Verifying and Validating Current Fire Models for Use in Nuclear Power Plant Applications[1]

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ABSTRACT

Both domestically and worldwide, risk-informed and performance-based analyses are being introduced into fire protection engineering practice. The commercial nuclear power industry is no exception. Reliance on fire modeling will play a key role in this transition. This paper describes the work performed to assess the relative accuracy of fire models for nuclear power plant (NPP) applications. The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research performed this project along with the Electric Power Research Institute (EPRI), the National Institute of Standards and Technology, and Electricité de France. The team conducted an extensive verification and validation study of fire models that support the use of National Fire Protection Association 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," as a risk-informed/performance-based alternative within the NRC's regulatory system. The report follows the guidance of American Society for Testing and Materials E 1355, International "Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models." The team evaluated five different fire models ranging from simple hand calculations to zone models up through a computational fluid dynamics model. The team then validated the models using 13 parameters from a common baseline of 26 experiments. The experiments selected for this study are applicable to the NPP environment and include a study on experimental uncertainty. The seven-volume report "Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications" (NUREG-1824; EPRI 1011999) documents the results of this project. The report is available to the public on the NRC's Web site.

INTRODUCTION

In the spring 2007 edition of the Society of Fire Protection Engineers magazine, *Fire Protection Engineering*, this team presented a brief overview of its multiyear fire modeling verification and validation (V&V) research program [1]. This paper will build on that overview and provide a more indepth discussion of key elements of the fire modeling V&V program.

Fire Modeling in Nuclear Power Plant Regulation

Both domestically and worldwide, risk-informed and performance-based analyses are being introduced into fire protection engineering practice. The commercial nuclear power industry is no exception. In the last 15 years, the U.S. Nuclear Regulatory Commission (NRC) directed a change in its policy to use risk-informed methods, where practical, to make regulatory decisions. As a result of this change, in the area of fire protection, the National Fire Protection

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[1] This paper was prepared in part by employees of the U.S. NRC. The views presented do not represent an official staff position. The NRC has neither approved nor disproved the paper's technical content.

Association (NFPA) issued the 2001 edition of NFPA 805, "Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants" [2]. The NRC amended its fire protection requirements in July 2004 to allow existing reactor licensees to voluntarily adopt the fire protection requirements contained in NFPA 805 as an alternative to the existing prescriptive fire protection requirements [3]. This allows plant operators and the NRC to use fire modeling and fire risk information, along with prescriptive requirements, to ensure that nuclear power plants (NPPs) can safely shut down in the event of a fire.

The concept of fire modeling is not new to the U.S. nuclear power industry. Many of the first NPPs designed in the 1960s and 1970s used then state-of-the-art "fire load" calculations to determine the required fire resistance of compartments needed to form fire areas [4]. After the 1975 Browns Ferry fire, the use of fire modeling to predict fire damage and ensure reactor safety was debated. In 1980, the NRC stated that it was "not possible to predict the specific conditions under which fires may occur and propagate the design basis protective features are specified rather than the design basis fire" [5]. As the science of fire modeling and probabilistic risk assessment (PRA) matured, the agency reintroduced the concept to the nuclear industry in the form of Supplement 4, "Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities," to Generic Letter 88-20 [6]. A part of this generic letter requested that licensees examine their NPPs to determine whether plant-specific internal fires could present vulnerabilities to severe accidents that could be fixed with low-cost plant modifications. Investigators selected fire models and PRAs as the tools of choice for performing these evaluations. Today, the NRC and the plant operators routinely use fire models in PRA calculations to identify fire scenarios with safety risks. They also use these tools to determine compliance with, or exemptions from, existing prescriptive fire protection regulatory requirements. As the commercial nuclear power industry moves toward a risk-informed, performance-based regulatory environment, the regulator and the plant operators need a high degree of confidence in the calculation results. NFPA 805 specifically requires fire models to be *verified* and *validated*. To this end, the NRC's Office of Nuclear Regulatory Research, along with the Electric Power Research Institute (EPRI) and the National Institute of Standards and Technology (NIST), has conducted an extensive V&V study of fire models that support the use of NFPA 805 as a risk-informed/performance-based alternative within the NRC's regulatory system.

At the start of a major project such as this, the study team must first decide which fire models to evaluate. From many meetings and discussions with all interested stakeholders, it became apparent that the best approach was not to evaluate a single fire model but rather to evaluate a suite of models that the industry and the regulator would use. The study team selected two simple hand calculation methods (NRC Fire Dynamics Tools (FDT^S) and EPRI Fire-Induced Vulnerability Evaluation, Revision 1 (FIVE-Rev1)), two zone models (NIST Consolidated Fire and Smoke Transport (CFAST v. 6.0.10) and Electricité de France MAGIC (v. 4.1.1b)), and one computational fluid dynamics (CFD) model (NIST Fire Dynamics Simulator (FDS v. 4.06)). This approach allows the users maximum flexibility to choose the most appropriate fire model to evaluate their specific fire scenario.

