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

Deytec, Inc.

Nuclear Engineering Services

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1 Abstract

This report 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. A synthesis of ICFMP results has been conducted as a project of Deytec, Inc. to benefit public safety and the scientific community. 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 the 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 the heat flux to cable targets. The development of 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.

Table of Contents

2 List of Figures

3 List of Tables

4 Executive Summary

This report presents the technical and programmatic "lessons learned" in the International Collaborative Fire Model Project (ICFMP). 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 author led the ICFMP project from 1999 to 2006. A synthesis of the ICFMP results has been conducted as projects of Deytec, Inc. in 2009 and 2010 to benefit public safety and the scientific community. The result of the project in 2009 on the author's work in the ICFMP was published earlier. This report documents the work of the project in 2010 and presents the technical and programmatic "lessons learned" in the ICFMP.

The International Collaborative Fire Model Project was initiated in 1999 by the USNRC 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 were 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. The project was completed in 2008.

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 scenarios in current state-of-the-art fire models, and to develop their capabilities and limitations for modeling such scenarios;
2. To develop the predictive accuracy of the models (model error) for important parameters in nuclear plant fire safety analysis.

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 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, analysis, and ideas among participants regarding the physics of fire phenomena, and successes and challenges in modeling such phenomena.

The development of the V&V process provided experience in the conduct of *blind* exercises and the issues that provided a challenge. 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.

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 benchmark exercises 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.

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 more useful tool for fire safety analysis.

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.

Great efforts were expended to develop the specification of the benchmark exercises in sufficient detail to minimize the uncertainty in the input parameters required to conduct the *blind* calculations. However, significant issues regarding the input parameters arose in the benchmark exercises. The main three input parameters that were issues in the V&V process were: (1) heat release rate; (2) radiative fraction; and (3) thermal parameters of compartment boundary. It should be noted that there are many other parameters that require input data in the fire models. All the issues regarding input parameters that arose in the ICFMP are not discussed in this report but are included in the full ICFMP reports of the benchmark exercises. The main three issues identified in this report are discussed in more detail to illustrate the need for improvements in the V&V process, especially for measurements and agreement on the appropriate values for inputs to fire models.

The specifications of the benchmark exercises were developed and transmitted to participants to conduct *blind* exercises. The experimental results were then 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. Presently, there is no international or national standard that establishes a formal procedure for the submission and collection of *blind* calculations for fire model validations. In the end, the participants in the ICFMP were permitted to categorize their calculations as *blind* or *open*. There was significant debate on the appropriate values of the input parameters that should be used in the benchmark exercises. Some participants modified their fire model input data based on their determination of appropriate model input data and conducted calculations after the release of the experimental data, assuming these would still constitute a *blind* calculation. There was also some confusion on the definition of a "*blind*" calculation because other definitions of the term exist in the literature.

As a result, the "*blind*" and "*open*" calculations could not be distinguished. Calculations conducted by different participants with the same fire model were shown to result in quite varied model predictive errors, as much as 45 % difference in model error. Also, calculations conducted with fire models known to be at the same level of sophistication resulted in large differences in model error, as much as 40 % difference in model error. Therefore, it is concluded that the ICFMP benchmark exercises failed to be conducted as *blind* exercises.

Further research on key input parameters required for fire modeling, and an international standard is necessary to ensure the success of *blind* exercises to determine true model errors needed to establish safety margins. Significant "lessons" were learned in the ICFMP so that such a standard for *blind* exercises can be developed. The objectives of the international standard should be 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 for parameters that are needed as input to fire models;
3. establish the process for conducting and ensuring that *blind* calculations are used to establish predictive model errors and determining safety margins;
4. examine and include "third party validation" as an option for establishing true model errors;

The third party validation option could address many of the issues 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. Strict quality control requirements are recommended for the development and validation of fire models, especially given the rudimentary stages of their development and expanding application in fire safety engineering.

5 Acronyms and Initialisms

BE	Benchmark Exercise
CFAST	Consolidated Fire and Smoke Transport
CFD	Computational Fluid Dynamics
CO2	Carbon Dioxide
CO	Carbon Monoxide
cm	Centimeter
C_p	Specific Heat
d	Distance
FDS	Fire Dynamic Simulator
FDTs	Fire Dynamics Tools
ft	Feet
Hc	Heat of Combustion
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
in	Inch
J	Joule
K	Thermal Conductivity or Kelvin
kg	Kilogram
kW	Kilowatt
m	Meter
mm	Millimeter
m2	Square meter
m3	Cubic meter
NIST	National Institute of Standards and Technology
O2	Oxygen
PVC	Polyvinyl Chloride
Q^o	Heat Release Rate
RPM	Revolutions per minute
s	Second
T	Temperature
USNRC	U.S. Nuclear Regulatory Commission
V&V	Verification and Validation
VTT	Valtion Teknillinen Tutkimuskeskus
XPE	Thermoset
α	Thermal diffusivity
ε	Emmisivity
ρ	Density

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 as part of the International Collaborative Fire Model Project (ICFMP). The author led the ICFMP project from 1999 to 2006. The synthesis of the ICFMP results was conducted as projects of Deytec, Inc. in 2009 and 2010 to benefit public safety and the scientific community.

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 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 (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.

The analysis conducted by the author with 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) is summarized in Dey, 2000e. 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; Klein-Hessling, 2006; and Riese, 2006). A summary of the work done for Benchmark Exercises 1-5 is contained in the ICFMP Summary Report (Rowekamp, 2008). The report presented here is a synthesis of 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 technical and programmatic "lessons learned" in the ICFMP project.

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.

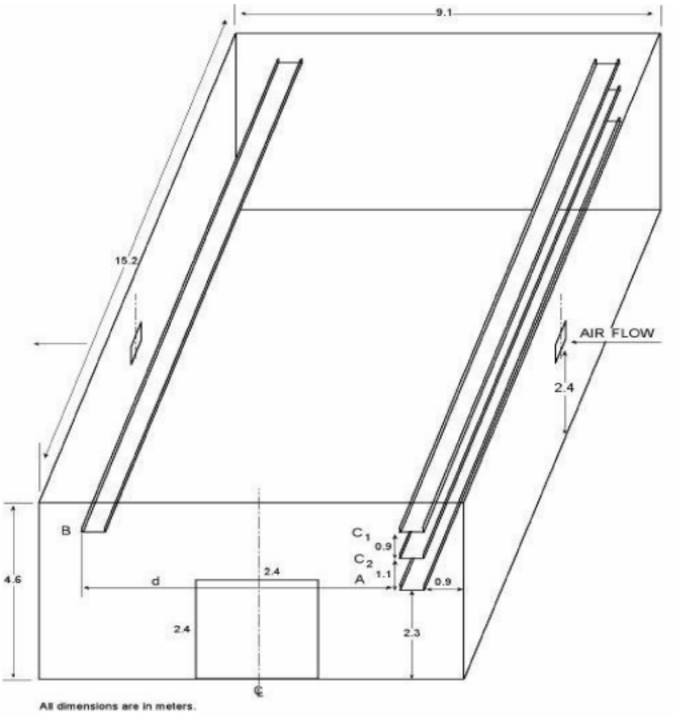

Figure 2-1 Simplified Schematic of Emergency Switchgear Room for BE No. 1

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

This benchmark exercise contained two parts. Part I was based on a series of full-scale experiments inside the VTT Test Hall in Finland, for which the sloping roof provided a challenge to zone models in particular. Each case involved a single pool fire, in the range 2 to 4 MW, for which there were experimental measurements of gas temperature at three thermocouple trees and above the fire source. For two cases the hall was nominally sealed, and 'infiltration ventilation' was incorporated by including small openings. For the third case mechanical exhaust ventilation was employed, and two doorway openings were provided.

