SCHULTE & ASSOCIATES
Building Code Consultants
880D Forest Avenue
Evanston, IL 60202
fpeschulte@aol.com
504/220-7475

MODEL VALIDATION/EVALUATION ISSUE
FIRE DYNAMICS SIMULATOR (FDS)
HUGHES ASSOCIATES, INC. PRESENTATION TO THE ICC CODE TECHNOLOGY COMMITTEE (CTC)
BALTIMORE, MARYLAND
MAY 22, 2008

In Dr. Craig Beyler's presentation before the Code Technology Committee (CTC), Dr. Beyler made reference to fire modeling studies utilizing the Fire Dynamics Simulator (FDS) to demonstrate that automatic (individually-activated) smoke/heat vents "work" in buildings protected by a sprinkler system and to also demonstrate that the concept of "ganged" roof vent operation will not have an adverse effect on the capability of sprinkler systems to control a fire.

Dr. Beyler's presentation to the CTC did not include a discussion of two critical issues regarding the Hughes Associates, Inc.'s (HAI) modeling studies. The first issue which was not addressed was how HAI determined the number and time at which individually-activated smoke/heat vents would operate in a sprinklered building. The second issue which was not addressed was the issue of the validation/evaluation of the FDS routines which predict the activation times of sprinklers.

Research sponsored by the National Fire Protection Research Foundation (NFPRF) and conducted at Underwriters Laboratories in Northbrook, Illinois in 1997 and 1998 demonstrated that the activation of standard sprinklers significantly delays or prevents the operation of individually-activated roof vents. On numerous occasions, Dr. Beyler has acknowledged that this is the case, including a proposal to amend NFPA 204. (A summary of Dr. Beyler's statements regarding sprinkler operation interference with opening of individually-activated smoke/heat vents can be found in Schulte & Associates' presentation to the CTC on May 22, 2008.) **Given the NFPRF research, and Beyler's acknowledgment of the fact that vents are unlikely to open in sprinklered buildings, HAI should provide an explanation of how the number of vents which open and the time at which the vents opens was determined in their study which HAI claims demonstrate that "vents work".**

The HAI research study on the "ganged" operation of smoke/heat vents concludes that the "ganged" operation of vents 60 seconds after the activation of the sprinkler water flow alarm will not have an adverse impact on the operation of the sprinkler system. This conclusion is based on the results of a total of only 16 runs of the FDS model. The HAI report on their research on "ganged" vent operation only briefly addresses the issue of whether or not the FDS model is capable of accurately predicting the activation times of multiple sprinklers.

The following exhibits are intended to address the issue of whether or not the FDS model routines which predict sprinkler activation times (and individually-activated roof vent opening times) have been validated/evaluated.

Exhibit #1	E-mail note from NIST dated June 10, 2008.
Exhibit #2	E-mail note from Dr. J. Floyd dated April 3, 2008.
Exhibit #3	Excerpts from "*Reliability of Computer Fire Model in Fire Safety Design*", authored by Dr. Alan N. Beard, Civil Engineering Section, School of the Built Environment, Heriot-Watt University, Edinburgh, Scotland, Industrial Fire Journal, April 2008 issue.
Exhibit #4	Excerpts from NUREG-1824 Final Report, Volume 1, U.S. Nuclear Regulatory Commission (NRC), May 2007.
Exhibit #5	Excerpts from NUREG-1824 Final Report, Volume 2, U.S. Nuclear Regulatory Commission (NRC), May 2007.
Exhibit #6	Excerpts from NUREG-1824 Final Report, Volume 3, U.S. Nuclear Regulatory Commission (NRC), May 2007.
Exhibit #7	Excerpts from NUREG-1824 Final Report, Volume 7, U.S. Nuclear Regulatory Commission (NRC), May 2007.
Exhibit #8	Excerpts from "Fire Dynamics Simulator (Version 5) Verification & Validation Guide Volume 1: Verification", National Institute of Standards and Technology (NIST), May 30, 2007.
Exhibit #9	Excerpts from "Fire Dynamics Simulator (Version 5) Technical Reference Guide" (NIST Special Publication 1018-5), National Institute of Standards and Technology (NIST), October 1, 2007.
Exhibit #10	Excerpts from "Sprinkler, Smoke & Heat Vent, Draft Curtain Interaction–Large Scale Experiments and Model Development" (NISTIR 6196-1), National Institute of Standards and Technology (NIST), September 1998.
Exhibit #11	Comparison of Sprinkler Activating Times-NFPRF Full-Scale Tests vs. Hughes Associates, Inc. Model Runs, Schulte & Associates.

Summary and Conclusions

Dr. Shyam Sunder's e-mail note dated June 10, 2008 (Exhibit #1) indicates that it is Dr. Craig Beyler's responsibility to evaluate the appropriateness of the use of the Fire Dynamics Simulator (FDS) and to demonstrate that the use of the FDS for the purpose utilized is appropriate (if the FDS is to be utilized). This e-mail note specifically makes reference to NUREG-1824, a validation study of the fire models commissioned by the U.S. Nuclear Regulatory Commission (NRC). Dr. Sunder is the director of the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST).

Dr. J. Floyd e-mail note dated April 3, 2008 (Exhibit #2) indicates that there is little validation of the use of the FDS to predict the activation time of multiple sprinklers. Dr. J. Floyd was formerly an employee of NIST and is presently employed by Hughes Associates, Inc.

Dr. Alan N. Beard's article (Exhibit #3) addressing the capability of fire models to actually predict the "real world" in a fire appeared in the April 2008 issue of the Industrial Fire Journal. Dr. Beard expresses the opinion that the results (predictions) of fire models must be cautiously interpreted and utilized.

Volumes 1, 2, 3 and 7 of NUREG-1824 (Exhibits #4, #5, #6 and #7) discuss validation studies of various fire models. Volume 7 of NUREG-1824 specifically addresses the Fire Dynamics Simulator and indicates that insufficient experimental data is available to validate the FDS predictions of sprinkler activation times and sprinkler suppression capabilities. (See Page 3-2 of Volume 7.) Further, Volume 7 includes a passage which states ". . .this higher degree of inaccuracy if the objective of the calculation is to assess the damage to or activation of some object or device near the ceiling [i.e. a sprinkler or an individually-activated smoke/ heat vent] ." (See page 6-12.)

The draft of the "Fire Dynamics Simulator Verification & Validation Guide" and the "Fire Dynamics Technical Reference Guide" (Exhibits #8 and #9) provide general information which addresses the validation/evaluation of the FDS and both documents indicate that the predictions of the FDS should be validated utilizing experiments.

NISTIR 6196-1 (Exhibit #10) is the report on research funded by the National Fire Protection Research Foundation (NFPRF) on the interaction of sprinklers, smoke/heat vents and draft curtains. This report states that the FDS model was not capable of predicting that a vent located directly over a fire would fail to operate in buildings protected by standard spray sprinklers.

The comparison of sprinkler activation times between the five plastic commodity tests conducted as part of the NFPRF research and the Hughes Associates, Inc. (HAI) model runs (Exhibit #11) demonstrates the difference in activation times between the plastic commodity test fires and the HAI model runs. This comparison demonstrates that the HAI FDS model did not accurately predict sprinkler activation times.

Based upon the information presented in the various exhibits, it is Schulte & Associates' opinion that the use of the Fire Dynamics Simulator (FDS) to predict sprinkler activation times of multiple sprinklers (as many as 20 sprinklers) has not been validated. Further, it is Schulte & Associates' opinion that the research study on the "ganged" operation of roof vents by Hughes Associates, Inc. has failed to provide sufficient experimental evidence for users of this study to determine whether or not it is appropriate to utilize the FDS for the purpose of predicting the activation times of multiple sprinklers.

Given the above, it is Schulte & Associates' opinion that the FDS has been improperly utilized by Hughes Associates, Inc. in HAI's research on smoke/heat vents.

Given the fact that Dr. Craig Beyler and Phil DiNenno of Hughes Associates, Inc. were both involved in the peer review of Volumes 1, 2, 3 and 7 of NUREG-1824 , it is Schulte & Associates' opinion that Hughes Associates, Inc. should have been fully aware that the FDS was being improperly used to support the HAI research on the concept of "ganged" operation of smoke/ heat vents.

Exhibit #1 E-mail note from NIST dated June 10, 2008

Subject: Re: FDS-Sprinkler Activation Sequence/Activation Times
Date: 6/10/2008 1:44:52 Central Daylight Time
From: sunder@nist.gov
To: FPESCHULTE@aol.com

Rich,

We (NIST) do a considerable amount of validation work, as evidenced by such documents as NISTIR 6196-1, the WTC reports, and NUREG 1824 -- the very extensive Verification and Validation study we participated in with the US NRC. We do validation work as a routine part of improving our models. However, model validation is technically the responsibility of the end user.