THE V&V PROCESS

Given the complexity and range of features in current fire models, it is impractical to evaluate the accuracy of every model output. Thus, the NRC and EPRI identified fire phenomena and hazards that are directly relevant to NPPs, such as the integrity of electrical cables and fire barriers, the effectiveness of smoke removal systems, and the movement of smoke and hot gases from compartment to compartment. In all, the NRC and EPRI chose 13 predicted quantities, including the depth and average temperature of the hot upper layer, ceiling jet and plume temperatures, the radiant and total heat flux onto walls and "targets," and the major gas species and smoke concentrations.

The study does not cover the entire spectrum of possible fire scenarios, either in NPPs or in other types of structures. To clarify its range of applicability, the study examined a variety of non-dimensional and normalized parameters that bound the spectrum of scenarios it does cover and recommends that users of the report be aware that scenarios falling outside of these bounds have not been rigorously validated. The final report discusses the limits of applicability of the study results.

In addition, the validation study uses the heat release rate of the experimental fires as an input rather than a predicted output. The study assesses the accuracy of current fire models in predicting the transport of a fire's heat and combustion products throughout a compartment. While some of the models evaluated do have the physical mechanisms to predict fire growth and spread (for example, the CFD model FDS), this study does not include an assessment of those functions. From the standpoint of NPP safety, it is important to assess the accuracy of the models in predicting the transport of energy from a specified fire, because that is how the nuclear industry currently uses these models. A major finding of this study is that the current generations of fire models predict transport fairly well.

This V&V study began in earnest in 2003, resulting in the seven-volume report "Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications" [4,7]. The report is available to the public on the NRC's Web site[2]. Five of the seven volumes contain individual evaluations of five fire models—(1) the NRC's FDT^{S}, (2) the EPRI FIVE-Rev1, (3) the NIST zone model CFAST v. 6.0.10, (4) the Electricité de France zone model MAGIC v. 4.1.1b, and (5) the NIST CFD model FDS v. 4.06.

Experimental Uncertainty as a Metric for Evaluating Fire Models

NUREG-1824 is based on American Society for Testing and Materials (ASTM) E 1355, "Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models" [8]. The guide describes four steps in the evaluation process for a given model. These are (1) definition of the model and scenarios, (2) assessment of the appropriateness of the model's theoretical basis and assumptions, (3) assessment of the model's mathematical and numerical robustness, and (4) quantification of the uncertainty and accuracy of the model results in predicting events in similar fire scenarios.

This study focuses on the last step, model *validation*. Validation entails comparing model predictions with full-scale fire experiments and quantifying the results. ASTM E 1355 provides some guidance for identifying and selecting experiments and measurements, but it does not define explicitly how to quantify the results. A useful means to evaluate quantitatively the hundreds of point-to-point comparisons of predictions and measurements emerged from the consideration of uncertainty in the experimental measurements. In selecting experiments for the model evaluations, the study team emphasized well-documented uncertainties in both the measurement of the 13 parameters of interest and the measurement of model inputs, such as material properties and the heat release rate of the fire. The combination of the experimental uncertainty associated with both the model input parameters and the measured model outputs served as a yardstick for evaluation of the models.

As an example of the process to determine experimental uncertainty, suppose that the uncertainty in the measurement of the heat release rate of a fire was determined to be about 15 percent. According to the well-known McCaffrey, Quintiere, Harkleroad correlation, the upper-layer gas temperature rise in a compartment fire is proportional to two-thirds the power of the heat release rate. This means that the 15 percent uncertainty in the measured heat release rate that is input into the fire models leads to a 10 percent uncertainty in the prediction of the upper layer temperature. Combining this with the uncertainty associated with the thermocouple temperature measurement leads to a combined uncertainty in the reported temperature of about

[2] http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/

13 percent. In short, the fire model cannot be shown to be more accurate than about 13 percent. Plotting all of the temperature predictions for the 5 models and 26 experiments on a single graph, along with the combined experimental uncertainty, gives a much better picture of model performance, as seen in Figure 1. In some sense, the experimental uncertainty provides the modeler with a very tangible goal—to predict the outcome of a fire to within experimental accuracy. Table 1 includes the combined uncertainties for the various measured quantities.

