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Final Report

Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications

Volume 5:
Consolidated Fire Growth and Smoke Transport Model (CFAST)

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May 2007

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ABSTRACT

There is a movement to introduce risk-informed and performance-based analyses into fire protection engineering practice, both domestically and worldwide. This movement exists in the general fire protection community, as well as the nuclear power plant (NPP) fire protection community. The U.S. Nuclear Regulatory Commission (NRC) has used risk-informed insights as part of its regulatory decision making since the 1990s.

In 2002, the National Fire Protection Association (NFPA) developed NFPA 805, *Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants, 2001 Edition.* In July 2004, the NRC amended its fire protection requirements in Title 10, Section 50.48, of the *Code of Federal Regulations* (10 CFR 50.48) 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. In addition, the NPP fire protection community has been using risk-informed, performance-based (RI/PB) approaches and insights to support fire protection decision-making in general.

One key tool needed to further the use of RI/PB 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.

This report is the first effort to document the verification and validation (V&V) of five fire models that are commonly used in NPP applications. The project was performed in accordance with the guidelines that the American Society for Testing and Materials (ASTM) set forth in ASTM E 1355, *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models*.
The results of this V&V are reported in the form of ranges of accuracies for the fire model predictions.

FOREWORD

Fire modeling and fire dynamics calculations are used in a number of fire hazards analysis (FHA) studies and documents, including fire risk analysis (FRA) calculations; compliance with and exemptions to the regulatory requirements for fire protection in 10 CFR Part 50; the Significance Determination Process (SDP) used in the inspection program conducted by the U.S. Nuclear Regulatory Commission (NRC); and, most recently, the risk-informed performance-based (RI/PB) voluntary fire protection licensing basis established under 10 CFR 50.48(c). The RI/PB method is based on the National Fire Protection Association (NFPA) Standard 805, *Performance-Based Standard for Fire Protection for Light-Water Reactor Generating Plants*.

The seven volumes of this NUREG-series report provide technical documentation concerning the predictive capabilities of a specific set of fire dynamics calculation tools and fire models for the analysis of fire hazards in postulated nuclear power plant (NPP) scenarios. Under a joint memorandum of understanding (MOU), the NRC Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) agreed to develop this technical document for NPP application of these fire modeling tools. The objectives of this agreement include creating a library of typical NPP fire scenarios and providing information on the ability of specific fire models to predict the consequences of those typical NPP fire scenarios. To meet these objectives, RES and EPRI initiated this collaborative project to provide an evaluation, in the form of verification and validation (V&V), for a set of five commonly available fire modeling tools.

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.

This document does not constitute regulatory requirements, and NRC participation in this study neither constitutes nor implies regulatory approval of applications based on the analysis contained in this text. The analyses documented in this report represent the combined efforts of individuals from RES and EPRI. Both organizations provided specialists in the use of fire models and other FHA tools to support this work. The results from this combined effort do not constitute either a regulatory position or regulatory guidance. 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.

Brian W. Sheron, Director
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REPORT SUMMARY

This report documents the verification and validation (V&V) of five selected fire models commonly used in support of risk-informed and performance-based (RI/PB) fire protection at nuclear power plants (NPPs).

Background

Since the 1990s, when it became the policy of the NRC to use risk-informed methods to make regulatory decisions where possible, the nuclear power industry has been moving from prescriptive rules and practices toward the use of risk information to supplement decision-making. Several initiatives have furthered this transition in the area of fire protection. 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. 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."

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.

Approach

This project team performed V&V studies on five selected models: (1) NRC's NUREG-1805 Fire Dynamics Tools (FDTS), (2) EPRI's Fire-Induced Vulnerability Evaluation Revision 1 (FIVE-Rev1), (3) National Institute of Standards and Technology's (NIST) Consolidated Model of Fire Growth and Smoke Transport (CFAST), (4) Electricité de France's (EdF) MAGIC, and (5) NIST's Fire Dynamics Simulator (FDS). The team based these studies on the guidelines of the ASTM E 1355, *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models*. 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.

Results

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.

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.

EPRI Perspective

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.

Keywords

Fire
Verification and Validation (V&V)
Risk-Informed Regulation
Fire Safety
Nuclear Power Plant
Fire Probabilistic Safety Assessment (PSA)
Fire Modeling
Performance-Based
Fire Hazard Analysis (FHA)
Fire Protection
Fire Probabilistic Risk Assessment (PRA)

PREFACE

This report is presented in seven volumes. Volume 1, the Main Report, provides general background information, programmatic and technical overviews, and project insights and conclusions. Volume 2 quantifies the uncertainty of the experiments used in the V&V study of these five fire models. Volumes 3 through 6 provide detailed discussions of the verification and validation (V&V) of the following five fire models:

Volume 3	Fire Dynamics Tools (FDT^{s})
Volume 4	Fire-Induced Vulnerability Evaluation, Revision 1 (FIVE-Rev1)
Volume 5	Consolidated Model of Fire Growth and Smoke Transport (CFAST)
Volume 6	MAGIC
Volume 7	Fire Dynamics Simulator (FDS)

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The verification and validation (V&V) studies for FDT^s (Volume 3), CFAST (Volume 5), and FDS (Volume 7) were conducted in collaboration with the U.S. Department of Commerce, National Institute of Standards and Technology (NIST), Building and Fire Research Laboratory (BFRL). Since the inception of this project in 1999, the NRC has collaborated with NIST through an interagency memorandum of understanding (MOU) and conducted research to provide the necessary technical data and tools to support the use of fire models in nuclear power plant fire hazard analysis (FHA).

We appreciate the efforts of Doug Carpenter and Rob Schmidt of Combustion Science Engineers, Inc. for their comments and contributions to Volume 3.

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We also appreciate the efforts of organizations participating in the International Collaborative Fire Model Project (ICFMP) to Evaluate Fire Models for Nuclear Power Plant Applications, which provided experimental data, problem specifications, and insights and peer comment for the international fire model benchmarking and validation exercises, and jointly prepared the panel reports used and referred to in this study. We specifically appreciate the efforts of the Building Research Establishment (BRE) and the Nuclear Installations Inspectorate in the United Kingdom, which provided leadership for ICFMP Benchmark Exercise (BE) #2, as well as Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) and Institut für Baustoffe, Massivbau und Brandschutz (iBMB) in Germany, which provided leadership and valuable experimental data for ICFMP BE #4 and BE #5. In particular, ICFMP BE #2 was led by Stewart Miles at BRE; ICFMP BE #4 was led by Walter Klein-Hessling and Marina Rowekamp at GRS, and R. Dobbernack and Olaf Riese at iBMB; and ICFMP BE #5 was led by Olaf Riese and D. Hosser at iBMB, and Marina Rowekamp at GRS. Simo Hostikka of VTT, Finland also assisted with ICFMP BE#2 by providing pictures, tests reports, and answered various technical questions of those experiments. We acknowledge and sincerely appreciate all of their efforts.

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LIST OF ACRONYMS

AGA	American Gas Association
AHJ	Authority Having Jurisdiction
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BE	Benchmark Exercise
BFRL	Building and Fire Research Laboratory
BRE	Building Research Establishment
BWR	Boiling-Water Reactor
CDF	Core Damage Frequency
CFAST	Consolidated Fire Growth and Smoke Transport Model
CFD	Computational Fluid Dynamics
CFR	*Code of Federal Regulations*
CSR	Cable Spreading Room
EdF	Electricité de France
EPRI	Electric Power Research Institute
FDS	Fire Dynamics Simulator
FDT^s	Fire Dynamics Tools (NUREG-1805)
FHA	Fire Hazard Analysis
FIVE-Rev1	Fire-Induced Vulnerability Evaluation, Revision 1

FM/SNL	Factory Mutual & Sandia National Laboratories
FPA	Foote, Pagni, and Alvares
FRA	Fire Risk Analysis
GRS	Gesellschaft für Anlagen-und Reaktorsicherheit (Germany)
HGL	Hot Gas Layer
HRR	Heat Release Rate
IAFSS	International Association of Fire Safety Science
iBMB	Institut für Baustoffe, Massivbau und Brandschutz
ICFMP	International Collaborative Fire Model Project
IEEE	Institute of Electrical and Electronics Engineers
IPEEE	Individual Plant Examination of External Events
MCC	Motor Control Center
MCR	Main Control Room
MQH	McCaffrey, Quintiere, and Harkleroad
MOU	Memorandum of Understanding
NBS	National Bureau of Standards (now NIST)
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation (NRC)
PMMA	Polymethyl-methacrylate
PWR	Pressurized Water Reactor

RCP	Reactor Coolant Pump
RES	Office of Nuclear Regulatory Research (NRC)
RI/PB	Risk-Informed, Performance-Based
SBDG	Stand-By Diesel Generator
SDP	Significance Determination Process
SFPE	Society of Fire Protection Engineers
SWGR	Switchgear Room
V&V	Verification & Validation

1

INTRODUCTION

As the use of fire modeling tools increases in support of day-to-day nuclear power plant (NPP) applications including fire risk studies, the importance of verification and validation (V&V) studies for these tools also increases. V&V studies provide the fire modeling analysts increased 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.

The main objective of this volume is to document a V&V study for the Consolidated Fire Growth and Smoke Transport (CFAST) zone model. As such, this report describes the equations that constitute the model, the physical bases for those equations, and an evaluation of the sensitivity and predictive capability of the model.

CFAST is a two-zone fire model capable of predicting the fire-induced environmental conditions as a function of time for single- or multi-compartment scenarios. Toward that end, the CFAST software calculates the temperature and evolving distribution of smoke and fire gases throughout a building during a user-prescribed fire. The model was developed, and is maintained, by the Fire Research Division of the National Institute of Standards and Technology (NIST), which officially released the latest version of the CFAST model in 2004.

CFAST is a zone model, in that it subdivides each compartment into two zones, or control volumes, in order to numerically solve differential equations, and the two volumes are assumed to be homogeneous within each zone. This two-zone approach has evolved from observations of layering in actual fires and real-scale fire experiments. The approximate solution of the mass and energy balances of each zone, together with the ideal gas law and the equation of heat conduction into the walls, attempts to simulate the environmental conditions generated by a fire.

To accompany the model and simplify its use, NIST has developed a Technical Reference Guide [Ref. 1] that provides a detailed description of the models and numerical solutions in CFAST. That guide also documents a V&V study for the broad applications of CFAST (without specific reference to NPPs). That study was conducted at the request of the U.S. Nuclear Regulatory Commission (NRC), in accordance with ASTM E 1355, *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models* [Ref. 2], issued by the American Society for Testing and Materials (ASTM). As such, this report extensively references both the CFAST Technical Reference Guide and ASTM E 1355.

Consistent with the CFAST Technical Reference Guide and ASTM E 1355, this report is structured as follows:

- Chapter 2 provides qualitative background information about CFAST and the V&V process.
- Chapter 3 presents a brief technical description of CFAST, including a review of the underlying physics and chemistry.
- Chapter 4 documents the mathematical and numerical robustness of CFAST, which involves verifying that the implementation of the model matches the stated documentation.
- Chapter 5 presents a sensitivity analysis, for which the researchers defined a base case scenario and varied selected input parameters in order to explore CFAST capabilities for modeling typical characteristics of NPP fire scenarios.
- Chapter 6 presents the results of the validation study in the form of percent differences between CFAST simulations and experimental data for relevant attributes of enclosure fires in NPPs.
- Appendix A presents the technical details supporting the calculated accuracies discussed in Chapter 6.
- Appendix B presents all of the CFAST input files for the simulations in this V&V study.

2
MODEL DEFINITION

This chapter provides qualitative background information about CFAST and the V&V process, as outlined by ASTM E 1355 [Ref. 2]. The definitive description of the CFAST model, including its developers, equations, assumptions, inputs, and outputs can be found in the CFAST Technical Reference Guide [Ref. 1], which also follows the guidelines for ASTM E 1355.

2.1 Name and Version of the Model

This V&V study focused on Version 6.0.10 of the Consolidated Fire Growth and Smoke Transport (CFAST) Model. Most of the code is written in FORTRAN 90. Chapter 2 of the CFAST Technical Reference Guide [Ref. 1] provides a more detailed description of the evolution of the model.

2.2 Type of Model

CFAST is a two-zone fire model that predicts the fire-induced environment as a function of time for single- or multi-compartment scenarios. CFAST subdivides each compartment into two zones (or volumes) in order to numerically solve differential equations, and the two volumes are assumed to be uniform in temperature and species concentration. The approximate solution of the conservation equations for each zone, together with the ideal gas law and the equation of heat conduction into the walls, attempts to simulate the environmental conditions generated by a fire.

2.3 Model Developers

The CFAST model was developed, and is maintained, by the Fire Research Division of NIST. The developers include Walter Jones, Richard Peacock, Glenn Forney, Rebecca Portier, Paul Reneke, John Hoover, and John Klote.

2.4 Relevant Publications

Relevant publications concerning CFAST include the CFAST Technical Reference Guide [Ref. 1] and User's Guide [Ref. 3]. The Technical Reference Guide describes the underlying physical principles, provides a comparison with experimental data, and describes the limitations of the model. The User's Guide describes how to use the model. In addition, numerous related documents available at http://cfast.nist.gov provide a wealth of information concerning Versions 2, 3, 4 and 5 of both the model and its user interface.

2.5 Governing Equations and Assumptions

Section 2.1.5 and Chapter 3 of the CFAST Technical Reference Guide [Ref. 1] fully describe the equations and assumptions associated with the CFAST model. The general equations solved by the CFAST model include conservation of mass and energy. The model does not explicitly solve the momentum equation, except for use of the Bernoulli equation for the flow velocity at vents. These equations are solved as ordinary differential equations.

The CFAST model is implemented based on two general assumptions: (1) two zones per compartment provide a reasonable approximation of the scenario being evaluated, and (2) the complete momentum equation is not needed to solve the set of equations associated with the model. Consequently, the two zones have uniform properties. That is, the temperature and gas concentrations are assumed to be constant throughout the zone; the properties only change as a function of time.

2.6 Input Data Required to Run the Model

All of the data required to run the CFAST model reside in a primary data file, which the user creates. Some instances may require databases of information on objects, thermophysical properties of boundaries, and sample prescribed fire descriptions. In general, the data files contain the following information:

- compartment dimensions (height, width, length)
- construction materials of the compartment (e.g., concrete, gypsum)
- material properties (e.g., thermal conductivity, specific heat, density, thickness, heat of combustion)
- dimensions and positions of horizontal and vertical flow openings such as doors, windows, and vents
- mechanical ventilation specifications
- fire properties (e.g., heat release rate, lower oxygen limit, and species production rates as a function of time)
- sprinkler and detector specifications
- positions, sizes, and characteristics of targets

The CFAST User's Guide [Ref. 3] provides a complete description of the required input parameters. Some of these parameters have default values included in the model, which are intended to be representative for a range of fire scenarios. Unless explicitly noted, default values were used for parameters not specifically included in this validation study.

2.7 Property Data

Required inputs for CFAST include a number of material properties related to compartment bounding surfaces, objects (called targets) placed in compartments for calculation of object surface temperature and heat flux to the objects, or fire sources. For compartment surfaces and targets, CFAST needs the density, thermal conductivity, specific heat, and emissivity.

For fire sources, CFAST needs to know the pyrolysis rate of fuel, the heat of combustion, stochiometric fuel-oxygen ratio, yields of important combustion products in a simplified combustion reaction (carbon monoxide, carbon dioxide, soot, and others), and the fraction of energy released in the form of thermal radiation.

These properties are commonly available in fire protection engineering and materials handbooks. Experimentally determined property data may also be available for certain scenarios. However, depending on the application, properties for specific materials may not be readily available. A small file distributed with the CFAST software contains a database with thermal properties of common materials. These data are given as examples, and users should verify the accuracy and appropriateness of the data.

2.8 Model Results

Once the simulation is complete, CFAST produces an output file containing all of the solution variables. Typical outputs include (but are not limited to) the following:

- environmental conditions in the room (such as hot gas layer temperature; oxygen and smoke concentration; and ceiling, wall, and floor temperatures)
- heat transfer-related outputs to walls and targets (such as incident convective, radiated, and total heat fluxes)
- fire intensity and flame height
- flow velocities through vents and openings
- sprinkler activation time

2.9 Uses and Limitations of the Model

CFAST has been developed for use in solving practical fire problems in fire protection engineering, while also providing a tool to study fundamental fire dynamics and smoke spread. It is intended for use in system modeling of building and building components. It is not intended for detailed study of flow within a compartment, such as is needed for smoke detector siting. It includes the activation of sprinklers and fire suppression by water droplets.

The most extensive use of the model is in fire and smoke spread in complex buildings. The efficiency and computational speed are inherent in the few computation cells needed for a zone model implementation. The use is for design and reconstruction of time-lines for fire and smoke spread in residential, commercial, and industrial fire applications. Some applications of the model have been for design of smoke control systems.

- **Compartments:** CFAST is generally limited to situations where the compartment volumes are strongly stratified. However, in order to facilitate the use of the model for preliminary estimates when a more sophisticated calculation is ultimately needed, there are algorithms for corridor flow, smoke detector activation, and detailed heat conduction through solid boundaries. This model does provide for non-rectangular compartments, although the application is intended to be limited to relatively simple spaces. There is no intent to include complex geometries where a complex flow field is a driving force. For these applications, computational fluid dynamics (CFD) models are appropriate.
- **Gas Layers:** There are also limitations inherent in the assumption of stratification of the gas layers. The zone model concept, by definition, implies a sharp boundary between the upper and lower layers, whereas in reality, the transition is typically over about 10% of the height of the compartment and can be larger in weakly stratified flow. For example, a burning cigarette in a normal room is not within the purview of a zone model. While it is possible to make predictions within 5% of the actual temperatures of the gas layers, this is not the optimum use of the model. It is more properly used to make estimates of fire spread (not flame spread), smoke detection and contamination, and life safety calculations.
- **Heat Release Rate**: There are limitations inherent in the assumptions used in application of the empirical models. As a general guideline, the heat release should not exceed about 1 MW/m^3. This is a limitation on the numerical routines attributable to the coupling between gas flow and heat transfer through boundaries (conduction, convection, and radiation). The inherent two-layer assumption is likely to break down well before this limit is reached.
- **Radiation**: Because the model includes a sophisticated radiation model and ventilation algorithms, it has further use for studying building contamination through the ventilation system, as well as the stack effect and the effect of wind on air circulation in buildings.
- **Ventilation and Leakage**: In a single compartment, the ratio of the area of vents connecting one compartment to another to the volume of the compartment should not exceed roughly 2 m^{-1}. This is a limitation on the plug flow assumption for vents. An important limitation arises from the uncertainty in the scenario specification. For example, leakage in buildings is significant, and this affects flow calculations especially when wind is present and for tall buildings. These effects can overwhelm limitations on accuracy of the implementation of the model. The overall accuracy of the model is closely tied to the specificity, care, and completeness with which the data are provided.

- **Thermal Properties**: The accuracy of the model predictions is limited by how well the user can specify the thermophysical properties. For example, the fraction of fuel which ends up as soot has an important effect on the radiation absorption of the gas layer and, therefore, the relative convective versus radiative heating of the layers and walls, which in turn affects the buoyancy and flow. There is a higher level of uncertainty of the predictions if the properties of real materials and real fuels are unknown or difficult to obtain, or the physical processes of combustion, radiation, and heat transfer are more complicated than their mathematical representations in CFAST.

In addition, there are specific limitations and assumptions made in the development of the algorithms. These are detailed in the discussion of each of these sub-models in the NIST Technical Reference Guide [Ref. 1].

3

THEORETICAL BASIS FOR CFAST

This chapter presents a technical description of the CFAST model, including its theoretical background and the underlying physics and chemistry inherent in the model. The description includes assumptions and approximations, an assessment of whether the open literature provides sufficient scientific evidence to justify the approaches and assumptions used, and an assessment of empirical or reference data used for constant or default values in the context of the model. In so doing, this chapter addresses the ASTM E 1355 guidance to “verify the appropriateness of the theoretical basis and assumptions used in the model.”

Chapter 3 of the CFAST Technical Reference Guide [Ref. 1] presents a comprehensive discussion concerning the theoretical basis for CFAST, including the theory underlying the implementation of the model. In so doing, it enables the user to assess the appropriateness of the model for specific problems. In addition, Chapter 3 of Reference 1 derives the predictive equations for zone fire models and presents a detailed explanation of those used in CFAST [Refs. 4 and 5].

3.1 The Two-Layer Model

CFAST is a classic two-zone fire model. For a given fire scenario, the model subdivides a compartment into two control volumes, which include a relatively hot upper layer and a relatively cool lower layer. In addition, mass and energy are transported between the layers via the fire plume. The lower layer is primarily fresh air. By contrast, the hot upper layer (which is also known as the hot gas layer) is where combustion products accumulate via the plume. Each layer has its own energy and mass balances.

The most important assumption for the model is that each zone has uniform properties. That is, the temperature and gas concentrations are assumed to be constant throughout the zone; the properties only change as a function of time. The CFAST model describes the conditions in each zone by solving equations for conservation of mass, species, and energy, along with the ideal gas law. The Technical Reference Guide for CFAST [Ref. 1] provides a detailed discussion concerning the specific derivation of these conservation laws.

For some applications, including long hallways or tall shafts, the two-zone assumption may not be appropriate. CFAST includes empirical algorithms to simulate smoke flow and filling in long corridors and for a single well-mixed volume in tall shafts.

CFAST also includes the following correlations (as sub-models), based on experimental data that are used to calculate various physical processes during a fire scenario:

- smoke production
- fire plume
- heat transfer by radiation, convection, and conduction
- natural flows through openings (vertical and horizontal)
- forced or natural ventilation
- thermal behavior of targets
- heat detectors
- water spray from sprinklers

Table 3-1. CFAST Capabilities Included in the V&V Study.

Fire Phenomena	**Algorithm/Methodology**	**V&V**
Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire With Natural Ventilation Compartment	Two-zone control volume model with uniform conditions in a zone	Yes
Predicting Hot Gas Layer Temperature in a Room Fire With Forced Ventilation Compartment	Two-zone control volume model with uniform conditions in a zone	Yes
Predicting Hot Gas Layer Temperature in a Fire Room With Door Closed	Two-zone control volume model with uniform conditions in a zone	Yes
Estimating Burning Characteristics of a Fire, Heat Release Rate, Burning Duration and Flame Height	User-specified HRR and species. Model limits burning by available oxygen. Hesketstad flame height correlation	Yes
Estimating Gas Concentrations Resulting from a Fire	User-specified time varying species yield from fire; global conservation of mass	Yes
Estimating Visibility Through Smoke	User-specified time varying smoke yield from fire; global conservation of mass	Yes
Estimating Flow Through Horizontal or Vertical Natural Flow Vents	Empirical correlation; global conservation of mass	No
Estimating Flow Through Horizontal or Vertical Forced Flow Vents	global conservation of mass	No
Estimating Radiant Heat Flux From Fire to a Target	Point Source Radiation from fire; four-surface radiation from compartment surfaces; gray gas absorption by gas layers	Yes

Fire Phenomena	**Algorithm/Methodology**	**V&V**
Estimating the Ignition Time of a Target Fuel	One dimensional heat conduction in solid	No
Estimating Sprinkler Activation	RTI Algorithm	No
Suppression by Water Spray	Empirical correlation	No
Estimating Smoke and Heat Alarm Response Time	One dimensional heat conduction in solid	No
Estimating Pressure Rise Attributable to a Fire in a Closed Compartment	Global conservation of mass and energy	Yes
Estimating flow in a corridor	Empirical algorithm based on FDS simulations	No

3.2 Zone Model Assumptions

The basic assumption of all zone fire models is that each compartment can be divided into a small number of control volumes, each of which is uniform in temperature and composition. In CFAST, all compartments have two zones, with an exception for well-mixed compartments (such as elevator shafts) that can be modeled as a single control volume. Since a real-world upper/lower interface is not as sharply defined as the one modeled by CFAST, the model has a spatial uncertainty of about 10% in determining the height of the hot gas layer. Uncertainty in layer temperature and position is discussed in detail in Volume 2.

The zone model concept best applies for an enclosure (compartment) in which the horizontal dimensions (width and length) are similar. If the horizontal dimensions of the compartment differ too much (i.e., the compartment looks like a corridor), the flow pattern in the room may become asymmetrical. If the enclosure is too shallow, the temperature may have significant radial differences. In addition, at some height, the width of the plume may become equal to the width of the room, and the model assumptions may fail in a tall and narrow enclosure.

Users should recognize approximate limits on the ratio of the length (L), width (W), and height (H) of the compartment as follows. If the aspect ratio (the maximum of length/width or width/length) is greater than about 5, the corridor flow algorithm should be used to provide the appropriate filling time. By contrast, a single zone approximation is more appropriate for tall shafts (elevators and stairways). In addition, the researchers experimentally determined that the mixing between a plume and lower layer (as a result of the interaction with the walls of the shaft) caused complete mixing. This is the inverse of the corridor problem, and occurs at an aspect ratio (the maximum of height/width or height/length) of about 5. A recommended rule is as follows. If the width-to-length aspect ratio (the maximum of length/width or width/length) is greater than 5, use of the corridor flow algorithm is appropriate. If the width-to-length aspect ratio is greater than 3 but less than 5, the corridor flow algorithm may or may not be appropriate; consider the results from a simulation with and without the algorithm to assess its appropriateness. If the room is not a corridor and the height aspect ratio (the maximum height/width or height/length) is greater than 5, the single zone approximation is appropriate.

3.3 Description of Sub-Models and Correlations

This section discusses each of the sub-models incorporated in CFAST. In general, Sections 3.3.1 through 3.3.11 are organized in a manner similar to the structure of the model itself.

3.3.1 The Fire

CFAST simulates a fire as a mass of fuel that burns at a prescribed “pyrolysis” rate and releases both energy and combustion products. The model also has the capability to simulate both unconstrained and constrained fires. For an unconstrained fire, CFAST simulates a fire that simply releases mass and energy at the pyrolysis rate prescribed by the user; the model neither calculates nor tracks the products of combustion. By contrast, for a constrained fire, CFAST calculates species production based on user-defined production yields, and both the pyrolysis rate and the resulting energy and species generation may be limited by the oxygen available for combustion. When sufficient oxygen is available for combustion, the heat release rate (HRR) for a constrained fire is the same as for an unconstrained fire. Fire height is also calculated by the model based on an available experimental correlation [Ref. 6].

CFAST also has the capability to simulate multiple fires in multiple compartments. In such instances, CFAST treats each individual fire as an entirely separate entity, with no interaction with other fire plumes.

The user must define fire growth because CFAST does not include a model to predict fire growth. While this approach does not directly account for increased pyrolysis attributable to radiative feedback from the flame or compartment, the user could prescribe such effects though multiple simulations.

3.3.2 Plumes

CFAST models the flame and plume regions around a fuel source using McCaffrey’s correlation, which divides the flame/plume into three regions [Ref. 7]. McCaffrey estimated temperature, velocity, and the mass entrained by the fire/plume from the lower layer into the upper layer. McCaffrey’s correlation is an extension of the common point source plume model, with a different set of coefficients for each region. These coefficients are experimental correlations. However, the model does not output plume temperatures. For a detailed description of constraints CFAST puts on air entrained into the plume, please refer to the CFAST Technical Reference Guide [Ref. 1].

3.3.3 Ceiling Jet

CFAST uses Cooper's correlation [Ref. 8] to simulate the ceiling jet flows and convective heat transfer from fire plume gases to the overhead ceiling surface in the room of fire origin. In so doing, the model accounts for the effect on heat transfer as a result of the fire's location within the room. Complete details are available in Reference 8.

3.3.4 Vent Flow

CFAST models both horizontal flow through vertical vents (doors, windows, wall vents, etc.) and vertical flow through horizontal vents (ceiling holes, hatches, roof vents, etc.). Horizontal flow is normally thought of when discussing fires.

Horizontal vent flow through vertical vents is determined using the pressure difference across a vent. Flow at a given elevation may be computed using Bernoulli's law by computing the pressure difference at that elevation and then the pressure on each side of the vent. This solution is augmented for restricted openings by using flow coefficients from Quintiere et al. [Ref. 9] to allow for constriction from finite door sizes. The flow (or orifice) coefficient is an empirical term, which addresses the problem of constriction of velocity streamlines at an orifice.

Cooper's algorithm [Ref. 10] is used for computing vertical mass flow through horizontal vents. The algorithm is based on correlations to model the two components of the flow, including a net flow dictated by a pressure difference, and the exchange flow based on the relative densities of the gases.

There is a special case of horizontal flow in long corridors. Specifically, CFAST incorporates a corridor flow algorithm to calculate the ceiling jet temperature and depth as a function of time until it reaches the end of the corridor. A computational fluid dynamics model was used to develop the correlations that CFAST uses to compute flows between corridors and compartments. A more detailed description of this work is found in the CFAST Technical Reference Guide [Ref. 1].

The model for mechanical ventilation used in CFAST is based on the model developed by Klote [Ref. 11]. Flow in ductwork is calculated with a mass and energy balance based on an analogy to electrical current flow in series and parallel based on Kirchoff's law. The CFAST Technical Reference Guide [Ref. 1] describes the modeling of ducts and fans in CFAST.

3.3.5 Heat Transfer

This section discusses radiation, convection, and conduction — the three mechanisms by which heat is transferred between the gas layers and objects and enclosing compartment walls. The CFAST Technical Reference Guide [Ref. 1] provides a more complete description of the algorithms used in CFAST.

3.3.5.1 Radiation

Radiative transfer occurs among the fire(s), gas layers, and compartment surfaces (ceiling, walls, and floor). This transfer is a function of the temperature differences and emissivity of the gas layers, as well as the compartment surfaces. The radiation model in CFAST assumes that (1) all zones and surfaces radiate and absorb like a gray body, (2) the fires radiate as point sources, and (3) the plume above the fire does not radiate at all. Radiative heat transfer is approximated using a limited number of radiating wall surfaces (four in the fire room and two everywhere else). The use of these and other approximations allows CFAST to perform the radiation computation in a reasonably efficient manner [Ref. 12].

3.3.5.2 Convection

The typical correlations that CFAST uses for convective heat transfer are available in the literature. Specifically, Atreya summarizes convective heat flux calculation methods in the SFPE handbook [Ref. 13].

3.3.5.3 Conduction

CFAST uses a finite difference scheme from Moss and Forney [Ref. 14], which utilizes a non-uniform spatial mesh to advance the wall temperature solution. The heat equation is discretized using a second-order central difference for the spatial derivative and a backward difference for the time derivative. This process is repeated until the heat flux striking the wall (calculated from the convection and radiation algorithms) is consistent with the flux conducted into the wall (calculated using Fourier’s law). Heat transfer between compartments can be modeled by merging the connected surfaces for the ceiling and floor compartments or for the connected horizontal compartments.

3.3.6 Targets

The calculation of the radiative heat flux to a target is similar to the radiative heat transfer calculation discussed in Section 3.3.5.1. The main difference is that CFAST does not compute feedback from the target to the wall surfaces or gas layers. The target is simply a probe or sensor that does not interact with the modeled environment. The net flux striking a target can be used as a boundary condition in order to compute the temperature of the target. The four sources of heat flux to a target are fire radiation, radiation from walls (including the ceiling and floor), gas layer radiation, and gas layer convection.

3.3.7 Heat Detectors

CFAST models heat detector (including sprinkler head) activation using Heskestad’s method [Ref. 15] with temperatures obtained from the ceiling jet calculation [Ref. 8]. Rooms without fires do not have ceiling jets; therefore, detectors in such rooms use gas layer temperatures instead of ceiling jet temperatures.

3.3.8 Fire Suppression via Sprinklers

For sprinkler suppression, CFAST uses the simple model by Madrzykowski and Vettori [Ref. 16], which is generalized for varying sprinkler spray densities according to Evans [Ref. 17]. The suppression correlation was developed by modifying the heat release rate of a fire. The CFAST Technical Reference Manual [Ref. 1] outlines the assumptions and limitations of this approach.

3.3.9 Species Concentration and Deposition

The combustion chemistry scheme used in CFAST is documented in the CFAST Technical Reference Guide [Ref. 1]. The scheme is based on a carbon-hydrogen-oxygen balance applied in three locations. The first is in the fire and plume in the lower layer of the compartment, the second is in the upper layer, and the third is in the vent flow between adjacent compartments. This scheme basically solves the conservation equations for each species independently.

CFAST tracks the masses of an individual species as they are generated, transported, or mixed. As fuel is combusted, the user-prescribed species yield defines the mass of the species to be tracked. Each unit mass of a species produced is carried in the flow to the various rooms and accumulates in the layers. The model keeps track of the mass of each species in each layer, and records the volume of each layer as a function of time. The mass divided by the volume is the mass concentration, which along with the molecular weight provides the concentration in volume percent or parts per million (ppm) as appropriate. For hydrogen chloride, CFAST includes an empirical correlation that allows for deposition on and absorption by material surfaces.

3.4 Review of the Theoretical Development of the Model

The current version of ASTM E 1355 includes provisions to guide assessment of the model's theoretical basis. Those provisions include 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. Publication of the theoretical basis of the model in a peer-reviewed journal article may be sufficient to fulfill this review" [Ref. 2]. NIST's Technical Reference Guide for CFAST [Ref. 1] addresses the necessary elements of a review of the model's technical bases.

CFAST has been subjected to independent review both internally (at NIST) and externally. NIST documents and products receive extensive reviews by NIST experts not associated with development. The same reviews have been conducted on all previous versions of the model and Technical Reference Guide over the last decade. Externally, the model's theoretical basis has been published in peer reviewed journals [Refs. 18, 19, and 20], and conference proceedings [Ref. 21]. In addition, CFAST is used worldwide by fire protection engineering firms that review the technical details of the model related to their particular application. Some of these firms also publish (in the open literature) reports documenting internal efforts to validate the model for a particular use. Finally, CFAST has been reviewed and included in industry-standard handbooks such as the Society of Fire Protection Engineers (SFPE) Handbook [Ref. 22], and referenced in specific standards including NFPA 805 [Ref. 23] and NFPA 551 [Ref. 24].

3.4.1 Assessment of the Completeness of Documentation

The two primary documents on CFAST are the Technical Reference Guide [Ref. 1] and Model User's Guide [Ref. 3]. The Technical Reference Guide documents the governing equations, assumptions, and approximations of the various sub models, and it includes a summary description of the model structure and numerics. In addition, the Technical Reference Guide documents a V&V study for the broad applications of CFAST (without specific reference to NPPs). That study was conducted at the request of the U.S. Nuclear Regulatory Commission (NRC), in accordance with ASTM E 1355 [Ref. 2]. The model User's Guide includes a description of the model input data requirements and model results.

3.4.2 Assessment of Justification of Approaches and Assumptions

The technical approach and assumptions associated with the CFAST model have been presented in peer-reviewed scientific literature and at technical conferences. Also, all documents released by NIST are required to undergo an internal editorial review and approval process. In addition to formal internal and peer review, CFAST is subjected to ongoing scrutiny because it is available to the general public and is used internationally by those involved in technical areas such as fire safety design and post-fire reconstruction. The source code for CFAST is also released publicly, and has been used at various universities worldwide, both in the classroom (as a teaching tool) and for research. As a result, flaws in the model's theoretical development and the computer program itself have been identified and rectified. The user base continues to serve as a means to evaluate the model, and this is as important to development of CFAST as formal internal and external peer review processes.

3.4.3 Assessment of Constants and Default Values

No single document provides a comprehensive assessment of the numerical parameters (such as default time step or solution convergence criteria) and physical parameters (such as empirical constants for convective heat transfer or plume entrainment) used in CFAST. Instead, specific parameters have been tested in various V&V studies performed at NIST and elsewhere. Numerical parameters are extracted from the literature and do not undergo a formal review. Model users are expected to assess the appropriateness of default values provided by CFAST and make changes to those values if needed.

4

MATHEMATICAL AND NUMERICAL ROBUSTNESS

4.1 Introduction

This chapter documents the mathematical and numerical robustness of CFAST, which involves verifying that the implementation of the model matches the stated documentation. Specifically, ASTM E 1355 suggests the following analyses to address the mathematical and numerical robustness of models:

- Analytical tests involve testing the correct functioning of the model. In other words, these tests use the code to solve a problem with a known mathematical solution. However, there are relatively few situations for which analytical solutions are known.
- Code checking refers to verifying the computer code on a structural basis. This verification can be achieved manually or by using a code-checking program to detect irregularities and inconsistencies within the computer code.
- Numerical tests investigate the magnitude of the residuals from the solution of a numerically solved system of equations (as an indicator of numerical accuracy) and the reduction in residuals (as an indicator of numerical convergence).

4.2 Comparison with Analytic Solutions

Certain CFAST sub-models address phenomena that have analytical solutions, for example, one-dimensional heat conduction through a solid or pressure increase in a sealed or slightly leaky compartment as a result of a fire or fan. The developers of CFAST routinely use analytical solutions to test sub-models to verify the correctness of the coding of the model as part of the development. Such routine verification efforts are relatively simple and the results may not always be published or included in the documentation. Two additional types of verification are possible. The first type, discussed in Section 3, “Theoretical Basis,” involves validating individual algorithms against experimental work. The second involves simple experiments, especially for conduction and radiation, for which the results are asymptotic (e.g., for a simple single-compartment test case with no fire, all temperatures should equilibrate asymptotically to a single value). Such comparisons are common and not usually published.

4.3 Code Checking

Two standard programs have been used to check the CFAST model structure and language. Specifically, FLINT and LINT have been applied to the entire model to verify the correctness of the interface, undefined or incorrectly defined (or used) variables and constants, and completeness of loops and threads.

The CFAST code has also been checked by compiling and running the model on a variety of computer platforms. Because FORTRAN and C are implemented differently for various computers, this represents both a numerical check as well as a syntactic check. CFAST has been compiled for Sun (Solaris), SGI (Irix), Microsoft® Windows®-based PCs (Lahey, Digital, and Intel FORTRAN), and Concurrent computer platforms. Within the precision afforded by the various hardware implementations, the answers are identical.[1]

The CFAST Technical Reference Guide [Ref. 1] contains a detailed description of the CFAST subroutine structure and interactions between the subroutines. A complete physical description of the code can be found in Reference 25.

This V&V project began using version 6.0.3 of CFAST. As part of the V&V process, several minor bugs have been corrected in this version. These include fixes to the graphical user interface to improve object plotting, the target flux calculation, burning outside the room of fire origin, and error checking for elements located outside a compartment. The updated version of CFAST used in this study (6.0.10) included these fixes.

4.4 Numerical Tests

Two components of the numerical solutions of CFAST must be verified. The first is the DAE solver (called DASSL), which has been tested for a variety of differential equations and is widely used and accepted [Ref. 26]. The radiation and conduction routines have also been tested against known solutions for asymptotic results.

The second component is the coupling between algorithms and the general solver. The structure of CFAST provides close coupling that avoids most errors. The error attributable to numerical solution is far less than that associated with the model assumptions. Also, CFAST is designed to use 64-bit precision for real number calculations to minimize the effects of numerical error.

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[1] Typically, an error limit of one part in 10^6.

5
MODEL SENSITIVITY

This chapter discusses the CFAST sensitivity analysis, which ASTM E 1355 defines as a study of how changes in model parameters affect the results. In other words, sensitivity refers to the rate of change of the model output with respect to input variations. The standard also indicates that model predictions may be sensitive to (1) uncertainties in input data, (2) the level of rigor employed in modeling the relevant physics and chemistry, and (3) the accuracy of numerical treatments. Thus, the purpose of a sensitivity analysis is to assess the extent to which uncertainty in the model inputs is manifested as uncertainty in the model results of interest.

Conducting a sensitivity analysis of a complex model is not a simple task. A sensitivity analysis involves defining a base case scenario, and varying selected input parameters. The resultant variations in the model output are then measured with respect to the base case scenario, in order to consider the extent to which uncertainty in model inputs influences model output. Therefore, a sensitivity analysis of CFAST should account for variations in the extensive number of input parameters that describe the building geometry, compartment connections, construction materials, and description of one or more fires.

ASTM E 1355 [Ref. 2] provides overall guidance on typical areas of evaluation of the sensitivity of deterministic fire models. Chapter 5 of the CFAST Technical Reference Guide [Ref. 1] provides a review of the sensitivity analyses that have been conducted using CFAST, with an emphasis on uncertainty in the input. Other sensitivity investigations of CFAST are also available in References 27, 28, and 29.

5.1 Previous Sensitivity Studies

Khoudja studied the sensitivity of an early version of the FAST model [Ref. 30] (predecessor to CFAST) with a fractional factorial design involving 2 levels of 16 different input parameters. The choice of values for each input parameter represented a range for each parameter. The analysis of the FAST model showed sensitivity to heat loss to the compartment walls and to the number of compartments in the simulation. Without the inclusion of surface thermophysical properties, this model treats surfaces as adiabatic for conductive heat transfer. Thus, consistent sensitivity should be expected. Sensitivity to changes in thermal properties of the surfaces was not explored.

Walker [Ref. 31] discussed the uncertainties in components of zone models and showed how uncertainty within user-supplied data affects the results of calculations using CFAST as an example. The study systematically varied inputs related to the fire (heat release rate, heat of combustion, mass loss rate, radiative fraction, and species yields) and compartment geometry (vent size and ceiling height) ranging from ±1% to ±20% of base values for a one-compartment scenario. Heat release rate and ceiling height are seen to be the dominant input variables in the simulations. Upper-layer temperature changed ±10% for a ±10% change in heat release rate. Typical variation of ±10 seconds in time to untenable conditions for a 20% variation was noted in the inputs for the scenarios studied.

In addition, the CFAST Technical Reference Guide demonstrates a partial sensitivity analysis for a few CFAST input parameters. For somewhat complex fire scenarios involving four interconnected rooms, the analysis found that upper-layer temperature and pressure are insensitive to small (10%) variations in fire room volume, while the upper-layer volume is neutrally sensitive. NIST's analysis also varied heat release rates to determine sensitivity to large changes in inputs. In so doing, the analysis determined that the upper-layer temperature is equally sensitive to heat release rate as to compartment volume. A second-level analysis indicated a strong functional upper-layer temperature dependence on heat release rate, but the sensitivity is less than 1 K/kW in the example case for HRRs greater than 100 kW. The third-level analysis indicated that HRRs have more of an effect on upper-layer temperatures than do vent areas.

Notarianni [Ref. 29] developed an iterative methodology for the treatment of uncertainty in fire-safety engineering calculations to identify important model parameters for detailed study of uncertainty. She defined a nine-step process to identify crucial model inputs and parameters, select sampling methods appropriate for the important parameters, and evaluate the sensitivity of the model to chosen outcomes. Both factorial designs and Latin hypercube sampling are included in a case study involving the CFAST model. In a performance-based design of a 16-story residential structure, the impact of model uncertainty on a chosen design and inclusion of residential sprinklers in the design would effect the resulting safety of the design. For a seven-compartment scenario representing one living unit in the structure, distributions of input variables based on Latin hypercube sampling of selected ranges of the inputs were developed and used as input for a series of 500 CFAST simulations for the scenario. The results of the calculations are presented in a series of cumulative distribution functions, which show the probability that a chosen criterion of the design is exceeded within a given time. Depending on the evaluation criterion chosen, times to unacceptable designs varied by as little as 10 seconds to as much as 470 seconds. To determine important input variables, Notarianni used a multivariate correlation of the input and output variables to determine statistical significance at a 95% confidence level. Input variables deemed important in the analysis included fire-related inputs (growth rate, heat of combustion, position of the base of the fire, and generation rates of products of combustion) and door opening sizes. Other inputs were determined to be less important.

Many of the outputs of the CFAST model are quite insensitive to uncertainty in the input parameters for a broad range of scenarios. Not surprisingly, heat release rate was consistently seen as the most important variable in a range of simulations. Heat release rate and related variables such as heat of combustion or generation rates of products of combustion provide the driving force for fire-driven flows. For CFAST, all of these are user inputs. Thus, careful selection of these fire-related variables are necessary for accurate predictions. Other variables related to compartment geometry such as compartment height or vent sizes, while deemed important for the model outputs, are typically more easily defined for specific design scenarios than fire related inputs. For some scenarios, such as typical building performance design, these vents may need to include the effects of leakage to ensure accurate predictions. For other scenarios, such as shipboard use or nuclear power facilities, leakage (or lack thereof) may be more easily defined and may not be an issue in the calculations.

5.2 Sensitivity to Heat Release Rate

Of all the physical input parameters, the simulation results are most sensitive to the heat release rate. In this section, one of the validation experiments (ICFMP Benchmark Exercise #3, Test 3) is used to demonstrate the result of increasing and decreasing the heat release rate by 15%. Figure 5-1 shows plots of various output quantities demonstrating their sensitivity to the change in heat release rate. Gas and surfaces temperatures, oxygen concentration, and compartment pressure show roughly 10% diversions from baseline, whereas the heat fluxes show roughly 20% diversions. The height of the hot gas layer is relatively insensitive to changes in the heat release rate. These results are expected and consistent with the analysis described in Volume 2 to assess the sensitivity of the quantities of interest to the uncertainty in the measured heat release rate.

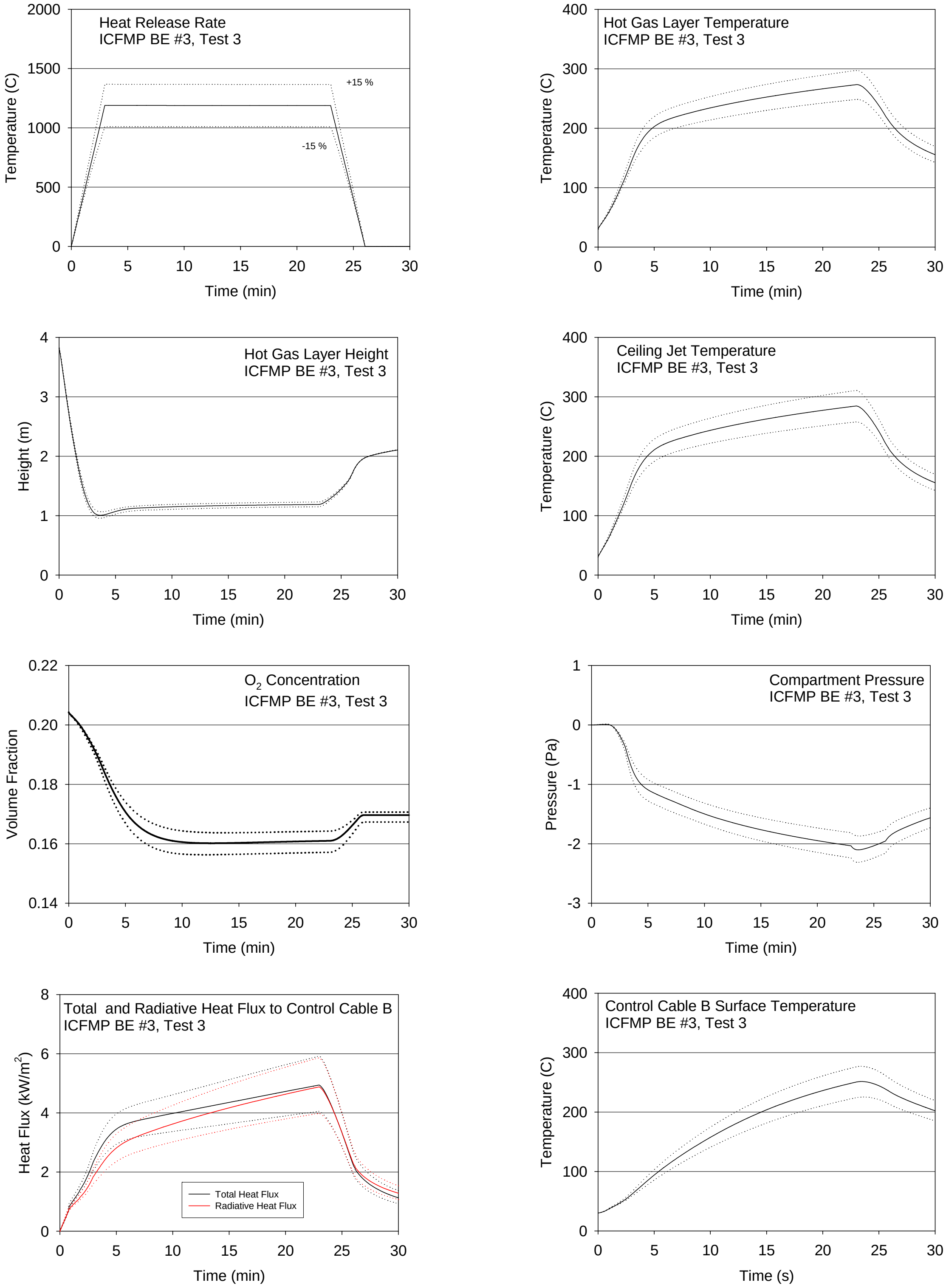


Figure 5-1. Sensitivity of Various Output Quantities to Changes in HRR

6
MODEL VALIDATION

CFAST has been subjected to extensive validation studies by NIST and others. Although some differences between the model and the experiments were evident in these studies, they are typically explained by limitations of the model and uncertainty of the experiments. Most prominent in the studies reviewed was the over-prediction of gas temperature often attributed to uncertainty in soot production and radiative fraction. Still, studies typically show predictions accurate within 10% to 25% of measurements for a range of scenarios. Like all predictive models, the best predictions come with a clear understanding of the limitations of the model and the inputs provided to the calculations. The CFAST Technical Reference Guide [Ref. 1] includes a detailed discussion of these previous validation efforts.

This chapter summarizes the results of the current validation study conducted for the CFAST model. This study focused on the predicted results of the CFAST fire model and did not include an assessment of the user interface for the model. However, all input files used for the simulations were prepared using the GUI and reviewed for correctness prior to the simulations. Six experimental test series have been used in the present model evaluation. A brief description of each is given here. Further details can be found in Volume 2 and in the individual test reports.

ICFMP BE #2: Benchmark Exercise #2 consists of eight experiments, representing three sets of conditions, to study the movement of smoke in a large hall with a sloped ceiling. The results of the experiments were contributed to the International Collaborative Fire Model Project (ICFMP) for use in evaluating model predictions of fires in larger volumes representative of turbine halls in NPPs. The tests were conducted inside the VTT Fire Test Hall, which has dimensions of 19 m high x 27 m long x 14 m wide (62 ft x 88.5 ft x 46 ft). Each case involved a single heptane pool fire, ranging from 2 MW to 4 MW. All three cases, representing averaged results from the eight tests, have been used in the current V&V effort.

ICFMP BE #3: Benchmark Exercise #3, conducted as part of the ICFMP and sponsored by the NRC, consists of 15 large-scale tests performed at NIST in June 2003. The fire sizes range from 350 kW to 2.2 MW in a compartment with dimensions 21.7 m high x 7.1 m long x 3.8 m wide, designed to represent a variety of spaces in a NPP containing power and control cables. The walls and ceiling were covered with two layers of marinate boards, each layer 0.0125 m (0.5 in) thick. The floor was covered with one layer of 0.0125-m (0.5-in) thick gypsum board on top of a 0.0183-m (23/32-in) layer of plywood. The room has one door with dimensions of 2 m x 2 m (6.6 ft x 6.6 ft), and a mechanical air injection and extraction system. Ventilation conditions and fire size and location are varied, and the numerous experimental measurements include gas and surface temperatures, heat fluxes, and gas velocities.

ICFMP BE #4: Benchmark Exercise #4 consists of kerosene pool fire experiments conducted at the Institut für Baustoffe, Massivbau und Brandschutz (iBMB) of the Braunschweig University of Technology in Germany. The results of two experiments were contributed to the ICFMP. These fire experiments involve relatively large fires in a relatively small [3.6 m x 3.6 m x 5.7 m (12 ft x 12 ft x 19 ft)] concrete enclosure. Only one of the two experiments was selected for the present V&V study (Test 1).

ICFMP BE #5: Benchmark Exercise #5 consists of fire experiments conducted with realistically routed cable trays in the same test compartment as BE #4. The compartment was configured slightly differently, and the height was 5.6 m (18.4 ft) in BE #5. Only Test 4 was selected for the present evaluation, and only the first 20 minutes, during which an ethanol pool fire pre-heated the compartment.