For example, the US NRC performed the model evaluation study of not just FDS and CFAST, but 5 fires models that are used throughout the nuclear industry. We participated in the study, as did the other developers, but at the end of the day the US NRC decided whether or not the models were sufficiently accurate for their own applications. They, and EPRI (who also participated), are the "end users."

Craig Beyler, in his study of roof vents, references NIST validation work, but it is he and his sponsors who have decided that the model is appropriate for their application, and that is an argument that he, and any other users of FDS, must make.

Organizations like the US NRC, NFPA Research Foundation, and the SFPE have all cited NIST validation reports, but also have done validation work on their own to determine if FDS and CFAST are appropriate for various applications of interest. They decide, not us, whether or not the model is appropriate for their application.

Shyam

==
Dr. S. Shyam Sunder
Director
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8600
Tel.: 301-975-5900; Fax: 301-975-4032
==

From: FPESCHULTE@aol.com [mailto:FPESCHULTE@aol.com]
Sent: Tuesday, June 10, 2008 7:53 AM
To: Shyam Sunder
Cc: kevin.mcgrattan@nist.gov; psimony@yahoo.com; mpfeiffer@iccsafe.org
Subject: Re: FDS-Sprinkler Activating Sequence/Activation Times

In a message dated 6/9/2008 11:18:31 A.M. Central Daylight Time, sunder@nist.gov writes:

> We have reviewed the information you recently sent us. At this time, we do not have an active research project or a planned research project on the issues you raise. Our most recent publication, and hence our position, on this topic dates back to September 1998 and may be found at http://fire.nist.gov/bfrlpubs/fire98/PDF/f98069.pdf. In general, NIST evaluates performance but does not endorse specific technologies, products, and systems. Further, we recognize that NIST tools such as FDS are used in practice but have made very clear (see FDS disclaimer below) that users of FDS (not NIST) assume responsibility for its use.

Shyam-

My questions regarding the Hughes Associates, Inc. study on the concept of "ganged" roof vent operation do not address the "ganged" roof vent concept, but rather how the FDS is used in the study in regard to sprinkler sequence of operation and activation times. (It's already obvious that opening 30 roof vents within 1 minute of the first operation will have a significant effect on sprinkler operation, regardless of what HAI concludes in their report.)

The specific questions that I am attempting to get a handle on are:

Can the FDS presently be utilized to determine the activation sequence and activation times of multiple sprinklers (anywhere from 2 sprinklers to 50 sprinklers) with a degree of accuracy which would make the predictions meaningful (without open roof vents)? (In other words, has this use of the FDS been verified, validated and evaluated?)

Can the FDS be utilized to reliably predict sprinkler "skipping"? (Again, has this use of the FDS been verified, validated and evaluated?)

The answers to these questions are totally independent of the roof vent issue which is addressed by the Hughes' study, but will determine whether or not the Hughes Associates Inc. study is meaningful research or simply "junk science" disguised as sophisticated research.

rich

* * * * *

Exhibit #2 **E-mail note from Dr. J. Floyd dated April 3, 2008** (Web Address: http://groups.google.com/group/fds-smv/browse_thread/thread/d11a1b14d7d09953#)

Andrew Louie View profile
More options Apr 3, 9:56 am

From: "Andrew Louie" <lou...@gmail.com>
Date: Thu, 3 Apr 2008 09:56:43 -0400
Local: Thurs, Apr 3 2008 9:56 am
Subject: Re: [fds-smv post:3250] Predefined sprinklerheads
On Thu, Apr 3, 2008 at 9:24 AM, Emiel van Rossum <> wrote:

Hi all,

I regualy have to simulate with sprinklers, but i am not a sprinkler expert.

Do you guy's have a set of predefined sprinklerheads or something like that?

dr_jfloyd View profile
More options Apr 3, 10:37 am

From: dr_jfloyd <drjfl...@gmail.com>
Date: Thu, 3 Apr 2008 07:37:11 -0700 (PDT)
Local: Thurs, Apr 3 2008 10:37 am
Subject: Re: Predefined sprinklerheads

It should also be noted that there is currently little to no validation basis for the suppression effects of water in FDS. Sprinkler activation has some validation, large drop movement (i.e. bucket test like simulations) has some validation provided one has measured that flow pattern for the specific nozzle being simulated.

* * * * *

Exhibit #3 “***Reliability of Computer Fire Model in Fire Safety Design***”, **authored by Dr. Alan N. Beard, Civil Engineering Section, School of the Built Environment, Heriot-Watt University, Edinburgh, Scotland, Industrial Fire Journal, April 2008 issue.**

(Web Address: http://www.hemmingfire.com/cp/6/Fire%20Modelling.pdf)

The following are selected excerpts from Dr. Beard’s article which appeared in the April 2008 issue of Industrial Fire Journal:

“This concern covers all kinds of models, including computational fluid dynamics [CFD] models. Concerns centre around the degree to which such models may or may not have the potential to represent the real world reasonably accurately and the ways in which such models may be used and results interpreted.”

“It is crucial, therefore, to conduct a priori comparisons with well instrumented experimental tests, but very few indeed have ever been performed.”

“A similar “round-robin” a priori study has just been carried out by Edinburgh University in collaboration with Strathclyde Fire Brigade, centred on the Dalmarnock fire tests. The results were presented at a meeting in Edinburgh in November 2007. In these tests a fire was started on a sofa in a two-bedroomed flat in Dalmarnock, Glasgow. . . . .The big question was, as with the CIB study: how would the predictions by model users compare with each other and with experimental results? Ten model user teams took part, eight using the same CFD model and two using a zone model. . . . As a general rule the predictions were not at all good: there was generally a wide scatter amongst the predictions by users and, also, predictions usually compared poorly with experimental results.”

“The basic message was clear: a predicted result from a model cannot be assumed to be accurate; ie to reflect the real world. Further, consistency cannot be assumed; ie that a given model will consistently over-predict or consistently under-predict.”

“Whether or not a model may be reliably used as part of fire safety decision-making depends not only upon the conceptual and numerical assumptions in the model itself but also upon how it is used and how the results are interpreted. Using models as part of decision-making may be dangerous.”

“A “knowledgeable user” must be capable of using an acceptable methodology to apply a particular model to a particular case in a comprehensive and exhaustive way, making all assumptions and procedures explicit, and interpreting results in a justifiable way.”

* * * * *

Exhibit #4   NUREG-1824, Volume 1

The following are selected excerpts from Volume 1 of NUREG-1824:

“This report describes research sponsored jointly by U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI).” (Page *iii*)

“One key tool needed to further the use of RI/PB (risk informed/performance based) fire protection is the availability of verified and validated fire models that can reliably predict the consequences of fires. Section 2.4.1.2 of NFPA 805 requires that only fire models acceptable to the Authority Having Jurisdiction (AHJ) shall be used in fire modeling calculations. Furthermore, Sections 2.4.1.2.2 and 2.4.1.2.3 of NFPA 805 state that fire models shall only be applied within the limitations of the given model, and shall be verified and validated.” (Page *v*)

“The road map for this project was derived from NFPA 805 and the American Society for Testing and Materials (ASTM) Standard E 1355, Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models. These industry standards form the methodology and process used to perform this study. Technical review of fire models is also necessary to ensure that those using the models can accurately assess the adequacy of the scientific and technical bases for the models, select models that are appropriate for a desired use, and understand the levels of confidence that can be attributed to the results predicted by the models. This work was performed using state-of-the-art fire dynamics calculation methods/models and the most applicable fire test data. Future improvements in the fire dynamics calculation methods/models and additional fire test data may impact the results presented in the seven volumes of this report.” (Page *vii*)

“Rather, these results are intended to provide technical analysis of the predictive capabilities of five fire dynamic calculation tools, and they may also help to identify areas where further research and analysis are needed.” (Page *vii*)

“We wish to acknowledge the team of peer reviewers who reviewed the initial draft of this report and provided valuable comments. The peer reviewers were Dr. Craig Beyler and Mr. Phil DiNenno of Hughes Associates, Inc., and Dr. James Quintiere of the University of Maryland.” (Page *xx*)

“In 2001, the National Fire Protection Association (NFPA) completed the development of NFPA Standard 805, Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants, 2001 Edition. Effective July 16, 2004, the NRC amended its fire protection requirements in Title 10, Section 50.48(c), of the Code of Federal Regulations [10 CFR 50.48(c)] to permit existing reactor licensees to voluntarily adopt fire protection requirements contained in NFPA 805 as an alternative to the existing deterministic fire protection requirements. (Page 1-1)

