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

Volume 4:
Consolidated Fire Growth and Smoke Transport Model (CFAST)

January 2006

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

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ABSTRACT

There is a movement to introduce risk- 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.

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 U.S. Nuclear Regulatory Commission (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 nuclear fire protection community wants to use risk-informed, performance-based (RI/PB) approaches and insights to support fire protection decision-making in general.

One key tool needed to support 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. Further, 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 *Standard E1355-04, “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.

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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

Over the past decade, there has been a considerable movement in the nuclear power industry to transition from prescriptive rules and practices towards the use of risk information to supplement decision-making. In the area of fire protection, this movement is evidenced by numerous initiatives by the U.S. Nuclear Regulatory Commission (NRC) and the nuclear community worldwide. 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 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 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

The objective of this project is to examine the predictive capabilities of selected fire models. These models may be used to demonstrate compliance with the requirements of 10 CFR 50.48(c) and the referenced NFPA 805, or support other performance-based evaluations in NPP fire protection applications. In addition to NFPA 805 requiring that only verified and validated fire models acceptable to the AHJ be used, the standard also requires that fire models only be applied within their limitations. The V&V of specific models is important in establishing acceptable uses and limitations of fire models. Specific objectives of this project are:

- Perform V&V study of selected fire models using a consistent methodology (ASTM E1355) and issue a report to be prepared by U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research (RES) and Electric Power Research Institute (EPRI).
- Investigate the specific fire modeling issues of interest to the NPP fire protection applications.
- Quantify fire model predictive capabilities to the extent that can be supported by comparison with selected and available experimental data.

The following fire models were selected for this evaluation: (i) NRC's NUREG-1805 Fire Dynamics Tools (FDT^{S}), (ii) EPRI's Fire-Induced Vulnerability Evaluation Revision 1 (FIVE-Rev. 1), (iii) National Institute of Standards and Technology's (NIST) Consolidated Model of Fire Growth and Smoke Transport (CFAST), (iv) Electricite de France's (EdF) MAGIC, and (v) NIST's Fire Dynamics Simulator (FDS).

Approach

This program is based on the guidelines of the ASTM E1355, "Evaluating the Predictive Capability of Deterministic Fire Models," for verification and validation of the selected fire models. The guide provides four areas of evaluation:

- Defining the model and scenarios for which the evaluation is to be conducted,
- Assessing the appropriateness of the theoretical basis and assumptions used in the model,
- Assessing the mathematical and numerical robustness of the model, and
- Validating a model by quantifying the accuracy of the model results in predicting the course of events for specific fire scenarios.

Traditionally, a V&V study reports the comparison of model results with experimental data, and therefore, the V&V of the fire model is for the specific fire scenarios of the test series. While V&V studies for the selected fire models exist, it is necessary to ensure that technical issues specific to the use of these fire models in NPP applications are investigated. The approach below was followed to fulfill this objective.

1. A set of fire scenarios were developed. These fire scenarios establish the "ranges of conditions" for which fire models will be applied in NPPs.
2. The next step summarizes the same attributes or "range of conditions" of the "fire scenarios" in test series available for fire model benchmarking and validation exercises.
3. Once the above two pieces of information were available, the validation test series, or tests within a series, that represent the "range of conditions" was mapped for the fire scenarios developed in Step 1. The range of uncertainties in the output variable of interest as predicted by the model for a specific "range of conditions" or "fire scenario" are calculated and reported.

The scope of this V&V study is limited to the capabilities of the selected fire models. There are potential fire scenarios in NPP fire modeling applications that do not fall within the capabilities of these fire models and therefore are not covered by this V&V study.

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 important to NPP fire modeling applications, e.g., plume temperature. The relative differences sometimes show agreement, but may also show both under-prediction and over-prediction. These relative differences are affected by the capabilities of the models, the availability of accurate applicable experimental data, and the experimental uncertainty of this data. The relative differences were used, 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 the 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 due to a combination of model capability and lack of relevant experimental data. The first can be addressed by improving the fire models while the second needs more applicable fire experiments.

EPRI Perspective

The use of fire models to support fire protection decision-making requires that their limitations and confidence in their predictive capability is well understood. While this report makes considerable progress towards that 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 present challenges that should be addressed if the fire protection community is to realize the full benefit of fire modeling and performance-based fire protection. This requires both short term and long term solutions. In the short term a methodology will be to educate the users on how the results of this work may affect known applications of fire modeling. This may be accomplished through pilot application of the findings of this report and documentation of the insights as they may influence decision-making. Note that the intent is not to describe how a decision is to be made, but rather to offer insights as to where and how these results may, or may not be used as the technical basis for a decision. In the long term, additional work on improving the models and performing additional experiments should be considered.

Keywords

Fire
Performance-based
Fire safety
Fire Probabilistic Risk Assessment (PRA)
Fire Modeling
Risk-informed regulation
Fire protection
Verification and Validation (V&V)
Fire Hazard Analysis (FHA)
Nuclear Power Plant
Fire Probabilistic Safety Assessment (PSA)

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. Volumes 2 through 6 provide detailed discussions of the verification and validation (V&V) of the following five fire models:

Volume 2	Fire Dynamics Tools (FDT^{s})
Volume 3	Fire-Induced Vulnerability Evaluation, Revision 1 (FIVE-Rev1)
Volume 4	Consolidated Model of Fire Growth and Smoke Transport (CFAST)
Volume 5	MAGIC
Volume 6	Fire Dynamics Simulator (FDS)

Finally, Volume 7 quantifies the uncertainty of the experiments used in the V&V study of these five fire models.

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 Part50; 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 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 E1355-04, "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 RES 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 of which provided specialists in the use of fire models and other FHA tools. 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, and they may also help to identify areas where further research and analysis are needed.

Carl J. Paperiello, Director
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The verification and validation (V&V) studies for FDT^s (Volume 2), CFAST (Volume 4), and FDS (Volume 6) 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 contribution to Volume 2.

In addition, we acknowledge and appreciate the extensive contributions of Electricité de France (EdF) in preparing Volume 5 for MAGIC.

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 fuer Anlagen-und Reaktorsicherheit (GRS) and Institut fuer 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. 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
CFAST	Consolidated Fire Growth and Smoke Transport Model
CFR	*Code of Federal Regulations*
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 fuer Anlagen-und Reaktorsicherheit (Germany)
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
MCC	Motor Control Center
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)
RES	Office of Nuclear Regulatory Research (NRC)
RI/PB	Risk-Informed, Performance-Based
SDP	Significance Determination Process
SFPE	Society of Fire Protection Engineers
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 NIST's Technical Reference Guide and ASTM E 1355.

Consistent with NIST's Technical Reference Guide and ASTM E1355, 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 required by ASTM E1355 [Ref. 2]. The definitive description of the CFAST model, including its developers, equations, assumptions, inputs, and outputs can be found in NIST's Technical Reference Guide [Ref. 1], which also follows the guidelines for ASTM E1355.

2.1 Name and Version of the Model

This V&V study focused on version 6.0.5 of the Consolidated Fire Growth and Smoke Transport (CFAST) Model. Most of the code is written in FORTRAN 90. Chapter 2 of NIST's Technical Reference Guide [Ref. 1] provides a more detailed description of the evolution of CFAST.

2.2 Type of Model

The CFAST zone model is an example of the "finite element" class of fire models. This two-zone fire model is capable of predicting the fire-induced environmental conditions as a function of time for single- or multi-compartment scenarios. Toward that end, CFAST subdivides each compartment into two zones (or volumes) in order to numerically solve differential equations, and the two volumes are assumed to be homogeneous within each zone. 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.

2.3 Model Developers

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

2.4 Relevant Publications

Relevant publications concerning the CFAST model include NIST's 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 NIST's 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 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.

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

NIST's User's Guide [Ref. 3] provides a complete description of the required input parameters.

2.7 Property Data

A number of material properties are needed as inputs for CFAST, related either 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. This data is given as an example, and users should verify the accuracy and appropriateness of the data.

2.8 Model Results

Once the simulation run is complete, the CFAST model 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

3
THEORETICAL BASIS FOR CFAST

This chapter presents a technical description of the CFAST model, including 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 E1355 requirement to “verify the appropriateness of the theoretical basis and assumptions used in the model.”

Chapter 3 of NIST’s 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 Ref 1 derives the predictive equations for zone fire models and presents a detailed explanation of those used in the CFAST model [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, 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.

The most important assumption for the model is that 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. NIST’s Technical Reference Guide for CFAST [Ref. 1] provides a detailed discussion concerning the specific derivation of these conservation laws.

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:

- combustion and flame spread
- 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

3.2 Limitations of the 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 the exception that the fire room has an additional zone for the plume. Since a real-world upper/lower interface is not as sharply defined as the one modeled by CFAST, the model has a spatial error of about 10 percent in determining the height of the hot gas layer [Refs. 6 and 11].

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. Therefore, users should recognize approximate limits on the ratio of the length (L), width (W), and height (H) of the compartment.

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.

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

The user must define fire growth since CFAST does not include a pyrolysis 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.

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 NIST's Technical Reference Guide [Ref. 1].

3.3.3 Ceiling Jet

CFAST uses Cooper's correlation [Ref. 10] 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. However, the current version of the model does not output ceiling jet temperatures. Complete details are available in Ref. 10.

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. 11] 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. 12] 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 NIST's Technical Reference Guide [Ref. 1].

The model for mechanical ventilation used in CFAST is based on the model developed by Klote [Ref. 13]. This is a simplified form of Kirchoff's law, which states that flow into a node must be balanced by flow out of the node. NIST's 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. NIST's 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 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. 14].

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. 19].

3.3.5.3 Conduction

CFAST uses a finite difference scheme from Moss and Forney [Ref. 20], 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 3.3.6.1. 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 modeled components of heat flux to a target are fires, 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. 21] with temperatures obtained from the ceiling jet calculation [Ref. 10]. 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. 22], which is generalized for varying sprinkler spray densities according to Evans [Ref. 23].
The suppression correlation was developed by modifying the heat release rate of a fire. NIST's Technical Reference Manual [Ref. 1] outlines the assumptions and limitations of this approach.

3.3.9 Species Concentration and Deposition

CFAST uses a combustion chemistry scheme 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 % or parts per million (ppm) as appropriate.

CFAST contains a special additional algorithm for hydrogen chloride, which 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. 25, 26, and 27], and conference proceedings [Ref. 28]. 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. 29], and referenced in specific standards including NFPA 805 [Ref. 30] and NFPA 551 [Ref. 31].

3.4.1 Assessment of the Completeness of Documentation

The two primary documents on CFAST are NIST's 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 E1355 [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 since 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 E1355 requires 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

General analytic solutions do not exist for fire dynamics problems, even for the simplest cases. That is, there are no closed form solutions to this type of problem. However, two 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 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. Since 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]

NIST's Technical Reference Guide [Ref. 1] contains a detailed description of the CFAST subroutine structure and interactions between the subroutines.

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 users interface to improve object plotting, the target flux calculation, and error checking for elements located outside a compartment. The updated version of CFAST used in this study is 6.0.5 and 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. 32]. 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 sensitivity analysis, which ASTM E1355 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 E1355 [Ref. 2] provides overall guidance on typical areas of evaluation of the sensitivity of deterministic fire models. Chapter 5 of NIST's 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 Refs. 33, 34, and 35. In addition, NIST's 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.

6
MODEL VALIDATION

This chapter summarizes the results of the validation study conducted for the model CFAST. 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 7 and in the individual test reports.

ICFMP BE #2: Benchmark Exercise #2 consists of 8 experiments, representing 3 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 by 27 m long by 14 m wide. Each case involved a single heptane pool fire, ranging from 2 MW to 4 MW. All three cases, representing averaged results from the 8 tests, have been used in the current V&V effort.

ICFMP BE #3: Benchmark Exercise #3, conducted as part of the International Collaborative Fire Model Project (ICFMP) and sponsored by the US 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 x 7.1 m x 3.8 m, designed to represent a variety of spaces in a NPP containing power and control cables. Walls and ceiling were covered with two layers of 25 mm thick marinate boards, while the floor was covered with two layers of 25 mm thick gypsum boards. The room has one 2 m x 2 m door 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 International Collaborative Fire Model Project (ICFMP). These fire experiments involve relatively large fires in a relatively small (3.6 m x 3.6 m x 5.7 m high) 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. Only one test (Test 4) was selected for the present evaluation, and only the first 20 min during which time an ethanol pool fire pre-heats 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 three of these tests have been used in the present evaluation (Tests 4, 5 and 21). Test 21 involves the full-scale mock-up. All are 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 for the current V&V study, only three 100 kW fire experiments have been used (Test 100A, 100O, and 100Z).

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.

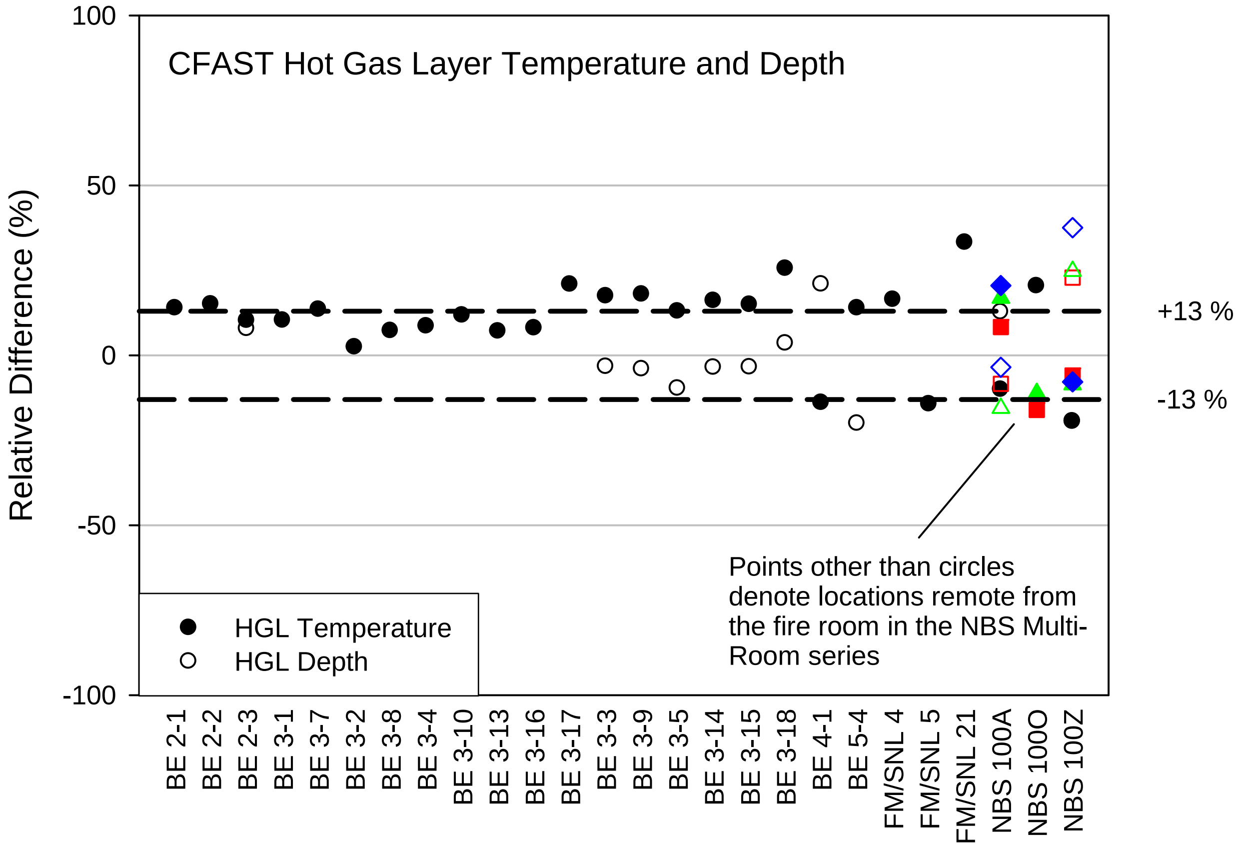
The measure of model "accuracy" used throughout this study is related to experimental uncertainty. Volume 7 discusses this issue in detail. In brief, the accuracy of a *measurement*, *e.g.* the gas temperature, is related to the measurement device, *e.g.* a thermocouple. In addition, the accuracy of 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 is 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 yard stick. If the numerical prediction falls within the range of uncertainty due 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 ell 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 height of the HGL 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 hot gas layer 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 summarizes 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 in 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.



Points other than circles denote locations remote from the fire room in the NBS Multi-Room series

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

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 3 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 s. 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.

<u>ICFMP BE #5</u>: 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 due to the complicated geometry within the compartment that includes a partial height wall that effects both plume entrainment and radiative heat transfer from the fire to surroundings.

<u>FM/SNL</u>: 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 due to 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.

<u>NBS Multi-Room</u>: 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 due 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 due 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. This is based on the results of a single test series however.

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. However, the ceiling jet temperature is not directly calculated nor reported in a CFAST calculation. For this reason, comparisons of experimentally measured ceiling jet temperatures with CFAST calculations are not appropriate and will not be included in this report.

6.3 Plume Temperature

CFAST includes a plume entrainment algorithm based on the work of McCaffrey that 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 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). From the CFAST calculations, the estimated flame height is 4.3 m.

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

- CFAST predicts the flame height consistent with visual observations of flame height for the experiments. This is not surprising since 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 (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.

Gas sampling data is available from ICFMP BE #3 and BE #5 (one test only). Figure 6-2 summarizes the relative difference for all of the tests.

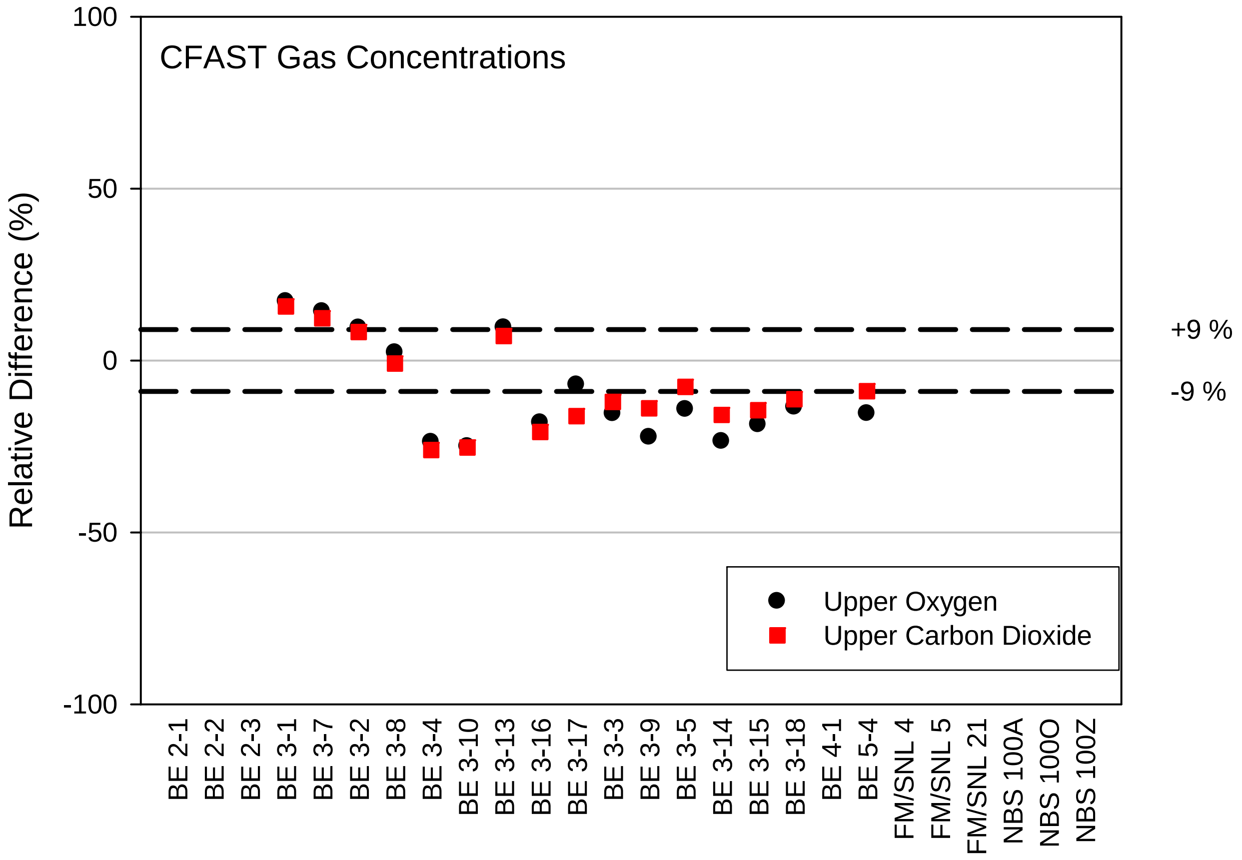


Figure 6-2. Relative Differences for Oxygen Concentration and Carbon Dioxide Concentration

ICFMP BE #3: CFAST predicts the upper layer concentrations of oxygen and carbon dioxide close to experimental uncertainty. For closed door tests 4 and 10, and for open door tests 9 and 14, the magnitude of relative difference is higher, under predicting by 22 % to 25 % (Figure 6-2 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 due to 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, basically a tracer gas whose mass fraction is dependent on a user-specified species yield. To model smoke movement, the user need only prescribe the smoke yield, that is, the fraction of the fuel mass that is converted to smoke particulate. Figure 6-3 summarizes the relative difference for all of the tests.

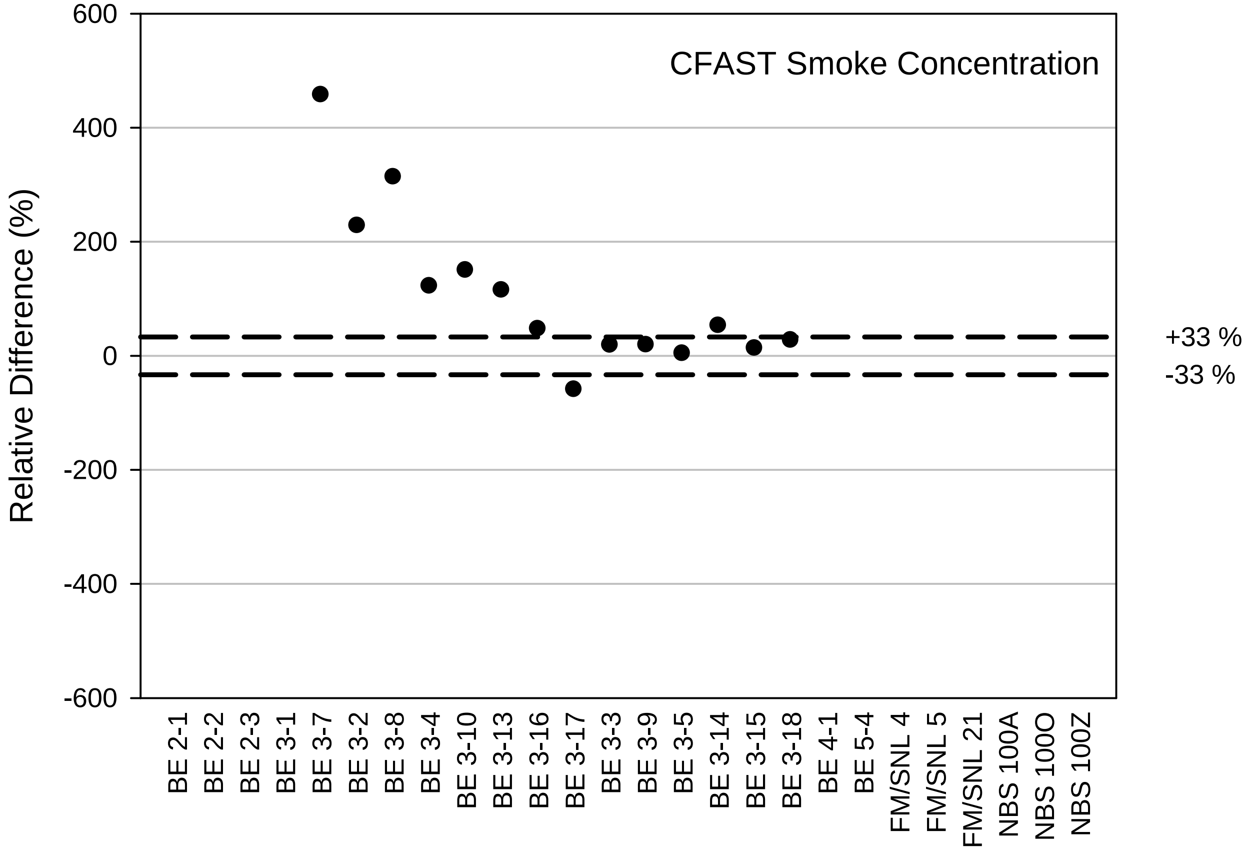


Figure 6-3. Relative Differences for Smoke Concentration

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 45 % (see Volume 7). 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 6).

Summary: 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 that 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 one 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 Appendix A.7. Figure 6-4 summarizes the relative difference for all of the tests.

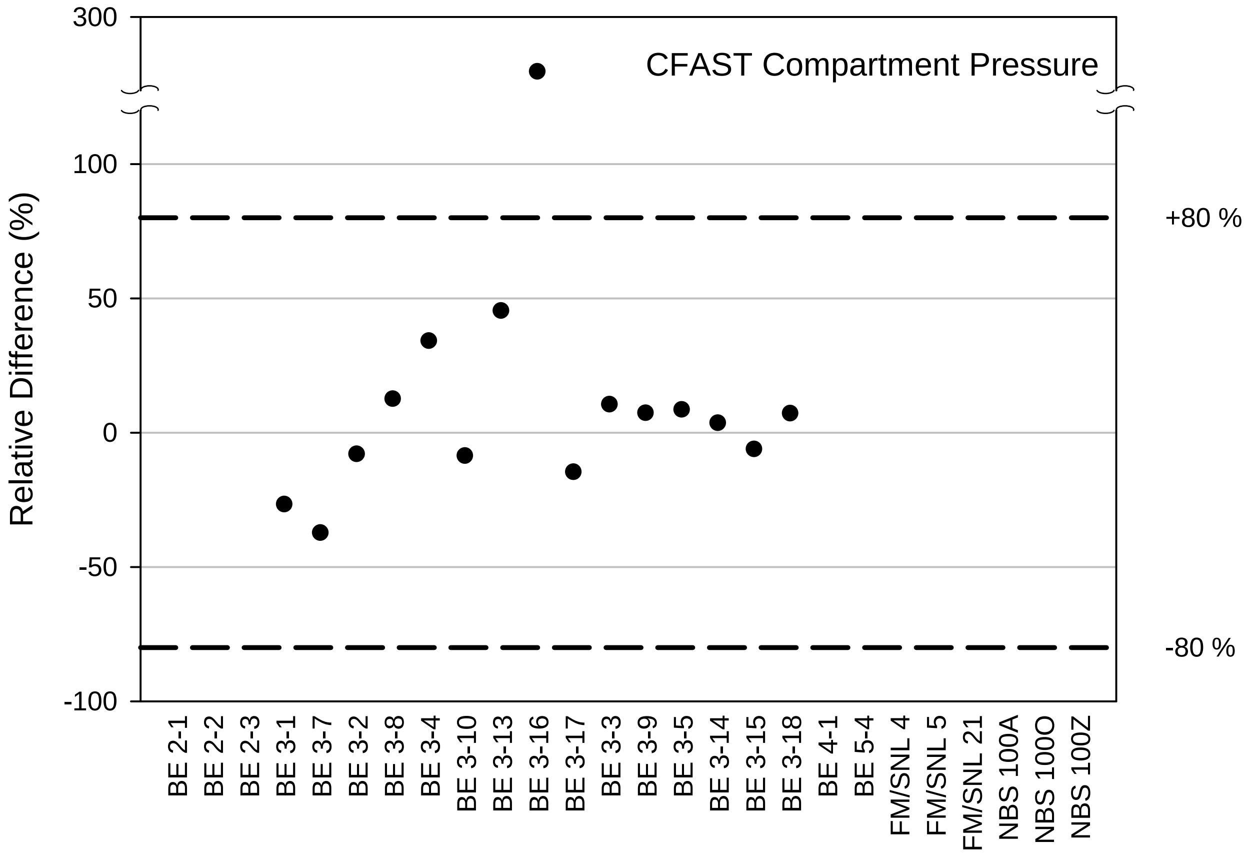


Figure 6-4. Relative Differences for Compartment Pressure

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. For both the open and closed door tests, CFAST predicts the pressure to within experimental uncertainty. The one notable exception is Test 16 (Figure 6-3 and Table A-3). This experiment was a large fire performed with the door closed and the ventilation on. Test 16 is a 2.3 MW fire, whereas Test 10, with a comparable geometry and ventilation is a 1.2 MW fire. There is considerable uncertainty in the magnitude of both the supply and return mass flow rates for test 16. The measured supply velocity is greater and the measured exhaust velocity is less in Test 10, compared to Test 16. 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 also is 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 totally 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, compartment pressures are predicted within experimental uncertainty.
- Prediction of compartment pressure for closed door tests is critically dependent on correct specification of the leakage from the compartment.

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 6-5 through Figure 6-7 summarizes the relative difference for all of the tests.

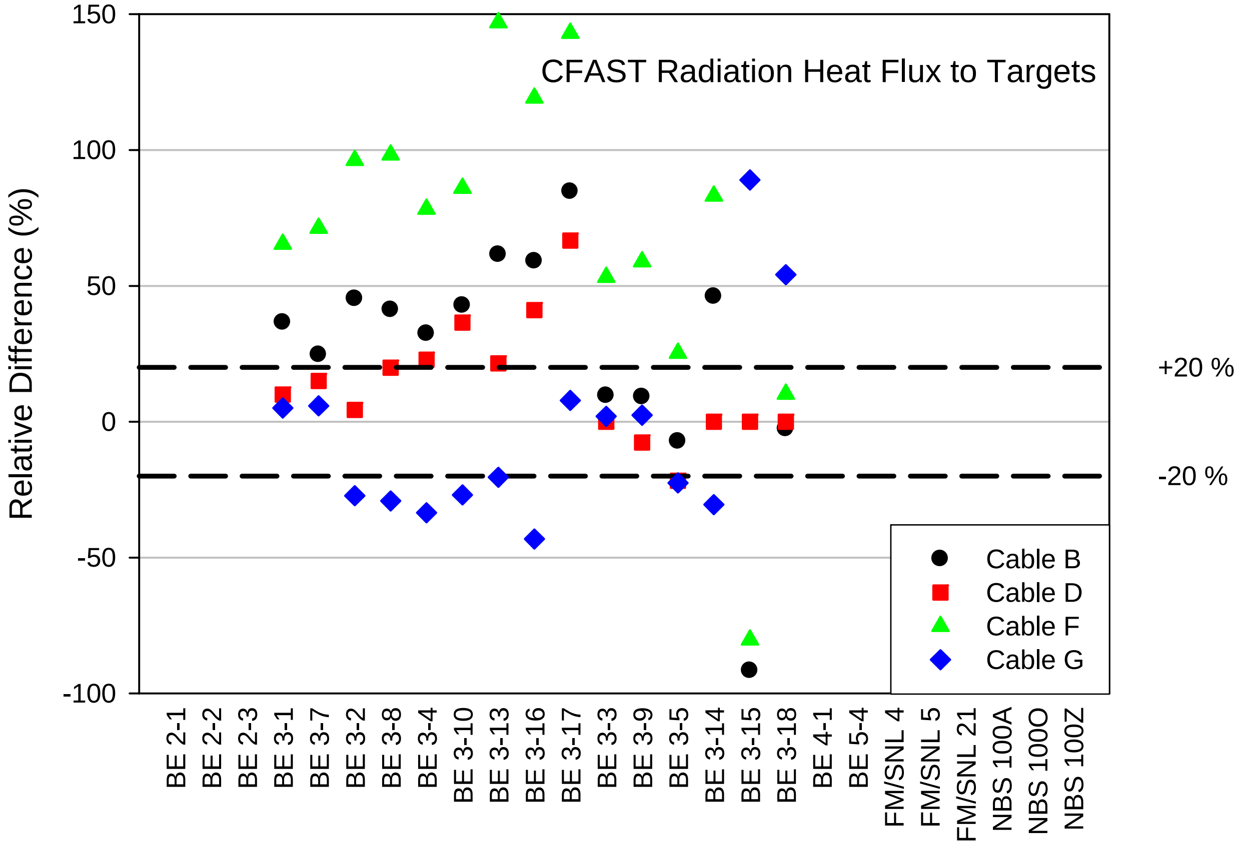


Figure 6-5. Relative Differences for Radiation to Targets

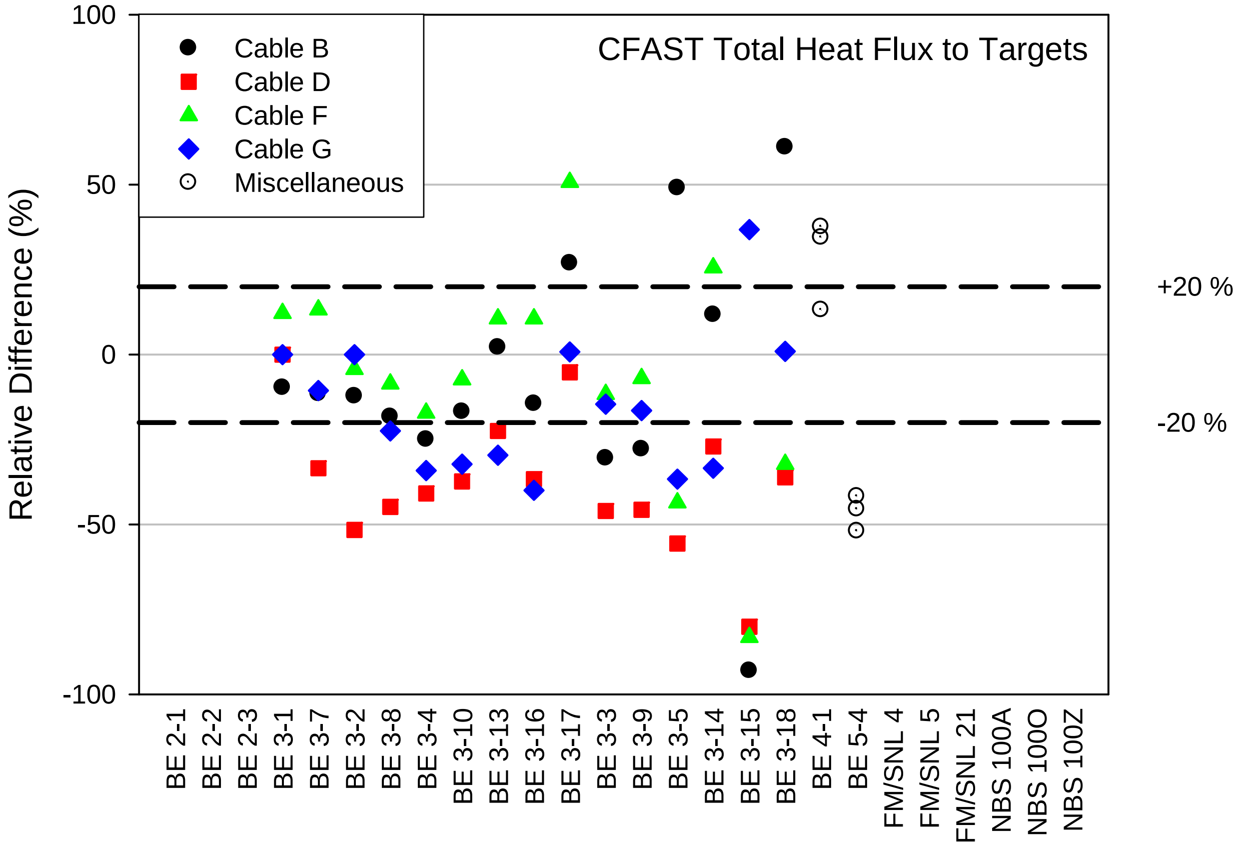


Figure 6-6. Relative Differences for Total Heat Flux to Targets

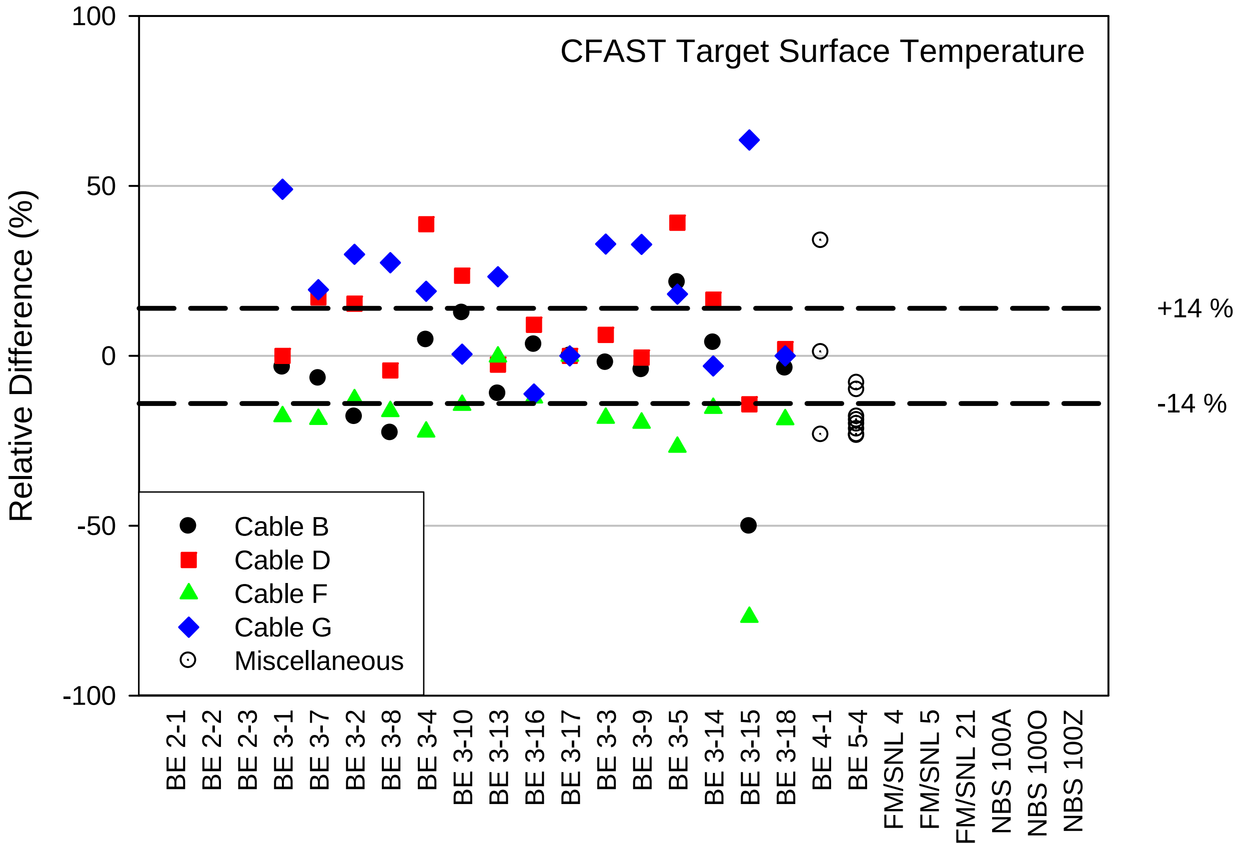


Figure 6-7. Relative Differences for Target Temperature

ICFMP BE #3: There are nearly 200 comparisons of heat flux and surface temperature on four different cables that are graphed in the Appendix. It is difficult to make sweeping generalizations about the accuracy of CFAST. At best, one can scan the figures and the associated tables to get a sense of the overall performance. A few trends to note:

- 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 about 30 %, and often under-predicted. Predictions for cable D and cable 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 typically-measured values in fire experiments.