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 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).

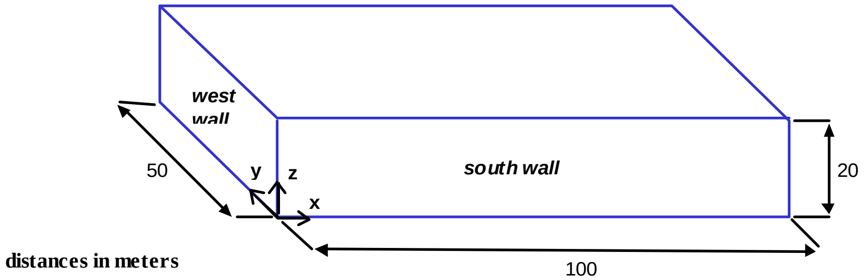

Figure 2-2 Building Geometry for BE No. 2, Part II – External Dimensions

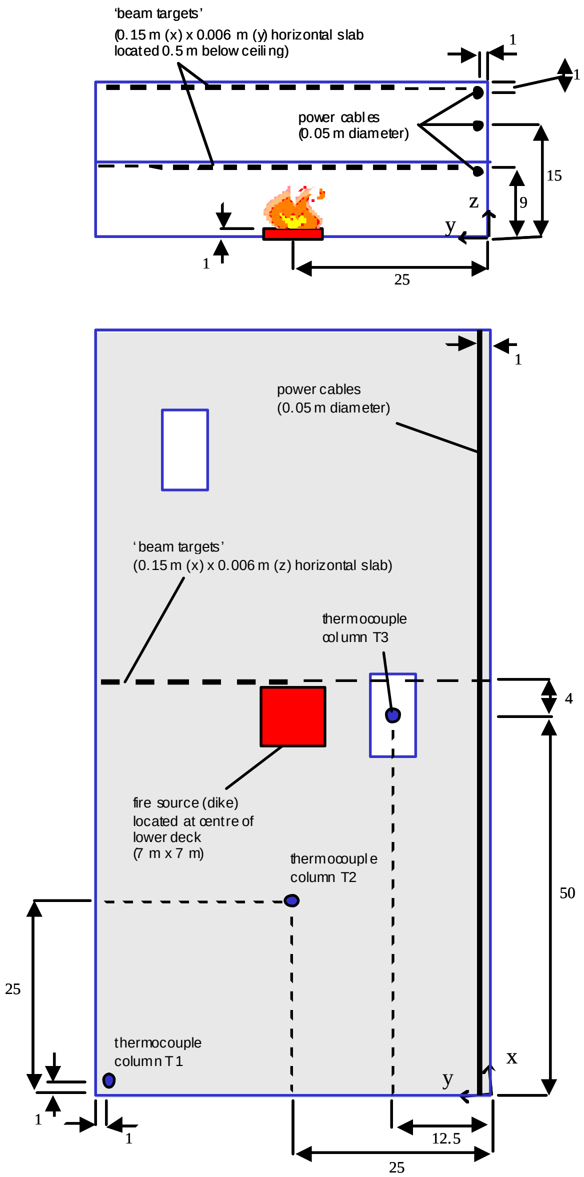

Figure 2-3 Location of Fire Source, Hatches and Targets for BE No. 2, Part II

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.

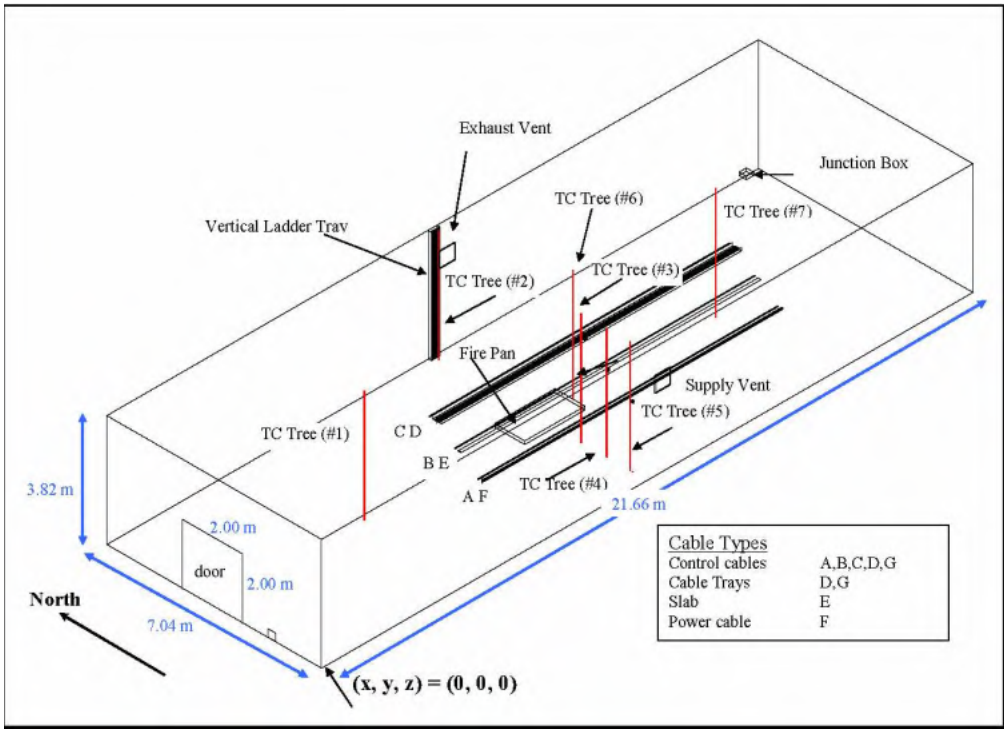

Figure 2-4 Schematic of Compartment for Benchmark Exercise No. 3

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 and experimental data from the tests are also available.

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.