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Table 1 Combined Uncertainty for the Quantities of Interest in the V&V

Quantity	Number of Tests	Uncertainty (%)
HGL Temperature	26	13
HGL Depth	26	9
Ceiling Jet Temperature	18	16
Plume Temperature	6	14
Gas Concentration	16	9
Smoke Concentration	15	33
Pressure	15	40 (no forced ventilation) 80 (with forced ventilation)
Heat Flux	17	20
Surface/Target Temperature	17	14

RESULTS

To simplify the use of experimental uncertainty as a metric for model accuracy, the study team devised a simple color system to indicate the extent of agreement between the model predictions and the experimental measurements. Green indicates that a particular model predicted a particular parameter with accuracy comparable to the experimental uncertainty. Yellow indicates that the model predictions were clearly outside of the uncertainty bounds, meaning that the difference between model and experiment could not be explained solely in terms of measurement uncertainty. In cases where the model consistently overpredicted the severity of the fire, the team assigned a ranking of Yellow+ to emphasize the point. Table 2 shows the overall results for all five models evaluated. Note that the individual reports that make up NUREG-1824 give the rationale for the colors.

Table 2 NUREG-1824 V&V Results

Parameter[5]		Fire Model				
		FDT[S]	FIVE-Rev1	CFAST	MAGIC	FDS
Hot gas layer temperature ("upper layer temperature")	Room of Origin	YELLOW+	YELLOW+	GREEN	GREEN	GREEN
	Adjacent Room	N/A	N/A	YELLOW	YELLOW+	GREEN
Hot gas layer height ("layer interface height")		N/A	N/A	GREEN	GREEN	GREEN
Ceiling jet temperature ("target/gas temperature")		N/A	YELLOW+	YELLOW+	GREEN	GREEN
Plume temperature		YELLOW–	YELLOW+	N/A	GREEN	YELLOW
Flame height		GREEN	GREEN	GREEN	GREEN	YELLOW
Oxygen concentration		N/A	N/A	GREEN	YELLOW	GREEN
Smoke concentration		N/A	N/A	YELLOW	YELLOW	YELLOW
Room pressure		N/A	N/A	GREEN	GREEN	GREEN
Target temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Radiant heat flux		YELLOW	YELLOW	YELLOW	YELLOW	YELLOW
Total heat flux		N/A	N/A	YELLOW	YELLOW	YELLOW
Wall temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Total heat flux to walls		N/A	N/A	YELLOW	YELLOW	YELLOW

Consider, for example, the predicted average temperature rise in the hot gas layer (HGL) (determined using a simple two-layer reduction method as described in NUREG-1824 [7]) from all the models compared to the experimental measurements (Fig. 1). The hand calculation methods show the greatest deviation and scatter when compared to the measurements and were rated Yellow+. Both the zone and CFD models show less scatter and very similar accuracy for the experiments considered, and all received a ranking of Green for this parameter.

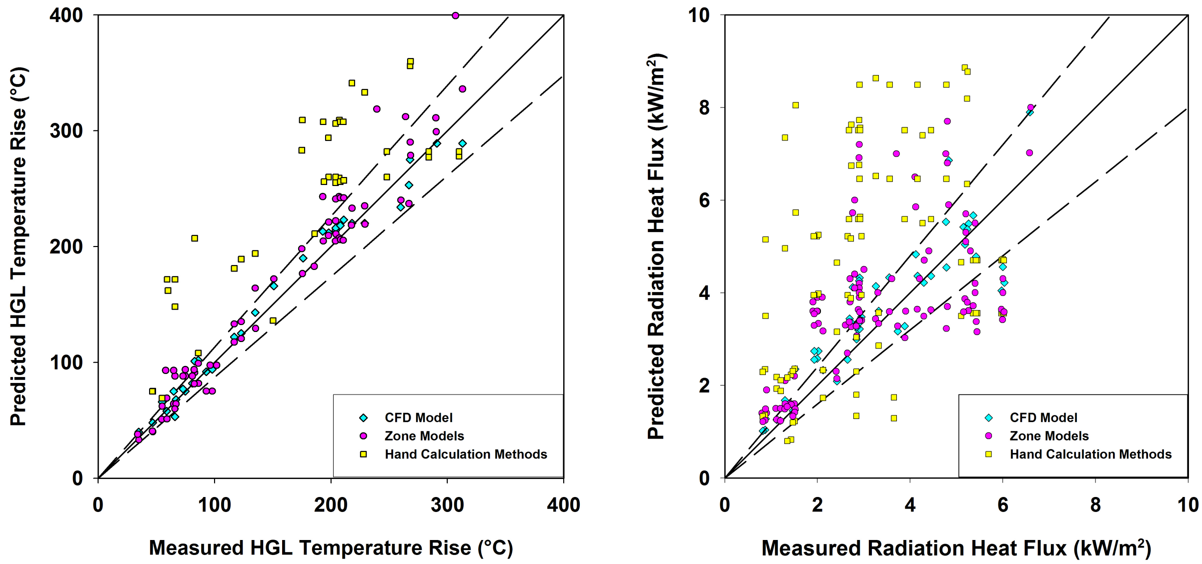

Fig. 1 Measured vs. Predicted Hot Gas Layer Temperature Rise (left) and Measured vs. Predicted Heat Flux (right)