ICFMP BE #4: CFAST over-predicts both the heat flux and surface temperature of three "slab" targets located about 1 m 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 the differences for the 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 hard to make 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:

- 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, plus wall surface temperature measurements are available from BE #4 and BE #5. As with target heat flux and surface temperature above, there are numerous comparisons. Figure 6-8 and Figure 6-9 summarizes the relative difference for all of the tests.

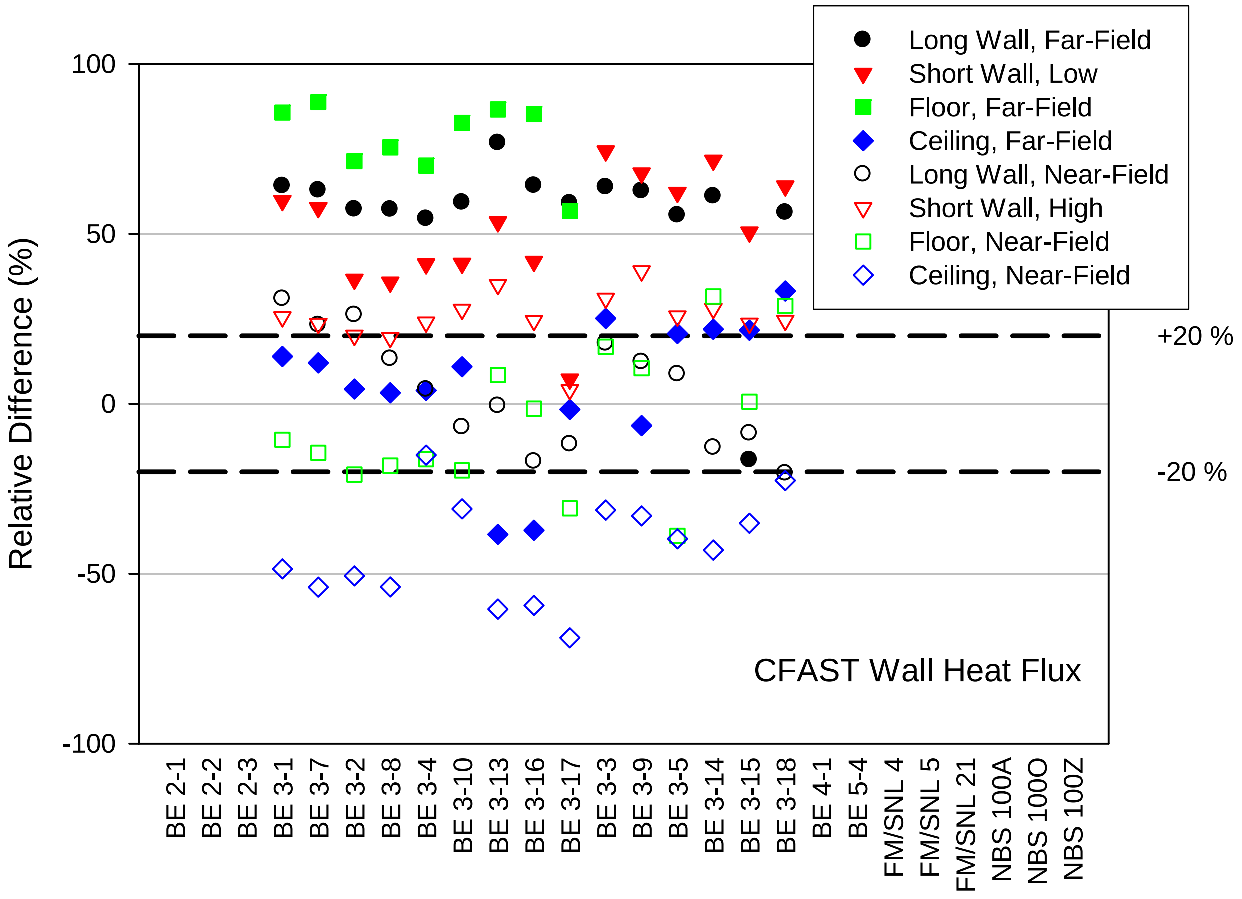


Figure 6-8. Relative Differences for Surface Heat Flux

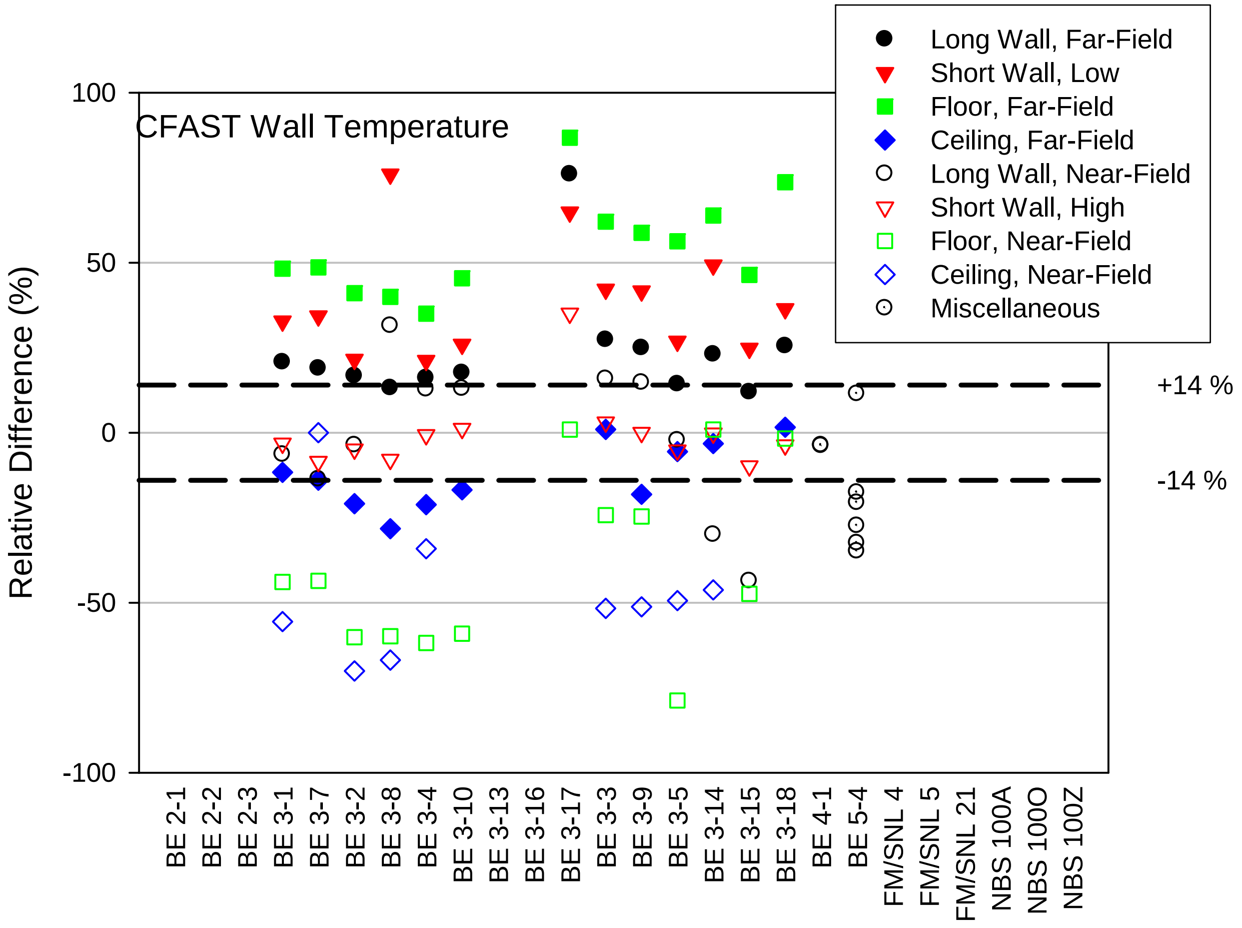


Figure 6-9. Relative Differences for Surface Temperature

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 since 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 the 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 3-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 worse 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 was under-predicted by nearly 70 % (Figure 6-9 and Table A-6). The two points are presumably very close to the fire because the temperatures are 600 °C to 700 °C 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 about more than 50 % (Figure 6-9 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. Only one test from this series has been used in the evaluation, thus, it is hard to make any firm conclusions.

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 due to 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: No color assigned
- 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 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. 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.

- CFAST predicts the flame height consistent with visual observations of flame height for the experiments. This is not surprising since 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 the user should take caution when using the model to evaluate that quantity. This typically indicates limitations in the use of the model. A few notes on the comparisons are appropriate:

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

- With exceptions, cable surface temperatures are predicted 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 the prediction of localized conditions such as target temperature and heat flux due to 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.

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.

CFAST predictions in this validation study were consistent with numerous earlier studies that show 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 of the inputs provided to do the calculations.

7

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A

TECHNICAL DETAILS OF CFAST VALIDATION STUDY

Appendix A 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 7 includes 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 apart in the lower two-thirds of the hall, and 1 m apart near the ceiling. Figure A-1 presents a snapshot from one of the simulations.

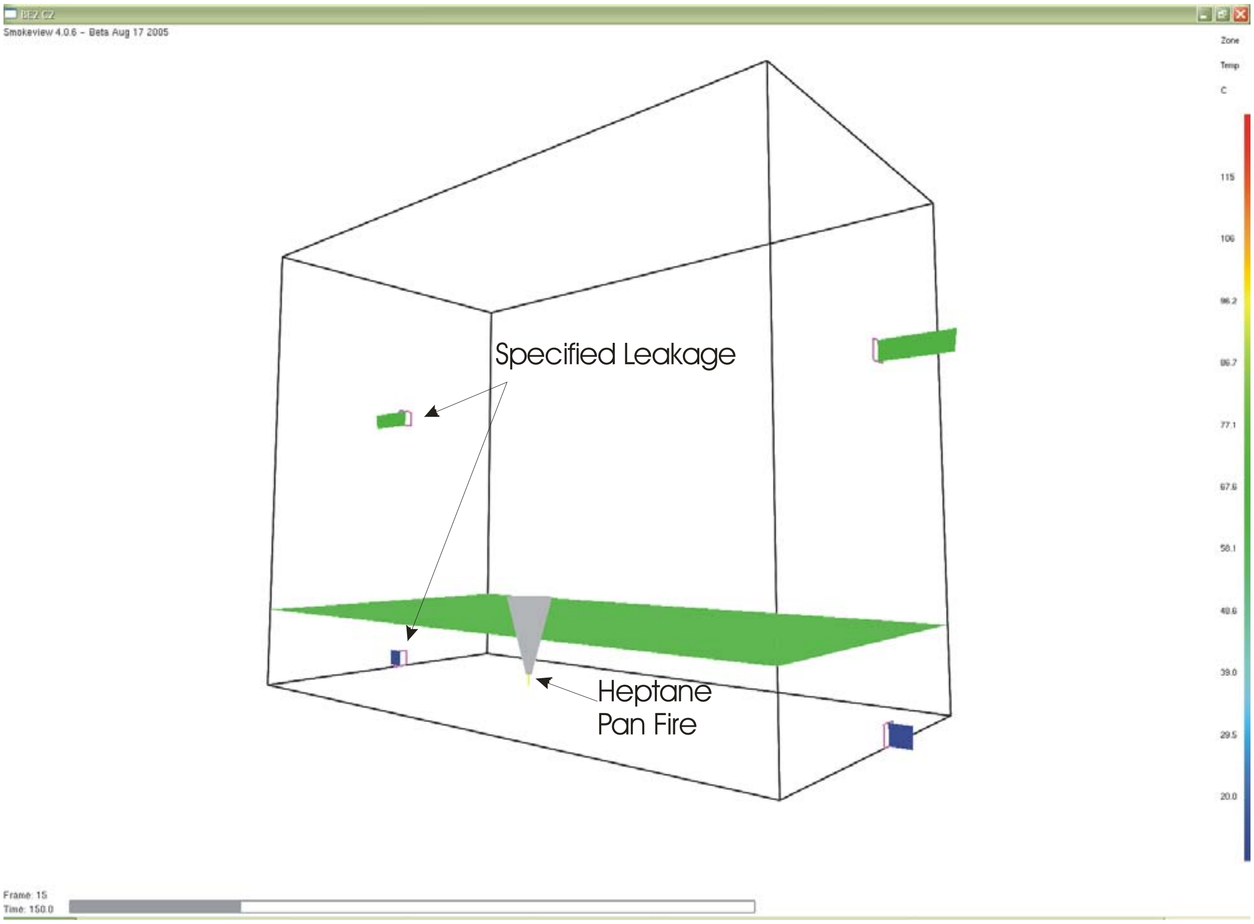


Figure A-1. Cut-away view of the simulation of ICFMP BE #2, Case 2.

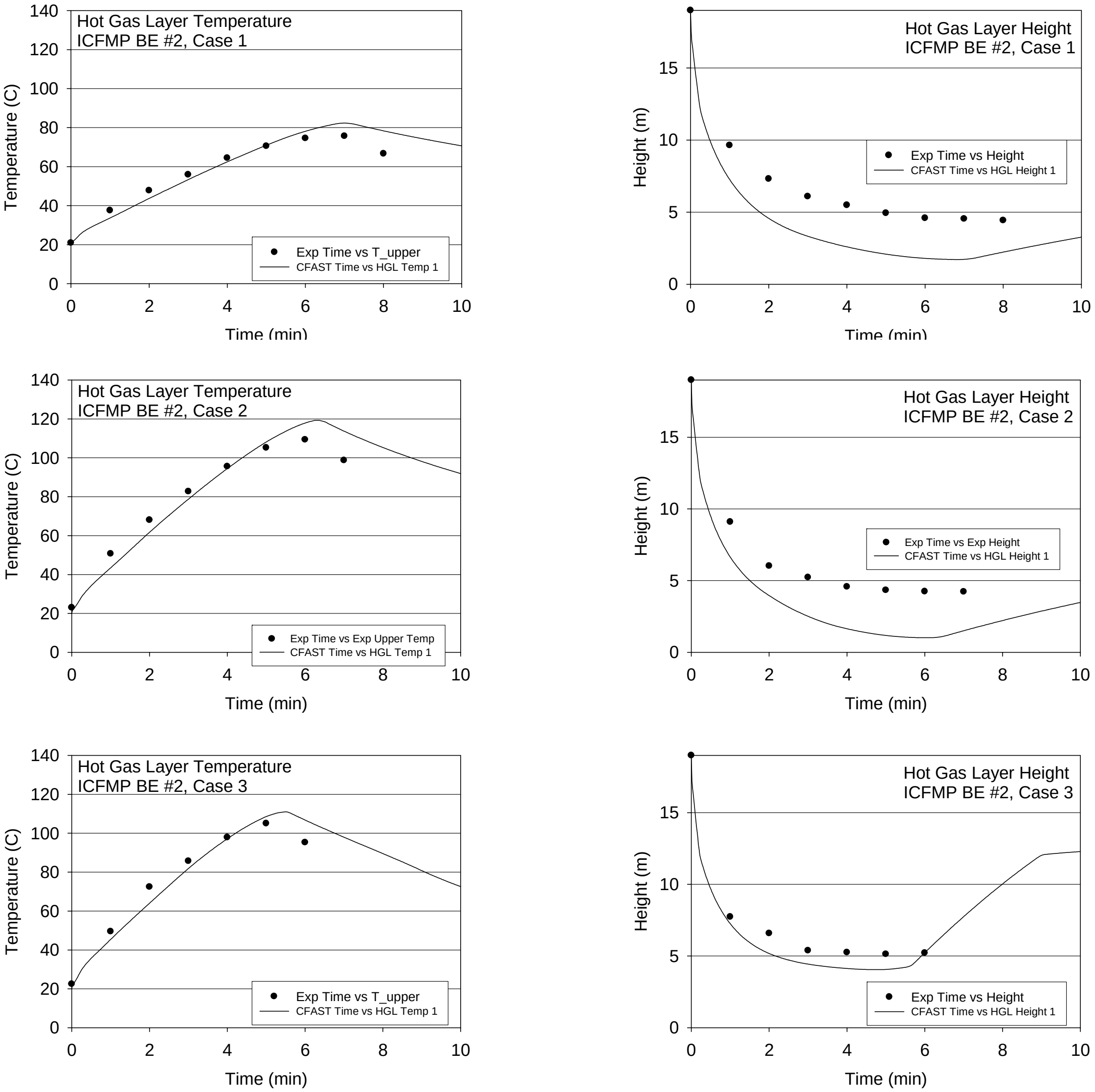


Figure A-2. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #2.

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, plus the 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 hot gas layer 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.

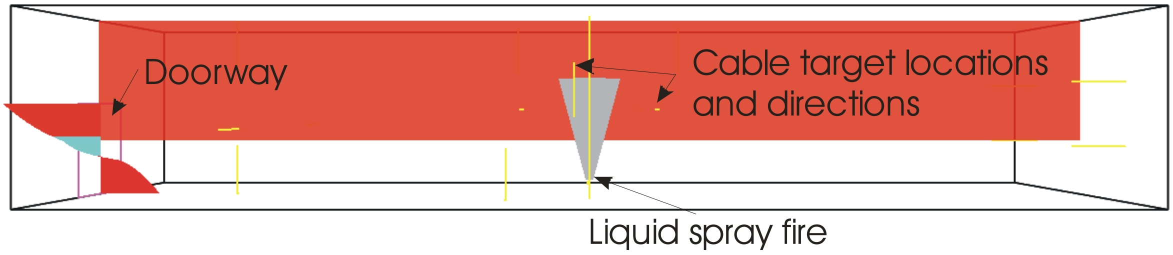


Figure A-3. Snapshot of simulation of ICFMP BE #3, Test 3.

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.

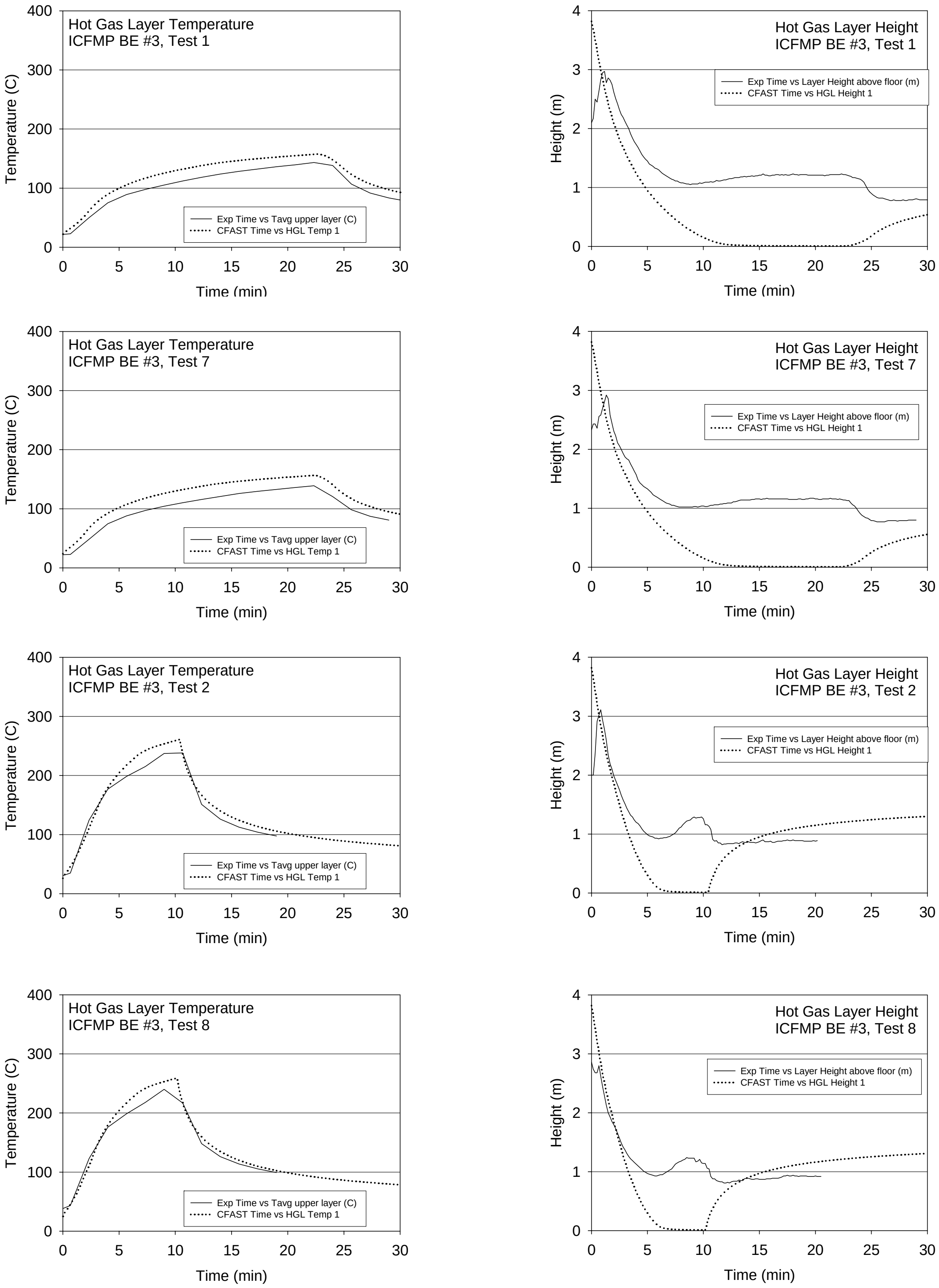


Figure A-4. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #3, closed door tests.

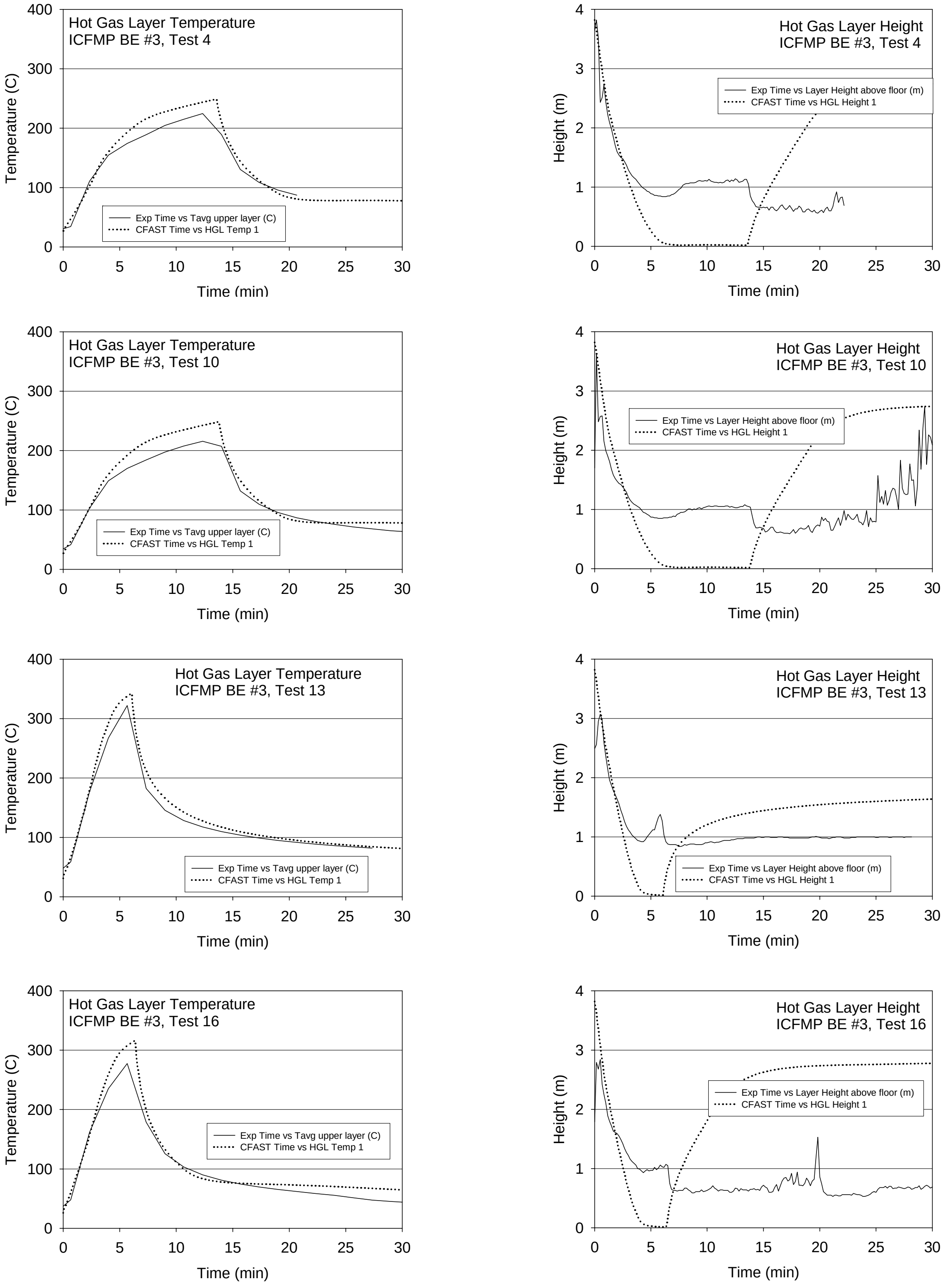
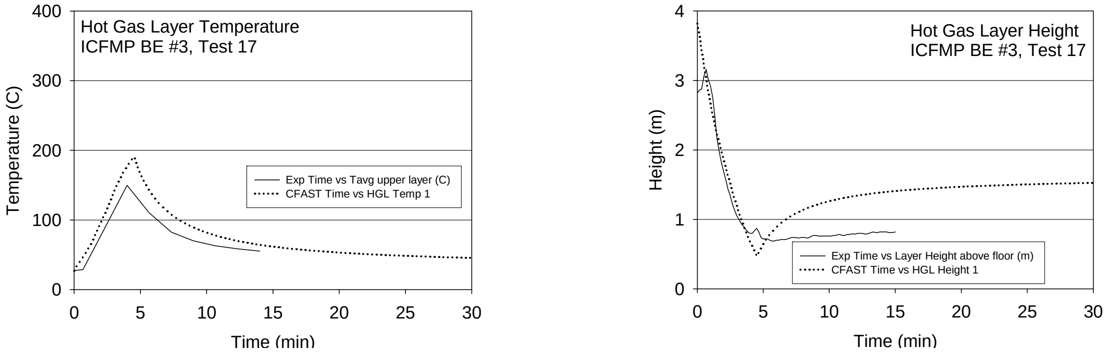


Figure A-5. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #3, closed door tests.



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

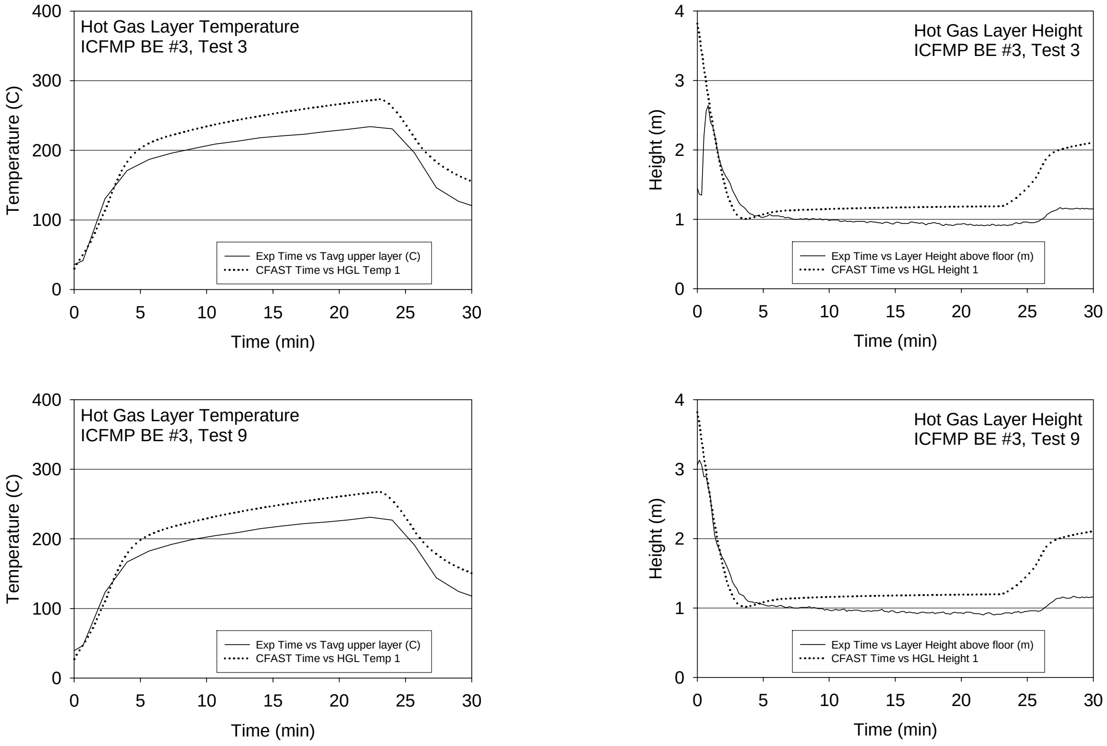


Figure A-6. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #3, open door tests.

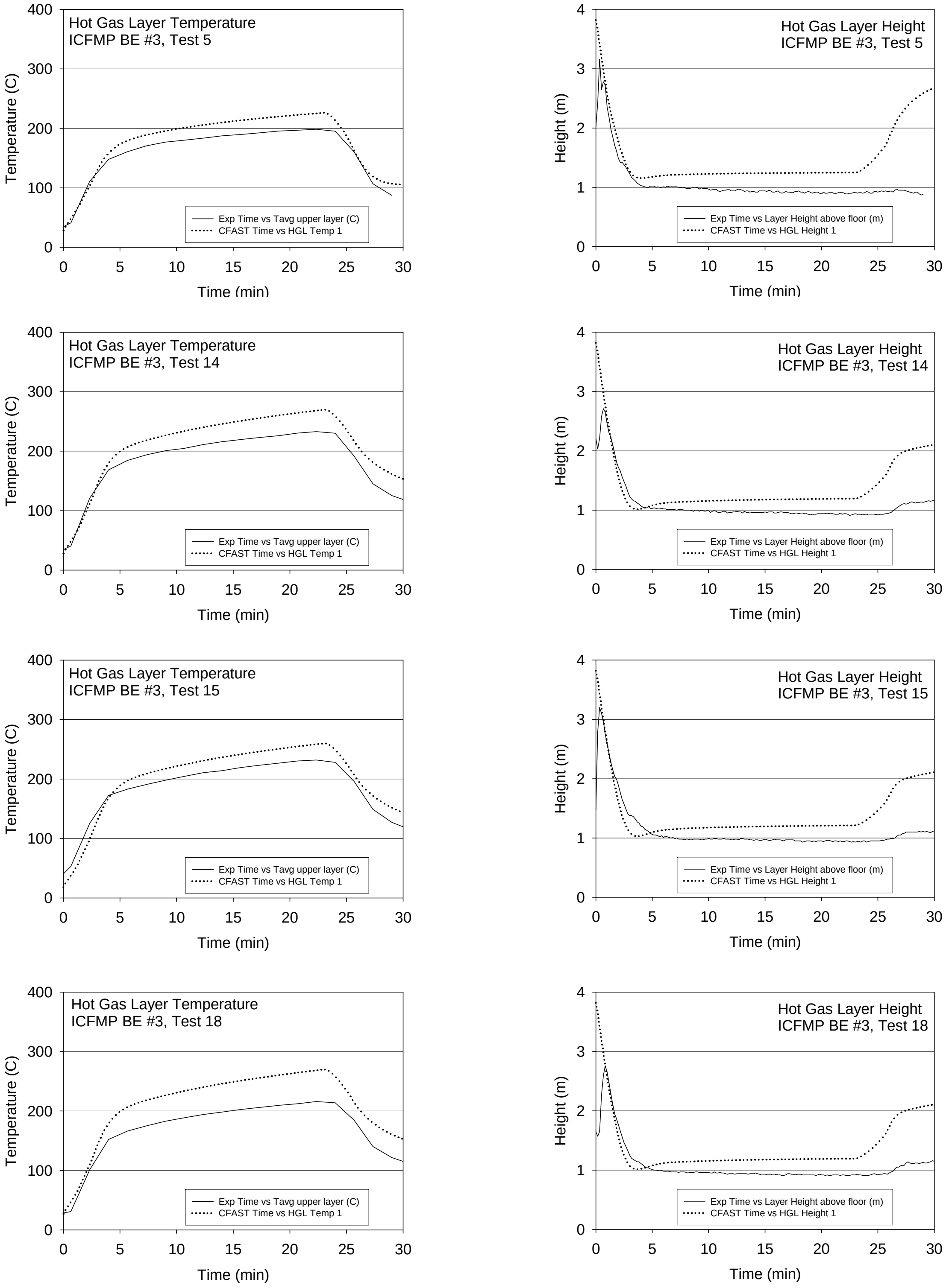


Figure A-7. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #3, open door tests.

