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Evaluation of Fire Models for Nuclear Power Plant Applications: Cable Tray Fires

International Panel Report

Compiled by Monideep K. Dey, Guest Researcher

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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Building and Fire Research Laboratory

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TECHNOLOGY ADMINISTRATION
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Abstract

This technical reference document was developed in the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications. This volume reports on the results of the first task in the international collaborative project. The objective of the first task was to evaluate the capability of fire models to analyze cable tray fires of redundant safety systems in nuclear power plants. The evaluation of the capability of fire models to analyze these scenarios was conducted through an international benchmark exercise. Consideration of appropriate input parameters and assumptions, interpretation of the results, and determination of the adequacy of the physical sub-models established useful technical information regarding the capabilities and limitations of the fire models. The participants in the benchmark exercise determined that results indicate that the models provide a comprehensive treatment of most physical phenomena of interest in the scenarios analyzed. The predicted trends from the models were found to be similar and reasonable for their intended use. These fire models can provide useful results for nuclear power plant fire safety analysis for the types of scenarios analyzed.

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Executive Summary

Objective

This technical reference document was developed in the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications. The objective of the collaborative project is to share the knowledge and resources of various organizations to evaluate and improve the state of the art of fire models for use in nuclear power plant fire safety and fire hazard analysis. The project is divided into two phases. The objective of the first phase is to evaluate the capabilities of current fire models for fire safety analysis in nuclear power plants. The second phase will implement beneficial improvements to current fire models that are identified in the first phase, and extend the validation database of those models. Currently, twenty-two organizations from six countries are represented in the collaborative project.

Problem

The first task of the international collaborative project was to evaluate the capability of various fire models to analyze cable tray fires of redundant safety systems in nuclear power plants. The evaluation of the capability of fire models to analyze these scenarios was conducted through an international benchmark exercise. The benchmark exercise was intended to simulate a basic scenario defined in sufficient detail to allow evaluation of the physics modeled in the fire computer codes. An assessment of appropriate input parameters and assumptions, interpretation of results, and determination of the adequacy of the physical sub-models in the codes for specific scenarios will establish useful technical information regarding the capabilities and limitations of the fire computer codes. Uncertainties in the predictions based on validations of each code will provide a basis for the confidence on the set of results developed in the exercise. Three zone, three Computational Fluid Dynamic (CFD), and two lumped-parameter models were used by eight organizations in the exercise.

A representative emergency switchgear room for a Pressurized Water Reactor (PWR) was selected for the benchmark exercise. There were two parts to the exercise. The objective of Part I was to determine the maximum horizontal distance between a specified transient (trash bag) fire and a cable tray that results in the ignition of the cable tray. Part II examined whether a target cable tray will be damaged by a fire of a cable tray stack that is separated by a horizontal distance, d. The effects of a fire door position (open & closed) and mechanical ventilation system are examined in both parts of the benchmark exercise.

Results

For Part I, none of the analyses conducted for the benchmark exercise predicted the ignition of the target cable (specified at 643 K) by the postulated trash bag fire for varying ventilation conditions in the room. The predicted temperature rise for all the cases in Part I were similar. Given the dimensions of the room and the heat release rate of the trash bag, the maximum surface temperature of the target outside the fire plume region for all the cases analyzed is less than 350 K. This temperature is much less than 643 K, which is specified for target damage. The target cable may ignite only if it is in the plume region of the fire. The temperature of the target cable is predicted to significantly increase when the distance between the trash bag and cable is between 0.4 m and 0. 5 m, and the target is exposed to the high plume gas temperature. The predicted maximum surface temperature of the target in this region is predicted to be 550 K. Although the maximum predicted heat flux from the plume incident on the target is predicted to be ≈ 14 kW/m^2, the duration of the exposure is not long enough to increase the surface of the cable to the ignition temperature. A fire of similar intensity sustained over a longer period could ignite the cable. Based on this, one could establish a minimum horizontal safe separation distance[1] of 1.0 m between the trash bag and the target cable.

The predicted maximum temperatures of the target cable, using a lower oxygen limit of 12 %, were below 400 K for all the cases analyzed in Part II. The cable tray fire was limited between 10 min and 15 min by the depletion of oxygen near the cable tray. Given the elevation of the fire source and the predicted extinction of the fire, cable damage is unlikely for the scenarios examined. The analysis of an elevated fire source is key to the accuracy of the predicted result.

Input Parameters

The process for defining the input parameters for the fire models resulted in three main issues: (1) specification of the fire source; (2) modeling of the target; and (3) value for the lower oxygen limit (LOL). The specification of the fire source is fundamental to the input for fire models, and can significantly affect the predicted thermal environment. The specification of the above three parameters could lead to "user effects," and are the largest sources of uncertainty in the predicted results from the input parameter specification process for the types of scenarios examined in the benchmark exercise.

Verification and Validation

Verification is defined here as the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. Validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

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[1]The concept of safe separation distance is not directly applicable in all countries.

Verification

The results of the analyses indicate that the trends predicted by the sub-models are reasonable for the intended use of the models for analyzing the specified scenarios. The constitutive equations for mass and energy balances in the fire models provide a reasonable prediction of the hot gas layer development and temperatures in the compartment. The fire models generally provide an adequate method to balance and estimate the concentration of oxygen. Mass flows that result from the pressurization of the compartment, or natural and mechanical ventilation are reasonably predicted by the zone, CFD, and lumped-parameter models. Convective and radiative heat fluxes to the boundaries and target are comprehensively treated in the models but utilize different approaches. The thermal response of the target is coupled to the thermal environment created by the fire and would benefit from further investigation.

The analyses of the scenarios also demonstrate the complexity in modeling an elevated fire source which can be affected by a limited oxygen environment. The extinction sub-models utilized in the computer codes are approximations of the interaction of the complex combustion process with a limited oxygen environment. Therefore, the results from the extinction sub-models represent an approximation of the conditions expected for the fire scenarios. The assumption for the LOL will affect the predicted peak target temperature. Therefore, conservative assumptions are warranted due to the uncertainty in the extinction models used in the computer codes. Also, the target sub-model in some of the computer codes requires the specification of target orientation by the user. This may result in a non-conservative result and a "user effect" since the orientation of the target will determine the heat flux incident on it. This limitation may be overcome by establishing procedures for the use of the models to obtain conservative and consistent results. In some cases it may be difficult to define conservatism, therefore, the development of best-estimate methods may be desirable.

The inclusion of emission/absorption due to soot, water vapor, and carbon dioxide may play a significant role both in the radiation heat transfer to the target cable and also in the general thermodynamics inside the compartment. The latter will influence various matters including heat loss to the compartment boundaries and the mass flow rates through the opening(s). Radiation from the flaming region will be important in determining damage to cables close to the fire source.

Validation

Most of the fire models used in the benchmark exercise have been compared with test data for fires ranging from 100 kW to 2.5 MW in compartments with volumes ranging from 10 m^3 to 1300 m^3 . The comparisons are generally satisfactory, with different accuracies reported for the range of data sets. Tests conducted in a compartment with a similar volume and fire source indicated that the relative variation of pressure, temperature, and oxygen concentration predicted with test data was within 20 %. The comparison of cable surface temperature evolution was less successful due to the vertical temperature gradient in the test data for the compartment and the vertical position of the target in the hot gas layer. The validations of the fire models conducted to date indicates that they generally provide a reasonably accurate representation of physical phenomena for the types of scenarios in the benchmark exercise.

Although the exercise reported here did not include comparisons of model results with test data, the analyses reported did include the comparison of the magnitudes of the parameters predicted by different fire models. Generally, the predictions were similar. Models developed independently, if based on the same fundamental laws, are expected to produce similar results. Codes that produce similar results in a benchmark exercise should accurately represent the physical phenomena modeled if the input parameters are representative (in particular for the fire source), and at least one of the codes has been validated for the studied configurations.

A distinction is made here between the variability of results due to differences in input parameters and to differences in the physics of the model. As indicated earlier, different assumptions of fire source power can significantly affect the results from the models. Other important input data are the thermophysical parameters, e.g., the convective heat transfer coefficient. It is judged that differences in model results due to the uncertainty of the models is less than differences caused by variations in input data and assumptions.

Conclusions

The international panel determined that the analysis of the results of the benchmark exercise demonstrates that current zone, CFD, and lumped-parameter fire models provide a comprehensive treatment of most physical phenomena of interest in the scenarios analyzed. The results indicate that the trends predicted by the sub-models are reasonable for the intended use of the models for analyzing the specified scenarios. The results obtained from these fire models can provide useful insights for nuclear power plant fire safety analysis for the types of scenarios analyzed.

There are benefits to extending the current validation database, especially for target response calculations. The continued validation of current models in international blind exercises will add confidence for the widespread use of these models in nuclear power plant fire safety analysis.

Most of the insights gained and conclusions drawn on the capabilities and limitations of fire models from this benchmark exercise is applicable to a broad range of fire scenarios expected in nuclear power plants. However, further benchmark and validation exercises are necessary for some specific configurations such as large compartments (like the turbine building) with large pool fires, multi compartments with horizontal and vertical vent connections, and control room configurations. Insights on some further specific modeling issues are likely to be developed from such exercises.

Foreword

This technical reference document was developed in the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications. The objective of the collaborative project is to share the knowledge and resources of various organizations to evaluate and improve the state of the art of fire models for use in nuclear power plant fire safety and fire hazard analysis. The project is divided into two phases. The objective of the first phase is to evaluate the capabilities of current fire models for fire safety analysis in nuclear power plants. The second phase will extend the validation database of those models, and implement beneficial improvements to the models that are identified in the first phase. Currently, twenty-two organizations from six countries are represented in the collaborative project.

This volume reports on the results of the first task in the international collaborative project. The objective of the first task was to evaluate the capability of fire models to analyze cable tray fires of redundant safety systems in nuclear power plants. The evaluation of the capability of fire models to analyze these scenarios was conducted through an international benchmark exercise. Three zone, three computational fluid dynamic (CFD), and two lumped-parameter fire models were used by eight organizations in the exercise. The benchmark exercise simulated a basic scenario defined in sufficient detail to allow the evaluation of the physics modeled in the fire computer codes. Consideration of appropriate input parameters and assumptions, and the interpretation of the results to evaluate the adequacy of the physical sub-models established useful technical information regarding the capabilities and limitations of the fire models. This technical information is presented in this volume which is the first of a series of technical reference documents for fire model users. The objective of the exercise was not to compare the capabilities and strengths of specific models, address issues specific to a model, nor to recommend specific models over others. Future volumes of this series will report on the findings of other benchmark and validation exercises that are planned for this project.