FM/SNL Series: The Factory Mutual & Sandia National Laboratories (FM/SNL) Test Series is a series of 25 fire tests conducted for the 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. The experiments were conducted in an enclosure measuring 18 m long x 12 m wide x 6 m high (60 ft x 40 ft x 20 ft), constructed at the FMRC fire test facility in Rhode Island. All of the tests involved forced ventilation to simulate typical NPP installation practices. The fires consist of a simple gas burner, a heptane pool, a methanol pool, or a polymethyl-methacrylate (PMMA) solid fire. Four of these tests were conducted with a full-scale control room mockup in place. Parameters varied during testing were fire intensity, enclosure ventilation rate, and fire location. Only Tests 4, 5 and 21 were used in the present evaluation. Test 21 involved the full-scale mockup. All were gas burner fires.

NBS Multi-Room Series: The National Bureau of Standards (NBS, now the National Institute of Standards and Technology, NIST) Multi-Compartment Test Series consists of 45 fire tests representing 9 different sets of conditions, with multiple replicates of each set, which were conducted in a three-room suite. The suite consists of two relatively small rooms, connected via a relatively long corridor. The fire source, a gas burner, is located against the rear wall of one of the small compartments. Fire tests of 100, 300, and 500 kW were conducted, but only three 100-kW fire experiments (Test 100A, 100O, and 100Z) were used for the current V&V study.

CFAST simulated all of the chosen experiments. Technical details of the calculations, including output of the model and comparison with experimental data, are provided in Appendix A.
The results are organized by quantity as follows:

- hot gas layer (HGL) temperature and height
- ceiling jet temperature
- plume temperature
- flame height
- oxygen and carbon dioxide concentration
- smoke concentration
- compartment pressure
- radiation heat flux, total heat flux, and target temperature

- wall heat flux and surface temperature

Comparisons of the model predictions with experimental measurements are presented as relative differences. The relative differences are calculated as follows:

$$\varepsilon = \frac{\Delta M - \Delta E}{\Delta E} = \frac{\left(M_p - M_o\right) - \left(E_p - E_o\right)}{\left(E_p - E_o\right)}$$

where ΔM is the difference between the peak value (M_p) of the evaluated parameter and its original value (M_o), and ΔE is the difference between the experimental observation (E_p) and its original value (E_o). Appendix A lists the calculated relative differences for all the fire modeling parameters listed above.

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* (e.g., the gas temperature) is related to the measurement device (e.g., 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 to the accuracy of the input parameters (e.g., the specified heat release rate), which in turn are based on experimental measurements. 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 quantify its accuracy further. At this stage, it is said that the prediction is *within experimental uncertainty.*

Each section in this chapter contains a scatter plot that summarizes the relative difference results for all of the predictions and measurements of the quantity under consideration. Details of the calculations, the input assumptions, and the time histories of the predicted and measured output are included in Appendix A. Only a brief discussion of the results is included in this chapter. Included in the scatter plots are an estimate of the combined uncertainty for the experimental measurements and uncertainty in the model inputs. It is important to understand that these are simply estimates of random uncertainty and do not include systematic uncertainty in either the experimental measurements or model predictions. Thus, these uncertainty bounds are only guidelines to judge the predictive capability of the model along with expert engineering judgment of the project team.

At the end of each section, a color rating is assigned to each of the output categories, indicating, in a very broad sense, how well the model treats that particular quantity. A detailed discussion of this rating system is included in Volume 1. For CFAST, only the Green and Yellow ratings have been assigned to 11 of the 13 quantities of interest because these quantities fall within the capability of the CFAST model. The color Green indicates that the research team concluded the physics of the model accurately represent the experimental conditions, and the calculated relative differences comparing the model and the experimental are consistent with the combined experimental and input uncertainty. The color Yellow suggests that one 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. Two of the quantities, plume temperature and ceiling jet temperature, are used internally by the model for its calculations, but are not reported as output. These were not assigned a color rating. Parameters that are not given a color rating indicate that the model does not include output to be able to evaluate that parameter in its as-tested version.

6.1 Hot Gas Layer (HGL) Temperature and Height

The single most important prediction a fire model can make is the temperature of the hot gas layer (HGL). The impact of the fire is not so much a function of the heat release rate, but rather the temperature of the compartment. A good prediction of the HGL height is largely a consequence of a good prediction of its temperature because smoke and heat are largely transported together and most numerical models describe the transport of both with the same type of algorithm. Typically, CFAST slightly over-predicts the HGL temperature, most often within experimental uncertainty. Hot gas layer height is typically within experimental uncertainty for well-ventilated tests and near floor level for under-ventilated tests where compartments are closed to the outside. Figure 6-1 shows a comparison of predicted and measured values for HGL temperature and depth along with a summary of the relative difference for all of the test series. For HGL height, only values from open-door tests are included in Figure 6-1 and Appendix A. For closed-door tests, visual observations typically show that the HGL fills the entire compartment volume from floor to ceiling, inconsistent with the calculated results for the experimental data. Thus, the calculated experimental values of HGL height for closed-door tests are not seen as appropriate for comparison to model results.

Following is a summary of the accuracy assessment for the HGL predictions of the six test series:

<u>ICFMP BE #2</u>: CFAST predicts the HGL temperature and height near experimental uncertainty for all three tests.

<u>ICFMP BE #3</u>: CFAST predicts the HGL temperature to within experimental uncertainty for all of the closed-door tests except Test 17. Test 17 was a rapidly growing toluene pool fire, which was stopped for safety reasons after 273 seconds. CFAST predicts an initial temperature rise starting somewhat earlier and peaking somewhat higher than the experimental values, but curve shapes match in all tests. Relative difference for the open-door tests is somewhat higher, ranging from 13 % for Test 5 to 26 % for Test 18 (Figure 6-1 and Table A-1). CFAST predicts HGL height to within experimental uncertainty for the open-door tests. For the closed-door tests, calculated CFAST values are consistent with visual observations of smoke filling in the compartment.

<u>ICFMP BE #4</u>: CFAST predicts the HGL temperature and height to within experimental uncertainty for the single test (Test 1), but there is some discrepancy in the shapes of the curves. It is not clear whether this is related to the measurement or the model.

ICFMP BE #5: CFAST predicts the HGL temperature to within experimental uncertainty for the single test (Test 4), although again there is a noticeable difference in the overall shape of the temperature curves. HGL height is under-predicted by 20 % (Figure 6-1 and Table A-1). This is likely because of the complicated geometry within the compartment that includes a partial height wall that affects both plume entrainment and radiative heat transfer from the fire to surroundings.

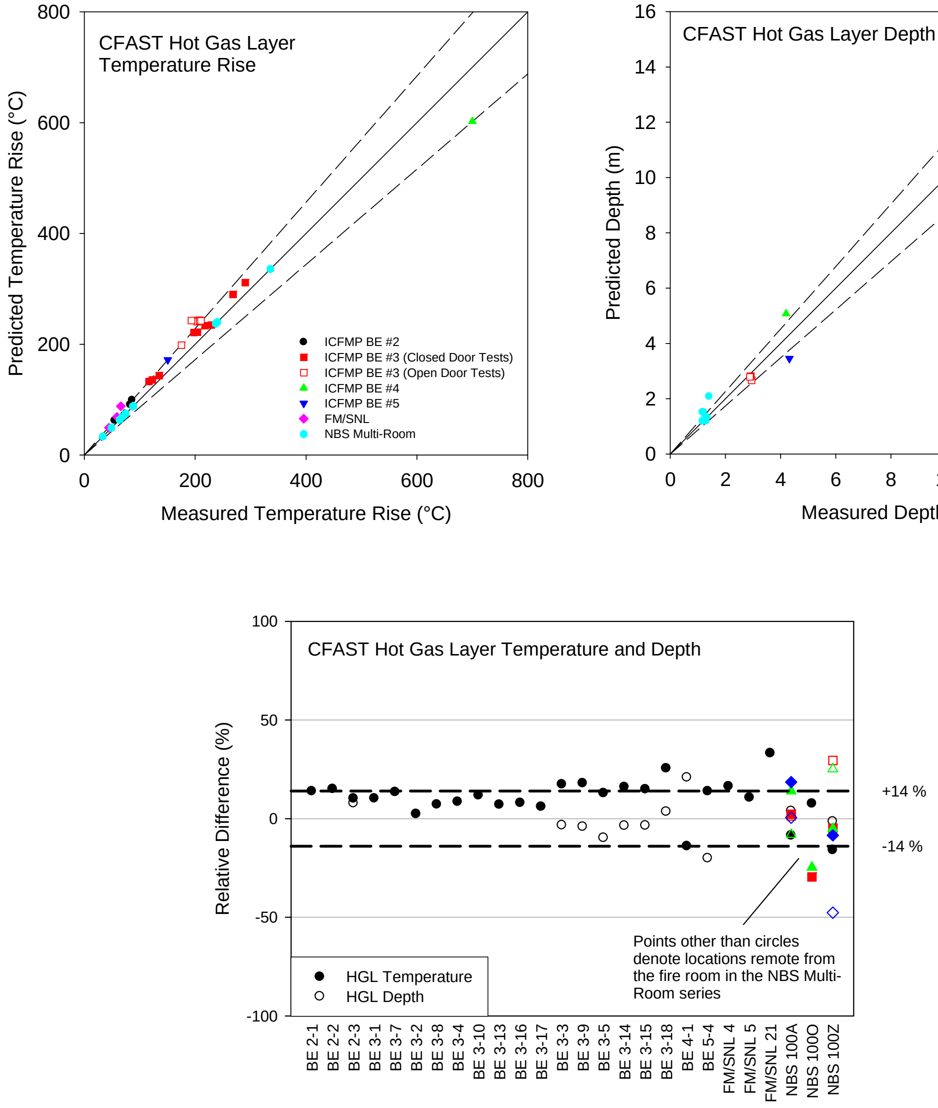


Figure 6-1. Comparisons and Relative Differences for Hot Gas Layer (HGL) Temperature and Height

FM/SNL: CFAST predicts the HGL temperature to within experimental uncertainty for Tests 4 and 5. For Test 21, there is a 33% over-prediction (Figure 6-1 and Table A-1). This is likely because of the configuration of the fire in the test, with the fire inside a cabinet in the fire compartment. This complex geometry leads to an interaction between the fire and the confining cabinet that a zone model cannot simulate.

NBS Multi-Room: CFAST predicts the HGL temperature and height to within experimental uncertainty for many of the measurement locations in the three tests considered. The discrepancies in various locations appear to be attributable to experimental, rather than model, error. In particular, the calculation of HGL temperature and height are quite sensitive to the measured temperature profile, which in these tests was determined with bare-bead thermocouples that are subject to quite high uncertainties. Wide spacing of the thermocouples also leads to higher uncertainty in HGL height.

Calculations of HGL temperature and height in the room remote from the fire have higher relative differences than those closer to the fire. This is likely a combination of the simplified single representative layer temperature inherent in zone models (temperature in the long corridor of this test series varied from one end of the compartment to the other) and the calculation of flow though doorways based on a correlation based on the pressure difference between the connected compartments.

Summary: HGL Temperature and Height (Green for fire compartment and Yellow for compartments remote from the fire)

Based on the model physics and comparisons of model predictions with experimental measurements, CFAST calculations of HGL temperature and height are characterized in the Green category within the fire compartment and Yellow in compartments remote from the fire for the following reasons:

- The two-zone assumption inherent in CFAST, modeled as a series of ordinary differential equations that describe mass and energy conservation of flows in a multiple-compartment structure are appropriate for the applications studied.

- The CFAST predictions of the HGL temperature and height are, with a few exceptions, within or close to experimental uncertainty. The CFAST predictions are typical of those found in other studies where the HGL temperature is typically somewhat over-predicted and HGL height somewhat lower (HGL depth somewhat thicker) than experimental measurements. These differences are likely attributable to simplifications in the model dealing with mixing between the layers, entrainment in the fire plume, and flow through vents. Still, predictions are mostly within 10% to 20% of experimental measurements.

- Calculation of HGL temperature and height has higher uncertainty in rooms remote from the fire compared to those in the fire compartment. However, this is based on the results of a single test series.

6.2 Ceiling Jet Temperature

CFAST includes an algorithm to account for the presence of the higher gas temperatures near the ceiling surfaces in compartments involved in a fire. In the model, this increased temperature has the effect of increasing the convective heat transfer to ceiling surfaces. The temperature and velocity of the ceiling jet are available from the model by placing a heat detector at the specified location. The ceiling jet algorithm is based on the model by Cooper [Ref. 8], with details described in the CFAST Technical Reference Guide [Ref. 1]. The algorithm predicts gas temperature and velocity under a flat, unconstrained ceiling above a fire source. Only two of the six test series (ICFMP BE #3 and FM/SNL) involved relatively large flat ceilings. Figure 6-2 shows a comparison of predicted and measured values for ceiling jet temperature along with a summary of the relative difference for the tests.

ICFMP BE #3: CFAST predicts ceiling jet temperature well within experimental uncertainty for all of the tests in the series, with an average relative difference of 5%. For these tests, the fire source was sufficiently large (relative to the compartment size) such that a well-defined ceiling jet was evident in temperature measurements near ceiling level.

FM/SNL: With fire sizes comparable to the smaller fire sizes used in the tests in ICFMP BE #3 and compartment volumes significantly larger, measured temperature rise near the ceiling in the FM/SNL tests was below 100 °C (212 °F) in all three tests. Hot gas layer temperatures for these tests were below 70 °C (158 °F). CFAST consistently predicts higher ceiling jet temperatures in the FM/SNL tests compared to experimental measurements. With a larger compartment relative to the fire size, the ceiling jet for the FM/SNL tests is not nearly as well-developed as those in the ICFMP BE #3. The difference between the experimental ceiling jet temperature and HGL temperature for the FM/SNL tests is less than half that observed in the ICFMP BE #3 tests. While the 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 shorter estimates of activation times for the simulated sprinkler or heat detector.

Summary: Ceiling Jet Temperature (Yellow+)

Based on the model physics and comparisons of model predictions with experimental measurements, CFAST calculations of ceiling jet temperature are characterized in the Yellow+ category for the following reasons:

- For tests with a well-defined ceiling jet layer, CFAST predicts ceiling jet temperatures well-within experimental uncertainty.

- For tests with a less well-defined ceiling jet layer, CFAST over-predicts the ceiling jet temperature. For the tests studies, over-predictions were noted when the HGL temperature was below 70 °C (158 °F).

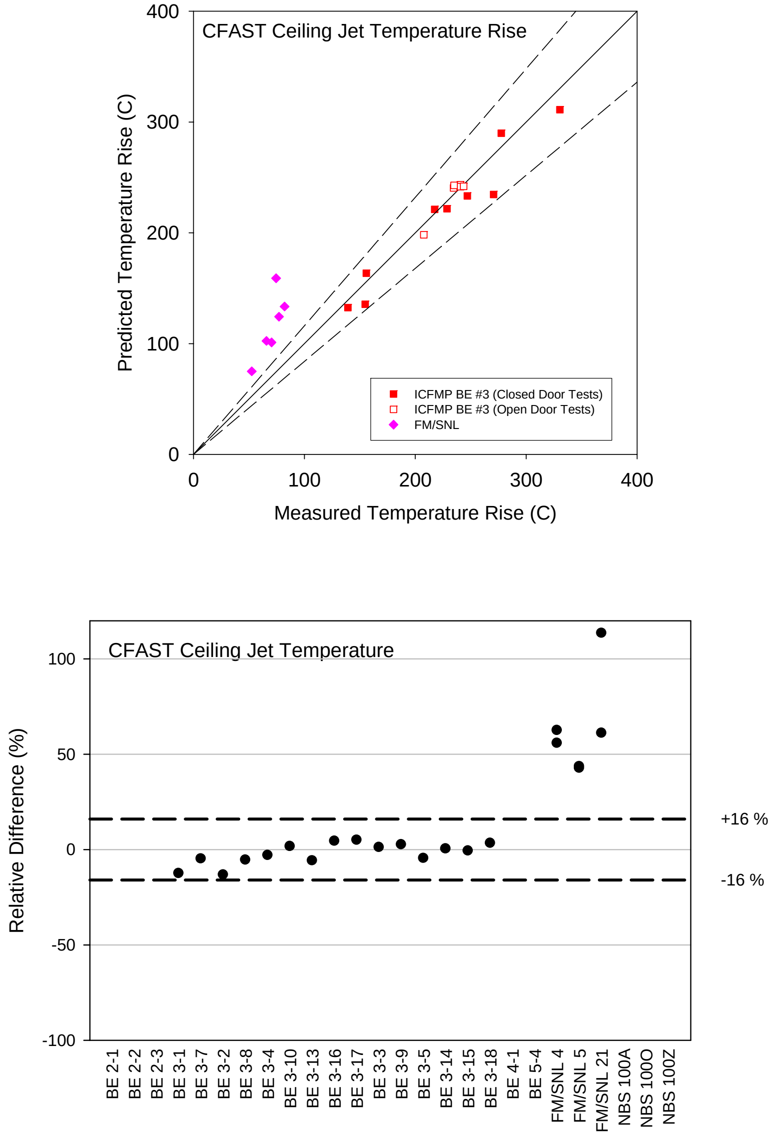


Figure 6-2. Comparisons and Relative Differences for Ceiling Jet Temperature

6.3 Plume Temperature

CFAST includes a plume entrainment algorithm based on the work of McCaffrey that models the transport of combustion products released by the fire with air in the fire compartment and movements of these gases into the upper layer in the compartment. Plume temperature is not directly calculated nor reported from this algorithm. For this reason, comparisons of experimentally measured plume temperatures with CFAST calculations are not appropriate and will not be included in this report.

6.4 Flame Height

Flame height is recorded by visual observations, photographs, or video footage. Videos from the ICFMP BE #3 test series and photographs from BE #2 are available. It is difficult to precisely measure the flame height, but the photos and videos allow one to make estimates accurate to within a pan diameter.

ICFMP BE #2: The height of the visible flame in the photographs has been estimated to be between 2.4 and 3 pan diameters [3.8 m to 4.8 m (12.5 ft to 15.7 ft)]. From the CFAST calculations, the estimated flame height is 4.3 m (14.1 ft).

ICFMP BE #3: CFAST estimates the peak flame height to be 2.8 m (9.2 ft), roughly consistent with the view through the doorway during the test. The test series was not designed to record accurate measurements of flame height.

Summary: Flame Height (Green)

Based on the model physics and comparisons of model predictions with experimental measurements, CFAST calculations of flame height are characterized in the Green category because the model predicts the flame height consistent with visual observations of flame height for the experiments. This is not surprising, given that CFAST simply uses a well-characterized experimental correlation to calculate flame height.

6.5 Oxygen and Carbon Dioxide Concentration

CFAST simulates a fire as a mass of fuel that burns at a prescribed pyrolysis rate and releases both energy and combustion products. CFAST calculates species production based on user-defined production yields, and both the pyrolysis rate and the resulting energy and species generation may be limited by the oxygen available for combustion. When sufficient oxygen is available for combustion, the heat release rate for a constrained fire is the same as for an unconstrained fire. Mass and species concentrations are tracked by the model as gases flow through openings in a structure to other compartments in the structure or to the outdoors.

Gas sampling data are available from ICFMP BE #3 and BE #5 (one test only). Figure 6-3 shows a comparison of predicted and measured values for oxygen and carbon dioxide concentrations, along with a summary of the relative difference for the tests.

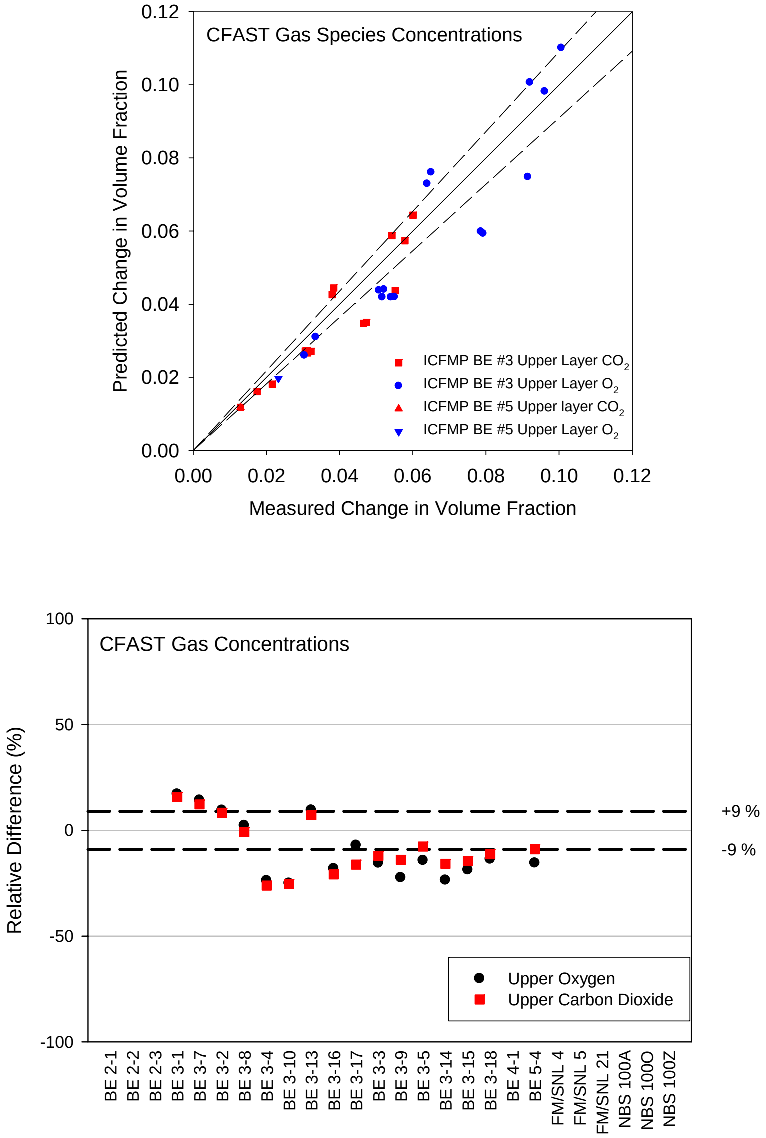


Figure 6-3. Comparisons and Relative Differences for Oxygen Concentration and Carbon Dioxide Concentration

<u>ICFMP BE #3</u>: CFAST predicts the upper-layer concentrations of oxygen and carbon dioxide close to experimental uncertainty. For closed-door Tests 4 and 10 and open-door Tests 9 and 14, the magnitude of relative difference is higher, under-predicting by 22% to 25% (Figure 6-3 and Table A-2). Tests 4, 10, and 16 were closed-door tests with the mechanical ventilation system on. The higher relative differences for these tests are likely because of a non-uniform gas layer in the experiments with higher oxygen concentration near the mechanical ventilation inlet and lower concentrations remote from the inlet. In CFAST, the flow from the mechanical ventilation system is assumed to completely mix with the gases in the appropriate gas layer of a compartment. CFAST consistently under-predicts the drop in oxygen concentration, with Tests 9 and 14

showing a higher relative uncertainty than other closed-door tests. The cause of a higher-than-average difference is not clear.

ICFMP BE #5: CFAST predicts the upper-layer oxygen and carbon dioxide concentration in Test 4 of this test series close to experimental uncertainty.

Summary: Oxygen and Carbon Dioxide Concentration (Green)

Based on the model physics and comparisons of model predictions with experimental measurements, CFAST calculations of oxygen and carbon dioxide concentration are characterized in the Green category for the following reasons:

- CFAST uses a simple user-specified combustion chemistry scheme based on a prescribed pyrolysis rate and species yields that is appropriate for the applications studied.

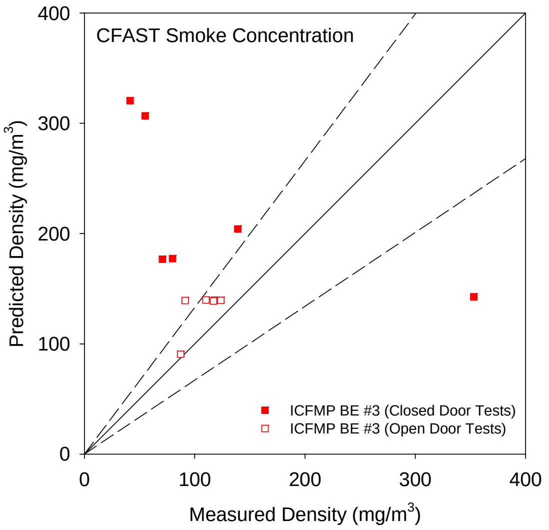
- CFAST predicts the major gas species close to experimental uncertainty.

6.6 Smoke Concentration

CFAST treats smoke like all other combustion products, with an overall mass balance dependent on interrelated user-specified species yields for major combustion species. To model smoke movement, the user prescribes the smoke yield relative to the yield of carbon monoxide. A simple combustion chemistry scheme in the model then determines the smoke particulate concentration in the form of an optical density. Figure 6-4 shows a comparison of predicted and measured values for smoke concentration along with a summary of the relative difference for the tests.

Only ICFMP BE #3 has been used to assess predictions of smoke concentration. For these tests, the smoke yield was specified as one of the test parameters. There are two obvious trends in the results. First, the predicted concentrations are within or near experimental uncertainties in the open-door tests. Second, the predicted concentrations are roughly three to five times the measured concentrations in the closed-door tests. The experimental uncertainty for these measurements has been estimated to be 33% (see Volume 2). The closed-door tests cannot be explained from the experimental uncertainty.

The difference between model and experiment is far more pronounced in the closed-door tests. Given that the oxygen and carbon dioxide predictions are no worse (and indeed even better) in the closed-door tests, there is reason to believe either that the smoke is not transported with the other exhaust gases or the specified smoke yield, developed from free-burning experiments, is not appropriate for the closed-door tests. These qualitative differences between the open- and closed-door tests are consistent with the FDS predictions (see Volume 7).



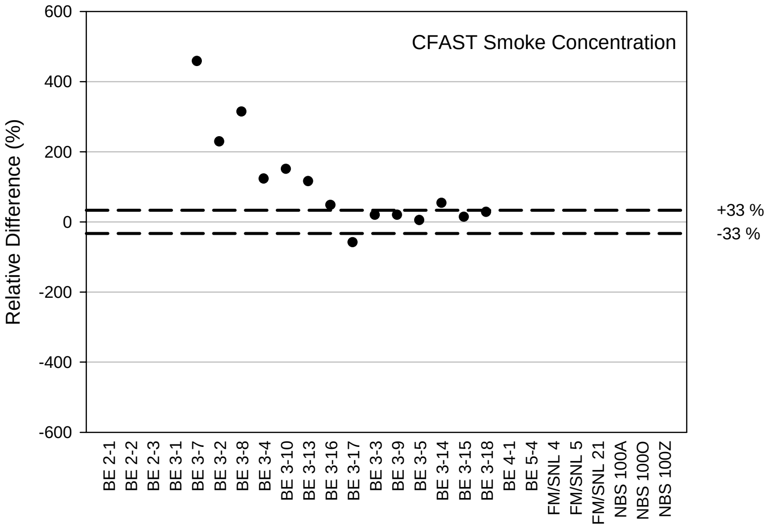


Figure 6-4. Comparisons and Relative Differences for Smoke Concentration

<u>Summary</u>: Smoke Concentration (Yellow)

Based on the model physics and comparisons of model predictions with experimental measurements, CFAST calculations of smoke concentration are characterized in the Yellow category for the following reasons:

- CFAST is capable of transporting smoke throughout a compartment, assuming that the production rate is known and its transport properties are comparable to gaseous exhaust products.

- CFAST typically over-predicts the smoke concentration in all of the BE #3 tests, with the exception of Test 17. Predicted concentrations for open-door tests are within experimental uncertainties, but those for closed-door tests are far higher. No firm conclusions can be drawn from this single data set. The measurements in the closed-door experiments are inconsistent with basic conservation of mass arguments, or there is a fundamental change in the combustion process as the fire becomes oxygen-starved.

6.7 Compartment Pressure

Comparisons between measurement and prediction of compartment pressure for BE #3 are shown in Section A.7 of Appendix A to this volume. Figure 6-5 shows a comparison of predicted and measured values for compartment pressure, along with a summary of the relative difference for the tests.

For those tests in which the door to the compartment is open, the over-pressures are only a few Pascals; however, when the door is closed, the over-pressures are several hundred Pascals. For both the open- and closed-door tests, CFAST predicts the pressure to within experimental uncertainty. The one notable exception is Test 16 (Figure 6-4 and Table A-3), which involved a large (2.3 MW) fire with the door closed and the ventilation on. By contrast, Test 10 involved a 1.2 MW fire with comparable geometry and ventilation. There is considerable uncertainty in the magnitude of both the supply and return mass flow rates for Test 16. Compared to Test 16, Test 10 involves a greater measured supply velocity and a lesser measured exhaust velocity. This is probably the result of the higher pressure caused by the larger fire in Test 16. CFAST does not adjust the ventilation rate based on the compartment pressure until a specified cutoff pressure is reached. This is also the most likely explanation for the over-prediction of compartment pressure in Test 16.

In general, prediction of pressure in CFAST in closed compartments is critically dependent on correct specification of the leakage from the compartment. Compartments are rarely entirely sealed, and small changes in the leakage area can produce significant changes in the predicted over-pressure.

Summary: Compartment Pressure (Green)

Based on the model physics and comparisons of model predictions with experimental measurements, CFAST calculations of pressure are characterized in the Green category for the following reasons:

- With one exception, CFAST predicts compartment pressures within experimental uncertainty.
- Prediction of compartment pressure for closed-door tests is critically dependent on correct specification of the leakage from the compartment.

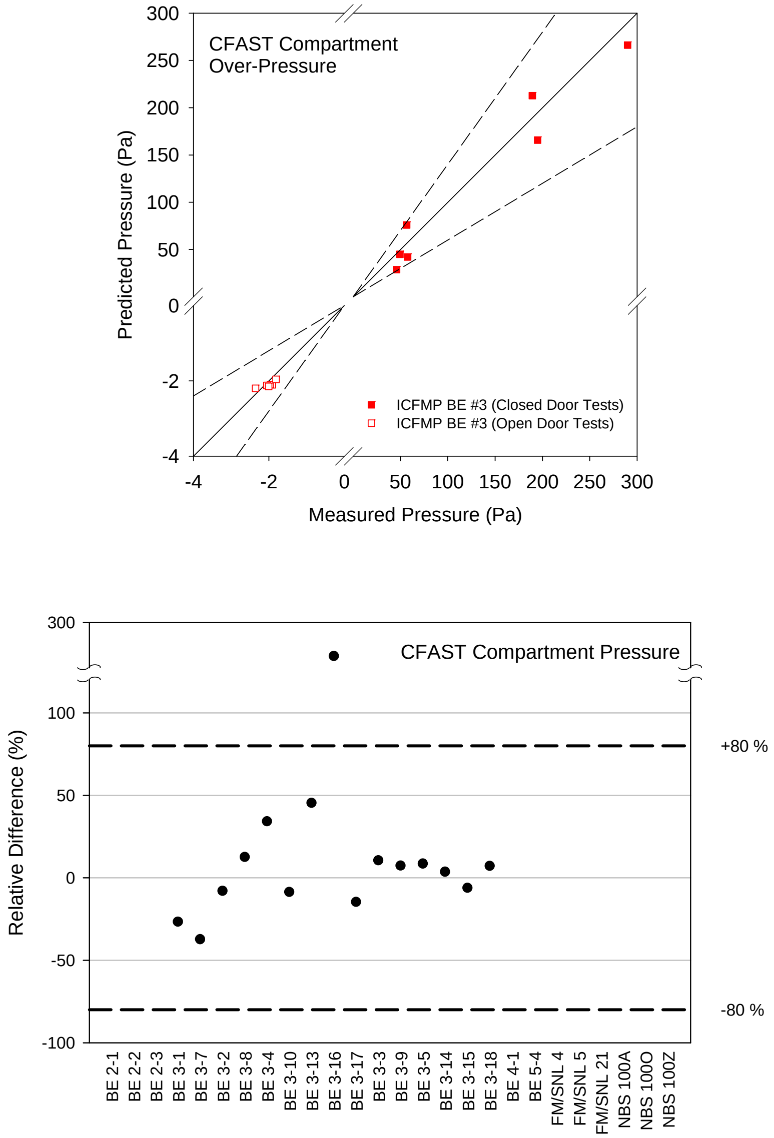


Figure 6-5. Comparisons and Relative Differences for Compartment Pressure

6.8 Radiation and Total Heat Flux to Targets and Target Temperature

Target temperature and heat flux data are available from ICFMP BE #3, #4, and #5. In BE #3, the targets are various types of cables in various configurations — horizontal, vertical, in trays, or free-hanging. In BE #4, the targets are three rectangular slabs of different materials instrumented with heat flux gauges and thermocouples. In BE #5, the targets are again cables, in this case, bundled power and control cables in a vertical ladder. Figure 6-6 shows a comparison of predicted and measured values for radiation, total heat flux, and target temperature, along with a summary of the relative difference for the tests.

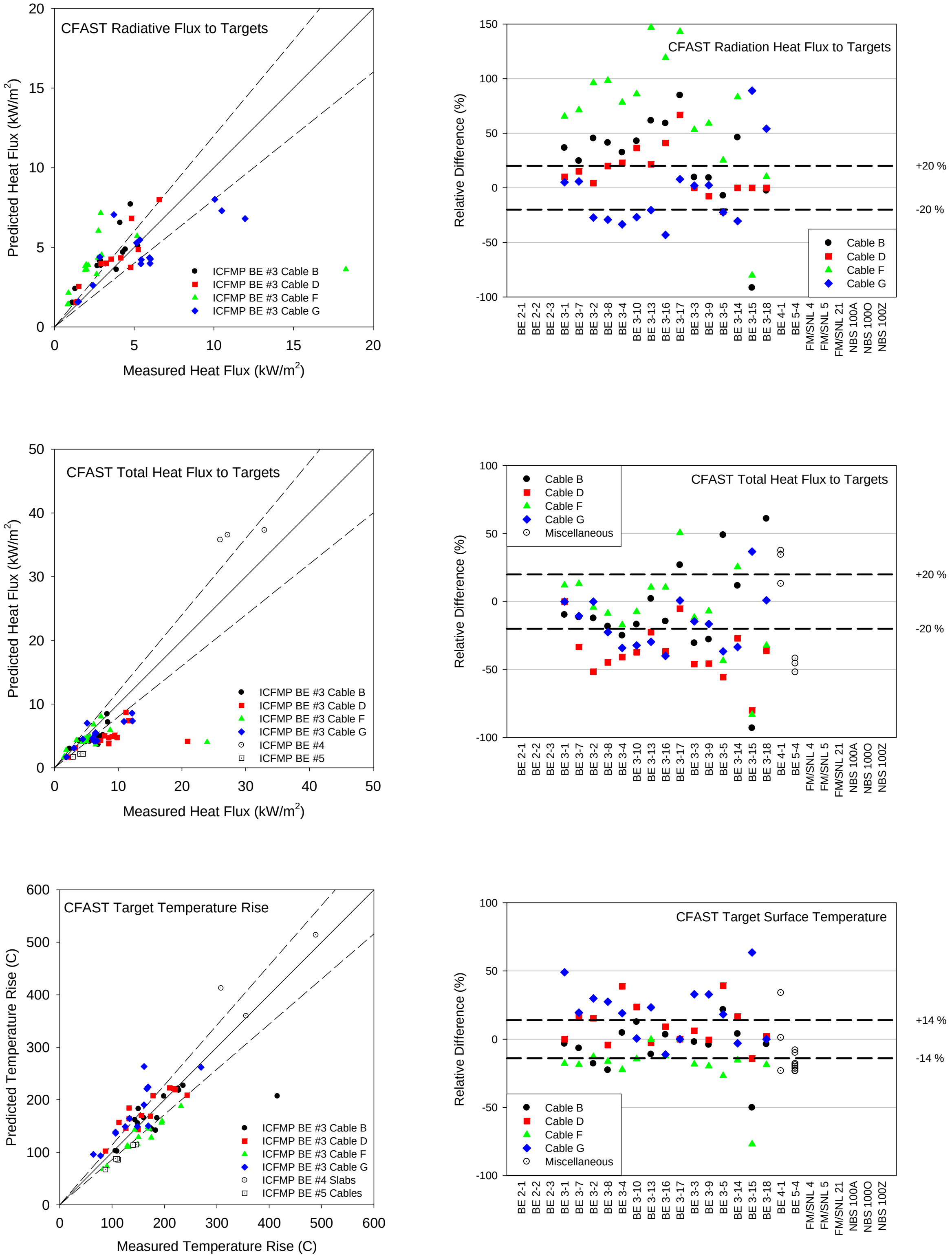


Figure 6-6. Comparisons and Relative Differences for Heat Flux to Targets and Target Temperature

ICFMP BE #3: Appendix A provides nearly 200 comparisons of heat flux and surface temperature on four different cables. It is difficult to make sweeping generalizations about the accuracy of CFAST. At best, one can scan the figures and associated tables to get a sense of the overall performance, which includes the following notable trends:

- The difference between predicted and measured cable surface temperatures is often within experimental uncertainty, with exceptions most often in the values for Cable G. Accurate prediction of the surface temperature of the cable should indicate that the flux to the target (a combination of radiation from the fire, surrounding surfaces, and the gas layers, along with convection from the surrounding gas) should be correspondingly accurate. For ICFMP BE #3, the cable surface predictions show lower relative difference overall compared to the total heat flux and (particularly) the radiative heat flux.

- Total heat flux to targets is typically predicted to within an average difference of 28% and often under-predicted. Predictions for Cables D and G are notable exceptions, with higher uncertainties.

- Radiative heat flux to targets is typically over-predicted compared to experimental measurements, with higher values for closed-door tests. For the closed-door tests, this may be a function of the over-prediction of the smoke concentration, which leads to the radiation contribution from the hot gas layer being a larger fraction of the total heat flux compared to the experimental values.

- For many of the experiments, the convective heat flux component, taken to be the difference between the total heat flux and the radiative heat flux is seen to be higher than the values typically measured in fire experiments.

ICFMP BE #4: CFAST over-predicts both the heat flux and surface temperature of three “slab” targets located about 1 m (3.3 ft) from the fire. The trend is consistent, but it cannot be explained solely in terms of experimental uncertainty. Again, the differences for surface temperature are smaller than those for total heat flux.

ICFMP BE #5: Predictions and measurements of gas temperature, total heat flux, and cable surface temperature are available at four vertical locations along a cable tray. CFAST under-predicts heat flux by about 50%, and under-predicts the cable surface temperature by about 20%. Although the surface temperature predictions are within experimental uncertainty, the heat flux predictions are not. Only one test from this series has been used in the evaluation; thus, it is difficult to draw any firm conclusions.

Summary: Radiation and Total Heat Flux to Targets and Target Temperature (Yellow)

Based on the model physics and comparisons of model predictions with experimental measurements, CFAST calculations of target heat flux and temperature are characterized in the Yellow category for the following reasons:

- Prediction of heat flux to targets and target surface temperature is largely dependent on local conditions surrounding the target. Like any two-zone model, CFAST predicts an average representative value of gas temperature in the upper and lower regions of a compartment. In addition, CFAST does not directly predict plume temperature or its effects on targets that may be within a fire plume. Thus, CFAST can be expected to under-predict values near a fire source, and over-predict values for targets remote from a fire.

- Cable target surface temperature predictions are often within experimental uncertainty, with exceptions, particularly for Cables F and G.

- Total heat flux to targets is typically predicted to within about 30%, and often under-predicted.

- Radiative heat flux to targets is typically over-predicted compared to experimental measurements, with higher relative difference values for closed-door tests.

6.9 Surface Heat Flux and Temperature

Heat flux and wall surface temperature measurements are available from ICFMP BE #3, and additional wall surface temperature measurements are available from BE #4 and BE #5. As with target heat flux and surface temperature (discussed above), there are numerous comparisons. Figure 6-7 shows a comparison of predicted and measured values for surface heat flux and temperature, along with a summary of the relative difference for the tests.

ICFMP BE #3: CFAST generally predicts the heat flux and surface temperature of the compartment walls to within 10% to 30%. Typically, CFAST over-predicts the far-field fluxes and temperatures and under-predicts the near-field measurements. This is understandable, given that any two-zone model predicts an average representative value of gas temperature in the upper and lower regions of a compartment. Thus, the values predicted by CFAST should be an average of values near the fire and those farther away.

However, differences for the ceiling and (particularly) floor fluxes and temperatures are higher, with a more pronounced difference between the near-field and far-field comparisons. In addition to the limitations of the two-zone assumption, calculations of the flux to ceiling and floor surfaces are further confounded by the simple point-source calculation of radiation exchange in CFAST for the fire source. In CFAST, the fire is assumed to be a point source of energy located at the base of the fire rather than a three-dimensional flame surface radiating to surroundings. With the fire typically at the floor surface, this makes the calculation of flux to the floor surface inherently less accurate than for other surfaces.

ICFMP BE #4: CFAST predicts one of the wall surface temperatures to within 8% of the measured values, while the other is under-predicted by nearly 70% (Figure 6-7 and Table A-6). The two points are presumably very close to the fire because the temperatures are 600 to 700 °C (1100 to 1300 °F) above ambient. For points very close to the fire, a significant under-prediction can be expected. The reason for the difference in the predictions is not clear.

ICFMP BE #5: CFAST typically under-predicts wall temperatures at two locations in the compartment by more than 50% (Figure 6-7 and Table A-6). The more complicated geometry inside the compartment, with a partial height wall inside the compartment is a particular challenge for the model. For example, the lowest thermocouple measurement location, TW 2-1 is hidden behind the cable tray and below the level of the partial height wall. Experimentally, this shielded the thermocouple from nearby hot surfaces and the fire resulting in only a 4 °C (7 °F) temperature rise. With the simple geometry modeling by CFAST, a much higher rise is understandable. Only one test from this series has been used in the evaluation; thus, it is difficult to draw any firm conclusions.

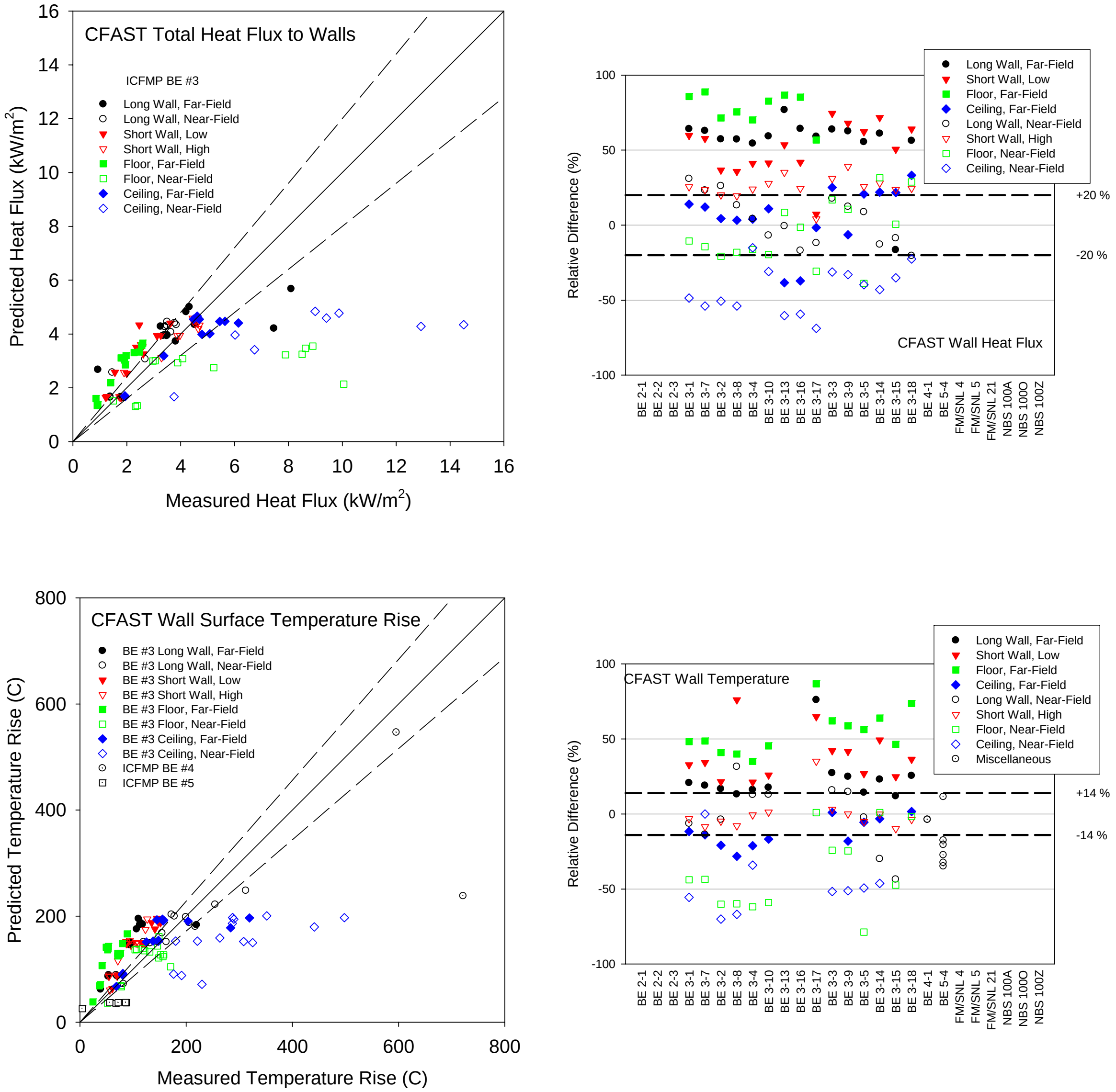


Figure 6-7. Comparisons and Relative Differences for Surface Heat Flux and Temperature

Summary: Surface Heat Flux and Temperature (Yellow)

Based on the model physics and comparisons of model predictions with experimental measurements, CFAST calculations of flame height are characterized in the Yellow category for the following reasons:

- CFAST is capable of predicting the surface temperature of a wall, assuming that its composition is fairly uniform and its thermal properties are well-characterized. Predictions are typically within 10% to 30%. Generally, CFAST over-predicts the far-field fluxes and temperatures, and under-predicts the near-field measurements. This is consistent with the single representative layer temperature assumed by zone fire models.

- CFAST predictions of floor heat flux and temperature are particularly problematic because of the simple point-source calculation of radiative exchange between the fire and compartment surfaces.

6.10 Summary

This chapter presents a summary of numerous comparisons of the CFAST model with a range of experimental results conducted as part of this V&V effort. Thirteen quantities were selected for comparison and a color rating assigned to each of the output categories, indicating, in a very broad sense, how well the model treats that particular quantity:

- Hot Gas Layer (HGL) Temperature and Height: Green
- Ceiling Jet Temperature: Yellow+
- Plume Temperature: No color assigned
- Flame Height: Green
- Oxygen and Carbon Dioxide Concentration: Green
- Smoke Concentration: Yellow
- Compartment Pressure: Green
- Radiation Heat Flux, Total Heat Flux, and Target Temperature: Yellow
- Wall Heat Flux and Surface Temperature: Yellow

Four of the quantities were assigned a Green rating, indicating that the research team concluded that the physics of the model accurately represent the experimental conditions, and the calculated relative differences comparing the model and the experimental values are consistent with the combined experimental and input uncertainty. A few notes on the comparisons are appropriate:

- The CFAST predictions of the HGL temperature and height are, with a few exceptions, within or close to experimental uncertainty. The CFAST predictions are typical of those found in other studies where the HGL temperature is typically somewhat over-predicted and HGL height somewhat lower (HGL depth somewhat thicker) than experimental measurements. Still, predictions are mostly within 10% to 20% of experimental measurements. Calculation of HGL temperature and height has higher uncertainty in rooms remote from the fire (compared to those in the fire compartment).

- For most of the comparisons, CFAST predicts ceiling jet temperature well within experimental uncertainty. For cases where the HGL temperature is below 70 °C (160 °F), significant and consistent over-prediction was observed.

- CFAST predicts the flame height consistent with visual observations of flame height for the experiments. This is not surprising, given that CFAST simply uses a well-characterized experimental correlation to calculate flame height.

- Gas concentrations and compartment pressure predicted by CFAST are within or close to experimental uncertainty.

Three of the quantities were assigned a Yellow rating, indicating that users should take caution when using the model to evaluate the given quantity. This typically indicates limitations in the use of the model. A few notes on the comparisons are appropriate:

- CFAST typically over-predicts smoke concentration. Predicted concentrations for open-door tests are within experimental uncertainties, but those for closed-door tests are far higher.

- With exceptions, CFAST predicts cable surface temperatures within experimental uncertainties. Total heat flux to targets is typically predicted to within about 30%, and often under-predicted. Radiative heat flux to targets is typically over-predicted compared to experimental measurements, with higher relative difference values for closed-door tests. Care should be taken in predicting localized conditions (such as target temperature and heat flux) because of inherent limitations in all zone fire models.

- Predictions of compartment surface temperature and heat flux are typically within 10% to 30%. Generally, CFAST over-predicts the far-field fluxes and temperatures and under-predicts the near-field measurements. This is consistent with the single representative layer temperature assumed by zone fire models.

Plume temperature is not directly calculated nor reported in a CFAST calculation. This was not assigned a color rating. Parameters that are not given a color rating indicate that the model does not include output to permit evaluation of the given parameter in its as-tested version.

CFAST predictions in this validation study were consistent with numerous earlier studies, which show that the use of the model is appropriate in a wide range of fire scenarios. The CFAST model has been subjected to extensive evaluation studies by NIST and others. Although differences between the model and the experiments were evident in these studies, most differences can be explained by limitations of the model as well as of the experiments. Like all predictive models, the best predictions come with a clear understanding of the limitations of the model and the inputs provided to perform the calculations.

7

REFERENCES

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1. Jones, W.W., R.D. Peacock, G.P. Forney, and P.A. Reneke, "Consolidated Model of Fire Growth and Smoke Transport (Version 6): Technical Reference Guide," NIST SP 1026, National Institute of Standards and Technology, Gaithersburg, MD, 2005.
2. *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models,* ASTM E1355-05a, American Society for Testing and Materials, West Conshohocken, PA, 2005.
3. Peacock, R.D., W.W. Jones, P.A. Reneke, and G.P. Forney, "Consolidated Model of Fire Growth and Smoke Transport (Version 6), User's Guide," SP 1041, National Institute of Standards and Technology, Gaithersburg, MD, 2005.
4. Incorpera, F.P., and D.P. DeWitt, *Fundamentals of Heat Transfer*, John Wiley & Sons, New York, NY, 1981.
5. Rehm, R., and G. Forney, "A Note on the Pressure Equations Used in Zone Fire Modeling," NISTIR 4906, National Institute of Standards and Technology, Gaithersburg, MD, 1992.
6. Heskestad, G., "Fire Plumes, Flame Height, and Air Entrainment" in *The SFPE Handbook of Fire Protection Engineering*, 3rd Ed., National Fire Protection Association, Quincy, MA, 2002.
7. McCaffrey, B.J., "Momentum Implications for Buoyant Diffusion Flames," *Combustion and Flame*, 52*:*149, Oxford, UK, 1983.
8. Cooper, L.Y., "Fire-Plume-Generated Ceiling Jet Characteristics and Convective Heat Transfer to Ceiling and Wall Surfaces in a Two-Layer Zone-Type Fire Environment," NISTIR 4705, National Institute of Standards and Technology, Gaithersburg, MD, 1991.
9. Quintiere, J.G., K. Steckler, and D. Corley, "An Assessment of Fire-Induced Flows in Compartments," *Fire Science and Technology*, 4:1, Tokyo, Japan, 1984.
10. Cooper, L.Y., "Calculation of the Flow Through a Horizontal Ceiling/Floor Vent," NISTIR 89-4052, National Institute of Standards and Technology, Gaithersburg, MD, 1989.
11. Klote, J.H., "A Computer Model of Smoke Movement by Air Conditioning Systems," NBS IR 87-3657, National Bureau of Standards, Gaithersburg, MD, 1987.
12. Forney, G.P., "Computing Radiative Heat Transfer Occurring in a Zone Fire Model," NISTIR 4709, National Institute of Standards and Technology, Gaithersburg, MD, 1991.
13. Atreya, A., "Convection Heat Transfer," *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, National Fire Protection Association, Quincy, MA, 2002.
14. Moss, W.F., and G.P. Forney, "Implicitly Coupling Heat Conduction Into a Zone Fire Model," NISTIR 4886, National Institute of Standards and Technology, Gaithersburg, MD, 1992.