ICFMP BE # 4

ICFMP BE # 4 consisted of two experiments, of which one was chosen for validation, Test 1. Compared to the other experiments, this fire was relatively large in a relatively small compartment. Thus, its HGL temperature is 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. .

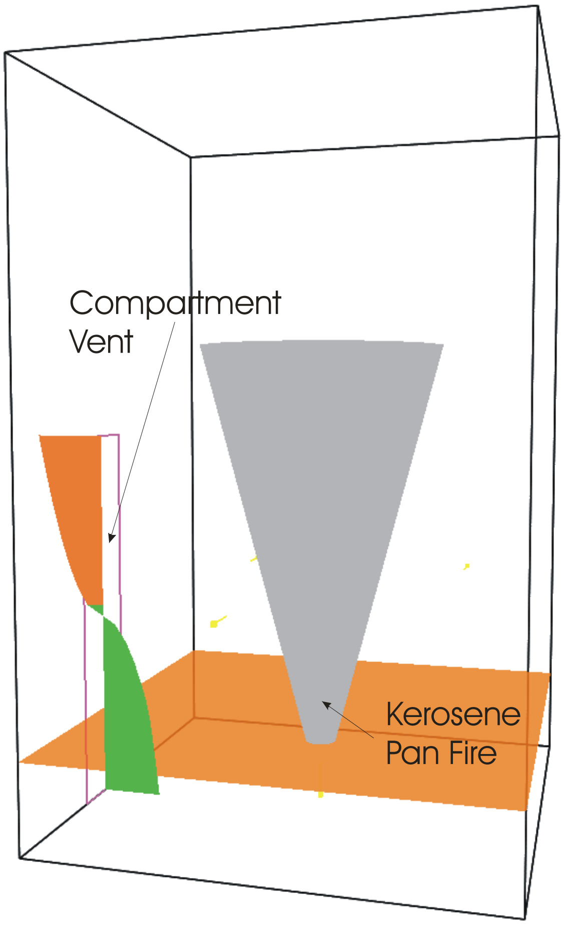


Figure A-8. Snapshot of the simulation of ICFMP BE #4, Test 1.

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.

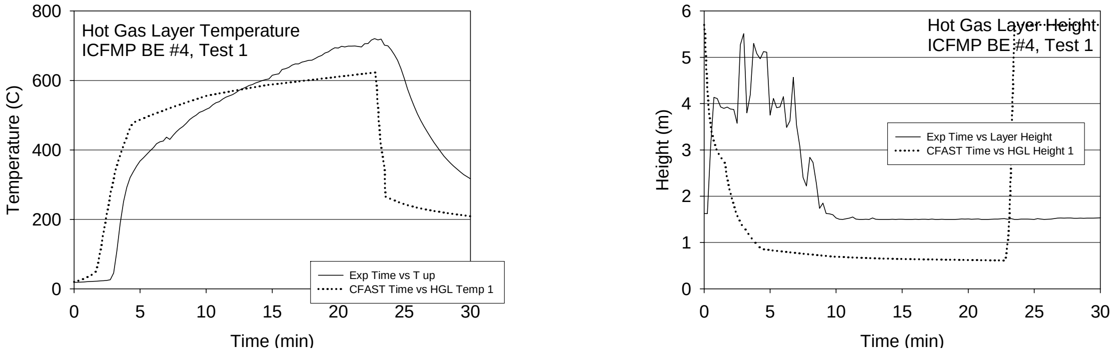


Figure A-9. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #4, Test 1.

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 min 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.

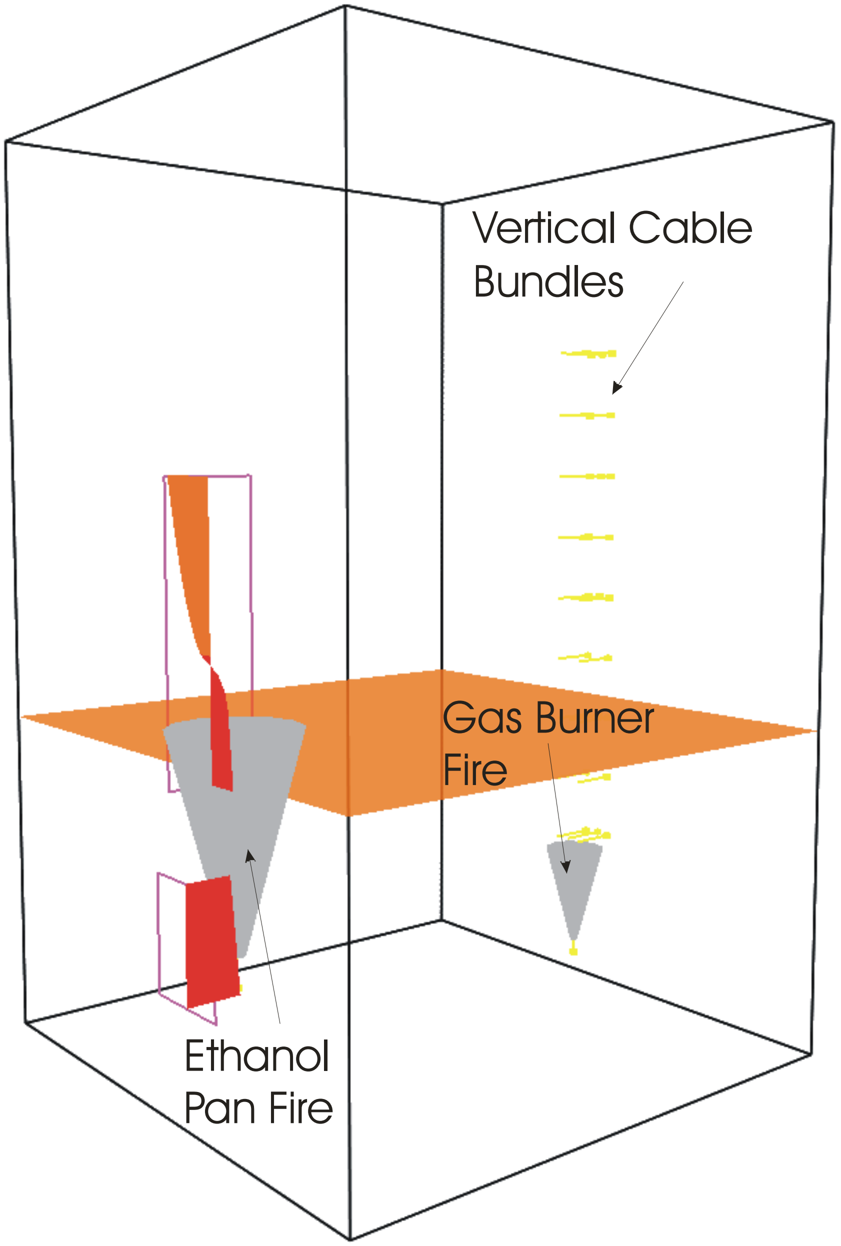


Figure A-10. Snapshot of the simulation of ICFMP BE #5, Test 4.

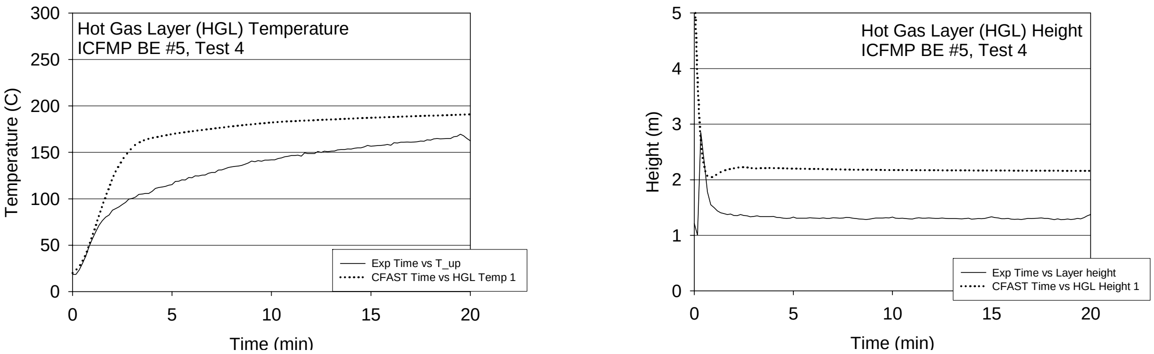


Figure A-11. Hot Gas Layer (HGL) Temperature and Height, ICFMP BE #5, Test 4.

FM/SNL Test Series

Tests 4, 5, and 21 from the FM-SNL test series were selected for comparison. The hot gas layer 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.

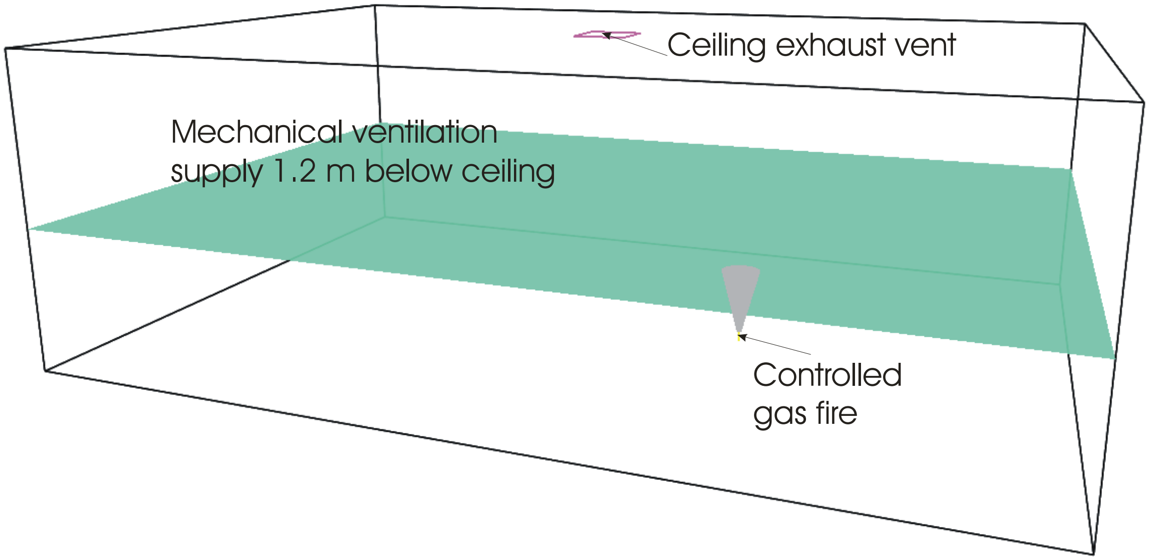


Figure A-12. Snapshot from simulation of FM/SNL Test 5.

Note the following:

- The experimental HGL heights are somewhat noisy due to 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 min in Test 5, the effect of which was a slight increase in the measured HGL temperature.

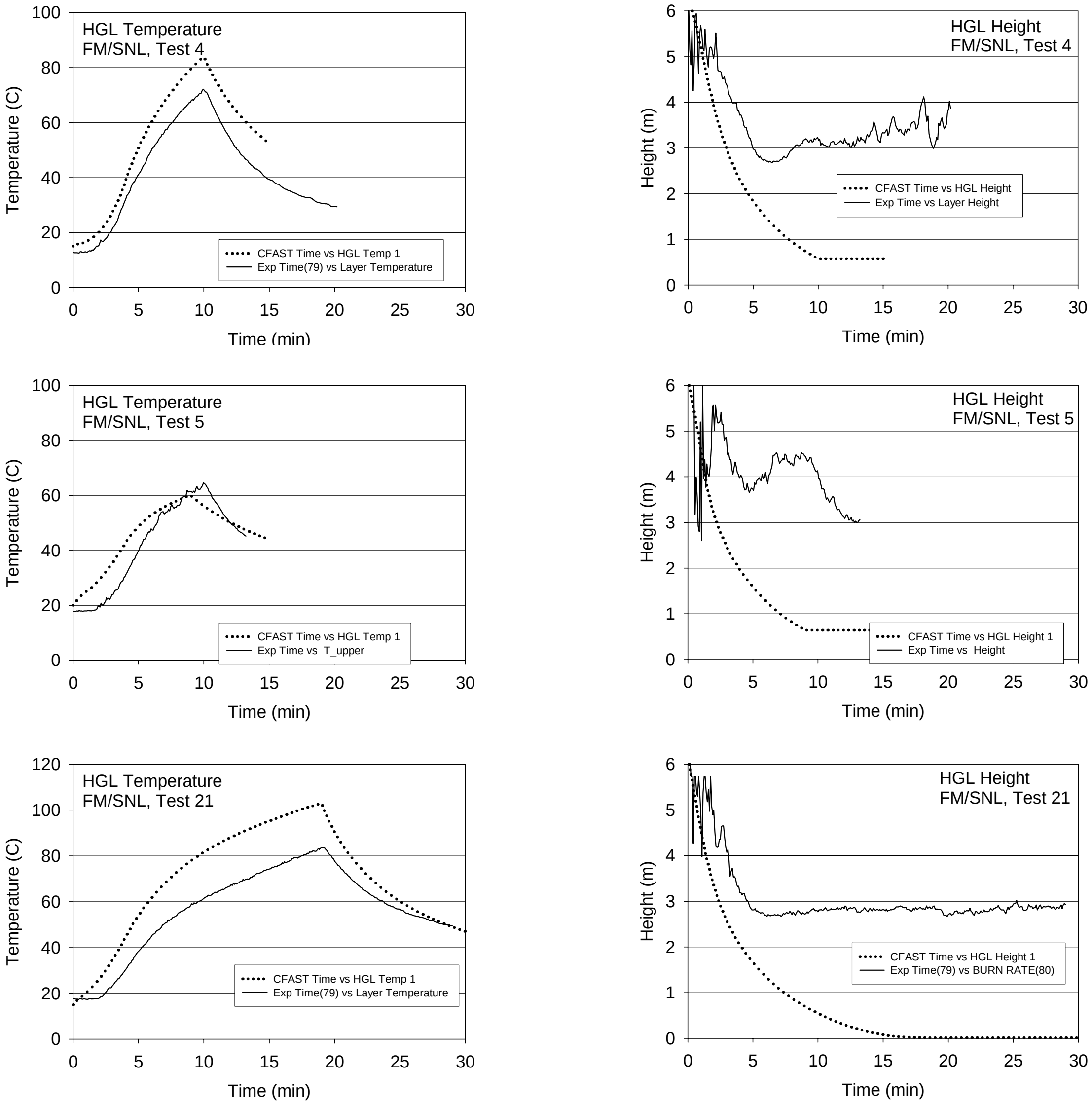


Figure A-13. Hot Gas Layer (HGL) Temperature and Height, FM/SNL Series.

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 (Peacock 1991).

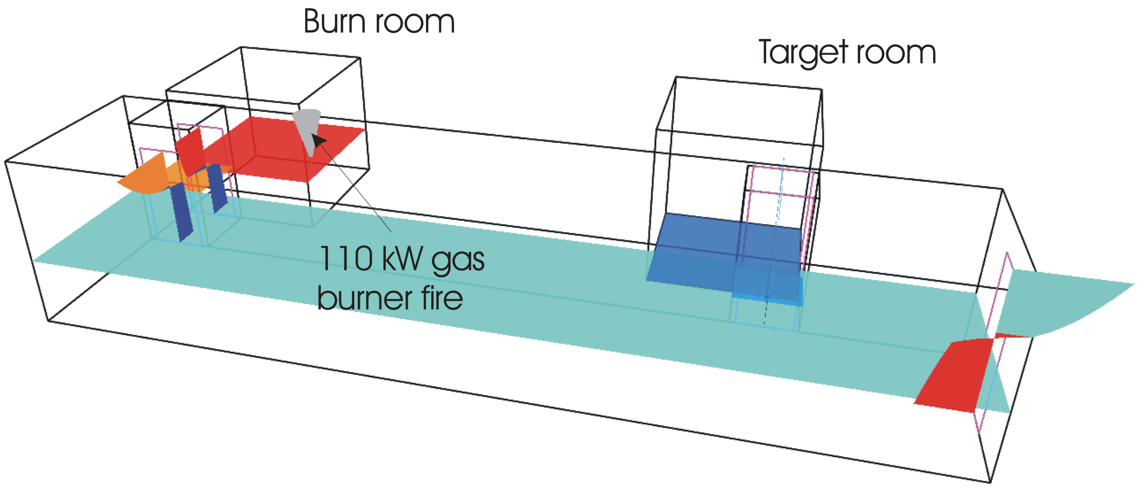


Figure A-14. Snapshot from simulation of NBS Multi-Room Test 100Z.

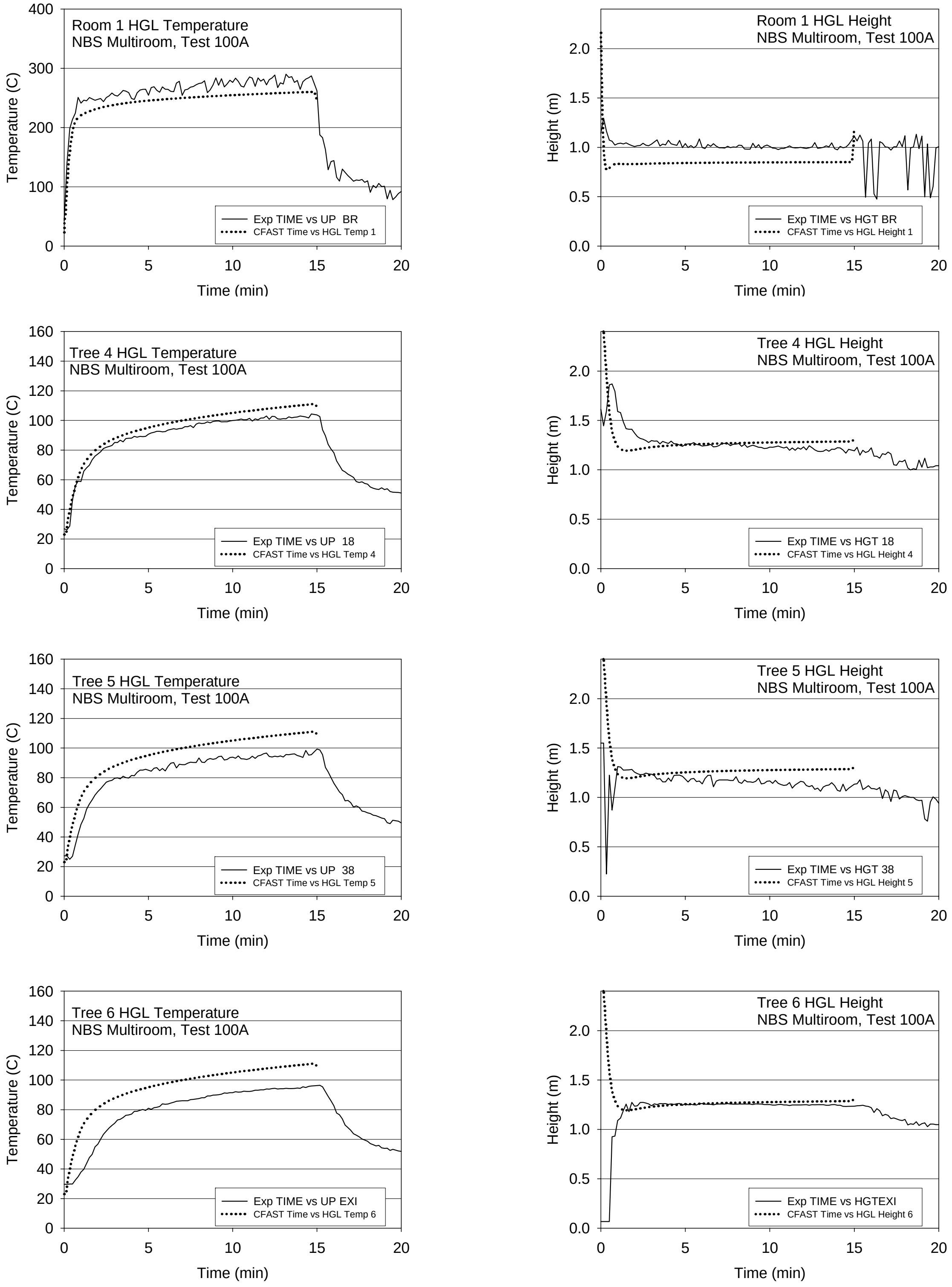


Figure A-15. Hot Gas Layer (HGL) Temperature and Height, NBS Multiroom, Test 100A.

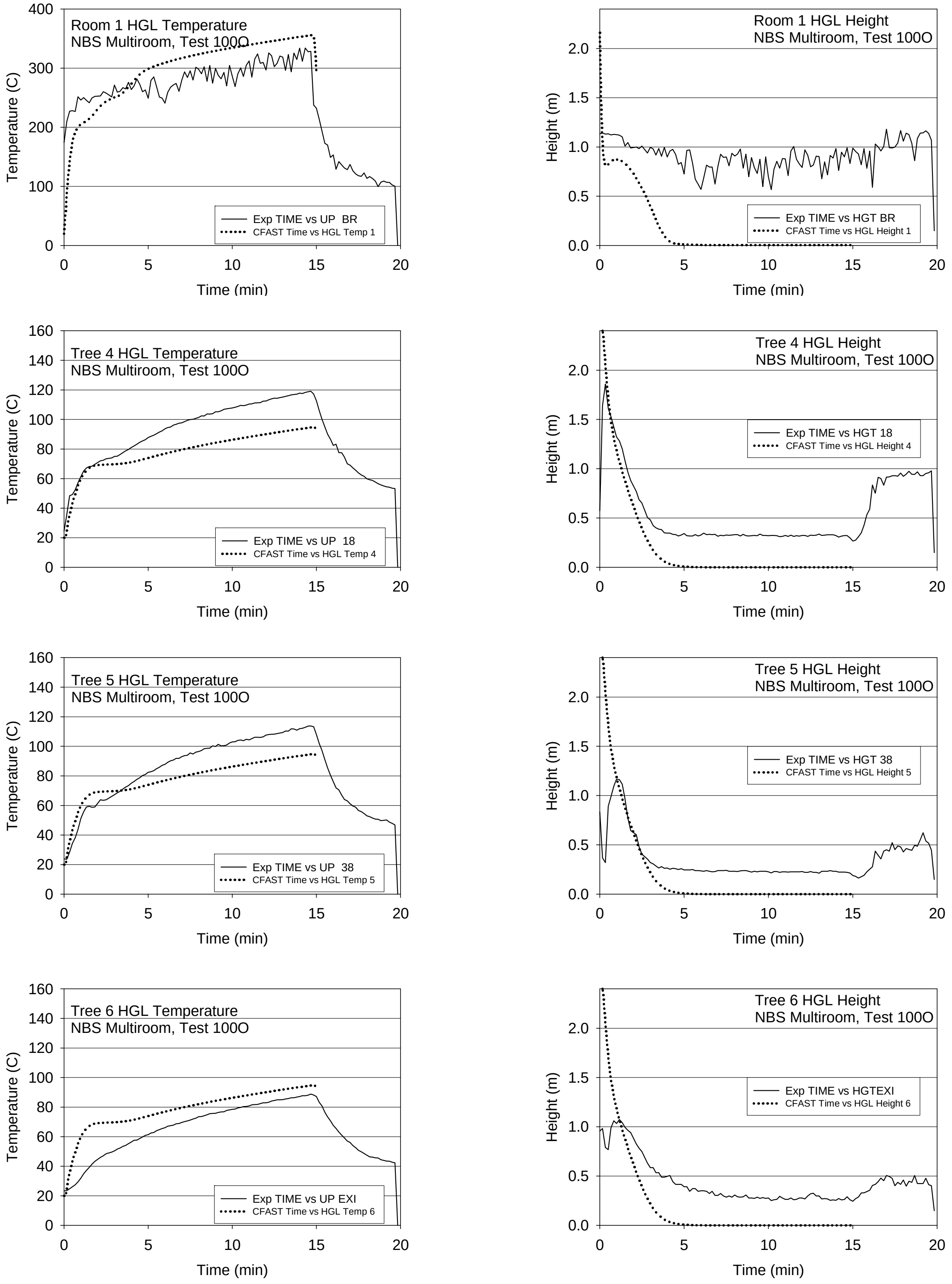


Figure A-16. Hot Gas Layer (HGL) Temperature and Height, NBS Multiroom, Test 100O.

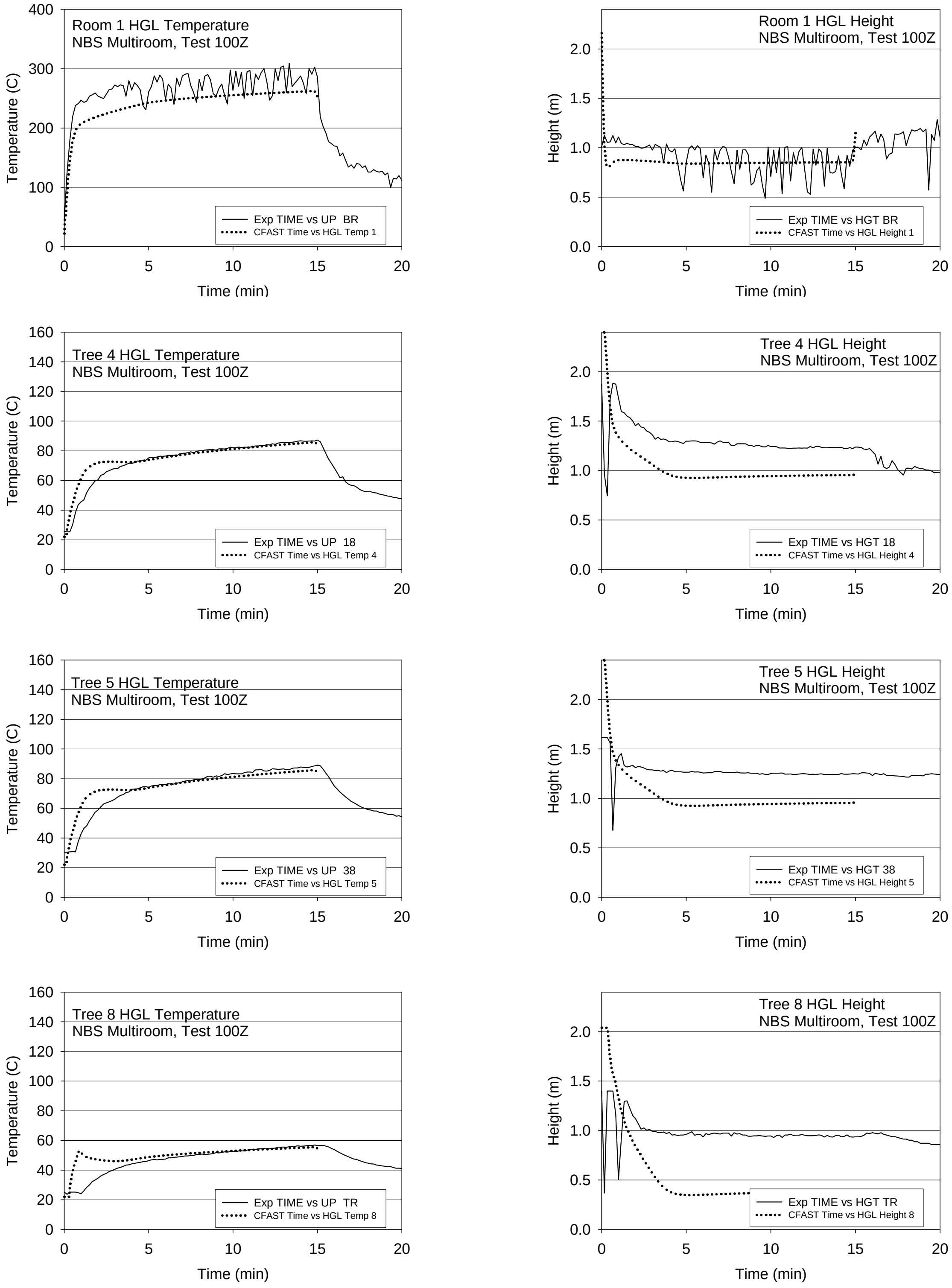


Figure A-17. Hot Gas Layer (HGL) Temperature and Height, NBS Multiroom, Test 100Z.

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	164	21			
	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		47	40	-14			
	Test 21		66	88	33			
NBS	MV100A	Burn Room	267	237	-11	1.2	1.3	11
		Corridor 18	81	88	8	1.3	1.2	-7
		Corridor 38	75	88	17	1.4	1.2	-14
		Corridor Exit	73	88	20	1.2	1.2	-2
	MV100O	Burn Room	313	336	7			
		Corridor 18	98	75	-24			
		Corridor 38	93	75	-19			
		Corridor Exit						
	MV100Z	Burn Room	260	240	-8	1.2	1.3	14
		Corridor 18	65	64	-1	1.2	1.5	24
		Corridor 38	67	64	-4	1.2	1.5	26
		Target Room	35	33	-4	1.5	2.1	39

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. However, the ceiling jet temperature is not directly calculated nor reported in a CFAST calculation. For this reason, comparisons of experimentally measured ceiling jet temperatures with CFAST calculations are not appropriate and will not be included in this report.

A.3 Plume Temperature

CFAST includes a plume entrainment algorithm based on the work of McCaffrey that 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 will not be 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-18 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). From the CFAST calculations, the estimated flame height is 4.3 m.

Figure A-18. 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 2 m by 2 m doorway. During BE #3, Test 3, the peak flame height is estimated to be 2.8 m, roughly consistent with the view through the doorway in the figure below.

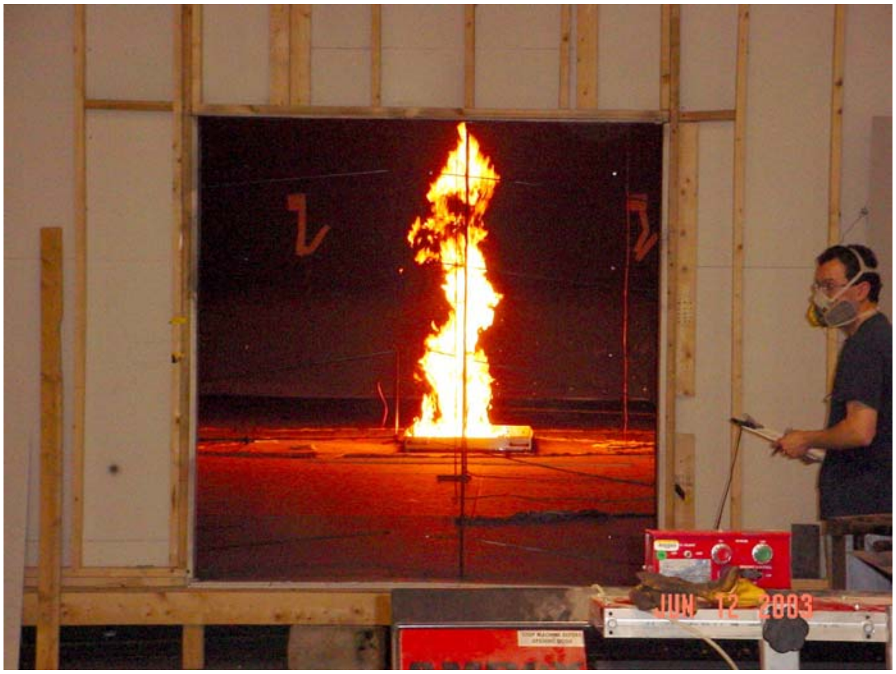


Figure A-19. Photograph and simulation of ICFMP BE #3, Test 3, as seen through the 2 m by 2 m doorway. Photo courtesy of Francisco Joglar, SAIC.

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, whether it be the transport of heat or the transport of mass.

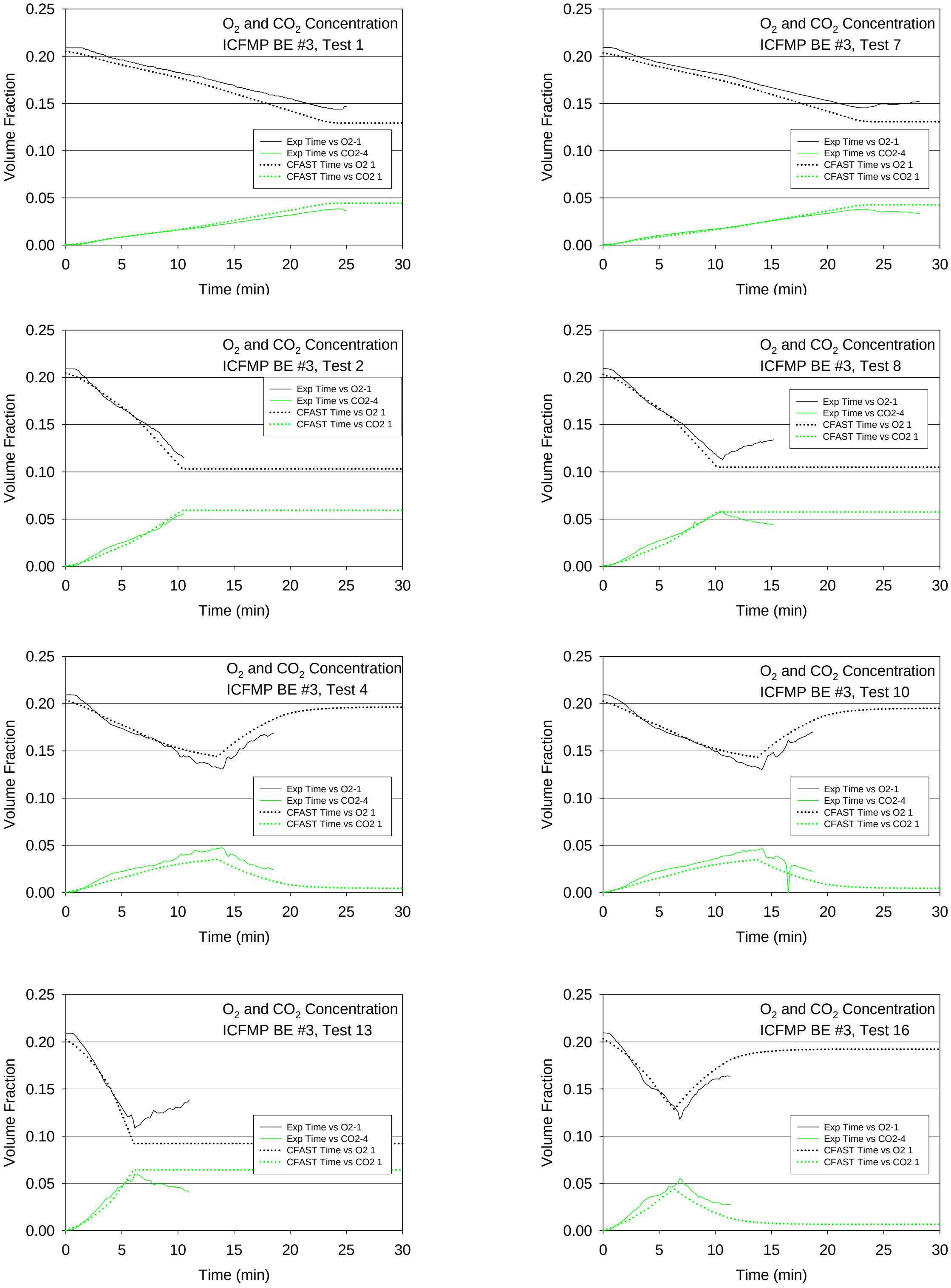


Figure A-20. O$_2$ and CO$_2$ concentration, ICFMP BE #3, closed door tests.