This document is not intended to provide guidance to users of fire models. Guidance on the use of fire models is currently being developed by several national and international standards organizations, industry groups, and utilities. This document is intended to be a source and reference for technical information and insights gained through the exercises conducted, and provided by the experts participating in this project. This information may be beneficial to users of fire models and developers of guidance documents or standards for the use of fire models in nuclear power plant applications.

Acronyms and Initialisms

BFS	Bundesamt fur Strahlenschutz
BRE	Building Research Establishment
CIB	International Council for Research and Innovation in Building and Construction
CFAST	Consolidated Model for Fire and Smoke Transport
CFD	Computational Fluid Dynamics
CL	centerline
COCOSYS	Containment Code System
EdF	Electricite de France
EPRI	Electric Power Research Institute
FDS	Fire Dynamics Simulator
GRS	Gesellschaft fuer Anlagen-und Reaktorsicherheit
HGL	hot gas layer
HRR	Heat Release Rate
iBMB	Institut fuer Baustoffe, Massivbau und Brandschutz
IPSN	Institute for Protection and Nuclear Safety
JASMINE	Analysis of Smoke Movement in Enclosures
LL	Lower layer
LOL	Lower Oxygen Limit
NII	H. M. Nuclear Installations Inspectorate
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PRA	Probabilistic Risk Analysis
PWR	Pressurized Water Reactor
TUV	Technical University of Vienna
UL	upper layer
VTT	Valtion Teknillinen Tutkimuskeskus
WPI	Worcester Polytechnic Institute

1 Introduction

The 1st planning meeting of the International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications was held at the University of Maryland at College Park, USA, on October 25-26, 1999. Attendees at the meeting agreed to share their knowledge and resources to evaluate and improve the state of the art of fire models for use in nuclear power plant (NPP) safety. It was decided that the project would be divided into two phases. The objective of the first phase would be to evaluate the capabilities of current fire models (zone, CFD, and lumped-parameter) for fire safety analysis in NPPs. The second phase will implement beneficial improvements to current fire models that are identified in the first phase, and extend the validation database of those models. The summary of the 1st meeting and the details of the objectives established for the project, including the goals for the benchmark exercise reported in this document may be found in NRC (2000). The benchmark exercise was defined at the 2nd project meeting at the Institute for Protection and Nuclear Safety (IPSN), Fontenay-aux-Roses, France, on June 19 and 20, 2000. The summary of the 2nd meeting is reported in NRC (2001).

The definition of the benchmark exercise is presented in Chapter 2. Chapter 3 provides a summary of the main issues that arose in the consideration of input parameters and assumptions for the scenarios in the exercise, and how participants decided to address the issues. Chapter 4 presents a summary of the main results that were sought in the definition of the benchmark exercise presented in Chapter 2. Chapter 5 finally provides a discussion of the general conclusions and issues derived from the benchmark exercise. Appendices A through I include the detailed results of the analyses for the benchmark exercise conducted by participants using different fire models.

This international panel report was developed by the following members that contributed either through the performance of analysis in the benchmark exercise, and/or by providing peer comments at various stages of the exercise:

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The following organizations sponsored or collaborated with the organizations represented at the meeting:

- Industry Management Committee, UK
- National Institute of Standards and Technology, USA

The main report of this document is a result of the collective efforts of the individuals and organizations listed above. It is based on the separate reports included in the appendices and discussions at project meetings on the task. The separate reports in the appendices are authored by the analyst(s) identified in the title pages. It is not possible to provide all the results and insights gained from the analyses presented in the appendices in the main text. The reader is encouraged to review the discussions in the appendices to obtain a more comprehensive understanding of the results of the benchmark exercise reported here.

2 Definition of the Benchmark Exercise

2.1 Background

The benchmark exercise was developed to evaluate the capability of fire modeling analyses to provide results for a probabilistic risk analysis (PRA). In a PRA study, fire models are used to estimate the conditional probability of safe-shutdown equipment damage given a postulated fire. The main fire protection features that effect the development of a fire are:

- Automatic or manual isolation of the fire rooms by the closure of fire doors and dampers.
- Automatic fire detection (detection by operators is also important).
- Fire suppression (automatic and manual) with gaseous suppression systems (Halon or CO_2), and nongaseous water-based suppression (sprinkler) systems.

In a PRA study, the target damage time is compared with the duration of a specific fire scenario identified in an event tree. The conditional probability of damage to the safe shutdown equipment is equal to the probability of that fire scenario if the damage time is less than the duration of the fire scenario.

Given the state of the art of fire modeling, the adequacy of fire detection and suppression is normally not included in fire modeling analyses to support a PRA. Therefore, the benchmark exercise did not include the evaluation of these systems or events.

The benchmark exercise is for a basic fire scenario for an NPP defined in sufficient detail to allow the evaluation of the physics modeled in the fire computer codes. This approach is similar to that adopted by the CIB W14 effort (Keski-Rahkonen, 1998) for fire code assessment. An assessment of appropriate input parameters and assumptions, interpretation of results, and determination of the adequacy of the physical models in the codes for specific scenarios will establish useful technical information regarding the capabilities and limitations of the codes. Generic insights regarding the capabilities of the models will also be developed in this process.

The comparisons between fire codes can be used to understand the physics in them, i.e., if all the codes produce similar results over a range of fire scenarios then the physics modeled in the codes is probably adequate for the proposed scenario. However, the compounding effects of different phenomena will also need to be evaluated. Some uncertainty in the results may be acceptable depending on how the results will be used. Uncertainties in the predictions of the fire models based on validations of each fire code can provide a basis for the confidence on the set of results developed in the benchmark exercise.

2.2 Procedure

The following procedure was adopted for the benchmark exercise:

- Analysts should discuss and agree on the input data for the various fire codes that will be used in the benchmark exercise. The goal is to analyze the same problem and minimize the variation of results due to different input parameters. "User effects" will be examined at a later stage.
- The form of the results to be compared should be agreed upon by participants prior to the commencement of the exercise.
- Developers of the fire codes, and those not involved in the development of the codes, can conduct the code analyses for the benchmark exercise.
- Blind simulations will be conducted, i.e., each analyst will independently conduct his or her analyses. The results will be shared between participants when all the analyses by participants have been completed and the results are available. The results will be simultaneously posted on the collaborative project web portal prior to a meeting of the participants.
- If desired, the same code (e.g., CFAST) can be used by different organizations since this will provide useful information on whether the results vary with different users. However, the same version of the code should be used (for CFAST, use Version 3.1.6).
- A series of benchmark exercises will be defined and conducted in this project. This will allow the evaluation of the full spectrum of fire model features and applications, and facilitate the formulation of a comprehensive technical reference for users on the capabilities and limitations of the current fire models.

2.3 Fire Codes Used in the Exercise

The following fire models were used in the benchmark exercise by the organizations listed:

Organization	Codes
1. IPSN	FLAMME-S (zone)
2. NRC/NIST	CFAST (zone), FDS (CFD)
3. GRS	COCOSYS (lumped parameter), CFX (CFD)
4. EdF	MAGIC (zone)
5. BRE/NII	CFAST, JASMINE (CFD)
6. iBMB/GRS	CFAST
7. CTICM	MAGIC

A description of these models with references is presented in the Appendices that document the results of analyses using the models.

2.4 Room Size and Conditions

A representative pressurized water reactor emergency switchgear room is selected for this benchmark exercise. A simplified schematic of the room, illustrating critical cable tray locations, is shown in Figure 1. The room is 15.2 m (50 ft) deep, 9.1 m (30 ft) wide, and 4.6 m (15 ft) high. The room contains the power and instrumentation cables for the pumps and valves associated with redundant safe-shutdown equipment. The walls, floor and ceiling are composed of concrete and 152 mm thick. The power and instrument cable trays run the entire depth of the room, and are separated horizontally by a distance, D. The value of D, the safe separation distance, is varied and examined in this problem. The cable trays are 0.6 m (≈24 in) wide and 0.08 m (≈3 in) deep.

The postulated fire scenario is the possibility of the initial ignition of the cable tray labeled as "A," located at 0.9 m (≈3 ft) from the right wall of the room at an elevation of 2.3 m (7.5 ft) above the floor, by a trash bag fire on the floor. Cables for the redundant train are contained in another tray, labeled "B," the target. A horizontal distance, D, as shown in Figure 1, separates tray B from tray A. The room has a door, 2.4 m x 2.4 m (8 ft x 8 ft), located at the midpoint of the front wall, assumed to lead to the outside. The room has a mechanical ventilation system with a flowrate of 5 volume changes per hour into and out of the room. A constant flowrate of the mechanical ventilation system was assumed. The midpoint of the vertical vents for the supply and exhaust air are located at an elevation of 2.4 m and have area of 0.5 m^2 each. The vents were assumed to be square and located at the center of the side walls (parallel to the cable trays). The air was assumed to be supplied from the outside through the right wall, and exhausted to the outside from the left wall. The effects of the fire door being open or closed, and the mechanical ventilation on and off were examined.

It was also assumed that other cable trays (C1 and C2) containing critical and non-critical cables are located directly above tray A, and no combustible material is found between trays A and B.

2.5 Objectives of Exercise

There are two parts to the benchmark exercise. The objective of Part I is to determine the maximum horizontal distance between the trash bag fire and the target, tray A, that results in the ignition of tray A. This information is of use in a fire PRA to calculate the area reduction factor for the transient source fire frequency, which are derived to be applicable to the total area of the rooms. Analyses of this part of the problem will also provide insights regarding the capabilities of the models to predict simpler fire scenarios for risk analyses than those associated with fires of redundant cable trays.

The goal of the analyses for Part II was to determine the time to damage of the target cable tray B for several heat release rates of the cable tray stack (A, C2, and C1), and horizontal distance, D. The effects of target elevation and ventilation were also examined.

2.6 Properties and Ambient Conditions

2.6.1 Properties

The following are properties used in Part I and/or II of the exercise. Table 1 presents the thermophysical data for the concrete walls, floor, and ceiling, and Table 2 lists the thermophysical data for the electrical cables.

Table 1 Thermophysical Data for Walls, Floor, and Ceiling (Concrete)

Specific Heat	1000 J/(kg.K)
Thermal Conductivity	1.75 W/(m.K)
Density	2200 kg/m^3
Emissivity	0.94

Table 2 Thermophysical Data for Cables

Heat of combustion of cable insulation	16 MJ/kg
Fraction of flame heat released as radiation	0.48
Density	1710 kg/m^3
Specific Heat	1040 J/(kg.K)
Thermal Conductivity	0.092 W/(m.K)
Emissivity	0.8

The chemical properties of cables are obtained from Tewarson (1995). The cable insulation was assumed to be polyvinyl chloride (PVC) with a chemical formula of C_2H_3Cl, and oxygen-fuel mass ratio of 1.408. The yields (mass of species/mass of fuel) of PVC are listed in the following Table 3 from Tewarson, 1995.