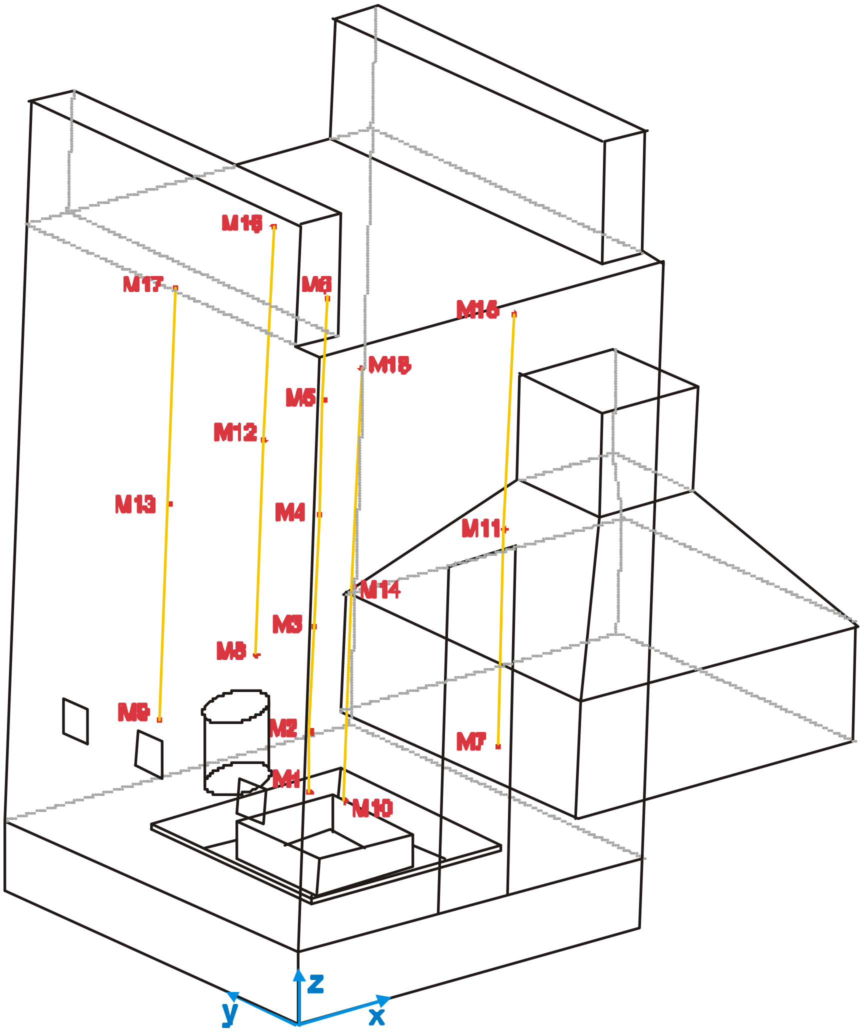

Figure 2-7 iBMB Oskar Compartment Used for Benchmark Exercise No. 4

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 1 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 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.

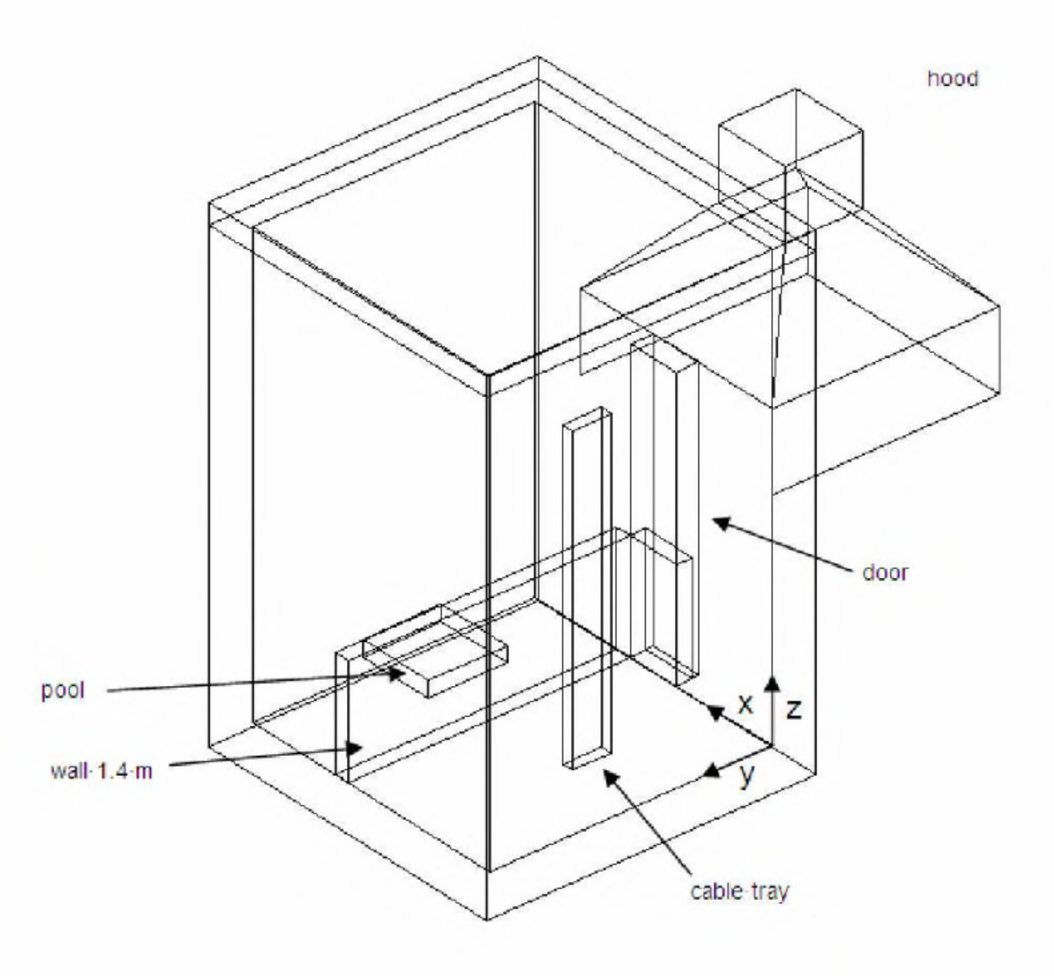

Figure 2-10 Schematic of Compartment for Benchmark Exercise No. 5

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. A pool 1 m² floor area filled with ethanol (ethylene alcohol) located in a trench is used as a pre-heating source. 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.

The full specification of the benchmark exercise can be found in Riese, 2006. Figure 2-11 is a picture of the pool fire used a pre-heating source.

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

3 Technical and Programmatic "Lessons Learned"

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 scenarios in current state-of-the-art fire models and to develop their capabilities and limitations for modeling such scenarios;
2. To develop the predictive accuracy of the models (model error) for important parameters in nuclear plant fire safety analysis.