15. Heskestad, G., and H.F. Smith, “Investigation of a New Sprinkler Sensitivity Approval Test: The Plunge Test,” Technical Report Serial No. 22485 2937, RC 76-T-50, Factory Mutual Research Corporation, Norwood, MA, 1976.
16. Madrzykowski, D., and R.L. Vettori, “A Sprinkler Fire Suppression Algorithm for the GSA Engineering Fire Assessment System,” Technical Report 4833, National Institute of Standards and Technology, Gaithersburg, MD, 1992.
17. Evans, D.D., “Sprinkler Fire Suppression for Hazard,” Technical Report 5254, National Institute of Standards and Technology, Gaithersburg, MD, 1993.
18. Jones, W.W., “Modeling Smoke Movement through Compartmented Structures,” *Journal of Fire Sciences*, 11**(**2):172, Thousand Oaks, CA, 1993.
19. Jones, W.W., “Multicompartment Model for the Spread of Fire, Smoke, and Toxic Gases,” *Fire Safety Journal*, 9**(**1):55, Okford, UK, 1985.
20. Jones, W.W., and J.G. Quintiere, “Prediction of Corridor Smoke Filling by Zone Models,” *Combustion Science and Technology*, 35:239, Oxfordshire, UK, 1984.
21. Jones, W.W., and G.P. Forney, “Modeling Smoke Movement through Compartmented Structures,” *Proceedings of the Fall Technical Meeting of Combustion Institute/Eastern States Section*, Ithaca, NY, 1991.
22. Walton, W.D., “Zone Fire Models for Enclosures,” *SFPE Handbook of Fire Protection Engineering*, 3rd Edition (P.J. DiNenno, C.L. Beyler, R.L.P. Custer, W.D. Walton, and J.M. Watts, Editors), National Fire Protection Association, Quincy, MA, 2002.
23. NFPA 805, *Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants*, 2001 Edition, 2004/2005 National Fire Codes, National Fire Protection Association, Quincy, MA, 2004.
24. NFPA 551, *Guide for the Evaluation of Fire Risk Assessment*, 2004 Edition, 2004/2005 National Fire Code, National Fire Protection Association, Quincy, MA, 2004.
25. Peacock, R.D., G.P. Forney, and P.A. Reneke, R.M. Portier, and W.W. Jones, “Consolidated Model of Fire Growth and Smoke Transport” NIST TN 1299, National Institute of Standards and Technology, Gaithersburg, MD, 1993.
26. Barnett, J.R., and C.L. Beyler, “Development of an Instructional Program for Practicing Engineers HAZARD I Users,” GCR 90-580, National Institute of Standards and Technology, Gaithersburg, MD, 1990.
27. Peacock, R.D., P.A. Reneke, C.L. Forney, and M.M. Kostreva, “Issues in Evaluation of Complex Fire Models,” *Fire Safety Journal*, 30:103–136, Okford, UK, 1998.
28. Beard, A., “Evaluation of Fire Models: Part I – Introduction,” *Fire Safety Journal*, 19:295–306, Oxford, UK, 1992.
29. Notarianni, K.A., “The Role of Uncertainty in Improving Fire Protection Regulation,” PhD Thesis, Carnegie Mellon University, Pittsburgh, PA, 2000.
30. Khoudja, N., “Procedures for Quantitative Sensitivity and Performance Validation of a Deterministic Fire Safety Model,” Ph.D. Dissertation, Texas A&M University, GCR-88-544, National Bureau of Standards, Gaithersburg, MD, 1988.

31. Walker, A.M., “Uncertainty Analysis of Zone Fire Models,” Fire Engineering Research Report 97/8, University of Canterbury, New Zealand, 1997.
32. Peacock, R.D., S. Davis, and B.T. Lee, *Experimental Data Set for the Accuracy Assessment of Room Fire Model*, Report NBSIR 88-3752, National Bureau of Standards, Gaithersburg, MD, April 1988.

A

TECHNICAL DETAILS OF CFAST VALIDATION STUDY

This appendix provides comparisons of CFAST predictions and experimental measurements for the six series of fire experiments under consideration. Each section to follow contains an assessment of the model predictions for the following quantities:

A.1 Hot Gas Layer Temperature and Height

A.2 Ceiling Jet Temperature

A.3 Plume Temperature

A.4 Flame Height

A.5 Oxygen and Carbon Dioxide Concentration

A.6 Smoke Concentration

A.7 Compartment Pressure

A.8 Target Heat Flux and Surface Temperature

A.9 Wall Heat Flux and Surface Temperature

Volume 2 includes a detailed discussion of the uncertainties associated with both the experimental data and model predictions presented in this appendix.

A.1 Hot Gas Layer Temperature and Height

CFAST is a classic two-zone fire model. For a given fire scenario, the model subdivides a compartment into two control volumes, which include a relatively hot upper layer and a relatively cool lower layer. In addition, CFAST adds a zone for the fire plume. The lower layer is primarily fresh air. By contrast, the hot upper layer (which is also known as the hot gas layer) is where combustion products accumulate via the plume. Each layer has its own energy and mass balances.

Within a compartment, each zone has homogeneous properties. That is, the temperature and gas concentrations are assumed to be constant throughout the zone; the properties only change as a function of time. The CFAST model describes the conditions in each zone by solving equations for conservation of mass, species, and energy, along with the ideal gas law.

ICFMP BE #2

The HGL temperature and depth were calculated from the averaged gas temperatures from three vertical thermocouple arrays using the standard reduction method. There were 10 thermocouples in each vertical array, spaced 2 m (6.6 ft) apart in the lower two-thirds of the hall, and 1 m (3.3 ft) apart near the ceiling. Figure A-1 presents a snapshot from one of the simulations.

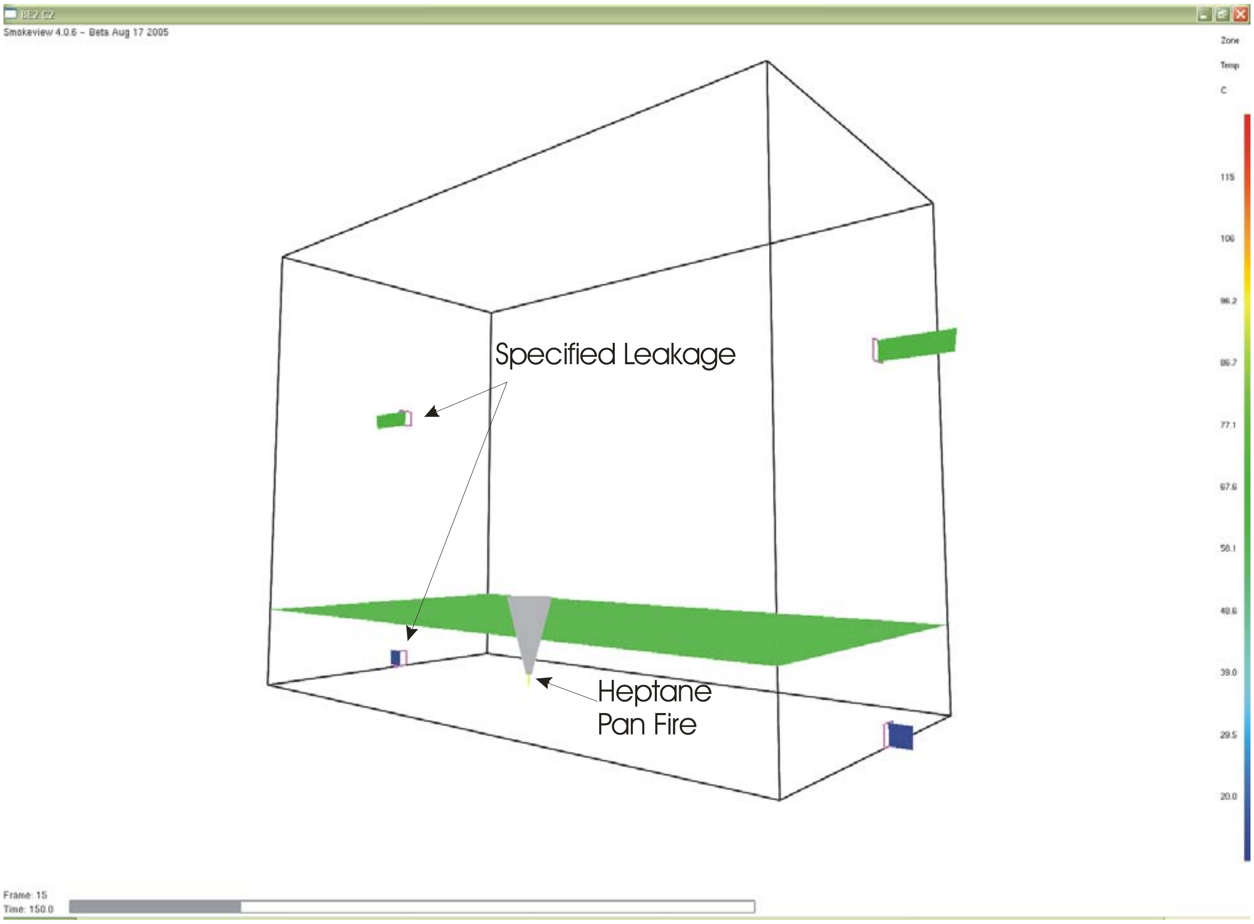


Figure A-1. Cut-Away View of the Simulation of ICFMP BE #2, Case 2

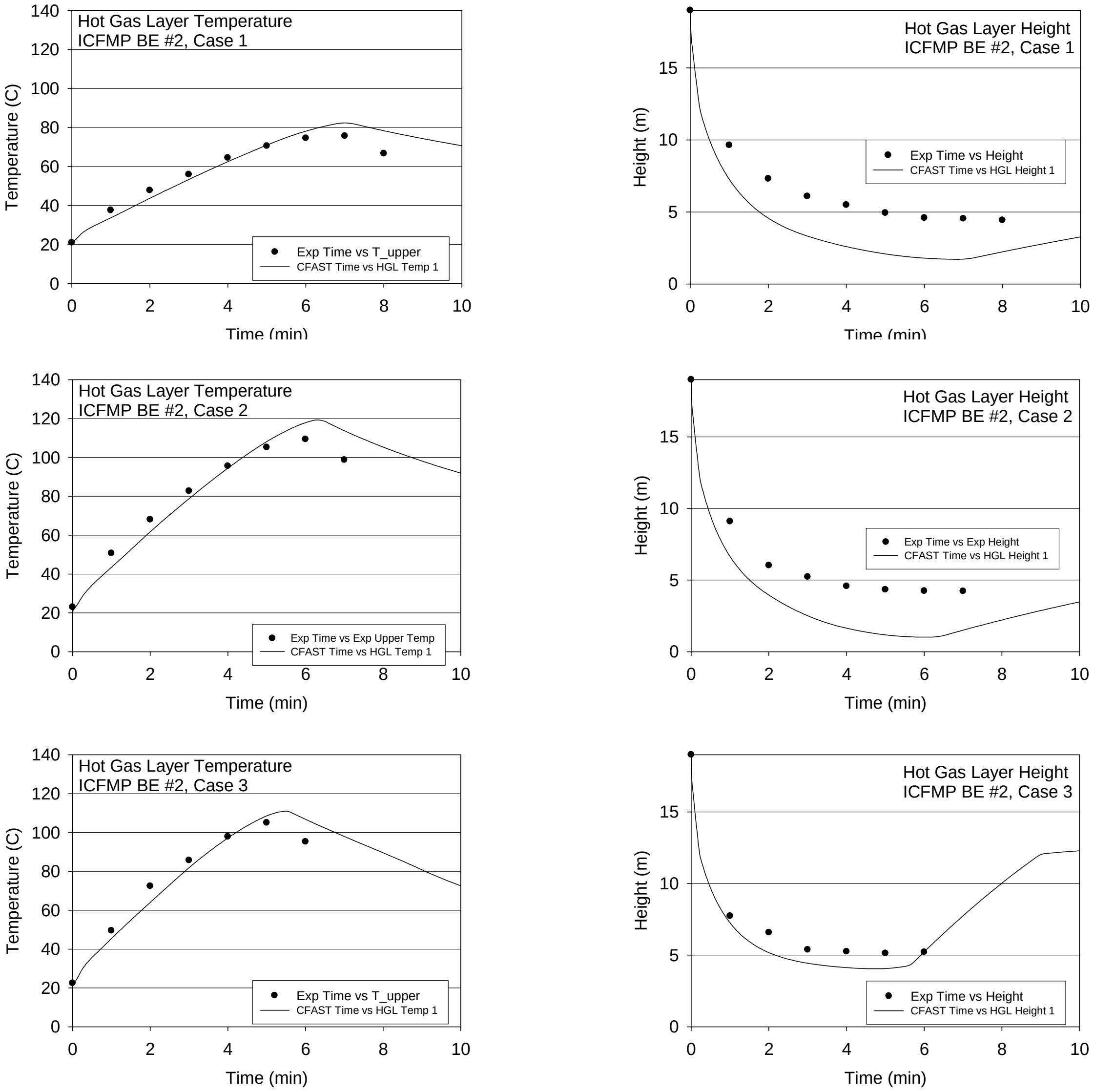


Figure A-2. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #2

ICFMP BE #3

BE #3 consists of 15 liquid spray fire tests with different heat release rate, pan locations, and ventilation conditions. The basic geometry and numerical grid are shown in Figure A-3. Gas temperatures were measured using seven floor-to-ceiling thermocouple arrays (or "trees") distributed throughout the compartment. The average HGL temperature and height were calculated using thermocouple Trees 1, 2, 3, 5, 6 and 7. Tree 4 was not used because one of its thermocouples (4-9) malfunctioned during most of the experiments.

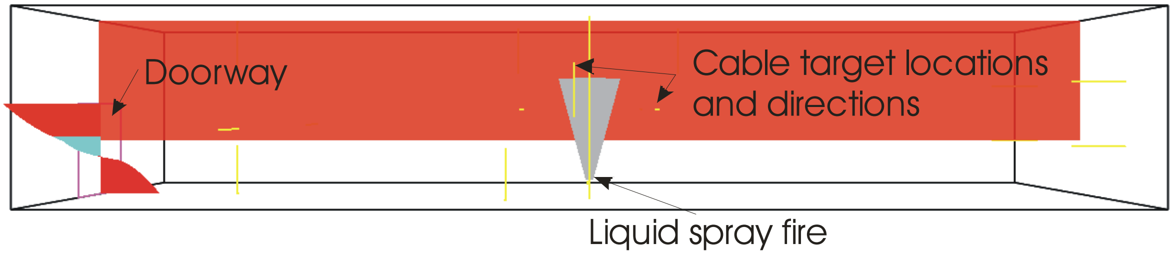


Figure A-3. Snapshot of Simulation of ICFMP BE #3, Test 3

A few observations about the simulations:

- In the closed-door tests, the HGL layer descended all the way to the floor. However, the reduction method, used on the measured temperatures, does not account for the formation of a single layer and, therefore, does not indicate that the layer dropped all the way to the floor. This is not a flaw in the measurements, but rather in the data reduction method.

- The HGL reduction method produces spurious results in the first few minutes of each test because no clear layer has yet formed.

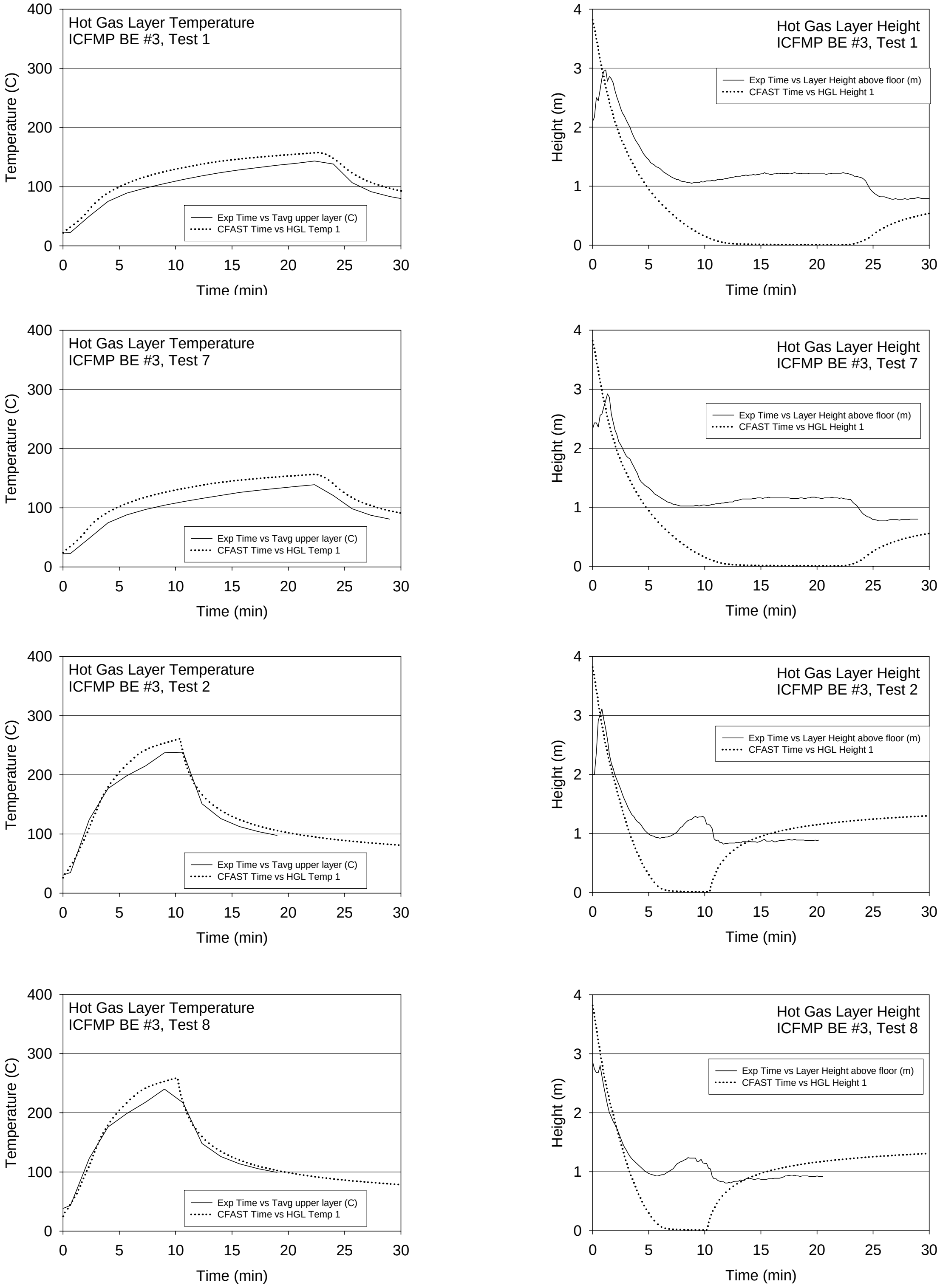


Figure A-4. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #3, Closed-Door Tests

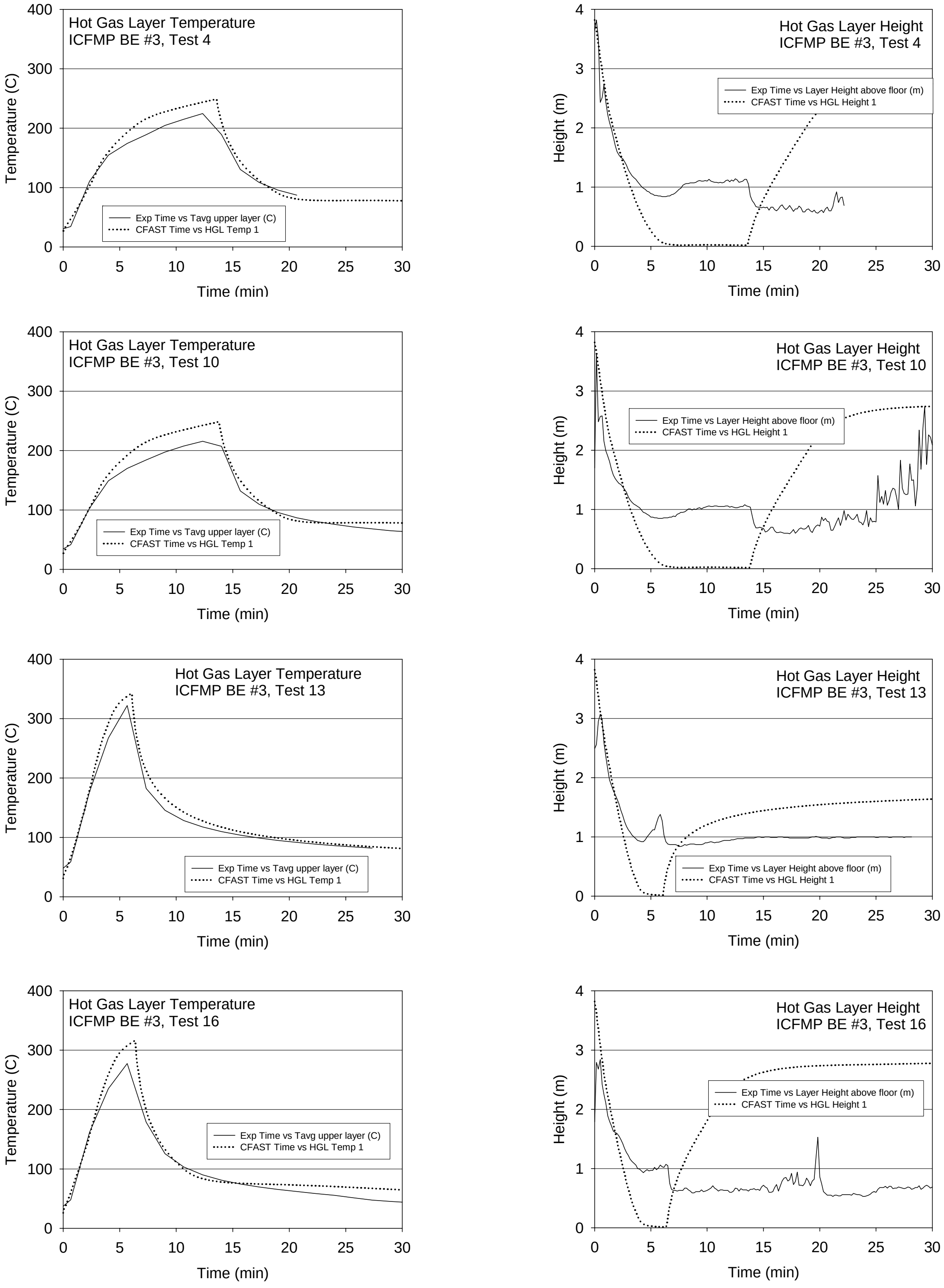
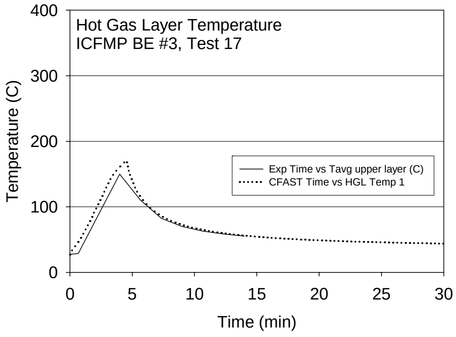
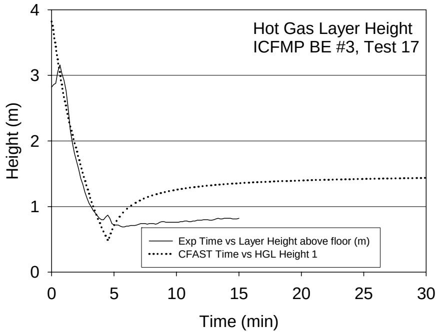


Figure A-5. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #3, Closed-Door Tests





Open-Door Tests to Follow

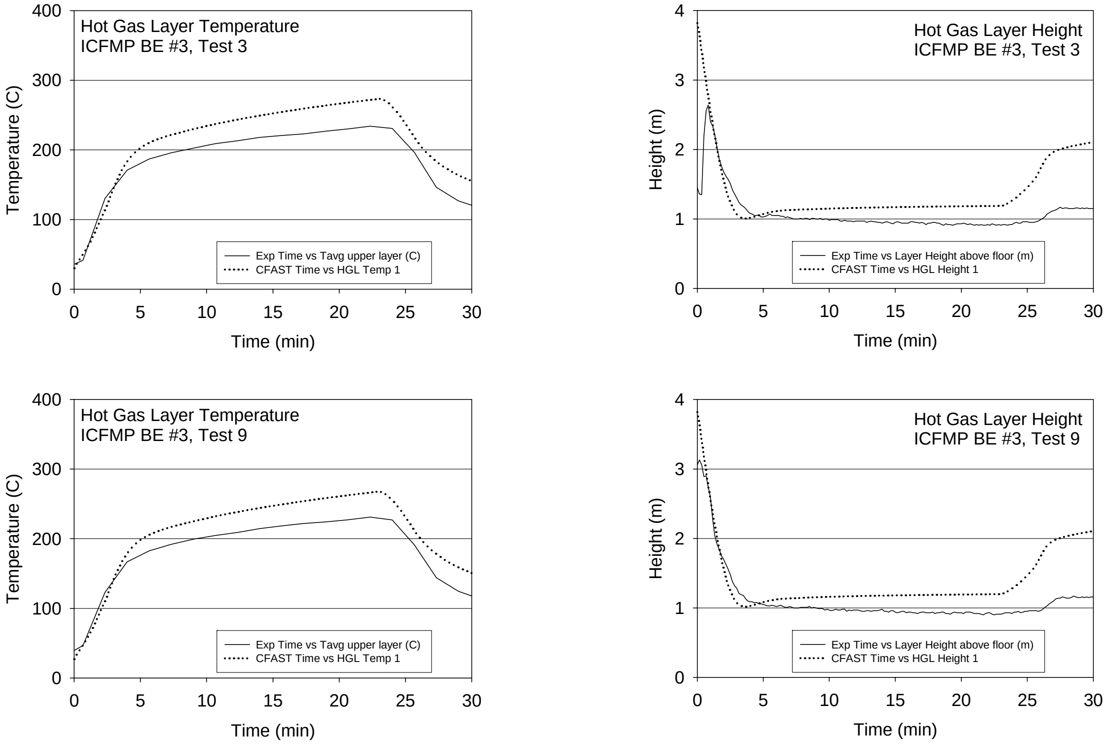


Figure A-6. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #3, Open-Door Tests

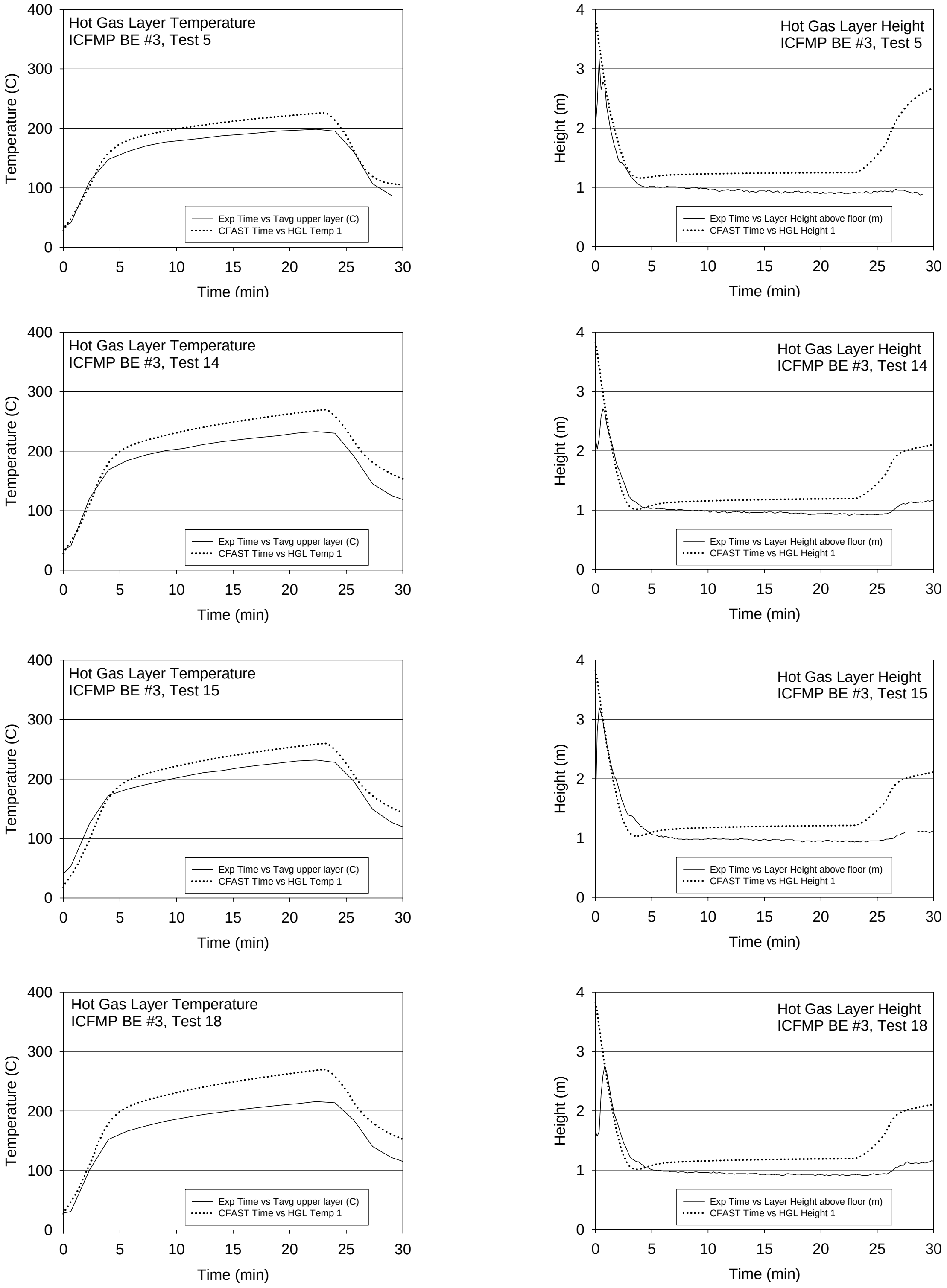


Figure A-7. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #3, Open-Door Tests

ICFMP BE #4

ICFMP BE #4 consisted of two experiments, of which one (Test 1) was chosen for validation. Compared to the other experiments, this fire was relatively large in a relatively small compartment. Thus, its HGL temperature was considerably higher than the other fire tests under study. As shown in Figure A-8, the compartment geometry is fairly simple, with a single large vent from the compartment.

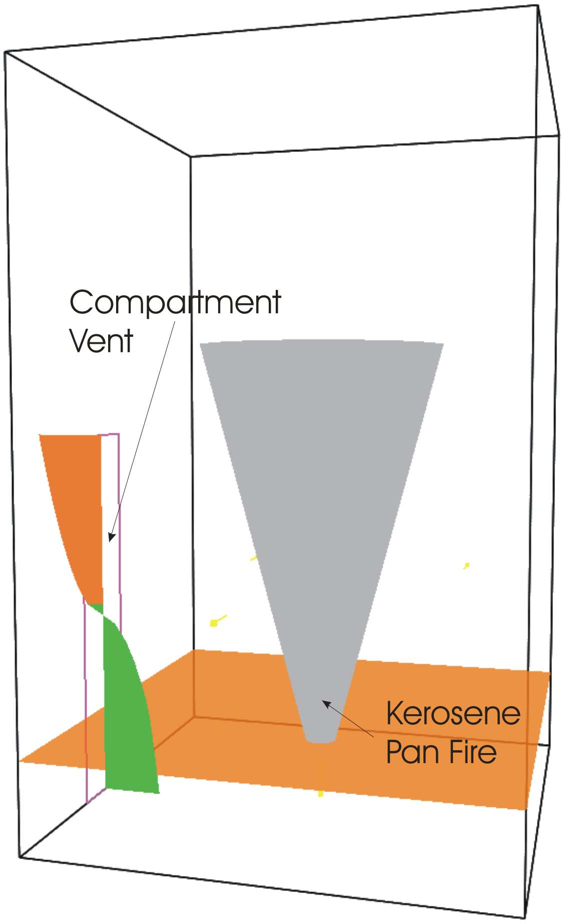


Figure A-8. Snapshot of the Simulation of ICFMP BE #4, Test 1

The HGL temperature prediction, while matching the experiment in maximum value, has a noticeably different shape than the measured profile, both in the first 5 minutes and following extinction. The HGL height prediction is distinctly different in the first 10 minutes and differs by about 40% after that time. There appears to be an error in the reduction of the experimental data.

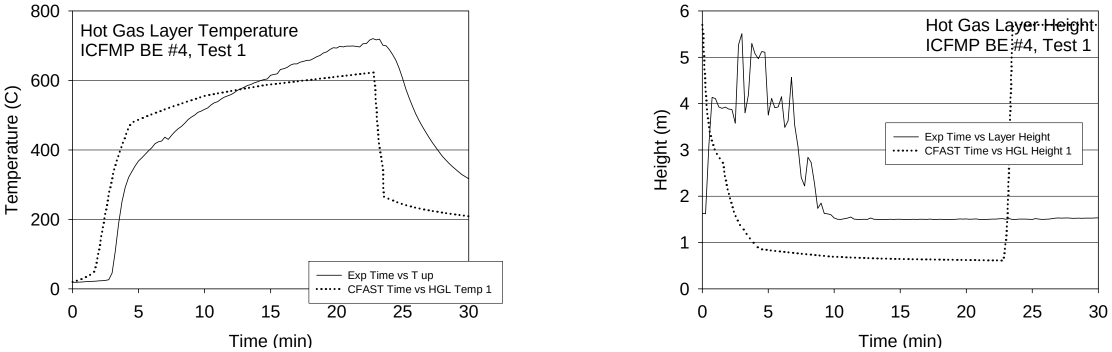


Figure A-9. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #4, Test 1

ICFMP BE #5

BE #5 was performed in the same fire test facility as BE #4. Figure A-10 displays the overall geometry of the compartment, as idealized by FDS. Only one of the experiments from this test series was used in the evaluation, Test 4, and only the first 20 minutes of the test, during the "pre-heating" stage when only the ethanol pool fire was active. The burner was lit after that point, and the cables began to burn.

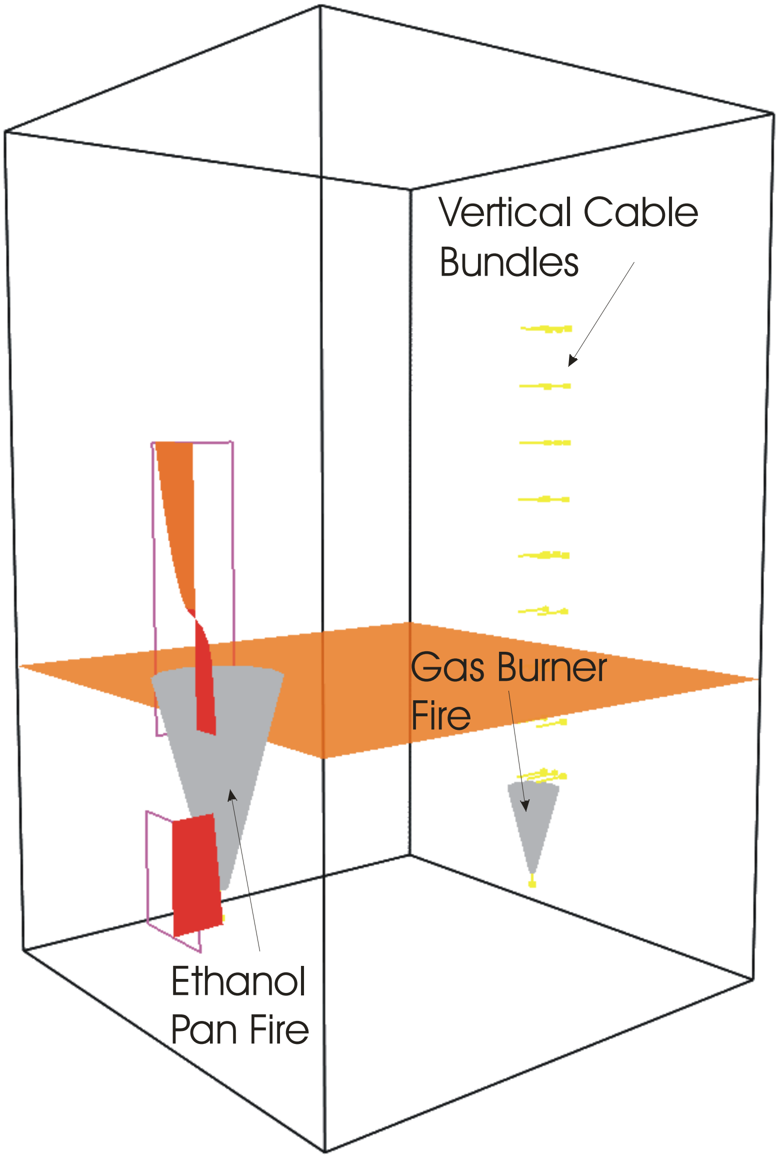


Figure A-10. Snapshot of the Simulation of ICFMP BE #5, Test 4

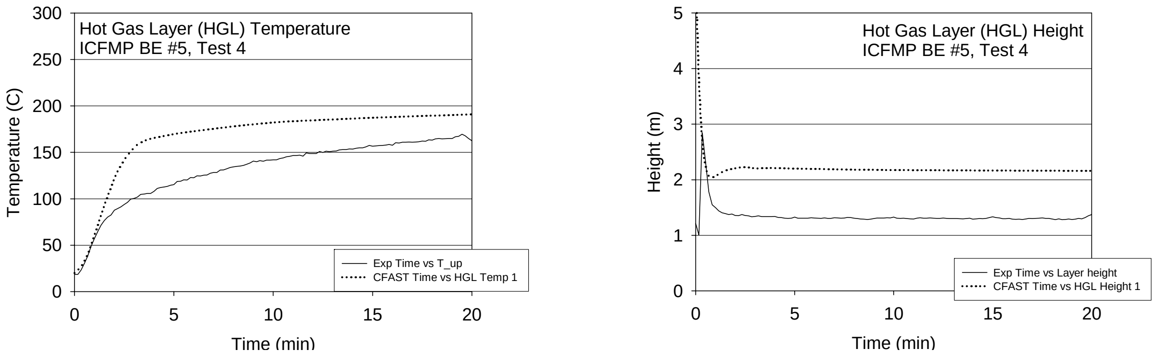


Figure A-11. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #5, Test 4

FM/SNL Test Series

Tests 4, 5, and 21 from the FM/SNL test series were selected for comparison. The HGL temperature and height were calculated using the standard method. The thermocouple arrays that are referred to as Sectors 1, 2, and 3 were averaged (with an equal weighting for each) for Tests 4 and 5. For Test 21, only Sectors 1 and 3 were used, as Sector 2 fell within the smoke plume.

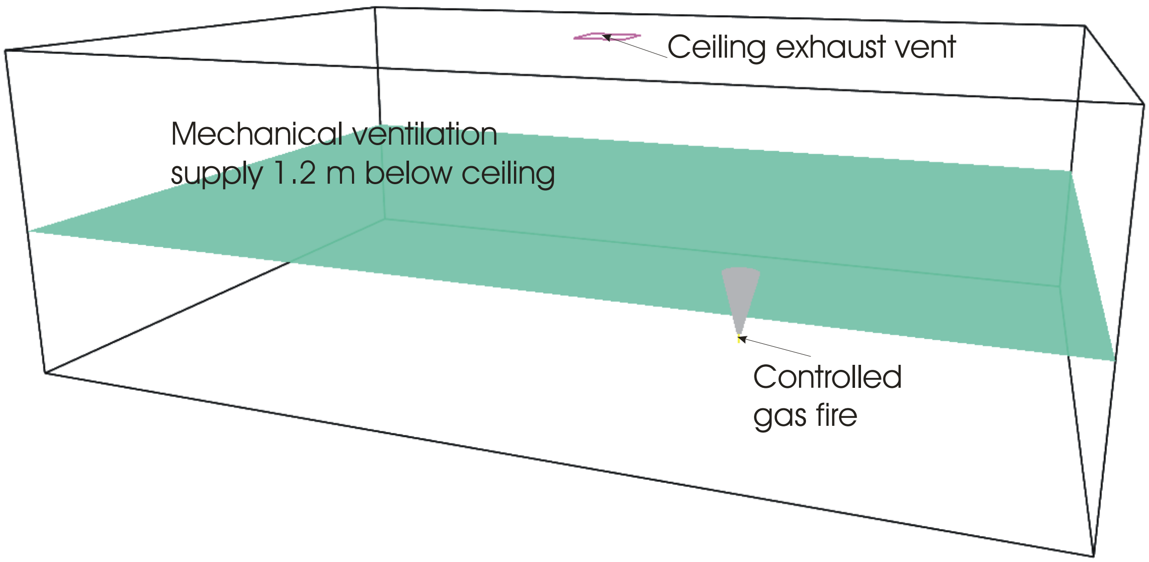


Figure A-12. Snapshot from Simulation of FM/SNL Test 5

Note the following:

- The experimental HGL heights are somewhat noisy because of the effect of ventilation ducts in the upper layer. The corresponding predicted HGL heights are consistently lower than experimental measurements, typically approaching floor level by the end of the test. This is likely a combination of the calculation technique for the experimental measurements and rules for flow from mechanical vents in the CFAST model.

- The ventilation was turned off after 9 minutes in Test 5, the effect of which was a slight increase in the measured HGL temperature.

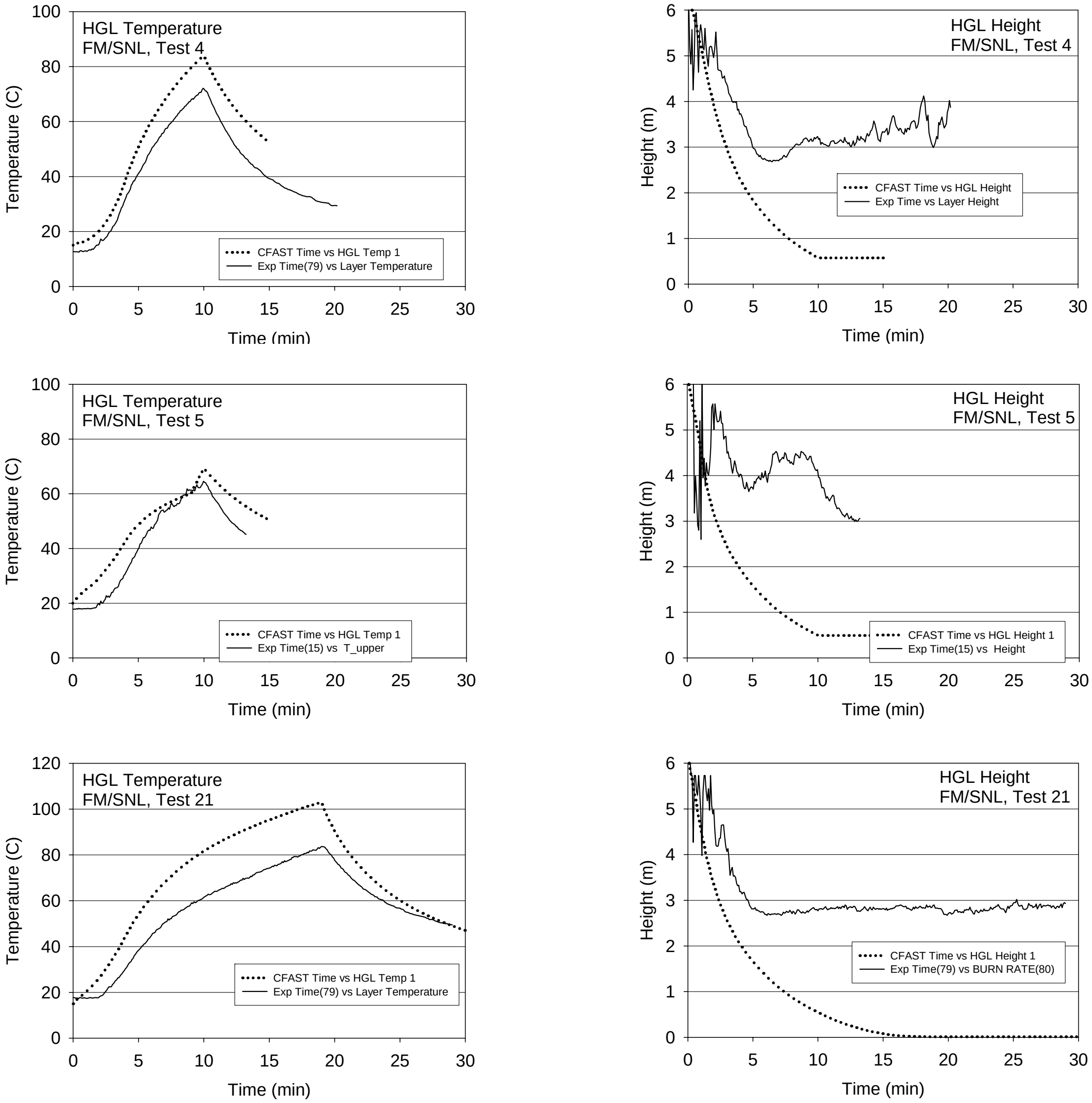


Figure A-13. Hot Gas Layer (HGL) Temperature and Height, FM/SNL Series

NBS Multi-Room Test Series

This series of experiments consisted of two relatively small rooms connected by a long corridor. The fire was located in one of the rooms. Eight vertical arrays of thermocouples were positioned throughout the test space (one in the burn room, one near the door of the burn room, three in the corridor, one in the exit to the outside at the far end of the corridor, one near the door of the other or "target" room, and one inside the target room). Four of the eight arrays were selected for comparison with model prediction (the array in the burn room, the array in the middle of the corridor, the array at the far end of the corridor, and the array in the target room). In Tests 100A and 100O, the target room was closed, in which case, the array in the exit doorway was used.

The standard reduction method was not used to compute the experimental HGL temperature or height for this test series. Rather, the test director reduced the layer information individually for the eight thermocouple arrays using an alternative method [Ref. 32].