Table 3 Yields for PVC

Species	Yield
CO_2	0.46
CO	0.063
HCl	0.5

Soot	0.172

The smoke potential of PVC is 1.7 ob.m^3/g, where the smoke potential is defined as the optical density (db/m or ob) x Volume of the compartment (m^3)/mass of the fuel pyrolyzed (g).

The following are details of the construction and properties of the fire door[2] that could be used in models that allow the incorporation of such features. The fire door is a metal-clad door with a wood core, and insulating panels between the wood core and the metal clad (on both sides of the wood core). The thickness of the metal clad, wood core, and insulating panels are 0.6 mm, 40 mm, and 3 mm respectively. The properties of the fire door are listed in Table 4.

Table 4 Properties of Fire Door

	Thermal Conductivity (W/(m.K))	Density (kg/m$^{3)}$	Specific Heat (kJ/(kg.K))
Metal Clad - Carbon Steel	43	7801	0.473
Wood Core - Yellow Pine	0.147	640	2.8
Fiber, insulating panel	0.048	240	

2.6.2 Ambient Conditions and Other Constants

Table 5 lists the internal and external ambient conditions, and Table 6 lists other constants and indices used in the exercise.

Table 5 Ambient Conditions

Temperature	300 K
Relative Humidity	50 %
Pressure	101300 Pa
Elevation	0
Wind Speed	0

[2]Derived from information in NFPA 80 and SFPE Handbook.

Table 6 Other Constants and Indices

Constriction coefficient for flow through door	0.68
Convective heat transfer coefficient (assumed the same for all surfaces)	15 $Wm^{-2}K^{-1}$
Lower Oxygen Limit	12 %*

*The fire source should pyrolyze at a rate corresponding to the specified heat release rate in Part II if oxygen depletion terminates combustion, i.e., the mass loss rate of the fuel is fixed rather than the "true" heat release rate associated with the oxidation process.

2.7 Heat Release Rates and Target Model

The following are the heat release rate data used for the two parts of the exercise.

2.7.1 Part I

The heat release rate for a 0.121-m^3 (2-gallon) trash bag fire (Lee, 1985, & Van Volkinburg, 1978) that was used for Part I of the exercise is characterized in Table 7. A linear growth between the data points was assumed for the calculation.

Table 7 32 Gallon Trash Bag Fire

Fire Growth Time (minutes)	Heat Release Rate (kW)
1	200
2	350
3	340
4	200
5	150
6	100
7	100
8	80
9	75
10	100

The trash bag consists of: (1) straw and grass cuttings (1.55 kg); (2) eucalyptus duffs (2.47 kg); and (3) a polyethylene bag (0.04 kg). The contents were thoroughly mixed, and then placed in the bag in a loose manner before ignition. The trash bag was approximated as a cylinder with a diameter of 0.49 m, and height of 0.62 m. A fraction of 0.3 for heat released as radiation was assumed, and the heat of combustion of the trash bag material is 24.1 MJ/kg.

The trash bag and the target (representing the tray A) were assumed to be at the center of the cable tray lengths. In order to conduct a simplified and conservative analysis, a single power cable with a diameter of 50 mm at the bottom left corner of the cable tray A was assumed as the target. For models in which the target is represented as a rectangular slab, the slab was assumed to be oriented horizontally with a thickness of 50 mm. The cable was assumed to ignite when the centerline of the cable reaches 643 K.

2.7.2 Part II

Predicting the heat release rate of a burning cable tray stack is extremely complex, and current models are not capable of realistically predicting such phenomena. Therefore, the mass loss rate of the burning cable tray stack was defined as input in the exercise. The consecutive ignition and burning of all 3 cable trays (trays A, C2, and C1) were modeled as one fire. The analyses were conducted assuming a peak heat release rate for the whole cable tray stack[3] between 1 MW – 3 MW. A t-squared fire growth with t_0 = 10 min, and Q_0 = 1 MW was assumed[4], where:

$$Q=Q_0\ (t/t_0)^2$$

The cable fire was assumed to last for 60 minutes at the peak heat release rate, and decay in a t-squared manner with similar constants as for growth.

For point source calculations, the heat source (trays A, C2, and C1) was assumed to be at the center of the cable tray length and width and at the same elevation as the bottom of tray C2. For 3-D calculations, the fire source was assumed to be the entire length of tray C2 (15.2 m), width (0.6 m), and height of 0.24 m (0.08 x 3). The target (representing tray B) was assumed to be at the center of the cable tray length. In order to conduct a simplified and conservative analysis, the target was assumed to be a single power or instrumentation cable, without an electrical conductor inside the cable, and with a diameter of 50 mm or 15 mm respectively at the bottom right corner of cable tray B. For models in which the target is represented as a rectangular slab, the slab was assumed to be horizontally oriented with a thickness of 50 mm or 15 mm. The cable was assumed to be damaged when the centerline of the cable reached 473 K.

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[3] The 1 MW to 3 MW range was chosen as bounding values for a stack of 3 cable trays. Considering a heat of combustion of 25 MJ/Kg and a surface controlled specific mass loss rate of about 3 g/m^2-sec for cables that pass the IEEE tests, a cable tray 15 m long and 0.6 m wide will have an effective heat release rate of 0.9 MW. An earlier study (NUREG/CR-4230), and fire tests reported in EPRI NP-2660 and EPRI NP-2751 also concluded that the peak heat release rate for a cable tray is limited from 0.8 MW to 2 MW for a well ventilated room.
[4] EdF CNPP tests (1997)

2.8 Cases for Exercise

The following defines the cases for Part I and II of the exercise.

2.8.1 Part I

For the base case, the distance between the midpoints of the trash bag and tray A was 2.2 m (≈7 ft), the door was closed, and mechanical ventilation system was off. In order to facilitate comparisons of code results, simulations for horizontal distances between the trash bag and tray A of 0.3, 0.9, and 1.5 (≈1, ≈ 3, and ≈ 5 ft) were conducted (Cases 1–3). Simulations were also conducted with (a) the door open and mechanical system turned off; and (b) mechanical ventilation system on and the door closed (Cases 4-5). Table 8 provides a summary of the cases analyzed in Part I.

Table 8 Summary of Cases for Part I

Fire Scenario	Distance from Fire (m)	Door	Ventilation System
Base Case	2.2	Closed*	Off
Case 1	0.3+		
Case 2	0.9		
Case 3	1.5		
Case 4		Open	
Case 5			On

* For simulations with the door closed, a crack (2.4 m x 0.005 m) at the bottom of the doorway was assumed.
+A value in a cell indicates the parameter was varied from the base case.

The maximum horizontal distance between the trash bag and tray A, which results in the ignition of tray A, was to be determined by the extrapolation of results for the simulations with the door closed and mechanical ventilation system off (Base Case to Case 3).

The resulting centerline temperature (CL) of the cable was calculated for these simulations. In addition, the following parameters were reported:

- Upper layer temperature
- Lower layer temperature
- Depth of the hot gas layer
- Heat release rate
- Oxygen content[5] (upper and lower layer)
- Flow rates through the door and vents

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[5]The oxygen present in the fuel was neglected in the calculation of the oxygen concentration in the compartment.

- Radiation flux on the target
- Target surface temperature
- Total heat loss to boundaries

For CFD and lumped-parameter models, the profiles at the midpoint of the room were presented. All results are presented in SI units.

2.8.2 Part II

For the base case, the heat release rate for the cable tray stack was 1 MW, reaching peak heat-release rate and decaying as specified above. The horizontal distance, D, was 6.1 m (20 ft). The door was closed and the ventilation system was off. The target was a power cable 1.1 m (3.5 ft) above tray A. The distance, D, was varied to 3.1 (≈10 ft), and 4.6 m (≈15 ft) for Cases 1 and 2. The peak heat release rate for the cable tray stack was varied at 2 MW, and 3 MW (reaching a peak heat-release rate and decaying as specified above) at a horizontal distance, D, of 3.1, 4.6, and 6.1 m (Cases 3-8). The door was closed and ventilation system operating initially; and the door opened, and ventilation system shut after 15 minutes in Case 9. The door and ventilation system was open throughout the simulation in Case 10. Two elevations for tray B were analyzed to examine the possible effects of the ceiling jet sublayer and the elevation of the target: (1) 2.0 m (6.5 ft) above tray A, (i.e., 0.3 m (1 ft) below the ceiling)in Case 11; and (2) at the same elevation as tray A in Case 12. An instrumentation cable with a diameter of 15 mm was used in Case 13.

The resulting centerline temperature of the target, and time to damage of the target, were to be calculated for these analyses. In addition, the following parameters were reported:

- Upper layer temperature
- Lower layer temperature
- Depth of the hot gas layer
- Heat release rate
- Oxygen content (upper and lower layer)
- Flow rates through the door and vents
- Radiation flux on the target
- Target surface temperature
- Total heat loss to boundaries
- Chemical species (CO, HCl, soot) in the upper layer
- Optical density of smoke (optional)

For CFD and lumped-parameter models, profiles at the midpoint of the room were reported. All results were presented in SI units.

Table 9 Summary of Cases for Part II

Fire Scenario	HRR (MW)	D (m)	Door Position	Mech. Vent. Sys.	Target	Target Elev. (m)
Base Case	1	6.1	Closed*	Off	Power Cable	1.1
Case 1		3.1+				
Case 2		4.6				
Case 3	2	3.1				
Case 4	2	4.6				
Case 5	2	6.1				
Case 6	3	3.1				
Case 7	3	4.6				
Case 8	3	6.1				
Case 9			Open>15 min	Off>15 min		
Case 10			Open	On		
Case 11						2.0
Case 12						Same
Case 13					Instrument Cable	

* For simulations with the door closed, a crack (2.4 m x 0.005 m) at the bottom of the doorway was assumed.
+A value in a cell indicates the parameter is varied from the base case.

3 Input Parameters and Assumptions

In accordance with the procedure established for the benchmark exercise presented above, efforts were made by the participants to arrive at a consensus on values for all the input parameters needed for the various codes to be used in the exercise. The following is a summary of the main issues that arose in the consideration of input parameters and assumptions for the scenarios in the exercise, and how participants decided to dispose the issues.

3.1 Summary

Three main issues arose regarding input parameters and assumptions for the fire scenarios in the benchmark exercise:

A. Specification of the fire source;
B. Modeling of the target in the compartment; and
C. Lower oxygen limit (LOL).

The specification of the fire source is fundamental to the input for fire models, and can significantly affect the predicted compartment thermal environment. A consensus was reached on the characterization of the heat release rate (HRR) for the fire scenarios for the benchmark exercise. However, it was noted that presently there is a lack of a consolidated source of information or guidance from where one can select data for heat release rates for different NPP fire scenarios. Although agreement was reached on the specification and values for the target model and LOL to be used for the benchmark exercise, participants did not reach a consensus on the most appropriate specification that could be recommended for model users. The specification of the above three parameters could lead to “user effects,” and are the largest sources of uncertainty in the predicted results from the input parameter specification process for the types of fire scenarios examined in the benchmark exercise. These three main issues are summarized below followed by a discussion of other issues of importance.