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 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, analysis, and ideas among participants regarding the physics of fire phenomena, and successes and challenges in modeling such phenomena. The experience in the ICFMP formed the basis of a V&V process for the evaluation of fire models for nuclear plant applications. Valuable improvements needed for the V&V process were also identified.

The findings on capabilities and limitations of current fire models is presented first in the next section followed by a discussion on the "lessons learned" about the V&V process to determine the predictive accuracy of the models.

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 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 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 (Iqbal, 2004) are suitable for simple fire scenarios and parameters, they are severely limited for most fire scenarios in nuclear plants.

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 (McGrattan, 2009) 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; and
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 CFAST (Jones, 2009) 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. 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 fire models used in the multi-level benchmark exercise (No. 2). The variation in flow patterns through the hatches led to a 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 are best suited for exploratory calculations where a rough estimate is sufficient, while acknowledging the answers may contain large inaccuracies.

3.2 The V&V Process to Determine Model Errors

3.2.1 Introduction

In order to determine model errors that would be widely accepted, the ICFMP project was established by the parties to conduct *blind* 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 uncertainty in the input parameters required to conduct the *blind* calculations. The specifications developed for the benchmark exercises (Dey, 2002; Miles, 2004; Dey, 2009a; Klein-Hessling, 2006; and Riese, 2006) demonstrate the level of detail provided within them.

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 then could be used by the respective organizations for application.

3.2.2 *Blind vs. Open* Fire Model Predictions

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 (Rein, 2009). 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 (Jahn et al. 2007, Jahn et al. 2008 and Lazaro et al. 2008) 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 'real world' fire engineering applications most frequently simulate events for which real behavior had not been (and will never be) measured (Beard, 2008). 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 modeling 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. 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.

3.2.3 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, 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 for the fire scenario. The safety factor for fire protection systems design will be based on this optimal predictive capability of the model.

The V&V procedures also addressed the argument that commonly arise in *blind* V&V exercises that experiments cannot be replicated and therefore the fire experimental data has 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 (Dey, 2009a). See Figure 3-1 for an example measurement that shows that compartment conditions were almost duplicated in the replicate tests. Other comparisons of measurements in the replicate tests can be found in Dey, 2009a. 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.

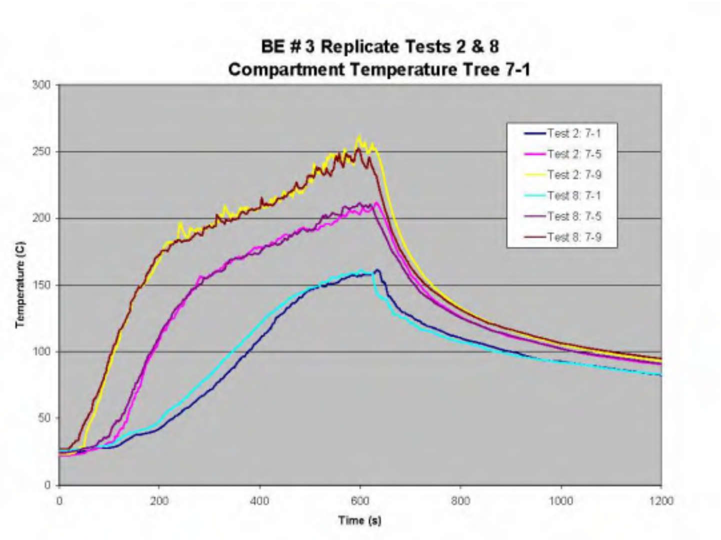

Figure 3-1 Measurement in Thermocouple Tree 7 in Replicate Tests 2 and 8

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, any minor changes to the test plan prior to the tests were communicated to ICFMP participants as addenda to the specification of the *blind* exercise.

3.2.4 Issues Identified in V&V Process

There were two categories of issues identified in the V&V exercise 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 issue regarding input data to the fire models is discussed first followed by the issue on the lack of a formal procedure for the submission and collection of *blind* calculations.

3.2.4.1 Parameters Issues

The main three input parameters that were issues in the V&V process were:

1. Heat Release Rate (HRR)
2. Radiative Fraction
3. Thermal Parameters of Compartment Boundary

These parameters have a big effect on compartment fires and parameters important for nuclear plant safety analysis. It should be noted that there are many other parameters that require input data in the fire models. All the issues regarding input parameters that arose in the ICFMP are not discussed here but are included in the full ICFMP reports (Dey, 2002; Miles, 2004; McGrattan, 2007; Klein-Hessling, 2006; and Riese, 2006) of the benchmark exercises. The three issues identified above are discussed in more detail here to illustrate the need for improvements in the V&V process.

3.2.4.1.1 Heat Release Rate

The measurement of the heat release rate was a major challenge and source of uncertainty in the validation process in the ICFMP. As indicated earlier, the current state of knowledge of the science of combustion and the fire phenomena does not allow modeling of combustion and the heat released. Research is continuing to improve our knowledge of combustion and heats released, but this research is still at the basic stages. Therefore, the heat released in experiments must be measured and then input to the fire models being validated. The fire models are then only validated for the prediction of the effects of a fire based on a heat release rate input to the model. Obviously, the heat release rate predominantly determines the magnitude of the fire effects.

The measurement of the heat release rate was a major challenge for Benchmark Exercises Nos. 3, 4, and 5. The challenges incurred for measuring the heat release rate for Benchmark Exercise no. 2, Part I is unknown because data from the tests conducted by VTT were provided without any discussion of uncertainties in the measurements.

Benchmark Exercise No. 3

The measurement for the heat release rate for Benchmark Exercise No. 3 was a significant challenge that resulted in the inability to conduct a blind benchmark exercise and derive true model errors.

The following is the sequence of events during the analysis of the heat release rate (HRR) data for Benchmark Exercise No. 3 which illustrates the significant difficulties faced by the experimentalists for this measurement.

The tests for Benchmark Exercise No. 3 were completed on June 5, 2003. The heat release rates for tests with open door and/or with mechanical ventilation were measured by two independent methods, measurement of the fuel flow and calorimetry. The fuel system was designed to deliver a controlled amount of liquid fuel in the form of a spray in all tests. The transient fuel flow rate was controlled during the tests by adjusting the speed (rpm) of the pump. The fuel flow was ramped up in a linear manner from zero to a longer steady burning period to establish nominal steady heat release rates during the 15 tests of the international benchmark exercise. After the steady burning period at the designed heat release rate, the fuel flow was ramped-down to zero in a linear manner over a period of 3 min. The fuel used for the tests was a commercially available blend of heptanes for most tests, and toluene for one test with nominal heat release rates ranging from 350 kW to 2 MW. The nominal fuel flow designed for each test was achieved by adjusting the speed of the fuel pump to result in the designed heat release rate. The desired pump speed for each test was determined <u>prior to each test</u> by measuring the fuel flow by means of volume output per a given time period. A fuel flow meter was not made available for measurement during the tests. A detailed description of the fuel system and the fuel flow rates during the tests is given in Hamins et al., 2003a.