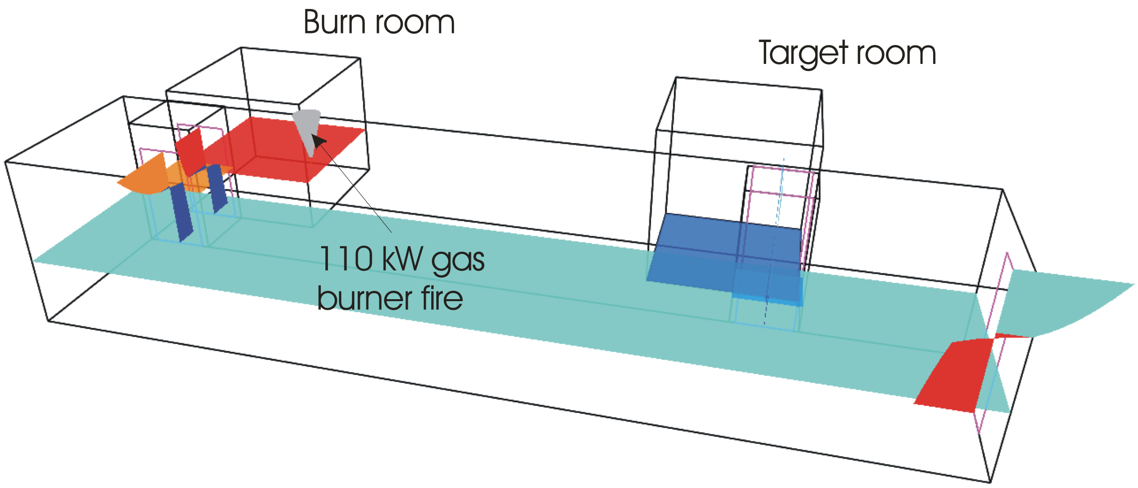


Figure A-14. Snapshot from Simulation of NBS Multi-Room Test 100Z

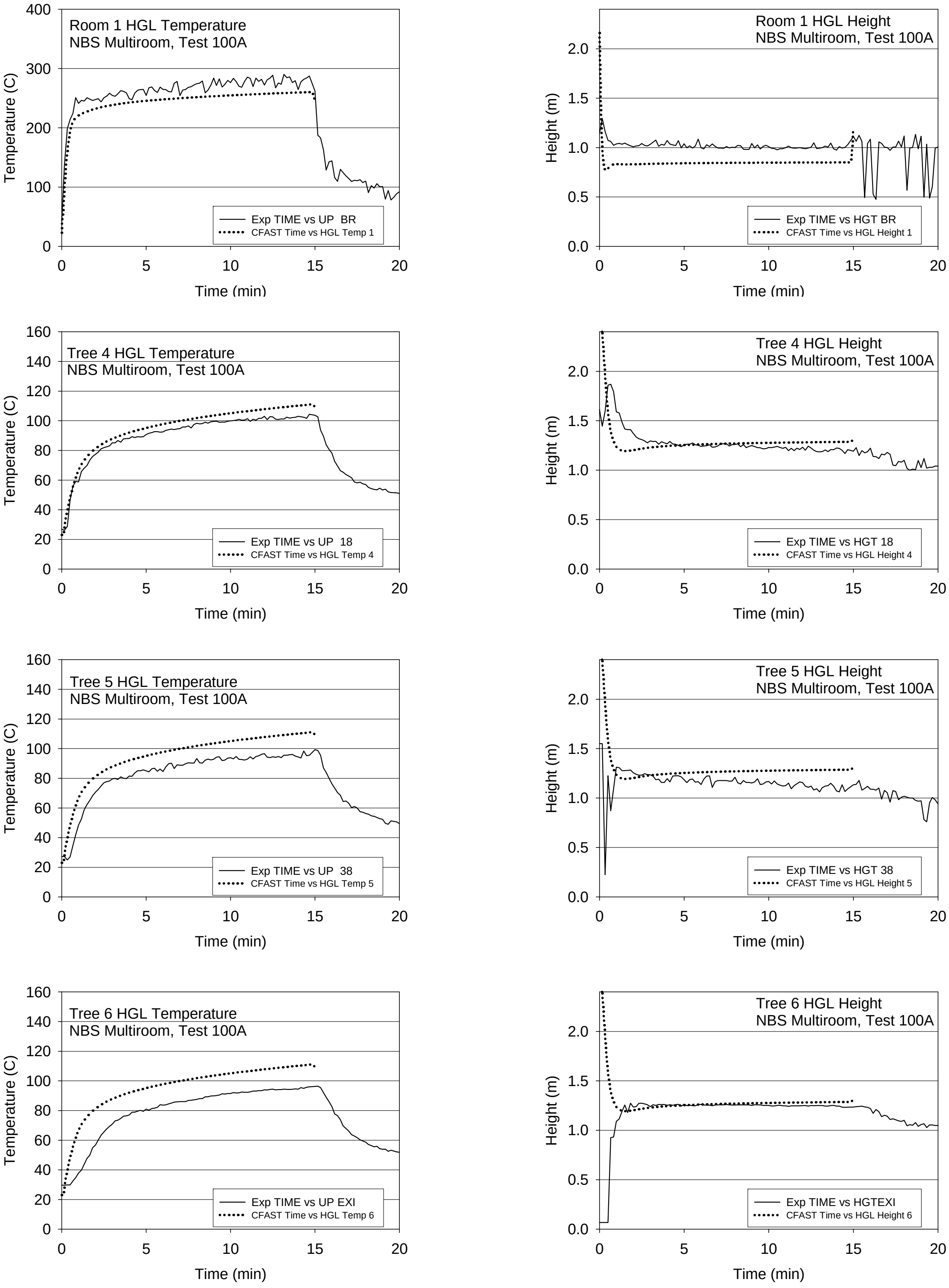


Figure A-15. Hot Gas Layer (HGL) Temperature and Height, NBS Multiroom, Test 100A

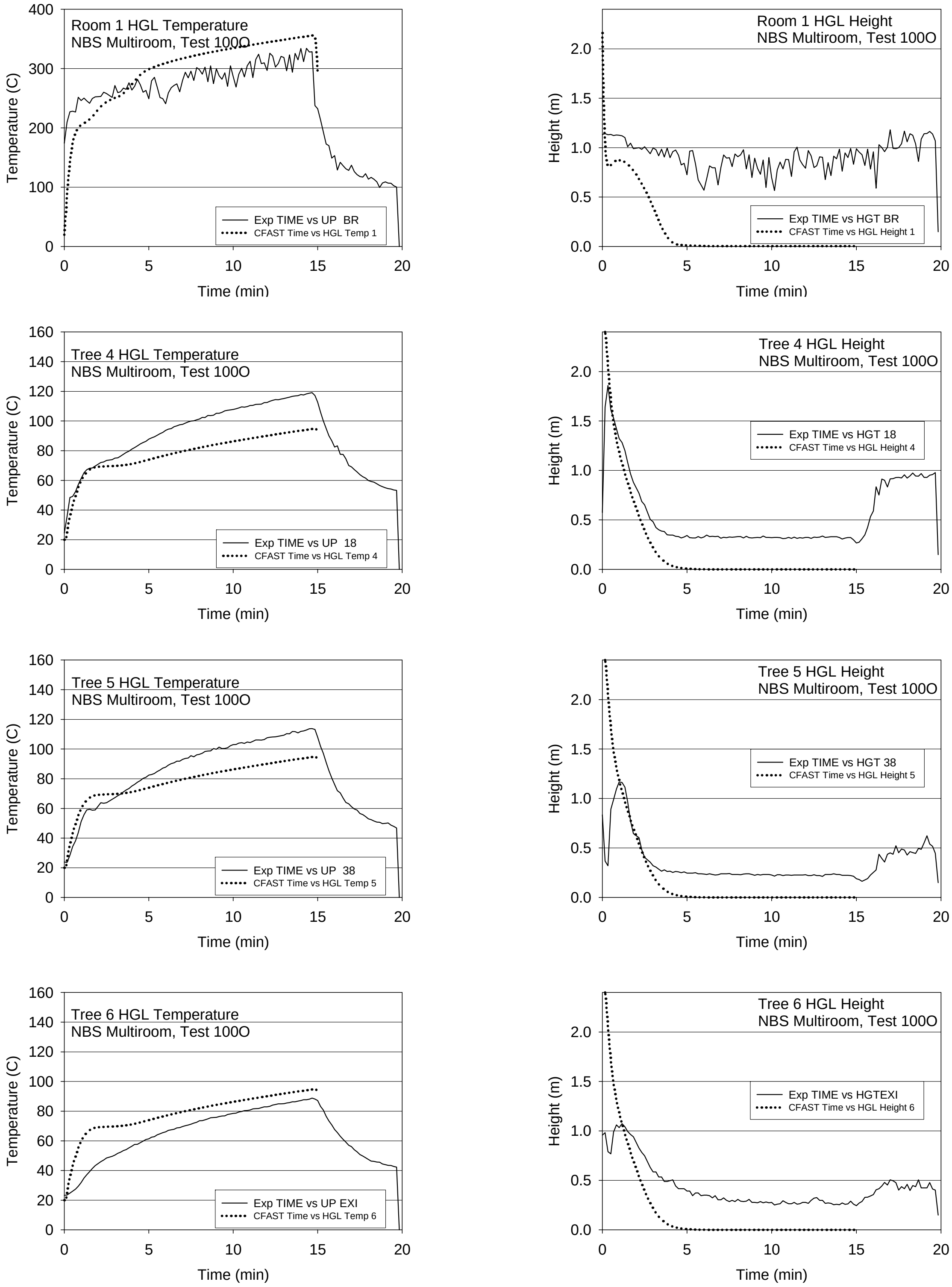


Figure A-16. Hot Gas Layer (HGL) Temperature and Height, NBS Multiroom, Test 100O

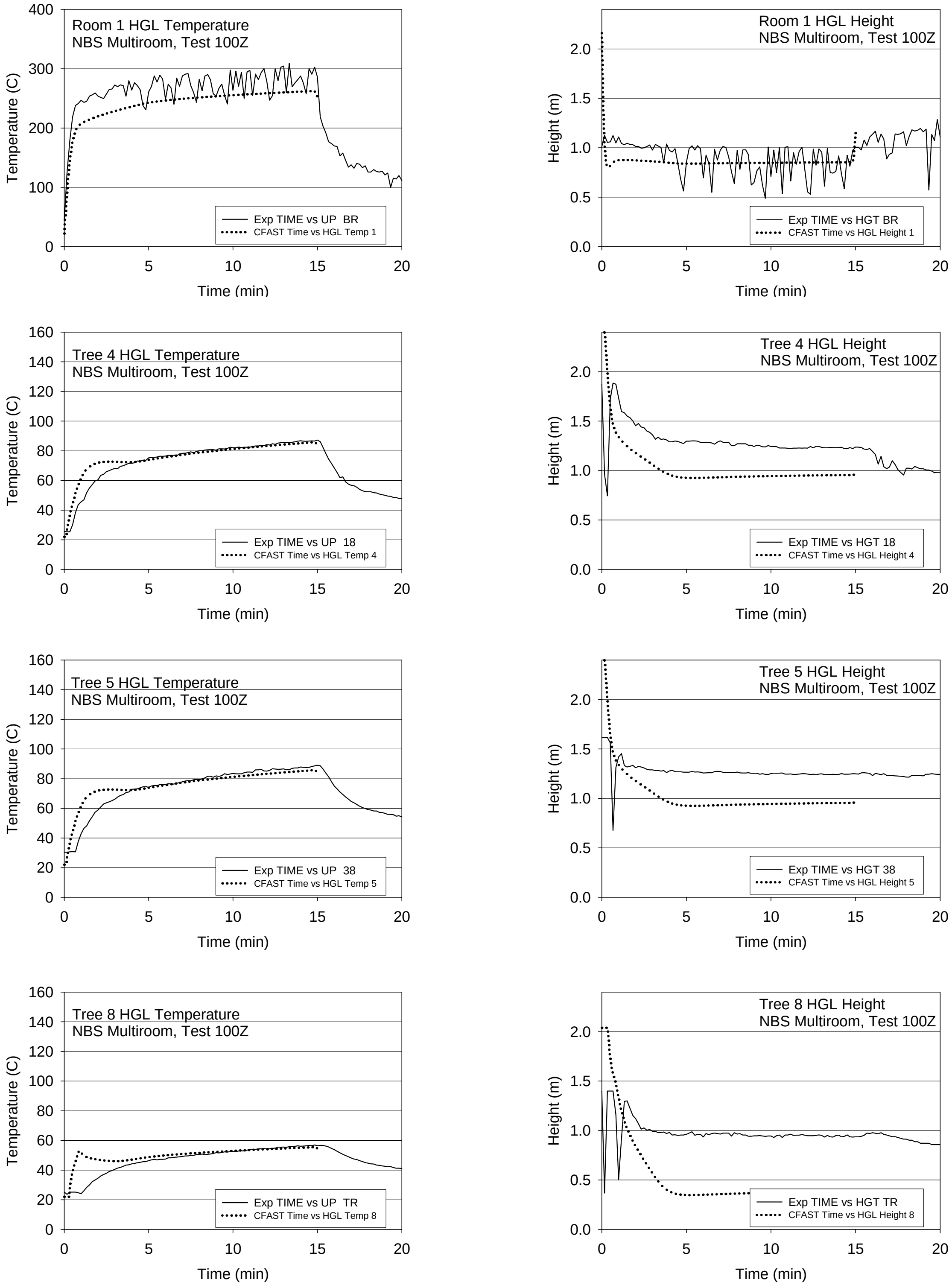


Figure A-17. Hot Gas Layer (HGL) Temperature and Height, NBS Multiroom, Test 100Z

Table A-1. Relative Differences for Hot Gas Layer (HGL) Temperature and Height

			Hot Gas Layer Temperature Rise			Hot Gas Layer Depth		
Series	Test	Measurement Position	Exp (°C)	CFAST (°C)	Relative Difference (%)	Exp (m)	CFAST (m)	Relative Difference (%)
BE2	Case 1		55	62	14			
	Case 2		86	99	15			
	Case 3		83	91	10	13.9	14.9	8
BE3	Test 1		123	135	10			
	Test 7		117	133	13			
	Test 2		229	235	2			
	Test 8		218	233	7			
	Test 4		204	222	9			
	Test 10		198	221	12			
	Test 13		290	311	7			
	Test 16		268	290	8			
	Test 17		135	143	6			
	Test 3		207	243	17	2.9	2.8	-3
	Test 9		204	241	18	2.9	2.8	-4
	Test 5		175	198	13	3.0	2.7	-10
	Test 14		208	242	16	2.9	2.8	-4
	Test 15		211	242	15	2.9	2.8	-3
	Test 18		193	243	26	2.9	-2.8	4
BE4	Test 1		700	602	-14	4.2	5.1	21
BE5	Test 4		151	172	14	4.3	3.5	-20
FM SNL	Test 4		59	69	16			
	Test 5		44	49	11			
	Test 21		66	88	33			
NBS	MV100A	Burn Room	259	237	-9	1.3	1.3	4
		Corridor 18	86	88	2	1.2	1.2	1
		Corridor 38	77	88	14	1.3	1.2	-8
		Corridor Exit	74	88	19	1.2	1.2	0
	MV100O	Burn Room	312	336	8			
		Corridor 18	106	75	-30			
		Corridor 38	99	75	-25			
		Corridor Exit						
	MV100Z	Burn Room	286	240	-16	1.3	1.3	-1
		Corridor 18	67	64	-5	1.2	1.5	29
		Corridor 38	67	64	-5	1.2	1.5	25
		Target Room	37	33	-8	1.4	2.1	-48

A.2 Ceiling Jet Temperature

CFAST includes an algorithm to account for the presence of the higher gas temperatures near the ceiling surfaces in compartments involved in a fire. In the model, this increased temperature has the effect of increasing the convective heat transfer to ceiling surfaces. Temperature and velocity of the ceiling jet is available from the model by placing a heat detector at the specified location. The ceiling jet algorithm is based on the model by Cooper [Ref. 8], with details described in the CFAST Technical Reference Guide [Ref. 1]. The algorithm predicts gas temperature and velocity under a flat, unconstrained ceiling above a fire source. Only two of the six test series (ICFMP BE #3 and FM/SNL) involved relatively large flat ceilings.

ICFMP BE #3 Test Series

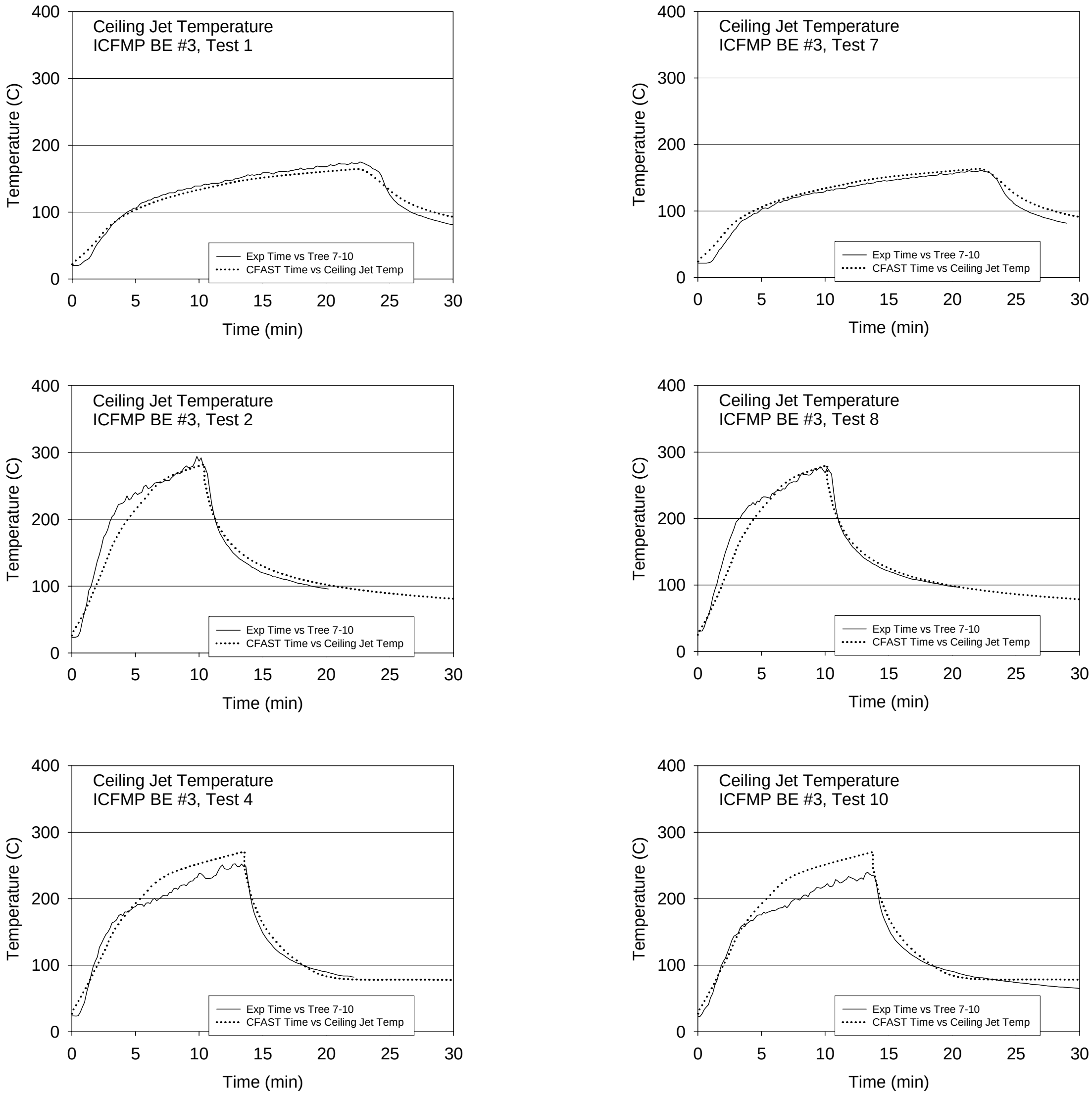
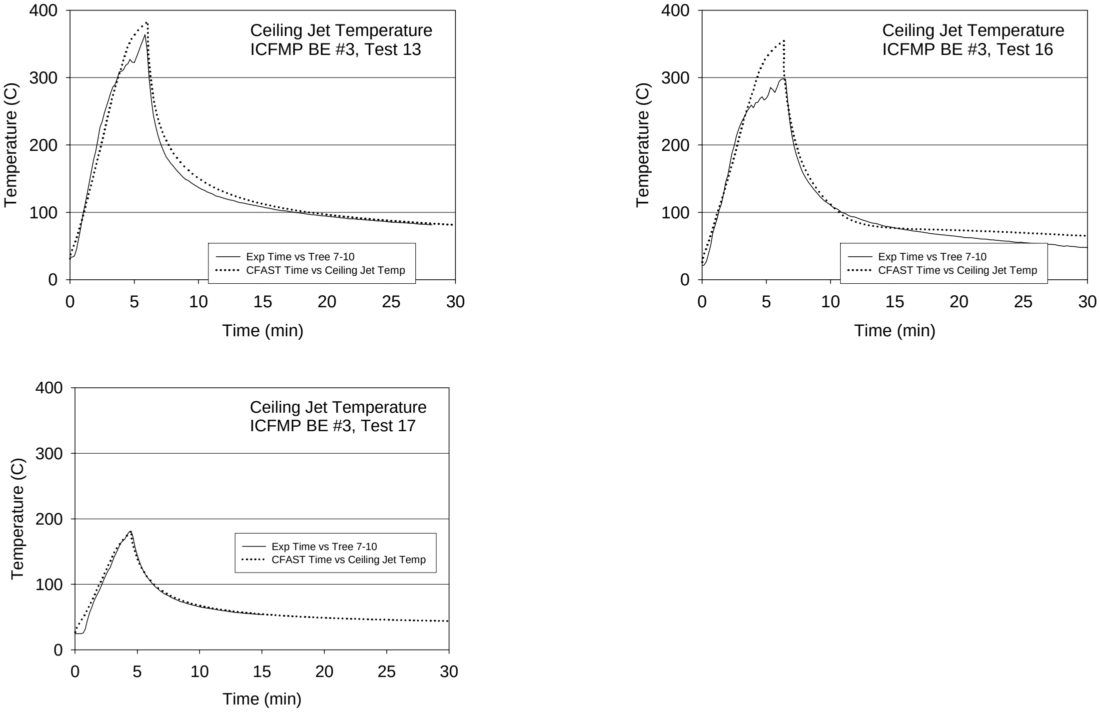


Figure A-18. Ceiling Jet Temperature, ICFMP BE #3, Closed-Door Tests



Open-Door Tests to Follow

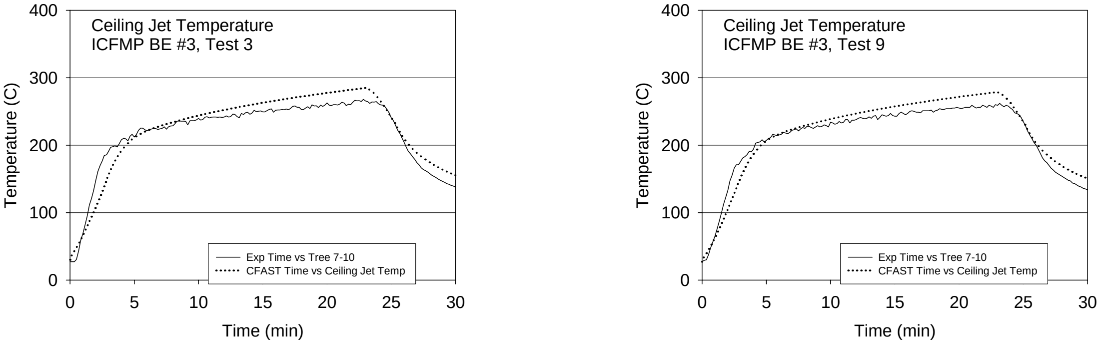


Figure A-19. Ceiling Jet Temperature, ICFMP BE #3, Closed-Door Tests

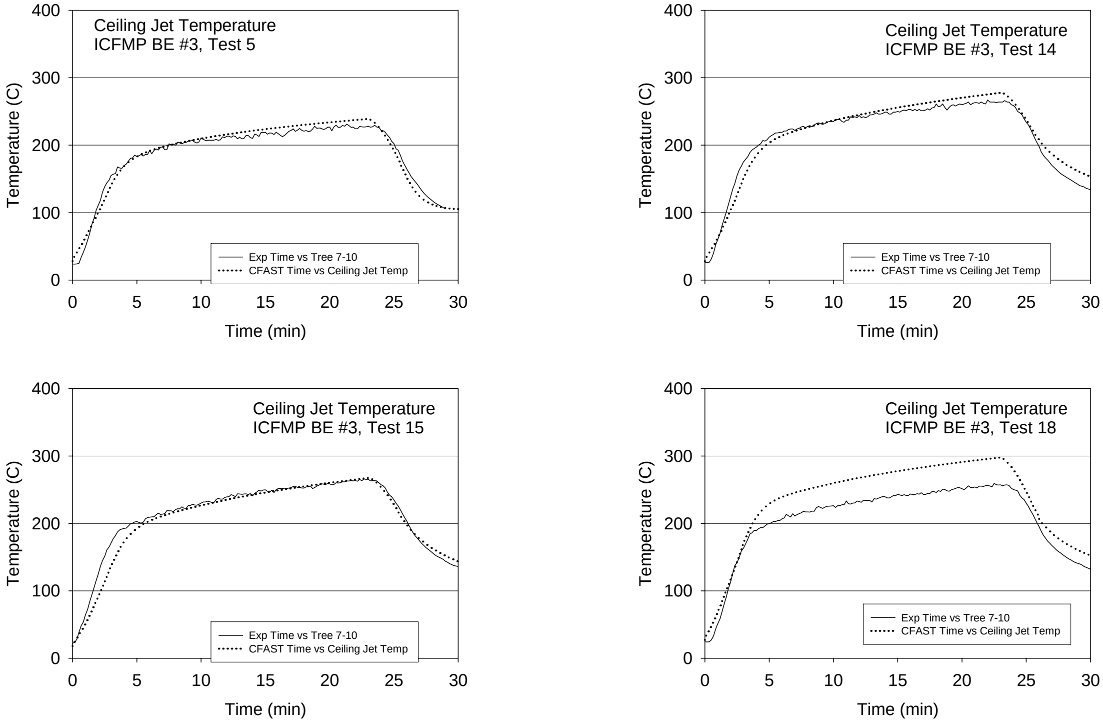


Figure A-20. Ceiling Jet Temperature, ICFMP BE #3, Open-Door Tests

FM / SNL Test Series

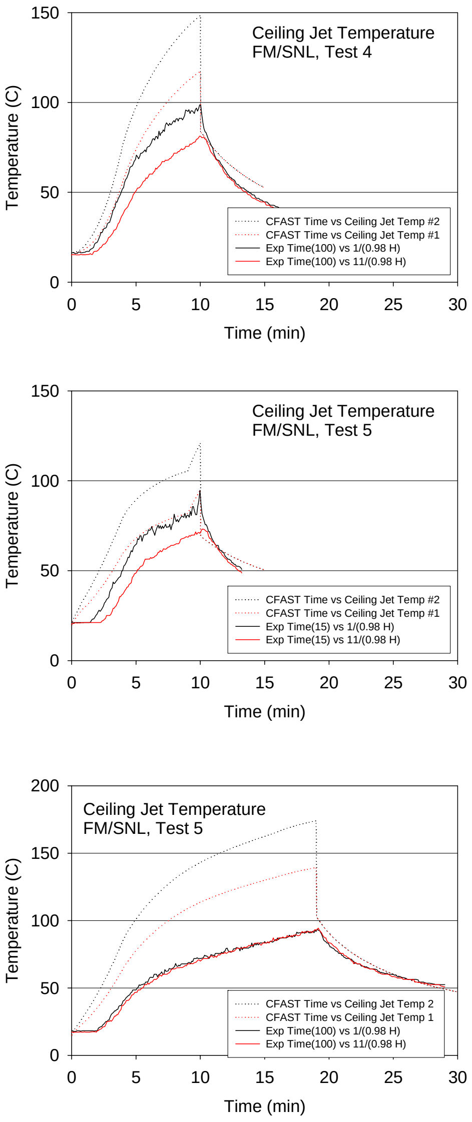


Figure A-21. Ceiling Jet Temperature, FM/SNL Tests

Table A-2. Relative Differences for Ceiling Jet Temperature

			Ceiling Jet Temperature Rise		
Series	Test	Measurement Position	Exp (°C)	CFAST (°C)	Relative Difference (%)
BE3	Test 1		155	135	-13
	Test 7		139	133	-5
	Test 2		271	235	-13
	Test 8		247	233	-6
	Test 4		229	222	-3
	Test 10		218	221	2
	Test 13		330	311	-6
	Test 16		278	290	4
	Test 17		156	143	-8
	Test 3		241	243	1
	Test 9		235	241	3
	Test 5		208	198	-5
	Test 14		241	242	0
	Test 15		244	242	-1
	Test 18		235	243	3
FM SNL	Test 4	Sec 1	82	133	62
		Sec 3	66	102	56
	Test 5	Sec 1	70	101	44
		Sec 3	53	75	43
	Test 21	Sec 1	75	159	113
		Sec 3	77	124	61

A.3 Plume Temperature

CFAST includes a plume entrainment algorithm based on the work of McCaffrey [Ref. 7], which models the mixing of combustion products released by the fire with air in the fire compartment and movements of these gases into the upper layer in the compartment. Plume temperature is not directly calculated nor reported in a CFAST calculation. For this reason, comparisons of experimentally measured plume temperatures with CFAST calculations are not appropriate and are not included in this report.

A.4 Flame Height

Flame height is recorded by visual observations, photographs or video footage. Videos from the ICFMP BE #3 test series and photographs from BE #2 are available. It is difficult to precisely measure the flame height, but the photos and videos allow one to make estimates accurate to within a pan diameter.

ICFMP BE #2

Figure A-22 contains photographs of the actual fire. The height of the visible flame in the photographs has been estimated to be between 2.4 and 3 pan diameters [3.8 m to 4.8 m (12.5 ft to 15.7 ft)]. From the CFAST calculations, the estimated flame height is 4.3 m (14.1 ft).

Figure A-22. Photographs of Heptane Pan Fires, ICFMP BE #2, Case 2 (Courtesy, Simo Hostikka, VTT Building and Transport, Espoo, Finland)

ICFMP BE #3

No measurements were made of the flame height during BE #3, but numerous photographs were taken through the doorway, which measured 2 m x 2 m (6.6 ft x 6.6 ft). During BE #3, Test 3, the peak flame height was estimated to be 2.8 m (9.2 ft), roughly consistent with the view through the doorway in the figure below.

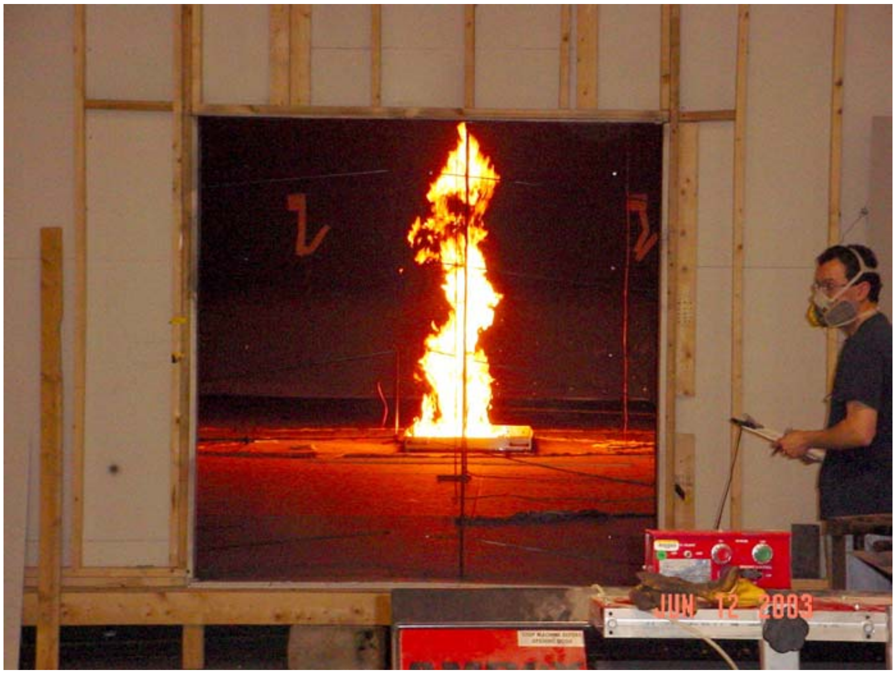


Figure A-23. Photograph and Simulation of ICFMP BE #3, Test 3, as seen through the 2 m x 2 m doorway (Courtesy of Francisco Joglar, SAIC)

A.5 Oxygen Concentration

CFAST simulates a fire as a mass of fuel that burns at a prescribed “pyrolysis” rate and releases both energy and combustion products. CFAST calculates species production based on user-defined production yields, and both the pyrolysis rate and the resulting energy and species generation may be limited by the oxygen available for combustion. When sufficient oxygen is available for combustion, the heat release rate (HRR) for a constrained fire is the same as for an unconstrained fire. Mass and species concentrations are tracked by the model as gases flow through openings in a structure to other compartments in the structure or to the outdoors.

The following pages present comparisons of oxygen and carbon dioxide concentration predictions with measurement for BE #3 and BE #5. In BE #3, there were two oxygen measurements, one in the upper layer, one in the lower layer. There was only one carbon dioxide measurement in the upper layer. For BE #5, Test 4, a plot of upper-layer oxygen and carbon dioxide is included along with the results for BE #3.

Not surprisingly, the accuracy of the gas species predictions is comparable to that of the HGL temperature. After all, CFAST uses the same basic algorithm for transport, regardless of whether it is the transport of heat or mass.

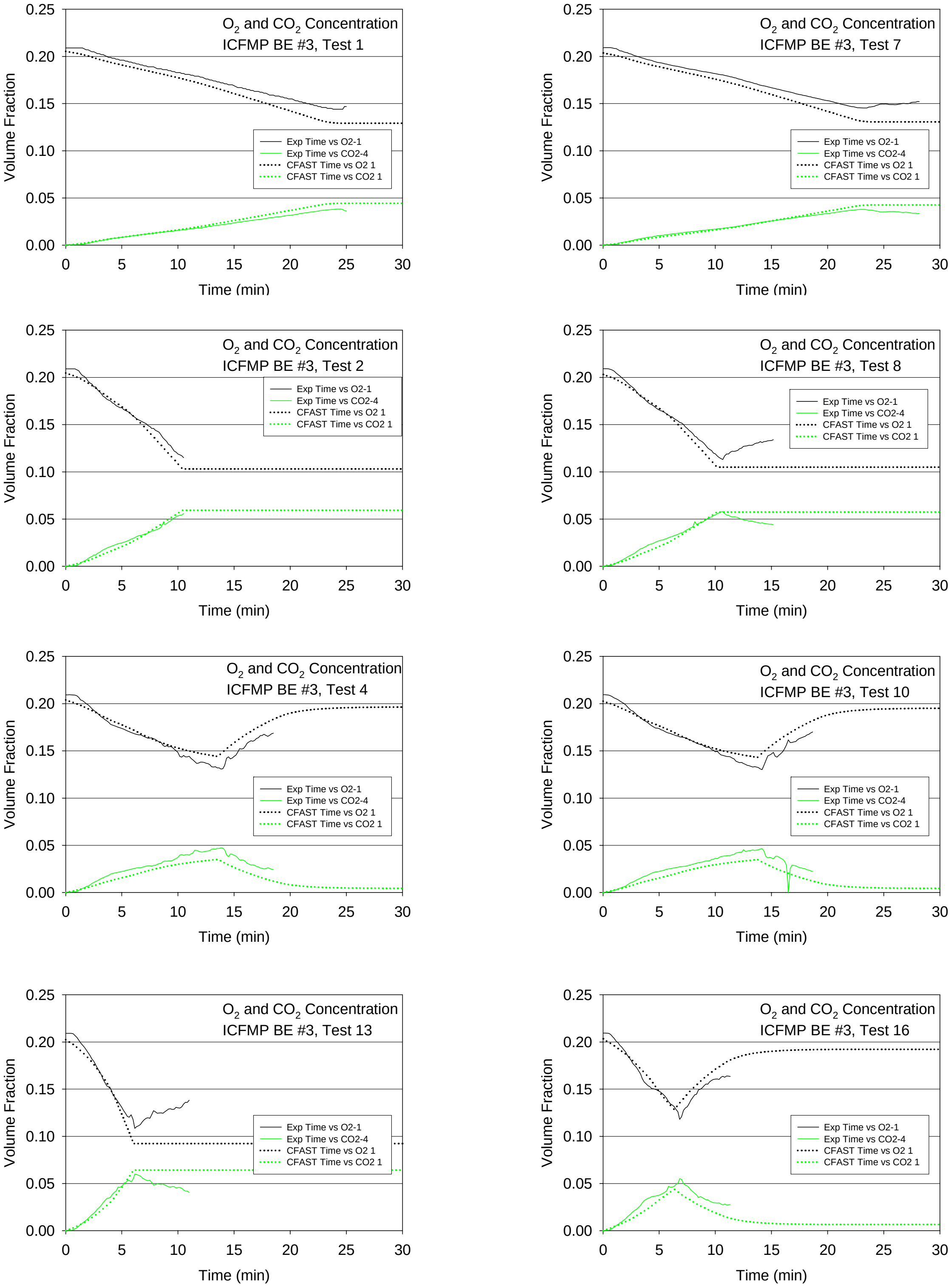


Figure A-24. Oxygen and Carbon Dioxide Concentration, ICFMP BE #3, Closed-Door Tests

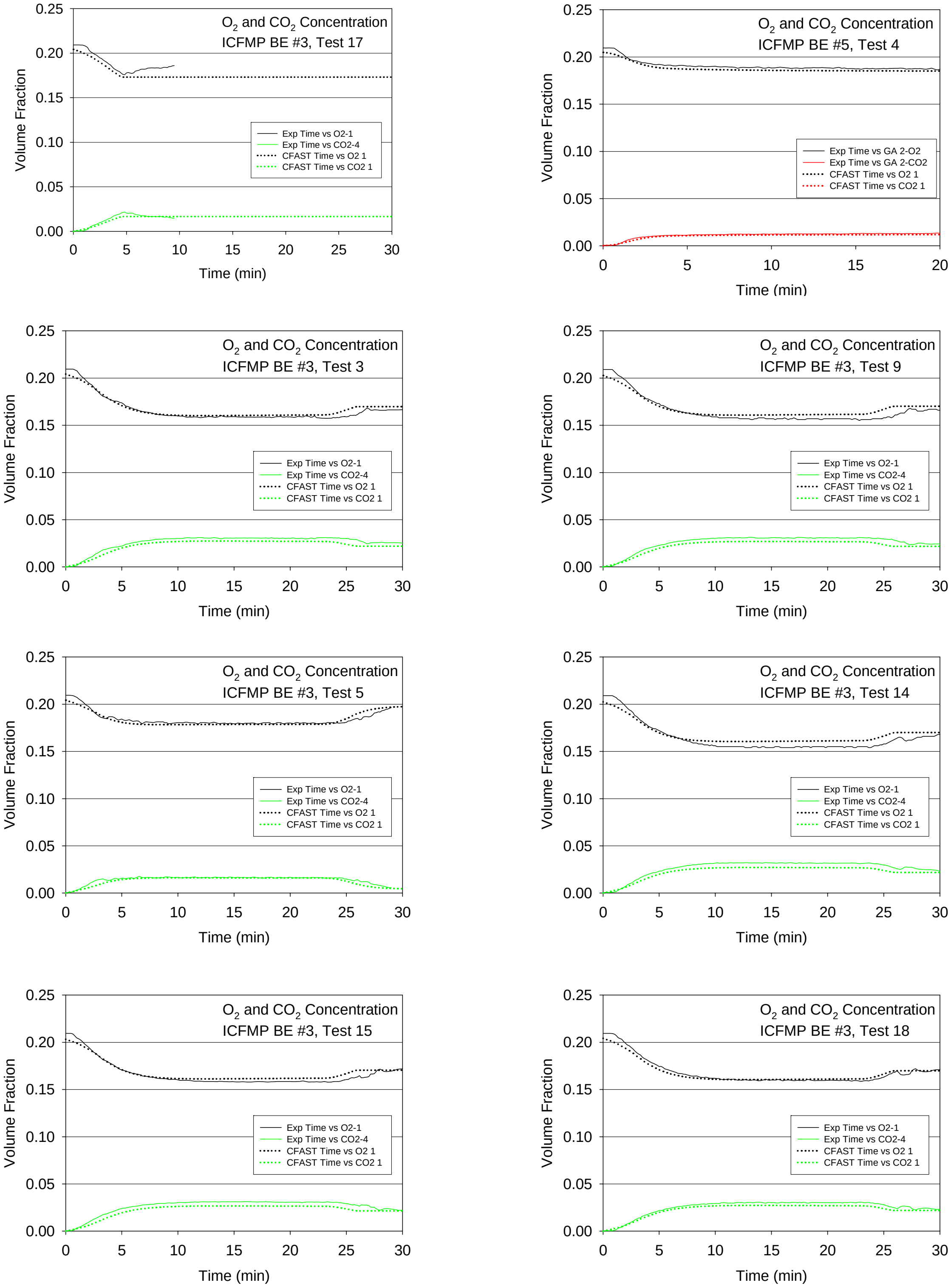


Figure A-25. Oxygen and Carbon Dioxide Concentration, ICFMP BE #3, Open-Door Tests (Note that the single test from ICFMP BE #5 is included at the upper right)

Table A-3. Relative Differences for Oxygen and Carbon Dioxide Concentration

		HGL Oxygen Concentration Decrease			HGL Carbon Dioxide Concentration		
Series	Test	Exp (molar fraction)	CFAST (molar fraction)	Relative Difference (%)	Exp (molar fraction)	CFAST (molar fraction)	Relative Difference (%)
BE3	Test 1	0.065	0.076	17	0.038	0.044	16
	Test 7	0.064	0.073	14	0.038	0.043	12
	Test 2	0.092	0.101	9	0.054	0.059	8
	Test 8	0.096	0.098	2	0.058	0.057	-1
	Test 4	0.079	0.060	-24	0.047	0.035	-26
	Test 10	0.079	0.059	-25	0.047	0.035	-25
	Test 13	0.101	0.110	10	0.060	0.064	7
	Test 16	0.091	0.075	-18	0.055	0.044	-21
	Test 17	0.033	0.031	-7	0.022	0.017	-23
	Test 3	0.052	0.044	-15	0.031	0.027	-12
	Test 9	0.054	0.042	-22	0.031	0.027	-14
	Test 5	0.030	0.026	-14	0.017	0.016	-8
	Test 14	0.055	0.042	-24	0.032	0.027	-16
	Test 15	0.052	0.042	-19	0.031	0.027	-15
	Test 18	0.051	0.044	-14	0.031	0.027	-11
BE5	Test 4	0.023	0.020	-15	0.013	0.012	-9

A.6 Smoke Concentration

CFAST treats smoke like all other combustion products, with an overall mass balance dependent on interrelated user-specified species yields for major combustion species. To model smoke movement, the user prescribes the smoke yield relative to the yield of carbon monoxide. A simple combustion chemistry scheme in the model then determines the smoke particulate concentration in the form of an optical density. For BE #3, the smoke yield was specified as one of the test parameters.

Figure A-26 and Figure A-27 contain comparisons of measured and predicted smoke concentration at one measuring station in the upper layer. There are two obvious trends in the figures. First, the predicted concentrations average 22% higher than the measured in the open-door tests, within experimental uncertainty with a single exception for Test 14. Second, the predicted concentrations are roughly three times the measured concentrations in the closed-door tests.

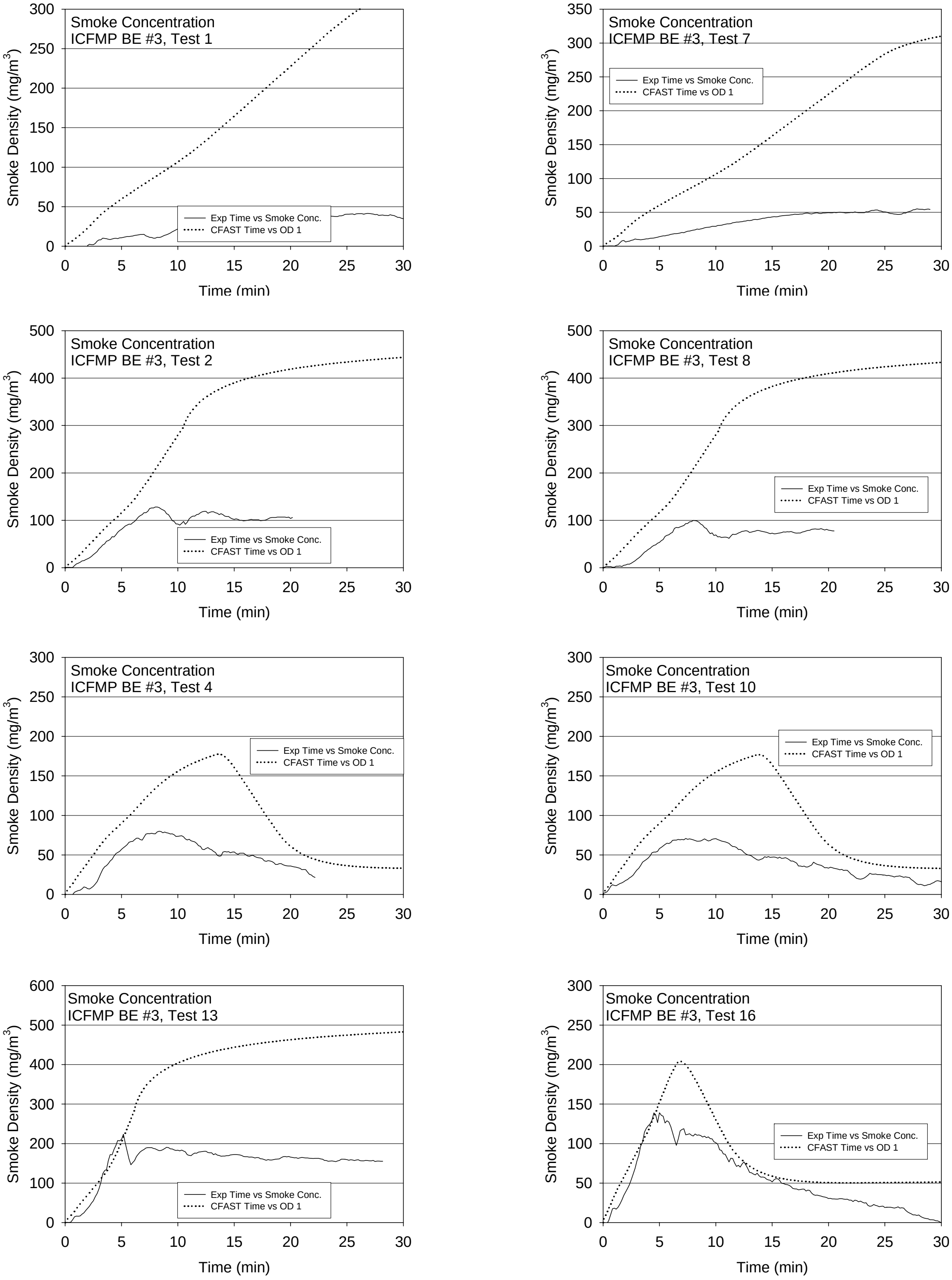
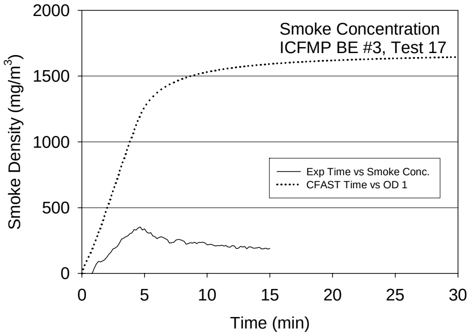


Figure A-26. Smoke Concentration, ICFMP BE #3, Closed-Door Tests



<u>Open-Door Tests to Follow</u>

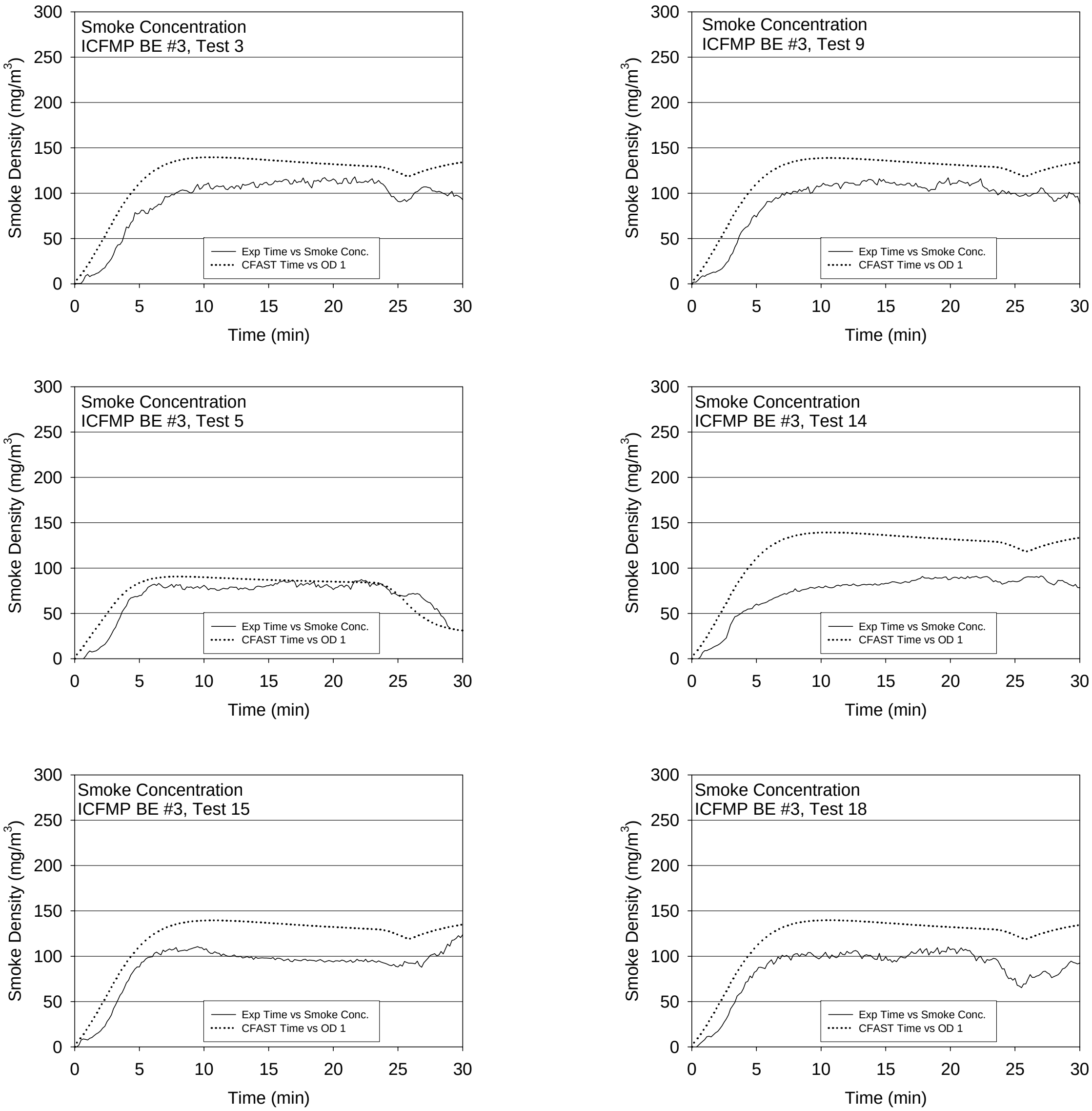


Figure A-27. Smoke Concentration, ICFMP BE #3, Open-Door Tests

Table A-4. Relative Differences for Smoke Concentration

		Smoke Concentration		
Series	Test	Exp (mg/m^3)	CFAST (mg/m^3)	Relative Difference (%)
BE3	Test 1	42	321	672
	Test 7	55	307	457
	Test 2	128	420	228
	Test 8	100	411	313
	Test 4	80	177	122
	Test 10	71	177	150
	Test 13	224	480	115
	Test 16	139	204	47
	Test 17	353	1590	350
	Test 3	118	140	18
	Test 9	117	139	19
	Test 5	87	91	4
	Test 14	91	139	53
	Test 15	124	140	13
	Test 18	110	140	27

A.7 Compartment Pressure

Experimental measurements for room pressure are available only from the ICFMP BE #3 test series. The pressure within the compartment was measured at a single point, near the floor. In the simulations of the closed-door tests, the compartment is assumed to leak via a small vent near the ceiling with an area consistent with the measured leakage area.

Comparisons between measurement and prediction are shown in Figure A-28 and Figure A-29. For those tests in which the door to the compartment is open, the over-pressures are only a few Pascals, whereas when the door is closed, the over-pressures are several hundred Pascals.

In general, the predicted pressures are of comparable magnitude to the measured pressures and, in most cases, differences can be explained using the reported uncertainties in the leakage area and the fact that the leakage area changed from test to test because of the thermal stress on the compartment walls. The one notable exception is Test 16. This experiment was performed with the door closed and the ventilation on, and there is considerable uncertainty in the magnitude of both the supply and return mass flow rates.

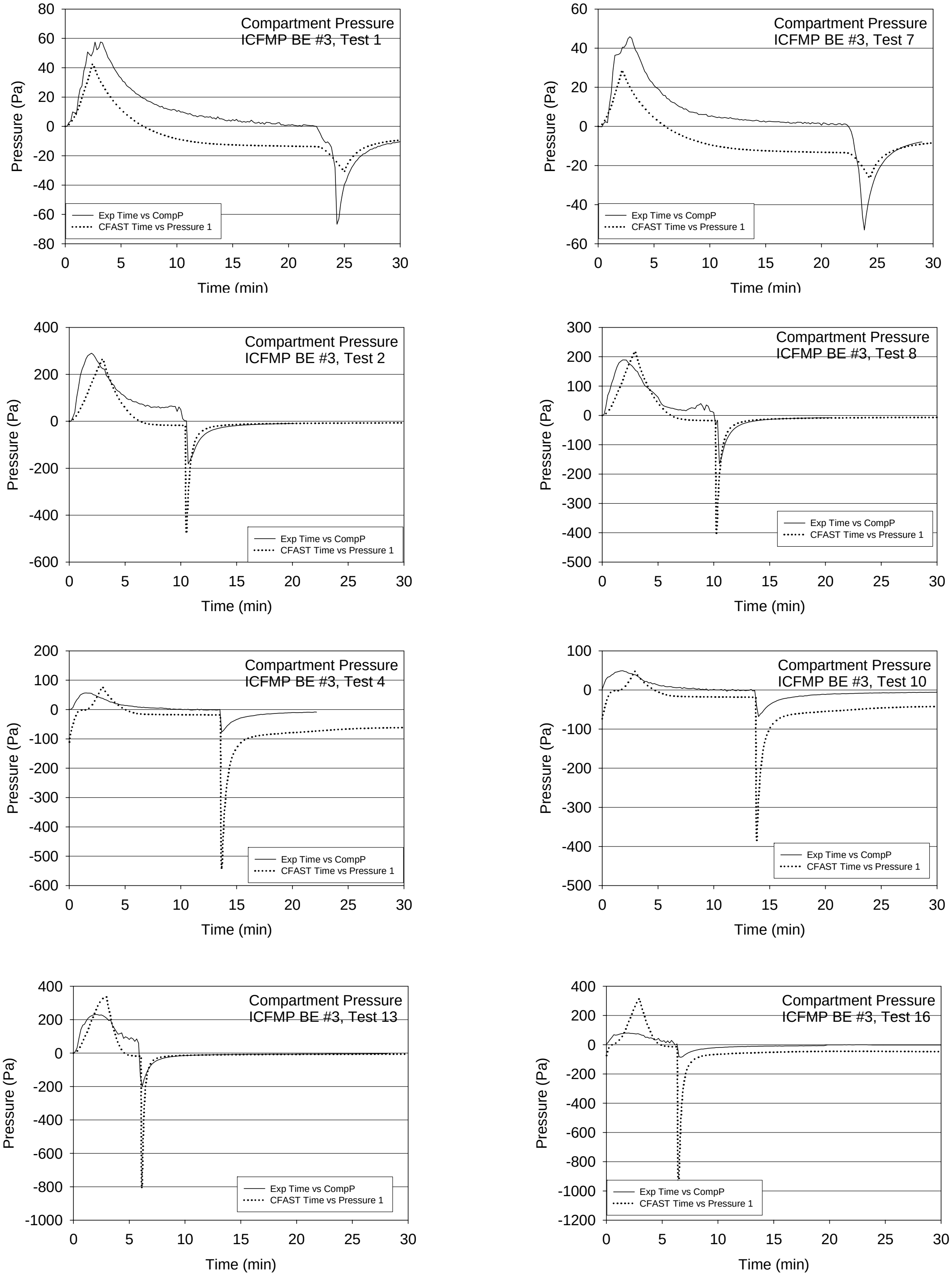
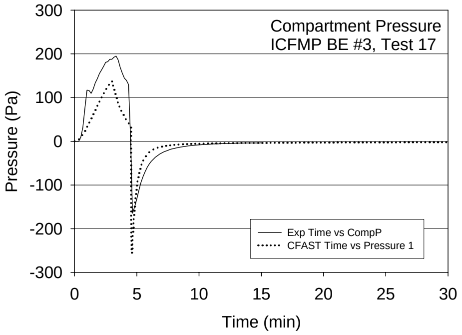


Figure A-28. Compartment Pressure, ICFMP BE #3, Closed-Door Tests



Open-Door Tests to Follow

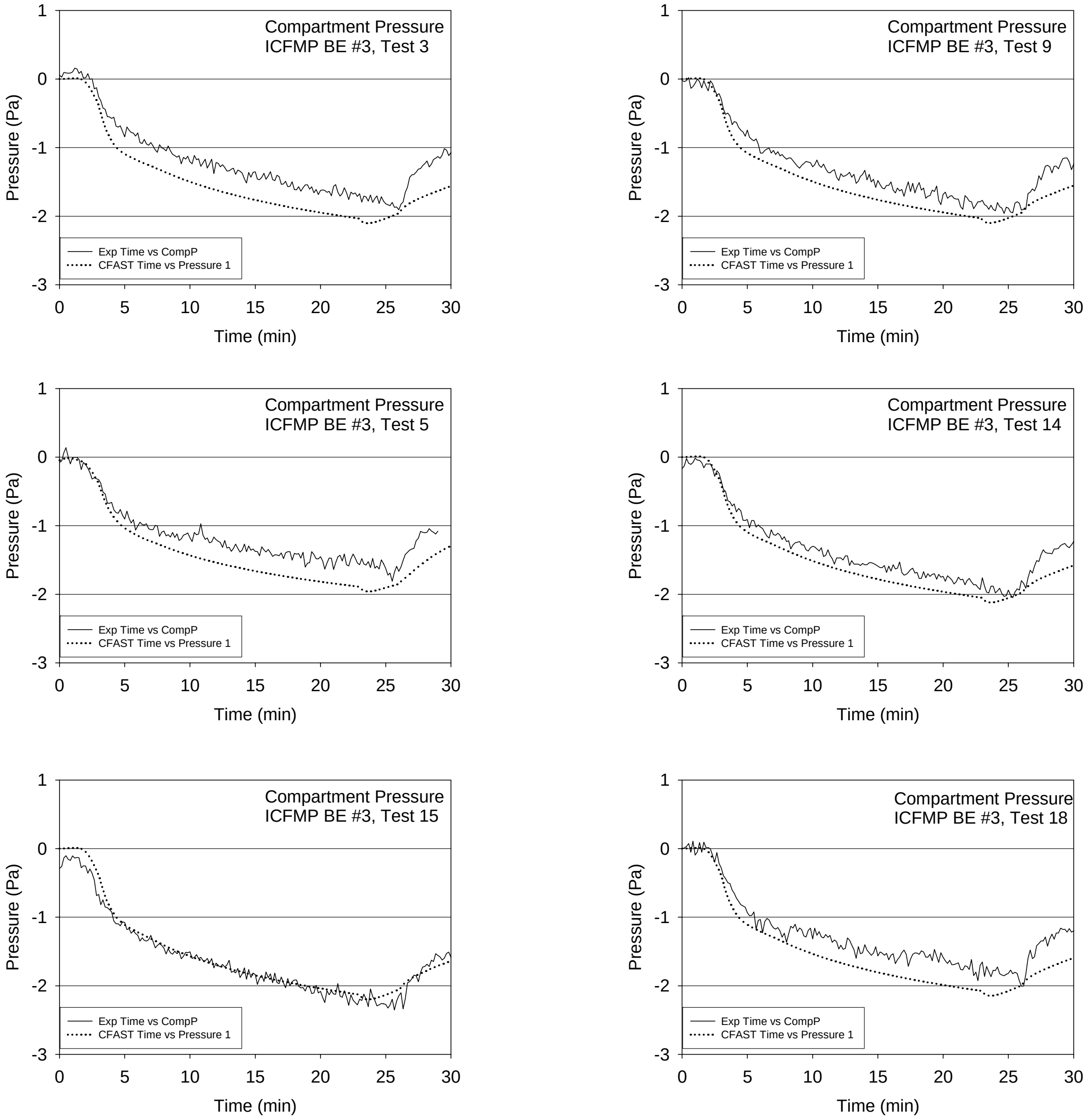


Figure A-29. Compartment Pressure, ICFMP BE #3, Open-Door Tests

Table A-5. Relative Differences for Compartment Pressure

		Comparment Pressure Rise		
Series	Test	Exp (Pa)	CFAST (Pa)	Relative Difference (%)
BE3	Test 1	58	42	-27
	Test 7	46	29	-38
	Test 2	290	266	-8
	Test 8	189	213	12
	Test 4	57	76	36
	Test 10	49	45	-7
	Test 13	232	336	45
	Test 16	81	309	283
	Test 17	195	138	-29
	Test 3	-1.9	-2.1	10
	Test 9	-2.0	-2.1	7
	Test 5	-1.8	-2.0	8
	Test 14	-2.1	-2.1	3
	Test 15	-2.4	-2.2	-6
	Test 18	-2.0	-2.1	7

A.8 Target Temperature and Heat Flux

Target temperature and heat flux data are available from ICFMP BE #3, #4, and #5. In BE #3, the targets are various types of cables in various configurations — horizontal, vertical, in trays, or free-hanging. In BE #4, the targets are three rectangular slabs of different materials instrumented with heat flux gauges and thermocouples. In BE #5, the targets are again cables, in this case, bundled power and control cables in a vertical ladder.