3.2 Main Issues

1. <u>HRR Curves for Cable Tray Fires</u>:

Predicting the HRR of a burning cable tray stack is extremely complex, and current models are not capable of realistically predicting such phenomena. Therefore, it is recommended that the HRRs of the burning cable tray stack be defined as input in the problem. For the benchmark exercise, the consecutive ignition and burning of all three cable trays (trays A, C2, and C1) were modeled as one fire. The analyses assumed peak HRRs for the whole cable tray stack between 1 MW and 3 MW. The 1 MW to 3 MW range was chosen as bounding values for a stack of 3 cable trays. Considering a heat of combustion of 25 MJ/Kg and a surface controlled a specific mass loss rate of about 3 g/(m^2.s) for cables that pass the IEEE-383 tests, a cable tray 15 m long and 0.6 m wide will have an effective HRR of 0.9 MW. An earlier study (NRC, 1985), and fire tests reported in EPRI (1992) and EPRI (1983) also concluded that the peak HRR for a cable tray is limited from 0.8 MW to 2 MW for a well-ventilated room. The growth characteristic of cable tray fires depends on the fire source, cables ignited with liquid combustibles result in rapid growth, whereas cables ignited by another cable tray fire result in slower growth. Based on tests conducted by EdF (Grondeau, 1997), a t-squared growth was assumed with t_0 = 600 s, and Q_0 = 1 MW, where:

$$\dot{Q} = \dot{Q}_0 (t / t_0)^2$$

A fire duration of 60 min at peak HRRs was assumed, followed by a t-squared decay with similar constants as for growth. The experiments conducted by EdF have shown that peak HRRs for cable tray fires generally do not last more than 60 minutes.

Given the complexity of modeling flame spread, and the developmental state of flame spread models, it is recommended that current fire modeling analyses use heat release rates derived from tests conducted that have configurations similar to that being analyzed.

The development of a comprehensive database of heat release rate test data for combustible materials in NPPs will be beneficial for the broader application of fire models for NPP fire safety analysis. Further, HRR's to be used for specific NPP fire scenarios will need to be established to avoid "user effects."

2. Cable Target Model and Dysfunction Temperature

A detailed heat transfer model for a cable tray will be fairly complex. Cable trays generally have a number of cables bundled together in layers, and most cables consist of several conductors. Cables configured in a single layer will get damaged and ignite at a lower flux than cables in a multilayer configuration because the flux to a single layer will not be shielded by cables above that layer. The damage or ignition temperature for cables in a multilayer configuration will depend on the volume-to-surface area ratio. Generally, current fire models are not capable of modeling complex cable configurations. As stated above in Chapter 2, for simplicity the target in the benchmark exercise was assumed to be one power cable conservatively composed only of PVC. Some of the codes used for the benchmark exercise have simple one-dimensional slab models for targets, and others have incorporated a 1-D radial model to approximate radial heat transfer in cables.

As stated in Chapter 2, simulations were conducted for power cables (50 mm diameter), and instrumentation cables (15 mm diameter). For models in which the target is represented as rectangular slabs, the slabs were assumed to be oriented horizontally with a thickness of 50 mm and 15 mm correspondingly. Some participants expressed concern regarding the adequacy of a one-dimensional target model since the incident radiative flux would vary with the orientation of the slab. Also, the specification of the slab thickness, and selection of the criterion for cable damage (surface temperature versus centerline temperature) would be key to the success of a one-dimensional target model. The cable surface temperature is not indicative of the effects of the thermal environment on cable functionality. Experiments in the PEPSI tests conducted by IPSN indicate that the temperature of the PVC insulation immediately surrounding the electrical conductors reaches about 473 K when cable malfunctions occur (Such, 1997). This corresponds to the temperature at which the PVC insulation softens. Experience from experiments conducted at VTT, indicated that the centerline temperature of a target slab, with a thickness equal to the diameter of the cable, best approximates the temperature of the PVC insulation surrounding the individual conductors. However, some participants felt that the slab dimensions specified for the benchmark exercise may be too thick and result in the simulation of a larger thermal inertia of the target than exists in reality.

This issue is discussed further later in this document when the results of the analyses are presented, and the effect of the cable target model on the results is examined.

3. <u>Lower Oxygen Limit</u>

In order to conduct a conservative analysis, some participants advocated the use of a value of zero for the LOL. This proposal was put forth based on experimental observations which indicated that it was difficult to determine an LOL value because of the complexity of the combustion phenomena, and effects of ventilation on combustion. Other participants felt that setting LOL at 0% for cases which were developed to examine the effects of ventilation will be contradictory, and for other cases would not yield best-estimate results. Based on this premise, it was suggested that the LOL be set at 12% in order to examine these effects. Several participants in the exercise conducted the analyses of the cases with LOL set at 0% and 12 % to determine the effect. The impact of LOL on the results will be discussed later in this report.

3.3 Other Issues

4. <u>Chemical Properties of Combustible Sources</u>

Generally, fire models require the specification of the chemical properties of the fire sources, and the species yielded in the combustion process. Such yields affect the emissivity and absorption of radiation by the hot gas and may be important. The content of the trash bag fire source was specified for the benchmark exercise as composed of: (1) straw and grass cuttings(1.55 kg); (2) eucalyptus duffs (2.47 kg); and a (3) polyethylene bag (0.04 kg). These contents were thoroughly mixed, and then placed in the bag in a loose manner before the heat release data was obtained in the tests. However, the chemical properties of the grass cuttings in the trash bag were not available and specified for the exercise. This was a limitation since the chemical properties of the fuel were necessary input for the fire models, especially in the calculation of radiation from the hot gas. Several analysts assumed the trash bag to contain wood for which the properties were available.

The cable insulation was assumed to be polyvinyl chloride (PVC), and its chemical properties were available. The chemical formula of PVC is C_2H_3Cl, and the oxygen-fuel mass ratio is 1.408. The yields (mass of species/mass of fuel) are 0.46 for CO_2, 0.063 for CO, 0.5 for HCL, and 0.172 for soot.

The development of a comprehensive database of chemical properties of combustible materials in NPPs will facilitate the modeling of specific fire scenarios.

5. User Effects

As proposed in the procedure for the benchmark exercise, analysts discussed and agreed on the input data for the various codes that will be used in the benchmark exercise. The goal was for participants to analyze the same problem and minimize the variation of results due to differing input data. Even with such efforts to minimize "user effects," some effects were evident in the benchmark exercise. "User effects," and their impacts are discussed later in the document after the results are presented.

6. Corner/Wall Effects

In practice, cable trays are installed nearer than 0.9 m from walls as specified in the proposed benchmark exercise. Also, transient combustibles may be present in the corner or along walls. In order to minimize the number of cases for the benchmark exercise, corner/wall effects were not examined. Corner/wall effects may be important for specific configurations when combustibles are near a corner or wall, and it is recommended that their impact on the results be examined.

7. Conditions Outside Compartment

In NPPs, doors in most compartments typically open to another compartment, and not to the outside ambient conditions. In order to simplify and make feasible the evaluation of model effects, multi compartment analysis was not included in the benchmark exercise since that would include additional considerations and effects on the results. In modeling realistic fire scenarios, the conditions outside the compartment may be important, and it is recommended that such effects be examined.

8. Constriction or Orifice Coefficient for Vents

Based on expert opinion of the participants, it was decided that a value of 0.68 used in some computer codes will be used for the benchmark exercise. The adequacy of this value is discussed later in the document when the results are presented.

9. Convective Heat Transfer Coefficient

Based on expert opinion of the participants, it was decided that the convective heat transfer coefficient would be set at 15 W/m^2K for the benchmark exercise. The adequacy of this value is discussed later in the document when the results are presented.

4 Results of Analyses

The following presents a summary of the results that were sought in the benchmark exercise presented in Chapter 2. The main results for the ignition of a cable tray by the trash bag fire, and damage of cable trays of redundant safety systems are presented in Section 4.2. This is followed by a discussion in Section 4.3 on an assessment of the adequacy of the physical models used in the codes for the specific scenario by examining and comparing the trends of the output variables.

The detailed results of the analyses for the benchmark exercise conducted by participants using different fire models are presented in Appendices A through I.

4.1 Summary of Results

4.1.1 Part I

None of the analyses conducted for the benchmark exercise predicted the ignition of the target cable (at 643 K) by the postulated trash bag fire for any of the ventilation conditions in the room. The predicted temperatures for all the cases in Part I are very similar. Given the dimensions of the room and the heat release rate of the trash bag, the maximum surface temperature of the target outside the fire plume region for all the cases analyzed is less than 350 K. The target cable may ignite only if it is in the fire plume region of the fire. The temperature of the target cable is predicted to significantly increase when the distance between the trash bag and cable is between 0.4 m and 0. 5 m and the target becomes exposed to the high plume gas temperature. The predicted maximum surface temperature of the target in this region is predicted to be ≈ 550 K. Although the maximum predicted heat flux from the plume incident on the target is predicted to be ≈ 14 kW/m^2, the duration of the exposure is not long enough to increase the surface of the cable to the ignition temperature. Based on this, one could establish a minimum horizontal safe separation distance[6] of 1.0 m between the trash bag and the target cable. A fire of similar intensity sustained over a longer period could ignite the cable.

4.1.2 Part II

The predicted maximum temperatures of the target cable were below 400 K for all the cases analyzed in Part II. The cable tray fire was limited between 10 min and 15 min by the depletion of oxygen near the cable tray. Given the elevation of the fire source and the predicted extinction of the fire, cable damage is unlikely for the scenarios examined. The analysis of an elevated fire source is key to the accuracy of the predicted result.

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[6]The concept of safe separation distance is not directly applicable in all countries.

4.2 Verification of Sub-models

This section mainly discusses the verification of the sub-models based on an examination and comparison of the trends from the different fire models used in the exercise. Verification is defined here as the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. Validation, which is discussed in Section 4.3, is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (AIAA, 1998). This section includes the comparison of the magnitudes of the parameters predicted by different fire models. These comparisons will be summarized and discussed in Section 4.3.

The benchmark exercise was aimed mainly at comparing zone models since there is more experience with these models in NPP applications. Therefore, this report mainly addresses zone models and their sub-models. In some instances, comparisons are made with CFD and lumped-parameter models in order to derive insights regarding the model assumptions in the different approaches. Experience with fire models that have been used for the first time for the type of problem posed in the benchmark exercise is discussed. The advantages of more advanced approaches, compared to the two-zone approach, are discussed in Chapter 5.