“Risk-informed, performance-based (RI/PB) fire protection often relies on fire modeling for determining the consequence of fires. NFPA 805 requires that the “fire models shall be verified and validated,” and “only fire models that are acceptable to the Authority Having Jurisdiction (AHJ) shall be used in fire modeling calculations.” (Page 1-1)

“The scope of this V&V study is limited to the capabilities of the selected fire models. As such, certain potential fire scenarios in NPP fire modeling applications do not fall within the capabilities of these fire models and, therefore, are not covered by this study. Examples of such fire scenarios include high-energy arcing faults and fire propagation between control panels [5, Section 7.2.2]. It is the user’s responsibility to determine whether a model can be applied to each specific fire scenario.” (Page 1-3)

“There is, however, a technical challenge in implementing these tasks. Specifically, the universe of fire scenarios in commercial NPPs is large and diverse. Also, scenarios may have characteristics or attributes that either cannot be modeled using state-of-the-art computational fire models, and/or no experimental data is available to support a V&V study of that particular characteristic or attribute. Improvements in these two specific limitations — limited fire modeling capabilities and/or insufficient experimental data — are needed.” (Page 2-1)

“However, some conditions in these scenarios cannot be predicted with available models or do not have any available experimental data to support a quantitative model evaluation.” (Page 2-1)

“As suggested earlier, (1) not all the predictive capabilities of each model have been subjected to the V&V process, and (2) not all the fire-generated conditions in the library of fire scenarios can be predicted with the capabilities of state-of-the-art models.” (Page 2-1)

“This section provides a general overview of the test series and experiments selected for this study. Volume 2 augments this overview by providing detailed descriptions of these experiments. Some test series included many experiments, from which only a few were chosen for this V&V study. One overriding reason for this is that the sheer amount of data that is generated and must be processed can be overwhelming, so limiting the number of experiments to consider was necessary. The experiments within the test series that were chosen are representative of the overall series of tests, as well as representative of the fire scenarios in NPPs listed above. Volume 2, Section 1.1, has a more complete explanation for the selection of the experiments.” (Page 2-15)

“In general, the use of the quantitative results of this validation in support of fire modeling requires the following two steps:

1. Applicability of V&V Results: First, the user needs to assess the applicability of the validation results for the scenario under consideration.

2. Characterization of fire model predictions based on the V&V results: Once the user determines the applicability of the validation, the user must determine the level of confidence in the model prediction based on the quantitative results of this validation."

(Page 2-25)

"The following is one method that may be used to determine applicability of these validation results to other specific NPP fire scenarios. The description of this method is reported here to demonstrate the rigor users should use in determining applicability of these validation results. Other methods may be appropriate." (Page 2-25)

"Once the user determines the validation results reported here are applicable (see Section 2.6.1), the user must determine the predictive capability of the fire models. ASTM E 1355 does not provide specific criteria by which to judge the predictive capability of the models based on the results of the V&V. As such, the V&V project team developed a grading criteria and methodology to judge the models' capabilities." (Page 2-32)

"Criterion 2: *Are there calculated relative differences outside the experimental and model input uncertainty?* This criterion is used as an indication of the accuracy of the model prediction. Since fire experiments are used as a way of establishing confidence in model prediction, the confidence can only be as good as our experiments and the model inputs derived from experiments. Therefore, if model predictions fall within the ranges of these combined uncertainties, the predictions are determined to be as accurate as the experiments and data." (Page 2-32)

"The user is advised to review and understand the model assumptions and inputs, as well as the conditions and results to determine and justify the appropriateness of the model prediction to the fire scenario for which it is being used." (Page 2-33)

"No color: This V&V study did not investigate this capability. This may be attributable to one or more reasons that include unavailability of appropriate data or lack of model, sub-model, or output." (Page 2-33)

"All five models have been verified by this study as appropriate for fire protection applications, within the assumptions for each individual model or sub-model. The project team used guidance in ASTM E 1355 about the theoretical basis and mathematical and numerical robustness to make this determination. The verification for each model is documented in Volumes 3 through 7." (Page 3-4)

“During the process of this study, a number of modifications and corrections to the five selected fire models were identified and implemented. These modification and corrections were identified during the validation as a result of trying to interpret the results. The nature of these modifications and corrections cover a wide range from inconsequential to those that could lead to incorrect result. Descriptions of these modifications can be found in Volume 3 through 7.” (Page 3-4)

“For the fire scenarios considered in the current validation study, and for the output quantities of interest, the libraries of engineering calculations (FDT^s, FIVE-Rev1) have limited capabilities. These libraries do not have appropriate methods for estimating many of the fire scenario attributes evaluated in this study. The correlations that the libraries do contain are typically empirically deduced from a broad database of experiments. The correlations are based on fundamental conservation laws and have gained a considerable degree of acceptance in the fire protection engineering community. However, because of their empirical nature, they are subject to many limiting assumptions. The user must be cautious when using these tools.” (Page 3-4)

“The decision to use any of these models can depend on many considerations. Real fire scenarios rarely conform neatly to some of the simplifying assumptions inherent in the models. Although engineering calculations and two-zone models can be applied in instances where the physical configuration is complex, their accuracy cannot be ensured. Field [CFD] model predictions can be more accurate in more these complex scenarios. However, the time it takes to get and understand a prediction may also be an important consideration in the decision to use a particular model for a specific scenario. FDS is computationally expensive and, while the two-zone models produce answers in seconds to minutes, FDS provides comparable answers in hours to days. FDS is better suited to predict fire environments within more complex configurations because it predicts the local effects of a fire.” (Page 3-5)

“Like all predictive models, the best predictions come with a clear understanding of the limitations of the model and of the inputs provided to do the calculations.” (Page 3-5)

“The use of fire models to support fire protection decision-making requires understanding of their limitations and confidence in their predictive capabilities. This report improves the understanding and evaluates the predictive capabilities of the models selected. Fully understanding the predictive capabilities of fire models is a challenge that should be addressed if the fire protection community is to realize the full benefit of fire modeling. The approach used in this study and documented and implemented in the individual volumes can be used as a roadmap to model users and developers for conducting a V&V for models other than those included in this study.” (Page 3-5)

"The results of this project clearly suggest that any fire modeling analysis should consider the predictive capabilities associated with the analytical tool when interpreting its results." (Page 3-5)

* * * * *

Exhibit #5 NUREG 1824, Volume 2

The following are selected excerpts from Volume 2 of NUREG-1824:

"We wish to acknowledge the team of peer reviewers who reviewed the initial draft of this report and provided valuable comments. The peer reviewers were Dr. Craig Beyler and Mr. Phil DiNenno of Hughes Associates, Inc., and Dr. James Quintiere of the University of Maryland." (Page *xxii*)

"The purpose of this volume is to provide a means for quantitative comparison of model simulations and measurements. The methodology employed follows the guidelines outlined in ASTM E 1355, Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models [1], for verification and validation (V&V) of the selected fire models. That guide outlines four parts of model evaluation:

1. Define the model and scenarios for which the evaluation is to be conducted.
2. Assess the appropriateness of the theoretical basis and assumptions used in the model.
3. Assess the mathematical and numerical robustness of the model.
4. Validate a model by quantifying the accuracy of the model results in predicting the course of events for specific fire scenarios."

