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

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Nuclear Engineering Services

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ABSTRACT

This paper presents a synthesis of the technical and programmatic "lessons learned" in the International Collaborative Fire Model Project (ICFMP) that was conducted from 1999 to 2008. The verification and validation (V&V) process in the ICFMP project was developed to examine the capabilities and limitations of fire models for nuclear plant fire safety and risk analysis, and to determine the predictive errors of fire models. Although current models can reliably predict global parameters in nuclear plant compartment fires such as hot gas temperature and interface height, they are limited and need to be improved for predicting important parameters like heat flux to cable targets. The development of the V&V process provided experience in the conduct of *blind* exercises, however, it was not possible to determine the true predictive errors of the models due to issues related to model input data and procedures for *blind* exercises. These issues could be addressed and the V&V process can be improved. The experience in the ICFMP has formed the basis of a V&V process for the evaluation of fire models for nuclear plant applications.

1. 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 and report presented the author's work conducted in the ICFMP [1], [2]. 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 [3]. The successes and difficulties faced in the ICFMP project in the verification and validation of computer fire models for reliable use in nuclear plant fire safety analysis is presented here.

2. 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 [4]. The 2nd, 3rd, 4th, and 5th international benchmark exercises consisted of tests simulating nuclear plant fire scenarios [5], [6], [7], [8]. 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. Gesellschaft fur Anlagenund Reaktorsicherheit (GRS) in Germany conducted tests for ICFMP Benchmark Exercise No. 4 to simulate intense fire scenarios in a compartment, and ICFMP Benchmark Exercise No. 5 to simulate pool fires and cable flame spread. 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 reports of the exercises cited above.

3. RESULTS

3.1 Capabilities and Limitations

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 and a reactor meltdown. 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 the prediction of parameters that are important for nuclear plant safety analysis proved much more difficult.

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.

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 computational fluid dynamic (CFD) codes like the Fire Dynamics Simulator (FDS) [9] 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 analysis of the five international benchmark exercises concluded that current models are 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. Zone models such as Consolidated Fire and Smoke Transport (CFAST) model [10] utilize a simple point source model for the fire and empirical correlations to determine plume flow and therefore do not predict flame and plume movement. Comparison of CFD codes like FDS with experimental data over a wide range of fire scenarios indicate that CFD codes are presently 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. Present fire models, including CFD codes like FDS, are limited by the simple approaches included in them for predicting under-ventilated conditions, combustion products, and extinction of the fire. Several initiatives are underway at research institutions to improve the modeling of the combustion process. 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. Current algorithms used in fire models 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. Most current models do not include a target model for such complex cable configurations or cable compositions. Most fire models have a simple one-dimensional slab model of uniform composition for targets such as cables.

Modeling vertical flow through horizontal vents in a zone model posed a challenge in Benchmark Exercise No. 2 which examined fires in multi-level buildings such as the turbine building in nuclear plants. This was due to the lack of spatial treatment in zone models to account for multiple hatches that separate levels in a building. 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 CFD fire models used in the multi-level benchmark exercise (No. 2). 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, empirical correlations in compilations such as FDTs [11]are best suited for exploratory calculations where a rough estimate is sufficient, while acknowledging the answers may contain large inaccuracies.

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.

3.2 Determination of Model Predictive Errors

3.2.1 Background

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 the 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.

When making comparisons of fire model results to experimental measurements, there are two general approaches that can be followed: a priori (aka blind) and a posteriori (aka open). In a priori simulations, the modeler knows only a description of the initial scenario. The modeler has no access to the experimental measurements of the event and thus will be providing a true forecast of the quantities of interest. In a posteriori simulations, before the simulation is run the modeler knows the initial scenario and also how the fire developed (i.e. via the experimental measurements). Most fire model validations in fire safety engineering have been conducted a posteriori.

Only comparison of a priori and a posteriori simulations of the same event allows one to investigate the possible effects that are introduced by prior knowledge of how the event developed. The importance of this effect in fire safety engineering is currently an advanced research topic and under study by different research groups.

The 2006 Dalmarnock Fire Tests conducted in a high-rise building were used to look into the problem. An international study of fire modeling was conducted prior to Dalmarnock Fire Test One [12]. The philosophy behind the tests was to provide measurements in a realistic fire scenario with very high instrumentation density (more than 450 sensors were installed in a 3.50 m by 4.75 m by 2.45 m compartment). Each of the seven participating teams independently simulated the test scenario a priori using a common detailed description. Comparison of the modeling results shows a large scatter and considerable disparity among the predictions and between predictions and experimental measurements.

The differences between a priori and a posteriori modeling become patent when comparing the round-robin results with the work conducted after the Dalmarnock data was publicly disseminated. Subsequent studies [13][14][15] show that it is possible to conduct a posteriori fire simulations that reproduce the general fire behavior to a satisfactory level. This was achieved due to the availability of experimental data of the real behavior for reference, allowing for iterations until an adequate input file was found.

As indicated above, current models provide reliable predictions for compartment global parameters that are good enough to be applied towards engineering problems if a robust and conservative methodology is defined. A prerequisite for this methodology is that it applies appropriate safety factors. An important point is that in the 'real world' fire engineering applications are most frequently applied to simulate events for which real behavior had not been (and will never be) measured [16]. These simulations are a priori simulation, not a posteriori. However, most fire model validations in fire engineering have been conducted a posteriori. Therefore, it is necessary to have a priori comparisons of fire models and address full model validation.