ICFMP BE #3

For each of the four cable targets considered, measurements of the target surface temperature and total heat flux are compared for Control Cable B, Horizontal Cable Tray D, Power Cable F, and Vertical Cable Tray G.

CFAST does not have a detailed model of the heat transfer within the bundled, cylindrical, non-homogenous cables. CFAST assumes all cable targets to be rectangular homogeneous slabs of thickness comparable to the diameter of the individual cables. Material properties for the targets are assumed to be those of the covering material for the respective cables.

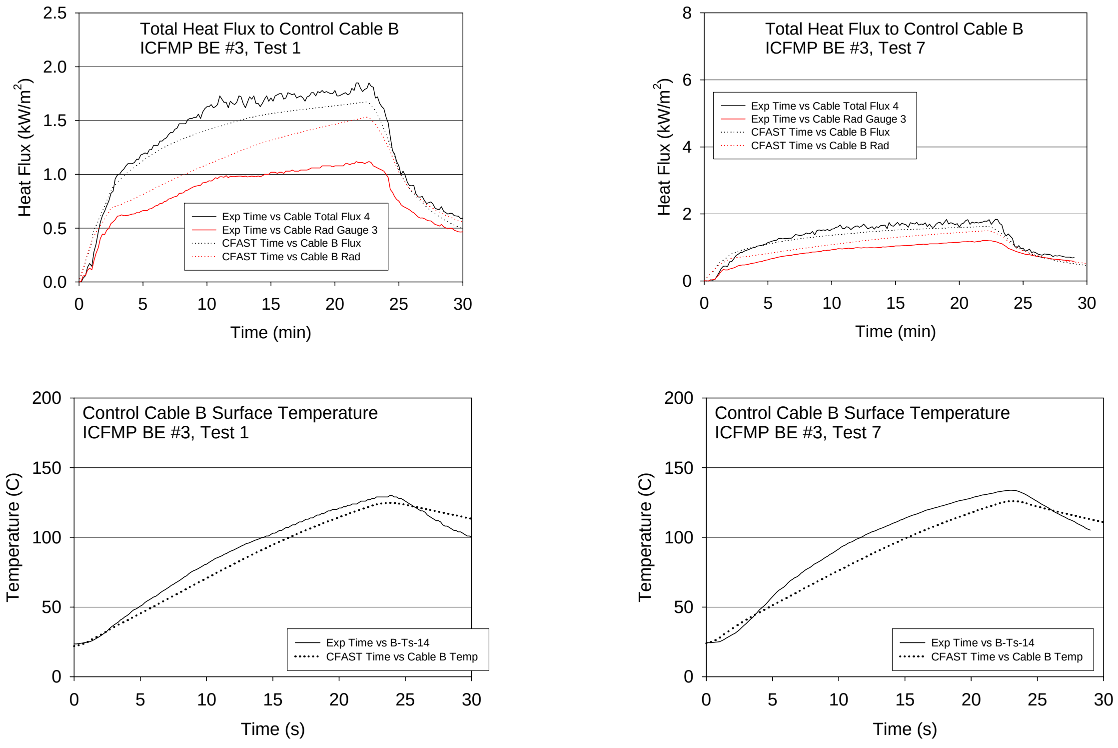


Figure A-30. Thermal Environment near Cable B, ICFMP BE #3, Tests 1 and 7

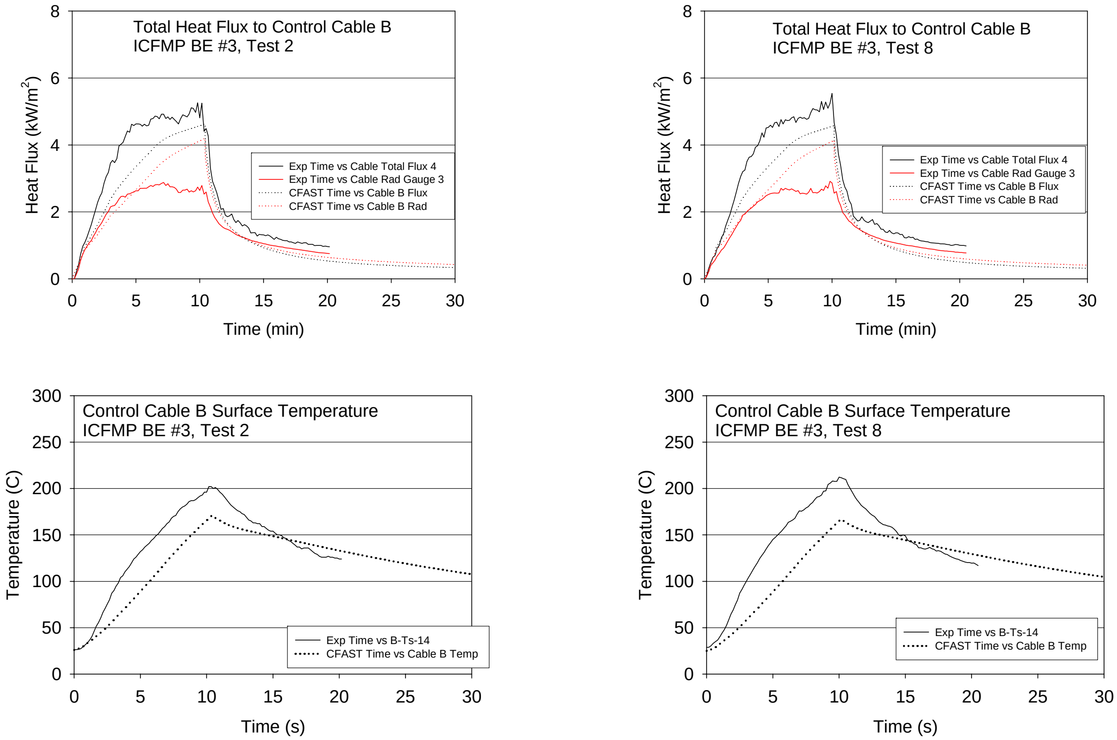


Figure A-31. Thermal Environment near Cable B, ICFMP BE #3, Tests 2 and 8

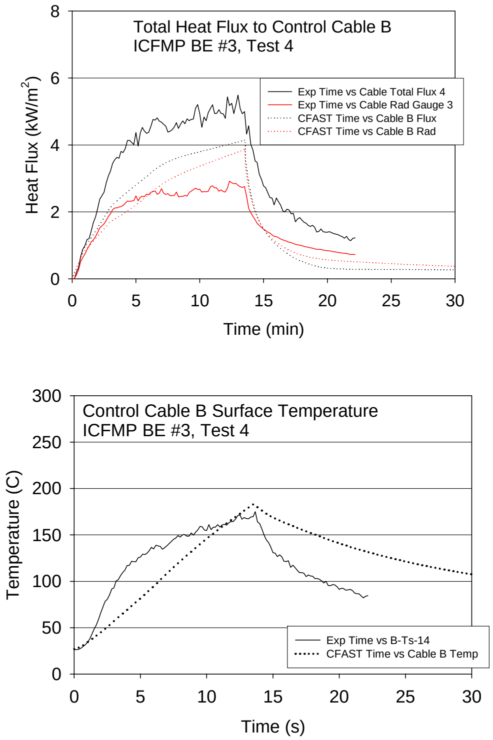


Figure A-32. Thermal Environment near Cable B, ICFMP BE #3, Tests 4 and 10

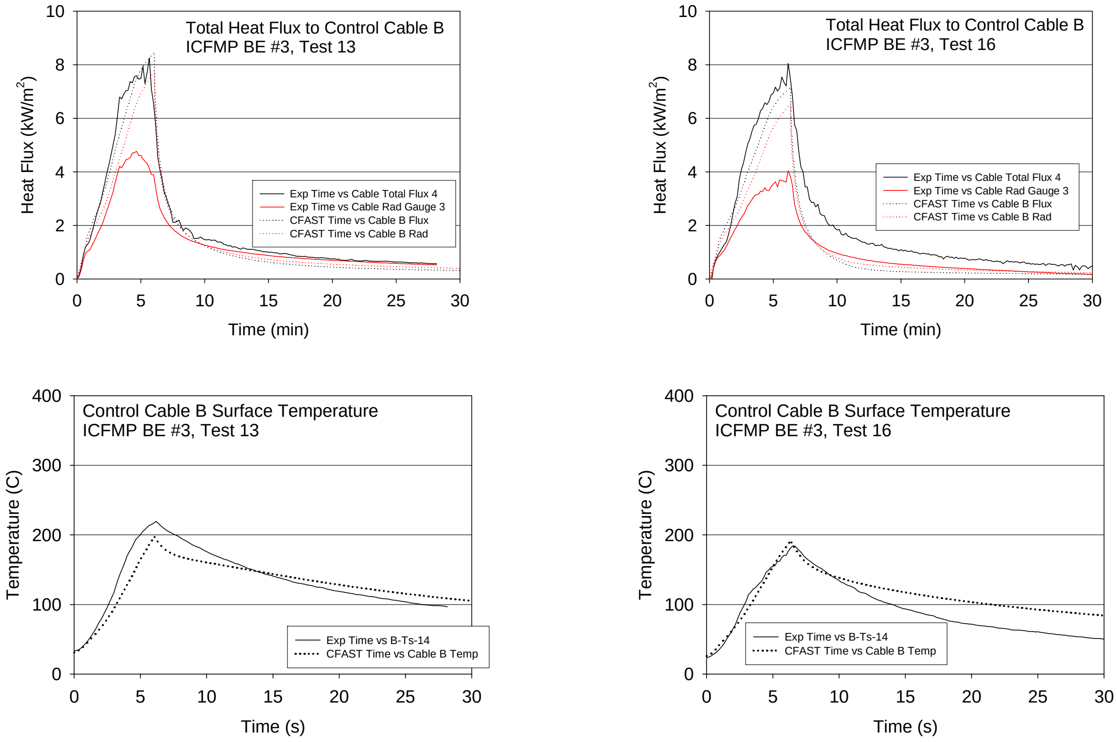


Figure A-33. Thermal Environment near Cable B, ICFMP BE #3, Tests 13 and 16

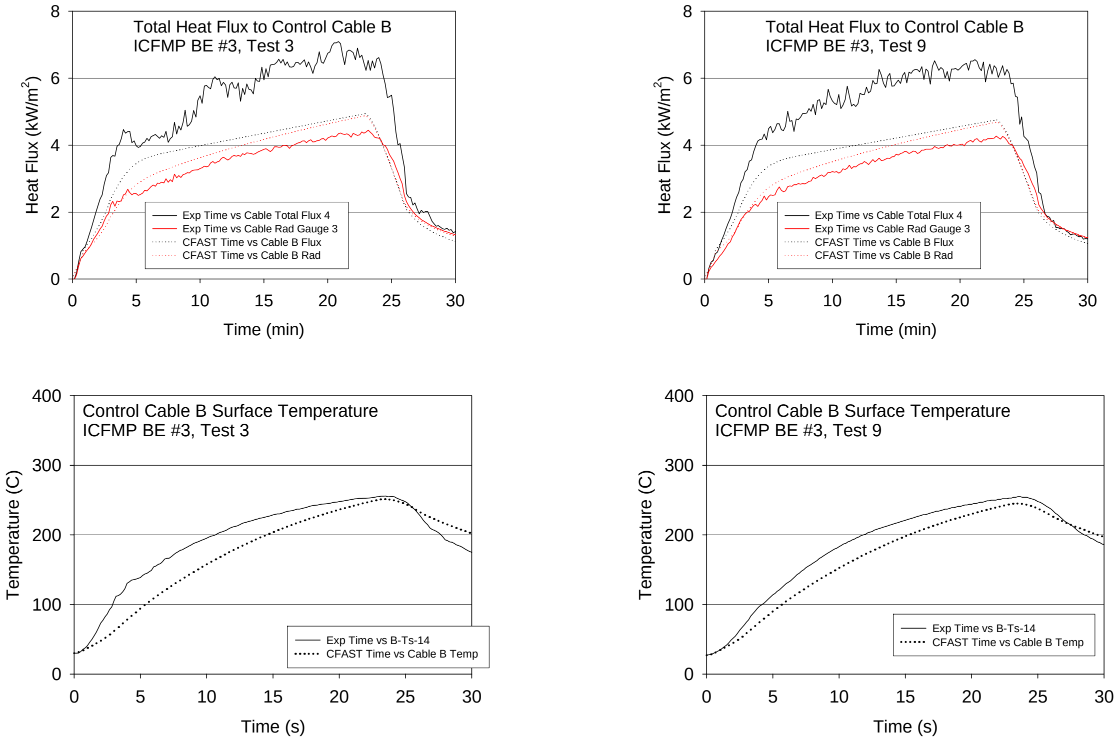


Figure A-34. Thermal Environment near Cable B, ICFMP BE #3, Tests 3 and 9

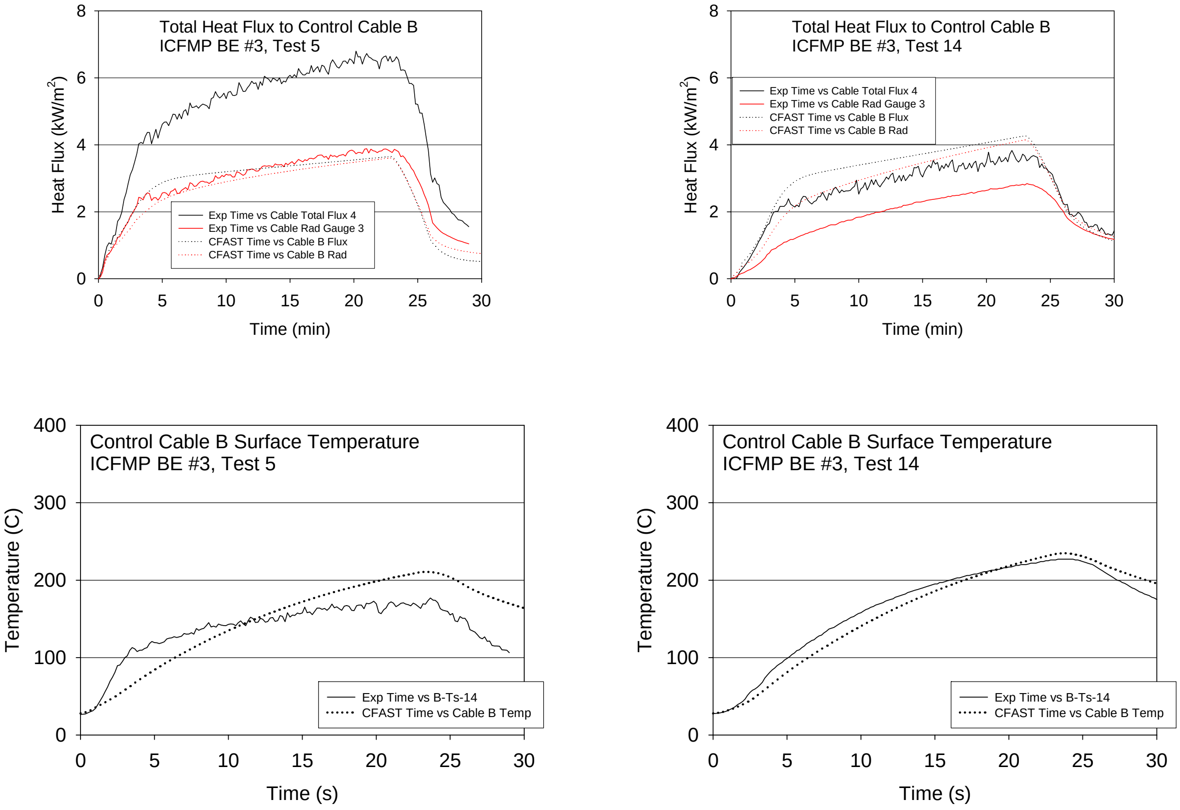


Figure A-35. Thermal Environment near Cable B, ICFMP BE #3, Tests 5 and 14

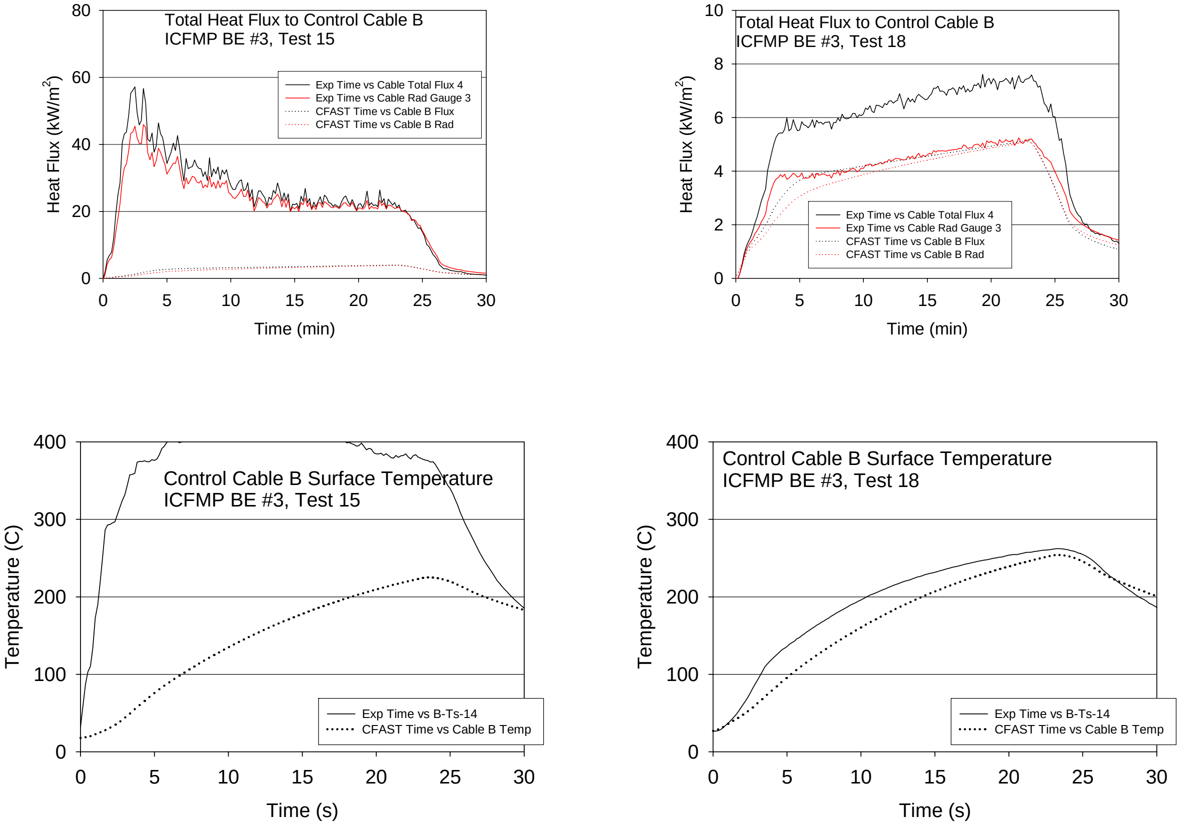


Figure A-36. Thermal Environment near Cable B, ICFMP BE #3, Tests 15 and 18

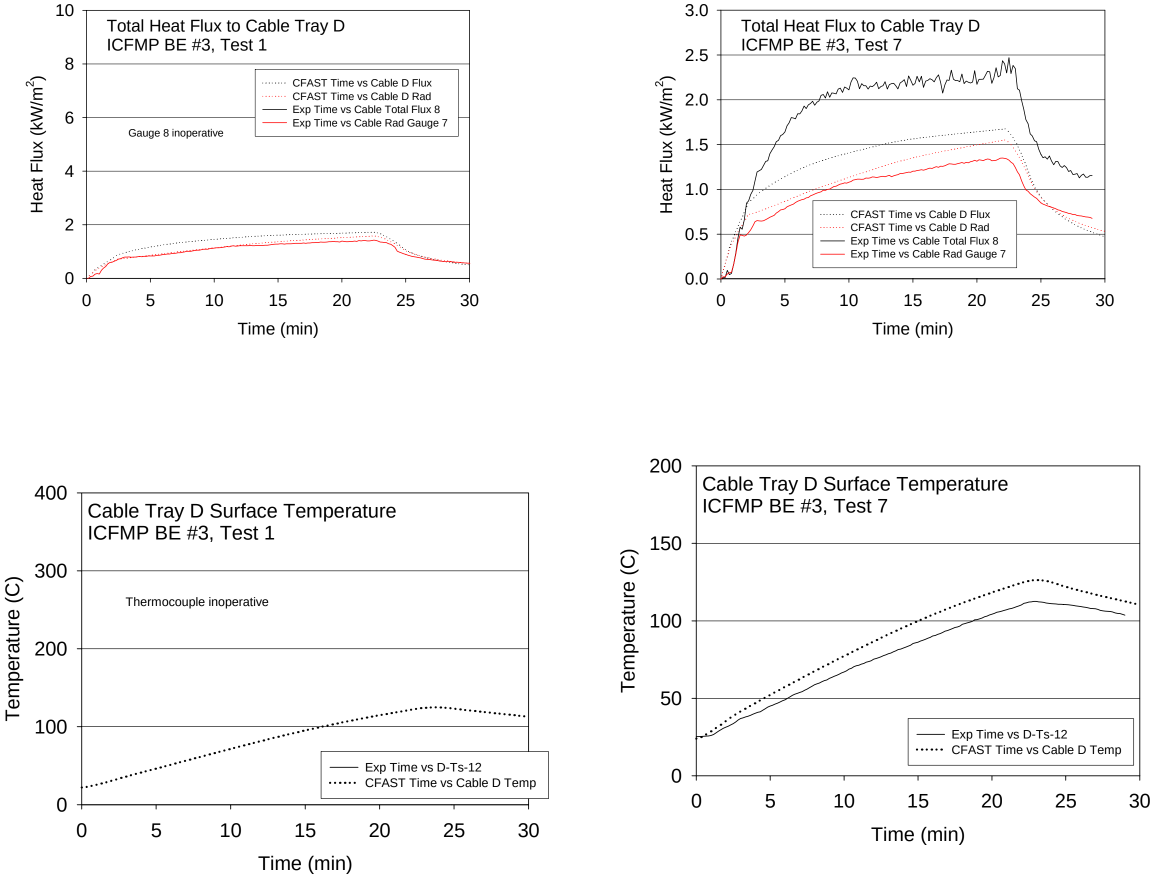


Figure A-37. Thermal Environment near Cable Tray D, ICFMP BE #3, Tests 1 and 7

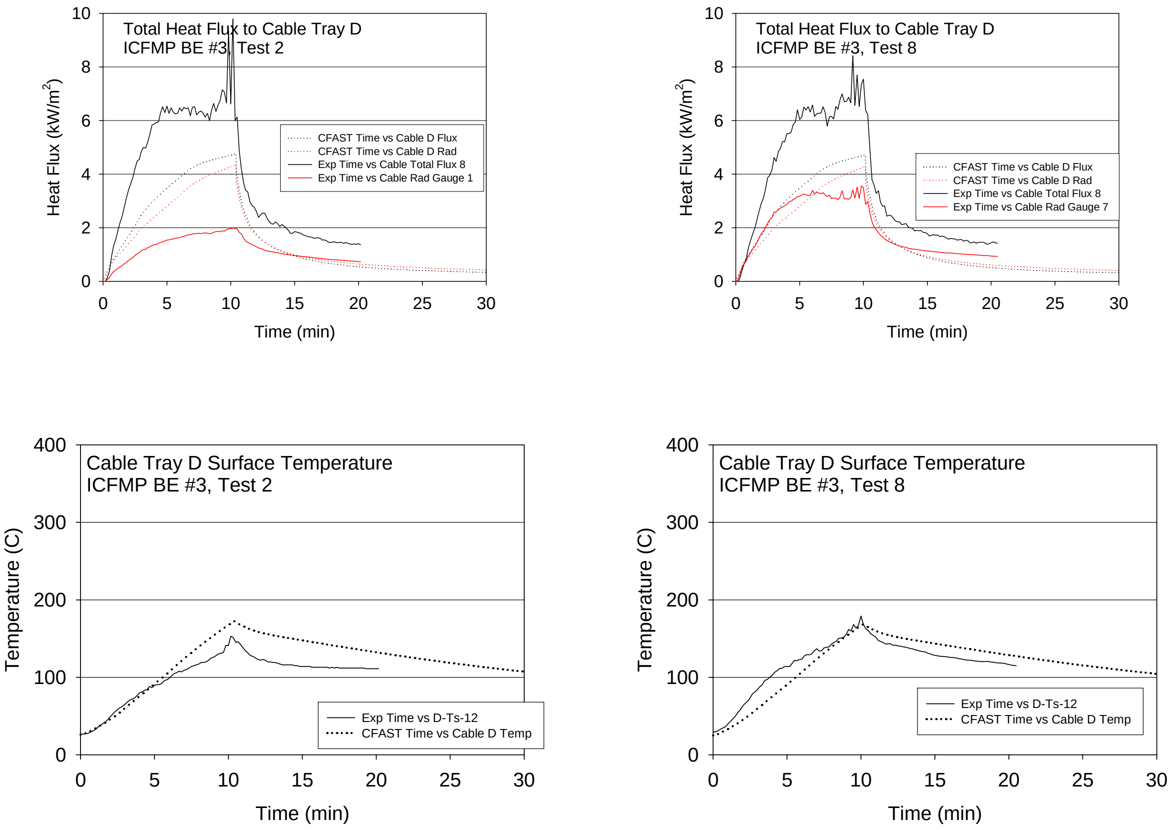


Figure A-38. Thermal Environment near Cable Tray D, ICFMP BE #3, Tests 2 and 8

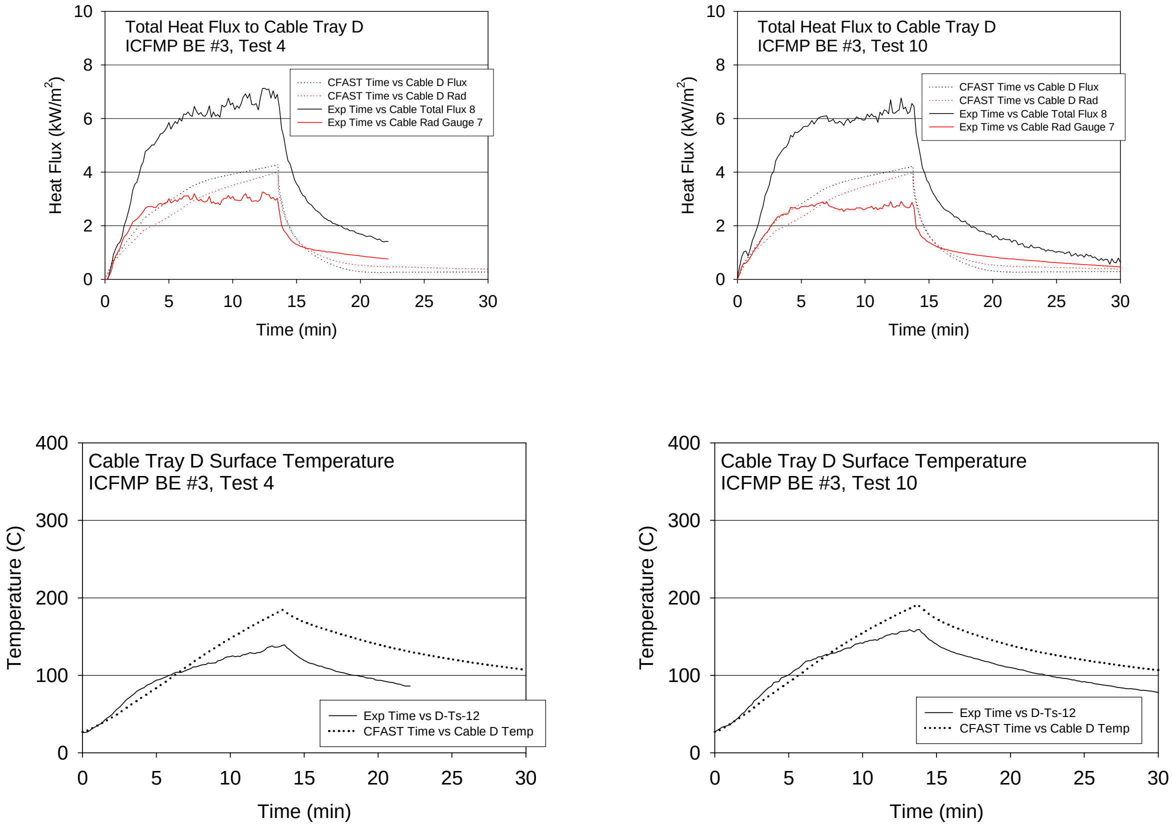


Figure A-39. Thermal Environment near Cable Tray D, ICFMP BE #3, Tests 4 and 10

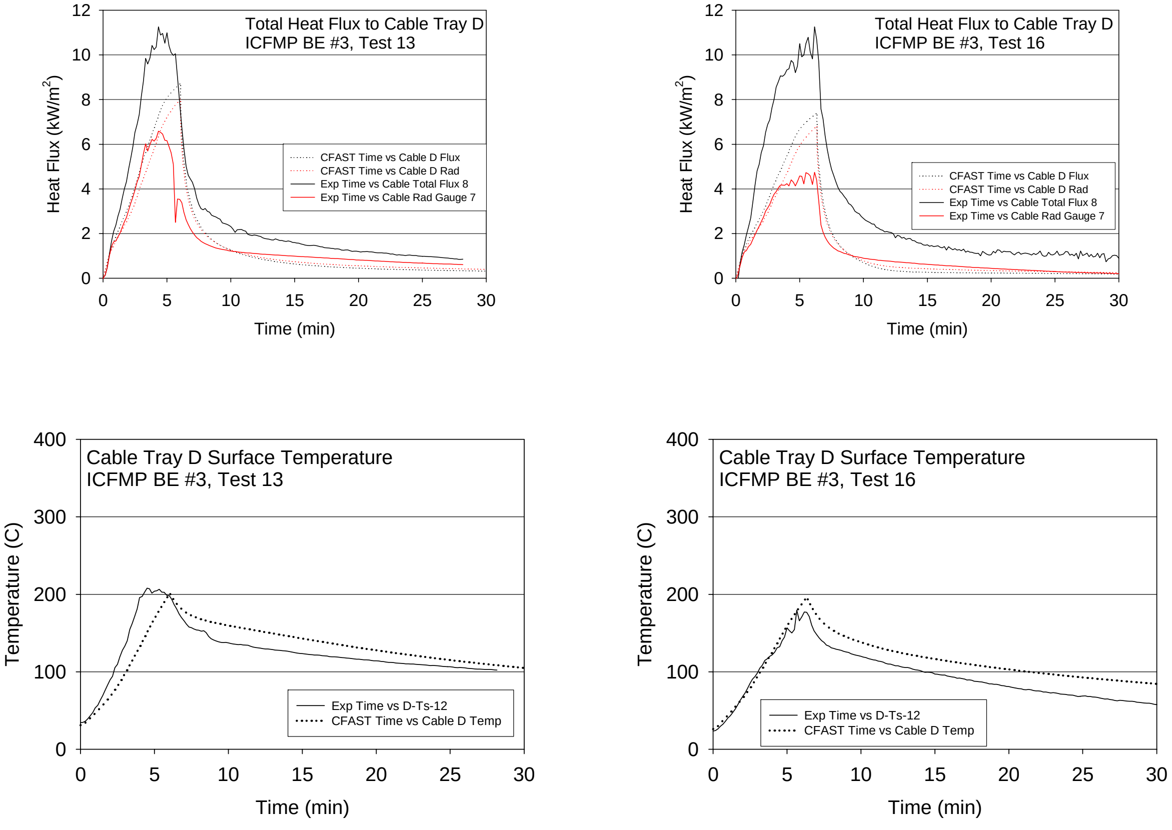


Figure A-40. Thermal Environment near Cable Tray D, ICFMP BE #3, Tests 13 and 16

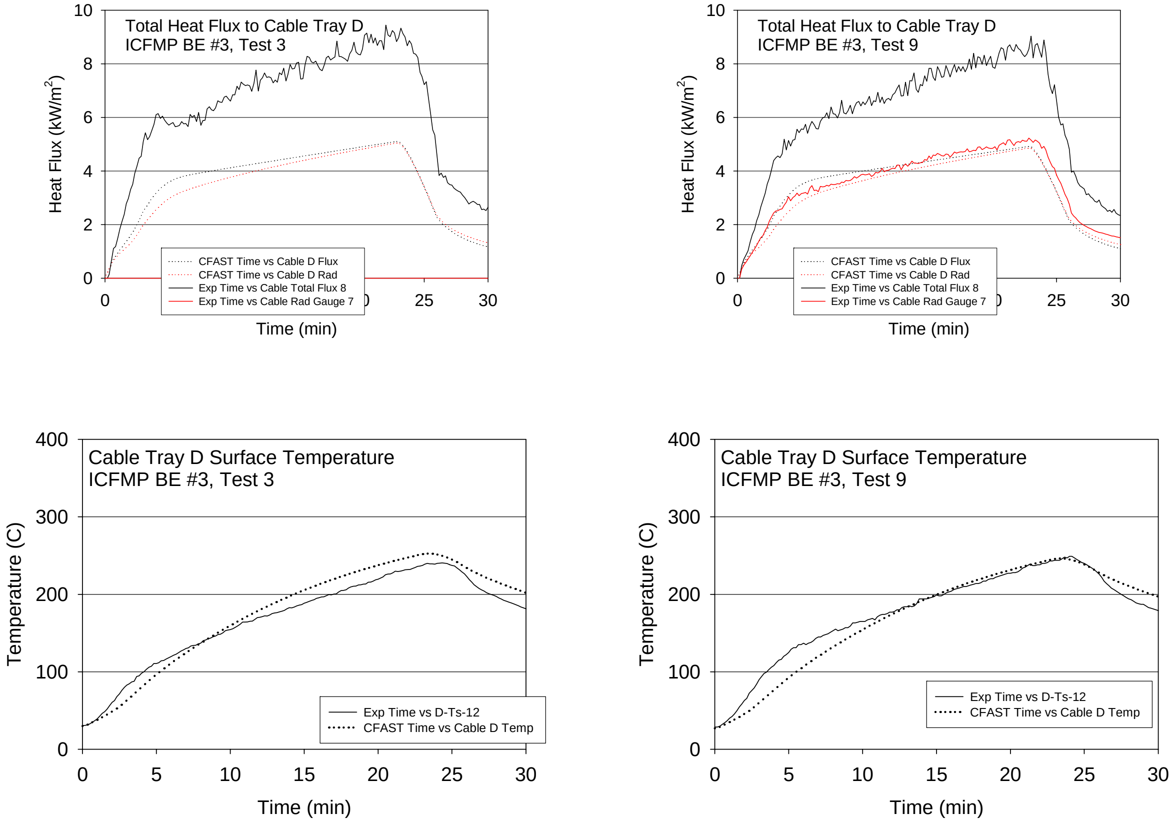


Figure A-41. Thermal Environment near Cable Tray D, ICFMP BE #3, Tests 3 and 9

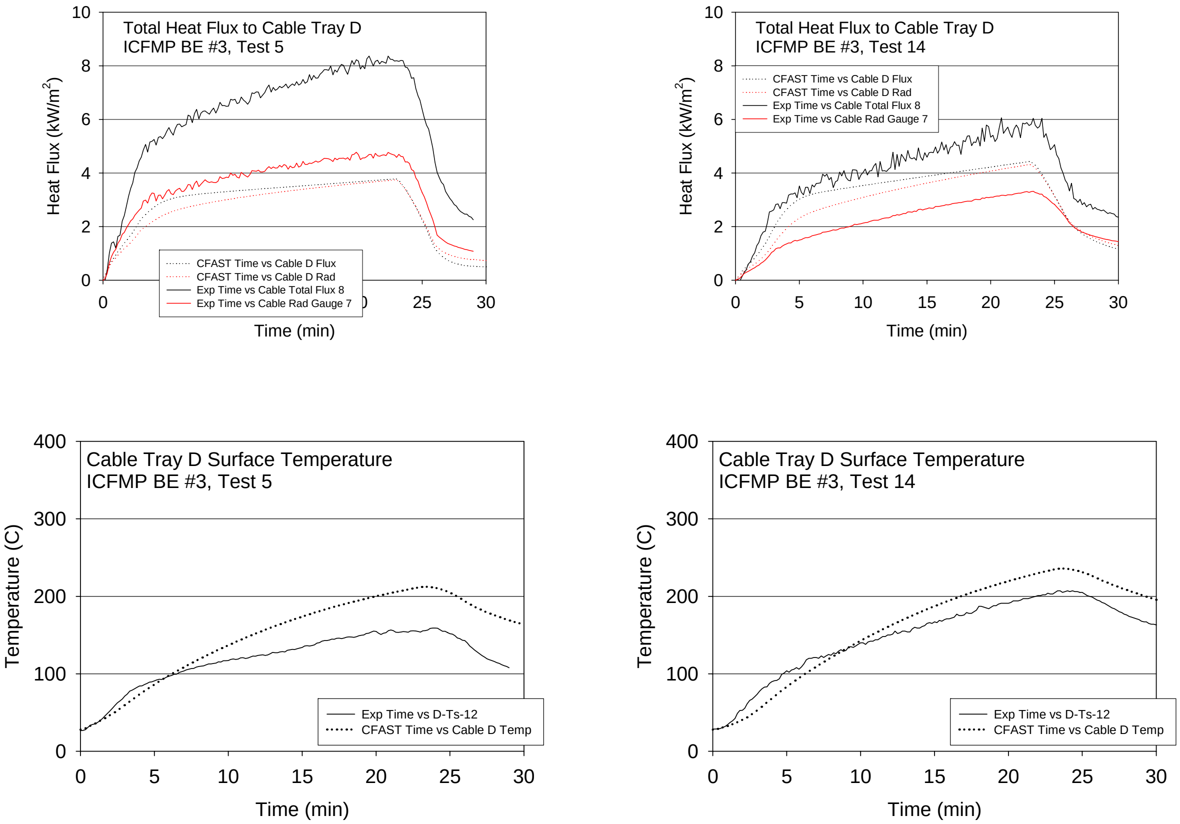


Figure A-42. Thermal Environment near Cable Tray D, ICFMP BE #3, Tests 5 and 14

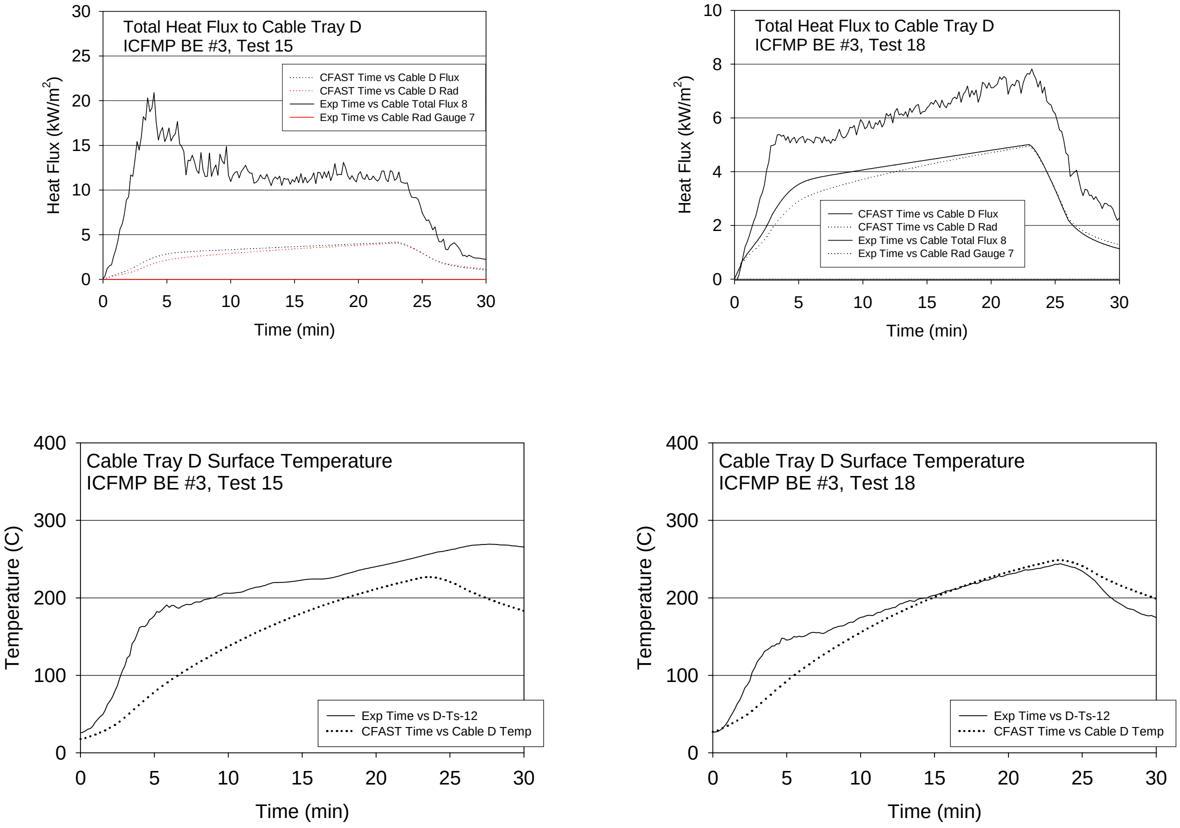


Figure A-43. Thermal Environment near Cable Tray D, ICFMP BE #3, Tests 15 and 18

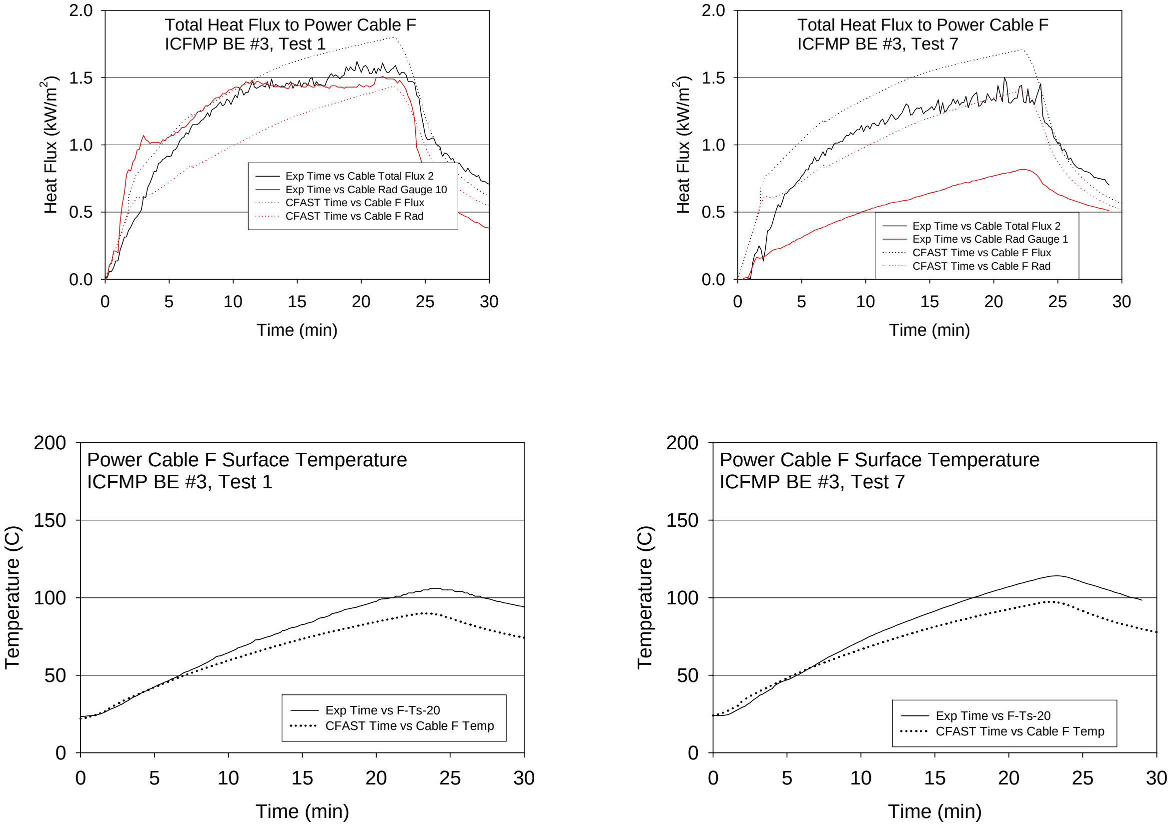


Figure A-44. Thermal Environment near Power Cable F, ICFMP BE #3, Tests 1 and 7

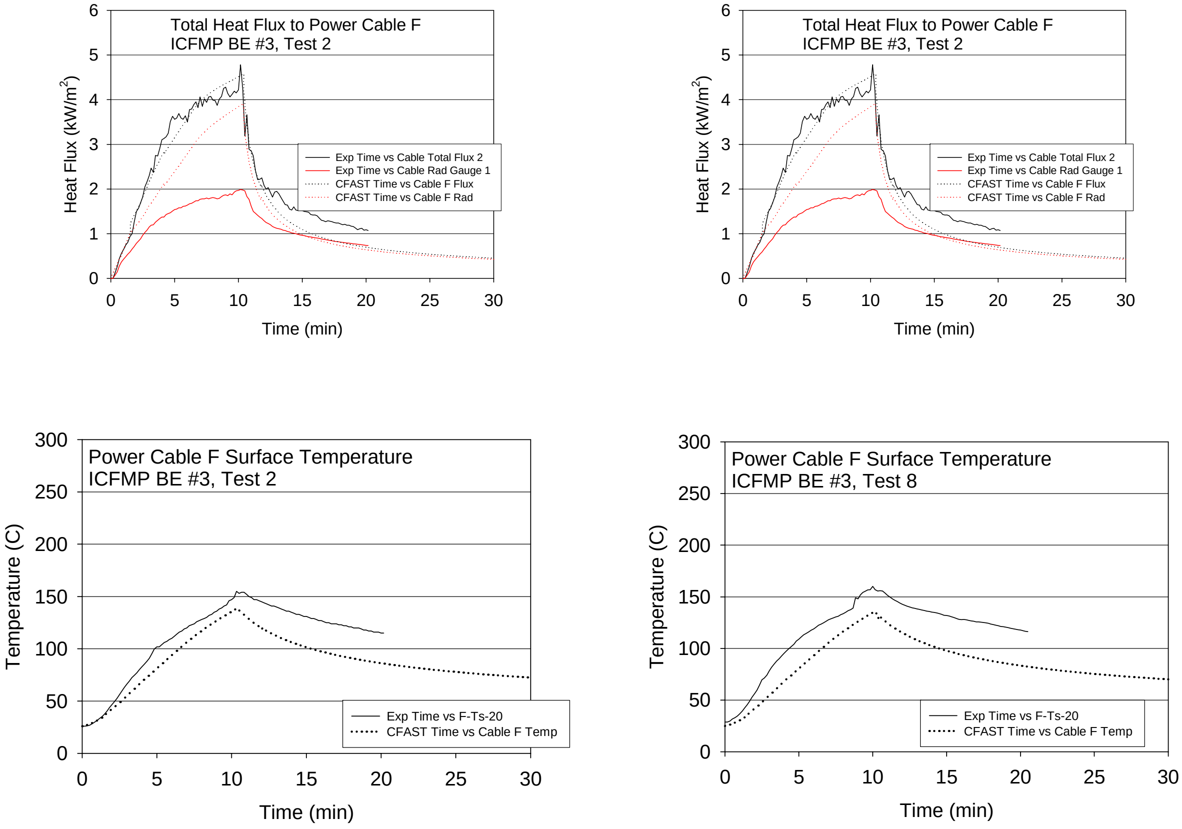


Figure A-45. Thermal Environment near Power Cable F, ICFMP BE #3, Tests 2 and 8

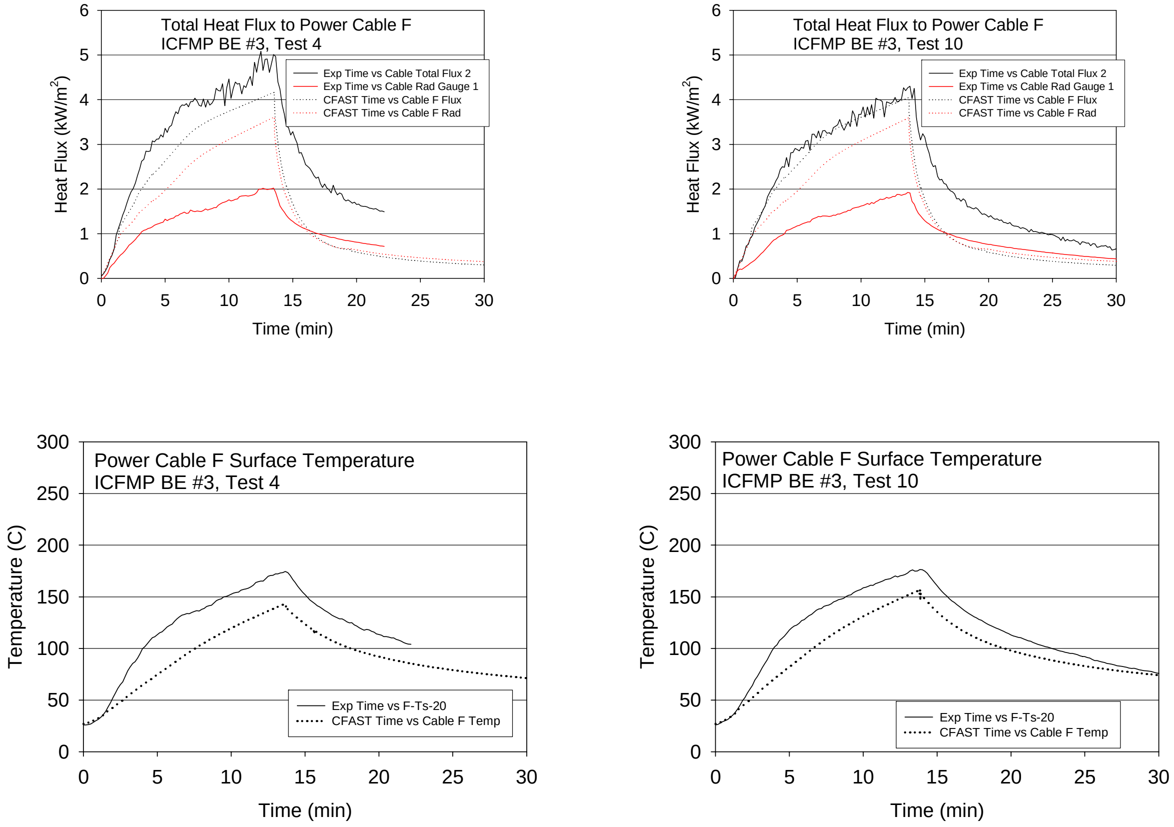


Figure A-46. Thermal Environment near Power Cable F, ICFMP BE #3, Tests 4 and 10

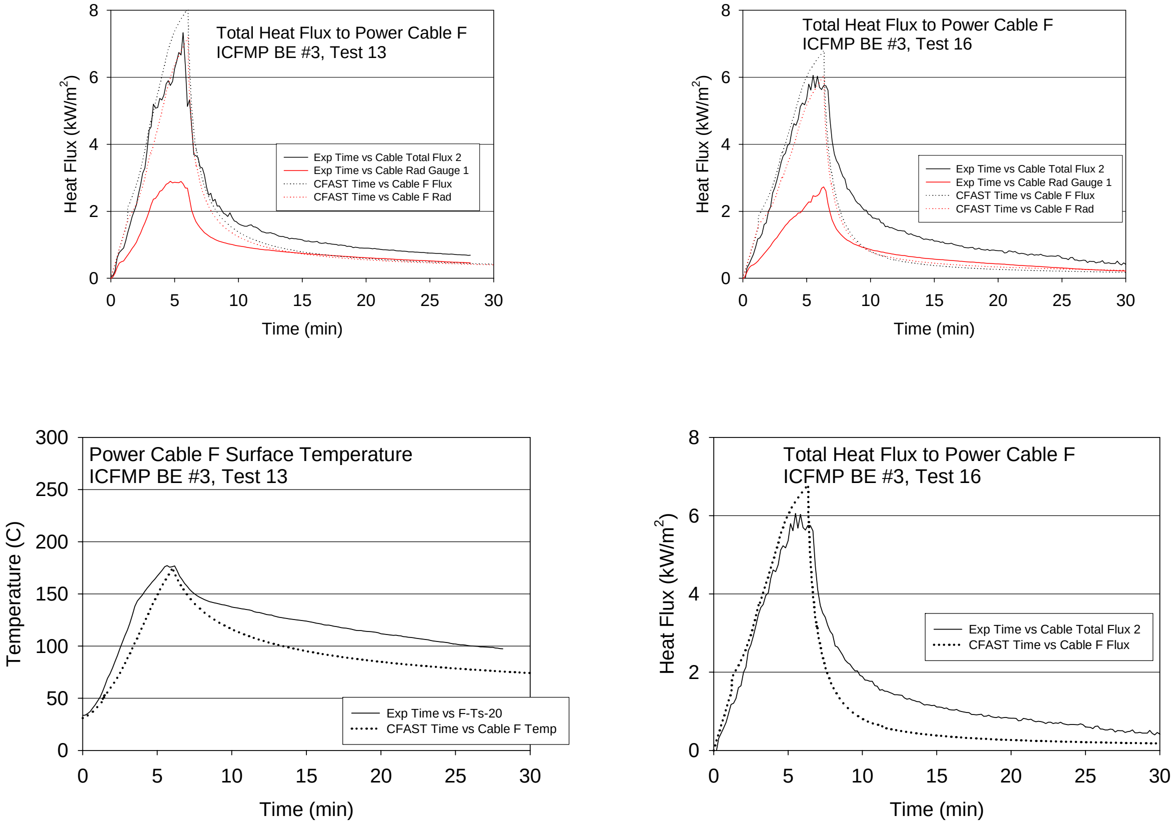


Figure A-47. Thermal Environment near Power Cable F, ICFMP BE #3, Tests 13 and 16