(Page 1-1)

"This volume describes the methodology used to addresses the fourth part of the ASTM model evaluation process. The other parts are found in Volumes 1 and 3 through 7 of this report series." (Page 1-1)

"Traditionally, model validation studies report the comparison of model results with experimental data. There are various ways of expressing the difference between the two, but there are no widely accepted criteria for judging whether the agreement is satisfactory or not. ASTM E 1355 [1] does not explicitly define how model validation should be accomplished, nor does it provide criteria regarding what constitutes "reasonable" agreement between models and experiments. Section 11.3.2.4 of ASTM E 1355 states that, "Where data are available, model predictions should be viewed in light of the variability of the full-scale test results and model sensitivity." No further guidance is supplied by ASTM E 1355 on the details of how experiments might be used to validate fire models." (Page 1-1)

“The relative differences sometimes show general agreement, and sometimes show under-prediction or over-prediction. The relative differences are attributable to a number of factors, including the capabilities and limitations of the predictive models, and the accuracy of the experimental measurements. In this study, the relative differences between the model predictions and the experimental measurements are compared to a combined uncertainty. This comparison allowed the determination of a graded characterization of a fire model’s capability to predict attributes important to NPP fire modeling applications.” (Page 1-1)

“The combined uncertainty includes the model input uncertainty, which is derived from experimental measurements and the experimental measurement uncertainty associated with each of the key quantities of interest (see Section 1.2). This metric allows quantification of the level of agreement between the model predictions and the experimental measurements.” (Page 1-2)

“Rather, this volume serves as a link between the experiments and the models, especially with regard to experimental uncertainties, which are often not reported in the original test reports. Here, estimates of the experimental uncertainties are provided, based on engineering judgment. Also, certain parameters required as input by the fire models, like the radiation loss from the fire, are often not provided in the original test reports, because these quantities have not been measured. Here, estimates of these quantities are provided, based on engineering judgment. This document provides information that cannot be found in the original test reports for implementing the models and comparing the model results to experimental measurements. In summary, this volume provides information on the model evaluation process, and the various forms of uncertainty that play a role in that process.” (Page 1-2)

“Often, the documentation associated with these six experimental studies did not completely address measurement uncertainty. In those cases, measurement uncertainty was estimated here using engineering judgment. For example, each of the experiments provided data that was used to characterize the fire heat release rate. More often than not, however, the uncertainty in the heat release rate was not reported. Since this parameter drives the thermal environment in a fire, and the model calculation results are particularly sensitive to uncertainty in this parameter, engineering judgment was used to provide a reasonable estimate for this parameter.” (Page 1-5)

“Fire protection engineers performing a hazard analysis are often content to demonstrate merely that the model is consistently “conservative”; that is, that a safety factor is implicit in the model formulation. Forensic experts, however, require the model to be as accurate as possible, with no built-in bias. In either case, model accuracy needs to be quantified. This means comparing model predictions to experimental measurements, as is done throughout Volumes 3 through 7, and then quantifying the differences between the two. The agreement between measurements and models is considered here in terms of the combined measurement and model input uncertainties.” (Page 1-7)

"For model evaluation, the impact of experimental uncertainty on the comparison of model simulations and the experiments is considered. The experimental uncertainty is considered in two ways. First, the uncertainty associated with parameters derived from experimental measurements that are used as model input is considered. Second, the uncertainty associated with the experimental measurements themselves (for those quantities that are model output) is considered. The former type of uncertainty is referred to here as model input uncertainty. The uncertainty in model input parameters may include uncertainty in the thermal properties of solid surfaces, in the chemical properties of the fuel, in the yields of the various products of combustion, and most importantly, in the heat release rate of the fire." (Page 1-7)

"Beyond the input uncertainty, uncertainty associated with the experimental measurements is also considered in the model evaluation process. Measurements by thermocouples, heat flux gauges and gas analyzers all have a certain degree of uncertainty related to their operation, calibration, etc. This is referred to as measurement uncertainty. A measurement result is fully documented only when accompanied by a quantitative statement of its uncertainty. There are two types of measurement uncertainty: instrument uncertainty and repeatability [Refs. 8, 9]. When these components of the measurement uncertainty are quantified, they are pooled into a combined uncertainty value that is a better representation of the total measurement uncertainty. The uncertainty is often expressed in terms of an expanded uncertainty, in which the confidence level that the measurement falls within the expanded bounds is high. The size of the expanded bounds is described by an expansion factor. For an expansion factor of two, the uncertainty is related to two standard deviations ($2 \cdot \sigma$) and the confidence level corresponds to 95%." (Page 1-8)

"Typically, it is possible to provide rational estimates of the experimental measurement uncertainty and the experimental model input uncertainty. Both are related to measurements. Another type of uncertainty, the model intrinsic uncertainty, is far more difficult to quantify. Model intrinsic uncertainty is uncertainty associated with the physical and mathematical assumptions and methods that are an intrinsic part of the model formulation and its implementation. This uncertainty is not part of the model input uncertainty. A methodology for examining this type of uncertainty is described in reference 10. Examples of intrinsic uncertainty are the two-layer assumption in a zone fire model, the description of turbulence in a CFD fire model, or the grid size used in a CFD fire model. We do not attempt to quantify model intrinsic uncertainty in this study. In this sense, only a portion of the total uncertainty in the model simulation results is considered here. However, a sense of the size of the intrinsic uncertainty of the models can be ascertained from the results of this study." (Page 1-8)

“This section describes the methodology used to compare the model and measurement results. NFPA 805 and ASTM E 1355 offer some suggestions, but do not specify one method over another for comparison of models and measurements. The method developed here is distinct in many ways from the methods suggested by those documents. In this report, the predictive capability of each of the models is determined through comparison with quantitative experimental results. The detailed plots of the comparisons are presented for each of the models in Appendix A to Volumes 3 through 7 of this report series. The fire models are used to simulate the experiments, and then the effects of experimental measurement uncertainty and the model sensitivity to model input uncertainty are considered as possible sources of the difference between the model calculation results and the measurements.” (Page 1-8)

“Although other means to judge the reasonableness of model validation may be possible, the method developed here provides a quantitative and rigorous approach that emphasizes the importance of experimental quality and measurement accuracy in the evaluation of fire models.” (Page 1-14)

“Because measurement uncertainty was not documented for many of the experiments, engineering judgment is used, in this and the following chapter, to estimate its value. Measurement uncertainty varies from experiment to experiment, and for each attribute being measured. Accurate determination of experimental uncertainty is challenging, and characterization of the uncertainty in experiments conducted by others is even more so. A good faith effort is made here to quantify measurement uncertainty, but the uncertainty determinations provided in this document should be regarded as estimates and the uncertainty bounds should be regarded as guidelines to assist in the evaluation of the predictive capabilities of the models. Some factors that contribute to experimental uncertainty were not considered here, but may be important. For measurements, systematic error may have been present, but may not have been identified. The potential for human error is always present in the implementation of instrumentation and interpretation of measurement results. In this sense, it is recognized that the uncertainty values presented here are not necessarily all-inclusive or definitive. This highlights the importance of expert judgment in the interpretation of the agreement between measurements and models.” (Page 2-1)

“The fire HRR is the single most important parameter in terms of characterizing a fire, and its uncertainty is the most significant model input uncertainty. The magnitude of HRR controls the thermal impact of a fire on its environment. The current generation of fire models cannot accurately predict the transient value of HRR , and for the fire model evaluations considered in this report, the value of HRR is prescribed (that is, HRR is an input parameter, rather than an output parameter that is calculated by a model). The sensitivity of model output to the uncertainty in HRR is an important part of the model evaluation in this report series and is discussed in detail in Chapter 5.” (Page 3-1)

“In the experiments considered in this report, the heat release rate was determined by measuring the mass loss rate of fuel or by oxygen consumption calorimetry.” (Page 3-2)

“For some of the experiments considered here, the HRR was estimated through measurement of the fuel flow rate. In these cases, the HRR was calculated based on the heat of combustion and an assumed combustion efficiency (Eq. 3.1). While the mass flow rate measurements typically have low uncertainties, the uncertainty in the combustion efficiency is not necessarily small. Inside a compartment, even less is known about combustion efficiency as the fire plume is partially engulfed in a hot upper layer and the oxygen volume fraction in the lower layer is vitiated.” (Page 3-2)

“Table 3-2 summarizes the material property information that was used in the model calculations, including the material thermal conductivity, specific heat, density, and emissivity. The material thickness is also given. In addition, the thickness of the compartment surfaces is given. This is important for consideration of heat losses via conduction through compartment surfaces. The information was obtained from a number of sources, mostly from the test reports or the model documentation as noted in the footnotes of the table. Uncertainty in these values has small impact on the modeling results as confirmed by a sensitivity analysis conducted using the CFAST and FDS models (see Volumes 5 and 7 of this report series). For this reason, uncertainties of material properties are not explicitly considered in this report series.” (Page 3-4)

“For many of the experiments and most of the measurements considered in this report, the experimental uncertainty was not documented.” (Page 4-1)

“The uncertainty estimates provided here are limited by knowledge of the details associated with each of the experiments. For this reason, the uncertainty values provided here should be thought of as rough estimates, rather than precise determinations of measurement uncertainty. Even for the experimentalists themselves, the accuracy of an uncertainty analysis is often limited by incomplete understanding. For example, in heat flux gauges, the uncertainty attributable to soot deposition on the face of the gauge is difficult to quantify. The amount of soot deposition depends on many parameters, such as the location of the gauge, the flow field and the temperature field near the gauge, the duration of the test, and the local soot volume fraction. Unexpected events or poor understanding limits the accuracy of an uncertainty analysis.” (Page 4-1)