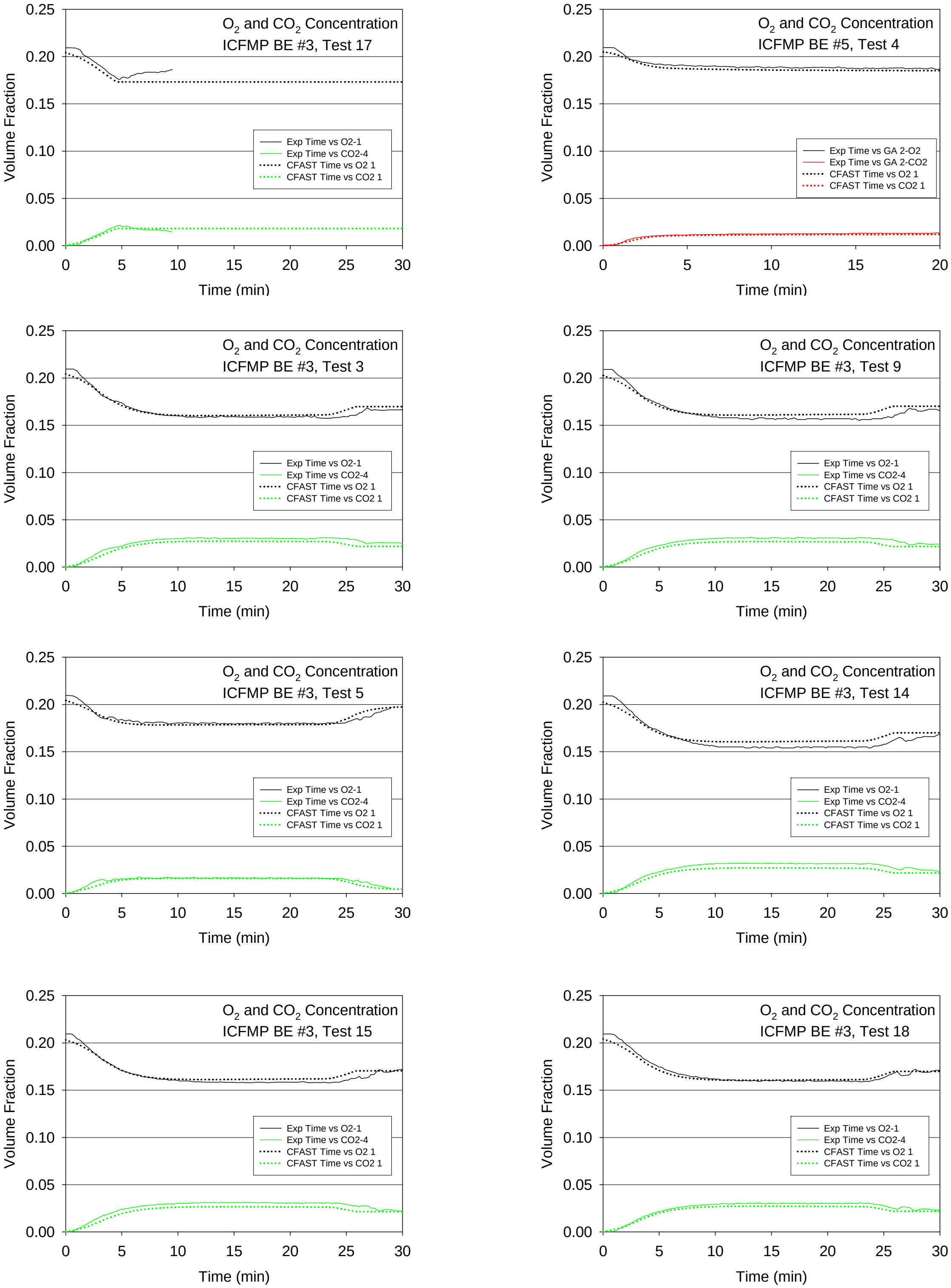


Figure A-21. O_2 and CO_2 concentration, ICFMP BE #3, open door tests. Note that the single test from ICFMP BE #5 is included at the upper right.

Table A-2. 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	0.018	-16
	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, basically a tracer gas whose mass fraction specified combustion chemistry. To model smoke movement, the user need only prescribe the smoke yield, that is, the fraction of the fuel mass that is converted to smoke particulate. For BE #3, the smoke yield was specified as one of the test parameters.

Figure A-22 and Figure A-23 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 are about 50 % higher than the measured in the open door tests. Second, the predicted concentrations are roughly three times the measured concentrations in the closed door tests.

Consider the first issue. The reported mass concentration of smoke was computed using the following expression:

$$M_s = \frac{\ln(I_0 / I)}{\phi_s L}$$

Errors in the measurement were due to errors in the path length L, the light attenuation I_0 / I, and the assumed specific extinction coefficient ϕ_s. Hamins reported the expanded uncertainty of the measurement to be 18 %. In addition, the simulation was subject to error mainly from the prescribed soot yield. The soot yields were given as 1.5 % ± 0.3 % (heptane) and 20 % ± 5 % (toluene, Test 17). The combination of numerical and measurement error for the heptane tests was therefore 18 % + 20 % = 40 %, and for the toluene test 18 % + 25 % = 45 %.

Assuming that the mixture fraction model is valid, at least for the open door tests, it can be assumed that virtually all of the carbon atoms in the fuel either ended up in the CO_2 or the soot (with relatively small amounts going to CO, unburned hydrocarbons, *etc*.). It can also be assumed that the soot (smoke) and CO_2 were transported together with no significant separation or reaction. If these assumptions are true, there is no reason to expect the predicted smoke concentration to be roughly 50 % higher than the measured value unless the soot yield uncertainty and the measurement error combined to cause it.

Now, consider the second issue. The difference between model and experiment is even 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 that the data analysis is flawed. It has been assumed throughout the test series that the specific extinction coefficient, ϕ_s, is constant. However, various studies have shown it to change as a function of the combustion efficiency.

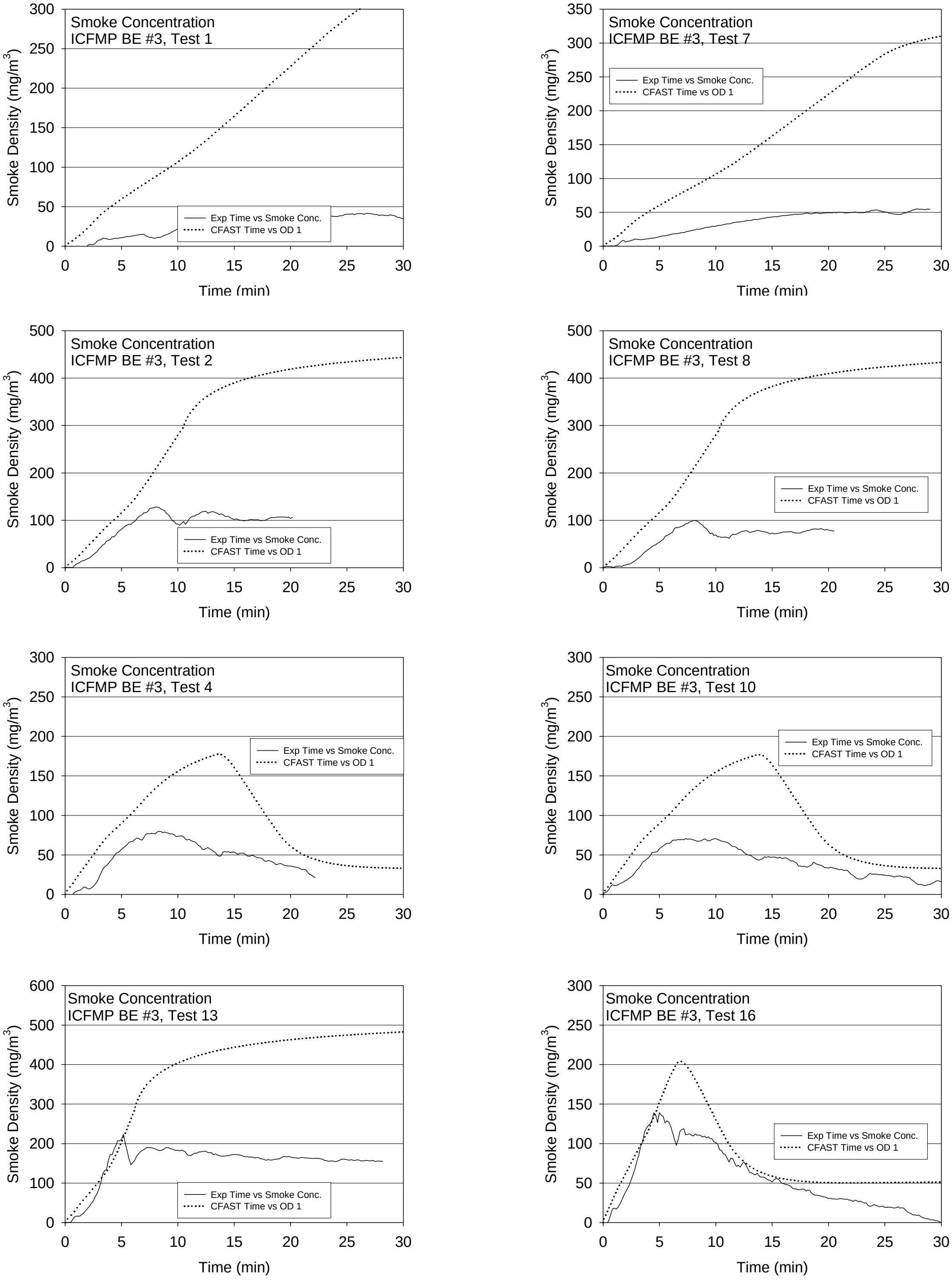
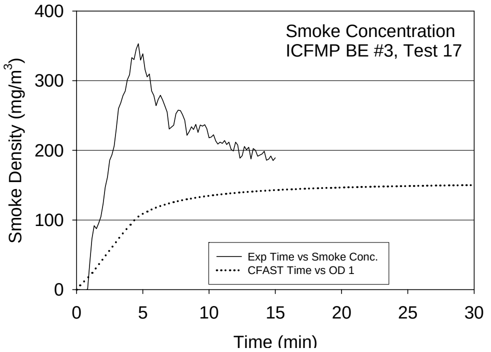


Figure A-22. Smoke Concentration, ICFMP BE #3, closed door tests.



Open Door Tests to Follow

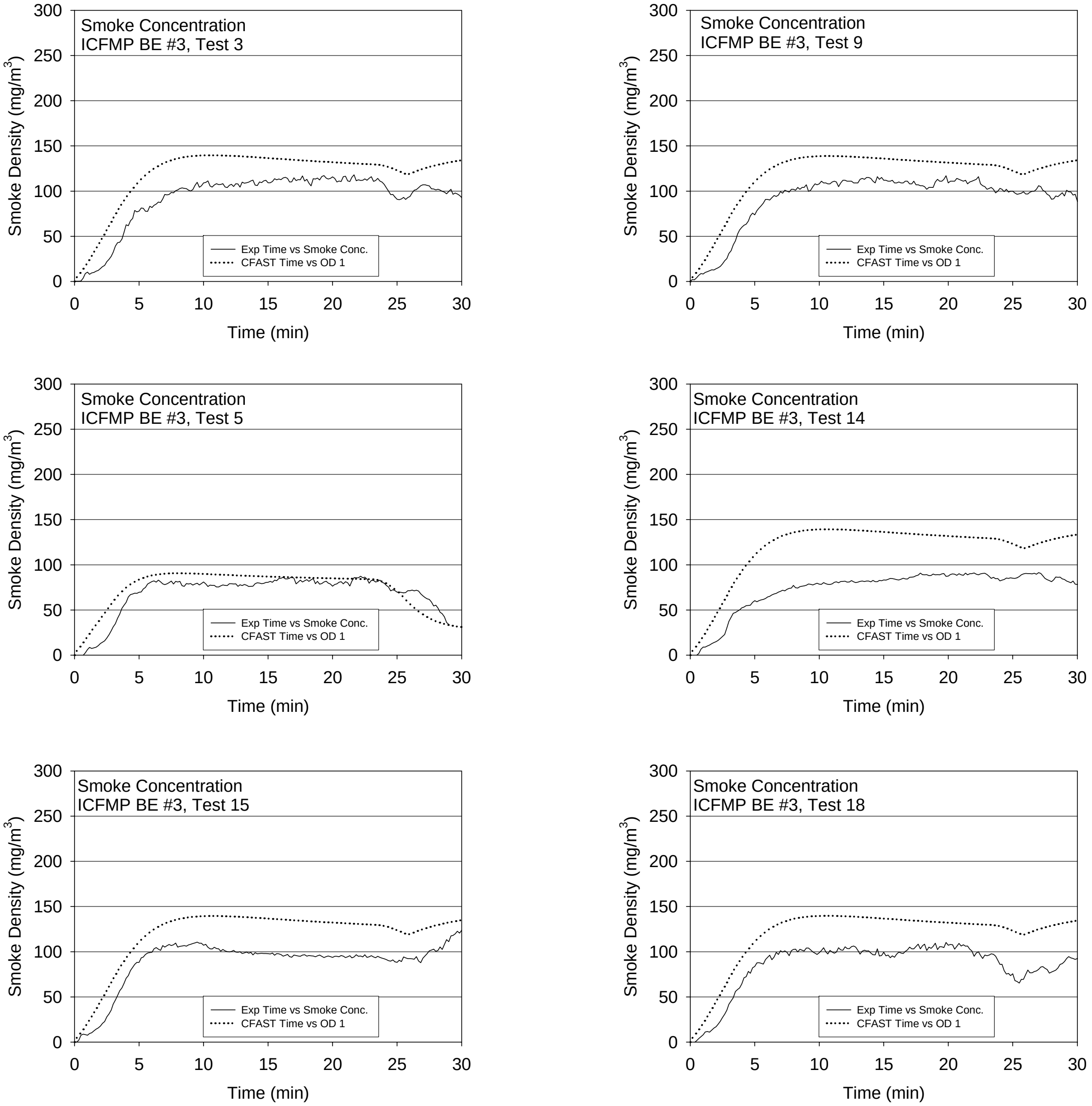


Figure A-23. Smoke concentration, ICFMP BE #3, open door tests.

Table A-3. 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	143	-60
	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 from the ICFMP BE #3 test series only. 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-24 and Figure A-25. 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.

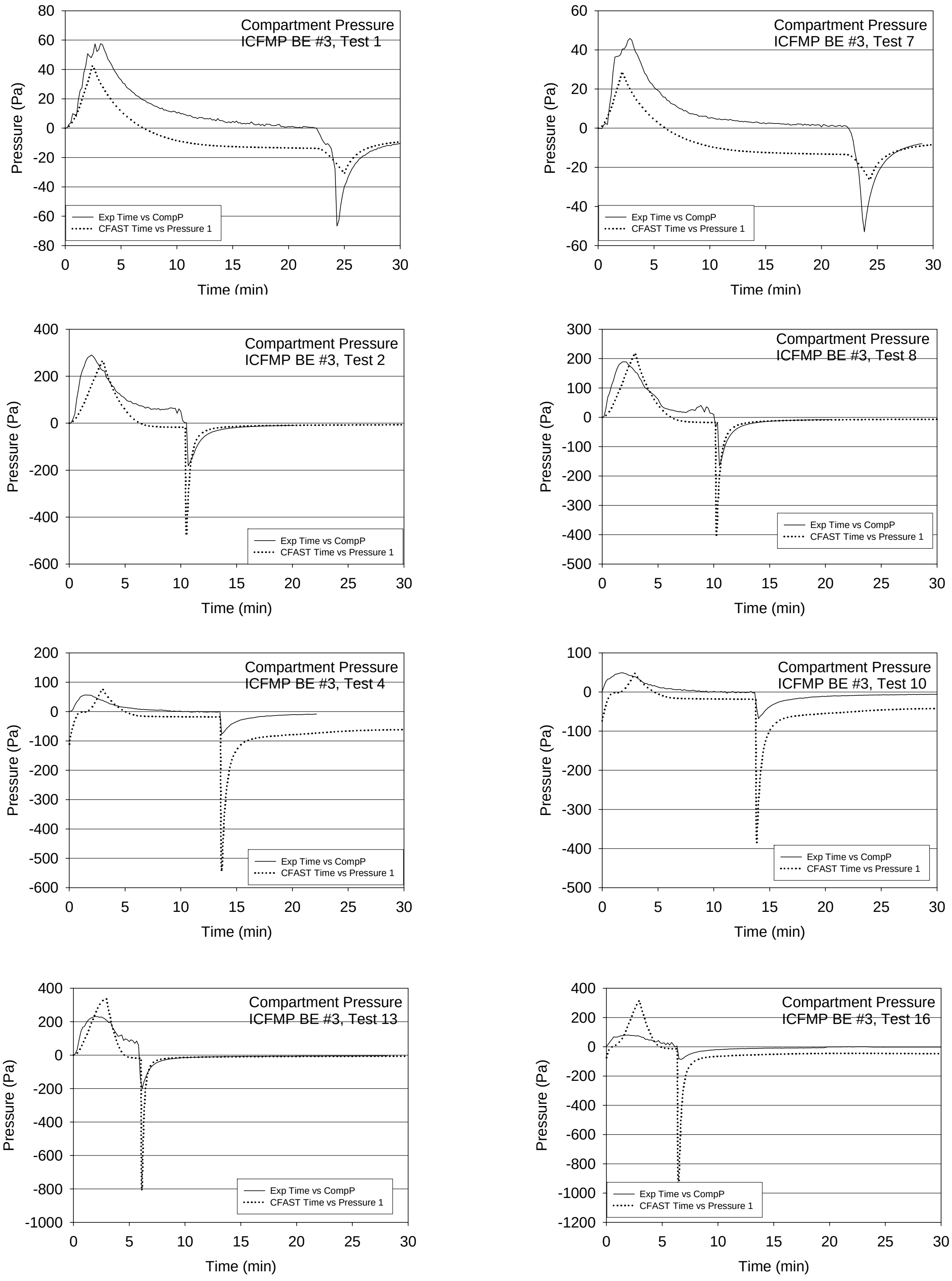
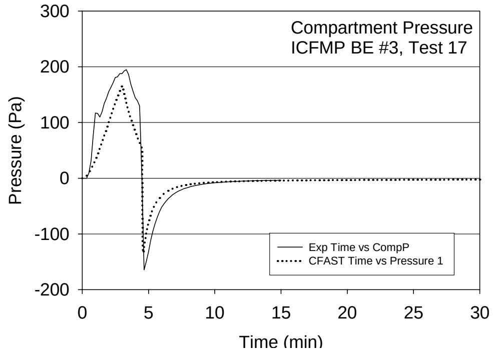


Figure A-24. Compartment pressure, ICFMP BE #3, closed door tests.



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

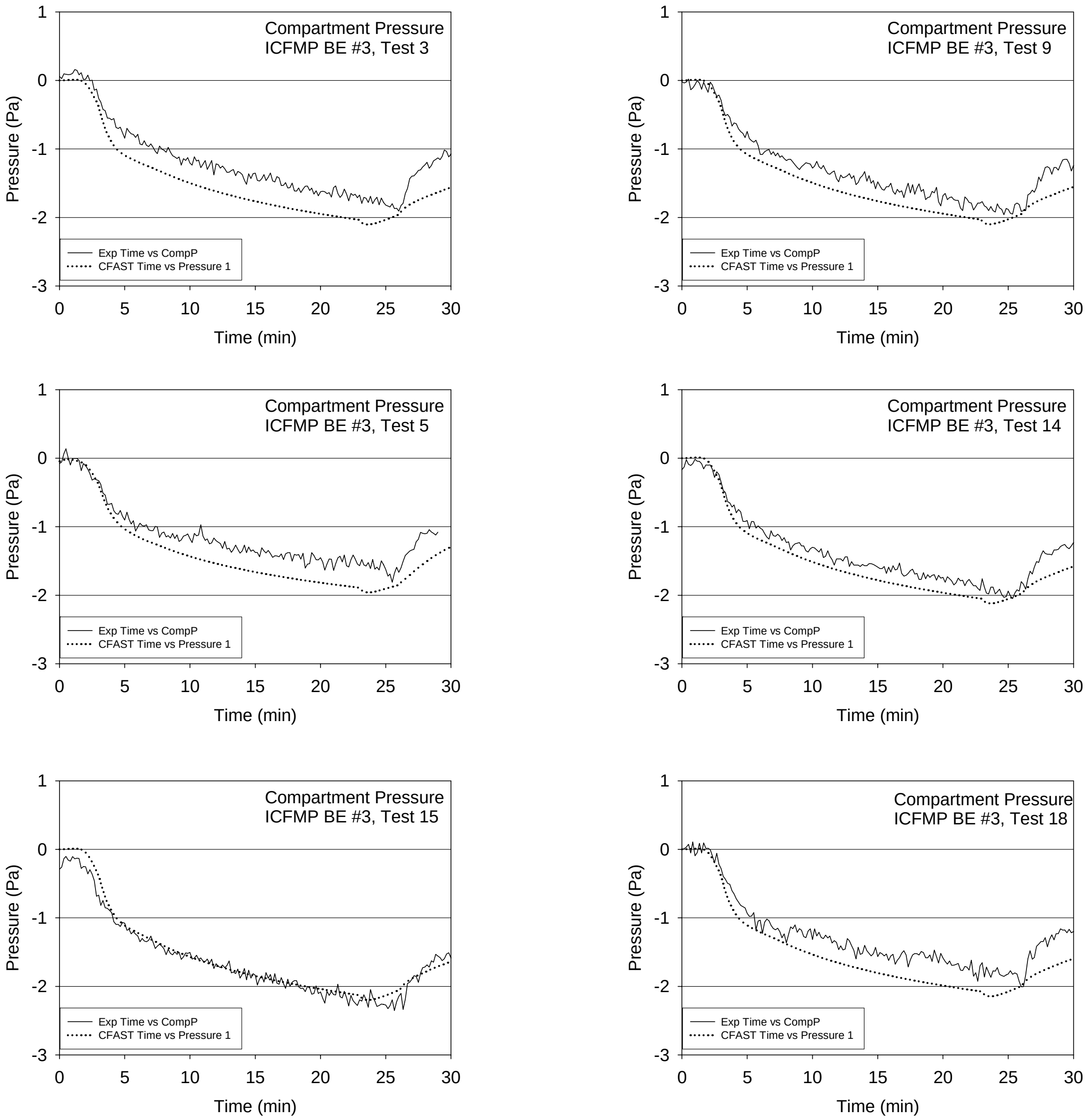


Figure A-25. Compartment pressure, ICFMP BE #3, open door tests.

Table A-4. Relative Differences for Compartment Pressure

Series	Test	Comparment Pressure Rise 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	34
	Test 10	49	45	-9
	Test 13	232	336	45
	Test 16	81	304	277
	Test 17	195	166	-15
	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. For all the cable targets, CFAST assumes them 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.

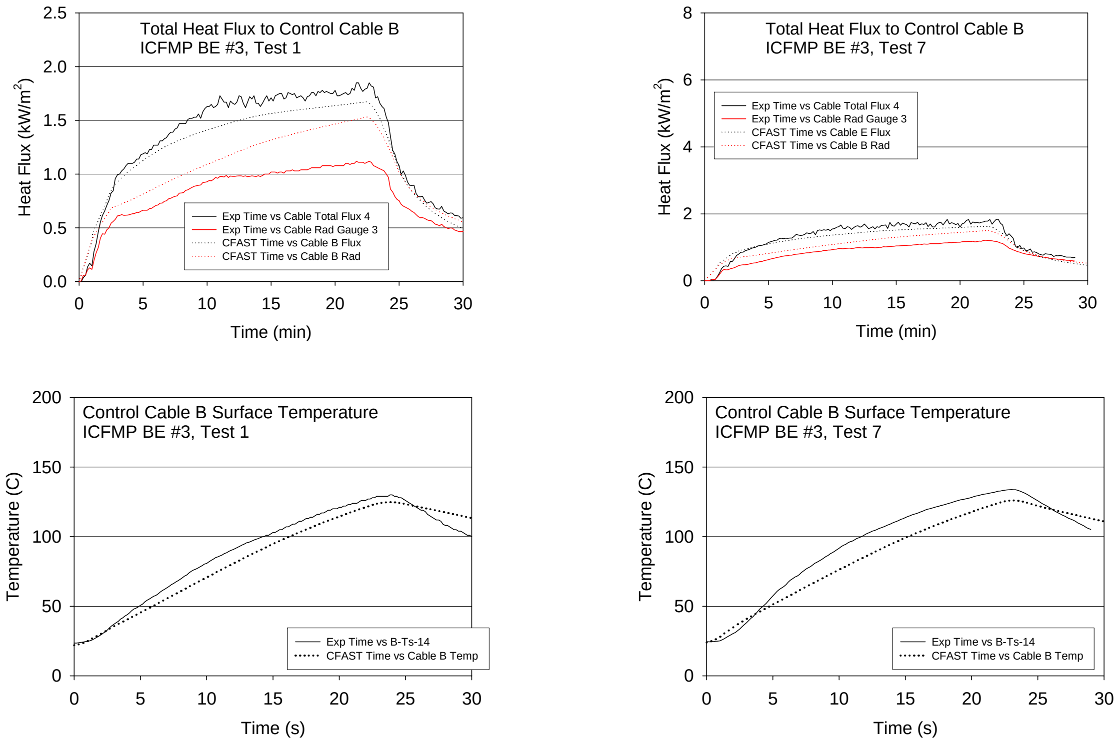


Figure A-26. Thermal environment near Cable B, ICFMP BE #3, Tests 1 and 7.

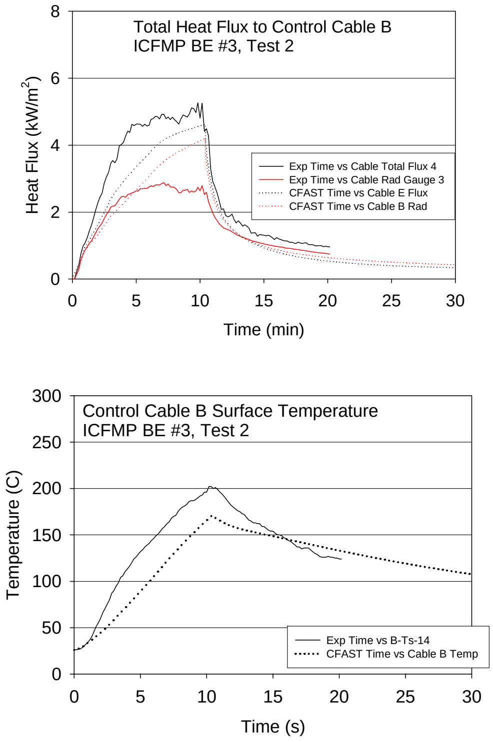


Figure A-27. Thermal environment near Cable B, ICFMP BE #3, Tests 2 and 8.

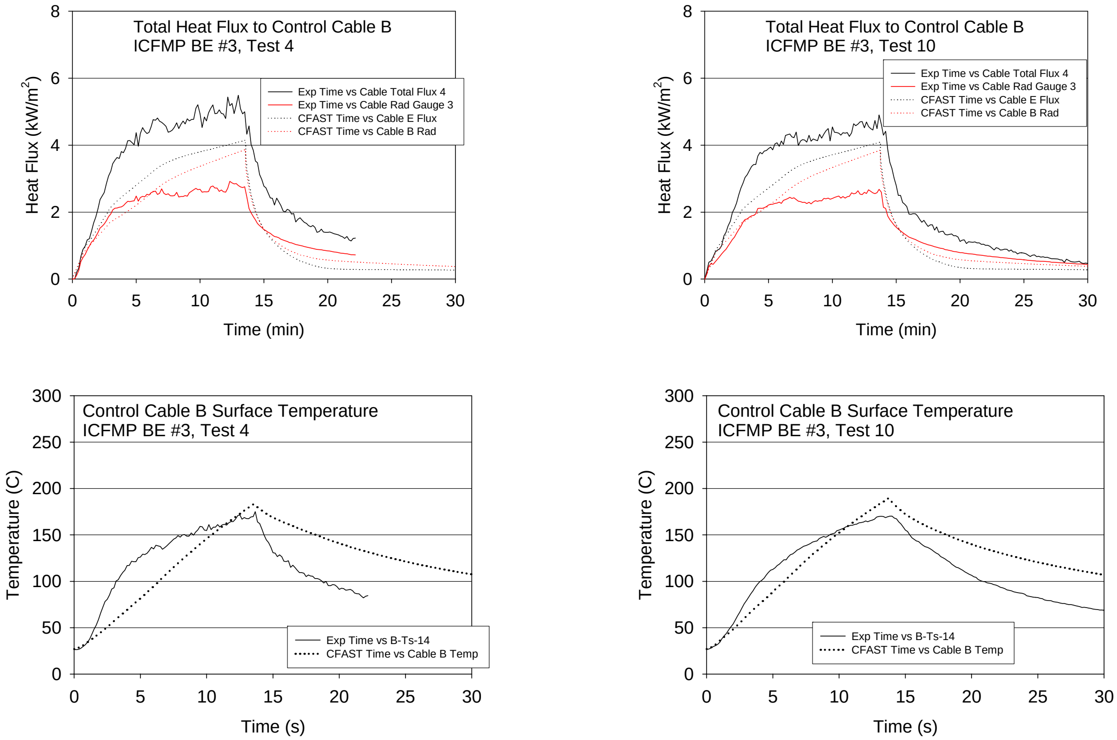


Figure A-28. Thermal environment near Cable B, ICFMP BE #3, Tests 4 and 10.

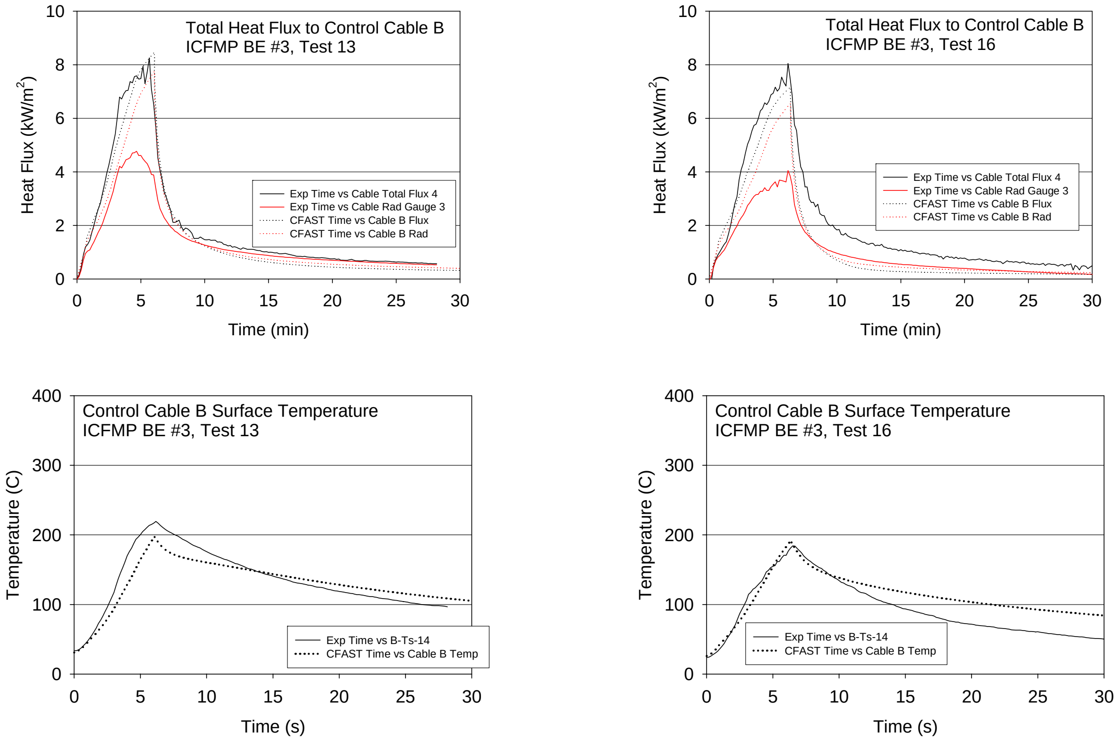


Figure A-29. Thermal environment near Cable B, ICFMP BE #3, Tests 13 and 16.

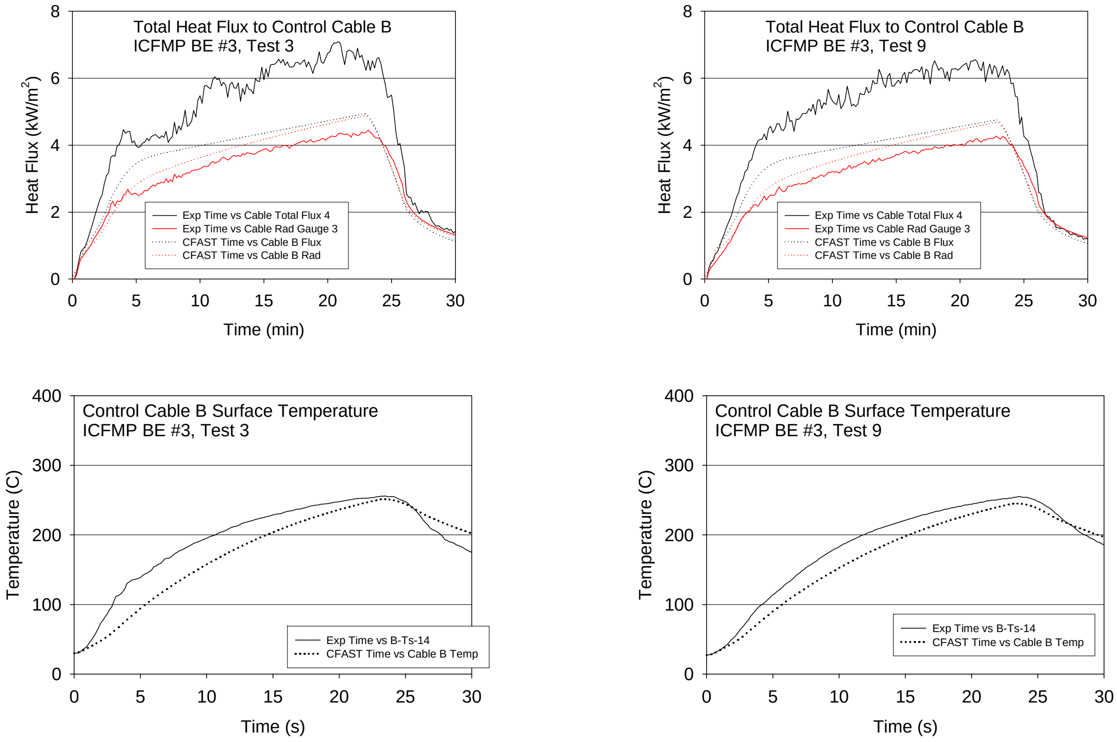


Figure A-30. Thermal environment near Cable B, ICFMP BE #3, Tests 3 and 9.

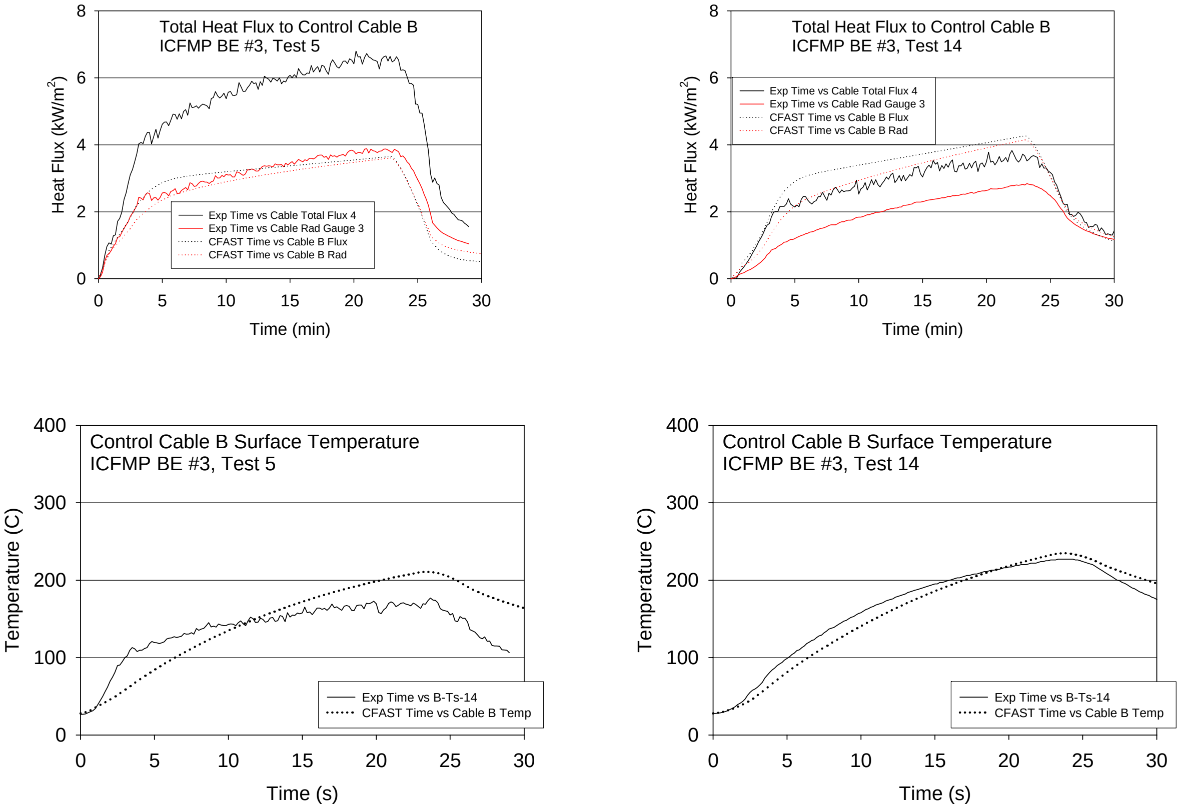


Figure A-31. Thermal environment near Cable B, ICFMP BE #3, Tests 5 and 14. Note the influence of the fan in Test 5.