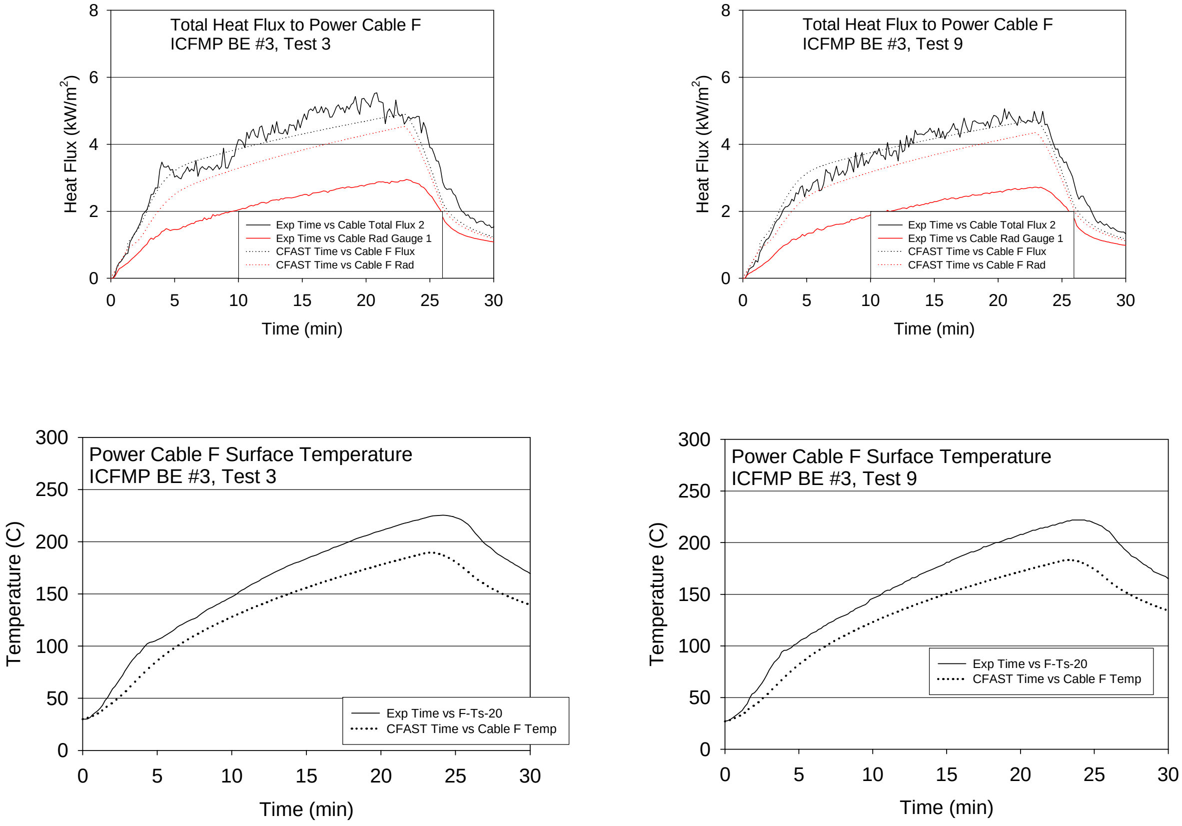


Figure A-48. Thermal Environment near Power Cable F, ICFMP BE #3, Tests 3 and 9

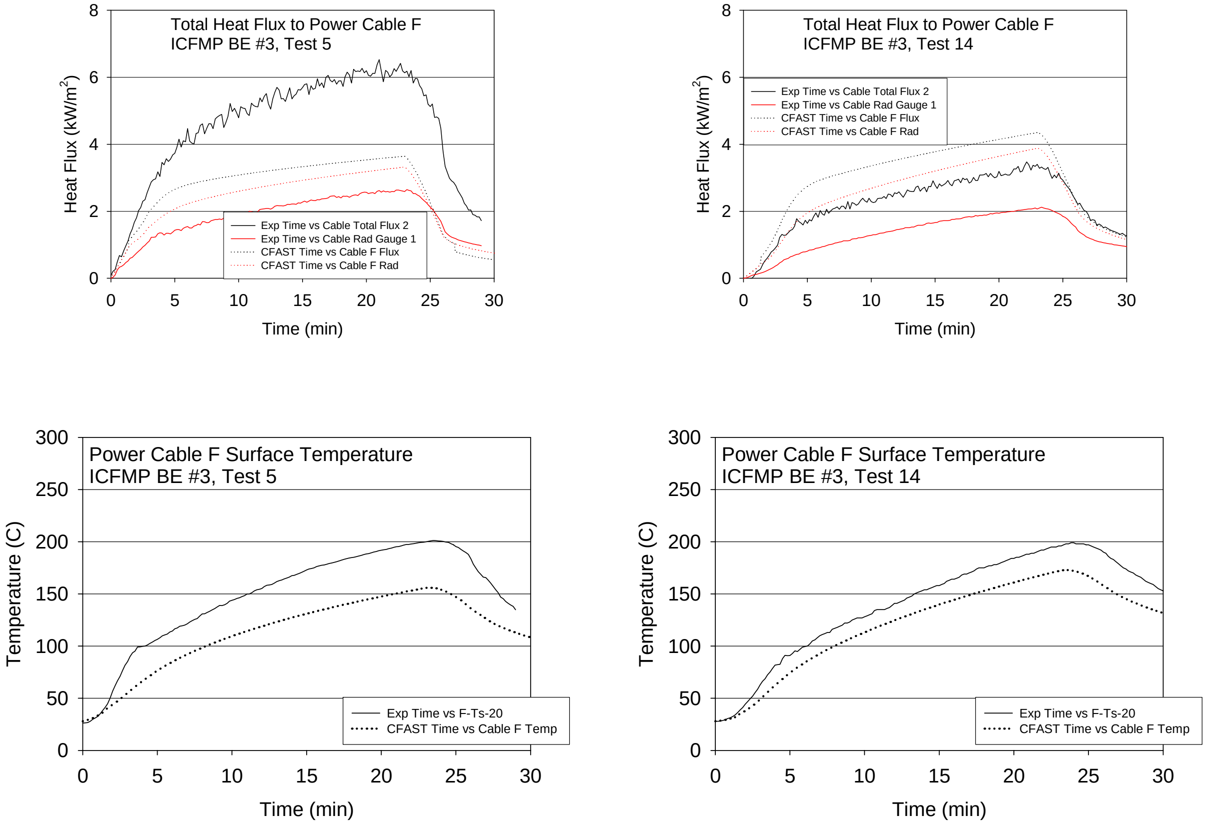


Figure A-49. Thermal Environment near Power Cable F, ICFMP BE #3, Tests 5 and 14

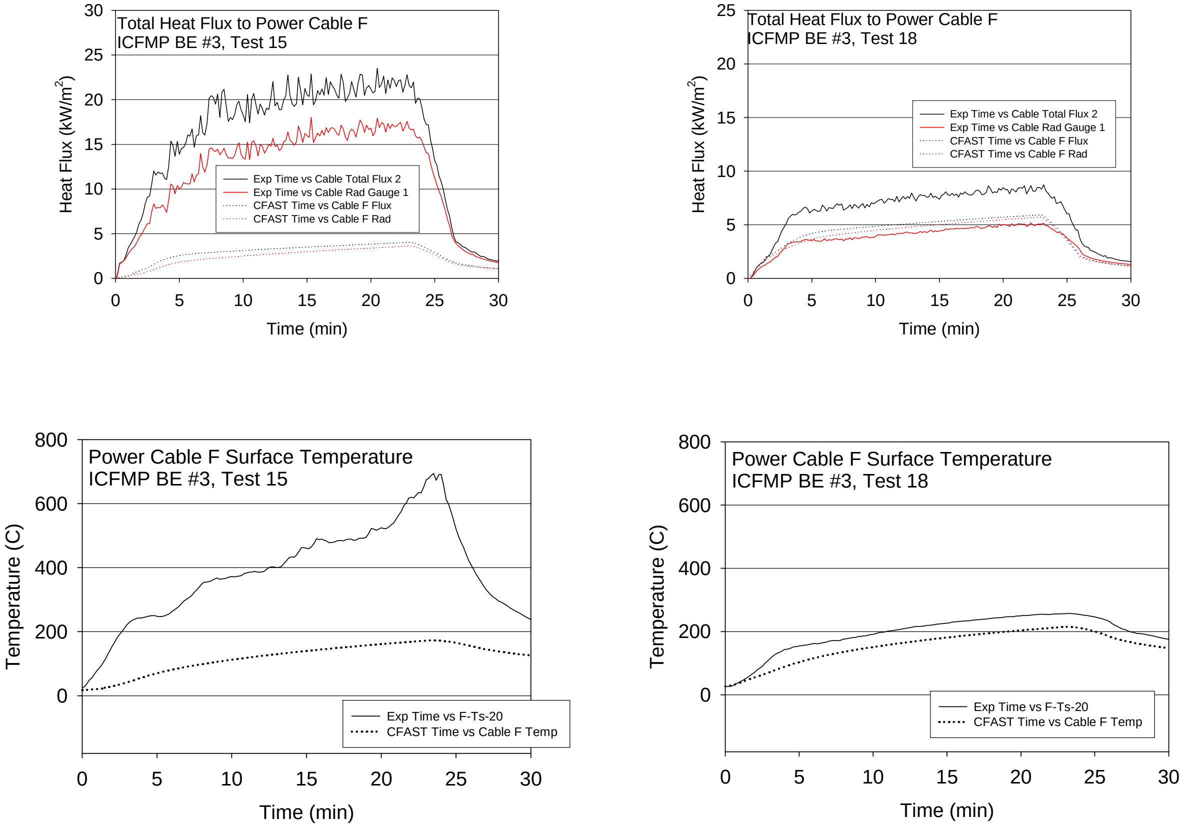


Figure A-50. Thermal Environment near Power Cable F, ICFMP BE #3, Tests 15 and 18

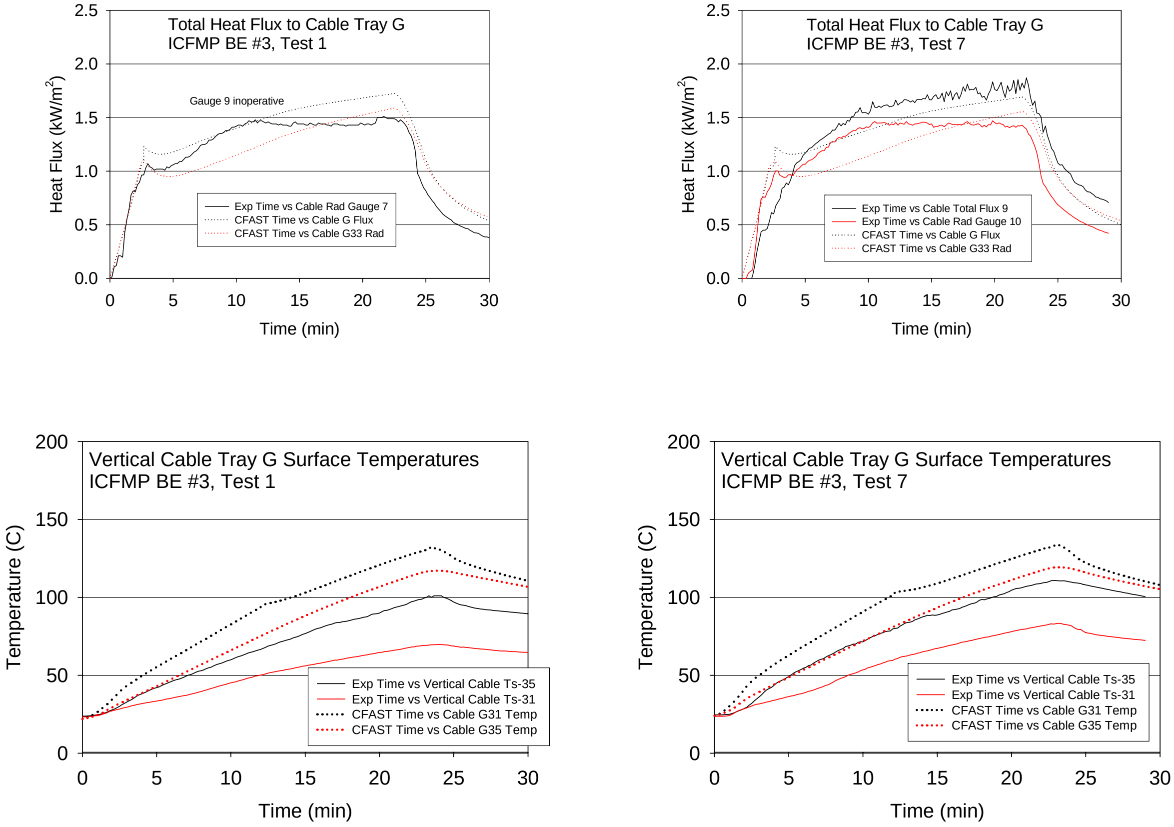


Figure A-51. Thermal Environment near Vertical Cable Tray G, ICFMP BE #3, Tests 1 and 7

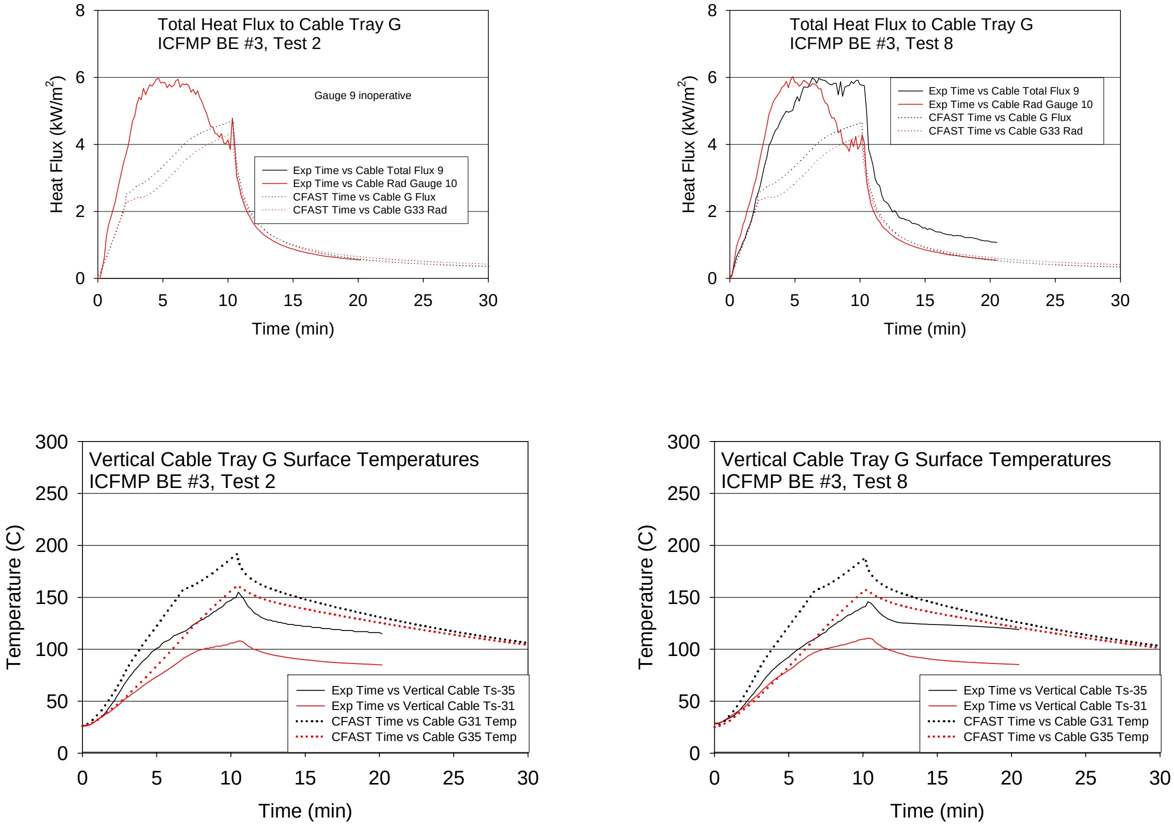


Figure A-52. Thermal Environment near Vertical Cable Tray G, ICFMP BE #3, Tests 2 and 8

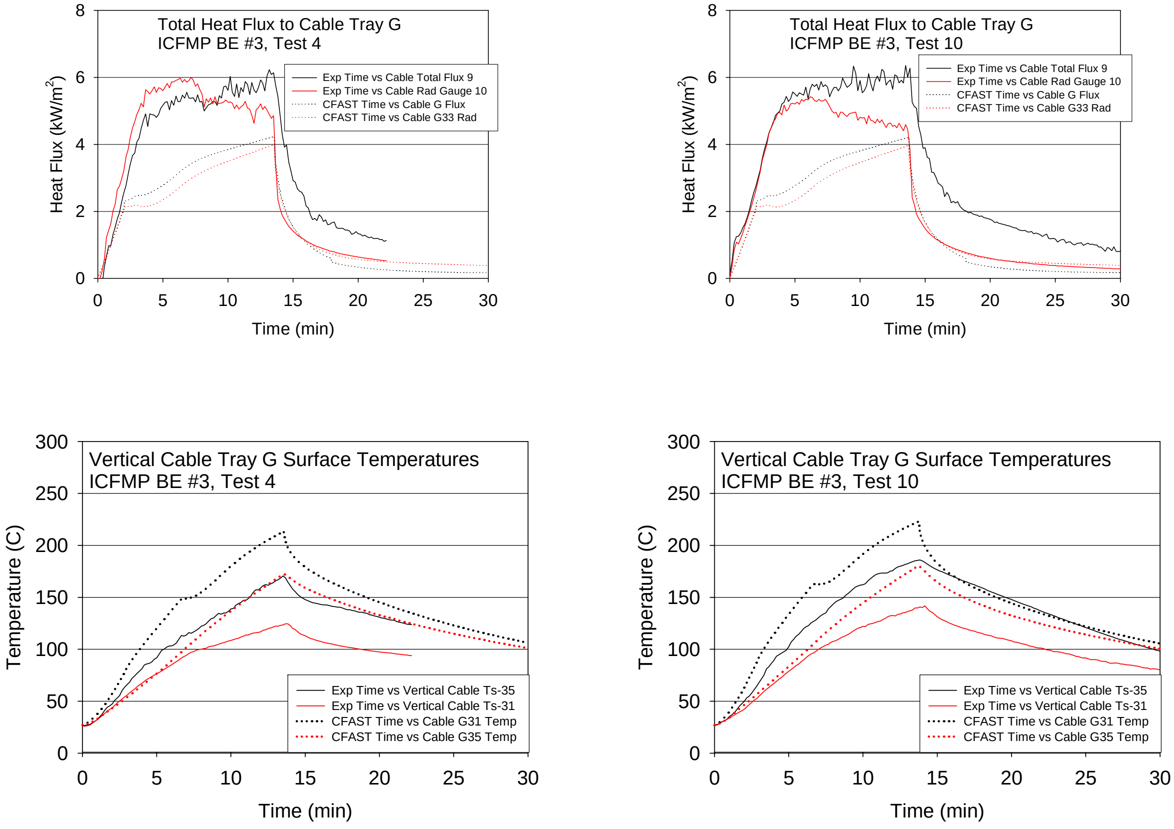


Figure A-53. Thermal Environment near Vertical Cable Tray G, ICFMP BE #3, Tests 4 and 10

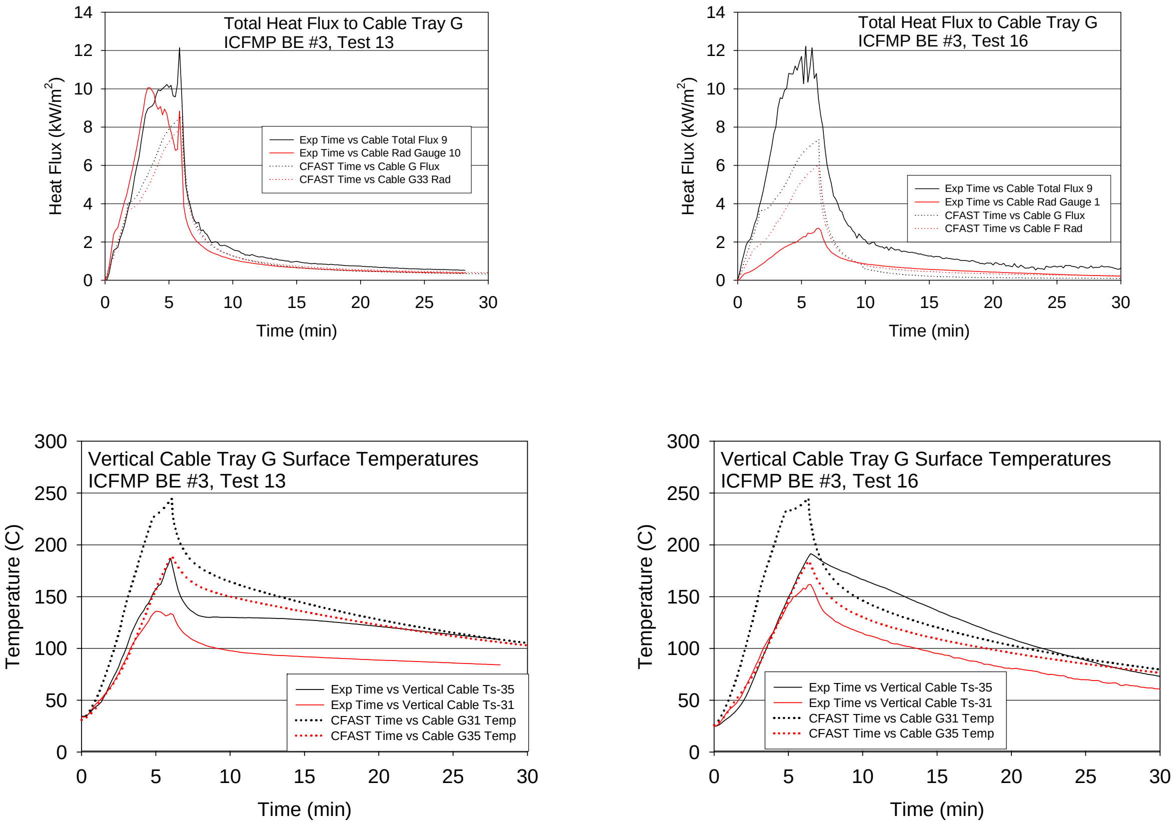


Figure A-54. Thermal Environment near Vertical Cable Tray G, ICFMP BE #3, Tests 13 and 16

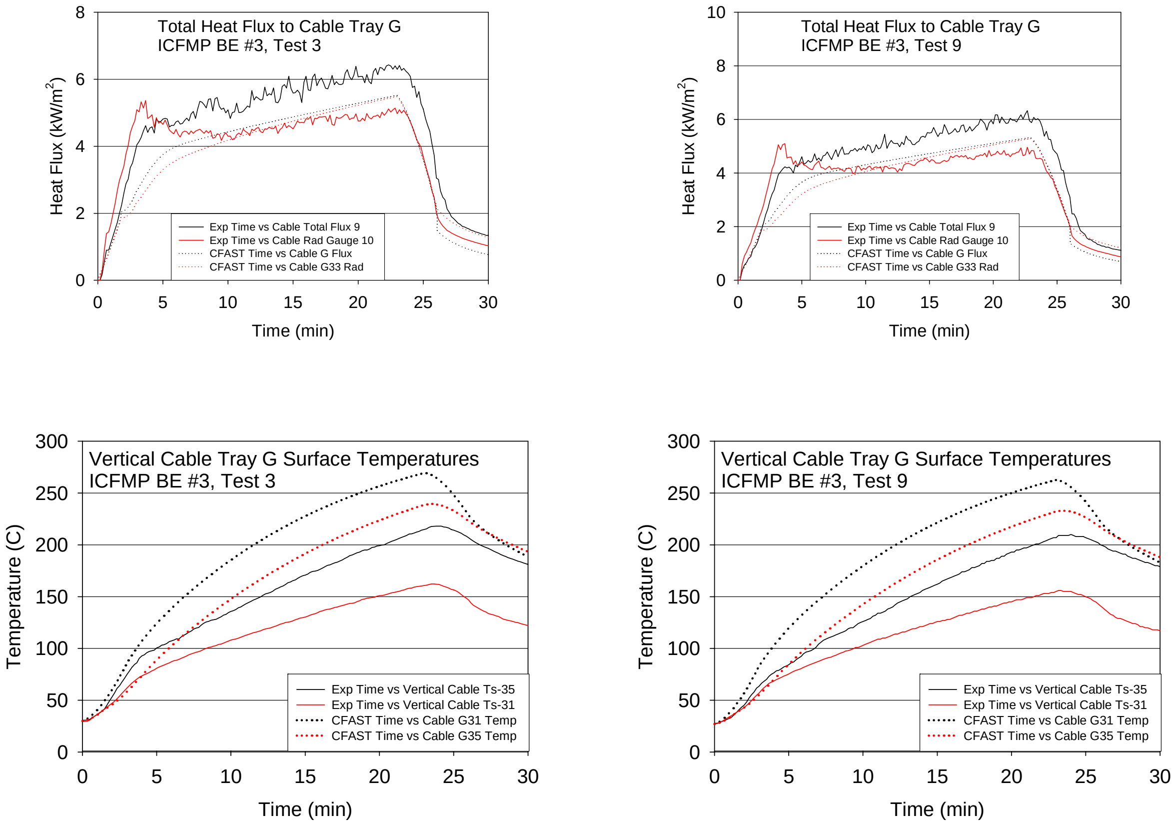


Figure A-55. Thermal Environment near Vertical Cable Tray G, ICFMP BE #3, Tests 3 and 9

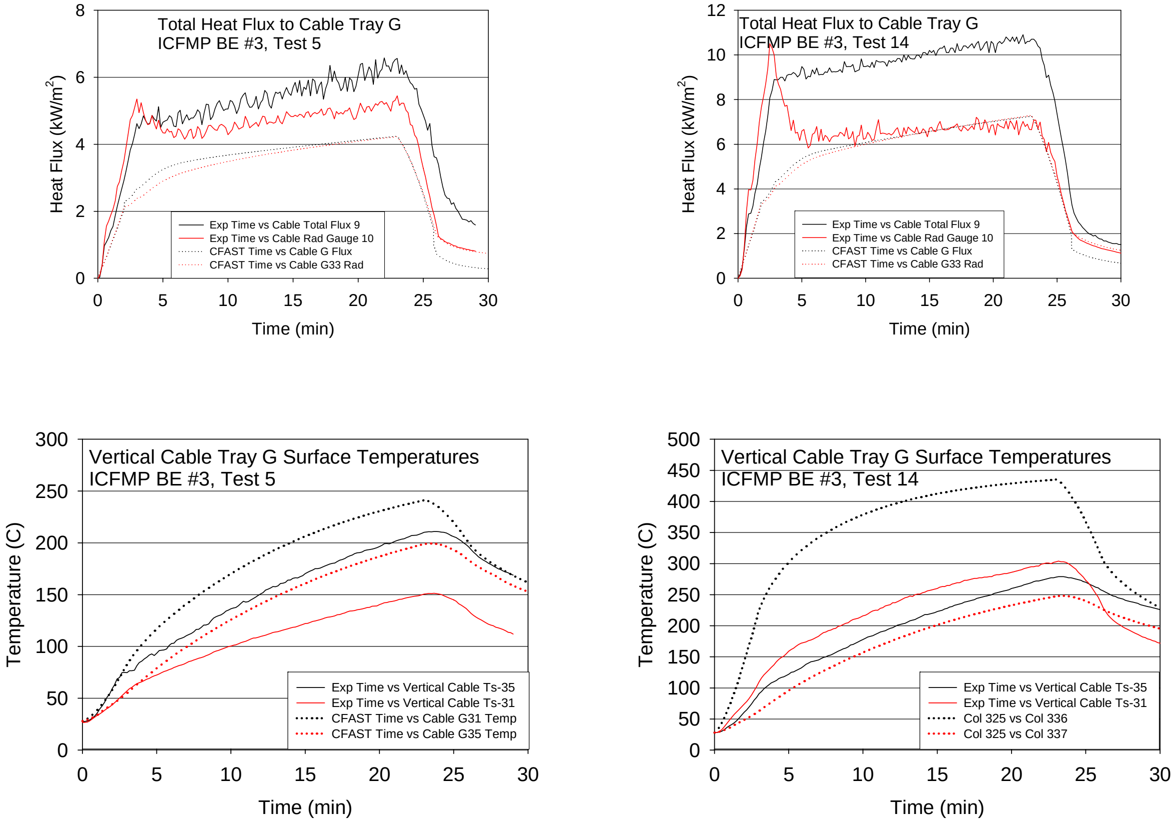


Figure A-56. Thermal Environment near Vertical Cable Tray G, ICFMP BE #3, Tests 5 and 14

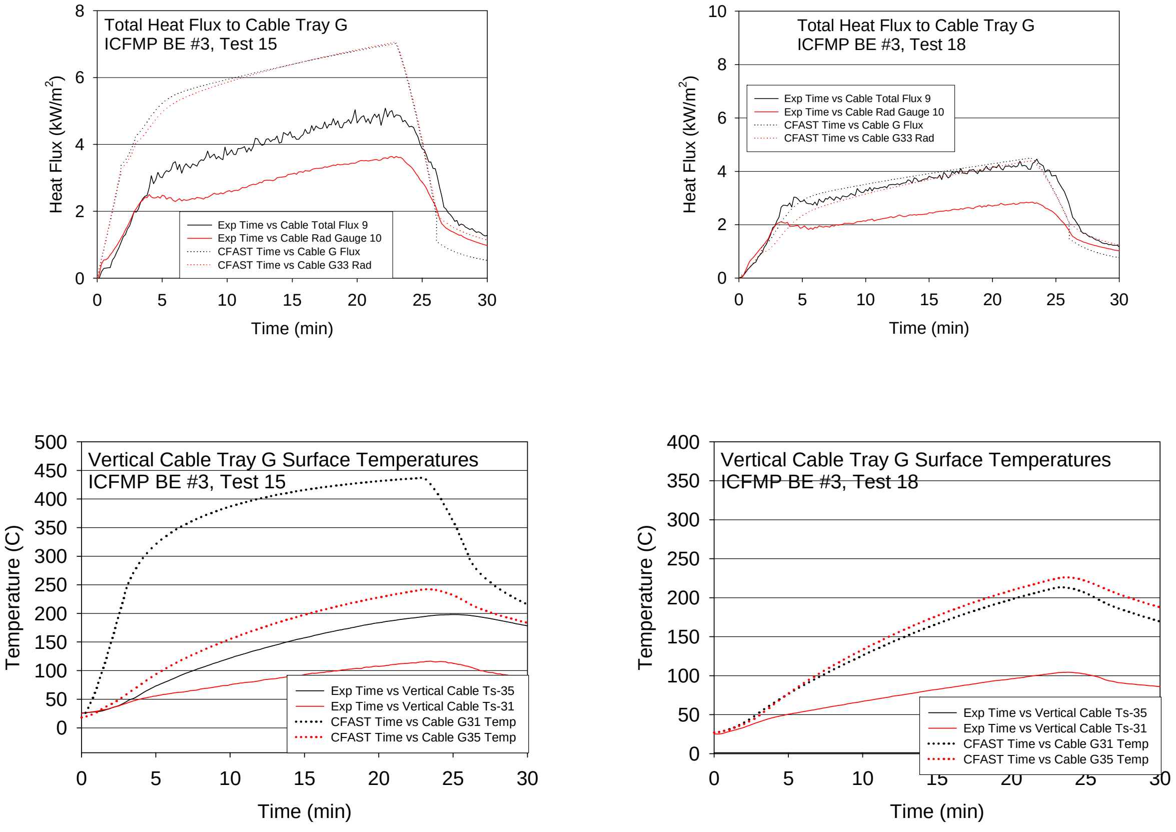


Figure A-57. Thermal Environment near Vertical Cable Tray G, ICFMP BE #3, Tests 15 and 18

ICFMP BE #4

Targets in BE #4, Test 1 were three material probes made of concrete, aerated concrete and steel. Sensor M29 represents the aerated concrete material while Sensors M33 and M34 represent the concrete and steel materials respectively.

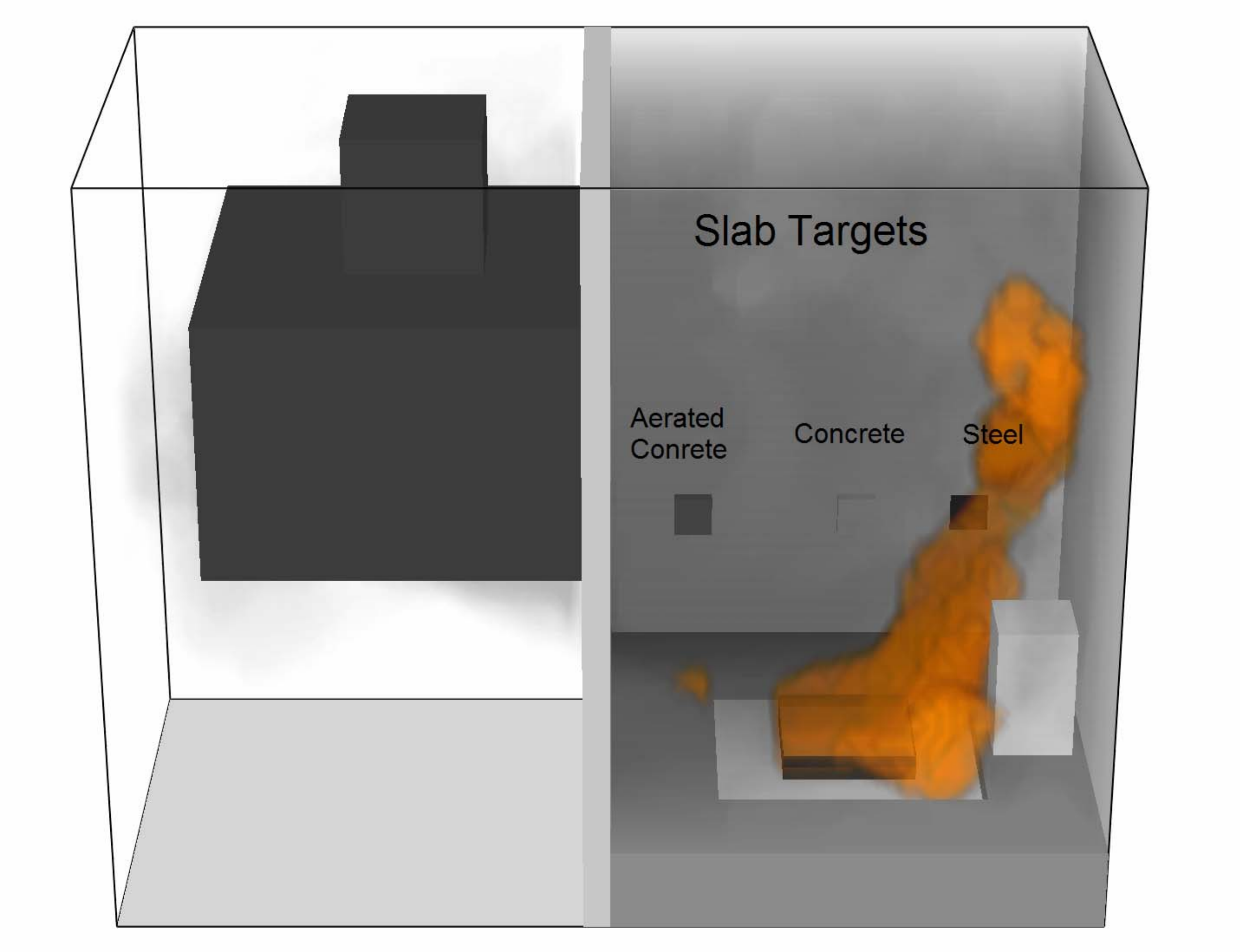


Figure A-58. Location of Three Slab Targets in ICFMP BE #4

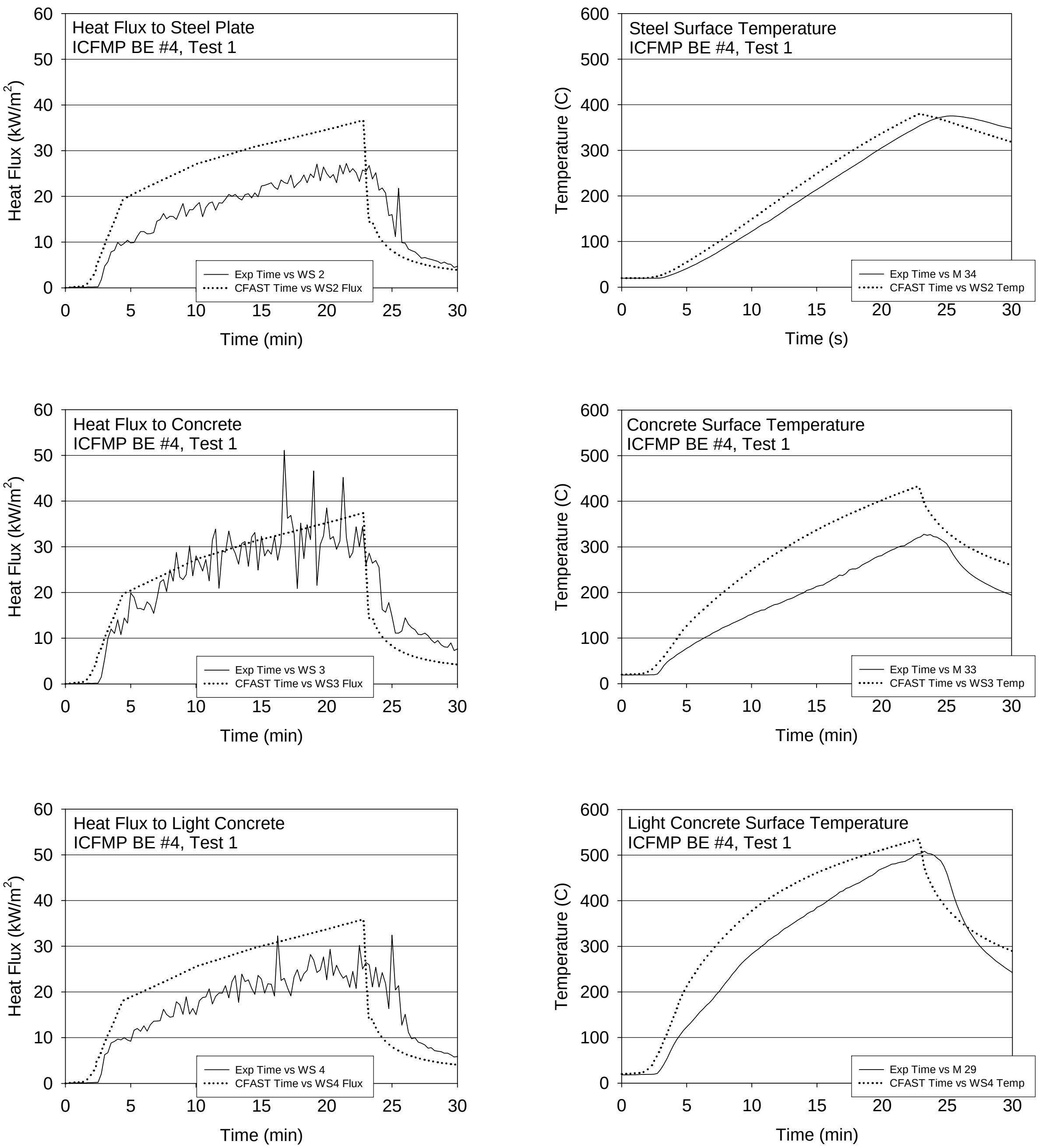


Figure A-59. Heat Flux and Surface Temperatures of Target Slabs, ICFMP BE #4, Test 1

ICFMP BE #5

A vertical cable tray was positioned near a wall opposite the fire. Heat flux gauges were inserted in between two bundles of cables (one containing power cables, and the other containing control cables). The following pages present plots of the gas temperature, heat flux, and cable surface temperatures at three vertical locations along the tray.

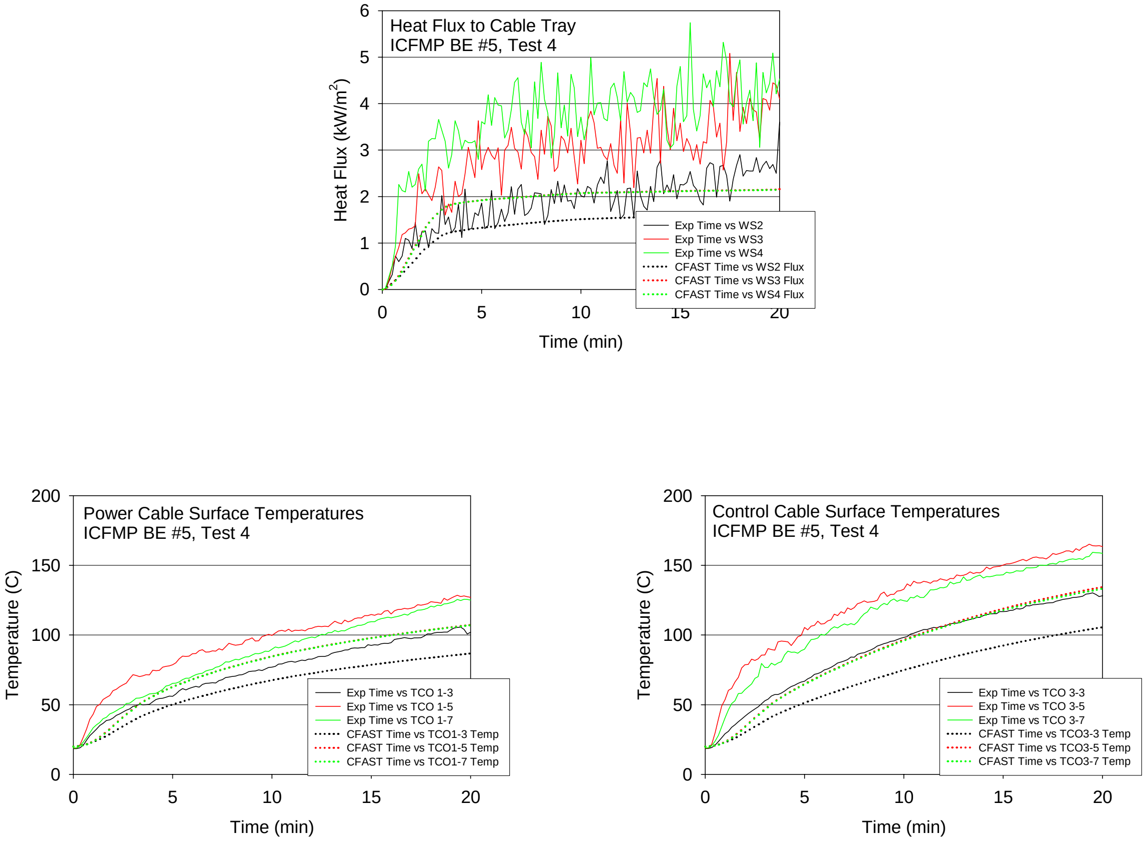


Figure A-60. Thermal Environment near Vertical Cable Tray, ICFMP BE #5, Test 4

Table A-6. Relative Differences for Radiation and Total Heat Flux to Targets and Target Temperature

			Radiant Heat Flux to Targets			Total Heat Flux to Targets			Target Temperature Rise		
	Test	Cable	Exp (kW/m^2)	CFAST (kW/m^2)	Diff (%)	Exp (kW/m^2)	CFAST (kW/m^2)	Diff (%)	Exp (°C)	CFAST (°C)	Diff (%)
BE3	Test 1	B	1.1	1.5	37	1.9	1.7	-10	106	103	-3
		D	1.4	1.6	10						
		F	0.9	1.4	65	1.6	1.8	12	83	68	-18
		G33	1.5	1.6	5				64	96	49
	Test 7	B	1.2	1.5	24.6	1.8	1.6	-12	109	102	-7
		D	1.3	1.6	15.0	2.5	1.7	-33	87	102	17
		F	0.8	1.4	71.2	1.5	1.7	13	90	73	-19
		G33	1.5	1.6	5.8	1.9	1.7	-11	78	93	19
	Test 2	B	2.9	4.2	45.3	5.3	4.6	-12	176	144	-18
		D	4.2	4.3	4	9.8	4.8	-52	126	146	15
		F	2.0	3.9	96	4.8	4.6	-4	129	112	-13
		G33	6.0	4.3	-27				107	138	30
	Test 8	B	2.9	4.1	41	5.6	4.6	-18	183	142	-23
		D	3.6	4.3	20	8.5	4.7	-45	150	143	-4
		F	1.9	3.8	98	4.9	4.5	-9	131	110	-16
		G33	6.0	4.3	-29	6.0	4.6	-22	107	136	27
	Test 4	B	2.9	3.9	32	5.5	4.1	-25	149	156	5
		D	3.3	4.0	23	7.2	4.3	-41	113	157	39
		F	2.0	3.6	78	5.0	4.2	-17	149	115	-22
		G33	6.0	4.0	-34	6.4	4.2	-34	125	149	19
	Test 10	B	2.7	3.8	43	4.9	4.1	-17	144	162	13
		D	2.9	4.0	36	6.7	4.2	-37	132	164	24
		F	1.9	3.6	86	4.4	4.0	-7	150	129	-14
		G33	5.4	4.0	-27	6.2	4.2	-32	148	149	0
	Test 13	B	4.8	7.7	61	8.3	8.4	2	186	165	-11
		D	6.6	8.0	22	11.2	8.7	-22	173	169	-3
		F	2.9	7.2	147	7.3	8.1	11	143	143	0
		G33	10.1	8.0	-20	12.2	8.6	-30	133	164	23
	Test 16	B	4.1	6.5	59	8.4	7.2	-14	160	166	3
		D	4.8	6.8	41	11.7	7.4	-37	156	170	9
		F	2.8	6.0	119	6.1	6.8	11	168	148	-12
		G33	12.0	6.8	-43	12.2	7.3	-40	169	150	-11
	Test 17	B	1.3	2.1	60	2.4	2.6	10			
		D	1.5	2.2	45	3.3	2.7	-18			
		F	0.9	1.9	111	1.9	2.4	30			
		G33	2.4	2.3	-5	3.1	2.7	-13			
	Test 3	B	4.4	4.9	10	7.1	4.9	-31	226	221	-2
		D				9.5	5.1	-46	210	223	6
		F	3.0	4.5	53	5.5	4.9	-12	195	160	-18
		G33	5.4	5.5	2	6.5	5.5	-15	169	224	33
	Test 9	B	4.3	4.7	9	6.6	4.8	-28	228	218	-4
		D	5.3	4.9	-8	9.1	4.9	-46	220	219	-1
		F	2.7	4.3	59	5.1	4.7	-7	195	156	-20
		G33	5.2	5.3	2	6.4	5.3	-17	166	221	33
	Test 5	B	3.9	3.6	-7	6.9	3.6	-47	150	183	22
		D	4.8	3.7	-22	8.5	3.8	-56	132	184	39
		F	2.6	3.3	25	6.4	3.6	-44	175	128	-27

			Radiant Heat Flux to Targets			Total Heat Flux to Targets			Target Temperature Rise		
	Test	Cable	Exp (kW/m^2)	CFAST (kW/m^2)	Diff (%)	Exp (kW/m^2)	CFAST (kW/m^2)	Diff (%)	Exp (°C)	CFAST (°C)	Diff (%)
		G33	5.4	4.2	-23	6.7	4.2	-37	161	190	18
	Test 14	B	2.8	4.1	46	3.8	4.3	12	199	207	4
		D				6.1	4.4	-27	178	208	17
		F	2.1	3.9	83	3.5	4.3	26	171	145	-15
		G33	10.5	7.3	-31	10.9	7.3	-33	270	262	-3
	Test 15	B	46.5	3.9	-92	57.7	4.0	-93	416	207	-50
		D				20.9	4.2	-80	243	209	-14
		F	18.3	3.6	-80	23.9	4.0	-83	669	155	-77
		G33	3.7	7.0	89	5.1	7.0	37	161	263	63
	Test 18	B	5.2	5.1	-3	7.6	5.1	-33	236	227	-4
		D				7.8	5.0	-36	217	221	2
		F	5.2	5.7	10	8.7	5.9	-32	232	188	-19
		G33	2.8	4.4	54	4.4	4.5	1			
BE4	Test 1	WS 2				27.2	36.5	34	356	360	1
		WS 3				46.6	37.3	-20	308	412	34
		WS 4				32.4	35.8	10	489	514	5
BE5	Test 4	WS 2 / TCO 1-3				3.6	1.7	-44	87	67	-23
		TCO 2-3							112	85	-24
		WS 3 / TCO 1-5				96.9	2.2	-98	110	88	-20
		TCO 2-5							146	115	-22
		WS 4 / TCO 1-7				5.7	2.2	-62	107	87	-18
		TCO 2-7							140	114	-19

A.9 Heat Flux and Surface Temperature of Compartment Walls

Heat fluxes and surfaces temperatures at compartment walls, floor, and ceiling are available from ICFMP BE #3. This category is similar to that of the previous section, "Heat Flux and Surface Temperature of Targets," with the exception that the focus here is on compartment walls, ceilings, and floors.