“In general, measurement uncertainty depends on many issues, including the exact type of instrumentation, the experimental procedure, and the details of the measurement scenario. The uncertainty in many of the experimental measurements is difficult to accurately estimate, because most of the test reports do not provide uncertainties for the individual measurements. For this reason, the values are inferred based upon engineering judgment and experience with similar instrumentation.” (Page 4-1)

"The interpretation of a bare bead TC signal must consider several possible sources of error. TC measurement error can occur because of the breakdown of the TC insulation at high temperatures, corrosion from acid combustion byproducts, de-calibration at high temperatures, inherent measurement accuracy limited by materials effects, and measurement error attributable to radiative exchange effects. The latter requires attention for the experiments considered in this report." (Page 4-2)

"Aspirated TCs provide accurate temperature information, but are typically used sparingly, because of their relatively high cost compared to bare bead TCs. FM/SNL used aspirated TCs in the experiments considered in this report and BE #3 used aspirated TCs to assess the accuracy of the bare bead TC results." (Page 4-2)

"In a hot upper layer of a compartment with lots of soot, a TC reading may be fairly accurate and not need to be corrected for radiative exchange effects. This is because the environment in such a scenario is nearly optically thick, for which radiative exchange effects are minimized." (Page 4-2)

"In those experiments, the measurement results of bare bead TCs were within 3 °C to 15°C (5°F to 27°F) of nearby aspirated TCs. In the three FM/SNL tests [2], for example, a bare bead TC in the upper layer was within 5°C to 6°C (9 °F to 11°F) of a nearby aspirated TC, for upper layer temperatures of about 60°C (140°F). In the hot upper layer of a heptane fire [31], bare bead TCs in the HGL were within 12 °C (22°F) of nearby aspirated TCs, for various tests in which the upper layer temperatures ranged from 400°C to 800°C (750°F to 1500°F). Intermediate temperatures were estimated based on linear interpolation between the higher and lower temperature results." (Page 4-3)

"In the lower layer of compartment fires with a smoky, high-opacity upper layer, radiative gain attributable to flux from the hot upper layer may lead to erroneously high TC readings. . . . .Neglecting uncertainty in the lower layer temperature measurement reduces the total uncertainty, and in this sense is a conservative approach for model validation. The most significant contributor to the uncertainty of the upper layer depth and the temperature is the physical distance between TCs, which is the spatial resolution of the measurement." (Page 4-3)

"Repeatability of the depth determination was investigated for BE #3 by examining the results for the repeat tests. The difference in the calculated upper layer depth and temperature for the four pairs of repeat measurements was about 1%, on average, a negligibly small contribution to the overall uncertainty. It was assumed that the repeatability in the other tests was similar to that determined in BE #3." (Page 4-5)

“Ceiling jet measurements were conducted in BE #3 and the FM/SNL tests, in which the temperatures were measured using bare bead and aspirated TCs, respectively. Temperatures in the plume were measured in BE #2 and the FM/SNL tests, in which the temperatures were measured using bare bead and aspirated TCs, respectively. Because the ceiling jet is located high in the hot smoky upper layer, radiative exchange effects on TCs should be minimal and the results are treated in the same way as the bare bead TCs in the upper layer.” (Page 4-6)

“The volume fractions of the combustion products, carbon monoxide (CO) and carbon dioxide (CO_2), were measured using gas sampling in conjunction with non-dispersive infrared analyzers, while the oxygen (O_2) volume fraction was typically measured using a paramagnetic analyzer. Gases were extracted through stainless steel or other types of lines and were pumped from the compartment and passed through the analyzers. For several reasons, water in the sample was typically filtered, so the reported results are denoted as “dry” and comparison with model results must be corrected. Analyzers were calibrated through the use of standard gas mixtures, with low relative uncertainties. Problems with the technique may involve instrument drift, analyzer response, incomplete and partial drying of sample gases, or (in the case when drying is not used) undetermined amounts of water vapor in the oxygen cell, which result in inaccurate readings.” (Page 4-7)

“The uncertainty associated with a heat flux measurement depends on many factors, including gauge characteristics, the calibration conditions and accuracy, as well as the incident flux modes (convective, radiative, conductive) and their magnitudes in the actual measurement situation [33].” (Page 4-9)

“Because uncertainty was not documented for most of the experiments considered in this report, engineering judgment was used to provide estimates of measurement uncertainty for each of the parameters of interest. This information on measurement uncertainty is combined with the model input uncertainty in Chapter 6 to provide a basis for the evaluation of the fire models, as described in Volumes 3 through 7 of this report.” (Page 4-11)

“A sensitivity analysis for the models could have been performed by running many calculations and determining the variation of a calculated output parameter as a function of the change in one or more input parameters. This is a brute force approach, which provides relevant information, but is labor intensive and does not necessarily offer physical insight. In addition, such an approach would be model specific. Rather than a brute-force method, the approach presented here is based on empirical closed-form expressions, which provides estimates on the effect of experimental uncertainty on the model output results, in a consistent and accepted manner for all of the models.” (Page 5-1)

“Smoke, or soot, is a product of incomplete combustion. Once formed, the smoke is transported with other combustion products. Smoke particulate is not a gas, but a complex solid, of which the form and concentration depend on the type of fuel and ventilation conditions within the compartment. Nonetheless, a simple assumption used in many zone and field fire models is that smoke is transported in the same way as gas products. The soot generation rate or soot yield per unit fuel mass, y_s, is difficult to predict, and the fire models are subject to error attributable to uncertainty in the prescribed soot yield.” (Page 5-5)

“For many of the measured quantities under consideration, the model input uncertainty is greater than the measurement uncertainty as discussed in the next chapter.” (Page 5-8)

* * * * *

Exhibit #6 NUREG 1824, Volume 3

The following are selected excerpts from Volume 3 of NUREG-1824:

Objectives

- To perform V&V studies of selected fire models using a consistent methodology (ASTM I 1335)
- To investigate the specific fire modeling issue of interest to NPP fire protection applications
- To quantify fire model predictive capabilities to the extent that can be supported by comparison with selected and available experimental data.

(Page *xvii*)

"The scope of these V&V studies was limited to the capabilities of the selected fire models and did not cover certain potential fire scenarios that fall outside the capabilities of these fire models." (Page *xvii*)

"The results of this study are presented in the form of relative differences between fire model predictions and experimental data for fire modeling attributes such as plume temperature that are important to NPP fire modeling applications. While the relative differences sometimes show agreement, they also show both under-prediction and over-prediction in some circumstances. These relative differences are affected by the capabilities of the models, the availability of accurate applicable experimental data, and the experimental uncertainty of these data. The project team used the relative differences, in combination with some engineering judgment as to the appropriateness of the model and the agreement between model and experiment, to produce a graded characterization of each fire model's capability to predict attributes important to NPP fire modeling applications." (Page *xviii*)

"This report does not provide relative differences for all known fire scenarios in NPP applications. This incompleteness is attributable to a combination of model capability and lack of relevant experimental data. The first problem can be addressed by improving the fire models, while the second problem calls for more applicable fire experiments." (Page *xviii*)

"The use of fire models to support fire protection decision-making requires a good understanding of their limitations and predictive capabilities. While this report makes considerable progress toward this goal, it also points to ranges of accuracies in the predictive capability of these fire models that could limit their use in fire modeling applications. Use of these fire models presents challenges that should be addressed if the fire protection community is to realize the full benefit of fire modeling and performance-based fire protection. Persisting problems require both short term and long-term solutions. In the short-term, users need to be educated on how the results of this work may affect known applications of fire modeling, perhaps through pilot application of the findings of this report and documentation of the resulting lessons learned. In the long-term, additional work on improving the models and performing additional experiments should be considered." (Page xviii)

"We wish to acknowledge the team of peer reviewers who reviewed the initial draft of this report and provided valuable comments. The peer reviewers were Dr. Craig Beyler and Mr. Phil DiNenno of Hughes Associates, Inc., and Dr. James Quintiere of the University of Maryland." (Page *xxii*)

"V&V studies give fire modeling analysts confidence in applying analytical tools by quantifying and discussing the performance of the given model in predicting the fire conditions measured in a particular experiment. The underlying assumptions, capabilities, and limitations of the model are discussed and evaluated as part of the V&V study." (Page 1-1)

"The technical bases for the models included in the FDT^{S} library were primarily derived from the National Fire Protection Association (NFPA) Fire Protection Handbook [2], the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering [3], and other fire science literature. This report describes the equations included in the spreadsheets that have been subjected to V&V, the technical bases of those equations, and evaluation of the sensitivities and predictive capabilities of the component spreadsheets." (Page 1-1)