The following is a list of the major sub-models implemented in the two-zone fire computer codes for modeling the physical phenomena in the scenarios:

- combustion chemistry (tracking concentrations of oxygen and combustion products)
- plume and ceiling jet flow
- mass and energy balance in the two zones (stratification)
- ventilation through doors and cracks
- forced ventilation
- heat transfer to boundaries
- heat transfer to targets
- thermal response of the target

4.2.1 Part I

The measured heat release rate of the trash bag fire which was used as input for Part I is shown in Figure 2. The peak heat release rate for the trash bag fire is ≈ 350 kW, and peaks at ≈ 150 s.

Base Case

Figure 3 shows the plume flow development during this scenario predicted by some of the fire models used in the exercise. The main plume flow increases rapidly at the initiation of the fire, and does not follow the fire heat release rate, as expected. This is due to the nature of the correlations used in the codes. CFAST over predicts mass entrainment at the initial stages of the fire because of the plume height used in the calculation of the entrained air. Initially, the plume height is assumed to be from the fire to the ceiling. This leads to an over prediction of the initial mass flow to the upper layer, and the rate of descent of the gas layer interface. The peak plume flow from the CFAST (BRE) analysis is less than that from the CFAST (NRC) analysis because of the assumed height of the fire (on the floor in CFAST (NRC) versus at the height of the top of the garbage bag (0.62 m) in CFAST (BRE)). This difference is caused by a "user effect" and is discussed further in Section 5. The peak plume flow predicted by FLAMME_S is less than CFAST by a factor of ≈ 2. Table 10 lists the peak plume flow predicted by the various fire models that were used in the exercise. Plume flow is not a normal output parameter from MAGIC. Plume flow is not directly computed in CFD and lumped-parameter models.

Figure 4 shows the predicted hot gas layer development predicted by some of the fire models used in the exercise. The interface height decreases rapidly initially due to high plume flow (see Figure 3). The rate of descent of the interface height decreases after ≈ 230 s when the HGL temperature has peaked (see Figure 8). Because of the two-zone assumption, the hot gas layer is prevented from reaching the floor due to air inflow at the crack below the door caused by a negative pressure in the compartment (see Figure 7). In reality, the hot gas layer is expected to reach the floor in parts of the room farthest from the door. CFAST predicts a more rapid descent of the HGL interface than FLAMME-S because of the higher predicted plume flow as shown in Figure 3. The trend of HGL development predicted by the fire models used in the exercise are as expected, given the two-zone assumption in the zone models. The HGL interface height is not directly computed in CFD and lumped-parameter models.

Figure 5 shows the oxygen depletion for the Base Case predicted by the fire models used in the exercise. The oxygen concentration in the upper layer decreases by ≈ 1% to 19.2 % generally[7]. The oxygen depletion predicted by the various models is similar. The fire will not be limited by oxygen in this fire scenario for the assumed HRR of the fire and dimensions of the room.

Figure 6 shows the pressure development predicted by the fire models used in the exercise, and Figure 7 shows the resulting flows in and out of the compartment. The pressure is predicted to peak at ≈ 150 s when the fire heat release rate peaks, as would be expected. At some point after the fire peaks, the heat released into the compartment by the fire is less than the heat loss through the concrete walls (see Figure 10 for a

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[7]The oxygen concentration output by the MAGIC code is the mass fraction, whereas the other codes output the mole fraction.

typical heat loss trend[8]) resulting in the decrease of compartment temperature and pressure. The pressure swings to a negative value resulting in flow into the compartment through the door crack. The predicted peak in the outflow is consistent with the pressure profile, and the outflow goes to zero when the pressure in the compartment is less than the outside. The predicted initiation of inflow is consistent with the pressure profile, and is much less than the outflow. Table 10 lists the peak pressure and lower layer outflows that were predicted by the various fire models used in the exercise. The peak over-pressure predicted generally varies between 600 Pa to 2000 Pa, resulting in an outflow of 0.4 kg/s to 0.6 kg/s from the crack under the door. The pressure evolution predicted by JASMINE is discussed by Miles (Appendix G) and was found to be sensitive to the heat release mechanism and amount of heat lost to the boundaries. The trends of pressure and vent flow predicted by zone, CFD, and lumped-parameter fire models used in the exercise vary by a factor of ≈ 3 and 1.5, respectively.

Figure 8 shows the hot gas layer (HGL) temperature. The upper layer temperature peaks at ≈ 200 s, about 50 s after the fire peaks, when the heat released into the compartment is less than the heat loss from the concrete walls. Table 10 lists the peak HGL temperatures predicted by the various fire models that were used in the exercise. The predicted peak temperature is between 330 K to 360 K. Therefore, in this scenario, the upper layer temperature is predicted to increase by only about 30 K to 60 K. The maximum temperature in the HGL under the ceiling is predicted to be between 400 K to 450 K by JASMINE, FDS, and COCOSYS. The trend of the HGL temperature predicted by the various fire models (zone, CFD, and lumped-parameter) used in the exercise is similar and as expected. The predicted peak HGL average temperature varies by up to 50 %.

One important difference in the results from the zone, CFD, and lumped-parameter codes for the type of scenarios examined for the Benchmark Exercise is the hot gas temperature. A two-zone code, calculates the *average* temperature of the hot gas layer, whereas CFD codes compute the entire temperature profile in the compartment. The peak average HGL temperature predicted by zone models for the Base Case is ≈ 350 K. The temperature profiles that were predicted by CFD codes for this case ranges from ≈ 350 K in the lower region to ≈ 400 K in the upper region of the hot gas. This temperature gradient in the hot gas will determine the convective heat flux to the cable tray depending on its vertical position and may become more prominent and important for scenarios with a high fire intensity.

Figure 9 shows the target surface temperatures predicted by the fire models used in the exercise. The target temperature is predicted to peak at ≈ 250 s, approximately 100 s after the fire and target flux reaches its peak due to the thermal inertia of the target. The trend of the target surface temperature predicted by the various fire models used in

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[8]The unsteady behavior of the curve is due to the numerical derivation of the integral heat inside the wall and door structure.

the exercise is similar and as expected. Table 10 lists the peak flux and temperature of the target. The low thermal conductivity of PVC induces a strong temperature gradient between the surface and center of the cable. The target surface temperature is generally predicted to only increase ≈ 20 K for this case. It should be noted that, although not evident in the results for this case, the fire models utilize different approaches for calculating the heat flux incident on the target. The target is modeled as a slab in CFAST. The orientation specified for the slab will determine the incident flux on it (Miles:Appendix G) and may be a source of "user effects." This is discussed further in Chapter 5. The target is also modeled as a slab in FLAMME_S (see Bouton:Appendix A). MAGIC and COCOSYS employ a 1-D radial model for cable targets in order to eliminate the need to specify the orientation of a slab and improve the predictive capability. CFX includes a 3-D conduction model for the target. The predicted fluxes on the target by these models will vary because of the different assumptions and approaches embedded in them.

Cases 1, 2 and 3: Effect of Distance

Cases 1, 2 and 3 examine the effect of the distance between the target and fire on target heating. The heating of the cable in this scenario is mainly due to the radiative heat flux from the fire and the convective heat transfer from the hot gas. Figure 11 shows the typical evolution of the target surface temperature for various distances (d) between the fire and target. The target surface temperature peaks at ≈ 200 s, ≈ 50 s after the fire reaches its peak intensity due to the thermal inertia of the target. The increase in target surface temperature between distances (d) of 0.9 m and 0.5 m is due to the increase in radiative flux from the fire that is incident on the target. Figure 12 shows the typical strong effect of distance on the radiative flux incident on the target. The target is within the plume region at a distance of ≈ 0.4 m and is heated by convection by the hot plume gas. Target heating in the plume region is not currently modeled in CFAST. The MAGIC code provides an option for a side calculation of target heating in the plume region. The heating can be calculated by hand using plume correlations. CFD codes can calculate target heating based on the principal formulations in the approach which does not explicitly require an empirical plume model. In lumped-parameter approaches, the plume is not really modeled and therefore the form of the plume is dependent on the nodalization around the fire (Klein-Hessling:Appendix F). Also, momentum is not balanced in the lumped-parameter approach. Figure 13 graphically illustrates the exposure of the target in the plume region in a CFD analysis.

Tables 11, 12 and 13 lists the peak fluxes and target surface and centerline temperatures predicted by the fire models used in the exercise. The Tables indicate that the target does not reach the ignition temperature even when it is in the plume region according to the criteria established for ignition, i.e., target centerline temperature of 643 K. The tables again indicate the strong gradient between the target surface and centerline due to the low thermal conductivity of PVC. As indicated above, it should also be noted here that the fire models used for the benchmark exercise utilized different approaches for calculating the heat flux incident on the target. The result of the different approaches is evident in Tables 11, 12 and 13. In Case 1, some of the fire models include a calculation for target heating in the plume region (e.g., FLAMME_S and CFX).

Cases 4 and 5: Effect of Natural and Mechanical Ventilation

The following presents some key features of the results of Cases 4 and 5. Figure 14 shows a typical development of the interface height for Case 4 versus the Base Case. The interface height approaches a constant value at ≈ 140 s, after the HGL reaches the top of the door at ≈ 100 s. Figure 15 shows a typical development of the upper layer outflow and lower layer inflow after the HGL interface reaches the door at ≈ 100 s, indicating the establishment of a neutral plane below the top of the door (at ≈ 2.2 m). Figure 18 is a typical vector plot of temperature in a plane parallel to the cable trays at the midpoint of the room (and the door), and illustrates the typical flow patterns predicted by a CFD code for Case 4 in which the door is open. Outflow and inflow at the door around the neutral plane are illustrated, as also predicted by the zone models. Figure 16 shows typical HGL temperature development for Cases 4 and 5. The HGL temperature for Case 4 is less than the Base Case after ≈ 270 s because of the outflow of hot gas from the upper layer (which reaches its peak value at ≈ 200 s) through the door, and higher plume flow. The HGL temperature for Case 5 is less than that in the Base Case after ≈ 100 s when the HGL reaches the mechanical vents, and ambient air is injected into and hot gas ejected from the hot gas layer in the two-zone formulation.

Figure 17 shows a typical development of flows in the mechanical ventilation system (for Case 5) simulated by zone models. The transitions in flows from the mechanical vents in and out of the gas layers occurs at about ≈ 100 s when the HGL reaches the mechanical vents. Figures 19, 20, and 21 show typical flow patterns predicted by CFD models that can be caused by the mechanical ventilation. This type of information will be useful for examining the local effects of ventilation on target heating, where assuming the target is exposed to the average conditions of the HGL will yield conservative results.