ICFMP BE #3

Thirty-six heat flux gauges were positioned at various locations on all four walls of the compartment, plus the ceiling and floor. Comparisons between measured and predicted heat fluxes and surface temperatures are shown on the following pages for a selected number of locations. More than half of the measurement points were in roughly the same relative location to the fire and hence the measurements and predictions were similar. For this reason, data for the east and north walls are shown because the data from the south and west walls are comparable. Data from the south wall are used in cases where the corresponding instrument on the north wall failed, or in cases where the fire was positioned close to the south wall. The heat flux gauges used on the compartment walls measured the *net* (not total) heat flux.

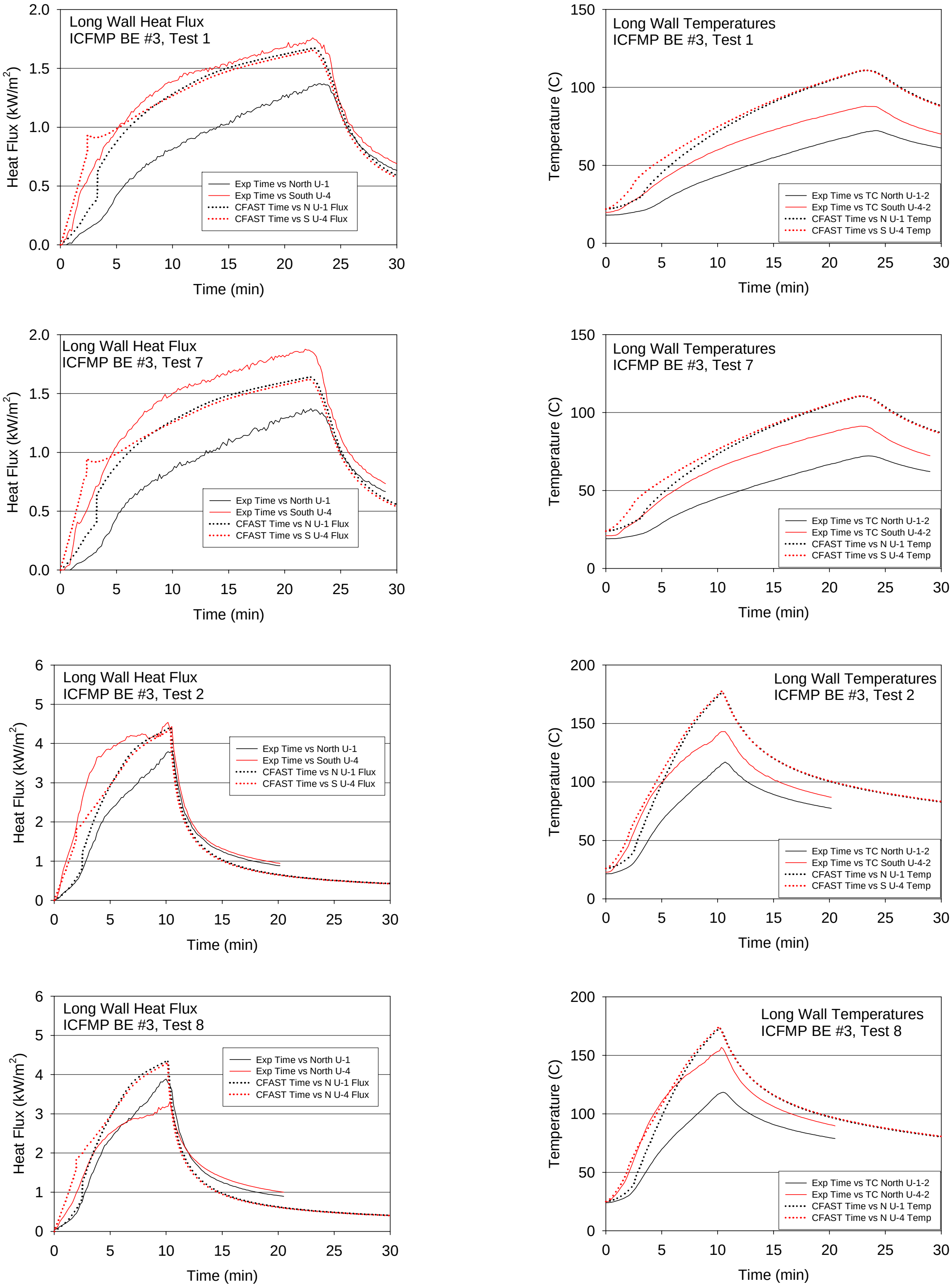


Figure A-61. Long Wall Heat Flux and Surface Temperature, ICFMP BE #3, Closed-Door Tests

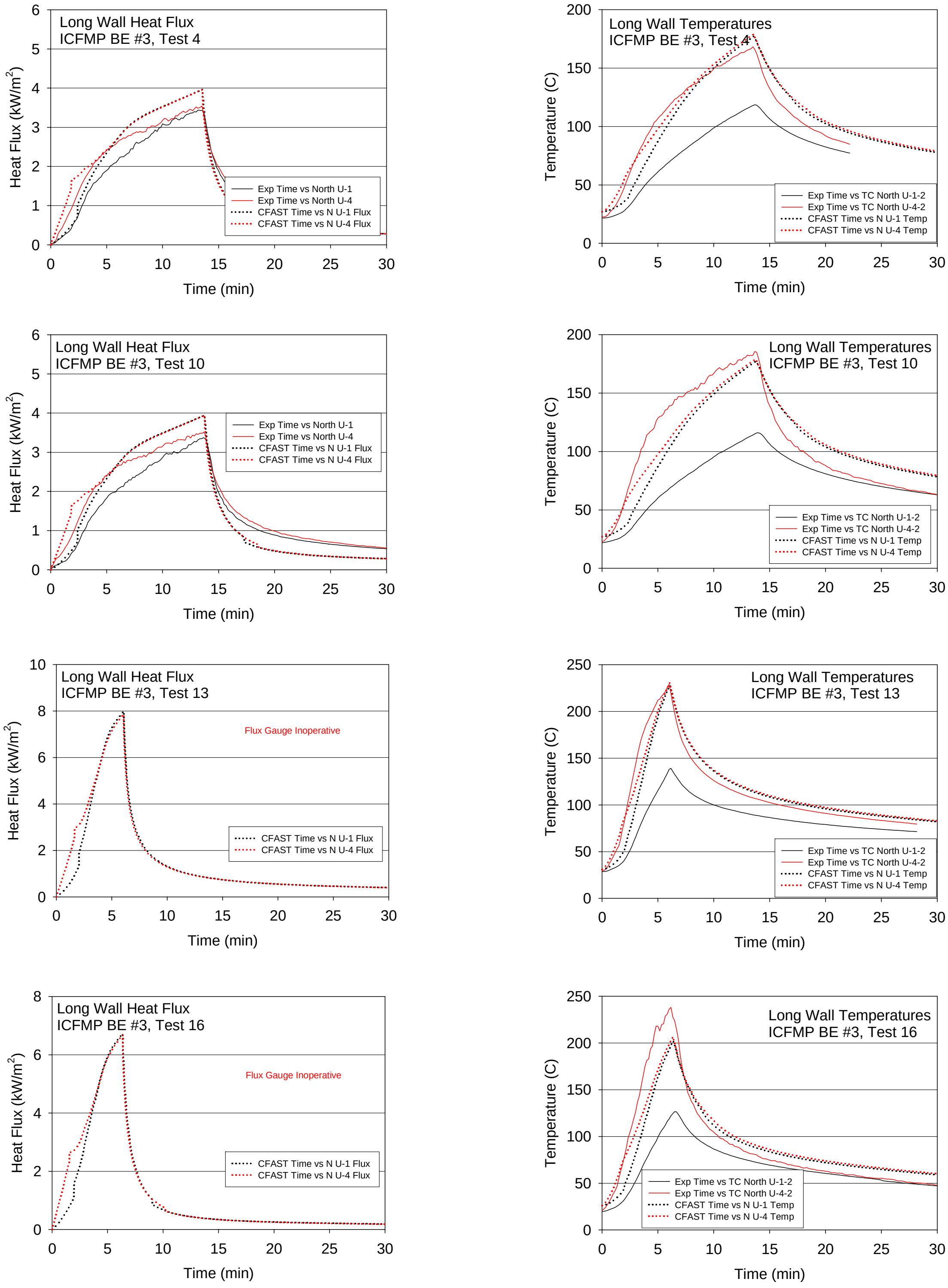
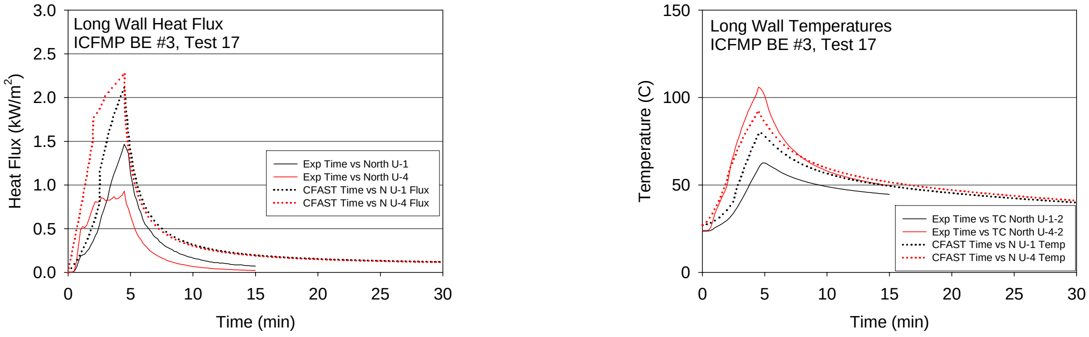


Figure A-62. Long Wall Heat Flux and Surface Temperature, ICFMP BE #3, Closed-Door Tests



Open-Door Tests to Follow

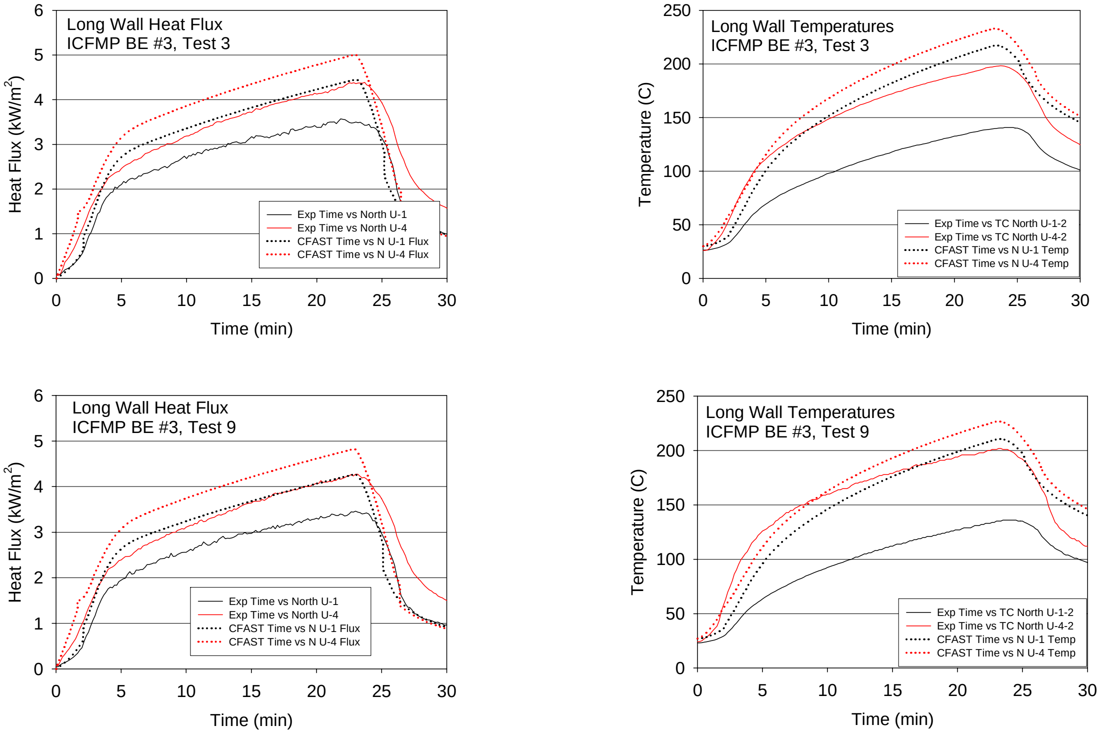


Figure A-63. Long Wall Heat Flux and Surface Temperature, ICFMP BE #3, Closed-Door Tests

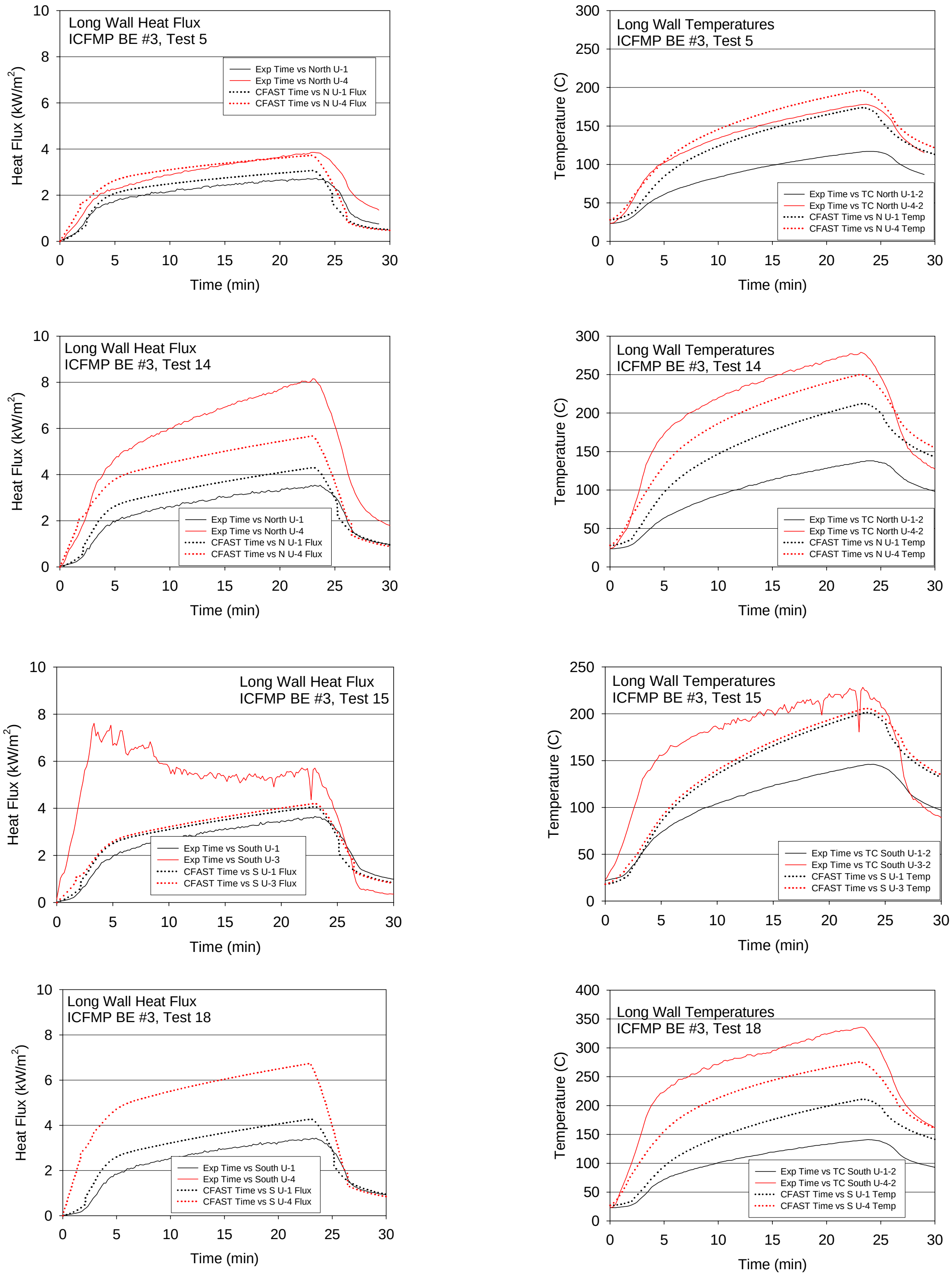


Figure A-64. Long Wall Heat Flux and Surface Temperature, ICFMP BE #3, Open-Door Tests

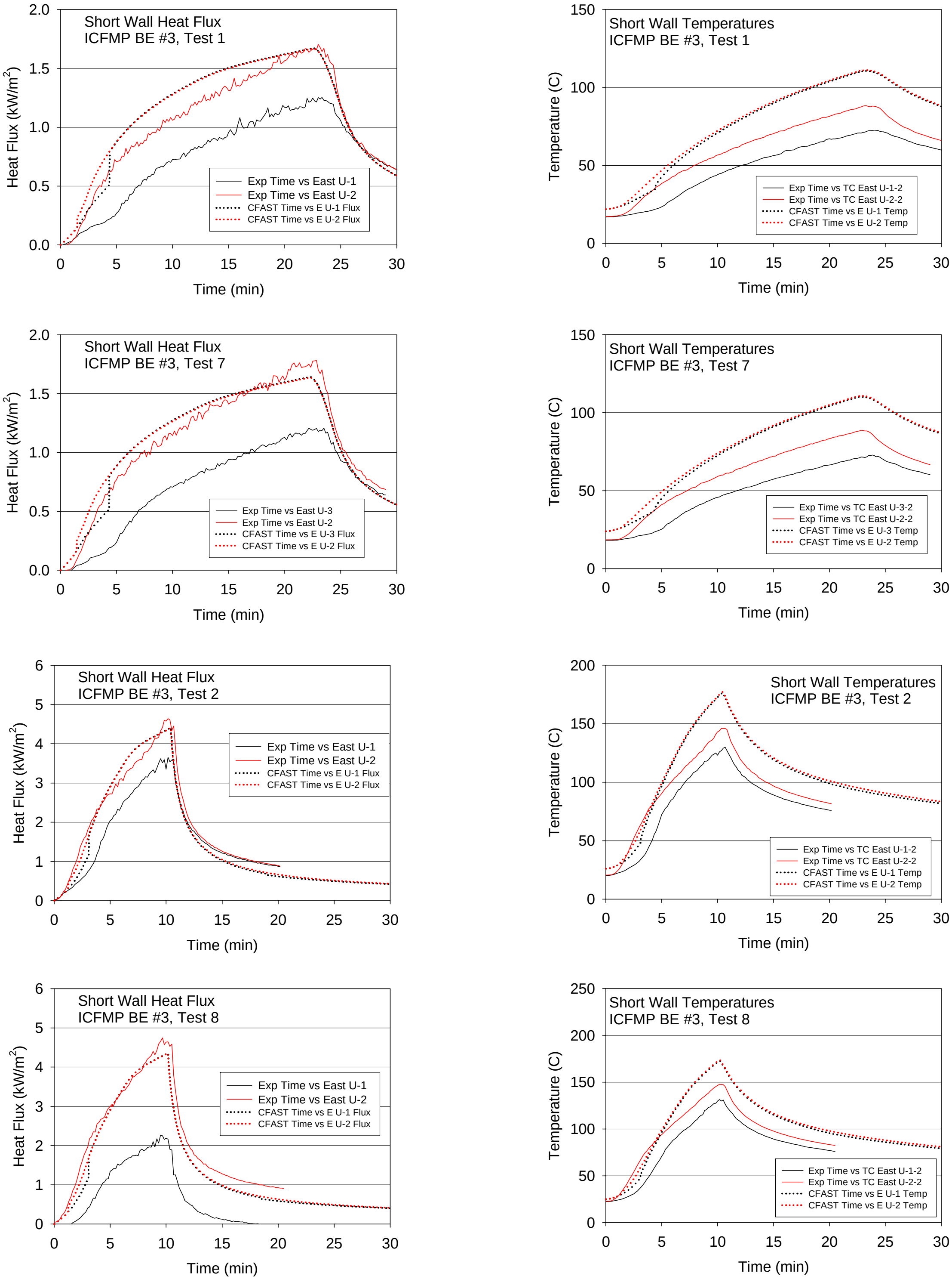


Figure A-65. Short Wall Heat Flux and Surface Temperature, ICFMP BE #3, Closed-Door Tests

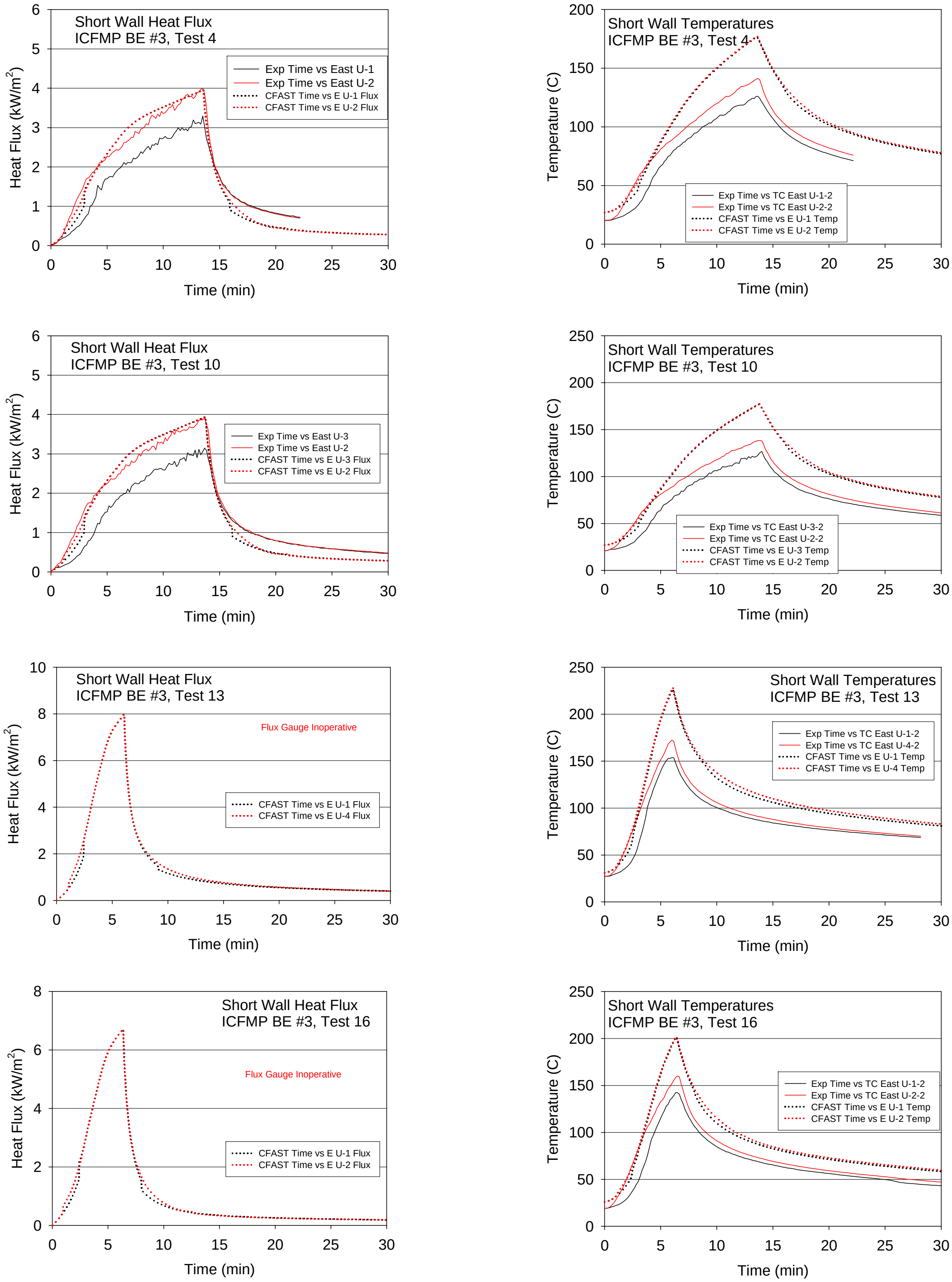
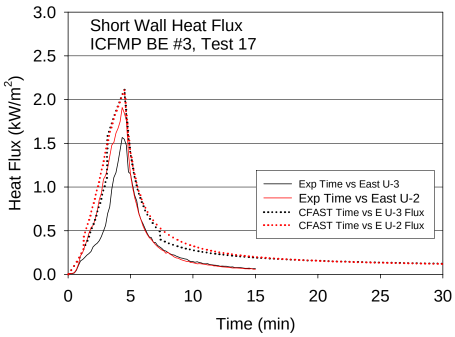
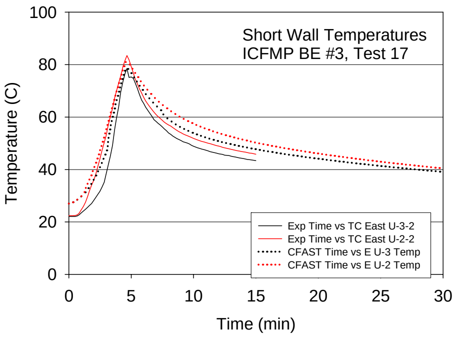


Figure A-66. Short Wall Heat Flux and Surface Temperature, ICFMP BE #3, Closed-Door Tests





Open-Door Tests to Follow

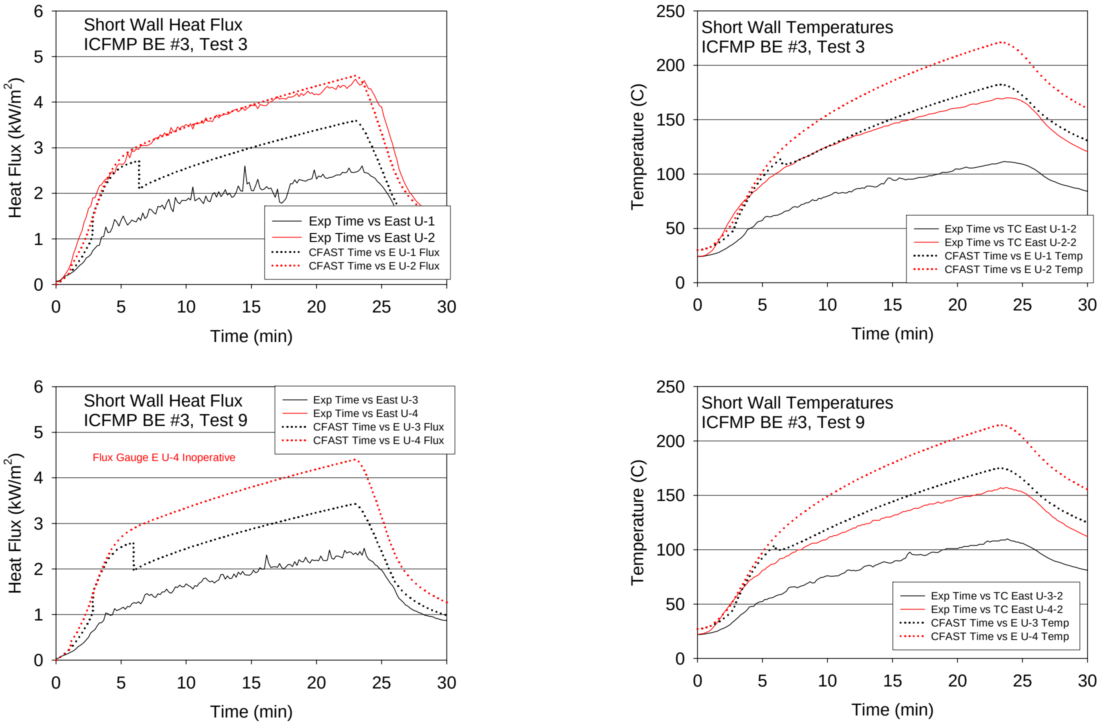


Figure A-67. Short Wall Heat Flux and Surface Temperature, ICFMP BE #3, Open-Door Tests

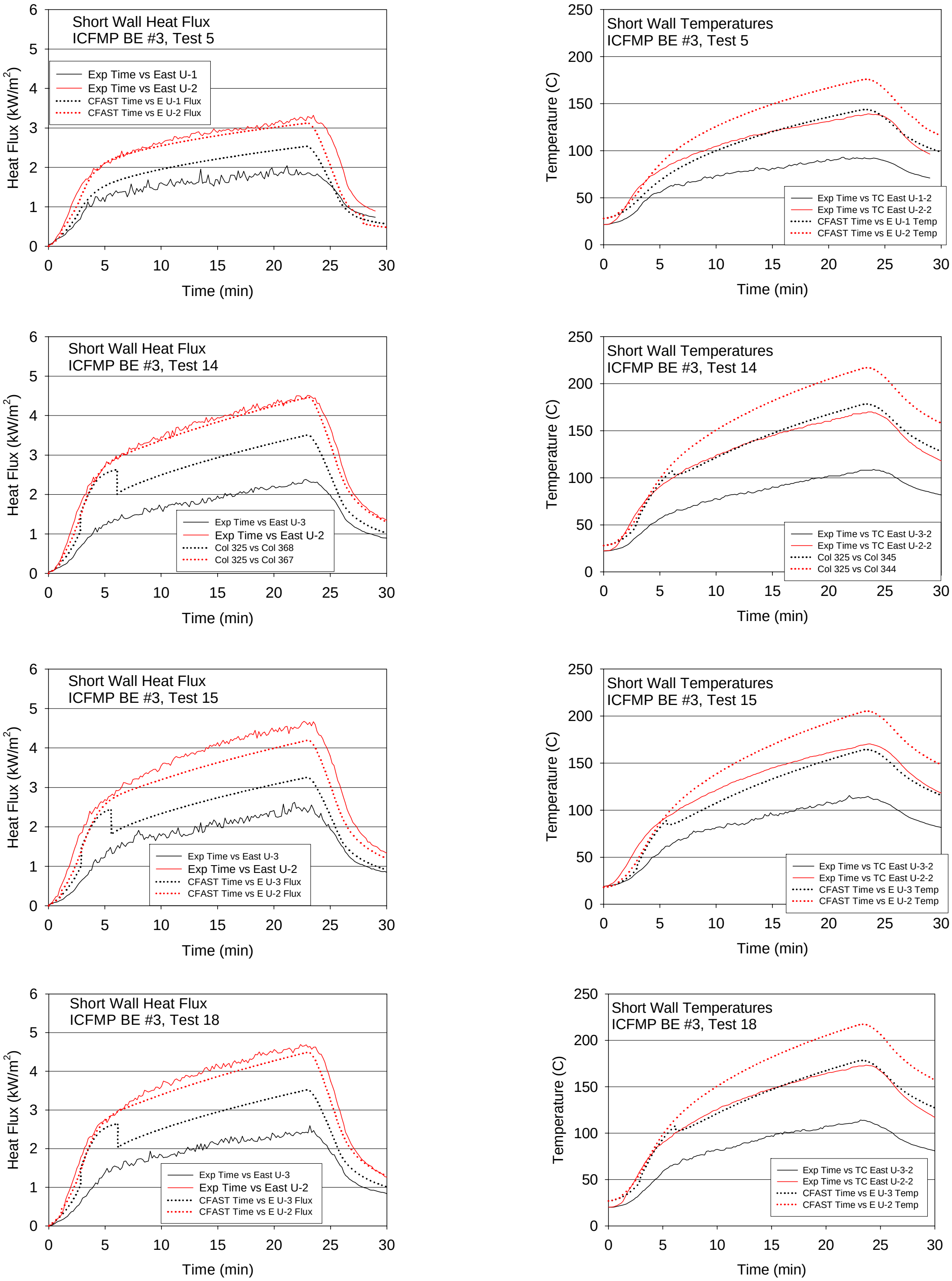


Figure A-68. Short Wall Heat Flux and Surface Temperature, ICFMP BE #3, Open-Door Tests

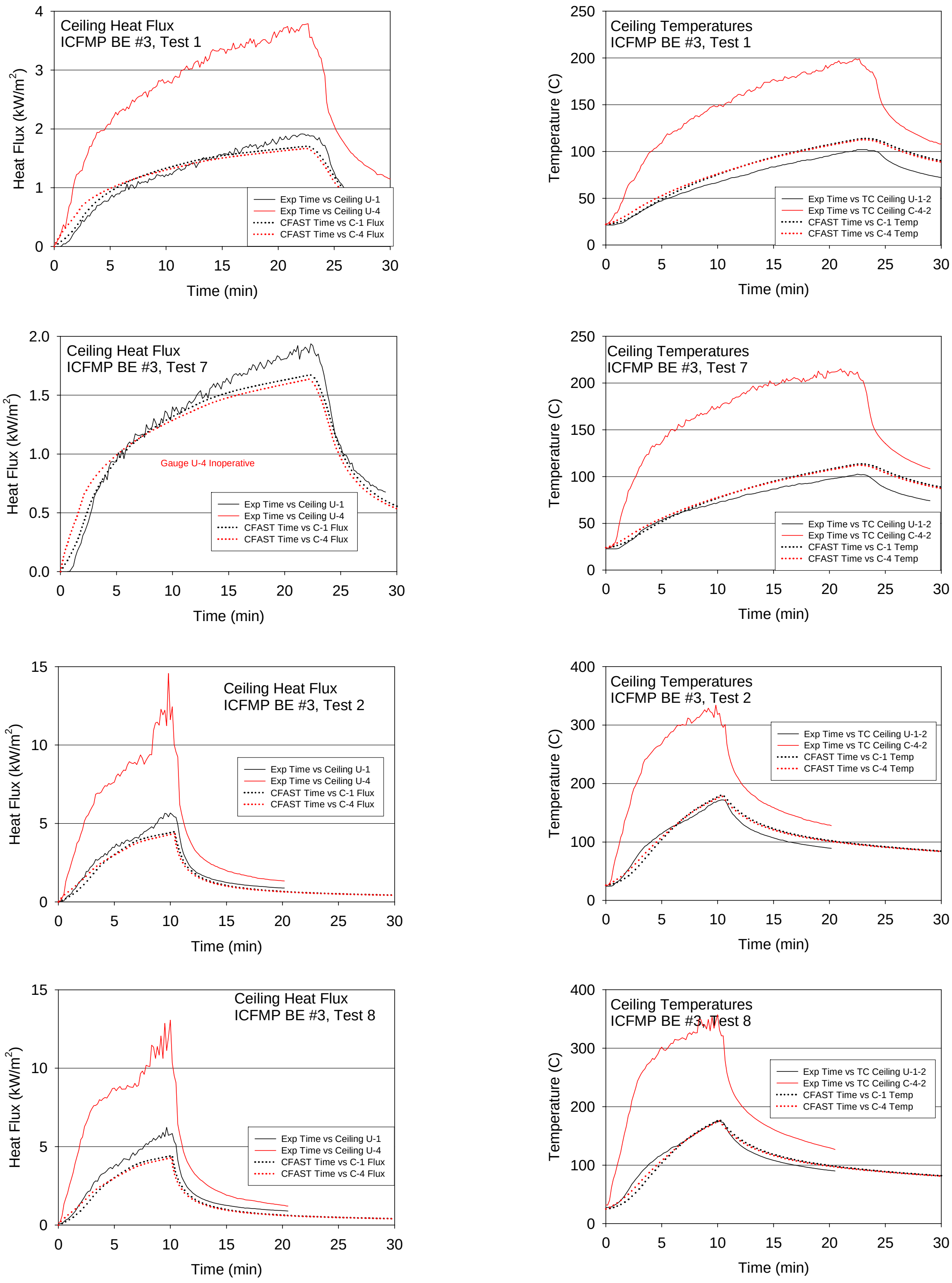


Figure A-69. Ceiling Heat Flux and Surface Temperature, ICFMP BE #3, Closed-Door Tests

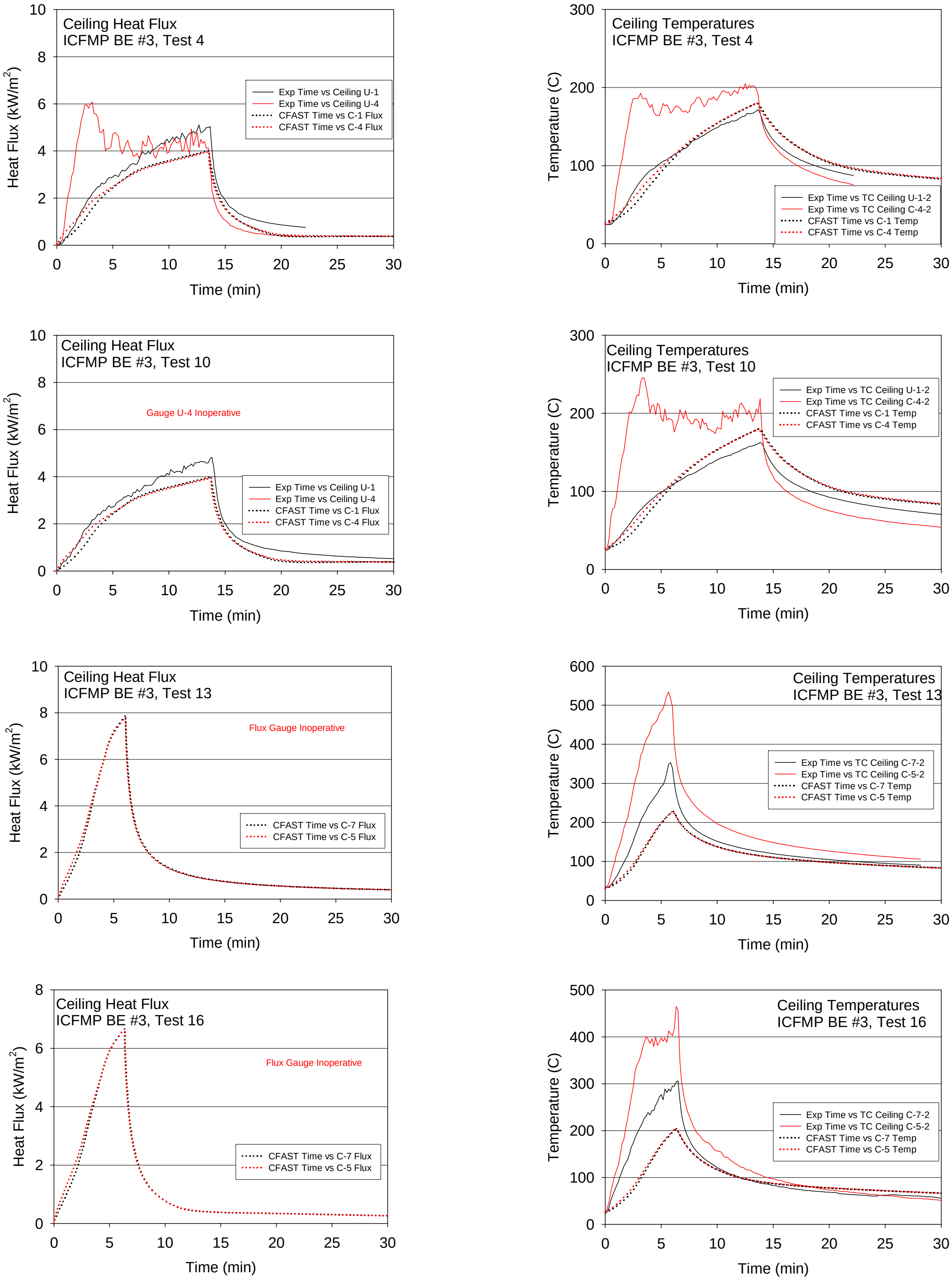
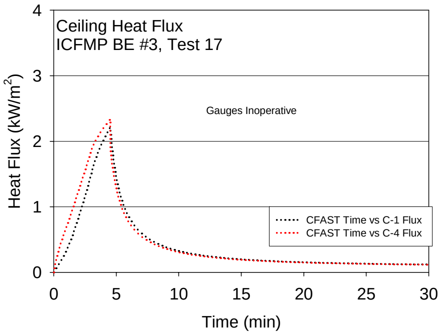
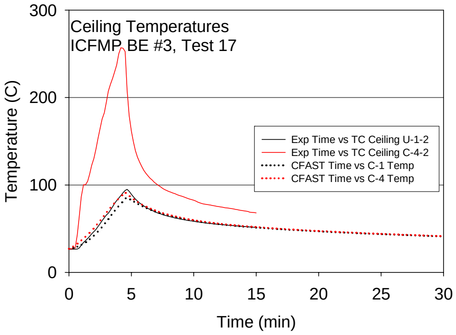


Figure A-70. Ceiling Heat Flux and Surface Temperature, ICFMP BE #3, Closed-Door Tests





Open-Door Tests to Follow

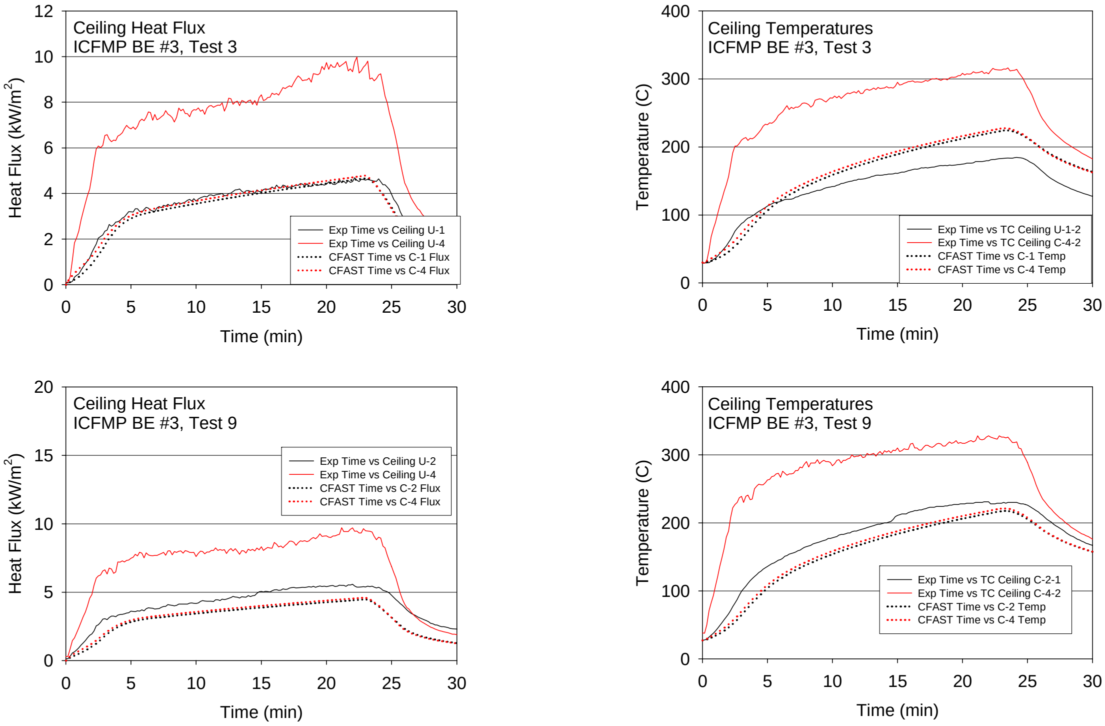


Figure A-71. Ceiling Heat Flux and Surface Temperature, ICFMP BE #3, Open-Door Tests

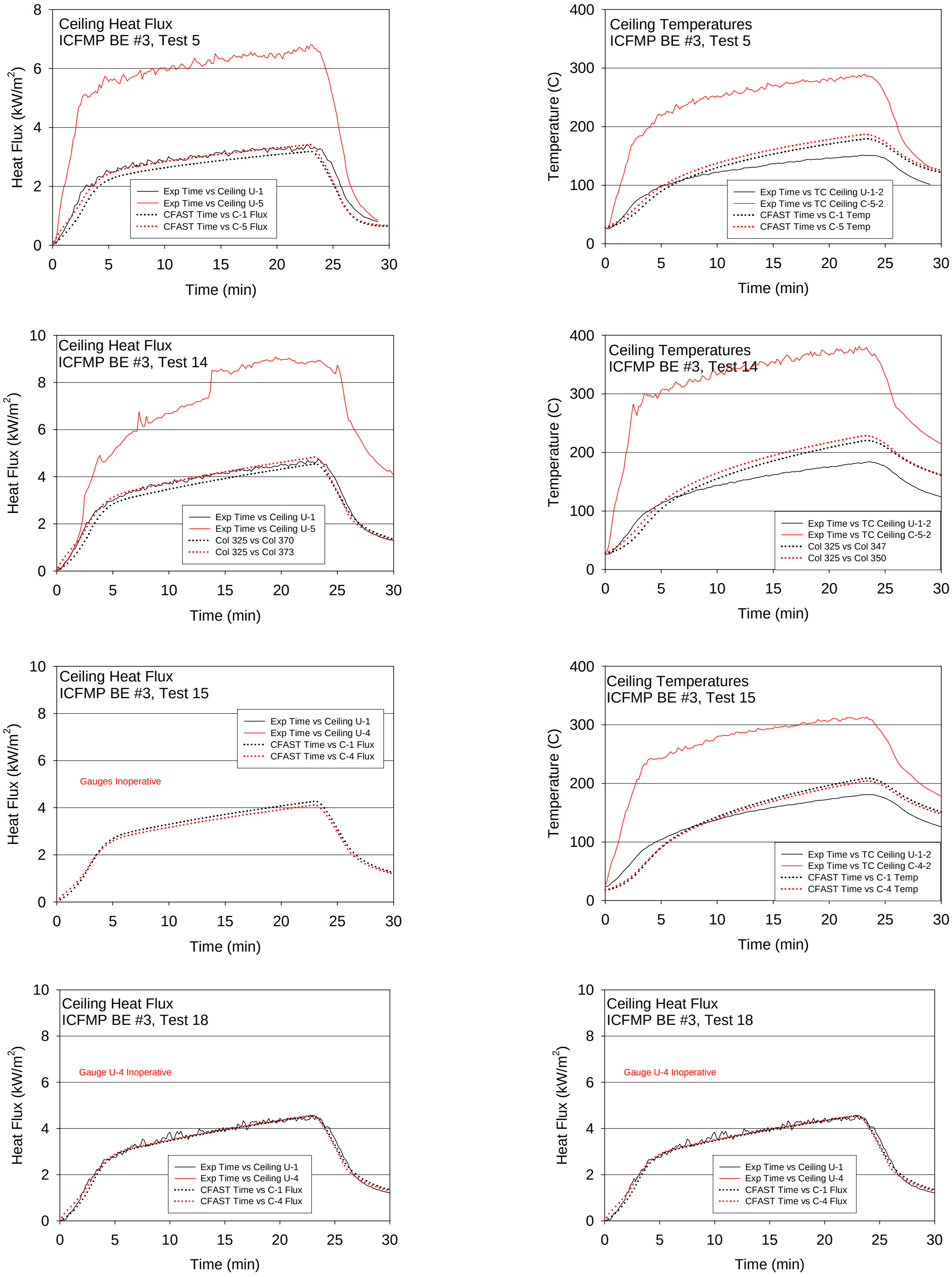


Figure A-72. Ceiling Heat Flux and Surface Temperature, ICFMP BE #3, Open-Door Tests

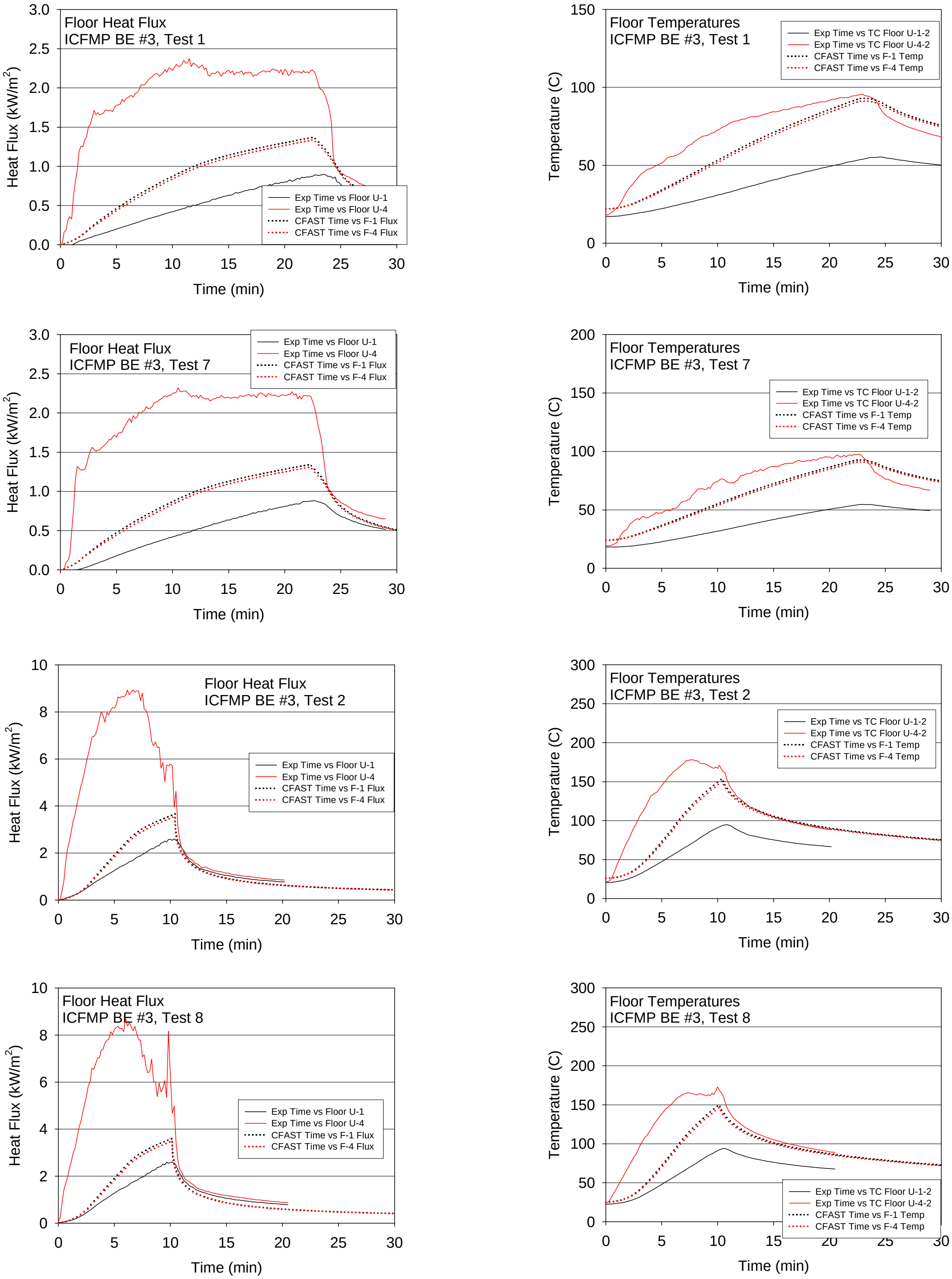


Figure A-73. Floor Heat Flux and Surface Temperature, ICFMP BE #3, Closed-Door Tests