"In accordance with ASTM E 1355, it is critical to evaluate fire models to establish their acceptable uses and limitations. Evaluation is also necessary to ensure that those using the models can assess the adequacy of their scientific and technical bases, select appropriate models for a desired use, and understand the levels of confidence that can be placed on the results predicted by the models. Adequate evaluation will also help to prevent unintended misuse of fire models." (Page 1-2)

"Evaluation of a fire model includes model verification and validation. Verification is the process to determine that a model correctly represents the developer's conceptual description. It is used to decide whether the model was "built" correctly. Validation is the process to determine that a model is a suitable representation of the real world and is capable of reproducing phenomena of interest. As such, validation is used to decide whether the right model was "built"." (Page 1-2)

“It is not possible to evaluate a fire model in its entirety. Thus, guidance such as that provided in ASTM E 1355 is intended to define a methodology for evaluating the predictive capabilities for a specific use. Validation for one application does not indicate validation for a different scenario.” (Page 1-2)

* * * * *

Exhibit #7 NUREG 1824, Volume 7

The following are selected excerpts from Volume 7 of NUREG-1824:

“We wish to acknowledge the team of peer reviewers who reviewed the initial draft of this report and provided valuable comments. The peer reviewers were Dr. Craig Beyler and Mr. Phil DiNenno of Hughes Associates, Inc., and Dr. James Quintiere of the University of Maryland.” (Page xxiv)

“This chapter contains information about the Fire Dynamics Simulator (FDS), its development, and its use in fire protection engineering. Most of the information has been extracted from the FDS Technical Reference Guide [Ref. 2], which contains a comprehensive description of the governing equations and numerical algorithms used to solve them. The format of this chapter follows that of ASTM E 1355, *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models*.” (Page 2-1)

“FDS was developed, and is currently maintained, by the Fire Research Division in the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST). A substantial contribution to the development of the model was made by VTT Building and Transport in Finland.” (Page 2-1)

“Sprinklers and Detectors**:** The activation of sprinklers and heat and smoke detectors are modeled using fairly simple correlations based on thermal inertia in the case of sprinklers and heat detectors, and the lag in smoke transport through smoke detectors. Sprinkler sprays are modeled by Lagrangian particles that represent a sampling of the water droplets ejected from the sprinkler.” (Page 2-3)

“A small file distributed with the FDS software contains a database with thermal properties of common materials. This data are given as examples, and users should verify the accuracy and appropriateness of the data.” (Page 2-3)

“In addition, the program records the following global quantities:

- total heat release rate (HRR)
- sprinkler and detector activation times
- mass and energy fluxes through openings or solids”

(Page 2-4)

"Although FDS can address most fire scenarios, there are limitations in all of its various algorithms. Some of the more prominent limitations of the model are listed here. More specific limitations are discussed as part of the description of the governing equations in the FDS Technical Reference Guide [Ref. 2]." (Page 2-5)

"Fire Growth and Spread**:** FDS was originally intended for design scenarios where the heat release rate of the fire is specified and the transport of heat and exhaust products is the principal aim of the simulation. However, for fire scenarios where the heat release rate is *predicted* rather than *prescribed*, the uncertainty of the model is higher. There are several reasons for this: (1) properties of real materials and real fuels are often unknown or difficult to obtain, (2) the physical processes of combustion, radiation, and solid phase heat transfer are more complicated than their mathematical representations in FDS, and (3) the results of calculations are sensitive to both the numerical and physical parameters." (Page 2-5)

"Until reliable models can be developed for building-scale fire simulations, simple empirical rules can be used that prevent burning from taking place when the atmosphere immediately surrounding the fire cannot sustain the combustion." (Page 2-5)

Fire Phenomena	Algorithm/Methodology	V&V
Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire With Natural Ventilation Compartment	Large Eddy Simulation transport for a specified fire	Yes
Predicting Hot Gas Layer Temperature in a Room Fire With Forced Ventilation Compartment	LES transport with forced flow boundary condition	Yes
Predicting Hot Gas Layer Temperature in a Fire Room With Door Closed	LES transport, Mixture Fraction combustion model	Yes
Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration and Flame Height	Mixture Fraction combustion model	Yes
Estimating Wall Fire Flame Height, Line Fire Flame Height Against the Wall, and Corner Fire Flame Height	Mixture Fraction combustion model	No
Estimating Radiant Heat Flux From Fire to a Target	Finite Volume Radiation Model	Yes
Estimating the Ignition Time of a Target Fuel	One dimensional heat conduction in solid with global one-step pyrolysis	No
Estimating Burning Duration of Solid Combustibles	Same	No
Estimating Centerline Temperature of a Buoyant Fire Plume	Large Eddy Simulation of a specified fire	Yes

Estimating Sprinkler Activation	RTI/C-Factor Algorithm	No
Suppression by water spray	Surface cooling or empirical correlation	No
Estimating Smoke Detector Response Time	Heskestad smoke detector model	No
Predicting Compartment Flashover	Mixture Fraction combustion with local extinction	No
Estimating Pressure Rise Attributable to a Fire in a Closed Compartment	Global conservation of mass and energy, plus leakage algorithm	Yes
Calculating the Fire Resistance of Structural Members	One-Dimensional conduction and radiative/convective heat flux	No
Estimating Visibility Through Smoke	Fixed smoke yield from fire and basic LES transport	Yes

(Pages 3-1 and 3-2)

“ASTM E 1355 includes guidance on assessing the theoretical basis of the model including a review of the model “by one or more recognized experts fully conversant with the chemistry and physics of fire phenomenon, but not involved with the production of the model.” FDS has been subjected to independent review both internally (at NIST), and externally. NIST documents and products receive extensive reviews by NIST staff who are not directly associated with their development. Internal reviews have been conducted on all previous versions of the FDS Technical Reference Guide over the last decade. Externally, the theoretical basis for the model has been published in peer-reviewed journals and conference proceedings. In addition, FDS is used worldwide by fire protection engineering firms, which validate the model for their particular applications. Some of these firms also publish in the open literature reports documenting internal efforts to validate the model for a particular use. Finally, FDS is referenced in the NFPA 805 standard.” (Page 3-4)

“The technical approach and assumptions of FDS have been presented in the peer-reviewed scientific literature and at technical conferences. All documents released by NIST go through an internal editorial review and approval process. FDS is subjected to continuous scrutiny because it is available to the general public and is used internationally by specialists in fire safety design and post-fire reconstruction. The source code for FDS is released publicly, and has been used at various universities worldwide, both in research and the classroom as a teaching tool. As a result, flaws in the theoretical development and the computer program itself have been identified and fixed.” (Page 3-4)

"No single document provides a comprehensive assessment of the numerical and physical parameters used in FDS. Specific parameters have been tested in various V&V studies performed at NIST and elsewhere. Numerical parameters are taken from the literature and do not undergo formal review. The model user is expected to assess the appropriateness of the FDS default values and change them if necessary." (Page 3-5)

"This V&V project began using Version 4.05 of FDS. As part of the V&V process, several improvements were made and a minor bug was corrected in this version." (Page 4-2)

"FDS can now predict thermocouple temperatures, rather than gas temperatures. Because temperatures are usually measured by thermocouples, this capability is useful when comparing FDS temperature outputs to experimental data." (Page 4-2)

"FDS now has the capability to mimic radiometers, net heat flux gauges, and total heat flux gauges. These are the most common measurement tools for heat flux. This capability is useful when comparing FDS heat flux outputs to experimental data." (Page 4-2)

"The final version of FDS used in this study is Version 4.06 and includes the changes described above." (Page 4-3)

"The use of finite differences to approximate spatial and temporal partial derivatives introduces error into the FDS calculation. This numerical error is dependent on the grid size. As the numerical grid is refined, the numerical error decreases. If the grid is refined to about 1 mm (0.04 inch) or less, the simulation becomes a *direct numerical simulation* (DNS), where no assumptions about the underlying turbulence need to be made." (Page 4-3)

"The most important numerical parameter in FDS is the grid cell size. CFD models solve an approximate form of the conservation equations of mass, momentum, and energy on a numerical grid. The error associated with the discretization of the partial derivatives is a function of the size of the grid cells and the type of differencing used." (Page 5-1)

"With any grid resolution study, a point of diminishing returns is reached when the improvement in the quality of the results is outweighed by the "cost" of the computation. When this point is reached depends on the application. It also depends on the quantities that are of interest. Some quantities, like HGL temperature or height, do not typically require as fine a numerical grid as quantities such as the heat flux to targets near the fire." (Page 5-1)

"Coarse grid CFD can provide reasonable predictions of certain quantities, especially those that can be traced directly to conservation equations of mass and energy, like average temperatures and pressures. However, the user has to be aware that the results are generally less reliable than those obtained from a finer grid, and certain results cannot be obtained at all." (Page 5-2)