The heat release rate (HRR) was also determined using oxygen consumption calorimetry by monitoring the flow of hot gases through the door during the open-door tests and vents for those with mechanical ventilation in the newly commissioned 9 m x 12 m hood at NIST. Bryant et al., 2004 describe the heat release measurement facility, instrumentation, and procedures in detail. Figure 3-2 shows typical calorimetric measurements of the HRR. Test 3 was open door, and Test 4 was closed door with mechanical ventilation and was under ventilated.

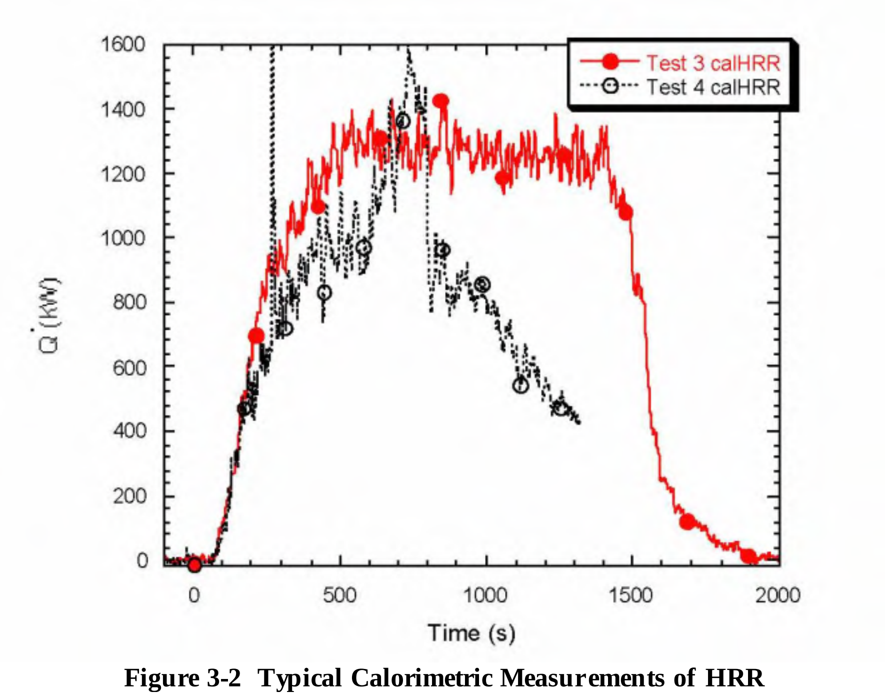

Figure 3-2 Typical Calorimetric Measurements of HRR

After the tests were completed, the experimentalists (at NIST) discovered a consistent discrepancy in the measured HRR though calorimetry and fuel flow. The HRR measured through calorimetry was much higher than that through fuel flow measurements. On July 2, 2003, NIST released a portion of the experimental results for Benchmark Exercise No.

3 to the International Collaborative Fire Model Project (ICFMP) (Hamins et al, 2003b). The HRR data from the fuel flow measurements, and calorimetry were reported to be 1050 ± 160 (15 %) kW, and 1150 ± 230 (20 %) kW respectively for Test 3[1]. The experimentalists reported that the estimated HRR from both measurements overlapped, thus perhaps justifying the discrepancy. Fire model analysts in the ICFMP that had made blind predictions of the tests results were left to determine how to use these results in their analyses and conclusions on the predictive capabilities of their models. ICFMP participants began to scrutinize the HRR measurements as they had become critical to the value of the benchmark exercise.

On July 21, 2003, NIST released a more expanded version of the experimental results for Benchmark Exercise No. 3 Hamins, 2003c. In this report, NIST revised the HRR data concluding that measured values through calorimetry were higher than reported in their earlier release on July 2, 2003. They reported that the HRR for Test 3 from calorimetry was 1260 kW ± 252 (20 %) kW which was much higher than the experimentalists had previously deduced. NIST indicated that the HRR data measured through calorimetry reported earlier was incorrect due to difficulties encountered in the measurement of this important parameter for the benchmark exercise.

A simple crude test was conducted to determine if perhaps the fuel flow measurements taken before the tests were incorrect. The fuel flow was measured before the tests and perhaps this flow changed during the tests. On September 9, 2003, NIST released a fuel flow correction factor of 1.09 and revised the HRR data for the tests. The HRR for Test 3 measured through fuel flow was reported as 1150 ± 172 (15 %) kW (NIST, 2003). Fire model analysts using the experimental data and HRR values were already faced with the discrepancy between the HRR measured through calorimetry and through fuel flow, and now were faced with greater uncertainty in the measured HRR values. It was evident at this stage that firm conclusions on true model errors through a blind exercise would unfortunately not be possible for this benchmark exercise. Several ICFMP participants disputed the correction factors established by NIST citing the test conducted was crude and the data derived from the tests did not justify a correction factor for the fuel flow. At this point, ICFMP participants utilized the HRR values for the benchmark exercise that they determined to be correct and justified based on their respective analyses.

On April 4, 2004, NIST released an expanded version of their experimental report for Benchmark Exercise No. 3 (Hamins, 2004). In the document, NIST reported HRR data for Test 3 through fuel flow (with correction factor) as 1150 kW ± 172 (15 %) kW, and 1260 kW ± 252 (20 %) kW through calorimetry. Experimentalists did not claim they had deduced the “true” value at this stage but that it was of interest to compare the HRR values derived through measurement of fuel flow and calorimetry. They indicated to the project participants that the results of the two measurements were not significantly different. Analysts were encouraged to conduct sensitivity analysis using the two sets of HRR data from fuel flow and calorimetry.

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[1] The heat release rate measured for Test 3 is used as an example to illustrate the challenges faced regarding this parameter in Benchmark Exercise No. 3. The same challenges were encountered for the heat release rates for all the tests in Benchmark Exercise No. 3.

A year later, in the final experimental report for Benchmark Exercise No. 3 (Hamins, 2005), NIST experimentalists again corrected the HRR measurements obtained through calorimetry down to 1190 kW based on stated further discovery of calibration issues of the calorimeter.

The above chronology of events (summarized in Table 3-1) indicates the significant difficulty and controversy in measuring and reporting the HRR for the tests conducted for Benchmark Exercise No. 3. Blind predictions of fire effects with models for this benchmark exercise were not possible due to these difficulties in the measurement of the main parameter that is input to the fire models. ICFMP participants utilized the HRR values for the benchmark exercise that they determined to be correct and justified based on their respective analyses.