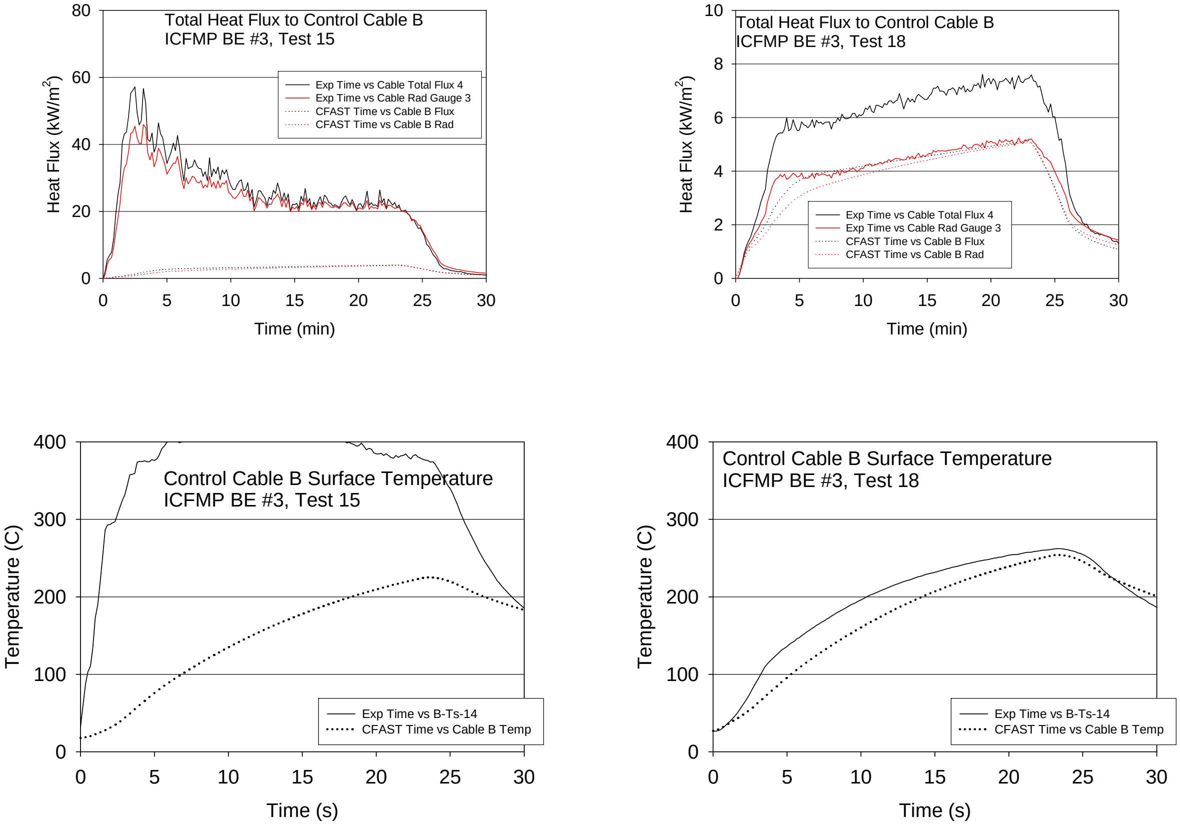


Figure A-32. Thermal environment near Cable B, ICFMP BE #3, Tests 15 and 18. Note that the cable was very close to the fire in Test 15.

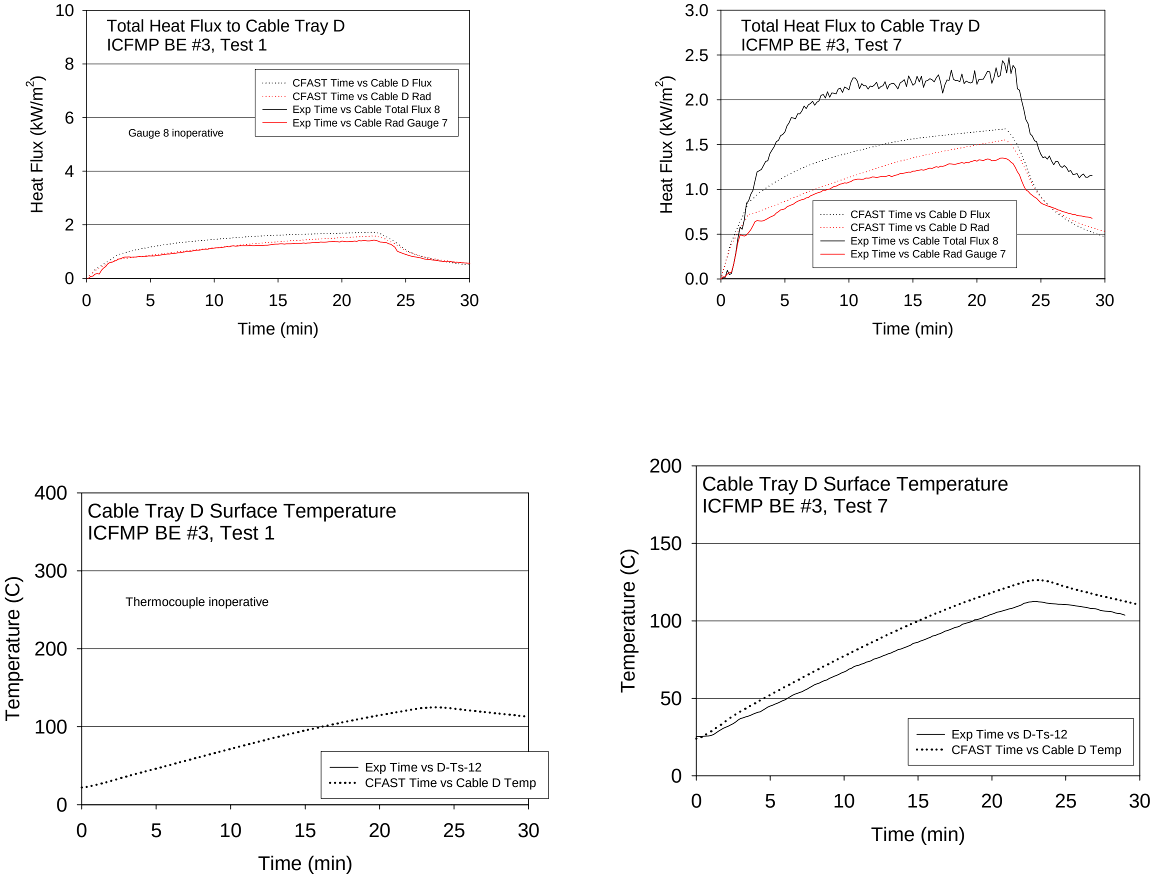


Figure A-33. Thermal environment near Cable Tray D, ICFMP BE #3, Tests 1 and 7.

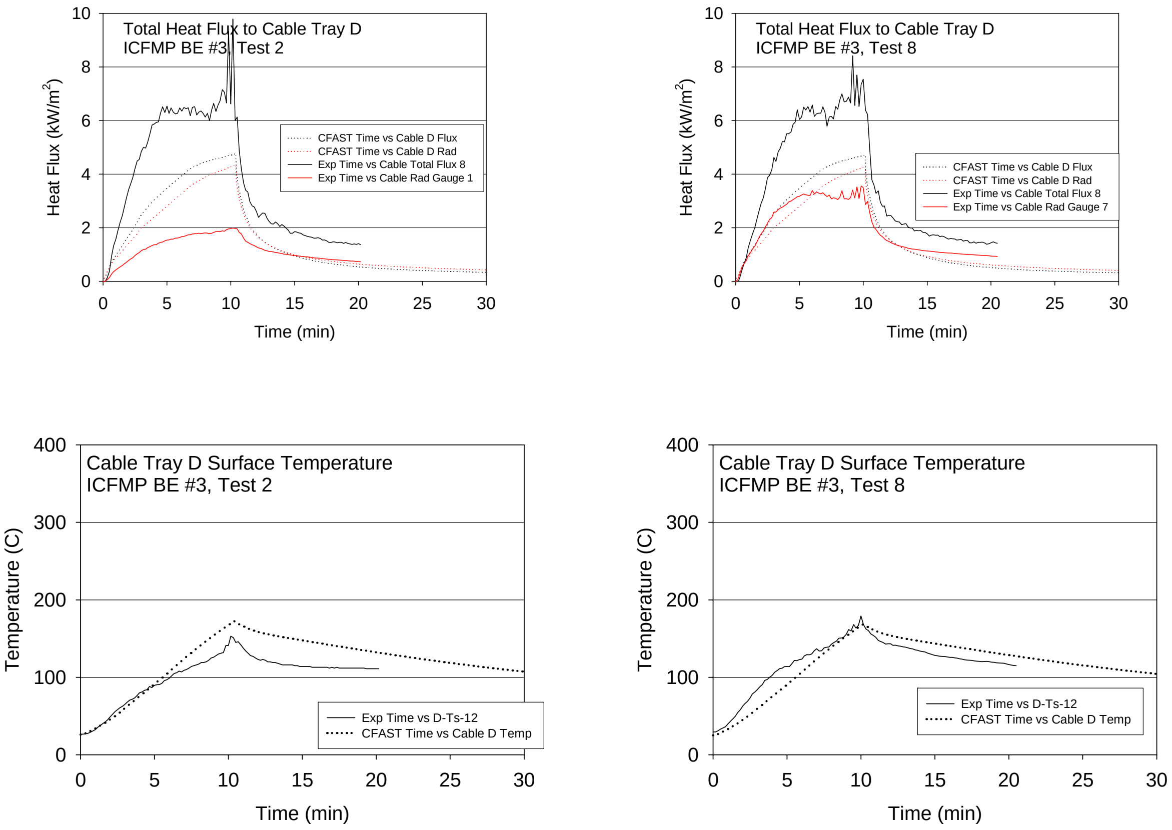


Figure A-34. Thermal environment near Cable Tray D, ICFMP BE #3, Tests 2 and 8.

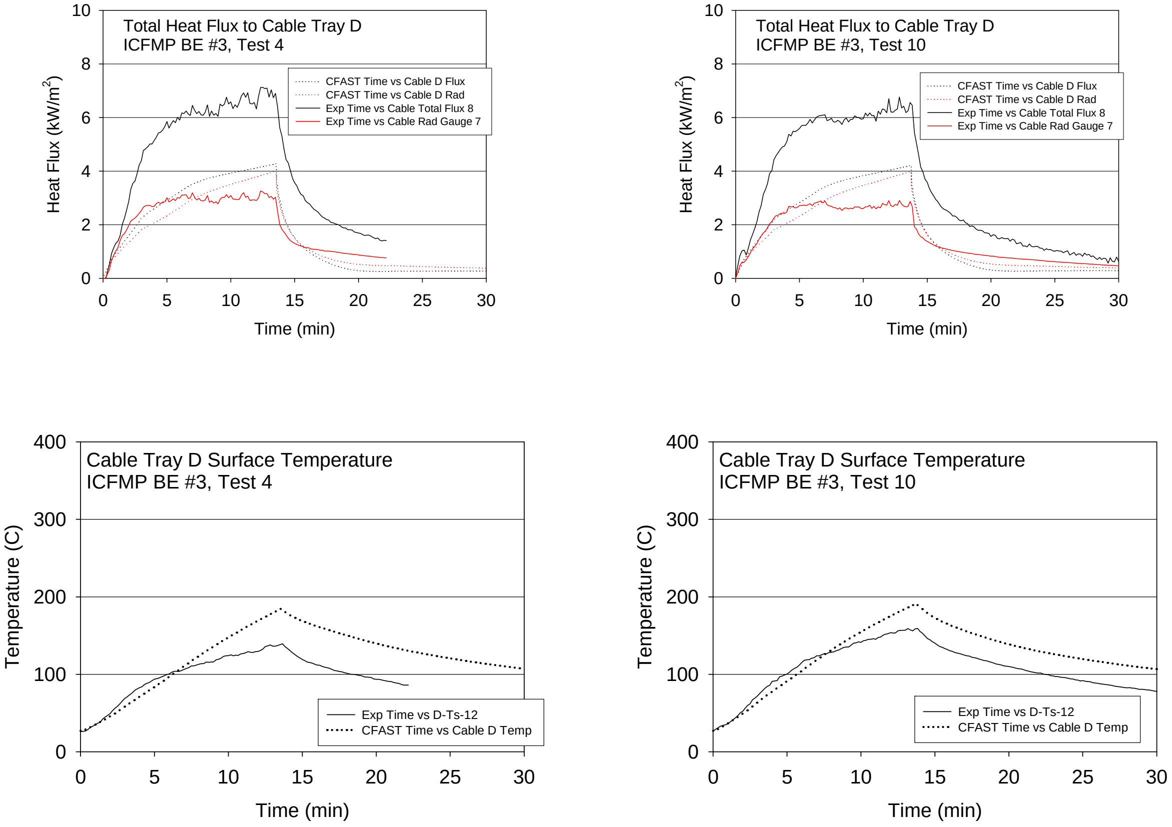


Figure A-35. Thermal environment near Cable Tray D, ICFMP BE #3, Tests 4 and 10.

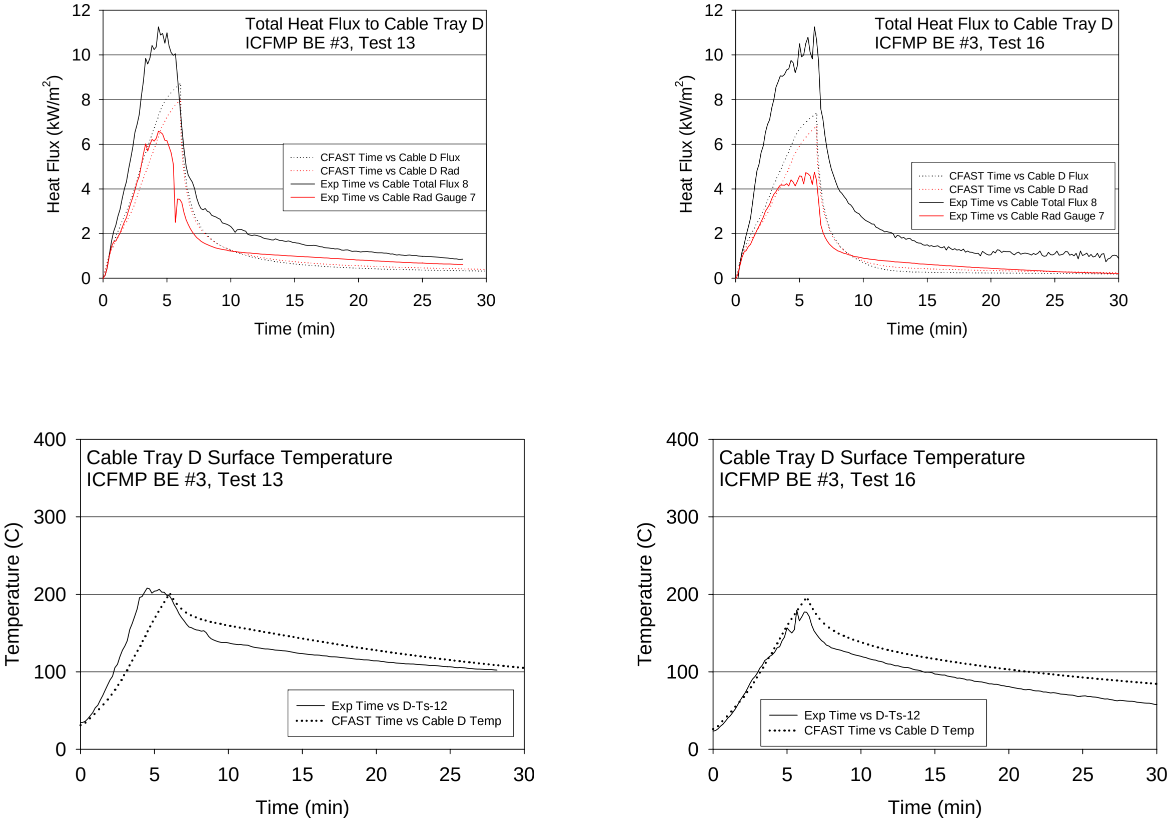


Figure A-36. Thermal environment near Cable Tray D, ICFMP BE #3, Tests 13 and 16.

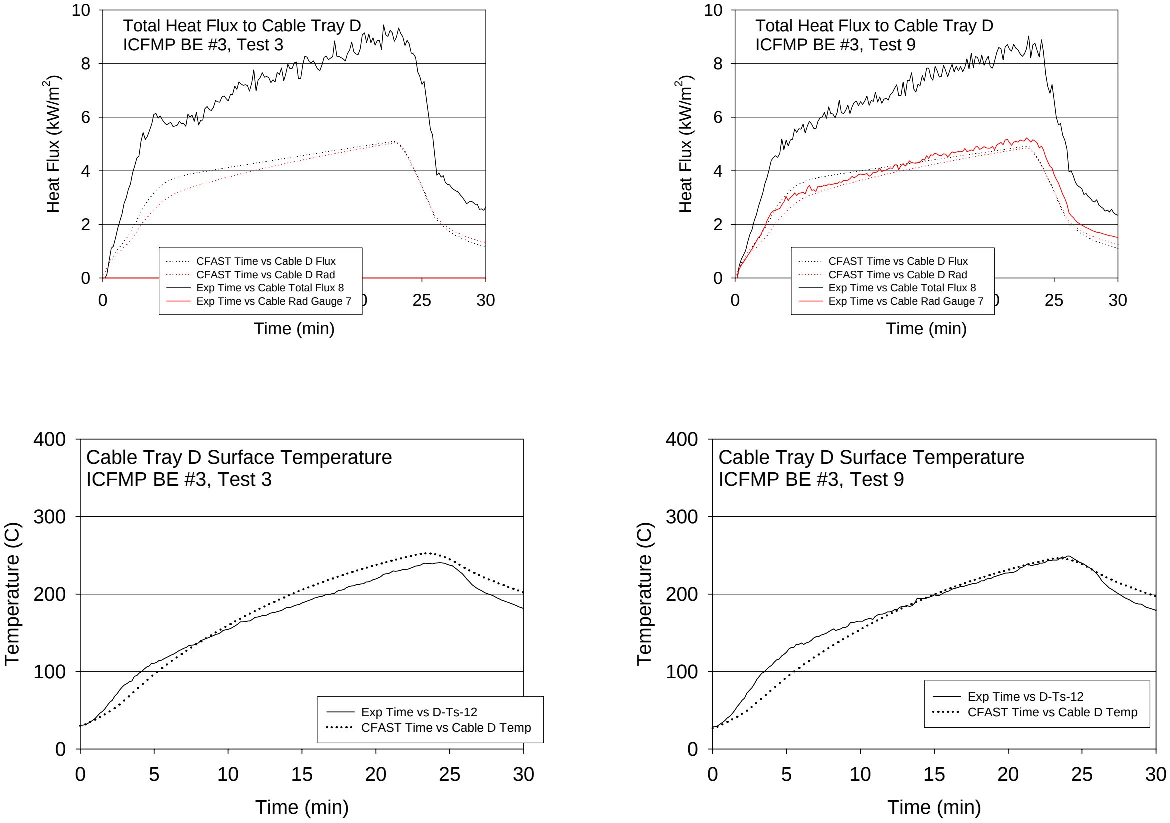


Figure A-37. Thermal environment near Cable Tray D, ICFMP BE #3, Tests 3 and 9.

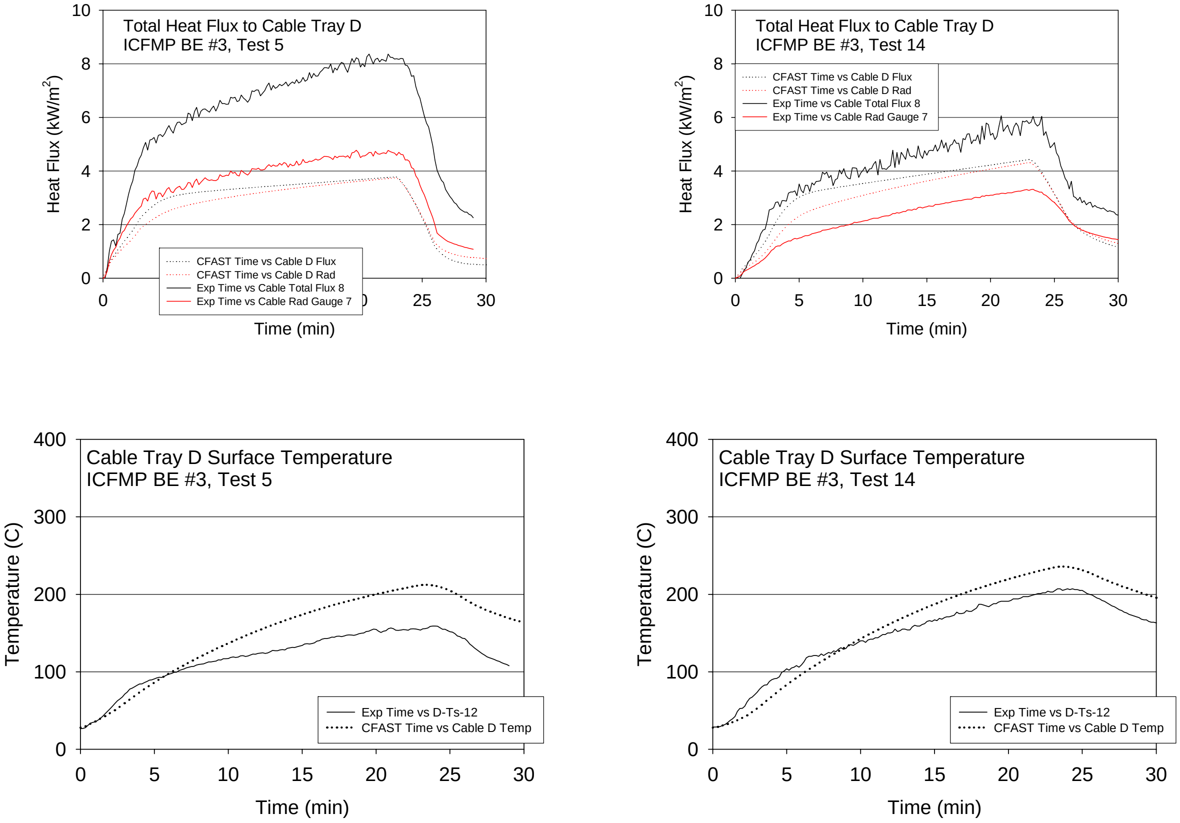


Figure A-38. Thermal environment near Cable Tray D, ICFMP BE #3, Tests 5 and 14.

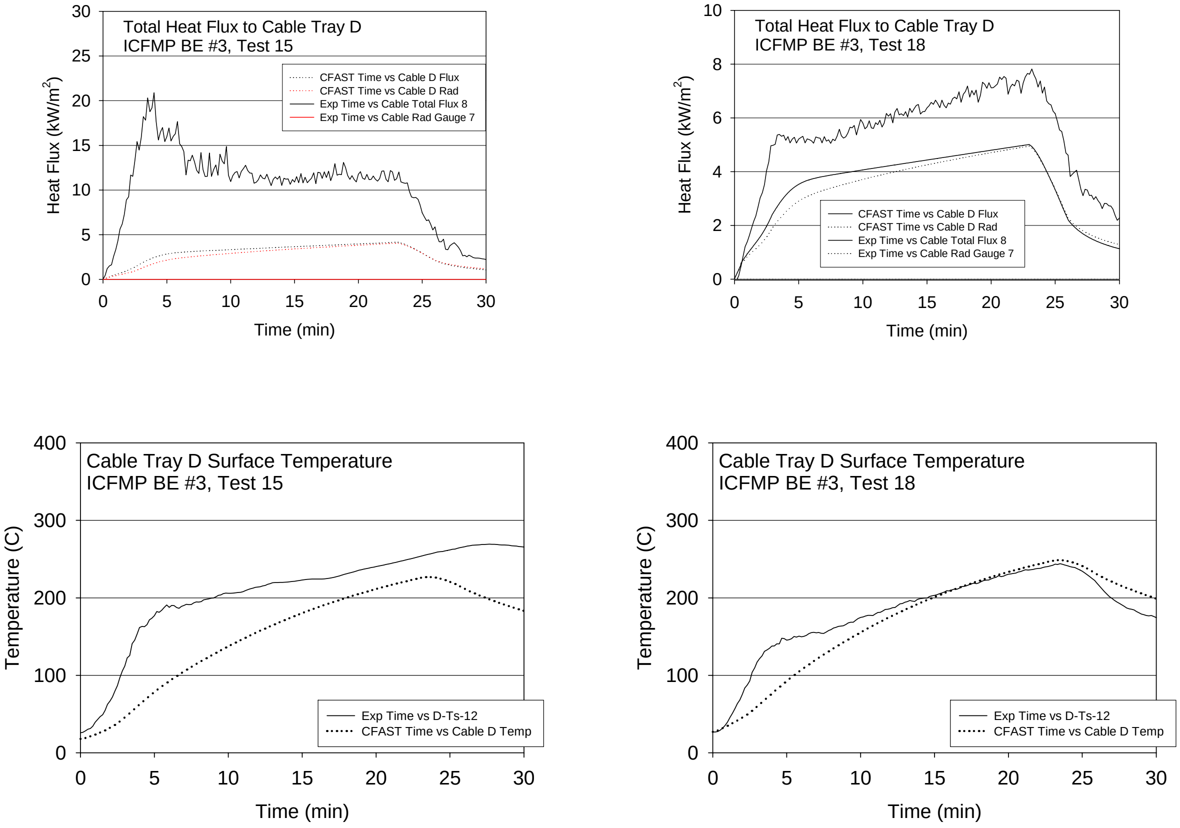


Figure A-39. Thermal environment near Cable Tray D, ICFMP BE #3, Tests 15 and 18.

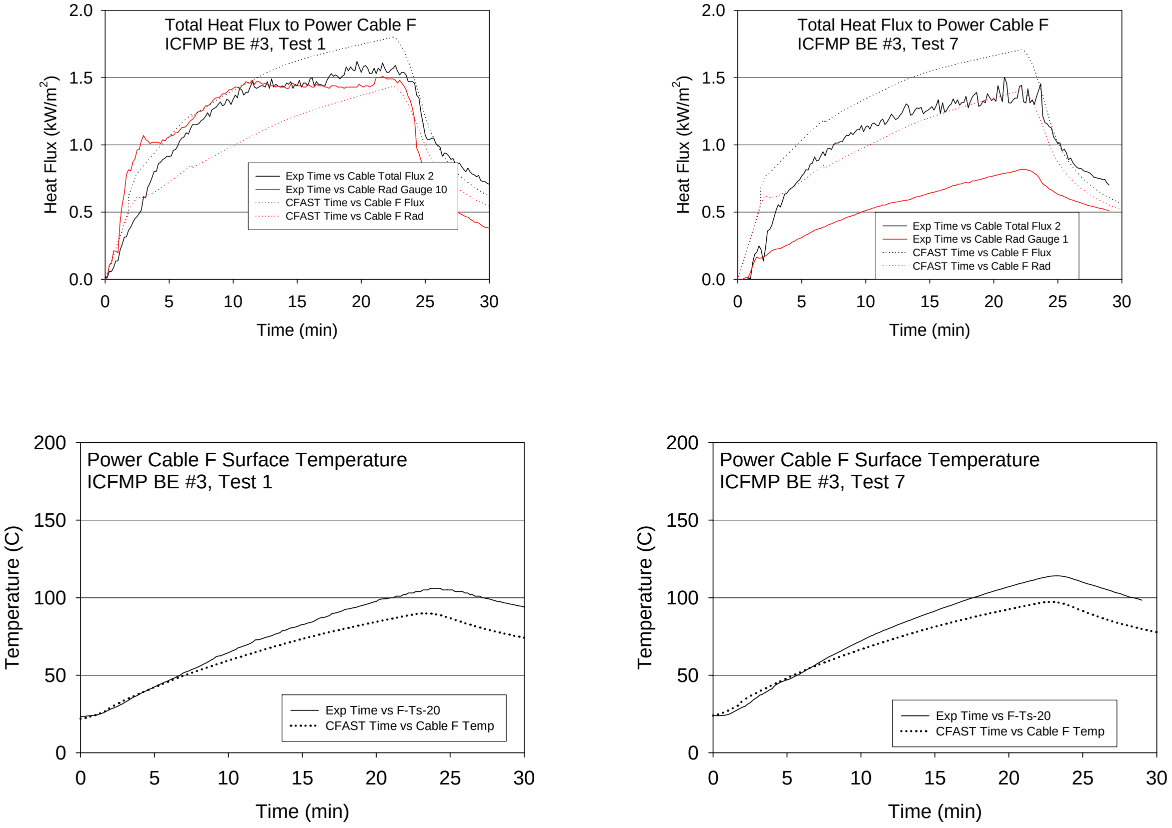


Figure A-40. Thermal environment near Power Cable F, ICFMP BE #3, Tests 1 and 7.

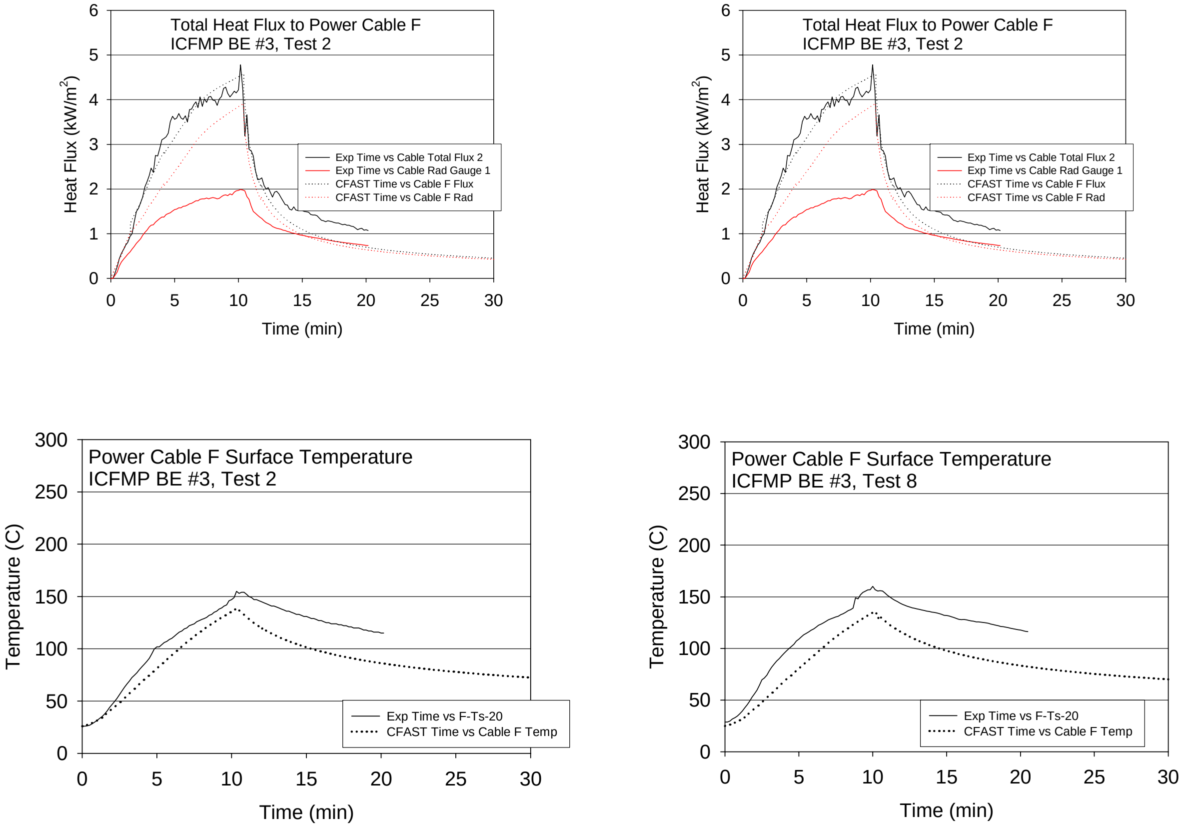


Figure A-41. Thermal environment near Power Cable F, ICFMP BE #3, Tests 2 and 8.

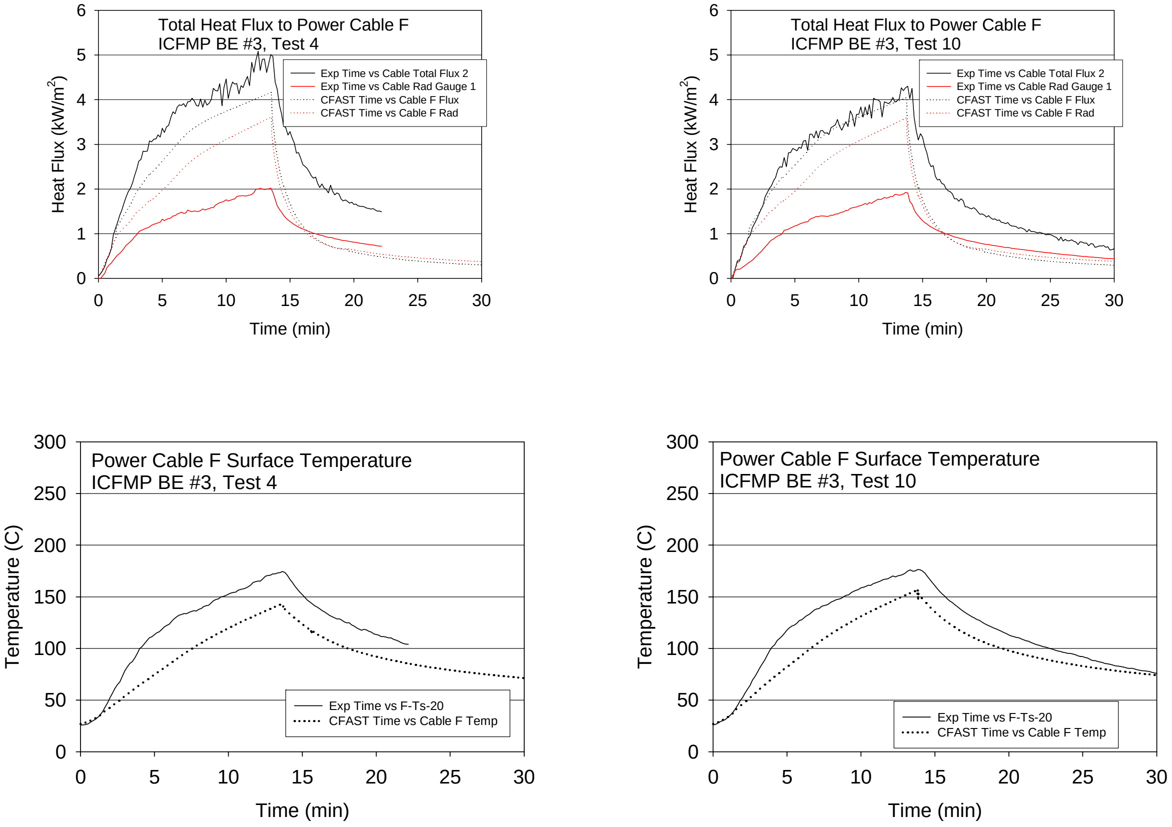


Figure A-42. Thermal environment near Power Cable F, ICFMP BE #3, Tests 4 and 10.