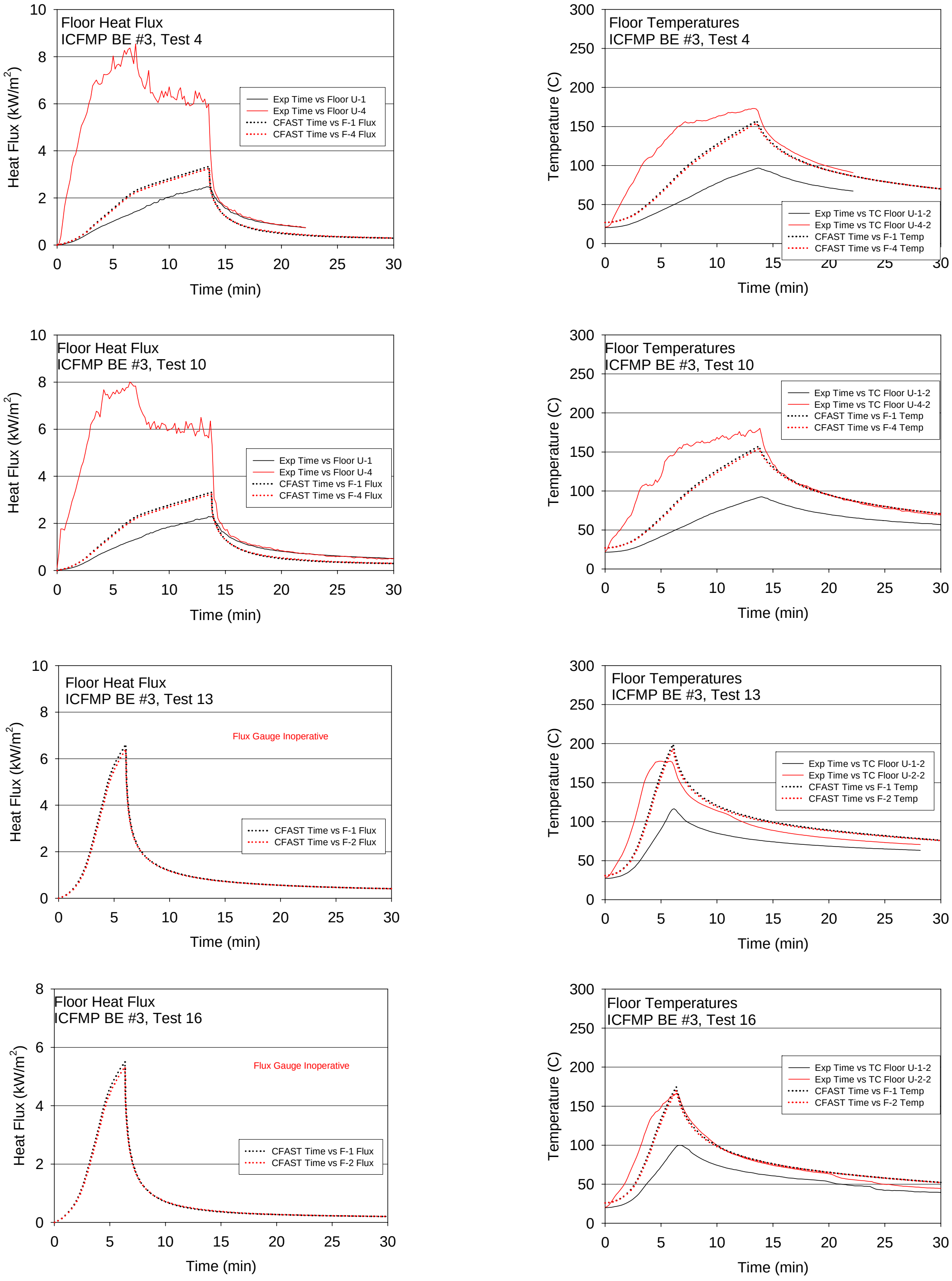
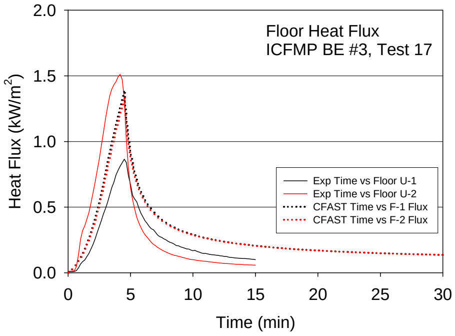
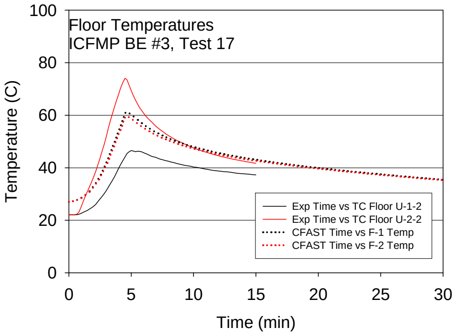


Figure A-74. Floor Heat Flux and Surface Temperature, ICFMP BE #3, Closed-Door Tests





Open-Door Tests to Follow

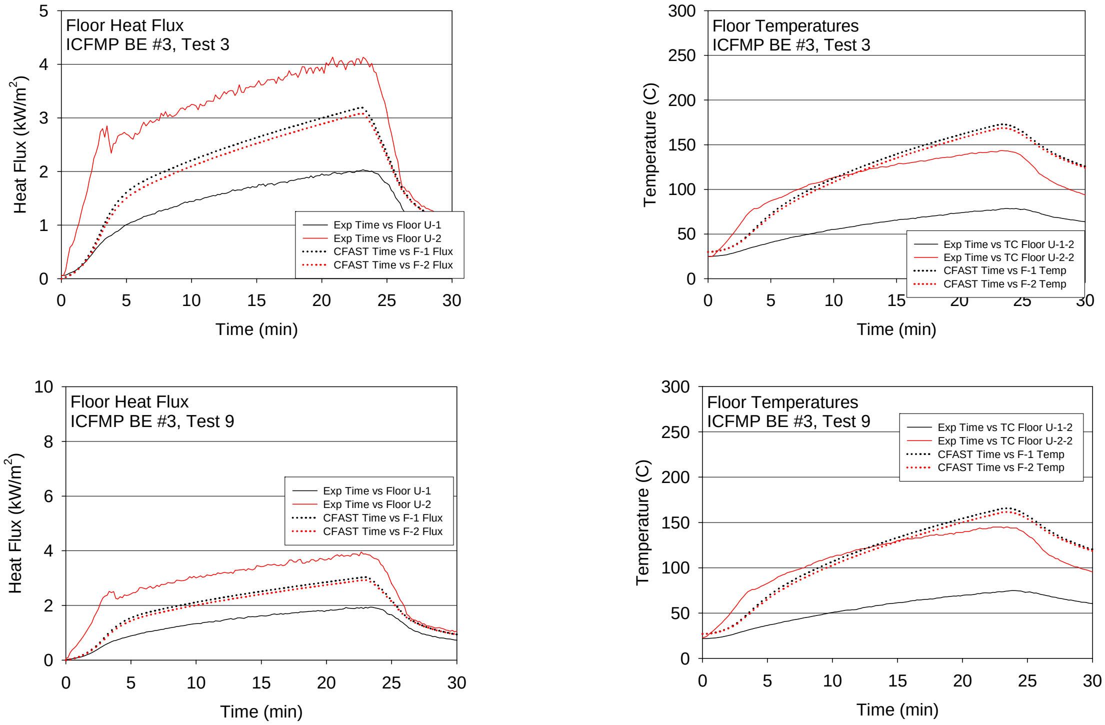


Figure A-75. Floor Heat Flux and Surface Temperature, ICFMP BE #3, Open-Door Tests

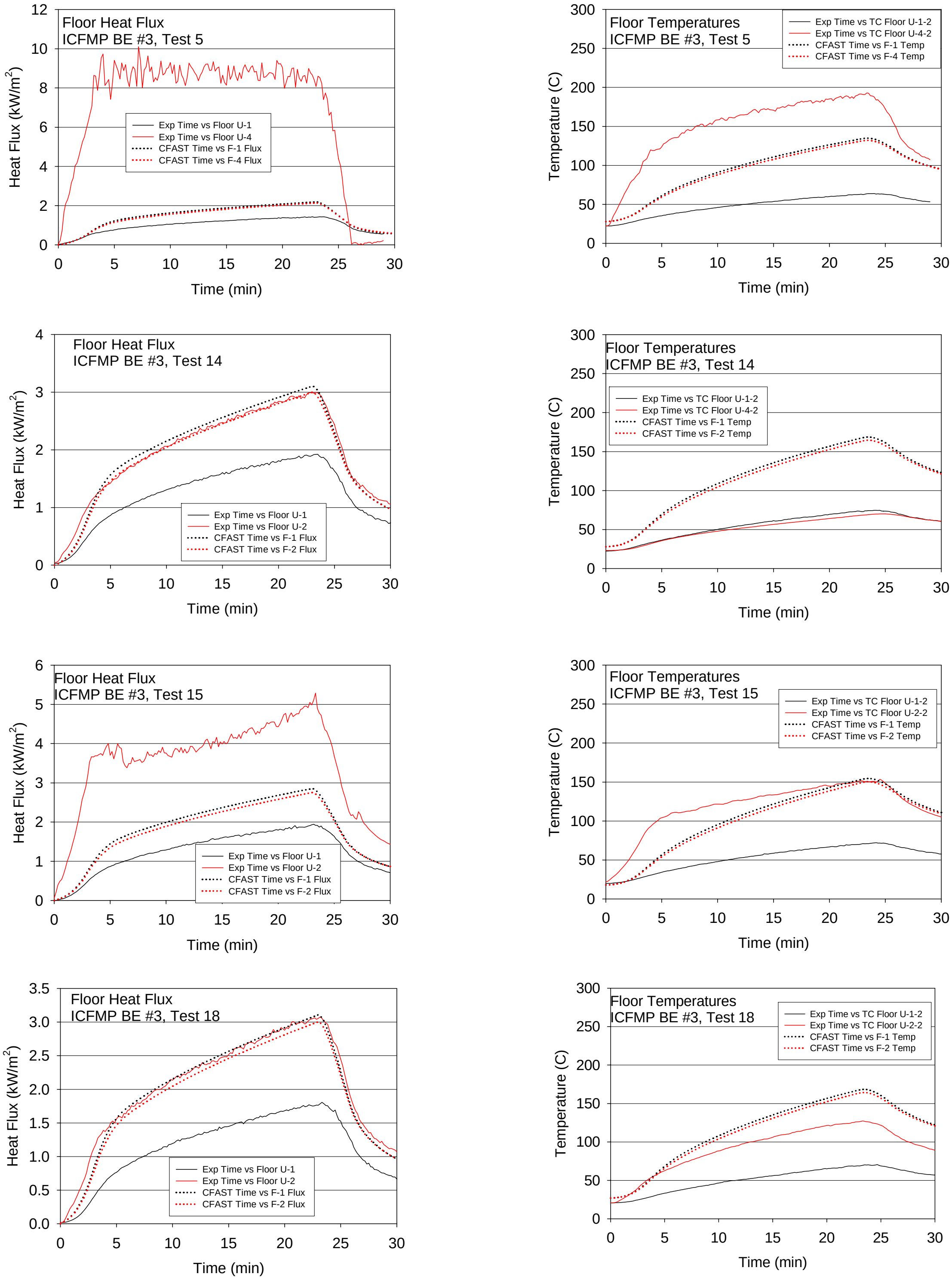


Figure A-76. Floor Heat Flux and Surface Temperature, ICFMP BE #3, Open-Door Tests

ICFMP BE #4

Thermocouples are positioned against the back wall of the compartment. Because the fire leans toward the back wall, temperatures measured by the thermocouples are considerably higher than those in other tests and higher than those predicted by the CFAST model that does not include the effects of an non-symmetric, wind-aided plume.

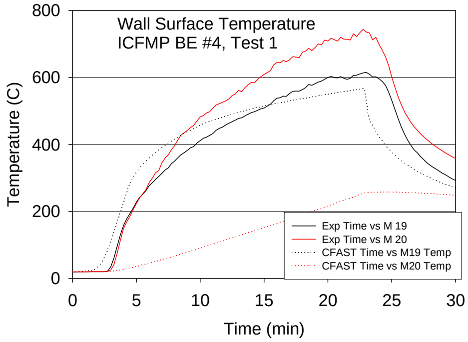


Figure A-77. Back Wall Surface Temperature, ICFMP BE #4, Test 1

ICFMP BE #5

Wall surface temperatures are measured in two locations in the BE #5 test series. The thermocouples labeled TW 1-x (Wall Chain 1) are against the back wall; those labeled TW 2-x (Wall Chain 2) are behind the vertical cable tray. Seven thermocouples are in each chain, spaced 0.8 m (2.6 ft) apart. In **Figure A-78**, the lowest (1), middle (4), and highest (7) locations are used for comparison.

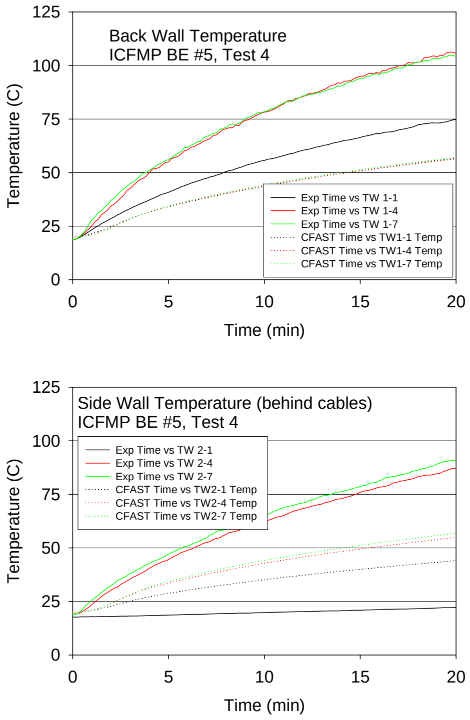


Figure A-78. Back and Side Wall Surface Temperatures, ICFMP BE #5, Test 1

Table A-7. Relative Differences for Surface Heat Flux and Temperature

			Total Flux to Surface			Surface Temperature		
Series	Test	Measurement Position	Exp	CFAST	Diff	Exp	CFAST	Diff
			(kW/m^2)	(kW/m^2)	(%)	(°C)	(°C)	(%)
BE3	Test 1	Long Wall	1.4	1.7	21	54	89	64
			1.8	1.7	-6	68	89	31
		Short Wall	1.3	1.7	33	55	89	60
			1.7	1.7	-3	71	89	26
		Floor	0.9	1.4	48	38	71	86
			2.4	1.3	-44	77	69	-11
		Ceiling	1.9	1.7	-12	81	92	14
			3.8	1.7	-56	176	91	-49
	Test 7	Long Wall	1.4	1.6	19	53	87	63
			1.9	1.6	-14	70	87	23
		Short Wall	1.2	1.6	34	55	86	58
			1.8	1.6	-9	70	87	24
		Floor	0.9	1.3	49	36	69	89
			2.3	1.3	-44	78	67	-14
		Ceiling	1.9	1.7	-14	80	89	12
						191	88	-54
	Test 2	Long Wall	3.8	4.4	17	96	150	57
			4.5	4.3	-4	120	151	26
		Short Wall	3.6	4.4	21	110	150	37
			4.6	4.4	-5	125	151	20
		Floor	2.6	3.7	41	74	127	71
			8.9	3.5	-60	156	124	-21
		Ceiling	5.6	4.5	-21	148	154	4
			14.5	4.3	-70	308	152	-51
	Test 8	Long Wall	3.8	4.3	13	95	149	57
			3.3	4.3	31	132	149	13
		Short Wall	2.5	4.3	76	109	148	36
			4.7	4.3	-8	125	149	19
		Floor	2.6	3.6	40	71	125	75
			8.6	3.5	-60	148	121	-18
		Ceiling	6.1	4.4	-28	148	153	3
			12.9	4.3	-67	325	150	-54
	Test 4	Long Wall	3.4	4.0	16	97	150	54
			3.5	4.0	13	146	152	4
		Short Wall	3.3	4.0	21	106	149	41
			4.0	3.9	-1	121	150	24
		Floor	2.5	3.3	35	76	130	70
			8.5	3.2	-62	152	127	-16
		Ceiling	5.1	4.0	-21	147	153	4
			6.0	4.0	-34	180	153	-15
	Test 10	Long Wall	3.3	3.9	18	94	150	59
			3.5	3.9	13	163	151	-7
		Short Wall	3.1	3.9	26	106	149	41

			Total Flux to Surface			Surface Temperature		
Series	Test	Measurement Position	Exp	CFAST	Diff	Exp	CFAST	Diff
			(kW/m^2)	(kW/m^2)	(%)	(°C)	(°C)	(%)
			3.9	3.9	1	117	150	28
		Floor	2.3	3.3	45	71	130	83
			7.9	3.2	-59	158	127	-20
		Ceiling	4.8	4.0	-17	138	153	11
						221	153	-31
	Test 13	Long Wall				110	195	77
						199	198	-1
		Short Wall				127	194	53
						145	196	35
		Floor				89	166	87
						149	161	8
		Ceiling				319	197	-38
						498	197	-60
	Test 16	Long Wall				107	175	64
						217	180	-17
		Short Wall				123	175	42
						141	176	24
		Floor				80	148	85
						146	144	-1
		Ceiling				284	178	-37
						441	180	-59
	Test 17	Long Wall	1.5	2.1	45	39	53	36
			0.9	2.3	468	82	65	-20
		Short Wall	1.6	2.1	35	56	52	-9
			1.9	2.1	11	61	54	-11
		Floor	0.9	1.4	62	24	34	40
			1.5	1.3	-11	52	33	-37
		Ceiling				69	58	-16
						230	65	-72
	Test 3	Long Wall	3.5	4.5	27	114	187	64
			4.3	5.0	16	172	203	18
		Short Wall	2.5	3.6	42	87	152	74
			4.4	4.6	3	146	191	31
		Floor	2.0	3.2	62	54	143	166
			4.1	3.1	-24	119	139	17
		Ceiling	4.6	4.7	1	155	194	25
			9.9	4.8	-52	287	197	-31
	Test 9	Long Wall	3.4	4.3	25	113	184	63
			4.2	4.8	15	178	200	12
		Short Wall	2.4	3.4	42	88	148	68
						135	188	39
		Floor	1.9	3.0	59	53	139	161
			3.9	2.9	-25	122	135	10
		Ceiling	5.5	4.5	-18	204	191	-6
			9.4	4.6	-51	290	194	-33

			Total Flux to Surface			Surface Temperature		
Series	Test	Measurement Position	Exp	CFAST	Diff	Exp	CFAST	Diff
			(kW/m^2)	(kW/m^2)	(%)	(°C)	(°C)	(%)
	Test 5	Long Wall	2.7	3.1	14	94	146	55
			3.8	3.7	-2	155	168	9
		Short Wall	2.0	2.5	27	71	116	62
			3.3	3.1	-5	118	148	26
		Floor	1.4	2.2	56	42	107	157
			10.1	2.1	-79	171	104	-39
		Ceiling	3.4	3.2	-6	125	151	21
			6.7	3.4	-49	263	159	-40
	Test 14	Long Wall	3.5	4.3	23	114	184	61
			8.1	5.7	-30	255	222	-13
		Short Wall	2.4	3.5	49	87	149	72
			4.5	4.5	0	148	189	28
		Floor	1.9	3.1	64	52	141	169
			3.0	3.0	1	104	137	32
		Ceiling	4.7	4.5	-3	158	192	22
			9.0	4.8	-46	352	200	-43
	Test 15	Long Wall	3.6	4.1	12	220	183	-17
			7.5	4.2	-44	205	188	-9
		Short Wall	2.6	3.3	25	96	145	50
			4.7	4.2	-10	151	187	24
		Floor	1.9	2.9	46	52	137	161
			5.2	2.8	-47	132	132	1
		Ceiling				157	191	22
						287	186	-35
	Test 18	Long Wall	3.4	4.3	25	118	185	56
						312	248	-21
		Short Wall	2.6	3.5	36	94	154	64
			4.7	4.5	-4	153	190	24
		Floor	1.8	3.1	74	50	141	185
			3.1	3.0	-2	107	137	29
		Ceiling	4.5	4.5	2	145	193	33
						250	194	-23
BE4	Test 1	M 19				596	546	-8
		M 20				722	238	-67
BE5	Test 4	TW 1-1				56	37	-34
		TW 2-1				4	24	441
		TW 1-4				87	36	-58
		TW 2-4				68	35	-49
		TW 1-7				86	37	-57
		TW 2-7				72	37	-49

B

CFAST INPUT FILES

This appendix includes the CFAST input files used for the simulations in this V&V study. They are organized by test series, as follows:

B.1 ICFMP Benchmark Exercise #2

B.2 ICFMP Benchmark Exercise #3

B.3 ICFMP Benchmark Exercise #4

B.4 ICFMP Benchmark Exercise #5

B.5 FM /SNL Test Series

B.6 NBS Test Series

B.1 ICFMP Benchmark Exercise #2

Case 1, Input File

```
VERSN,6,ICFMP 2 Test 1 Leakage vents only
!!
!!Environmental Keywords
!!
TIMES,600,-10,0,10,1
EAMB,293.15,101300,0
TAMB,293.15,101300,0,50
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,13.8,27,19,0,0,0,SteelBE2,ConcreteBE2,SteelBE2
ROOMA,1,4,372.6,372.6,51.3,51.3
ROOMH,1,4,0,12,17.1,19
!!
!!vent keywords
!!
HVENT,1,2,1,0.71,0.71,0,1,6.55,0,4,1
HVENT,1,2,2,0.71,0.71,0,1,6.55,0,2,1
HVENT,1,2,3,0.71,12.71,12,1,6.55,0,4,1
HVENT,1,2,4,0.71,12.71,12,1,6.55,0,2,1
!!
!!fire keywords
!!
OBJECT,NRC BE2 1,1,7.2,16,0,1,1,0,0,0,1
```

Case 1, Fire Definition File

```
NRC BE2 1
7,0,0,0,0,1.08,0,0.19,0.0026,0.0049,0,0,0
0.1002,13,1245000,0.0279148,0,1.08,0,0.19,0.0026,0.0049,0,0,0
395.15,90,1709000,0.03831838,0,1.08,0,0.19,0.0026,0.0049,0,0,0
295.15,288,1858000,0.04165919,0,1.08,0,0.19,0.0026,0.0049,0,0,0
0,327,1783000,0.03997758,0,1.08,0,0.19,0.0026,0.0049,0,0,0
0.35,409,1356000,0.03040359,0,1.08,0,0.19,0.0026,0.0049,0,0,0
10000,438,0,0,0,1.08,0,0.19,0.0026,0.0049,0,0,0
1
1
0.25
4.46E+07
METHANE
```

Case 2, Input File

```
VERSN,6,ICFMP 2 Test 2 Leakage vents only
!!
!!Environmental Keywords
!!
TIMES,600,-10,0,10,1
EAMB,293.15,101300,0
TAMB,293.15,101300,0,50
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,13.8,27,19,0,0,0,SteelBE2,ConcreteBE2,SteelBE2
ROOMA,1,4,372.6,372.6,51.3,51.3
ROOMH,1,4,0,12,17.1,19
!!
!!vent keywords
!!
HVENT,1,2,1,0.71,0.71,0,1,6.55,0,4,1
HVENT,1,2,2,0.71,0.71,0,1,6.55,0,2,1
HVENT,1,2,3,0.71,12.71,12,1,6.55,0,4,1
HVENT,1,2,4,0.71,12.71,12,1,6.55,0,2,1
!!
!!fire keywords
!!
OBJECT,NRC BE2 2,1,7.2,16,0,1,1,0,0,0,1
```

Case 2, Fire Definition File

```
NRC BE2 2
9,0,0,0,0,2.01,0,0.19,0.0026,0.0049,0,0,0
0.1002,14,2151000,0.0482287,0,2.01,0,0.19,0.0026,0.0049,0,0,0
395.15,30,2542000,0.05699551,0,2.01,0,0.19,0.0026,0.0049,0,0,0
295.15,91,3063000,0.06867713,0,2.01,0,0.19,0.0026,0.0049,0,0,0
0,193,3259000,0.07307175,0,2.01,0,0.19,0.0026,0.0049,0,0,0
0.35,282,3129000,0.07015695,0,2.01,0,0.19,0.0026,0.0049,0,0,0
10000,340,2737000,0.06136771,0,2.01,0,0.19,0.0026,0.0049,0,0,0
1,372,2275000,0.05100897,0,2.01,0,0.19,0.0026,0.0049,0,0,0
1,395,0,0,0,2.01,0,0.19,0.0026,0.0049,0,0,0
0.25
4.46E+07
METHANE
```

Case 3, Input File

```
VERSN,6,ICFMP 3 Test 3 Leakage vents and mechanical ventilation
!!
!!Environmental Keywords
!!
TIMES,600,-10,0,10,1
EAMB,293.15,101300,0
TAMB,293.15,101300,0,50
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,13.8,27,19,0,0,0,SteelBE2,ConcreteBE2,SteelBE2
ROOMA,1,4,372.6,372.6,51.3,51.3
ROOMH,1,4,0,12,17.1,19
!!
!!vent keywords
!!
HVENT,1,2,1,0.71,0.71,0,1,6.55,0,4,1
HVENT,1,2,2,0.71,0.71,0,1,6.55,0,2,1
HVENT,1,2,3,0.71,12.71,12,1,6.55,0,4,1
HVENT,1,2,4,0.71,12.71,12,1,6.55,0,2,1
HVENT,1,2,5,0.8,4,0,1,8.9,8.9,1,1
HVENT,1,2,6,0.8,4,0,1,8.9,8.9,3,1
MVENT,1,2,1,H,12,3.14,H,12,3.14,11,200,300,1
!!
!!fire keywords
!!
OBJECT,NRC BE2 3,1,7.2,16,0,1,1,0,0,0,1
```

Case 3, Fire Definition File

```
NRC BE2 3
8,0,0,0,0,2.01,0,0.19,0.0026,0.0049,0,0,0
0.1002,13,2426000,0.05439462,0,2.01,0,0.19,0.0026,0.0049,0,0,0
395.15,63,3184000,0.07139014,0,2.01,0,0.19,0.0026,0.0049,0,0,0
295.15,166,3601000,0.08073991,0,2.01,0,0.19,0.0026,0.0049,0,0,0
0,256,3639000,0.08159193,0,2.01,0,0.19,0.0026,0.0049,0,0,0
0.35,292,3450000,0.07735426,0,2.01,0,0.19,0.0026,0.0049,0,0,0
10000,330,2654000,0.05950673,0,2.01,0,0.19,0.0026,0.0049,0,0,0
1,345,0,0,0,2.01,0,0.19,0.0026,0.0049,0,0,0
1
0.25
4.46E+07
METHANE
```

B.2 ICFMP Benchmark Exercise #3

Test 1, Input File

```
VERSN,6,"BE 3, Test 1, XPE Cable, Heptane, Door Closed, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,295.15,101300,0
TAMB,295.15,101300,0,34
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,8.47,3.82,3.81,1,0.555,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 1,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 1, Fire Definition File

```
NRC BE3 1
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,148,410000,0.009111111,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,1350,410000,0.009111111,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,1500,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 2, Input File

```
VERSN,6,"BE 3, Test 2, XPE Cable, Heptane, Door Closed, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,299.15,101300,0
TAMB,299.15,101300,0,36
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,8.29,3.82,3.81,1,0.555,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 2,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 2, Fire Definition File

```
NRC BE3 2
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,180,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,625,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,626,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 3, Input File

```
VERSN,6,"BE 3, Test 3, XPE Cable, Heptane, Door Open, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,303.15,101300,0
TAMB,303.15,101300,0,34
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,2,2,0,1,2.58,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 3,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 3, Fire Definition File

```
NRC BE3 3
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,178,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,1379,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,1562,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 4, Input File

```
VERSN,6,"BE 3, Test 4, XPE Cable, Heptane, Door Closed, MV On"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,300.15,101300,0
TAMB,300.15,101300,0,44
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,8.29,3.82,3.81,1,0.555,0,4,1
MVENT,2,1,1,V,2.4,0.49,V,2.4,0.49,0.9,200,300,1
MVENT,1,2,2,V,2.4,0.49,V,2.4,0.49,1.7,200,300,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 4,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 4, Fire Definition File

```
NRC BE3 4
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,178,1200000,0.02666667,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,814,1200000,0.02666667,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,815,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 5, Input File

```
VERSN,6,"BE 3, Test 5, XPE Cable, Heptane, Door Open, MV On"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,301.15,101300,0
TAMB,301.15,101300,0,37
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,5.8,3.82,3.81,1,0.555,0,4,1
HVENT,1,2,2,2,2,0,1,2.58,2.58,1,1
MVENT,2,1,1,V,2.4,0.49,V,2.4,0.49,0.9,200,300,1
MVENT,1,2,2,V,2.4,0.49,V,2.4,0.49,1.7,200,300,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 5,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 5, Fire Definition File

```
NRC BE3 5
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,178,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,1379,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,1562,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 7, Input File

```
VERSN,6,"BE 3, Test 7, PVC Cable, Heptane, Door Closed, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,297.15,101300,0
TAMB,297.15,101300,0,58
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,10.17,3.82,3.81,1,0.555,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 7,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,PVC_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 7, Fire Definition File

```
NRC BE3 7
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,129,400000,0.008888889,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,1332,400000,0.008888889,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,1460,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 8, Input File

```
VERSN,6,"BE 3, Test 8, XPE Cable, Heptane, Door Closed, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,298.15,101300,0
TAMB,298.15,101300,0,63
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,9.21,3.82,3.81,1,0.555,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 8,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 8, Fire Definition File

```
NRC BE3 8
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,176,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,610,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,611,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 9, Input File

```
VERSN,6,"BE 3, Test 9, XPE Cable, Heptane, Door Open, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,300.15,101300,0
TAMB,300.15,101300,0,62
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,2,2,0,1,2.58,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 9,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 9, Fire Definition File

```
NRC BE3 9
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,175,1170000,0.026,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,1376,1170000,0.026,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,1560,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 10, Input File

```
lVERSN,6,"BE 3, Test 10, PVC Cable, Heptane, Door Closed, MV On"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,300.15,101300,0
TAMB,300.15,101300,0,63
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,10.17,3.82,3.81,1,0.555,0,4,1
MVENT,2,1,1,V,2.4,0.49,V,2.4,0.49,0.9,200,300,1
MVENT,1,2,2,V,2.4,0.49,V,2.4,0.49,1.7,200,300,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 10,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,PVC_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 10, Fire Definition File

```
NRC BE3 10
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,176,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,826,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,827,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 13, Input File

```
VERSN,6,"BE 3, Test 13, XPE Cable, Heptane, Door Closed, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,304.15,101300,0
TAMB,304.15,101300,0,52
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,11.9,3.82,3.81,1,0.555,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 13,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 13, Fire Definition File

```
NRC BE3 13
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,177,2330000,0.05177778,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,364,2330000,0.05177778,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,365,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 14, Input File

```
VERSN,6,"BE 14, Test 3, XPE Cable, Heptane, Door Open, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,301.15,101300,0
TAMB,301.15,101300,0,61
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,2,2,0,1,2.58,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 14,1,10.83,5.21,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 14, Fire Definition File

```
NRC BE3 14
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,176,1180000,0.02622222,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,1381,1180000,0.02622222,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,1567,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 15, Input File

```
VERSN,6,"BE 15, Test 3, PVC Cable, Heptane, Door Open, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,291.15,101300,0
TAMB,291.15,101300,0,95
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,2,2,0,1,2.58,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 15,1,10.83,5.21,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,PVC_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 15, Fire Definition File

```
NRC BE3 15
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,180,1180000,0.02622222,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,1380,1180000,0.02622222,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,1567,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 16, Input File

```
VERSN,6,"BE 3, Test 16, PVC Cable, Heptane, Door Closed, MV On"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,299.15,101300,0
TAMB,299.15,101300,0,55
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,10.17,3.82,3.81,1,0.555,0,4,1
MVENT,2,1,1,V,2.4,0.49,V,2.4,0.49,0.9,200,300,1
MVENT,1,2,2,V,2.4,0.49,V,2.4,0.49,1.7,200,300,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 16,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,PVC_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 16, Fire Definition File

```
NRC BE3 16
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,177,2300000,0.05111111,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,382,2300000,0.05111111,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,383,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 17, Input File

```
VERSN,6,"BE 3, Test 17, PVC Cable, Toluene, Door Closed, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,300.15,101300,0
TAMB,300.15,101300,0,40
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,10.17,3.82,3.81,1,0.555,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 17,1,10.85,3.52,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,PVC_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 17, Fire Definition File

```
NRC BE3 17,,,,,,,,,,,,
4,0,0,0,0,1,0,0.19,0.022,0.058,0,0,0
0.0921,181,1160000,0.02577778,0,1,0,0.19,0.022,0.058,0,0,0
395.15,272,1160000,0.02577778,0,1,0,0.19,0.022,0.058,0,0,0
295.15,273,0,0,0,1,0,0.19,0.022,0.058,0,0,0
0,,,,,,,,,,,,
0.44,,,,,,,,,,,,
10000,,,,,,,,,,,,
1,,,,,,,,,,,,
1,,,,,,,,,,,,
0.25,,,,,,,,,,,,
4.50E+07,,,,,,,,,,,,
METHANE,,,,,,,,,,,,
```

Test 18, Input File

```
VERSN,6,"BE 3, Test 18, XPE Cable, Heptane, Door Open, MV Off"
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,300.15,101300,0
TAMB,300.15,101300,0,40
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,21.7,7.04,3.82,0,0,0,MARIBE3,GYPBE3,MARIBE3
!!
!!vent keywords
!!
HVENT,1,2,1,2,2,0,1,2.58,0,4,1
!!
!!fire keywords
!!
OBJECT,NRC BE3 18,1,12.33,1.55,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.91,7.04,1.49,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,7.04,1.87,0,-1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.91,0,1.49,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,9.55,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,12.15,0,1.87,0,1,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,1.59,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,1.12,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,21.7,5.76,2.43,-1,0,0,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,9.11,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,10.85,5.17,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,13.02,5.97,3.82,0,0,-1,MARIBE3,IMPLICIT,PDE
TARGET,1,3.04,3.59,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,9.11,2,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2.39,0,0,0,1,GYPBE3,IMPLICIT,PDE
TARGET,1,10.85,2,3.2,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,1.25,2.7,0,0,-1,PVC_C_BE3,IMPLICIT,PDE
TARGET,1,10.55,1.3,2.8,0,0,-1,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.85,0.5,2.2,0,0,-1,XLP_P_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
TARGET,1,10.8,6.8,1.75,0,-1,0,XLP_C_BE3,IMPLICIT,PDE
```

Test 18, Fire Definition File

```
NRC BE3 18
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,178,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,1379,1190000,0.02644444,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,1562,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

B.3 ICFMP Benchmark Exercise #4

Test 1, Input File

```
VERSN,6,CFAST Simulation
!!
!!Environmental Keywords
!!
TIMES,1800,-10,0,10,1
EAMB,293.15,101300,0
TAMB,293.15,101300,0,50
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,3.6,3.6,5.7,0,0,0,ConcreteBE4,LiteConcBE4,ConcreteBE4
!!
!!vent keywords
!!
HVENT,1,2,1,0.7,3,0,1,1.8,1.8,1,1
MVENT,1,2,1,H,5.7,1.46,H,5.7,1.46,1.1,200,300,1
MVENT,1,2,2,H,5.7,1.46,H,5.7,1.46,1.1,200,300,1
!!
!!fire keywords
!!
OBJECT,NRC BE4 1,1,1.8,1.8,0,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,3.6,1.5,1.8,-1,0,0,ConcreteBE4,IMPLICIT,PDE
TARGET,1,0,2.8,1.7,1,0,0,SteelBE4,IMPLICIT,PDE
TARGET,1,0,1.9,1.7,1,0,0,ConcreteBE4,IMPLICIT,PDE
TARGET,1,0,0.7,1.7,1,0,0,LiteConcBE4,IMPLICIT,PDE
TARGET,1,2.45,3.6,1.5,0,-1,0,GYPSUM,IMPLICIT,PDE
TARGET,1,2.45,3.6,3.35,0,-1,0,GYPSUM,IMPLICIT,PDE
```

Test 1, Fire Definition File

```
NRC BE4 1
9,0,0,0,0,1.08,0,0.18,0.0026,0.0049,0,0,0
0.165,92,119840,0.0028,0,1.08,0,0.18,0.0026,0.0049,0,0,0
395.15,180,1583600,0.037,0,1.08,0,0.18,0.0026,0.0049,0,0,0
295.15,260,2623640,0.0613,0,1.08,0,0.18,0.0026,0.0049,0,0,0
0,600,3197160,0.0747,0,1.08,0,0.18,0.0026,0.0049,0,0,0
0.35,822,3351240,0.0783,0,1.08,0,0.18,0.0026,0.0049,0,0,0
10000,870,3381200,0.079,0,1.08,0,0.18,0.0026,0.0049,0,0,0
1,1368,3518160,0.0822,0,1.08,0,0.18,0.0026,0.0049,0,0,0
1,1395,0,0,0,1.08,0,0.18,0.0026,0.0049,0,0,0
0.25
4.28E+07
METHANE
```

B.4 ICFMP Benchmark Exercise #5

Test 4, Input File

```
VERSN,6,CFAST Simulation
!!
!!Environmental Keywords
!!
TIMES,2300,-10,0,10,1
EAMB,293.15,101300,0
TAMB,293.15,101300,0,50
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,3.6,3.6,5.6,0,0,0,LiteConcBE4,LiteConcBE4,ConcreteBE4
!!
!!vent keywords
!!
HVENT,1,2,1,0.7,3.6,1.4,1,1.8,1.8,1,1
HVENT,1,2,2,0.6,1.4,0.7,1,1.8,1.8,2,1
!!
!!fire keywords
!!
OBJECT,NRC BE5 4F,1,3.05,1.75,0.6,1,1,0,0,0,1
OBJECT,NRC BE5 4B,1,0.6,2.1,0.4,1,1,0,0,0,1
!!
!!target and detector keywords
!!
TARGET,1,0.41,2.13,1.2,1,0,0,LiteConcBE4,IMPLICIT,PDE
TARGET,1,0.41,2.13,2,1,0,0,LiteConcBE4,IMPLICIT,PDE
TARGET,1,0.41,2.13,2.8,1,0,0,LiteConcBE4,IMPLICIT,PDE
TARGET,1,0.41,2.13,3.6,1,0,0,LiteConcBE4,IMPLICIT,PDE
TARGET,1,0.41,2.13,4.4,1,0,0,LiteConcBE4,IMPLICIT,PDE
TARGET,1,0.44,2.24,1.2,1,0,0,PVC_P_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.24,1.6,1,0,0,PVC_P_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.24,2,1,0,0,PVC_P_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.24,2.4,1,0,0,PVC_P_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.24,2.8,1,0,0,PVC_P_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.24,3.2,1,0,0,PVC_P_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.24,3.6,1,0,0,PVC_P_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.24,4,1,0,0,PVC_P_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.24,4.4,1,0,0,PVC_P_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.05,1.2,1,0,0,PVC_C_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.05,1.6,1,0,0,PVC_C_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.05,2,1,0,0,PVC_C_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.05,2.4,1,0,0,PVC_C_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.05,2.8,1,0,0,PVC_C_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.05,3.2,1,0,0,PVC_C_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.05,3.6,1,0,0,PVC_C_BE4,IMPLICIT,PDE
TARGET,1,0.44,2.05,4,1,0,0,PVC_C_BE4,IMPLICIT,PDE
```

```
TARGET,1,0.44,2.05,4.4,1,0,0,PVC_C_BE4,IMPLICIT,PDE
TARGET,1,2.6,3.6,0.4,0,-1,0,ConcreteBE4,IMPLICIT,PDE
TARGET,1,2.6,3.6,2.8,0,-1,0,ConcreteBE4,IMPLICIT,PDE
TARGET,1,2.6,3.6,5.2,0,-1,0,ConcreteBE4,IMPLICIT,PDE
TARGET,1,0,2.2,0.4,1,0,0,ConcreteBE4,IMPLICIT,PDE
TARGET,1,0,2.2,2.8,1,0,0,ConcreteBE4,IMPLICIT,PDE
TARGET,1,0,2.2,5.2,1,0,0,ConcreteBE4,IMPLICIT,PDE
```

Test 4, Fire Definition Files

```
NRC BE5 4F
12,0,0,0,0,0,0,0.18,0.0026,0.0049,0,0,0
0.046,60,120000,0.003921569,0,0.49,0,0.18,0.0026,0.0049,0,0,0
395.15,120,220000,0.007189543,0,0.49,0,0.18,0.0026,0.0049,0,0,0
295.15,180,280000,0.009150327,0,0.49,0,0.18,0.0026,0.0049,0,0,0
0,240,290000,0.009477125,0,0.49,0,0.18,0.0026,0.0049,0,0,0
0.2,300,300000,0.009803922,0,0.49,0,0.18,0.0026,0.0049,0,0,0
10000,480,320000,0.01045752,0,0.49,0,0.18,0.0026,0.0049,0,0,0
0.7,600,330000,0.01078431,0,0.49,0,0.18,0.0026,0.0049,0,0,0
0.7,900,340000,0.01111111,0,0.49,0,0.18,0.0026,0.0049,0,0,0
0.1,1800,360000,0.01176471,0,0.49,0,0.18,0.0026,0.0049,0,0,0
3.06E+07,2299,360000,0.01176471,0,0.49,0,0.18,0.0026,0.0049,0,0,0
METHANE,2300,0,0,0,0,0,0.18,0.0026,0.0049,0,0,0
```

```
NRC BE5 4B
7,0,0,0,0,0,0,0.18,0.0026,0.0049,0,0,0
0.165,1200,0,0,0,0,0,0.18,0.0026,0.0049,0,0,0
395.15,1201,50000,0.001168224,0,0.09,0,0.18,0.0026,0.0049,0,0,0
295.15,2100,50000,0.001168224,0,0.09,0,0.18,0.0026,0.0049,0,0,0
0,2120,100000,0.002336449,0,0.09,0,0.18,0.0026,0.0049,0,0,0
0.35,2280,100000,0.002336449,0,0.09,0,0.18,0.0026,0.0049,0,0,0
10000,2300,0,0,0,0,0,0.18,0.0026,0.0049,0,0,0
0.3
0.3
0.4
4.28E+07
METHANE
```

B.5 FM / SNL Test Series

Test 4, Input File

```
VERSN,6,FM Test 4
!!
!!Environmental Keywords
!!
TIMES,1200,-50,0,10,1
EAMB,288.15,101300,0
TAMB,288.15,101300,0,50
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,18.3,12.2,6.1,0,0,0,MariniteFM,ConcreteFM,MariniteFM
!!
!!vent keywords
!!
VVENT,2,1,1.08,2,1
MVENT,2,1,1,H,4.9,0.66,H,4.9,0.66,0.38,200,300,1
!!
!!fire keywords
!!
OBJECT,FM SNL 4,1,12,6.1,0,1,1,0,0,0,1
```

Test 4, Fire Definition File

```
FM SNL 4
11,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,30,7968.75,0.0001770833,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,60,31875,0.0007083333,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,90,71718.75,0.00159375,0,1,0,0.19,0.0026,0.0049,0,0,0
0,120,127500,0.002833333,0,1,0,0.19,0.0026,0.0049,0,0,0
0.35,150,199218.8,0.004427084,0,1,0,0.19,0.0026,0.0049,0,0,0
10000,180,286875,0.006375,0,1,0,0.19,0.0026,0.0049,0,0,0
1,210,390468.8,0.008677085,0,1,0,0.19,0.0026,0.0049,0,0,0
1,240,510000,0.01133333,0,1,0,0.19,0.0026,0.0049,0,0,0
0.25,600,510000,0.01133333,0,1,0,0.19,0.0026,0.0049,0,0,0
4.5E+07,601,0,0,0,0,0,0.19,0.0026,0.0049,0,0,0
METHANE
```

Test 5, Input File

```
VERSN,6,FM Test 5
!!
!!Environmental Keywords
!!
TIMES,900,-50,0,10,1
EAMB,293.15,101300,0
TAMB,293.15,101300,0,50
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,18.3,12.2,6.1,0,0,0,MariniteFM,ConcreteFM,MariniteFM
!!
!!vent keywords
!!
VVENT,2,1,1.08,2,1
MVENT,2,1,1,H,4.9,0.66,H,4.9,0.66,3.78,200,300,1
EVENT,M,2,1,1,540,0,1
!!
!!fire keywords
!!
OBJECT,FM SNL 5,1,12,6.1,0,1,1,0,0,0,1
```

Test 5, Fire Definition File

```
FM SNL 5
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,240,480000,0.01066667,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,540,480000,0.01066667,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,541,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.35
10000
1
1
0.25
4.5E+07
METHANE
```

Test 21, Input File

```
VERSN,6,FM Test 21
!!
!!Environmental Keywords
!!
TIMES,1800,-50,0,10,1
EAMB,288.15,101300,0
TAMB,288.15,101300,0,50
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Compartment 1,18.3,12.2,6.1,0,0,0,MariniteFM,ConcreteFM,MariniteFM
!!
!!vent keywords
!!
VVENT,2,1,1.08,2,1
MVENT,2,1,1,H,4.9,0.66,H,4.9,0.66,0.38,200,300,1
!!
!!fire keywords
!!
OBJECT,FM SNL 21,1,12,6.1,0,1,1,0,0,0,1
```

Test 21, Fire Definition File

```
FM SNL 21
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.1002,240,470000,0.01044444,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,1140,470000,0.01044444,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,1141,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.35
10000
1
1
0.25
4.5E+07
METHANE
```

B.6 NBS Test Series

Test MV100A, Input File

```
VERSN,6,"NBS Test MV100A, Open Corridor Door, No Target Room"
!!
!!Environmental Keywords
!!
TIMES,1500,-10,0,10,1
EAMB,296.15,101300,0
TAMB,296.15,101300,0,45
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Fire Room,2.34,2.34,2.16,9.85,0,0,CeramicNBS,FireBrickNBS,CeramicNBS
COMPA,Entry to Fire
Room,1.03,1.02,2,11.16,2.34,0,MariniteNBS,GypsumNBS,MariniteNBS
COMPA,Corridor,12.19,2.44,2.44,0,3.36,0,MariniteNBS,GypsumNBS,MariniteNBS
COMPA,Target Room,2.22,2.24,2.43,2.07,0.33,0,GypsumNBS,ConcreteNBS,GypsumNBS
COMPA,Entry to Target
Room,0.94,0.79,2.04,2.07,2.57,0,GypsumNBS,ConcreteNBS,GypsumNBS
!!
!!vent keywords
!!
HVENT,1,2,1,0.81,1.6,0,1,1.42,0,3,1
HVENT,2,3,1,0.81,1.6,0,1,0.11,0,3,1
HVENT,3,6,1,0.76,2.03,0,1,0.84,0,4,1
HVENT,3,5,1,0.79,2.04,0,1,2.14,0,1,0
HVENT,4,5,1,0.79,2.04,0,1,0.075,0,3,0
!!
!!fire keywords
!!
OBJECT,NBS MV100A,1,1.17,0,0,1,1,0,0,0,1
```

Test MV100A, Fire Definition File

```
NBS MV100A
4,0,0,0,0,0.1156,0,0,0.07,0,0,0,0
0.016,10,110000,0.0022,0,0.1156,0,0,0.07,0,0,0,0
493,890,110000,0.0022,0,0.1156,0,0,0.07,0,0,0,0
300,900,0,0,0,0.1156,0,0,0.07,0,0,0,0
0
0.2
5
0.4
0.4
0.65
```

```
5E+07
METHANE
```

Test MV100O, Input File

```
VERSN,6,"NBS Test MV100O, Closed Corridor Door, No Target Room"
!!
!!Environmental Keywords
!!
TIMES,1500,-10,0,10,1
EAMB,293.15,101300,0
TAMB,293.15,101300,0,45
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Fire Room,2.34,2.34,2.16,9.85,0,0,CeramicNBS,FireBrickNBS,CeramicNBS
COMPA,Entry to Fire
Room,1.03,1.02,2,11.16,2.34,0,MariniteNBS,GypsumNBS,MariniteNBS
COMPA,Corridor,12.19,2.44,2.44,0,3.36,0,MariniteNBS,GypsumNBS,MariniteNBS
COMPA,Target Room,2.22,2.24,2.43,2.07,0.33,0,GypsumNBS,ConcreteNBS,GypsumNBS
COMPA,Entry to Target
Room,0.94,0.79,2.04,2.07,2.57,0,GypsumNBS,ConcreteNBS,GypsumNBS
!!
!!vent keywords
!!
HVENT,1,2,1,0.81,1.6,0,1,1.42,0,3,1
HVENT,2,3,1,0.81,1.6,0,1,0.11,0,3,1
HVENT,3,6,1,0.76,2.44,2.43,1,0.84,0,4,1
HVENT,3,5,1,0.79,2.04,0,1,2.14,0,1,0
HVENT,4,5,1,0.79,2.04,0,1,0.075,0,3,0
!!
!!fire keywords
!!
OBJECT,NBS MV100O,1,1.17,0,0,1,1,0,0,0,1
```

Test MV100O, Fire Definition File

```
NBS MV100O
4,0,0,0,0,0.1156,0,0,0.07,0,0,0,0
0.016,10,110000,0.0022,0,0.1156,0,0,0.07,0,0,0,0
493,890,110000,0.0022,0,0.1156,0,0,0.07,0,0,0,0
300,900,0,0,0,0.1156,0,0,0.07,0,0,0,0
0
0.3
5
0.4
0.4
0.65
5E+07
METHANE
```

Test MV100Z, Input File

```
VERSN,6,"NBS Test MV100Z, Open Corridor Door, Open Target Room"
!!
!!Environmental Keywords
!!
TIMES,1500,-10,0,10,1
EAMB,295.15,101300,0
TAMB,295.15,101300,0,62
LIMO2,10
WIND,0,10,0.16
CJET,WALLS
!!
!!Compartment keywords
!!
COMPA,Fire Room,2.34,2.34,2.16,9.85,0,0,CeramicNBS,FireBrickNBS,CeramicNBS
COMPA,Entry to Fire
Room,1.03,1.02,2,11.16,2.34,0,MariniteNBS,GypsumNBS,MariniteNBS
COMPA,Corridor,12.19,2.44,2.44,0,3.36,0,MariniteNBS,GypsumNBS,MariniteNBS
COMPA,Target Room,2.22,2.24,2.43,2.07,0.33,0,GypsumNBS,ConcreteNBS,GypsumNBS
COMPA,Entry to Target
Room,0.94,0.79,2.04,2.07,2.57,0,GypsumNBS,ConcreteNBS,GypsumNBS
!!
!!vent keywords
!!
HVENT,1,2,1,0.81,1.6,0,1,1.42,0,3,1
HVENT,2,3,1,0.81,1.6,0,1,0.11,0,3,1
HVENT,3,6,1,0.76,2.03,0,1,0.84,0,4,1
HVENT,3,5,1,0.79,2.04,0,1,2.14,0,1,1
HVENT,4,5,1,0.79,2.04,0,1,0.075,0,3,1
!!
!!fire keywords
!!
OBJECT,NBS MV100Z,1,1.17,0,0,1,1,0,0,0,1
```

Test MV100Z, Fire Definition File

```
NBS MV100Z
4,0,0,0,0,0.1156,0,0,0.07,0,0,0,0
0.016,10,110000,0.0022,0,0.1156,0,0,0.07,0,0,0,0
493,890,110000,0.0022,0,0.1156,0,0,0.07,0,0,0,0
300,900,0,0,0,0.1156,0,0,0.07,0,0,0,0
0
0.3
5
0.4
0.4
0.65
5E+07
METHANE
```