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

Release Date	July 2, 2003**	July 21, 2003	September 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

Benchmark Exercise No. 4

In Benchmark Exercise No. 4, the pyrolysis rate and heat release rate was determined through measurement of the weight loss of the fuel during the experiments. As indicated in Chapter 2, the fuel was located in the center of the floor area in a steel pan. The steel pan was installed on a weight scale. In Test 1 of the Benchmark Exercise No. 4, the measurements of the weight loss show a continuous decrease but at about the midpoint of the test the measurement became defective. The experimentalists recommended that the weight loss should be assumed to have decreased at the same rate during the second half of the transient. The HRR data was valuable until this point but questions arose regarding how the transient would have progressed had the measurement been successful.

In Test 3 of Benchmark Exercise No. 4, the measurement of the weight loss showed a constant decrease rate in the initial phase. However, during the last third of the test the fire transitioned from a fuel controlled state to one that was controlled by ventilation due to the increased pyrolysis rate and complete consumption of the oxygen available. The HRR measured during the test increased rapidly to 1500 kW in ~ 50 s, and then increased more gradually reaching 2700 kW at 850 s. The HRR then increased rapidly from this point to 6000 kW at ~ 1050 s before being extinguished. In this phase of the test some erratic weight loss measurements occurred with deviations of more than 80 kg. The reason for the erratic measurements was not resolved by the experimentalists. The peak heat release rate thus had significant errors.

The difficulties faced by the experimentalists in Benchmark Exercise No. 4 did not completely invalidate the blind predictions and exercise, but it did result in some debate and uncertainty among the ICFMP participants, particularly for the peak HRR achieved in Test 3 which drove many of the peaks of the measured parameters of the fire effects, e.g. hot gas temperature and heat flux.

Benchmark Exercise No. 5

Benchmark Exercise No. 5 involved a number of complex experiments to investigate flame ignition and spread. The heat release rate of a pool fire used to heat the compartment prior to the cable experiments was measured in a similar manner to the experiments for Benchmark Exercise No. 4. The measurements of the HRR from the pool were successful but the values released to the ICFMP participants for conducting blind predictions had an error in them (about 20 %). Although this simple error was subsequently corrected and not one that resulted from a difficulty faced with this measurement, it did invalidate the blind nature of this portion of the exercise.

3.2.4.1.2 Radiative Fraction

As indicated earlier, the current state of knowledge of the science of combustion and the fire phenomena does not allow modeling of combustion and the heat released. Research is continuing to improve our knowledge of combustion and heats released, but this research is still at the basic stages. Therefore, the combustion properties of the test fuels, including the heat released in experiments, must be measured and then input to the fire models being validated. The fire models are then only validated for the prediction of the effects of a fire based on a heat release rate input to the model. The heat released in the combustion process is emitted as a convective component in the fire plume, but also radiated from the fire plume. The radiative fraction of the heat emitted from the fire plume must also be input to the fire models. This parameter is critical to the calculation of the effects of fire in terms of temperature of the hot gas in the compartment and also the radiative heating of targets like cables in nuclear power plants. There was considerable debate in the ICFMP as to the appropriate values of the radiative fraction that should be used in the benchmark exercises.

Benchmark Exercise No. 2

Some ICFMP participants predicted higher smoke layer temperatures than those measured when using the original benchmark specification in Benchmark Exercise No. 2, Part I. Two principle mechanisms were identified by some participants, to which modifications were able to reduce the temperature of the smoke layer. The first of these was the proportion of heat attributed to the convective power of the fire plume, the value being dependent on the choice of heat of combustion, combustion efficiency and radiative fraction. The second was the boundary heat loss which is discussed later.

The varying of the radiative fraction has a large impact on the prediction of fire effects, e.g. the smoke layer temperature. The benchmark specification recommended a value of 0.2 for the radiative fraction. Since this was not a measured value for the specific configuration of the benchmark exercise, some ICFMP participants argued that values for the radiative fraction as high as 0.4 to be more appropriate. The choice of the radiative fraction had a significant effect on calculated parameters. The uncertainty in the correct values of radiative fraction negated the value of Benchmark Exercise No. 2, Part I as a blind exercise.

Benchmark Exercise No. 3

As discussed above, Benchmark Exercise No. 2 identified the radiative fraction and other combustion properties to have a significant effect on the calculation of parameters indicative of the effects of the fire. Therefore, considerable effort and resources were expended in Benchmark Exercise No. 3 to measure the parameters for the specific configuration of the benchmark exercise.

Table 3-2 below lists the results of the measurements of the combustion properties of the test fuels that were included in the specification of the benchmark exercise. The Table includes the combustion efficiency, radiative fraction, and the yields of soot, CO, and CO2, which were determined through a series of measurements using the same spray burner and hardware that were used in the experiments for Benchmark Exercise No. 3. It was noted that the radiative fraction in the Table is representative of several studies reported in the literature for pool fires. In addition, test results on the heat of combustion (H_c) for the fuels are included in the Table and in the specification of the benchmark exercise.

Table 3-2 Combustion Properties of the Test Fuels for Benchmark Exercise No. 3

Fuel	Hc (kJ/g)[1]	Combustion efficiency[2]	Radiative fraction[3]	Soot yield[2]	CO yield[2]	CO_2 yield[2]
Heptanes	45.0	1.0 ± 0.06	0.35 ± 0.08	0.0149 ± .0033	<0.006	3.03 ± 0.37
Toluene	40.3	0.76 ± 0.05	0.36 ± 0.08	0.194 ± 0.062	0.070 ± 0.016	2.53 ± 0.31

1. Report of Test Results, Galbraith Labs, March 2003. The expanded uncertainty is not reported but is typically 5 %.
2. The Global Combustion Behavior of 1 MW to 3 MW Hydrocarbon Spray Fires Burning in an Open Environment (Hamins, 2003d).
3. Hamins, Kashiwagi and Buch in Fire Resistance of Industrial Fluids (Eds.: Totten and Reichel), ASTM STP 1284, 1996

Even though considerable effort and resources were expended to measure the above combustion properties of the test fuels in the specific configuration for the Benchmark Exercise, there was still debate about the correctness of the values. Some ICFMP participants argued that lower values (0.2) of the radiative fraction were more appropriate and used those values in their calculations.

Benchmark Exercise Nos. 4 and 5

The specification of the radiation fraction for Benchmark Exercise No. 4 was left up to the user. Values from 20 % to 40% were used by ICFMP participants in the benchmark exercise. The radiative fraction for Benchmark Exercise No. 5 was specified as 0.2 even though the authors of the exercise indicated that Tewarson (Tewarson, 2003) cites a value of 0.15 for ethanol. No reason was given for the higher value chosen for Benchmark Exercise No. 5. Again values from 15 % to 45 % were used by ICFMP participants in the benchmark exercise as there was no certainty on the correct values for the test fuels.