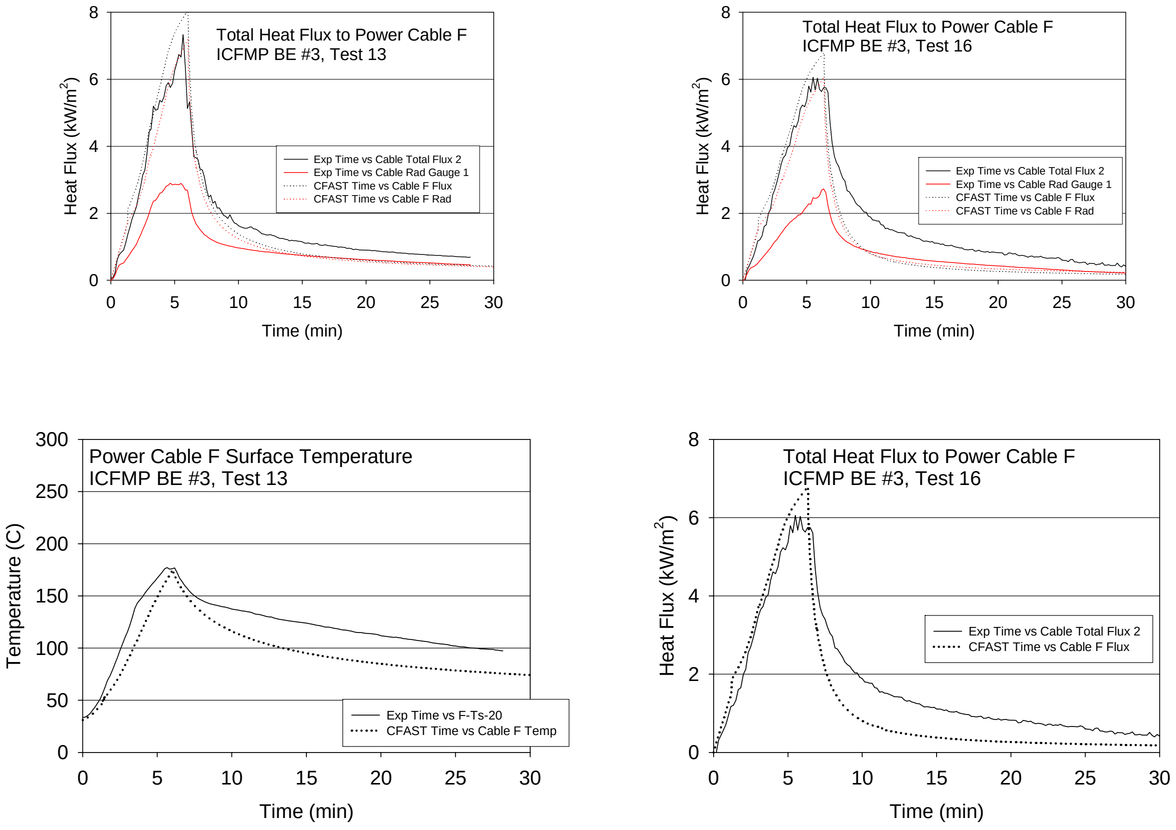


Figure A-43. Thermal environment near Power Cable F, ICFMP BE #3, Tests 13 and 16.

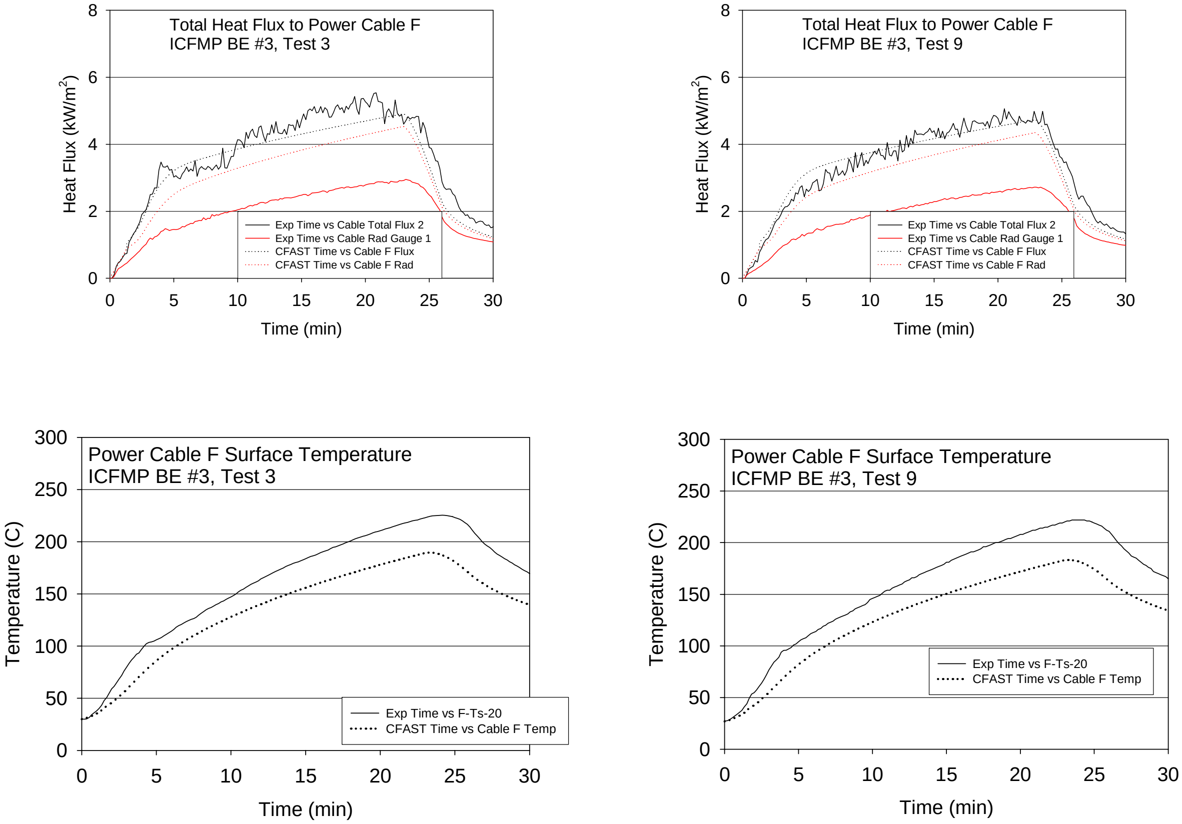


Figure A-44. Thermal environment near Power Cable F, ICFMP BE #3, Tests 3 and 9.

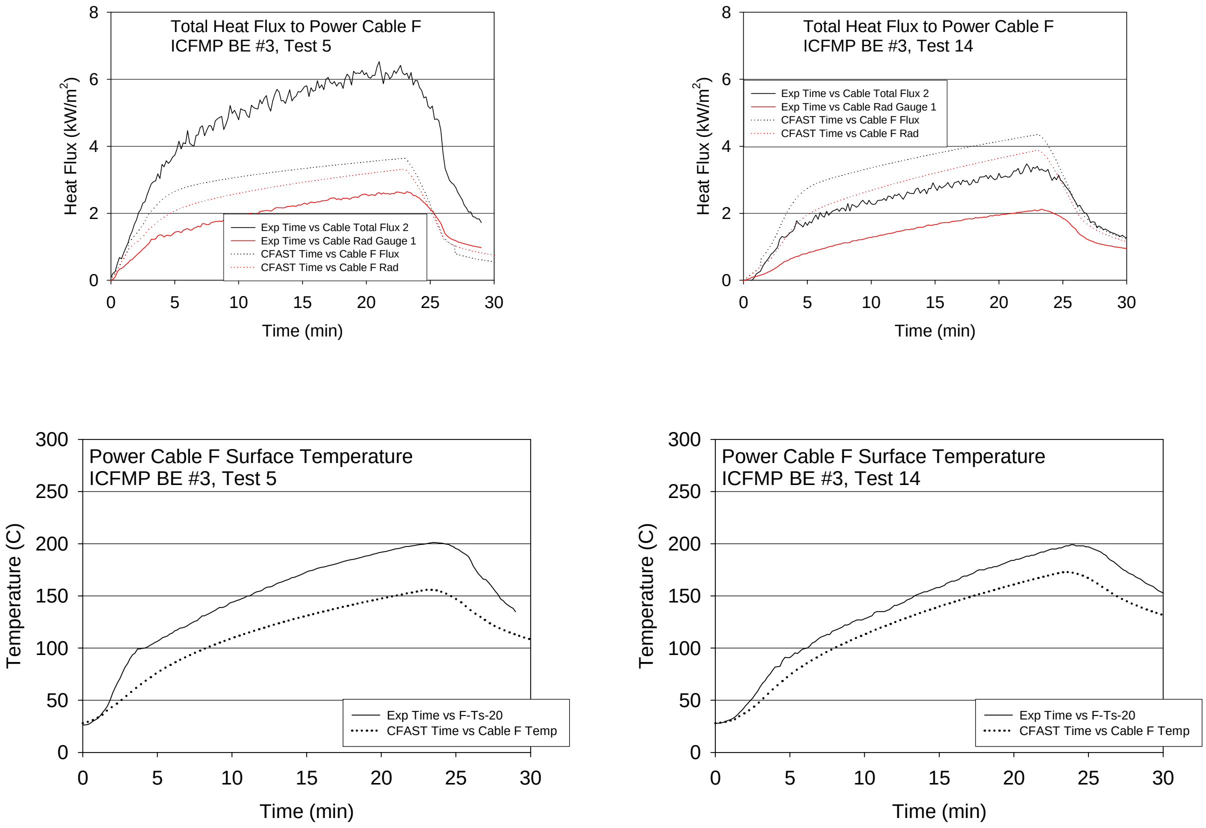


Figure A-45. Thermal environment near Power Cable F, ICFMP BE #3, Tests 5 and 14.

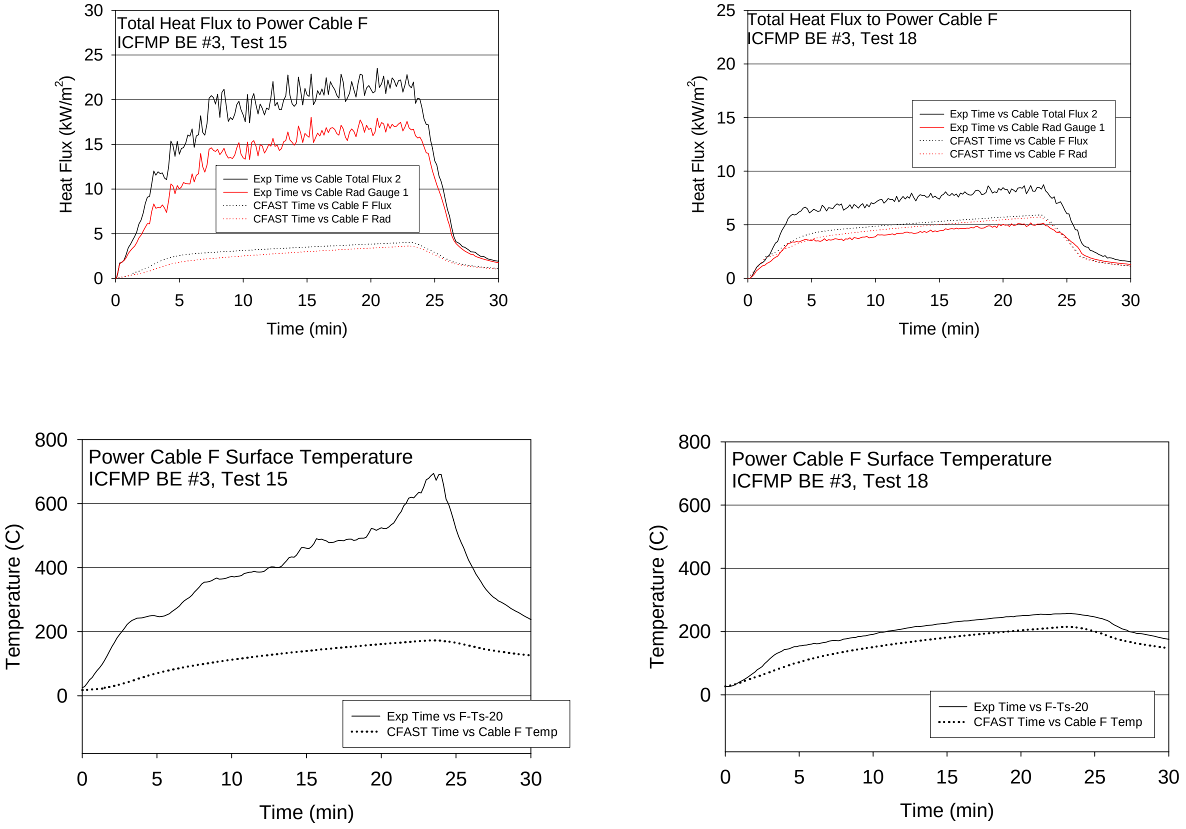


Figure A-46. Thermal environment near Power Cable F, ICFMP BE #3, Tests 15 and 18.

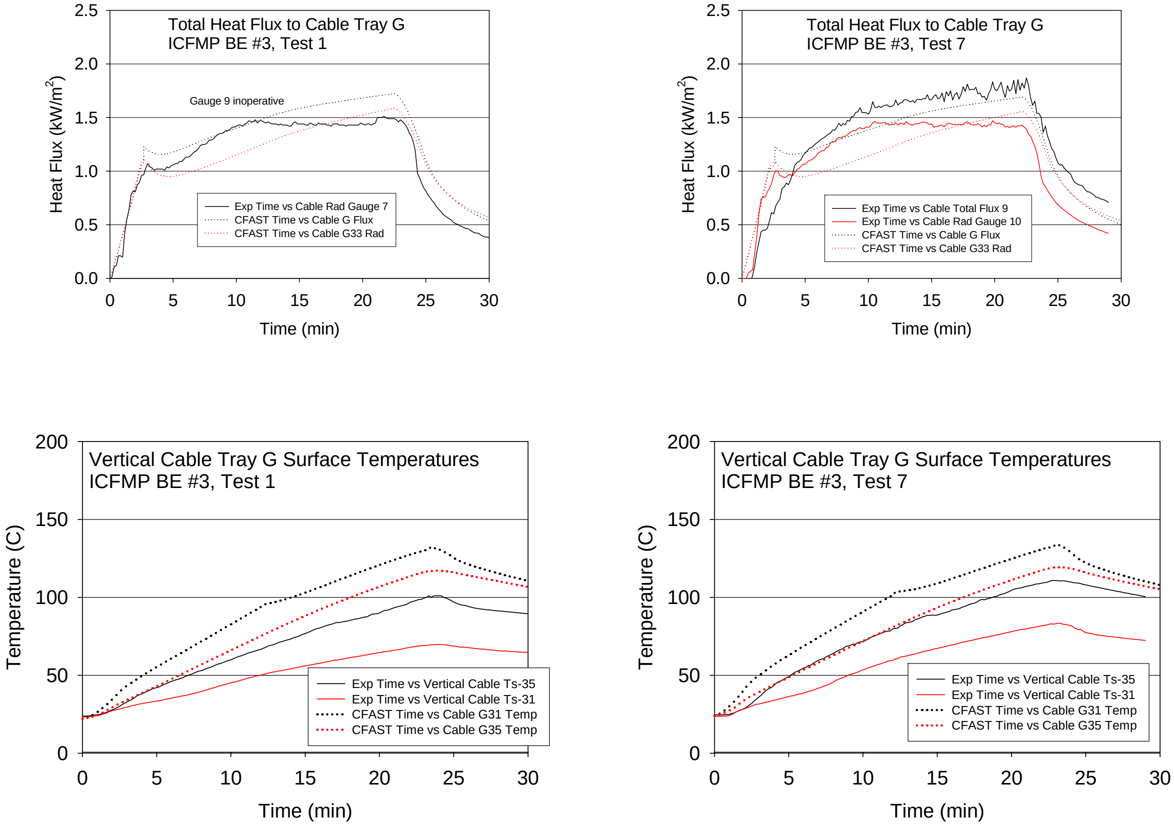


Figure A-47. Thermal environment near Vertical Cable Tray G, ICFMP BE #3, Tests 1 and 7.

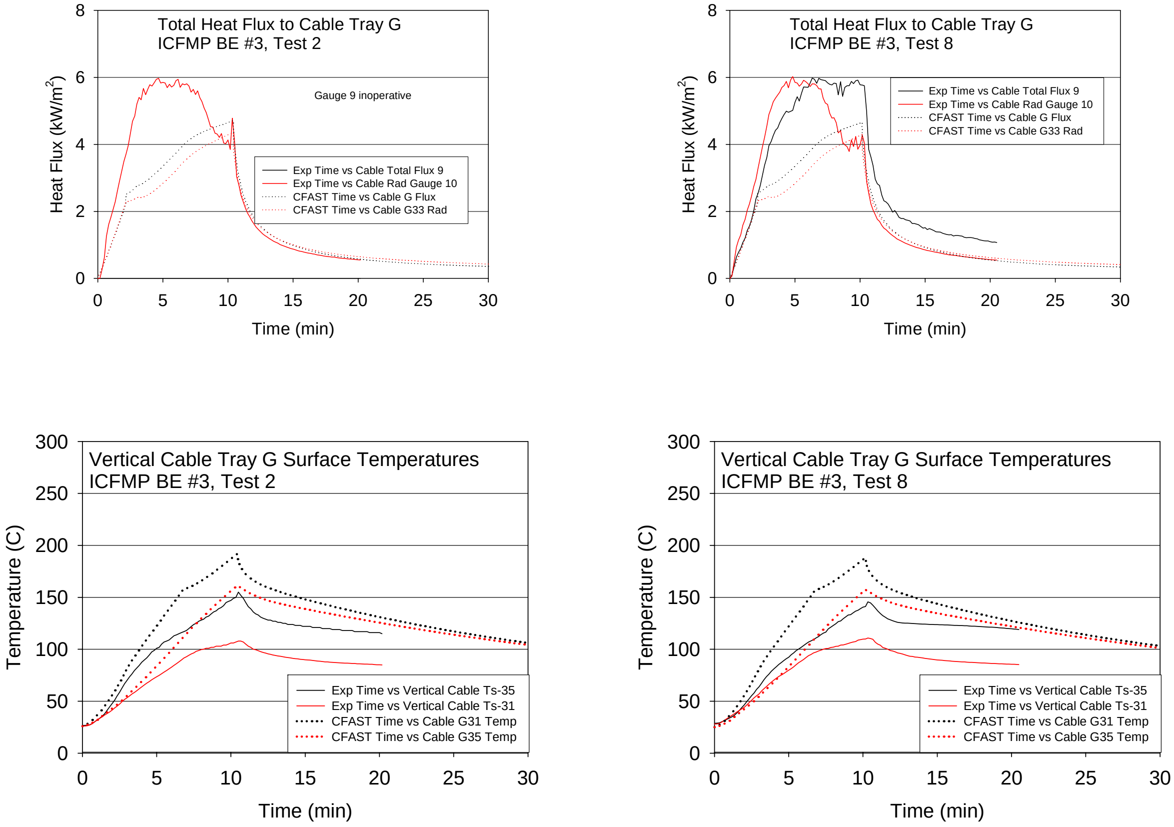


Figure A-48. Thermal environment near Vertical Cable Tray G, ICFMP BE #3, Tests 2 and 8.

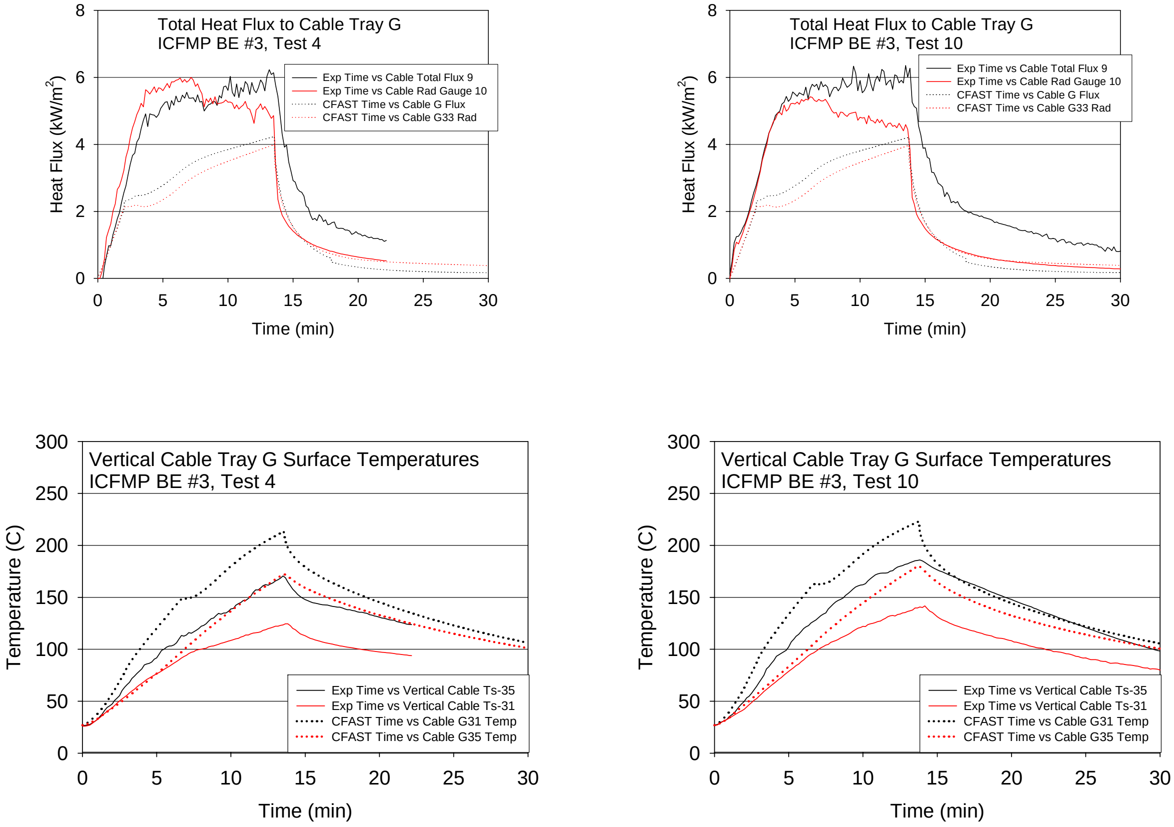


Figure A-49. Thermal environment near Vertical Cable Tray G, ICFMP BE #3, Tests 4 and 10.

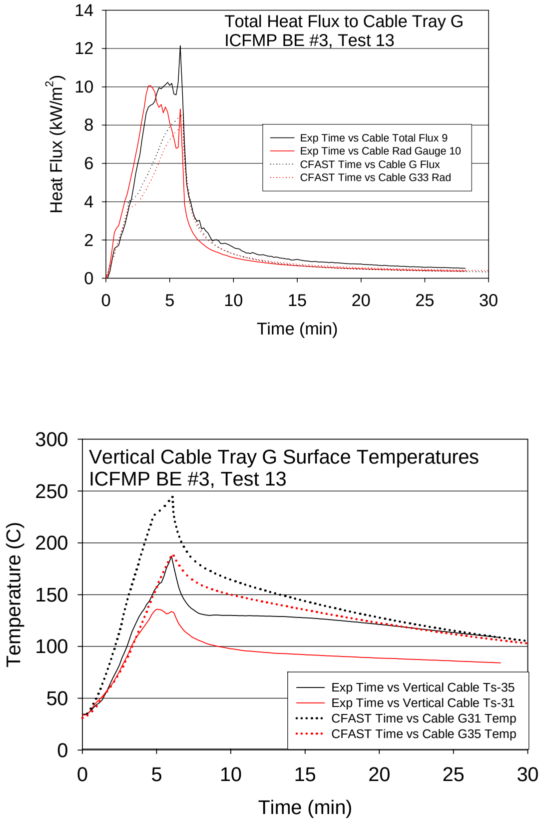


Figure A-50. Thermal environment near Vertical Cable Tray G, ICFMP BE #3, Tests 13 and 16.

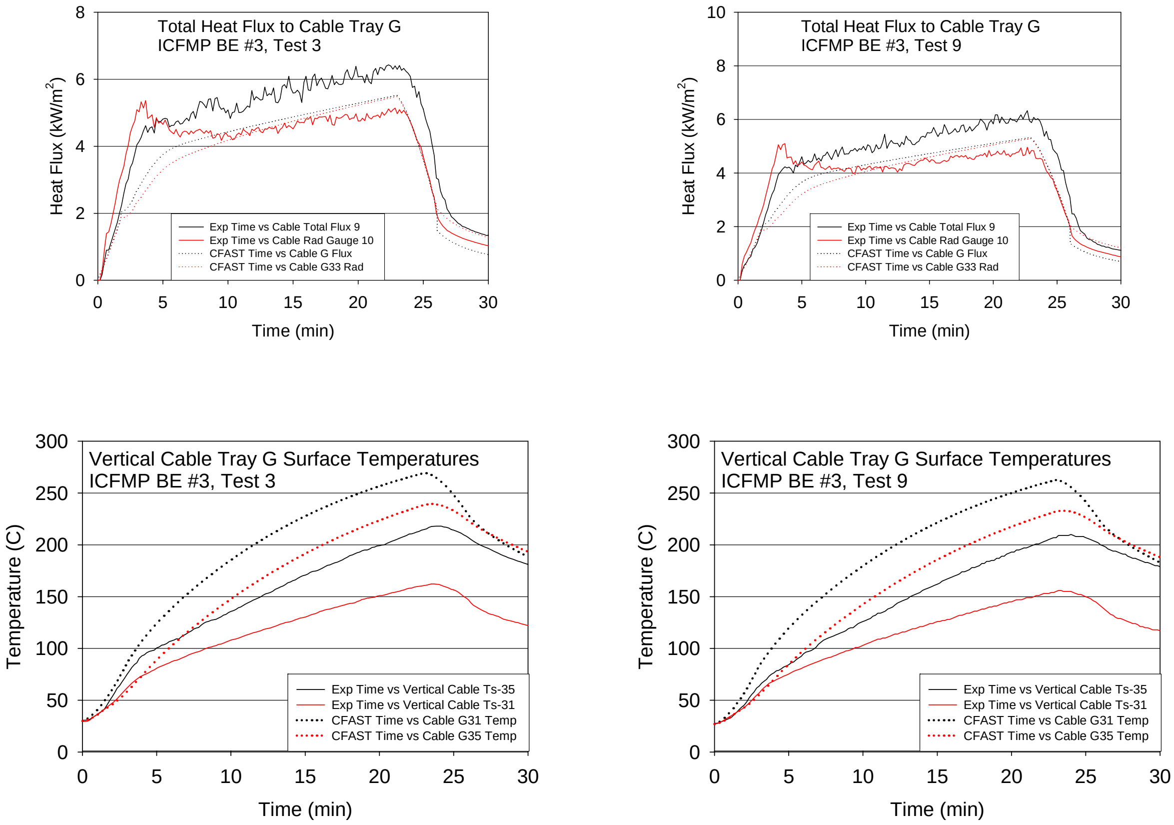


Figure A-51. Thermal environment near Vertical Cable Tray G, ICFMP BE #3, Tests 3 and 9.

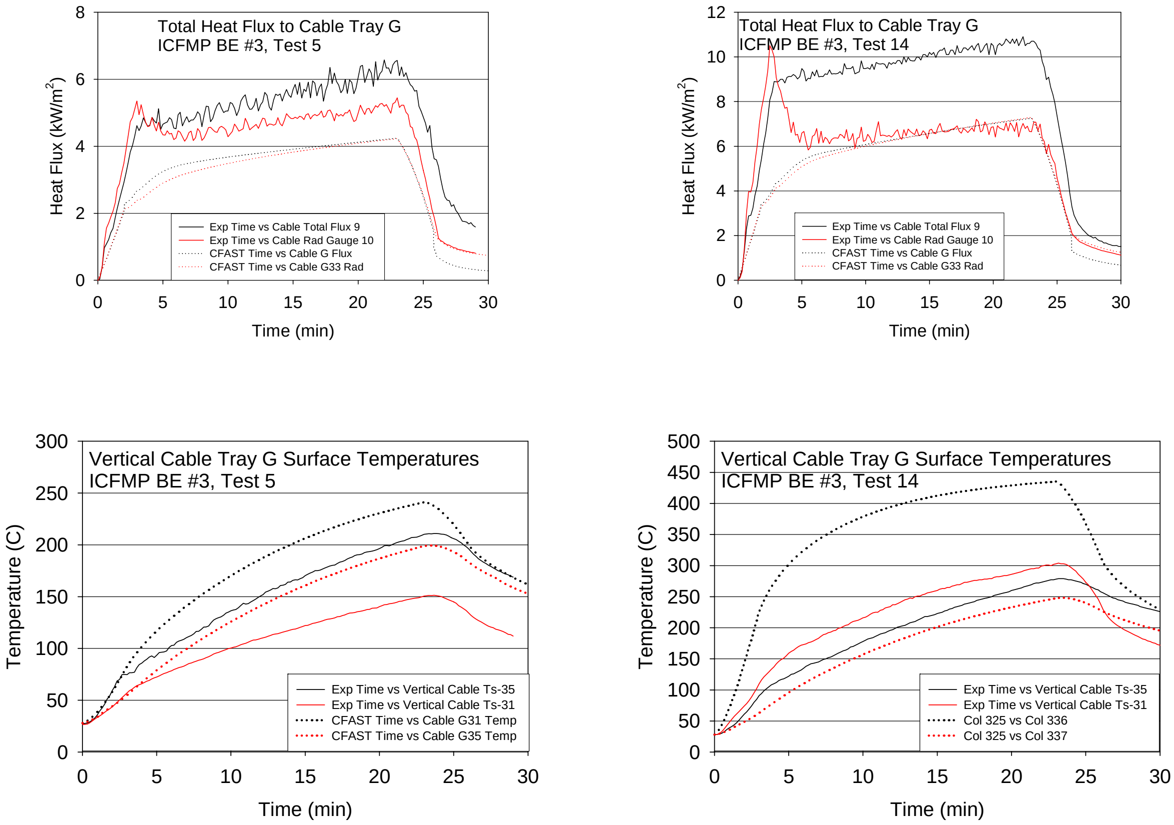


Figure A-52. Thermal environment near Vertical Cable Tray G, ICFMP BE #3, Tests 5 and 14.

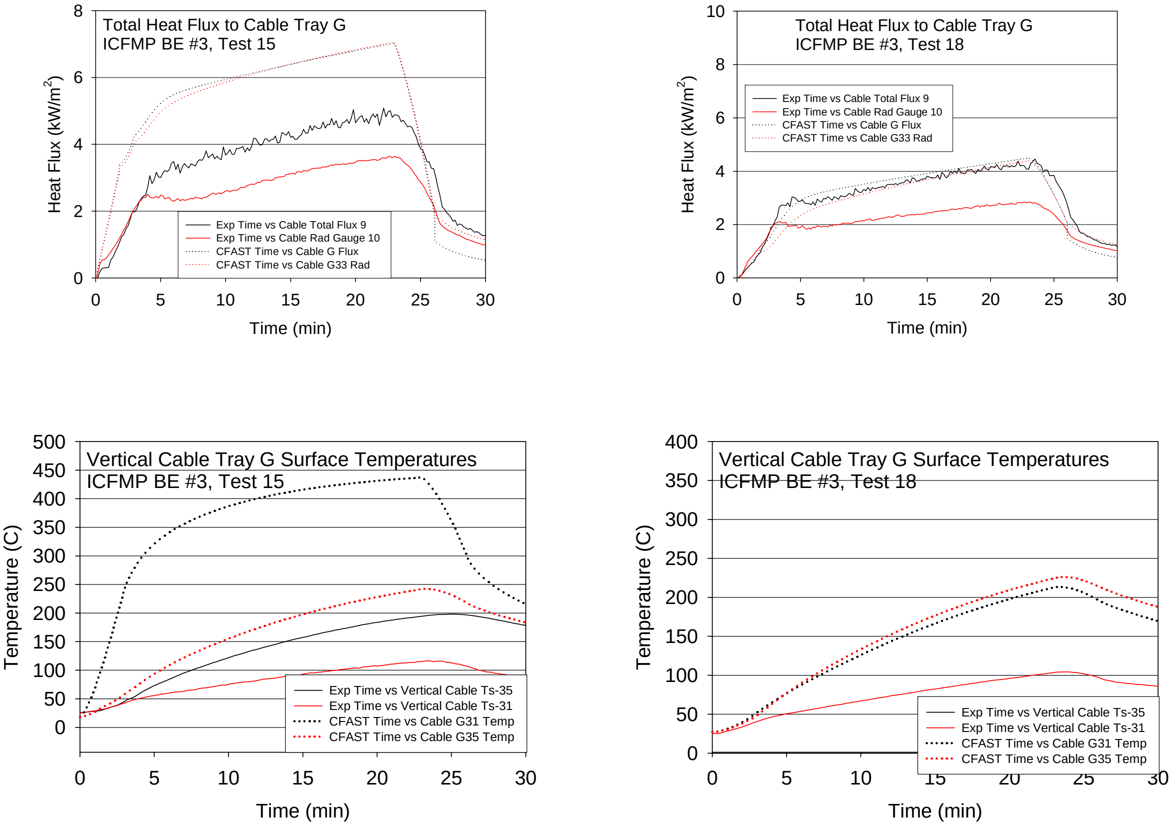


Figure A-53. Thermal environment near Vertical Cable Tray G, ICFMP BE #3, Tests 15 and 18.

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.

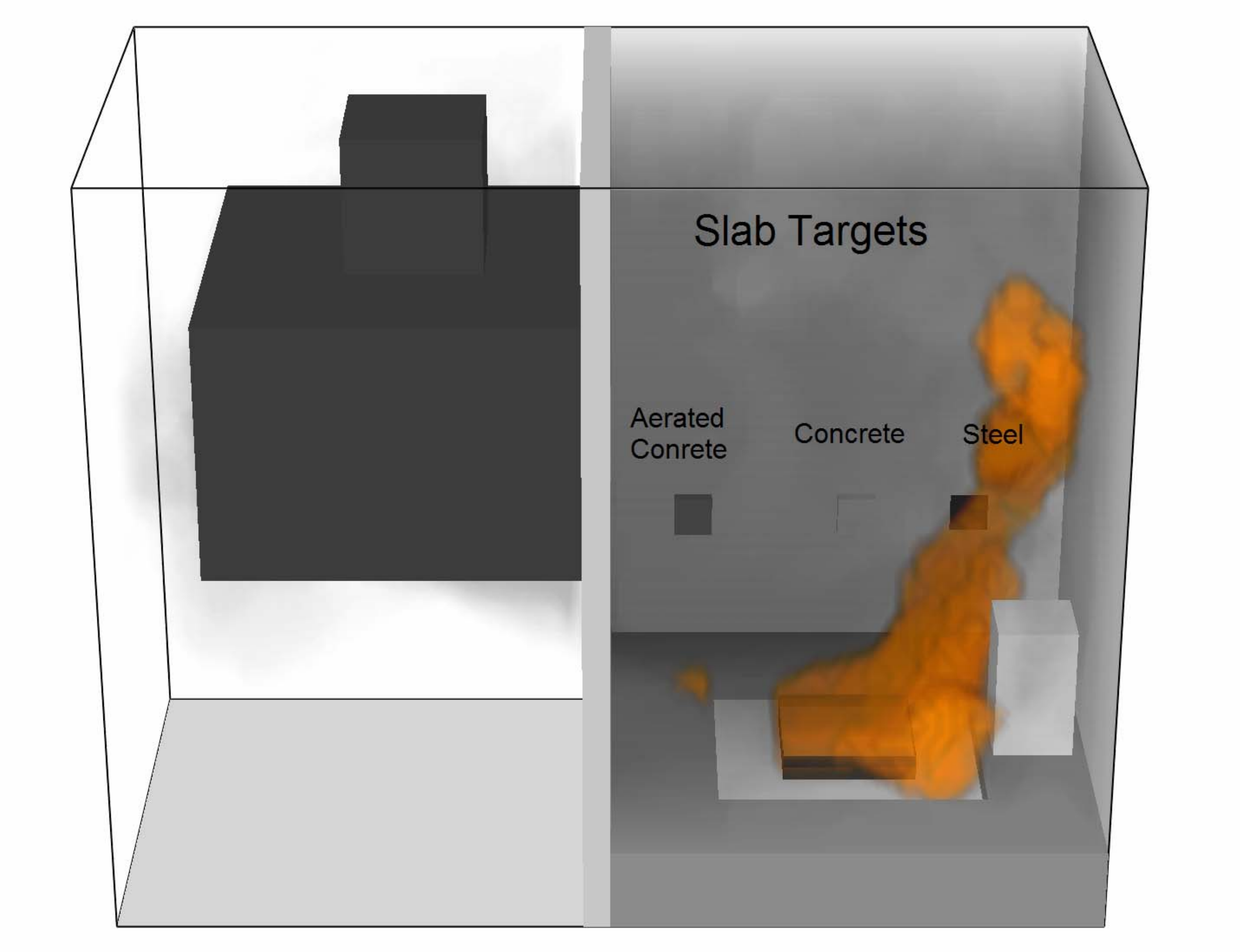


Figure A-54. Location of 3 slab targets in ICFMP BE #4.