The above indicates that the predicted flow patterns for natural and mechanical ventilation by both zone, CFD, and lumped-parameter models are similar, as expected. CFD models have the advantage of providing more detailed flow information for examining local effects.

Tables 14 and 15 list the peaks of some parameters predicted by the fire models used in the exercise. The natural ventilation through the door (Case 4) and mechanical ventilation (Case 5) do not have a strong effect on the target temperature which is in the HGL. The target surface temperature for Case 4 and 5 is less than in the Base Case because of cooler hot gas layer temperatures, but by only 2 K to 4 K of a total increase of 20 K. The predicted peak outflow from the door for Case 5 ranges from 0.4 to 1.3 kg/s. The variation in the predicted outflow is generally consistent with the variation in the plume flows listed in Table 10. The predicted oxygen concentration in Case 5 is consistently slightly higher than the Base Case due to inflow of ambient air into the HGL. The maximum variation in the predicted HGL temperature by the various codes is ≈ 45 % for Case 4, and ≈ 30 % for Case 5.

Conclusion

The international panel determined that the above analysis of the results for Part I demonstrate that current zone, CFD, and lumped-parameter fire models provide a comprehensive treatment of most physical phenomena of interest in the scenarios analyzed. The results indicate that the trends predicted by the sub-models are reasonable for the intended use of the models for analyzing the specified scenarios. The results of the analyses for the specified scenarios provide useful insights for nuclear power plant fire safety analysis.

4.2.2 Part II

Base Case

Figures 22 to 26 show the predicted results of the main parameters of interest with the fire models used for the benchmark exercise. Figure 27 shows a typical result of the species concentrations predicted by the fire models, and Figure 28 shows the pyrolysis rate specified for the case.

The predicted trends for the heat release rate, interface height, and oxygen concentration in Figures 22, 23, and 24 are collectively examined. The fire models predict the HGL lowers to the fire source (at an elevation of 3.4 m) between 200 s and 400 s. This variation is due to the different approaches used in modeling the fire source (e.g., the cable tray is divided into 10 fire sources in the FLAMME_S analysis). The fire models predict the heat release rate decreases rapidly between 500 s and 700 s when the oxygen concentration in the HGL reaches the LOL of 12 % specified for the exercise. The variation of the predicted time at which the fire is extinguished is due to slight variations of the predictions of oxygen concentration in the HGL. It should be noted that the MAGIC (CTICM) and COCOSYS utilized LOL values of 0 % and 4 % for the analyses. The effect of a lower LOL on the heat release profile is evident in Figure 22 which shows the fire is sustained over a longer period. The HRR predicted by COCOSYS is sustained even longer due to the higher predicted oxygen concentration as seen in Figure 24. Fluctuations in the HRRs predicted by CFAST (shown in Figure 22) are due to the movement of the interface height around the fire source as shown in Figure 23. The extinction models utilized in all the computer codes are approximations of the interaction of the complex combustion process with a limited oxygen environment. Therefore, the results represent an approximation of the conditions expected for this fire scenario.

The HGL profiles shown in Figure 25 are consistent with the HRR profiles shown in Figure 22. As listed in Table 16, the fire models generally predict a peak HGL temperature of ≈ 450 K. The MAGIC (CTICM) and FLAMME_S profiles indicate a decrease in the slope of the HGL temperature when the HRR becomes constant at 1 MW (see Figure 22). The change in the slope is due to the dynamic balance of heat addition to the HGL and loss to the boundaries. The peak temperature predicted by JASMINE and COCOSYS under the ceiling is ≈ 500 K and ≈ 650 K respectively. The higher prediction by COCOSYS is due to the lower LOL value (4 %) used for the analysis, however, other modeling assumptions may also account for the difference.

Table 16 lists the peak flux on the target, and Figure 26 shows the target surface temperature profiles. As indicated earlier, the fire models utilize different approaches for computing the heat flux on the target. For example, the effect of the orientation of the slab in CFAST analyses is seen in Table 16 and Figure 26. The heat flux reported for COCOSYS is only from convection since radiative fluxes are not calculated for Part II (Klein-Hessling:Appendix F). The variation of the peak target surface temperature predicted by models with similar predictions of heat flux on the target are due to the fire HRR and HGL temperature profiles, i.e., the target temperature increase is based on the duration of its exposure to the environment.

The species concentration predicted by FLAMME_S shown in Figure 27 is consistent with its predicted HRR profile shown in Figure 22. The production of the species from combustion is terminated at ≈ 700 s when the fire is extinguished.

The analysis demonstrates the complexity in modeling an elevated fire source which can be affected by a limited oxygen environment. The assumption for the LOL will have a significant effect on the predicted peak target temperature. Conservative assumptions are warranted due to the uncertainty in the extinction models used in the computer codes.

Cases 1 and 2: Effect of Distance

Tables 17 and 18 list the peak heat fluxes and target temperatures for Cases 1 and 2 reported by the fire models used for the exercise. A consistent trend in the effect of distance on target heating is not evident from the Tables due to the different approaches used for computing heat fluxes. The typical strong effect of the distance between the fire and target on the radiative flux incident on the target was discussed in Section 4.2.1.

Cases 3 to 8: Effect of Fire Intensity and Distance

As discussed above, the cable tray fire in the Base Case is limited by the oxygen depletion in the environment. Cable tray fires that could be potentially more intense (as specified by the pyrolysis rate for these cases) are also limited, i.e., the HRRs are similar to that specified for the Base Case. Therefore, these cases are not discussed further here.

Case 10: Effect of Ventilation

Table 19 lists the peak values of the heat flux, and HGL and target temperatures for Case 10. The peak values predicted by the zone models are generally similar to those for the Base Case because the fire source is in the HGL. The mechanical ventilation system inserts ambient air and ejects air for the lower layer in the two-zone formulation without affecting the HGL. The two-zone approach establishes an artificial boundary between the two zones. In reality, there will be some mixing of mass between the zones. Figures 19, 20, and 21 graphically present the effects of mechanical ventilation on the plume and flow patterns in the compartment predicted by CFD codes. The fire source could be exposed to higher concentrations of oxygen than the HGL average predicted by zone models, if the fire source is near a mechanical ventilation inlet vent. Conservative values of the LOL could be assumed in analyses with zone models to account for this uncertainty.

Cases 11 and 12: Effect of Cable Tray Elevation

Table 20 and 21 lists the peak values for heat flux and target temperatures for Cases 11 and 12. The model used for the target cable will determine the manner in which the target elevation affects the incident heat flux and heating of the cable. As indicated earlier, different approaches are utilized by the fire models used in the exercise leading to the variation in results listed in the tables. Generally, a higher target elevation would expose it to the HGL for a longer period leading to higher temperatures. However, the effect of target elevation is not significant. It should be noted that the target remains outside the ceiling jet layer in this scenario. None of the zone models used in the exercise include a model to predict target heat by the ceiling jet. It will be useful to have this capability for other scenarios in which the target is located in the ceiling jet.

Case 13: Effect of Target Structure

Table 22 lists peak target surface and centerline temperatures that were predicted by the fire models used in the exercise. The structure of the cable has a strong effect on its thermal resistance and heating. The power cable has more thermal inertia and resists heating for a longer period as compared to the instrumentation cable. Table 22 shows that the peak centerline temperatures for the instrumentation cable for Case 13 are much higher than those for the power cable in the Base Case. Figure 29 shows the typical temperature profiles for the power and instrumentation cables. The difference between the core temperature profiles for Case 13 and the Base Case are evident in the figure. The core temperature of the target is much less than the surface temperature due to the low thermal conductivity of the cable insulation, PVC (0.092 W/m.K), except for Case 13. In Case 13, the core temperature is much higher because the diameter of the instrumentation cable is less than that of the power cable by a factor of three. Also, note that the core cable temperature continues to increase after the surface temperature has peaked for all the cases. The figure shows that the maximum temperature (core or surface) is less than the specified damage temperature of 473 K for all the cases in Part II.

A comparison of the fire duration with the time needed for heat to reach the core of the target provides an insight as to why the target is not damaged (Bouton:Appendix A). An estimate of the time taken for the rear face of the target to increase in temperature when the front face is exposed to a heat flux is given by the formula:

$$t_p \approx \frac{e^2}{16(\lambda/\rho c)}$$

where e is the wall thickness, λ the thermal conductivity, ρ the density, and c the specific heat. This equation provides a thermal penetration time of 200 s and 20 s for the power and instrumentation cables, respectively. The duration of the fire is ≈ 720 s for all the cases. For the power cable, the thermal penetration time and fire duration are of the same magnitude. Therefore, the core of the power cable does not approach the surface temperatures. For the instrumentation cable, the thermal penetration time is much less than the fire duration. Therefore, with a short delay, the temperature profile of the cable centerline is similar to that at the surface.

Special Cases

Since the fire was extinguished after ≈ 720 s and well before 4800 s, the expected duration of the fire, several participants in the exercise analyzed special cases. These cases varied slightly but mainly analyzed a cable tray fire at an elevation below the top of the door. Natural ventilation of the hot gases through the door prevented the HGL from reaching and extinguishing the cable tray fire. Therefore, a fire that was sustained at the specified intensity for 3600 s was achieved. Table 23 lists the results of the analyses. All the cases listed analyzed similar conditions, except Case S3 which analyzed a 3 MW fire and a shorter distance between the fire and the cable target. Case S4 analyzed similar conditions but with LOL set at 0 %.

Figure 30 shows the HGL and target surface temperature development for typical results from two fire models. Both models predict an initial rapid rise in the HGL temperature followed by a less rapid increase after the fire intensity has peaked. As indicated earlier, the change in the slope is due to the dynamic balance of heat addition to the HGL from the fire and loss to the boundaries. The target surface in these cases approaches the HGL temperature due to longer exposure of the target to the thermal environment in the compartment. The difference in the peak HGL temperatures predicted by the two models is 35 %. The peak HGL temperatures predicted by other models listed in Table 23 vary by less than this, e.g., the difference between the CFAST and FLAMME_S predictions is ≈ 17 %. Case S4 produces a less severe condition than Case S5 because the fire is extinguished after ≈ 900 s even though LOL is set at 0 % (see MAGIC (CTICM) results in Figure 22).

Table 23 shows that the cable centerline temperatures approach the surface temperatures for these cases because of the long duration of the fire. The thermal penetration time of the power cable, 200 s, is much less than the duration of the fire (sustained for 3600 s) in these cases. Table 23 also shows that the target centerline temperature exceeds the specified damage criteria of 473 K only for Case S3 which analyzed a target 3.1 m from a 3-MW fire sustained for 3600 s.