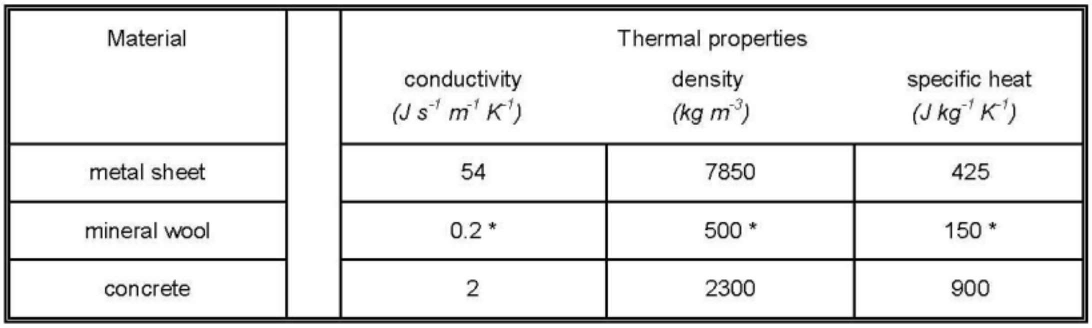
3.2.4.1.3 Thermal Properties of Compartment Boundary

Benchmark Exercise No. 2

As indicated above, some ICFMP participants predicted higher smoke layer temperatures than those measured when using the original benchmark specification in Benchmark Exercise No. 2, Part I. Two principle mechanisms were identified by some participants, to which modifications were able to reduce the temperature of the smoke layer. The first of these was the proportion of heat attributed to the convective power of the fire plume, the value being dependent on the choice of heat of combustion, combustion efficiency and radiative fraction. The uncertainty in the radiative fraction was discussed above.

The second mechanism was the boundary heat loss. Some ICFMP participants justified increasing the boundary heat losses by arguing that there was probable error in the thermal properties specified (see Table 3-3) for mineral wool, where more "realistic" values reduce the thermal inertia by about 50%. There was no consensus on the appropriate material properties that should be used for benchmark exercise which negated the value of the benchmark exercise as a blind exercise.

Table 3-3 Material Properties for Benchmark Exercise No. 2, Part I



Material		Thermal properties		
		conductivity ($J\ s^{-1}\ m^{-1}\ K^{-1}$)	density ($kg\ m^{-3}$)	specific heat ($J\ kg^{-1}\ K^{-1}$)
metal sheet		54	7850	425
mineral wool		0.2 *	500 *	150 *
concrete		2	2300	900

Benchmark Exercise No. 3

As discussed above, Benchmark Exercise No. 2 identified the material thermal properties of the boundary to have a significant effect on the calculation of parameters indicative of the effects of the fire, e.g. temperature of the hot gas and cable targets. Therefore, considerable effort and resources were expended in Benchmark Exercise No. 3 to measure the material thermal properties. All the material properties that were relevant in the benchmark exercise and measured are discussed below to illustrate the extent of the effort made to conduct a blind exercise, although only the properties of the compartment boundary (marinite and gypsum) were controversial.

The Structure and Properties of Cables

Thermal property information including the specific heat (c_p), the thermal diffusivity (α), the thermal conductivity (K) of the PVC and XLP cable insulation were determined using ASTM E1269 and ASTM E1461. The cable types used in the benchmark exercise is listed in Table 3-4. Table 3-5 lists the material properties and also includes the spectrally integrated value of the emissivity (ε). This was accomplished by normalizing the measurement of the spectrally dependent reflectivity (from 1.5 μm to 19 μm) using the spectral distribution from a fire assumed to behave like a blackbody source at 1200 K. This range of the spectrum considered (1.5 μm to 19 μm) covers a major fraction (~95 %) of the intensity of a 1200 K blackbody. The XLP cable insulation is the same type for Cables #1 and #3 in Table 3-4, and therefore the properties of Cable #1 apply to Cable #3. The PVC cable insulation is the same type for Cables #2 and #4 in Table 3-4, and therefore the properties of Cable #4 apply to Cable #2.

Table 3-4 Cable Types

#	Conductors	AWG	Insulator	Jacket	Ground	Nominal O.D. (cm)
1	7	14	XLP ^{A}	Hypalon ^{B}	N	1
2	7	14	PVC/Nylon	PVC	N	1.3± 0.1
3	3	6	XLP	Hypalon	Y	1.9± 0.1
4	3	6	PVC/Nylon	PVC	Y	1.6 ± 0.1

^{A} flame retarded crosslinked polyethylene
^{B} Hypalon is a registered DuPont trademark for chlorosulfinated polyethylene (CSPE)

Table 3-5 Material and Optical Properties of the Cable Materials

Properties of the PVC from Cable # 4 in Table 3-4				
T (^{o}C)	K (W/m K) *	α (m^2/s) *	c_p(J/kg K) *	ε **
23	0.192	1.08×10^{-7}	1289	0.95±0.01
50	0.175	9.4×10^{-8}	1353	-
75	0.172	8.9×10^{-8}	1407	-
100	0.147	7.3×10^{-8}	1469	-
125	0.141	6.7×10^{-8}	1530	-
150	0.134	6.2×10^{-8}	1586	-
Properties of the XLP from Cable # 3 in Table 3-4				
T (^{o}C)	K (W/m K) *	α (m^2/s) *	c_p(J/kg K) *	ε **

23	0.235	1.23×10^{-7}	1390	0.95±0.01
50	0.232	1.14×10^{-7}	1476	-
75	0.223	1.06×10^{-7}	1526	-
100	0.210	9.8×10^{-8}	1560	-
125	0.190	8.7×10^{-8}	1585	-
150	0.192	8.7×10^{-8}	1607	-

* Taylor, R.E., Groot, H., and Ferrier, J., *Thermophysical Properties of PVC, PE and Marinite*, Report TPRL 2958, April 2003.
** Hanssen, L., Report of Optical Test Data, March 2003.

Properties of Gypsum, Marinite, Feraloy, and the Plastic Slab

Table 3-6 lists the measured properties of the marinite used for the walls and ceiling of the compartment. Feraloy is a proprietary manufactured product that is a gray-iron alloy. Its properties are approximated as iron in Table 3-7. The PVC slab was made of PVC insulation from Cable # 4; therefore its properties are the same as Cable # 4 and are found in Table 3-5.

Table 3-6 Material and Optical Properties of Marinite.

T (^{o}C)	K (W/m K) *	α (m^2/s) *	c_p(J/kg K) *	ε **
23	0.111	2.13×10^{-7}	778	0.74±0.04
50	0.114	2.15×10^{-7}	795	
100	0.126	2.17×10^{-7}	871	
200	0.140	2.17×10^{-7}	965	
300	0.153	2.18×10^{-7}	1047	
400	0.160	2.21×10^{-7}	1082	
500	0.175	2.26×10^{-7}	1160	
600	0.190	2.36×10^{-7}	1205	
650	0.198	2.42×10^{-7}	1223	

* Taylor, R.E., Groot, H., and Ferrier, J., *Thermophysical Properties of PVC, PE and Marinite*, Report TPRL 2958, April 2003.
** Hanssen, L., Report of Optical Test Data, March 2003.