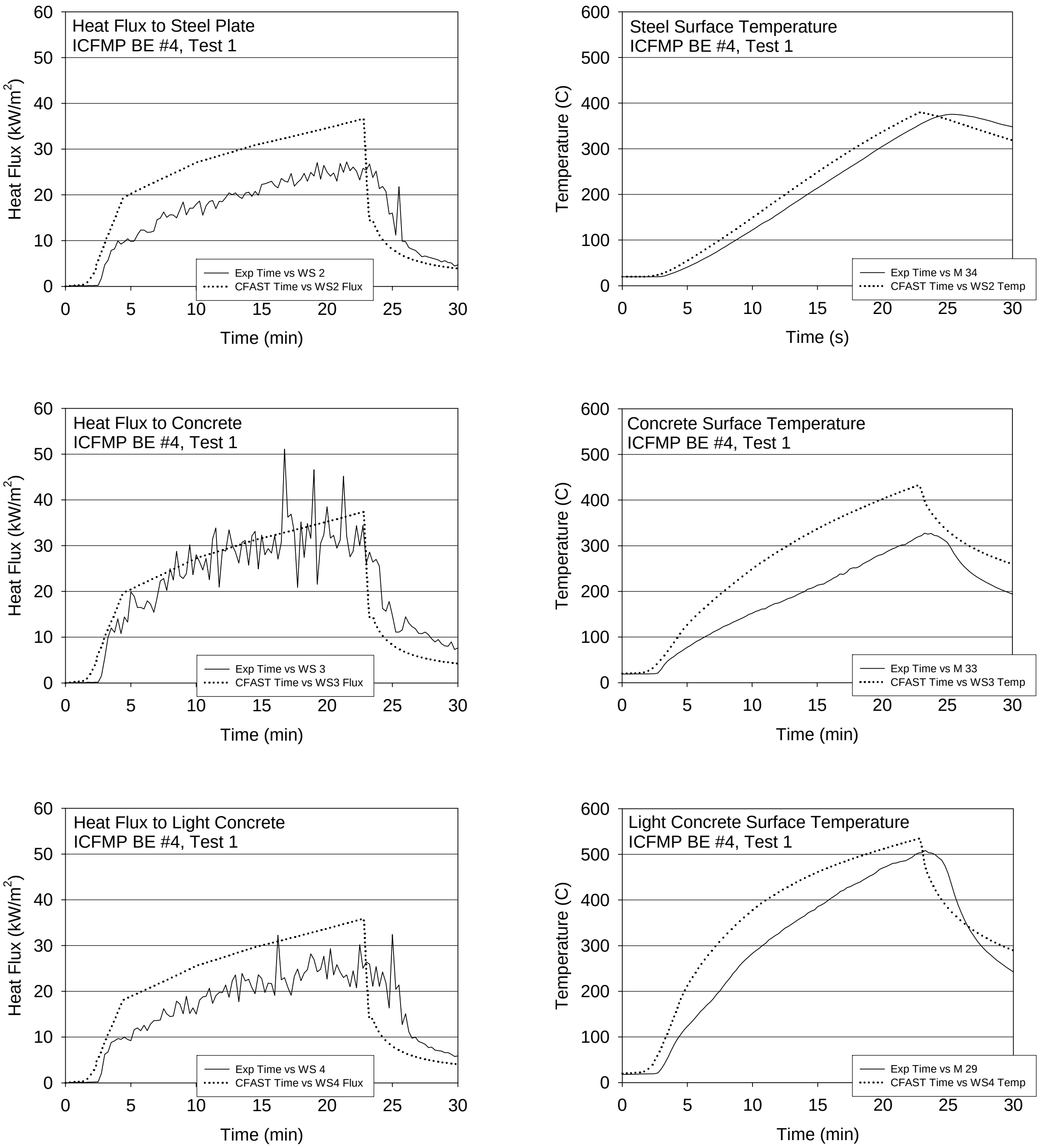


Figure A-55. Heat Flux and Surface Temperatures of Target Slabs, ICFMP BE #4, Test 1.

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, the other, control. On the following pages are plots of the gas temperature, heat flux and cable surface temperatures at three vertical locations along the tray.

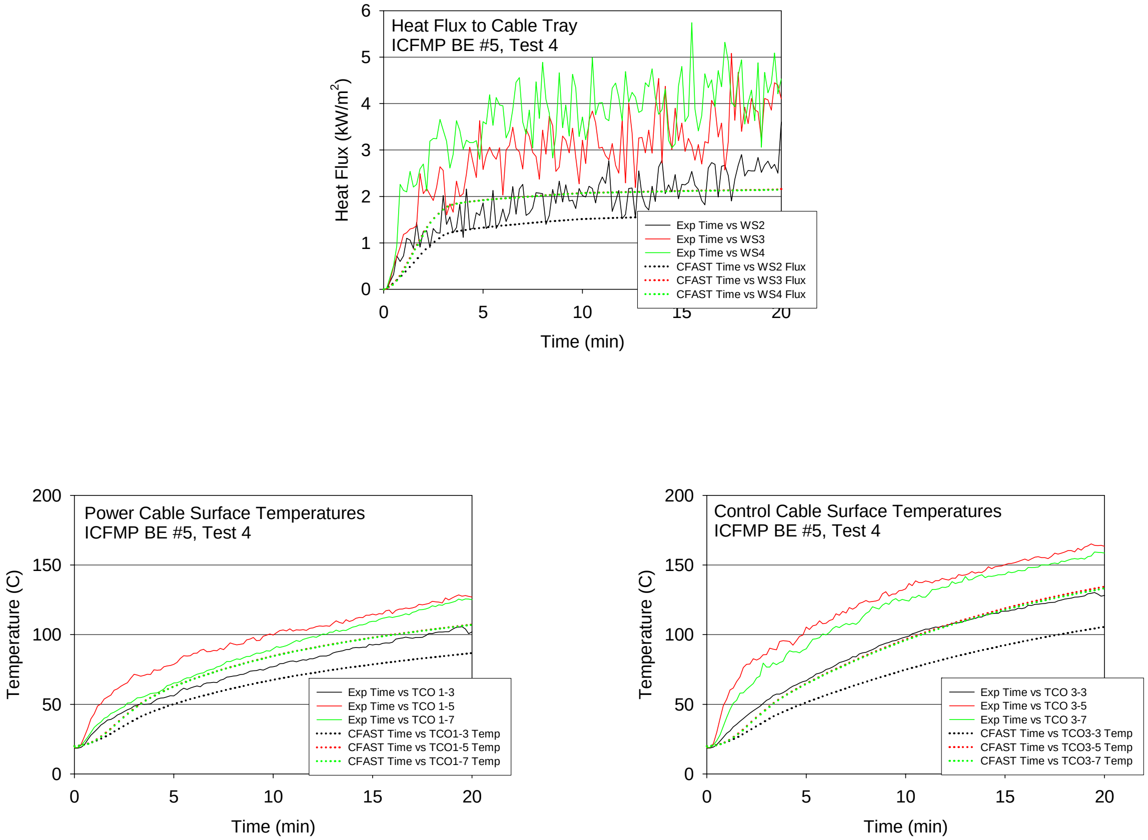


Figure A-56. Thermal environment near Vertical Cable Tray, ICFMP BE #5, Test 4.

Table A-5. 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	2.4	85	2.4	3.0	27			
		D	1.5	2.5	67	3.3	3.1	-5			
		F	0.9	2.1	143	1.9	2.8	51			
		G33	2.4	2.6	8	3.1	3.1	1			
	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

			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 (%)
	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
		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	-53	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, only here the focus is on compartment walls, ceiling 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. Over 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 is 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. FDS has an option for outputting the net heat flux, but this output cannot be compared directly with the measured net heat flux because the predicted and measured wall temperatures can differ, and this will affect the heat flux. In a sense, the net heat flux and surface temperature are coupled, and it is difficult to assess the accuracy of the models if the two quantities cannot be uncoupled. For the purpose of comparing prediction and measurement, the following correction was applied to both the measured and predicted net heat fluxes:

$$\dot{q}''_{total} = q''_{net} + \sigma(T_s^4 - T_\infty^4) + h(T_s - T_\infty)$$

T_s is the temperature of the surface. A constant convective heat transfer coefficient is assumed (5 W/m^2/K) and an emissivity of 1. After applying the correction, it is easier to heat fluxes independently of the surface temperature.

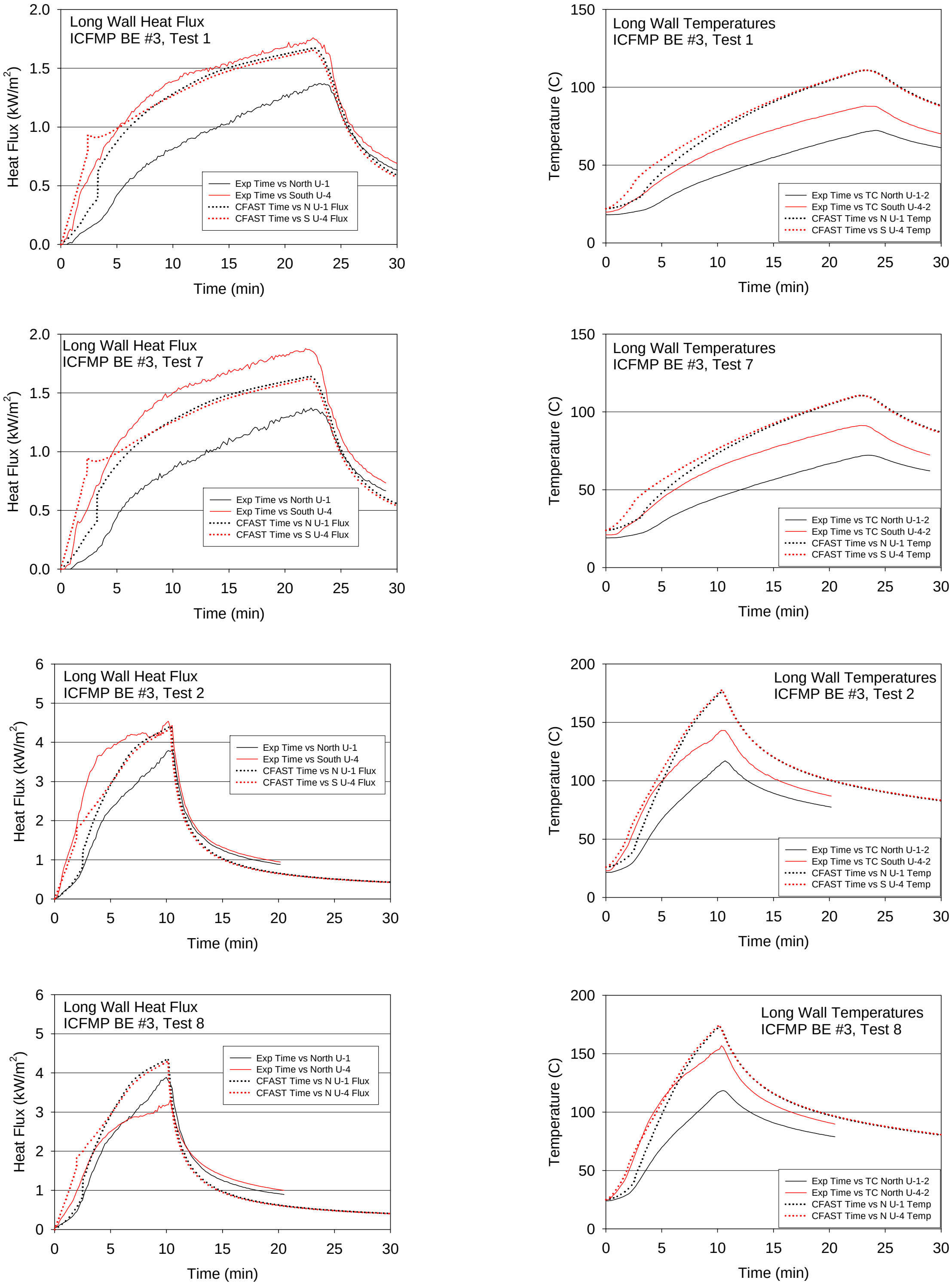


Figure A-57. Long wall heat flux and surface temperature, ICFMP BE #3, closed door tests.

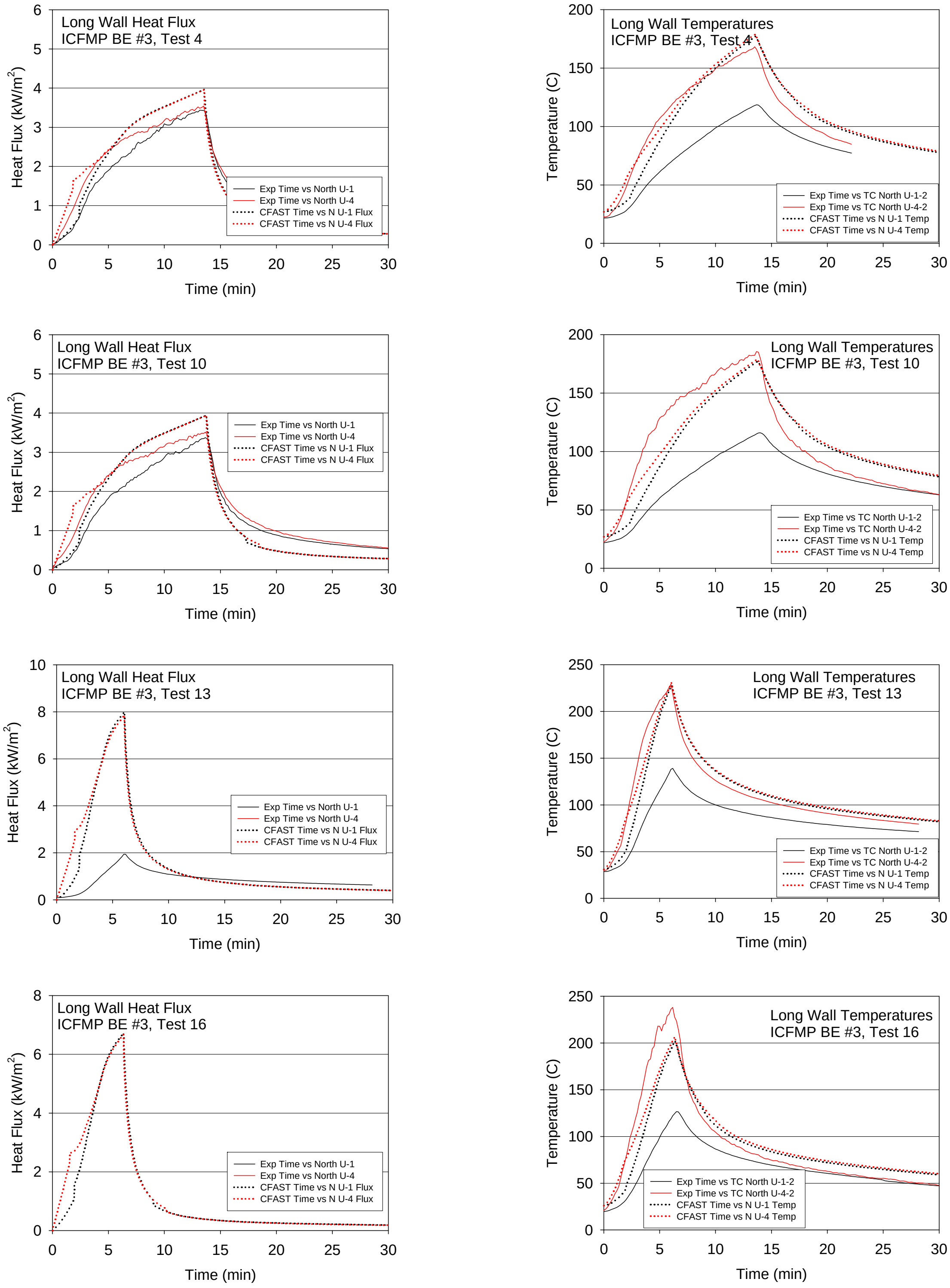
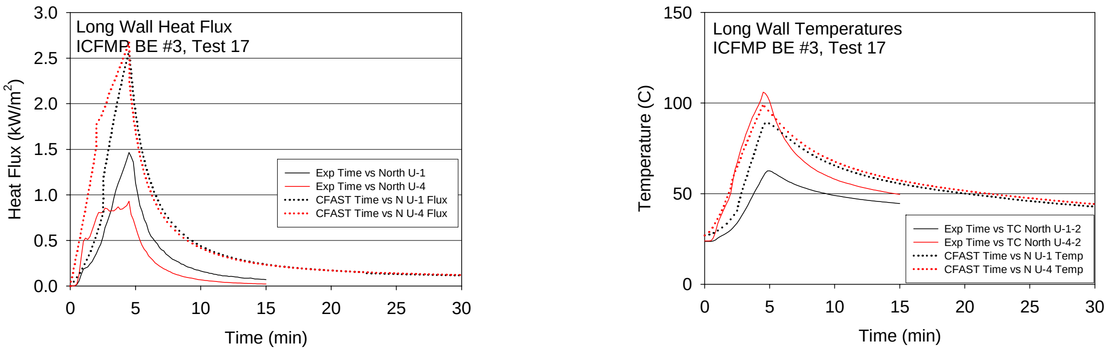


Figure A-58. Long wall heat flux and surface temperature, ICFMP BE #3, closed door tests.



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

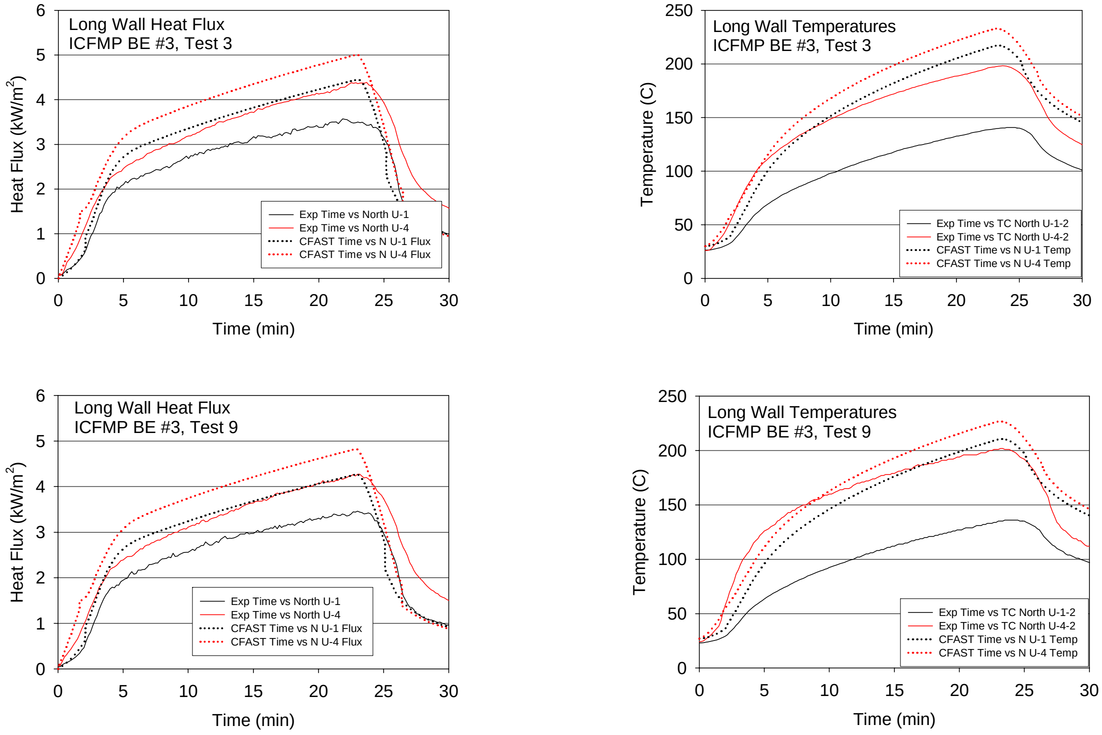


Figure A-59. Long wall heat flux and surface temperature, ICFMP BE #3, closed door tests.

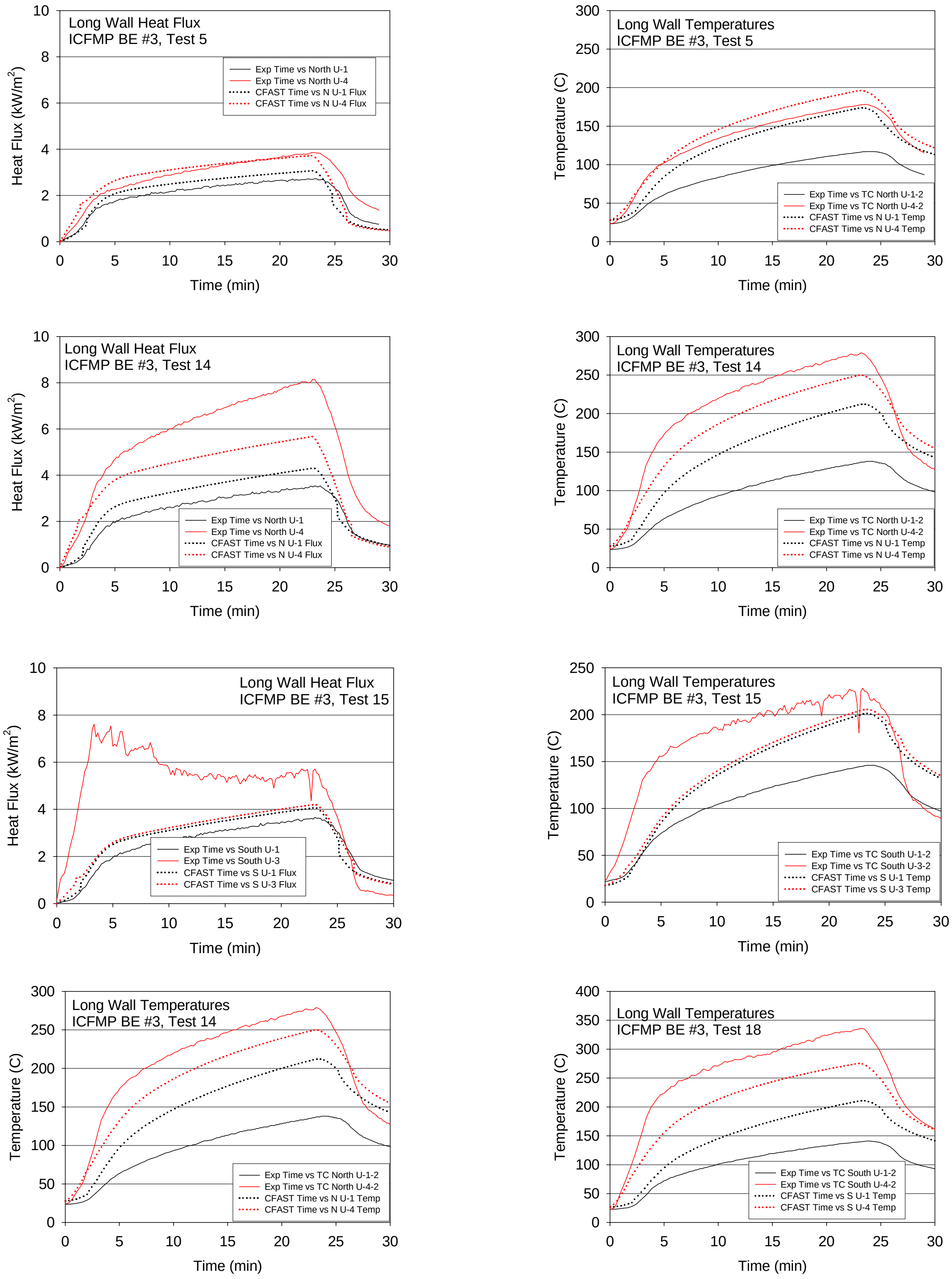


Figure A-60. Long wall heat flux and surface temperature, ICFMP BE #3, open door tests.

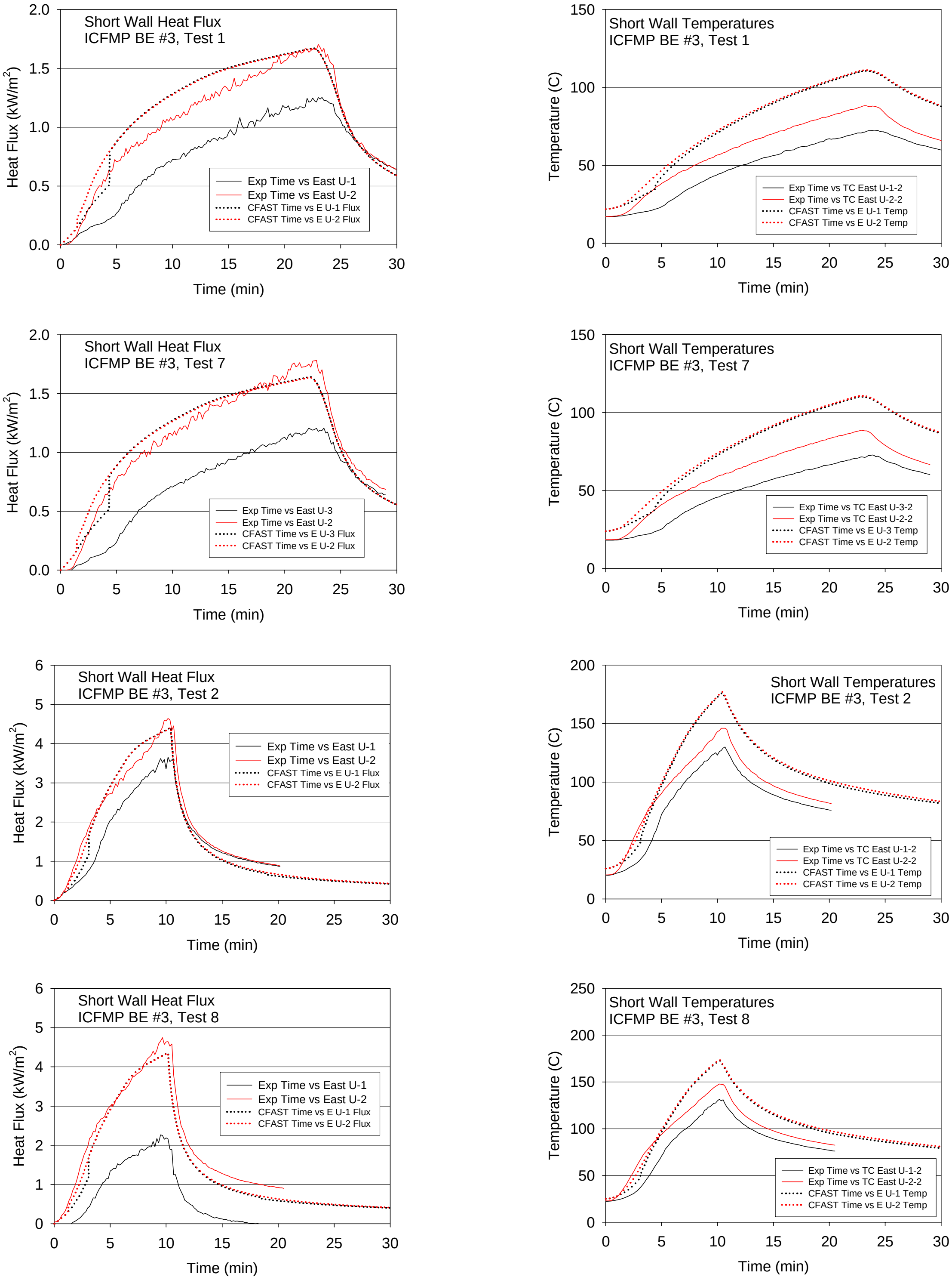


Figure A-61. Short wall heat flux and surface temperature, ICFMP BE #3, closed door tests.

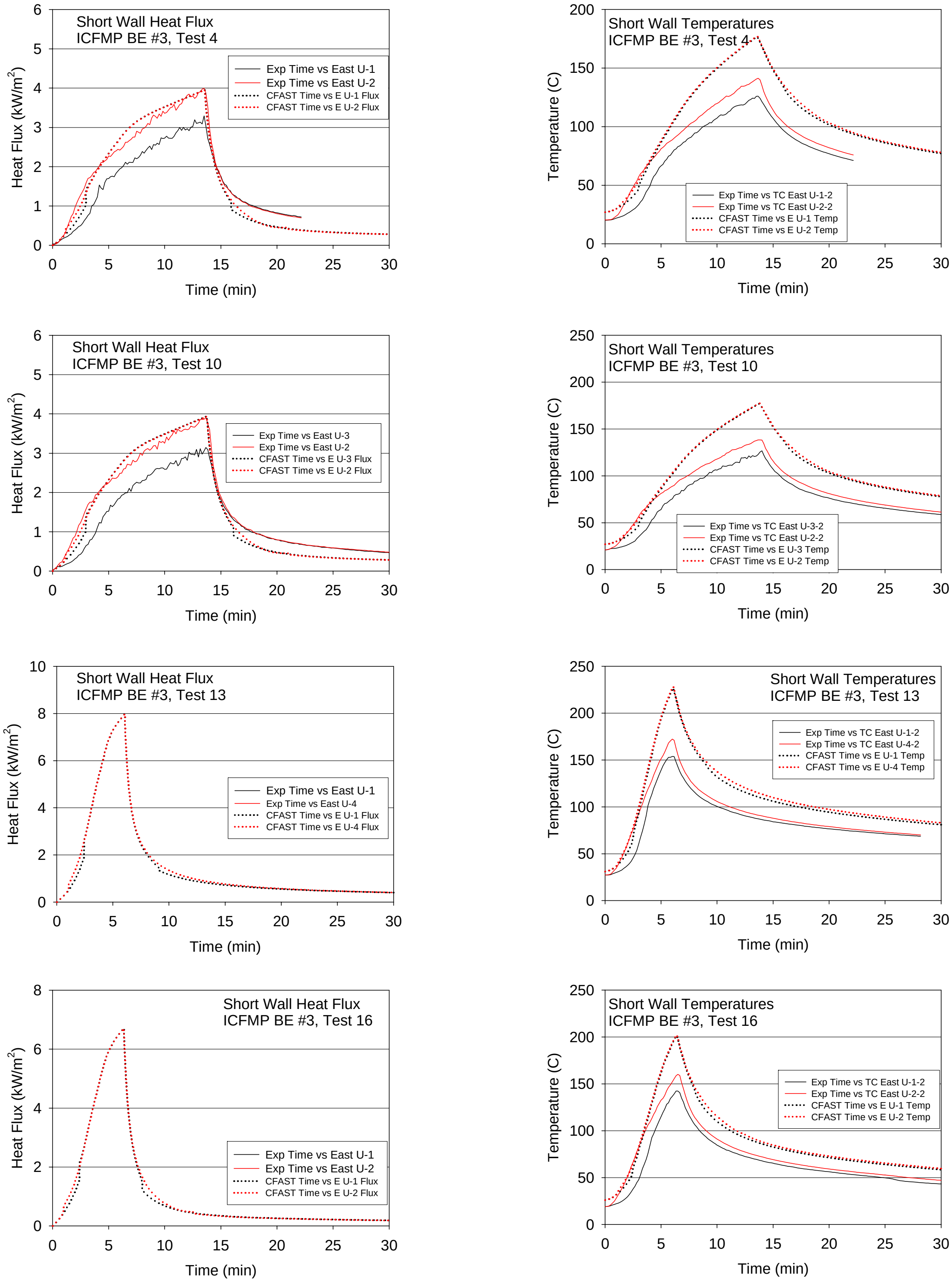
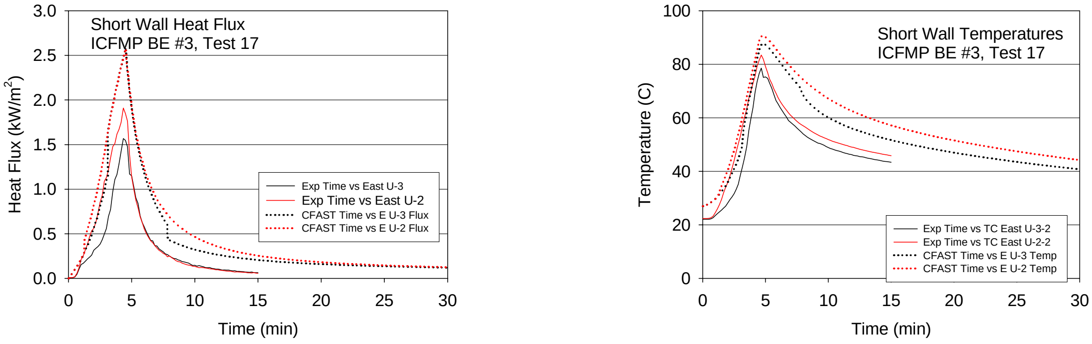


Figure A-62. Short wall heat flux and surface temperature, ICFMP BE #3, closed door tests.



Open Door Tests to Follow

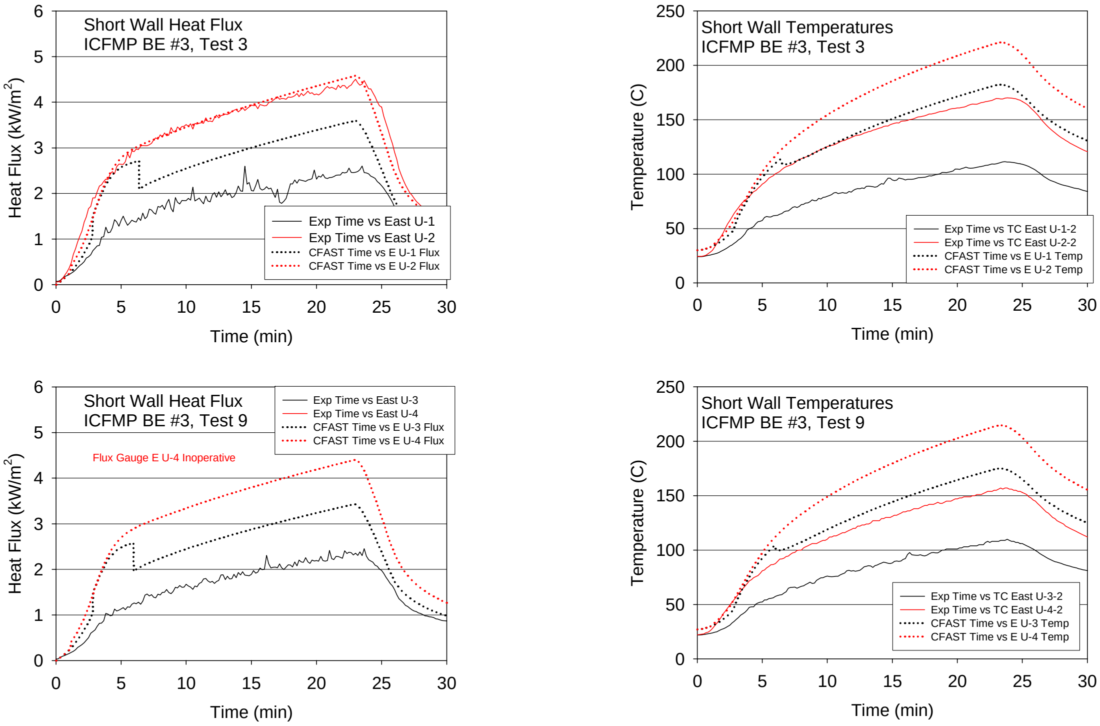


Figure A-63. Short wall heat flux and surface temperature, ICFMP BE #3, open door tests.