“This reduces the magnitude of the “artificial” viscosity added to the numerical solution, allowing for a greater level of eddy formation and, thus, greater mixing. In this case, the reduction in the coefficient leads to about a 15% reduction in the plume temperature, moving the simulation closer to the experiment. While the rationale for reducing the coefficient is grounded in physics, it has been found over the years that the lower value makes FDS more prone to numerical instabilities. Because FDS is used for a wide variety of applications, the Smagorinsky coefficient has been chosen to balance accuracy and numerical stability.” (Page 5-5)

“Of all the physical input parameters, the simulation results are most sensitive to the heat release rate.” (Page 5-5)

“FM/SNL Series: The Factory Mutual & Sandia National Laboratories (FM/SNL) Test Series is a series of 25 fire tests conducted for the US NRC by Factory Mutual Research Corporation (FMRC), under the direction of Sandia National Laboratories (SNL). The primary purpose of these tests was to provide data with which to validate computer models for various types of NPP compartments.” (Pages 6-1 and 6-2)

“The measure of model “accuracy” used throughout this study is related to experimental uncertainty. Volume 2 discusses this issue in detail. In brief, the accuracy of a *measurement*, for example, a gas temperature, is related to the measurement device, a thermocouple. In addition, the accuracy of the *model prediction* of the gas temperature is related to the simplified physical description of the fire and the accuracy of the input parameters, especially the *specified* heat release rate. Ideally, the purpose of a validation study is to determine the accuracy of the model in the absence of any errors related to the measurement of both its inputs and outputs. Because it is impossible to eliminate experimental uncertainty, at the very least a combination of the uncertainty in the measurement of model inputs and output can be used as a yardstick. If the numerical prediction falls within the range of uncertainty attributable to both the measurement of the input parameters and the output quantities, it is not possible to further quantify its accuracy. At this stage, it is said that the prediction is *within experimental uncertainty.*” (Page 6-2 and 6-3)

“For FDS, only the Green and Yellow ratings have been assigned to the 13 quantities of interest. The color Green indicates that the research team has concluded that the model physics accurately represent the experimental conditions, and the differences between model prediction and experimental measurement are less than the combined experimental uncertainty. The color Yellow suggests that one should exercise caution when using the model to evaluate this quantity; consider carefully the assumptions made by the model, how the model has been applied, and the accuracy of its results. There is specific discussion of model limitations for the quantities assigned a Yellow rating.” (Page 6-3)

"In many instances, *D** is comparable to the physical diameter of the fire (in which case, *Q** is on the order of 1). FDS employs a numerical technique known as large eddy simulation (LES) to model the unresolvable or "sub-grid" motion of the hot gases. The effectiveness of the technique is largely a function of the ratio of the fire's characteristic diameter, *D**, to the size of a grid cell, δ*x*. In short, the greater the ratio *D**/δ*x*, the more the fire dynamics are resolved directly, and the more accurate the simulation. Past experience has shown that a ratio of 5 to 10 usually produces favorable results at a moderate computational cost [Ref. 24]." (Page 6-5)

"While the slight over-prediction of ceiling jet temperature could be considered conservative for some applications, for scenarios involving sprinkler or heat detector activation, the increased temperature in the ceiling jet would lead to a quicker response of the simulated sprinkler or heat detector." (Page 6-10)

"Overall, FDS is slightly less accurate in its prediction of the near-ceiling temperature than of the overall HGL temperature. This makes sense because the ceiling jet, as with the fire plume, is a region of the flow field exhibiting relatively high levels of buoyancy and/or shear induced turbulence. Inaccuracies in its prediction tend to be averaged out when examining the bulk HGL temperature, but it is important to consider this higher degree of inaccuracy if the objective of the calculation is to assess the damage to or activation of some object or device near the ceiling." (Page 6-12)

"FDS has only been evaluated for oxygen and carbon dioxide. The conclusions should not be extended to carbon monoxide, smoke, or other exhaust products whose yields and/or transport properties are not as well-characterized as oxygen and carbon dioxide." (Page 6-17)

"FDS treats smoke like all other combustion products, basically a tracer gas for which the local mass concentration is a function of the local mixture fraction. To model smoke movement, the user need only prescribe the smoke yield (that is, the fraction of the fuel mass that is converted to smoke particulate)." (Page 6-18)

"Curiously, the smoke production rate appears to decrease as the fire becomes more oxygen-starved, or possibly the optical properties of the smoke change, leading to a misleading measurement of the smoke mass per unit volume." (Page 6-18)

"FDS is capable of transporting smoke throughout a compartment, assuming that the production rate is known and that its transport properties are comparable to gaseous exhaust products. This assumption may break down in closed-door fires, or if an appreciable part of the flame extends into the upper layer." (Page 6-20)

“The thermal properties of the gypsum board and the plywood were not measured, and the exact composition of each batch changes depending on the supply of raw materials. Therefore, it cannot be concluded that FDS is less accurate in predicting floor temperatures than it is predicting wall or ceiling temperatures.” (Page 6-27)

“For a fire for which the heat release rate is known, FDS can reliably predict gas temperatures, major gas species concentrations, and compartment pressures to within about 15%, and heat fluxes and surface temperatures to within about 25%.” (Page 6-29)

“Once validated for the simple compartment geometries, FDS can then be used to look at more complicated geometries where non-uniformities of temperature, and non-idealized gas flows cannot be addressed by simple two-zone models.” (Page 6-29)

* * * * *

Exhibit #8 Fire Dynamics Simulator (Version 5) Verification & Validation Guide Volume 1: Verification (Draft), National Institute of Standards and Technology (NIST), May 30,2007

The following are selected excerpts from Volume 1 of the “Fire Dynamics Simulator Verification & Validation Guide”:

“This guide is based in part on the “Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models,” ASTM E 1355 [1]. ASTM E 1355 defines model evaluation as “the process of quantifying the accuracy of chosen results from a model when applied for a specific use.” The model evaluation process consists of two main components: verification and validation. Verification is a process to check the correctness of the solution of the governing equations. Verification does not imply that the governing equations are appropriate; only that the equations are being solved correctly. Validation is a process to determine the appropriateness of the governing equations as a mathematical model of the physical phenomena of interest. Typically, validation involves comparing model results with experimental measurement. Differences that cannot be explained in terms of numerical errors in the model or uncertainty in the measurements are attributed to the assumptions and simplifications of the physical model.” (Page *i*)

“Evaluation is critical to establishing both the acceptable uses and limitations of a model. Throughout its development, FDS has undergone various forms of evaluation, both at NIST and beyond. This guide provides a survey of work conducted to date to evaluate FDS.” (Page *i*)

“The software package is a computer model that may or may not have predictive capability when applied to a specific set of factual circumstances. Lack of accurate predictions by the model could lead to erroneous conclusions with regard to fire safety. All results should be evaluated by an informed user.” (Page *iii*)

“The heat release rate is the most important physical parameter, as it is the source term in the energy equation. Property data, like the thermal conductivity, density, heat of vaporization, heat capacity, etc., ought to be assessed in terms of their influence on the heat release rate. Validation studies have shown that FDS predicts well the transport of heat and smoke when the HRR is prescribed. In such cases, minor changes in the properties of bounding surfaces do not have a significant impact on the results. However, when the HRR is not prescribed, but rather predicted by the model using the thermophysical properties of the fuels, the model output is sensitive to even minor changes in these properties.” (Page 31)

"The most important decision made by a model user is the size of the numerical grid. In general, the finer the numerical grid, the better the numerical solution of the equations. FDS is second-order accurate in space and time, meaning that halving the grid cell size will decrease the discretization error in the governing equations by a factor of 4. Because of the non-linearity of the equations, the decrease in discretization error does not necessarily translate into a comparable decrease in the error of a given FDS output quantity. To find out what effect a finer grid has on the solution, model users usually perform some form of grid sensitivity study in which the numerical grid is systematically refined until the output quantities do not change appreciably with each refinement. Of course, with each halving of the grid cell size, the time required for the simulation increases by a factor of 2^4 = 16 (a factor of two for each spatial coordinate, plus time). In the end, a compromise is struck between model accuracy and computer capacity." (Page 32)

"Errors of 100 % in heat flux were caused by errors of 20 % in absolute temperature." (Page 34)

"Moisture content of wooden fuels is very important and difficult to measure." (Page 35)

"Flame spread over complicated objects, like cables laid out in trays, can be modeled if the surface area of the simplified object is comparable to that of the real object. This suggests sensitivity not only to physical properties, but also geometry. It is difficult to quantify the extent of the geometrical sensitivity." (Page 35)