Table 3-7 Material and Optical Properties of Feraloy and Gypsum.

Material	K (W/m K)	ρ (kg/m^3)	c_p (J/kg K)	ε
Feraloy*	78.2**	787**	456**	-
Gypsum	0.16 $^+$	790 $^+$	900 $^+$	0.9 $^+$

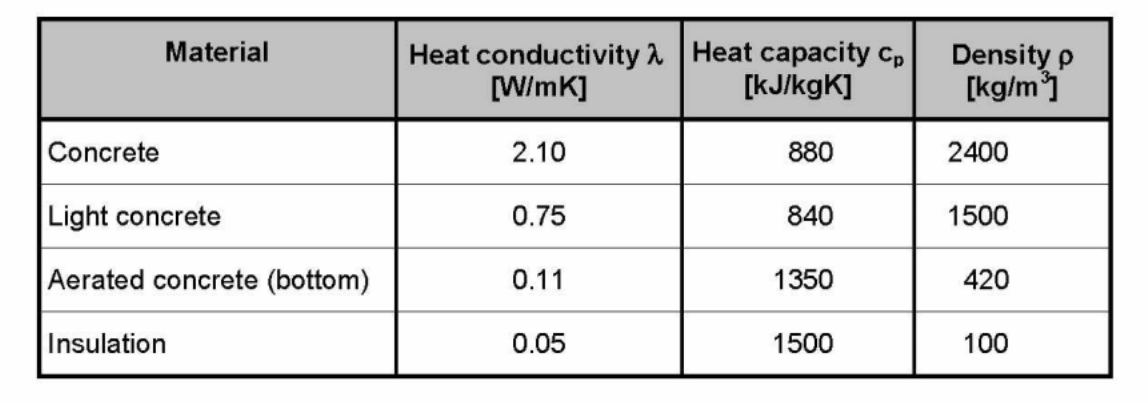
* assumed to have properties similar to iron.
** Smithells Metals Reference Book. 7th Ed., Ed.: E.A. Brandes and G.B. Brook.
\+ from the CFAST database (`http://fast.nist.gov/`)

The above indicates the extensive efforts undertaken in benchmark Exercise No. 3 to measure the material properties relevant in the benchmark exercise, especially the compartment boundary. However, there was still debate on the validity of these measurements and values. Some ICFMP participants disputed the measured values and instead adopted thermal properties from Handbooks.

Benchmark Exercise Nos. 4 and 5

The properties of the compartment materials specified for Benchmark Exercise Nos. 4 and 5 taken from handbooks are shown below in Table 3-8.

Table 3-8 Material Properties for Benchmark Exercises Nos. 4 and 5



Material	Heat conductivity λ [W/mK]	Heat capacity c_p [kJ/kgK]	Density ρ [kg/m^3]
Concrete	2.10	880	2400
Light concrete	0.75	840	1500
Aerated concrete (bottom)	0.11	1350	420
Insulation	0.05	1500	100

Some participants in the ICFMP argued that other values for the compartment thermal properties from other sources were more appropriate than those provided in the specifications of the benchmark exercises. The thermal properties were varied as much as 35 % below and above than those specified.

3.2.4.2 Procedure Issues

As indicated earlier, in order to determine model errors that would be widely accepted, the ICFMP project was established by the parties to conduct *blind* 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 uncertainty in the input parameters required to conduct the *blind* calculations.

The specifications of the benchmark exercises, including addenda if appropriate, were developed and transmitted to participants to conduct *blind* exercises. The experimental results were then 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. Presently, there is no international or national standard that establishes a formal procedure for the submission and collection of *blind* calculations for fire model validations. In the end, the participants in the ICFMP were permitted to categorize their calculations as *blind* or *open*. As discussed above, there was significant debate on the appropriate values of the input parameters that should be used in the benchmark exercises. Some participants modified their fire model input data based on their determination of the appropriate values and conducted calculations after the release of the experimental data, assuming these would still constitute a *blind* calculation. There was also some confusion on the definition of "*blind*" calculation because the term as defined in the ICFMP is not the same as defined in ASTM 1355 (ASTM, 2005).

As a result, the *"blind"* and *"open"* calculations could not be distinguished. Calculations conducted by different participants with the same fire model were shown to result in quite varied predictive model errors, as much as 45 % difference in model error. Also, calculations conducted with fire models known to be at the same level of sophistication resulted in large differences in model error, as much as 40 % difference in model error.

3.2.5 Conclusion

It is concluded that the ICFMP benchmark exercises failed to be conducted as *blind* exercises for the reasons discussed in the previous sections. It is also concluded that further research on key input parameters required for fire modeling is needed and an international standard is necessary to ensure the success of *blind* exercises to determine true model errors. Significant "lessons" were learned in the ICFMP so that such a standard for *blind* exercises can be developed.

4 Conclusions and Recommendations

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 scenarios in nuclear power plants. The benchmark exercises were specified in sufficient detail to allow the evaluation of the physics modeled in the fire computer codes. 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, analysis, and ideas among participants regarding the physics of fire phenomena, and successes and challenges in modeling such phenomena.

The development of the V&V process provided experience in the conduct of *blind* exercises and the issues that provided a challenge. 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.

Capabilities and Limitations

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 fire safety analysis proved much more difficult. The benchmark exercises 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.

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 more useful tool for fire safety engineering.

V&V Process

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

3. Lack of agreement among participants on the measurements and data needed as input to the fire models being exercised;
4. 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; (2) radiative fraction; and (3) thermal parameters of compartment boundary. It should be noted that there are many other parameters that require input data in the fire models. All the issues regarding input parameters that arose in the ICFMP are not discussed in this report but are included in the full ICFMP reports of the benchmark exercises. The three issues identified in this report are discussed in more detail to illustrate the need for improvements in the V&V process, especially for measurements and agreement on the appropriate values for inputs to fire models.

The "*blind*" and "*open*" calculations conducted in the ICFMP could not be distinguished due to procedural difficulties and disagreements on the correct values for model input data. Calculations conducted by different participants with the same fire model were shown to result in quite varied model errors, and calculations conducted with fire models known to be at the same level of sophistication also resulted in large differences in model error. Therefore, it is concluded that the ICFMP benchmark exercises failed to be conducted as *blind* exercises.

Further research on key input parameters for fire modeling is needed and an international standard should be established to ensure the success of *blind* exercises for determining true model errors. Significant "lessons" were learned in the ICFMP so that such a standard for *blind* exercises can be developed. The objectives of the international standard should be 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 for parameters that are needed as input to fire models;
3. establish the process for conducting and ensuring that *blind* calculations are used to establish predictive model errors and safety margins; and
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. Strict quality control requirements are recommended for the development and validation of fire models, especially given the rudimentary stages of their development and expanding application in fire safety engineering.

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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