Next, consider the predicted heat fluxes onto various horizontally and vertically oriented targets, shown in the same figure. The CFD model, overall, is more accurate for this parameter, even though the zone and CFD models are of comparable accuracy in predicting the gas temperature. The CFD model is more accurate in predicting heat flux because the heat flux at a target is dependent on the thermal environment of the surroundings, and the CFD model is inherently better able to predict the details of that environment. Hand calculations and zone models predict average temperatures over the entire compartment and thus are less accurate in predicting a heat flux to a single point. Nevertheless, the team assessed all of the models as Yellow for this category, merely to indicate to the model user that even though CFD might be more accurate, it is still challenging to predict a heat flux, especially very close to the fire, with any model.

Whereas the CFD model is more accurate in predicting heat fluxes and surface temperatures, the simpler models perform equally well, and sometimes better, in predicting plume and ceiling jet temperatures and flame heights. The reason is that hand calculations and two-zone models use well-established correlations for these fire phenomena. A CFD model solves the basic transport equations, which makes it truly predictive of these quantities, but not necessarily more accurate. In addition, the increased cost of a CFD calculation is substantial. The spreadsheet and two-zone models produce results in seconds to minutes, versus a CFD model that takes hours to days. If hand calculations and zone model results are obtained faster and are equal to (or better than) CFD results, why should an engineer use a CFD model? Real fire scenarios can be more complex than the experiments used in this study and may not

conform to the assumptions inherent in the hand calculations and zone models. Fire plumes may not be free and clear of obstacles because fires sometimes occur in cabinets or near walls. Ceilings may not be flat and unobstructed because duct work, structural steel, and cable trays are often present. Although hand calculations and zone models can be applied in these instances, the results require more extensive explanation and justification. Since CFD models can make predictions on a more local level with fewer assumptions, the results are likely to be more applicable in these more complex situations.

CONCLUSION

This study has attempted to answer the question "How accurate are fire models today?" The NRC/EPRI fire model evaluation provides the clearest picture to date of the relative accuracy of the three major types of fire models. Although the study evaluated only five specific models, the process outlined above provides a means to evaluate any fire model in a consistent manner against a common database of experiments. NUREG-1824, which includes experimental data files and model input files, is publicly available so anyone can perform a similar study using other fire models. The study highlights the use of experimental uncertainty as a means to assess the level of agreement between models and measurements. The method that the assessment team developed provides a quantitative and rigorous approach, which emphasizes the importance of experimental quality and measurement accuracy in the evaluation of fire models. This approach places a burden on researchers to document and reduce the uncertainty associated with the measurements used for model validation and on modelers to improve the accuracy of their computations in concert with the reduction in measurement uncertainty.

In its current version, ASTM E 1355 is useful as a checklist providing a list of elements that a V&V study should include, but those who set out to evaluate a model should start by deciding the details of the metrics to be used in their evaluation. ASTM E 1355 provides many details of documentation needs for model validation, but concepts for sensitivity analysis and metrics for comparison of model calculations to experimental data are less well developed. Techniques for assessment of model sensitivity in the ASTM guide are too complex for practical application. Like most documents of its kind, ASTM E 1355 does not explicitly discuss how to quantify the accuracy of the model. It merely lists different types of experiments that might be used to validate the model and summarizes techniques for comparison. Assessing experimental uncertainty and its use to determine model accuracy did not originate in the evaluation guide ASTM E 1355. Its use was seen as crucial to understanding the validity of the models. Future versions of the ASTM guide should incorporate the use of experimental uncertainty in the evaluation of model validity.

NUREG-1824 shows areas where the models can be improved, but it also highlights areas where engineers should have confidence or concerns when using the current generation of fire models. Much remains to be done to improve fire models beyond the basic transport capabilities assessed in this study. However, before any improvements can be made, the accuracy of the commonly used models has to be quantified, so that research dollars can be spent on facets of the models that need the most improvement. At this stage, the basic transport algorithms within the zone and CFD models evaluated in this study have proved to be robust and nearly comparable to the uncertainty of the measurements against which they were compared. Heat flux and surface temperature predictions are more challenging and could benefit from continued development. Hand calculations are typically less accurate than zone or CFD models but are easy to use and predictably conservative. In selecting a fire model for a particular application, all of these issues come into play. The work described in NUREG-1824 provides the practicing engineer with information valuable in making this selection.

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