Conclusion

The international panel determined that the above analysis of the results for Part II demonstrates that current zone, CFD, and lumped-parameter fire models provide a comprehensive treatment of most physical phenomena of interest in the scenarios analyzed. The results indicate that the trends predicted by the sub-models are reasonable for the intended use of the models for analyzing the specified scenarios.

The analyses of the scenarios also demonstrate the complexity in modeling an elevated fire source which can be affected by a limited oxygen environment. The extinction sub-models utilized in all the computer codes are approximations of the interaction of the complex combustion process with a limited oxygen environment. Therefore, the results from the extinction sub-models represent an approximation of the conditions expected for the fire scenarios. The assumption for the LOL will affect the predicted peak target temperature. Therefore, conservative assumptions are warranted due to the uncertainty in the extinction models used in the computer codes. Also, as indicated earlier, the target sub-model in some of the computer codes requires the specification of target orientation by the user. This may result in non-conservative results and "user effects." This limitation may be overcome by establishing procedures for the use of the models to obtain conservative and consistent results. The results of the analyses for the specified scenarios provide useful insights for nuclear power plant fire safety analysis.

4.3 Validation of Models

This section presents a brief discussion of model validation which was defined above as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

4.3.1 Validation Studies and Uncertainty Estimate

The fire models used in the benchmark exercise have all been compared with test data for fires ranging from 100 kW to 2.5 MW in compartments with volumes ranging from 10 m^3 to 1300 m^3 . These comparisons are summarized and referenced in the individual reports for the fire models included in the appendices. The comparisons are generally satisfactory, with different accuracies reported for the range of data sets. Gautier (Appendix C) reports that the difference in temperatures between those predicted by the model and measured for steady fires is rarely less than 10 K, but predictions that are 50 K or higher are common. The data sets in the validation database include data for the configuration (power, compartment volume) analyzed in the benchmark exercise reported here. IPSN has reported (Such, 1997) tests conducted in a compartment with a volume of 400 m^3 volume and a 1 MW fire for 4200 s. The relative variation of pressure, temperature, and oxygen concentration predicted by FLAMME_S with test data was within 20 %. The comparison of cable surface temperature evolution was less successful due to the compartment vertical temperature gradient in the test data and the difficulty in measuring the cable surface temperature. The validations of the fire models conducted to date indicates that they generally provide a reasonably accurate representation of the real world for the types of scenarios in the benchmark exercise.

Although the exercise reported here did not include comparison of model results with test data, the analysis reported above did include the comparison of the magnitudes of the parameters predicted by different fire models. Generally, the predictions were similar. Models developed independently, if based on the same fundamental laws, are expected to produce similar results.

A distinction is made here between the variability of results due to different assumptions of input data, either for model coefficients, compartment configuration, or fire source data, and the uncertainty of model predictions given the inherent approximations contained in them. As indicated earlier, different assumptions of fire source power can significantly affect the results from the models. Other important input data are the thermophysical parameters, e.g., the convective heat transfer coefficient. The international panel judged that differences in model results due to the uncertainty of the models is less than differences that can be caused by variations in input data and assumptions.

4.3.2 Benefit of Extending Validation Database

Although the above discussion proposes a certain degree of confidence in the current fire models, there are benefits to extending the validation database. As discussed in previous sections, the sub-model for the target, and issues regarding the thermal environment of the target, is a source of uncertainty for these types of scenarios. As indicated in the analysis of the results, the target response is sensitive to the magnitude and duration of the heat flux incident on it. A target may be more sensitive to the duration of the exposure than the magnitude of the heat flux and intensity of the thermal environment if it has a high thermal inertia. It will be useful to conduct international collaborative validation exercises in which the sensitivity of target response is explored and the predictive capability of target damage is the main focus of the program. Also, more refined measurements and data analyses will be useful to estimate the quantitative uncertainties of the parameters predicted in the analyses of these fire scenarios. The computer code results, with quantitative estimates of the uncertainties in the predicted parameters, will extend the confidence in the models for supporting engineering judgments in nuclear power plant fire safety analysis.

5 General Conclusions and Recommendations

This final chapter provides a discussion of the general conclusions and issues derived from the benchmark exercise.

5.1 Capabilities and Limitations

As indicated above, the international panel determined that the analysis of the results of the benchmark exercise demonstrates that current zone, CFD, and lumped-parameter fire models provide a comprehensive treatment of most physical phenomena of interest in the scenarios analyzed. The results indicate that the trends predicted by the sub-models are reasonable for the intended use of the models for analyzing the specified scenarios. The results obtained from these fire models can provide useful insights for nuclear power plant fire safety analysis for the type of scenarios analyzed.

Capabilities

The constitutive equations for mass and energy in the fire models provide a reasonable prediction of the hot gas layer development and temperatures in the compartment. The fire models generally provide an adequate method to balance and estimate the concentration of oxygen and combustion products in the compartment. Mass flows that result from the pressurization of the compartment, and natural or mechanical ventilation, are reasonably predicted for the zone, CFD, and lumped-parameter models. Convective and radiative heat fluxes to the boundaries and target are comprehensively treated in the models. The thermal response of the target is also adequately estimated in the models.

Limitations

Fire Source

The mass loss rate in the models is generally not coupled with the thermal behavior of the source. This limitation necessitates the specification of the mass loss rate profile. The heat release rate is then calculated in the model based on the availability of oxygen. The coupling of mass loss and heat release, which entails modeling the combustion process, is complex and difficult, especially for solid fires. Until further research is conducted and accurate models developed to overcome this limitation, characteristic mass loss rate profiles will need to be developed and specified. An international effort to develop standardized mass loss profiles is recommended.

A related limitation exists for the extinction sub-models utilized in the computer codes. The sub-models used are approximations of the interaction of the complex combustion process with a limited oxygen environment. The results from the extinction sub-models represent an approximation of the conditions expected for the fire scenarios. Some tests have shown that fires can be maintained at low oxygen concentrations through the establishment of flames distant from the source. Conservative assumptions for the LOL may be warranted to compensate for the limitations in the extinction models used in the computer codes. Participants in the exercise reported here used an LOL value ranging from 0 % to 12 % based on their experience and judgment, and degree of conservatism needed for the analysis. It is recommended that users of fire models determine an appropriate value based on the ventilation conditions for their application, scenario configuration (single versus multi-compartment), and desire for conservatism in the analysis. A sensitivity analysis for different LOL values may be appropriate for a best-estimate calculation.

Target Model

The fire models generally include a simple sub-model for the target that allows the modeling of one cable. This is acceptable as long as the goal of the analysis is to provide a conservative estimate. The modeling of a cable bundled with other cables in a tray will result in lower cable temperatures. The ability to model bundled cables, and the structure of the cable tray may be beneficial. The target sub-model in some of the computer codes requires the specification of target orientation by the user. This may result in non-conservative results (for a single cable) and a "user effect." This limitation may be overcome by including a 1-D radial heat transfer model for the target, or establishing procedures for the use of the slab model in a consistent manner. The ability to model a target with more than one material may also be useful to determine the temperature gradient in the cable, otherwise the property of the single material to be specified needs to be developed. Target heating in the plume and ceiling jet is not included in most of the models, thereby limiting the analysis of certain types of scenarios.

Given the above complexity in estimating cable damage, an evaluation should be conducted to determine whether consistent results can be obtained in modeling cable damage directly (modeling heat conduction into a cable or tray of cables) or defining a conservative safety criterion based on gas temperature and/or incident flux may be prudent.

Two-Zone Approximation

The two-zone approximation may limit the analysis of certain types of scenarios and issues. This includes issues for which the local effects of natural and mechanical ventilation need to be examined (e.g., under ventilated scenarios), or the local temperature in the HGL is necessary to calculate the target temperature.

Other Modeling Issues

The following is a summary of modeling issues that are discussed in the reports by the analysts in the appendices, or that were raised and discussed at the 4th meeting when the results of the analyses were presented.

Radiation from Hot Gas

Radiation from the hot gas in the upper layer or the plume region is likely to be the main contributing factor to cable damage for the types of scenarios analyzed in the exercise. The predicted concentration of soot is an important factor in calculating the radiation from the hot gas. A sensitivity study is recommended to examine the impact of soot concentration on the overall radiative flux from the hot gas. A review should also be conducted to assess the need for additional data for soot yields.

Plume Models

The plume correlation in zone models provides the driving force for the generation of hot gases. Certain limitations in the plume model for CFAST were noted earlier. Although plume correlations and calculations have been extensively reviewed and used in the development of zone, CFD, and lumped-parameter models, they should be examined for any limitations for the types of fire sources of interest in nuclear power plants.

Convective Heat Transfer Coefficient

During the development of input data for the models, it was decided that the convective heat transfer coefficient would be set at 15 W/m^2 K for the benchmark exercise. This value may be too high and unrealistic, especially for some surfaces. This parameter should be reviewed to determine if another value based on a free convection correlation should be used, and if different values should be used for the floor, wall, ceiling, and cable.

5.2 User Interface

The following are recommendations made regarding the user interface.

As evident from the discussions in this document, users of fire models should have knowledge of basic heat transfer, thermodynamics, and fluid mechanics. A fundamental course in fire dynamics, available at the graduate level in several universities, will provide additional beneficial knowledge for the use of the models. It is not necessary to be a developer or an expert to use the models. Short courses that provide basic training in the use of specific models will also be beneficial.

In order to prevent misuse, the fire models should be adequately documented with a technical reference manual, user's guide, and verification and validation report. The documentation should include sample problems which include input data and results for the scenarios analyzed so that the user is able to replicate the analyses. The inclusion of several sample problems will allow the user to verify the correct installation of a code, gain confidence in the use of the model, and have access to input data for a range of fire scenarios. Allowable options in the models should be adequately explained, e.g., constrained versus unconstrained fire in CFAST, to prevent misuse of the options for conditions for which they were not intended (Will:Appendix H). Specific parameters that may be subject to "user effects" should be identified and discussed, e.g., target orientation in CFAST and the mesh for the conduction calculation in MAGIC.

Results may vary if different versions of the code are used. The legacy of the fire models should be documented to identify the differences between various versions of the code. The compatibility of older codes with newer operating platforms should be identified, e.g. CFAST version 3.1.6 is not compatible with Windows NT (Will:Appendix H). The effect of different compilers on the model installation should also be discussed.

The fire models should have a graphical user interface (GUI) to allow users to efficiently input data for the models and minimize errors in this process. The lack of a GUI for CFAST Version 4.0 may have led to errors (Will:Appendix H). The GUI should provide automatic controls for the input of data and alert the user when values are beyond recommended ranges, or are incorrect. A GUI with this type of feature to check for errors will minimize the input of incorrect data, and the improper use of the model.