"As a rule of thumb, in simulations of limited resolution FDS predictions are more reliable in the farfield because the substantial numerical diffusion mimics the unresolved sub-grid scale mixing. This is hard to quantify other than through comparisons with experiment. In some of the sensitivity studies discussed above, the authors conclude that the model works best with a cell size of a given value, and often this cell is not the smallest one tested. In these cases, the authors have found a flow scenario where the unresolved convective mixing is almost exactly offset by numerical diffusion. This is fortuitous, but the conclusion does not necessarily extend to other scenarios. The disadvantage of any turbulence model, large eddy simulation included, is that good results are not guaranteed on grids of limited resolution. The advantage of LES over other turbulence models is that the solution of the actual governing equations, not a temporal or spatial average, is obtained as the mesh is refined." (Pages 35 and 36)

"The same can be said for phenomena closer in to the fire. However, grid resolution is more critical for near-field phenomena because numerical diffusion near the fire on coarse grids does not have the same fortuitous effect as it does on far-field results. In general, coarse resolution will decrease temperatures and velocities by smearing the values over the large grid cells. This can affect the radiative flux, convection to surrounding solids, and ultimately flame spread and fire growth." (Page 36)

* * * * *

Exhibit #9 **Fire Dynamics Simulator (Version 5) Technical Reference Guide, National Institute of Standards and Technology (NIST), October 1, 2007**

The following are selected excerpts from the “Fire Dynamics (Version 5) Technical Reference Guide”:

“Sufficient evaluation of any model is necessary to ensure that users can judge the adequacy of its technical basis, appropriateness of its use, and confidence level of its predictions. This document provides the theoretical basis for the Fire Dynamics Simulator (FDS), following the general framework set forth in the “Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models,” ASTM E 1355 [3].” (Page *i*)

“The US Department of Commerce makes no warranty, expressed or implied, to users of the Fire Dynamics Simulator (FDS), and accepts no responsibility for its use. Users of FDS assume sole responsibility under Federal law for determining the appropriateness of its use in any particular application; for any conclusions drawn from the results of its use; and for any actions taken or not taken as a result of analysis performed using these tools.” (Page *iii*)

“The basic idea behind the LES technique is that the eddies that account for most of the mixing are large enough to be calculated with reasonable accuracy from the equations of fluid dynamics. The hope (which must ultimately be justified by comparison to experiments) is that small-scale eddy motion can either be crudely accounted for or ignored.” (Page 2)

“The major assumptions of the model, for example the large eddy simulation technique and the mixture fraction combustion model, have undergone a roughly 40 year development and are now documented in popular introductory text books. More specific sub-models, like the sprinkler spray routine or the various pyrolysis models, have yet to be developed to this extent. As a consequence, all documents produced by NIST staff are required to go through an internal editorial review and approval process. This process is designed to ensure compliance with the technical requirements, policy, and editorial quality required by NIST. The technical review includes a critical evaluation of the technical content and methodology, statistical treatment of data, uncertainty analysis, use of appropriate reference data and units, and bibliographic references.” (Page 13)

"Any user of the numerical model [FDS] must be aware of the assumptions and approximations being employed. There are two issues for any potential user to consider before embarking on calculations. First, for both real and simulated fires, the growth of the fire is very sensitive to the thermal properties (conductivity, specific heat, density, burning rate, etc.) of the surrounding materials. Second, even if all the material properties are known, the physical phenomena of interest may not be simulated due to limitations in the model algorithms or numerical grid. Except for those few materials that have been studied to date at NIST, the user must supply the thermal properties of the materials, and then validate the performance of the model with experiments to ensure that the model has the necessary physics included**.** Only then can the model be expected to predict the outcome of fire scenarios that are similar to those that have actually been tested." (Page 71)

* * * * *

Exhibit #10 Sprinkler, Smoke & Heat Vent, Draft Curtain Interaction–Large Scale Experiments and Model Development (NISTIR 6196-1), National Institute of Standard and Technology (NIST), September 1998

The following are selected excerpts from NISTIR 6196-1 dated September 1998:

"In parallel with the large scale fire tests, a program was conducted at NIST to develop a numerical field model, Industrial Fire Simulator (IFS), that incorporated the physical phenomena of the experiments. A series of bench scale experiments was conducted to develop necessary input data for the model. These experiments generated data describing the burning rate and flame spread behavior of the cartoned plastic commodity, thermal response parameters and spray pattern of the sprinkler, and the effect of the water spray on the burning commodity. Simulations were first performed for the heptane spray burner tests, where they were shown to be in good *quantitative* agreement in terms of both predicting sprinkler activation times and near-ceiling gas temperature rise. The sprinkler activation times were predicted to within about 15% of the experiments for the first ring, 25% for the second. The gas temperatures near the ceiling were predicted to within about 15%." (Page *i*)

"The significant cooling effect of sprinkler sprays on the near-ceiling gas flow often prevented the automatic operation of vents. This conclusion is based on thermocouple measurements within the vent cavity, the presence of drips of solder on the fusible links recovered from unopened vents, and several tests where vents remote from the fire and the sprinkler spray activated. In one cartoned plastic commodity experiment, a vent did not open when the fire was ignited directly beneath it. The model simulations could not predict this phenomenon." (Page *ii*)

Exhibit #11 Comparison of Sprinkler Activating Times-NFPRF Full-Scale Tests vs. Hughes Associates, Inc. Model Runs

	Total # of Activations	1st A.S. Activations	1st Four A.S. Activations	1st Five A.S. Activations	1st Six A.S. Activations	1st Seven A.S. Activations
Test P-1	20 A.S.	76 sec.	303 sec.	511 sec.	515 sec.	562 sec.
Test P-2	23+ A.S.	100 sec.	121 sec.	150 sec.	152 sec.	154 sec.
Test P-3	19+ A.S.	67 sec.	123 sec.	131 sec.	242 sec.	307 sec.
Test P-4	5 A.S.	93 sec.	199 sec.	200 sec.	-----	-----
Test P-5	7 A.S.	74 sec.	147 sec.	201 sec.	213 sec.	304 sec.
Average		**82.0 sec.**	**178.6 sec.**	**238.6 sec.**	**280.5 sec.**	**331.8 sec.**
Range		**67-100 sec.**	**121-303 sec.**	**131-511 sec.**	**152-515 sec.**	**154-562 sec.**

Note: The "+" sign indicates that sprinklers immediately adjacent to the edge of the "mock-up" operated and that it is possible that additional sprinklers may have operated had the "mock-up" extended further.

	Total # of Activations	1st A.S. Activations	1st Four A.S. Activations	1st Five A.S. Activations	1st Six A.S. Activations	1st Seven A.S. Activations
Run #1	5 A.S.	69 sec.	74 sec.	88 sec.	-----	-----
Run #2	6 A.S.	70 sec.	74 sec.	92 sec.	92 sec.	-----
Run #3	6 A.S.	70 sec.	74 sec.	86 sec.	90 sec.	-----
Run #4	19 A.S.	71 sec.	74 sec.	82 sec.	84 sec.	96 sec.
Run #5	18 A.S.	71 sec.	74 sec.	83 sec.	84 sec.	97 sec.
Run #6	20 A.S.	71 sec.	74 sec.	83 sec.	84 sec.	96 sec.
Run #7	21 A.S.	70 sec.	74 sec.	83 sec.	84 sec.	98 sec.
Run #8	19 A.S.	70 sec.	74 sec.	82 sec.	82 sec.	99 sec.
Run #9	20 A.S.	70 sec.	73 sec.	83 sec.	84 sec.	99 sec.
Run #10	20 A.S.	64 sec.	75 sec.	90 sec.	92 sec.	92 sec.
Run #11	18 A.S.	70 sec.	74 sec.	84 sec.	84 sec.	98 sec.
Run #12	17 A.S.	69 sec.	74 sec.	85 sec.	86 sec.	98 sec.
Run #13	19 A.S.	68 sec.	79 sec.	79 sec.	85 sec.	92 sec.
Run #14	22 A.S.	63 sec.	76 sec.	87 sec.	93 sec.	93 sec.
Run #15	20 A.S.	65 sec.	81 sec.	84 sec.	90 sec.	97 sec.
Run #16	21 A.S.	65 sec.	79 sec.	85 sec.	86 sec.	92 sec.
Average		**68.5 sec.**	**75.2 sec.**	**84.8 sec.**	**86.7 sec.**	**95.9 sec.**
Range		**64-71 sec.**	**73-81 sec.**	**79-92 sec.**	**82-93 sec.**	**92-99 sec.**

* * * * *