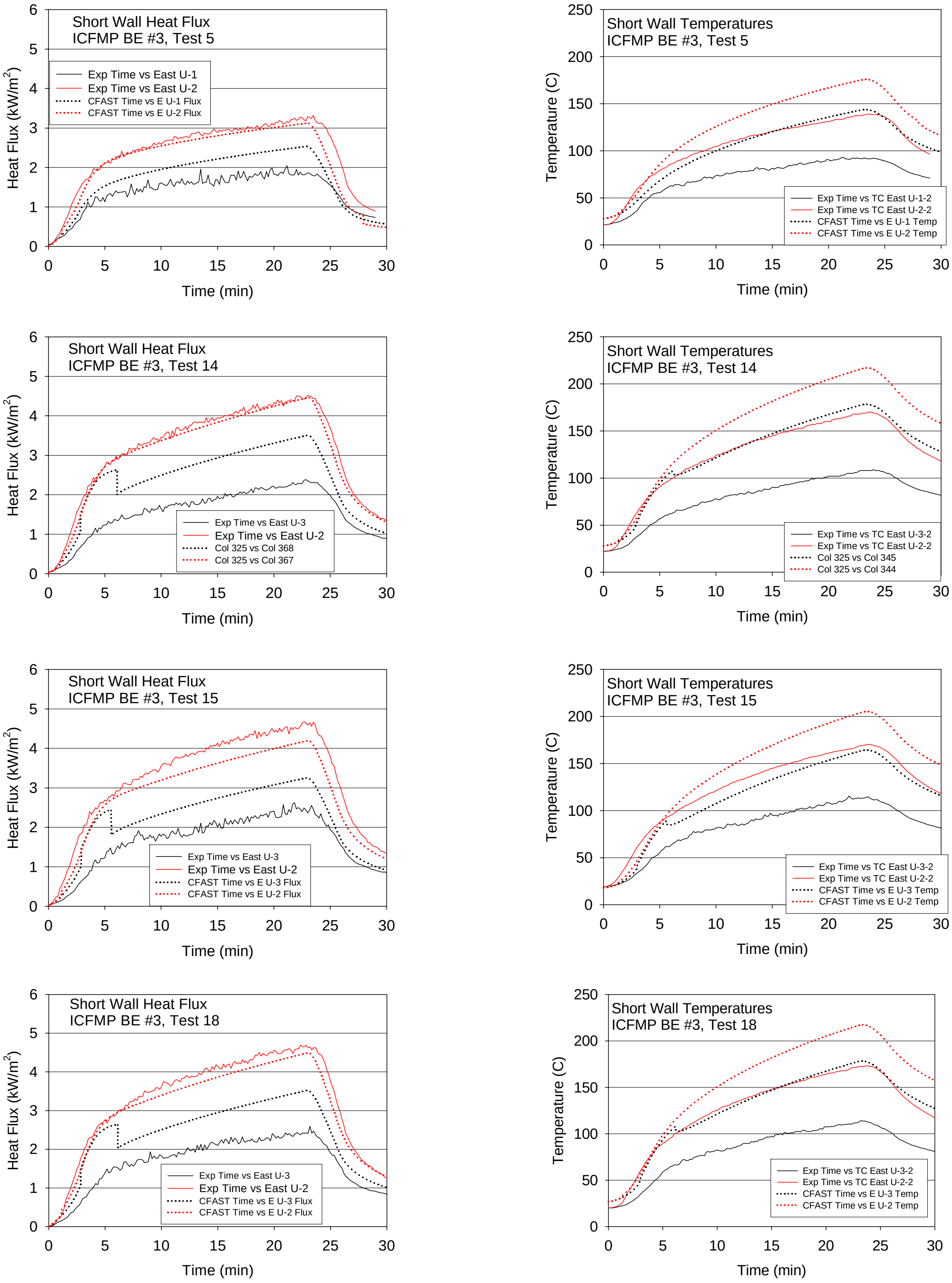


Figure A-64. Short wall heat flux and surface temperature, ICFMP BE #3, open door tests.

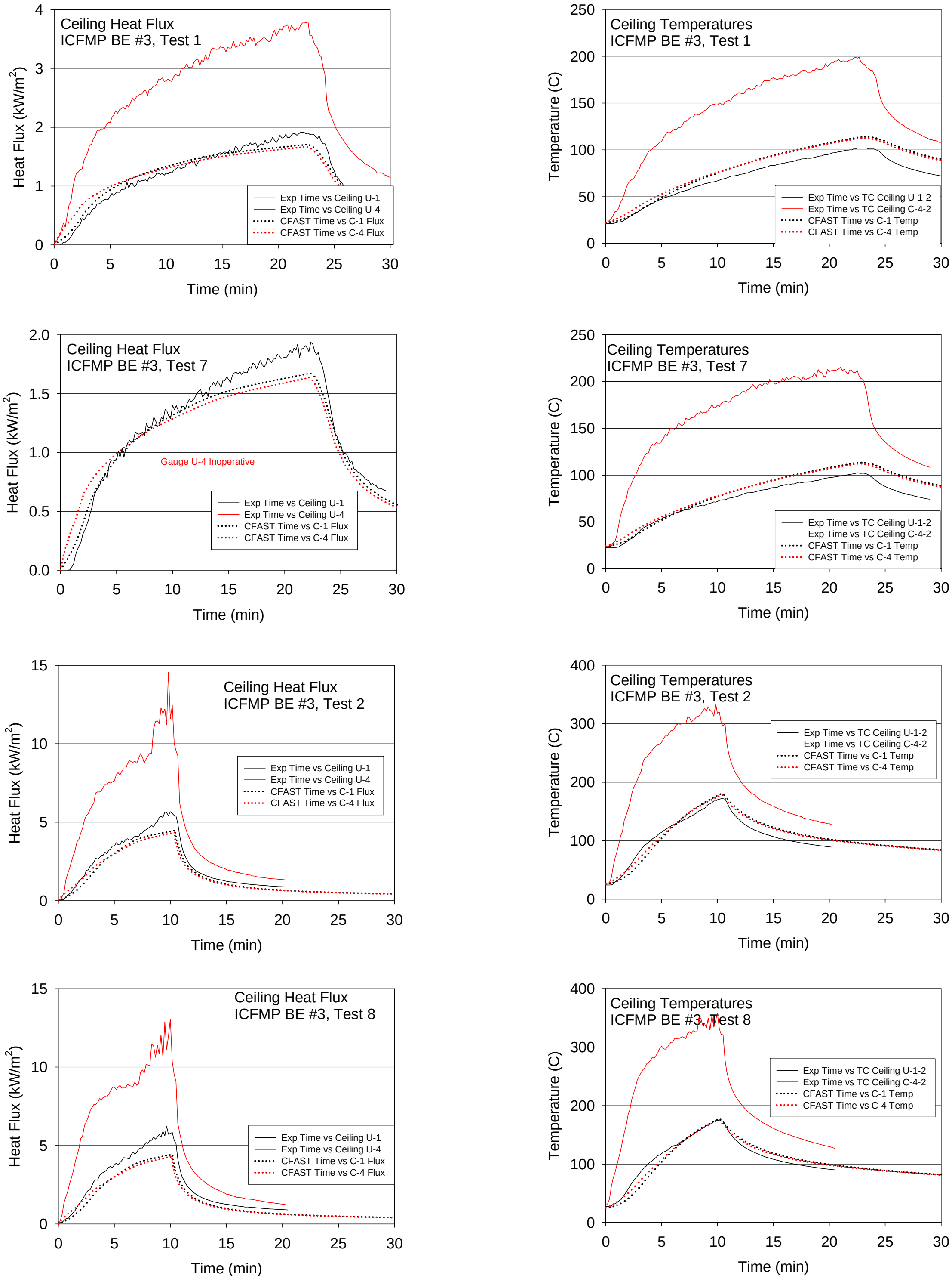


Figure A-65. Ceiling heat flux and surface temperature, ICFMP BE #3, closed door tests.

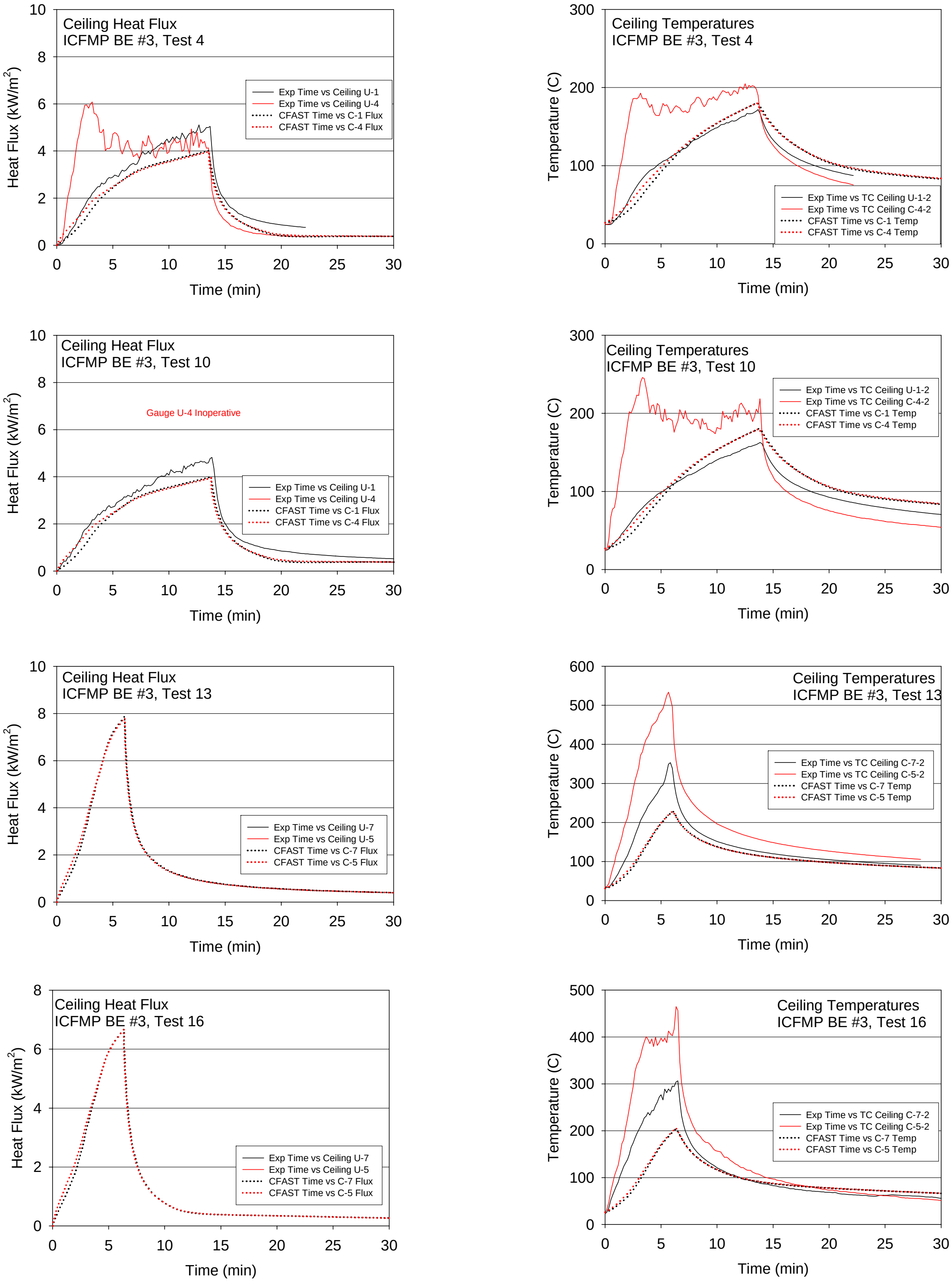
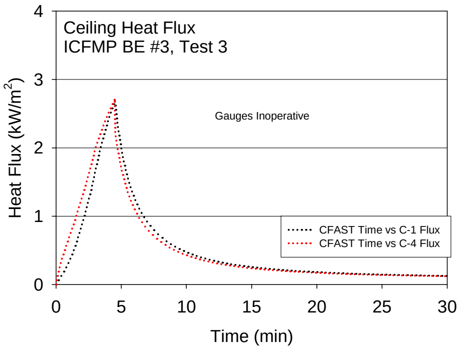
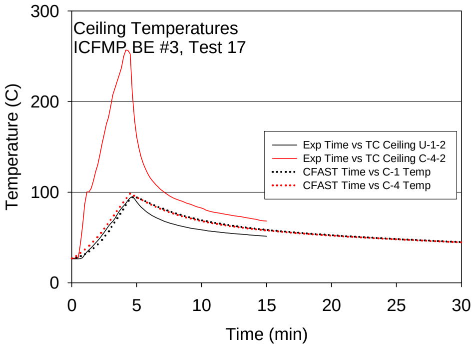


Figure A-66. Ceiling heat flux and surface temperature, ICFMP BE #3, closed door tests.





Open Door Tests to Follow

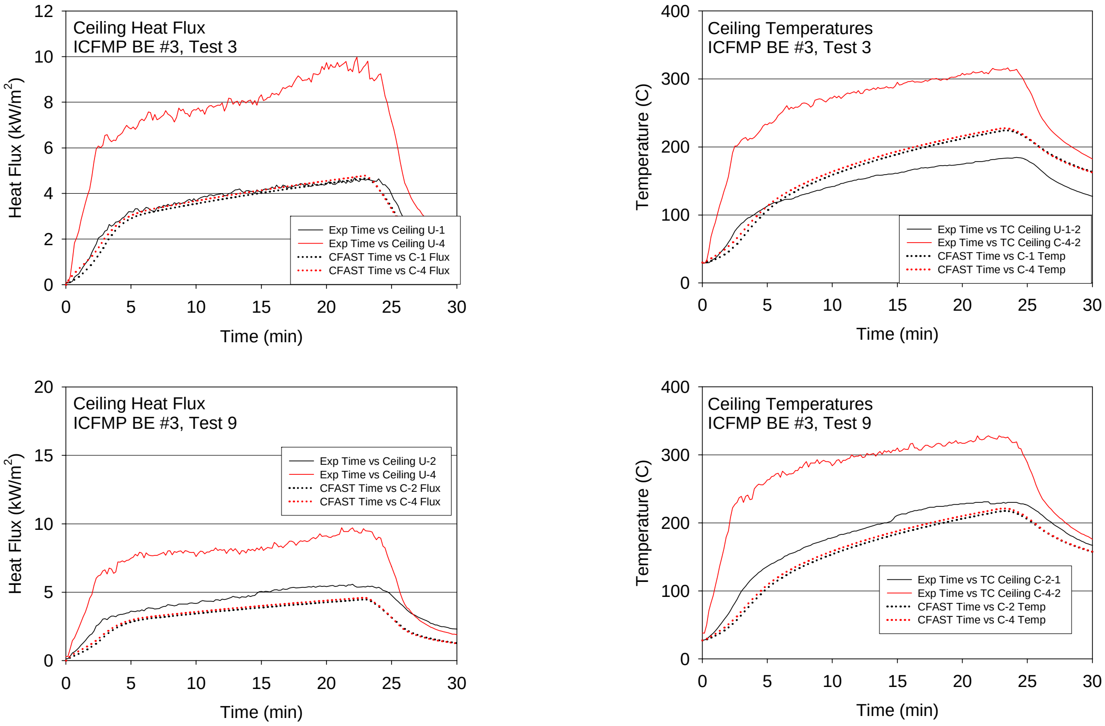


Figure A-67. Ceiling heat flux and surface temperature, ICFMP BE #3, open door tests.

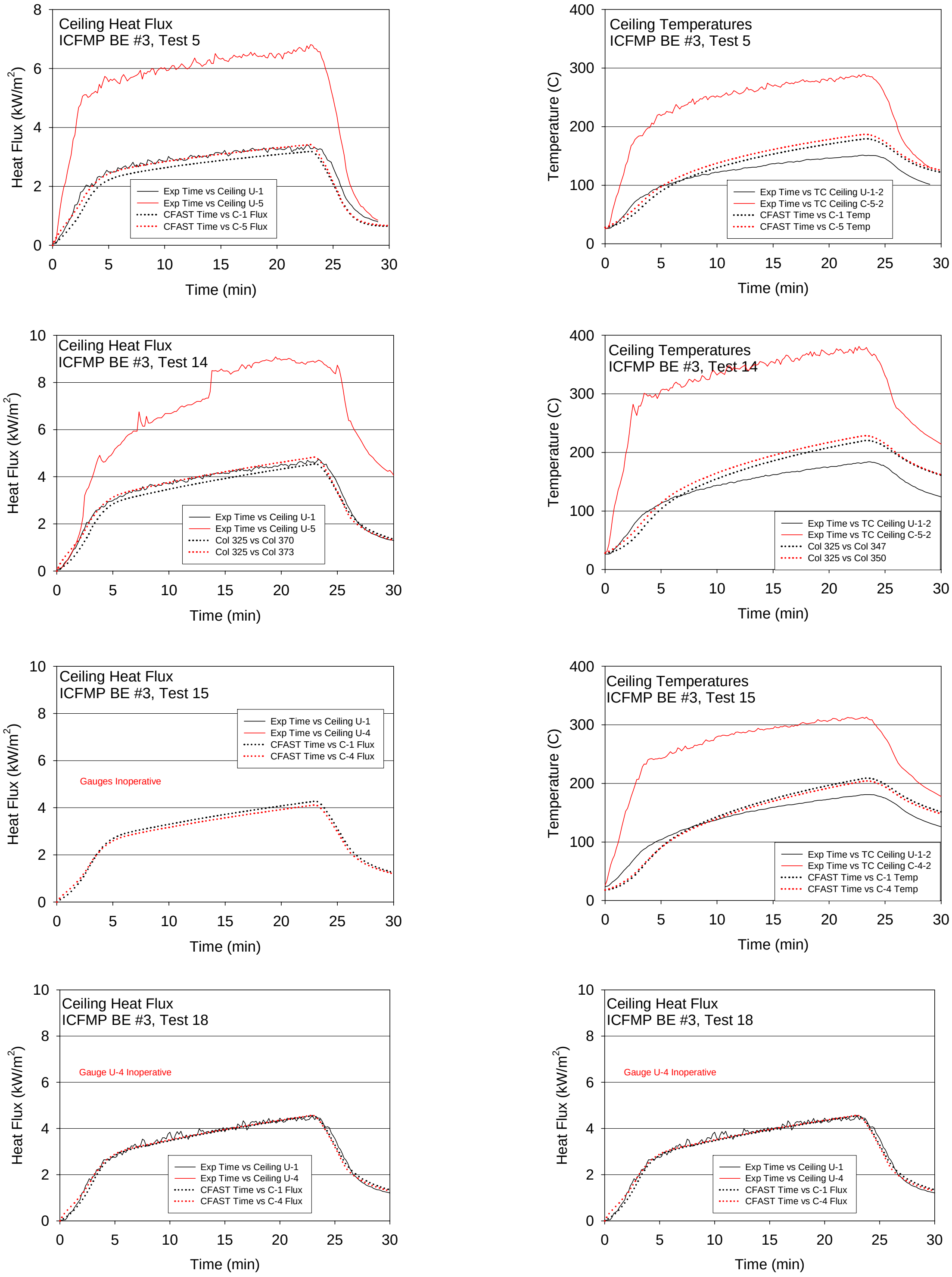


Figure A-68. Ceiling heat flux and surface temperature, ICFMP BE #3, open door tests.

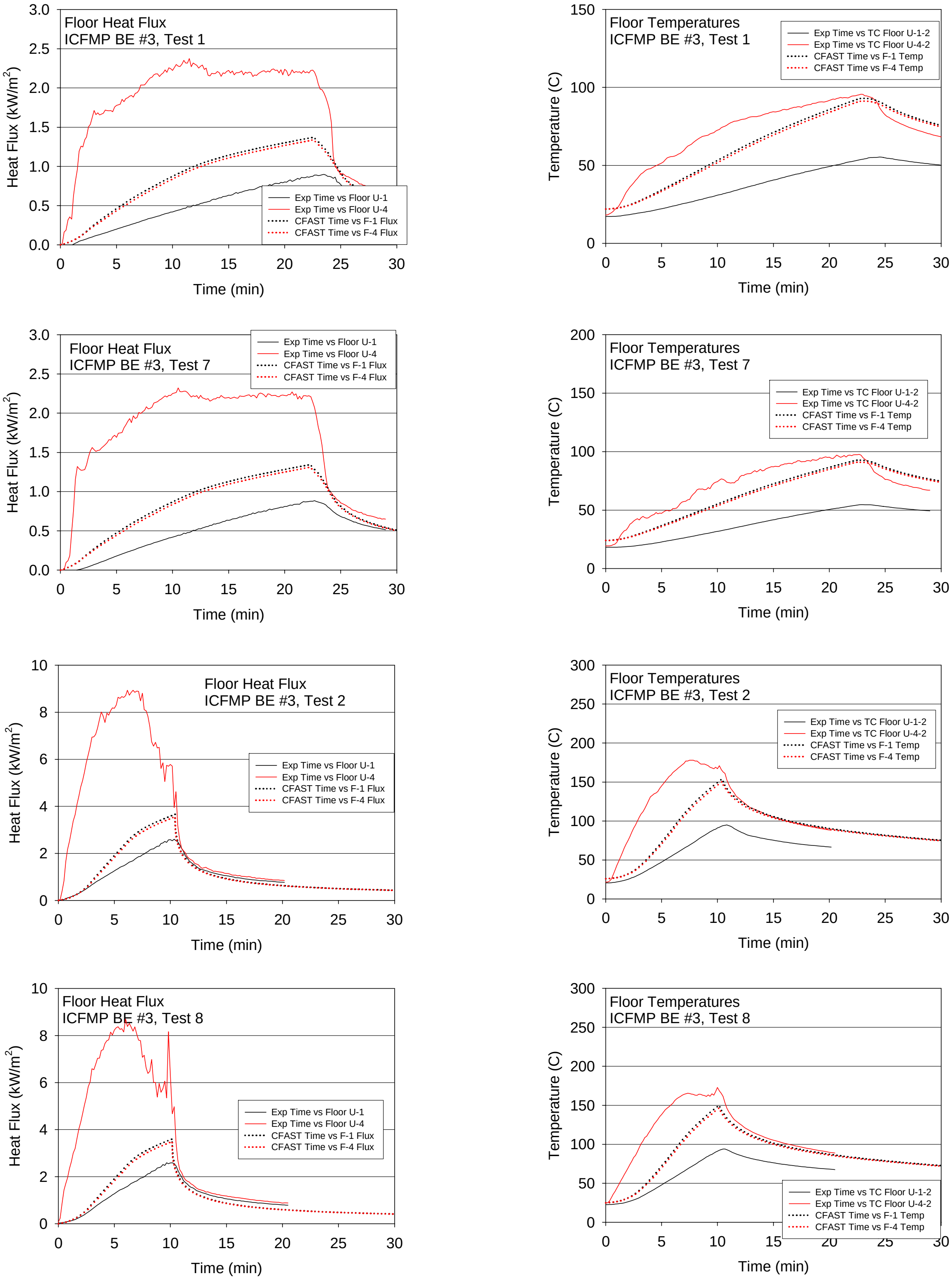


Figure A-69. Floor heat flux and surface temperature, ICFMP BE #3, closed door tests.

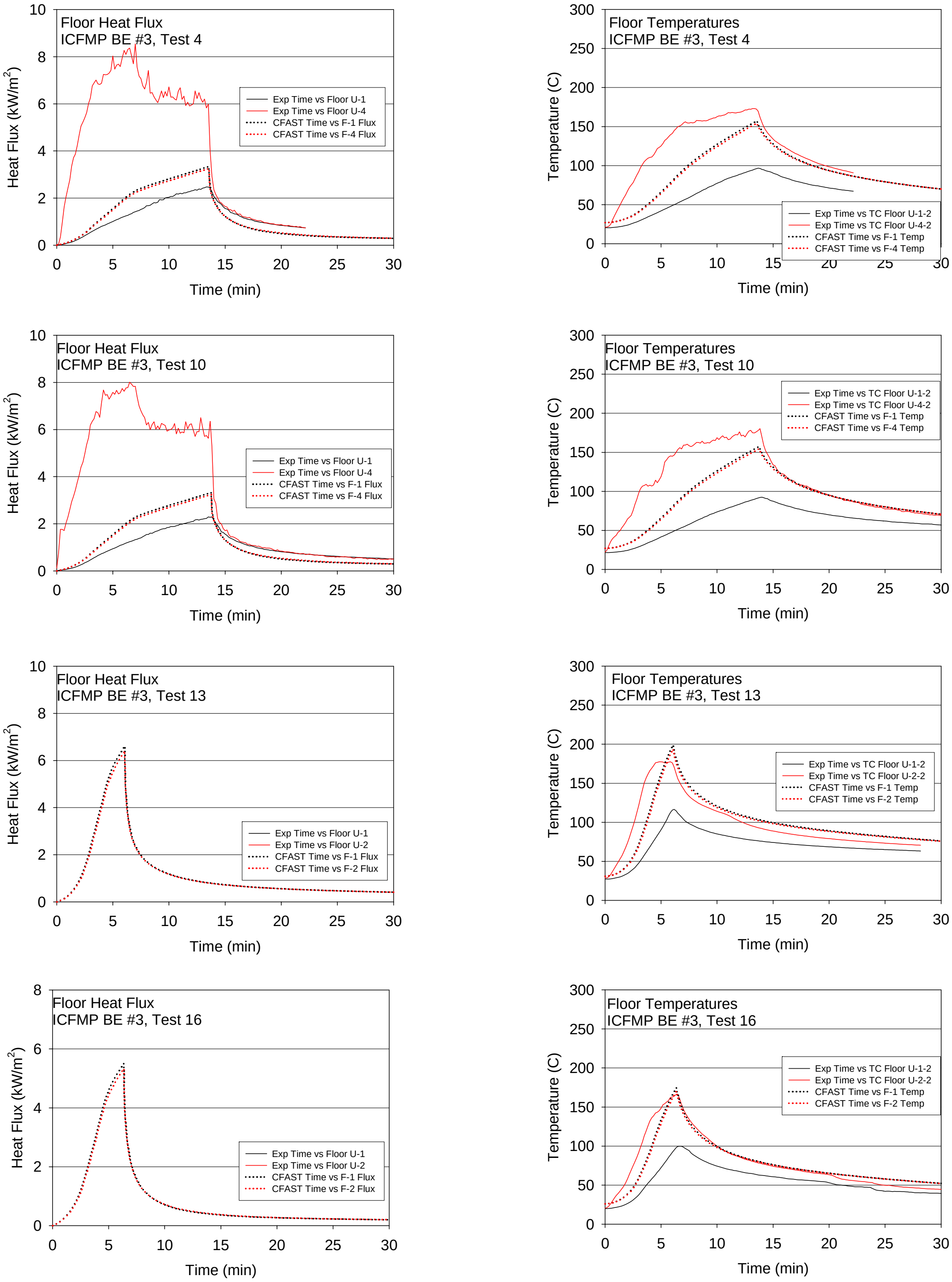
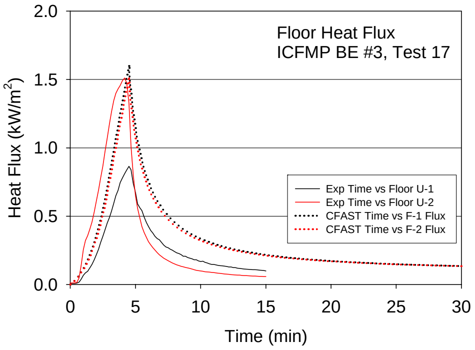
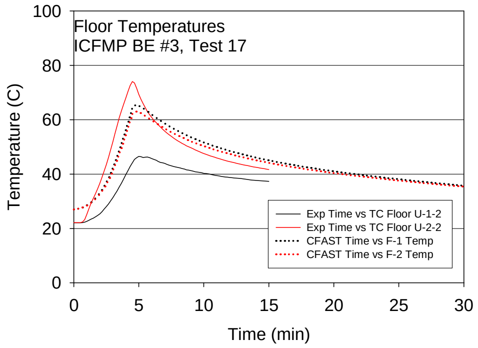


Figure A-70. Floor heat flux and surface temperature, ICFMP BE #3, closed door tests.





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

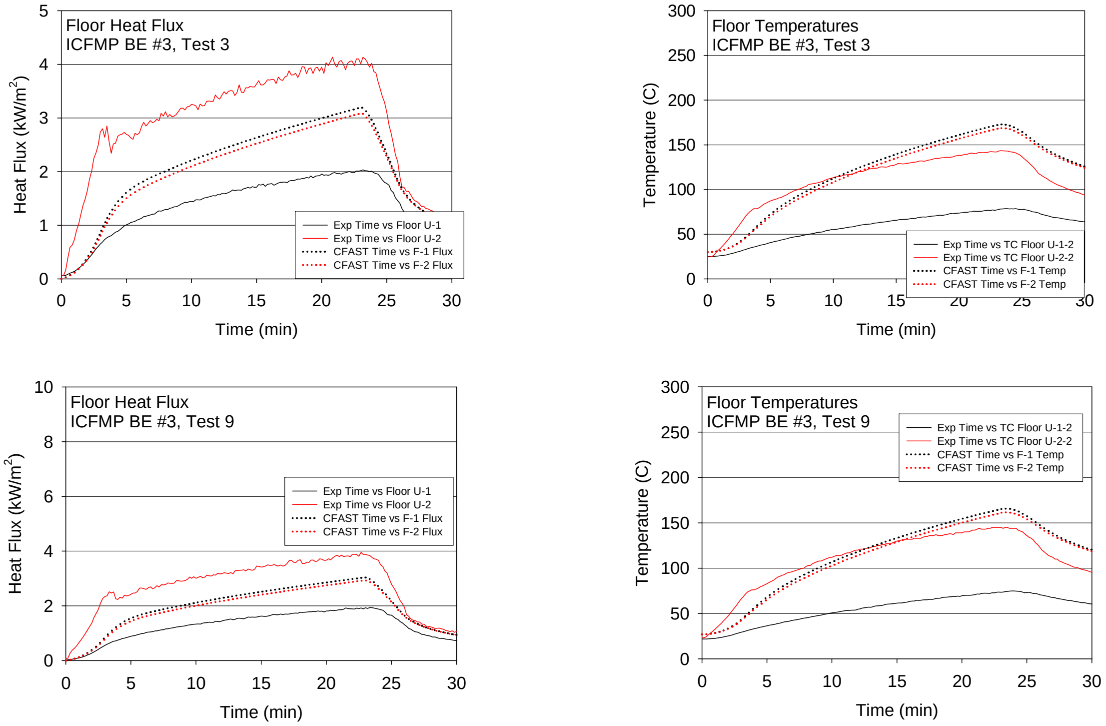


Figure A-71. Floor heat flux and surface temperature, ICFMP BE #3, open door tests.

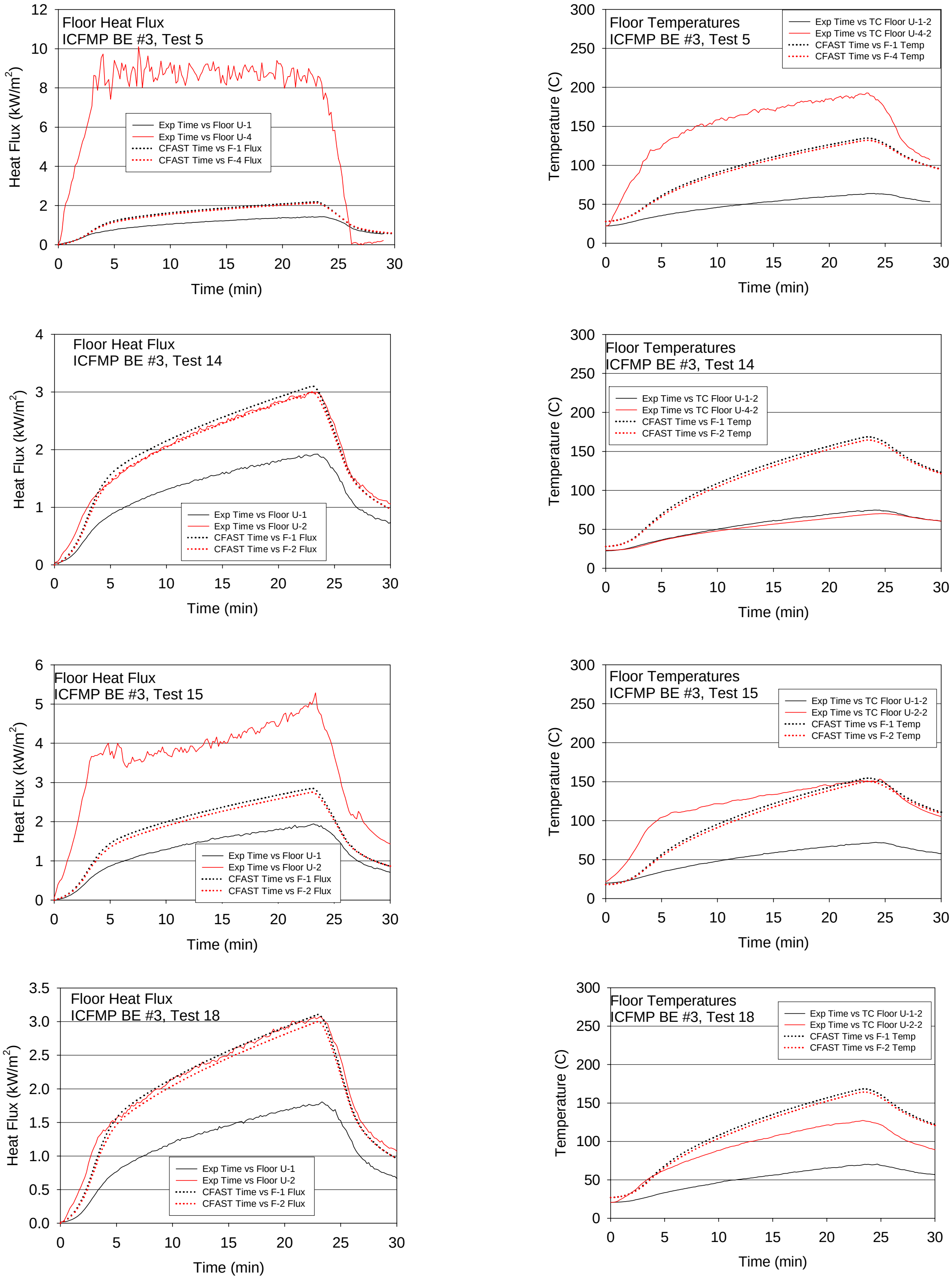


Figure A-72. Floor heat flux and surface temperature, ICFMP BE #3, open door tests.

Table A-6. 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	2.6	76	39	62	59
			0.9	2.7	188	82	72	-12
		Short Wall	1.6	2.6	65	56	61	7
			1.9	2.6	35	61	64	4
		Floor	0.9	1.6	87	24	38	57
			1.5	1.5	1	52	36	-31
		Ceiling				69	67	-2
						230	72	-69
	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	26	480
		TW 1-4				87	36	-58
		TW 2-4				68	35	-49
		TW 1-7				86	37	-57
		TW 2-7				72	37	-49

A.10 References

McCaffrey, B. J. Momentum Implications for Buoyant Diffusion Plumes. *Combustion and Flame*, vol. 52, pp. 149 (1983).

B

CFAST INPUT FILES

Appendix B 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 ICFMP Benchmark Exercise #2

B.6 FM /SNL Test Series

B.7 NBS Test Series

B.1 CFMP 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 CFMP 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
4,0,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0.0921,181,1160000,0.02577778,0,1,0,0.19,0.0026,0.0049,0,0,0
395.15,272,1160000,0.02577778,0,1,0,0.19,0.0026,0.0049,0,0,0
295.15,273,0,0,0,1,0,0.19,0.0026,0.0049,0,0,0
0
0.44
10000
1
1
0.25
4.5E+07
METHANE
```

Test 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
```