Only a priori simulations are free of the possible bias that could be introduced by prior knowledge of how the event developed. The magnitude and importance of this bias in fire engineering is currently unknown. The ICFMP project attempted to address this issue through the conduct of blind benchmark exercises. The project recognized that it is important to derive true model errors without any biases introduced such that appropriate safety factors and margins can be introduced in fire safety designs when using the fire models.

3.2.2 V&V Procedures Established in ICFMP

As mentioned earlier, the specifications of the benchmark exercises in the ICFMP were developed with great efforts to include sufficient details about the inputs required for the fire models. The goal was to minimize the uncertainty and debate about input parameters such that the predictive errors of the models could be determined. As evidenced by the specifications of the benchmark exercises [5][6][7][8], the model input data were specified in sufficient detail such that there was minimal reason for "user effects' to affect the model results, i.e. from different analysts making different assumptions about input data.

Analysts were required to make some assumptions about their models for the benchmark exercises, e.g., initial conditions, grid size for CFD and lumped-parameter calculations, and any options available for their specific models. These assumptions are also necessary for engineering calculations. An engineering calculation for a design fire is a blind calculation as experimental data for that particular fire scenario does not exist. Although sensitivity analysis is appropriate in design calculations, analysts must choose the optimal value for the assumption, e.g., grid size, which the analyst believes is most appropriate and/or practical for the analysis of the fire scenario. Any sensitivity/uncertainty analysis about this optimal value can be done and presented in a blind calculation, but the optimal prediction of the model is with the optimal assumption of grid size, etc. for the fire scenario. The safety factor for fire protection systems design will be based on the optimal predictive capability of the model derived in this manner.

The V&V procedures in the ICFMP also addressed the argument that commonly arises in blind V&V exercises that experiments cannot be replicated and therefore the fire experimental data have large uncertainties for the purpose of blind fire model validations. Of the fifteen tests that were conducted for Benchmark Exercise No. 3, four were replicate tests representing the wide range of compartment conditions in the test series for the exercises. It was shown that the compartment conditions were almost duplicated in the replicate tests [6]. There was no challenge to the test results from ICFMP participants based on the argument that fire tests can never be conducted to duplicate the same results.

The test series for Benchmark Exercise No. 3 was very successful in being conducted according to the test plan and specification of the exercise distributed to participants in the blind exercise. This addressed the issue that arises in blind validations that tests are seldom conducted according to the test plan. The uncertainty of the heat release rate in the experiments was due to a deficiency in the measurement system and not because fire experiments cannot be conducted according to a test plan. Also, minor changes to the test plan prior to the tests were communicated to ICFMP participants as addenda to the specification of the blind exercise.

The experimental results were released to all participants after the blind fire model predictions were submitted to a central contact. However, the submission and collection of blind calculations was not conducted per an established international standard and was informal due to the collegial nature of the collaborative project.

3.2.3 Issues Identified in the V&V Process

There were two categories of issues identified in the V&V exercises in the ICFMP:

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 V&V process were: (1) Heat Release Rate (HRR); (2) Radiative Fraction; and (3) Thermal Parameters of Compartment Boundary. These input parameters also have the greatest effect on output parameters of interest in nuclear plant 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. The disagreement on the values of these parameters extended to Benchmark Exercise No. 3 even though extensive efforts were made to specifically measure the values of those parameters for materials used in the exercise [3]. Extensive discussion of the data issues is provided in the full ICFMP reports and Reference No. 3.

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

Release Date	July 2, 2003[b]	July 21, 2003	Sept. 9, 2003	April 4, 2004	June 2005
HRR - from fuel flow	1050[a]	1050	1150	1150	1150
HRR – from calorimetry	1150	1260	1260	1260	1190

[a] HRR specified in kW.

[b] 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.

4. 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 nuclear plant fire safety analysis. Research is recommended on the measurements that are needed to provide the input values to fire models as documented in this paper 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 and safety margins in safety analysis;
4. Examine and include "third party validation" as an option for establishing true model errors.

It should be noted that the input required for fire models is very dependent on the applications as fire models are presently used in a wide range of applications in many industries. A general standard is possible, but the specifics for each application should be developed as addenda to the standard. The specifics for nuclear plant applications can be developed based on the issues identified in the ICFMP.

The third party validation option could address many of the issues identified in this report regarding the conduct of blind calculations. The differences between blind and open results have been studied and documented. 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 was found. Only blind simulations are free of the possible bias that could be introduced by prior knowledge of how the event developed. 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. It is recommended that standards established in other industries, where model accuracy is important for safety, such as the medical field where extensive literature exists be reviewed in the development of the standard for fire model validation. For example, the Food and Drug Administration (FDA) quality control requirements for medical software and models are very complex, and require expert documented and non developer validation and verification. An international standard for fire model validation could also limit the liability exposure of modelers that develop fire safety systems.

Finally, it should be noted that substantial efforts and resources were expended in the ICFMP for the assessments reported here and elsewhere. At least 35 participants from seven organizations in five countries contributed significant resources to the effort over ten years. In contrast to this effort, substantially more resources will be required to improve the models to make them more reliable and useful for nuclear and other applications. Also, significant resources will be required to improve the V&V process and establish an international standard that will bring fire models to the same level of reliability as those models approved by safety organizations such as the Food and Drug Administration. National and international safety and research organizations are encouraged to provide the necessary sponsorship of programs to improve fire models and ensure their reliable use in safety applications.

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