish a process to ensure that blind calculations are used to establish model errors that are used to establish safety margins in safety analysis;
4. Examine and include "third party validation" as an option for establishing true model errors.

Third party validation could address the issue of the possible bias introduced in fire model validations by providing an independent assessment and determination of the model errors. Third party validation could also be used to provide validations as newer versions of a particular fire model are released.

CONCLUSION

The V&V process in the ICFMP project resulted in very valuable information. The capabilities and limitations of current state-of-the-art fire models were identified as well as areas in which models can be improved. Experience was gained in the conduct of blind V&V exercises, and challenges in terms of model input data and process issues were identified. These issues could be addressed in a standard that establishes data and process for the blind validations of fire models.

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