5.3 Benefits of Hand Calculations

Although hand calculations can provide bounding results for many scenarios, the results discussed above showed the strong coupling between the target response and the thermal environment created by the fire. Therefore, for the types of scenarios analyzed in the exercise reported here, zone models provide the minimum simulation capability to examine the dynamic response of the target to the fire environment.

5.4 Need for Model Improvements

Several of the models used may benefit from an improved target model, especially to address the "orientation" issue discussed above. However, the benefit from such an improvement will need to be examined given zone models do not provide local temperatures of the hot gas around the target. There may be a steep vertical temperature gradient in the hot gas, especially for large fires. The fire models generally include a simple sub-model for the target that allows the modeling of one cable. This is acceptable as long as the goal of the analysis is to provide a conservative estimate. The modeling of a cable bundled with other cables in a tray will result in lower cable temperatures. The ability to model bundled cables, and the structure of the cable tray, may be beneficial. The ability to model a target with more than one material may also be useful to determine the temperature gradient in the cable. Target heating in the plume and ceiling jet regions may also be beneficial improvements to the models that do not have this feature.

5.5 Need for Advanced Models

The mass loss rate in the models is generally not coupled with the thermal behavior of the source. This limitation necessitates the specification of the mass loss rate profile. The coupling of mass loss and heat release, which entails modeling the combustion process, is complex and difficult, especially for solid fires like cables. Several efforts are underway to address this issue. CFD codes provide the opportunity to address this issue because of the availability of localized information that is necessary for coupling mass loss and heat release. A related benefit of this improvement will be the ability to more accurately predict the point of extinction in under ventilated fires.

CFD models may be beneficial to verify the results of a zone model study. CFD models, which are computationally more expensive, may be used following the analysis of the problem with a zone model, including sensitivity calculations. A few important scenarios can then be analyzed with a CFD model to provide a comparison and verification of the results obtained from the zone model.

CFD models may also be beneficial for analyzing issues when local effects are important. Figures 19, 20 and 21 illustrated the ability of CFD models to provide detailed information of the flow patterns in the compartment. This type of information can be useful in calculating target heating in the plume region, and for determining effects of ventilation on the fire source and target. Lumped-parameter models also provide local information to determine the effects of ventilation. Also, both CFD and lumped-parameter models provide information on the temperature gradient in the hot gas layer which may be important for determining target response.

The prediction of radiative fluxes from the plume in the near field is a complex problem. CFD models, in combination with a radiation model, can provide a better estimate of the radiative fluxes from the flaming region and hot gas layer. The radiation model may be as important as the fluid dynamics for thermal damage analysis. In order to maintain efficiency in the computations, radiation fluxes and gas temperatures could be stored at target locations, and used later in a separate conduction model.

5.6 Need for Additional Test Programs

The need for additional test programs for supporting the use of fire models may be divided into three categories.

1. Fire Model Validation

The need for additional fire model validation was discussed in Section 4.3.2. The sub-model for the target, and issues regarding the thermal environment of the target, is a source of uncertainty for the types of scenarios that are important in nuclear power plants. It will be useful to conduct international collaborative validation exercises in which the predictive capability of target damage is the main focus of the validation. Also, more refined measurements and data analyses will be useful to estimate the quantitative uncertainties of the parameters predicted in the analyses of these fire scenarios. The data from tests can also be used for improving target models, and developing models for target heating in the ceiling jet and plume regions.

2. Mass Loss Rate Data

Given the complexity of modeling flame spread, and the developmental state of flame spread models, it was recommended earlier that current fire modeling analyses use mass loss rates derived from tests conducted with configurations similar to that being analyzed. The development of a comprehensive database of mass loss rate profiles for combustible materials in NPPs will be beneficial for the broader application of fire models in fire safety analysis.

3. Cable Damage Criteria

The temperature at a specific point in the cable was used in the exercise to specify the criterion for cable damage. Information regarding cable damage criteria is limited. It will be beneficial to generate damage criteria for cables and a broad range of equipment of interest. This information is essential for fire safety analysis. The full benefit of fire models in nuclear power plant fire safety analysis can be achieved by establishing a broad database for damage criteria.

5.7 Generic Applicability of Conclusions

Most of the insights gained and conclusions drawn from this benchmark exercise are applicable to a broad range of fire scenarios expected in nuclear power plants. However, further benchmark and validation exercises are necessary for some specific configurations such as large compartments (like the turbine building) with large pool fires, multi compartments with horizontal and vertical vent connections, and control room configurations. Insights on some further specific issues are likely to be developed from such exercises.

Table 10 Comparison of Results for Part I, Base Case

O_2 Conc. in HGL at 600 s (Vol. %)	Peak Plume Flow (kg/s)	Peak Pressure (Pa)	Peak LL Outflow (kg/s)	Layer Ht. at 240 s (m)	Peak HGL Temp. (K)	Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cb: 19.0 cn: 19.3 f: 19.9 me: 22[6] j: 19.9 o: 19.3	cb: 3.6 cn: 4.7 f: 2.2 o:0.3	cb: 1770 cn: 2057 f: 1444 me:961 o: 975 h: 210 j: 46 s: 600[4]	cb:0.54 cn:0.59 f: 0.41 me:0.39 o: 0.40 H: 0.35 j: 0.08	cb: 1.37 cn: 0.82 f: 1.83 me:1.37 h: 0.3	cb: 359 cn: 357 f: 347 me:336 mc:336 o: 449[1] h: 349 x: 360 j: 400[3] s: 400[5]	cb: 1330 cn: 1257 me:1839 o: 472 x: 210 j: 4287 s: 1197	cb:317 cn:322 mc:319 o: 312 s: 333 me: 318 x: 360	f: 303[2] me:301 mc:300 o: 301 h: 310 x: 300

[1]COCOSYS reported temperatures are maximum values at the ceiling.
[2]FLAMME_S reported target temperatures for Part I are at the end of calculation (600 s).
[3]JASMINE reported temperatures are the "center top" values which are higher than average "hot layer" temperatures.
[4]The crack area was twice the area specified due to grid size used in simulation.
[5]FDS reported temperature is the maximum value at the ceiling.
[6]The oxygen concentration from MAGIC are reported as mass percent.

cb: CFAST-BRE
cn: CFAST-NRC/NIST
f: FLAMME_S
me: MAGIC-EdF
mc: MAGIC-CTICM
o: COCOSYS
h: HADCRT
j: JASMINE
s: FDS
x: CFX

Table 11 Comparison of Results for Part I, Case 1

Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cb: 3120 cn: 1932 me: 12,855 o: 26,763 x: 210 j: 4029	f: 773[1] cb:353 cn:332 mc:346 o: 327 x: 550[1]	f: 349 me: 303 mc: 300 o: 300 x: 300

[1]Target calculations by FLAMME_S and CFX account for the convective heat transfer from the hot gases in the plume region to the target.

Table 12 Comparison of Results for Part I, Case 2

Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cb: 2430 cn: 1808 me: 4665 o: 711	cb:340 cn:329 mc:333 o: 315	f: 308 me: 302 mc: 300 o: 300

Table 13 Comparison of Results for Part I, Case 3

Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cb: 1770 cn: 1537 me: 2732 o: 648	cb:329 cn:321 mc:323 o: 314	f: 308 me: 302 mc: 300 o: 300

Table 14 Comparison of Results for Part I, Case 4

Peak UL Outflow (kg/s)	Layer Ht. at 240 s (m)	Peak HGL Temp. (K)	Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cb:0.92 cn:1.36 f: 0.50 me:0.86 o: 1.26 h: 0.4 j: 0.90	cb: 1.86 cn: 1.67 f: 2.03 me:1.77 h: 1.5	cb: 365 cn: 357 f: 348 me:336 mc:336 o: 452 j: 400	cb: 1340 cn: 1298 me:1845 o: 486 j: 4560 s: 981	cb:322 cn:318 mc:320 o: 311 s: 325	f: 303 me:301 mc:300 o: 301 h: 306

Table 15 Comparison of Results for Part I, Case 5

O_2 Conc. in HGL at 600 s (%)	Peak Pressure (Pa)	Layer Ht. at 240 s (m)	Peak HGL Temp. (K)	Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cn: 19.7 f: 20.3 me:22.5 m: 19.7 o: 19.7	cn: 2200 f: 1071 me: 714 o: open h: ≈ 0	cn: 0.82 f: 1.83 me: 1.43 h: 1.0	cn: 348 f: 348 me: 334 mc: 334 o: 451 x: 350	cn: 1239 me: 2042 o: 396 x: 210 s: 890	cn: 319 s: 319 mc:318 o: 308 x: 360	f: 303 me: 301 mc: 300 o: 300 h: 309 x:300

Table 16 Comparison of Results for Part II, Base Case

O_2 Conc. of HGL at 600 s (%)	Peak Pressure (Pa)	Peak HGL Temp. (K)	Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cb: 12.5 cn: 13.2 me: 17.0[2] f: 17.2[2] f: 17.6 j: 16.1 o: 17.6[2]	cb: 715 cn: 805 me: 721 f: 676 o: 2104 j: 305	cb: 524 cn: 441 f: 465 me:440 o: 646[1] x: 680 j: 500	cb: 3170[4] cn: 1594[5] me: 3785 o: 2400 x: 840 j: 2420	cb: 357 cn: 323 o: 436 f: 403	f: 325[3] o: 374 me: 311 x: 301

[1]COCOSYS reported temperatures are maximum values at the ceiling.
[2]Reported at 500 s.
[3]FLAMME_S reported target temperatures for Part II are at the end of calculation (1200 s).
[4] Reported fluxes are incident on top side of target slab for Part II results
[5] Reported fluxes are on bottom side of target slab for Part II results

Table 17 Comparison of Results for Part II, Case 1

Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cb: 2740 j: 2620 me: 3784 o: 814	cb: 357 o: 438 f: 427	f: 325 me: 311 o: 374

Table 18 Comparison of Results for Part II, Case 2

Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cb: 2500 me: 3784 j: 2530 o: 2368	cb: 349 o: 435 f: 427	f: 325 me: 311 o:373

Table 19 Comparison of Results for Part II, Case 10

Peak HGL Temp. (K)	Peak Flux on Target (W/m²)	Peak Target Temp. (K) Surface	CL
cn: 448 f: 465 me: 441 o:702 x: 525 j: 550	cn: 2234 me: 3792 o: 2158 x: 500 j: 3310	cn: 373 o: 555	f: 324 me: 311 o:472 x: 335

Table 20 Comparison of Results for Part II, Case 11

Peak Flux on Target (W/m²)	Peak Target Temp. (K) Surface	CL
cb: 4080 cn: 2155 me: 3784 o: 2527 j: 3250	cb: 387 cn: 343 o:446	me: 311 o: 379

Table 21 Comparison of Results for Part II, Case 12

Peak Flux on Target (W/m²)	Peak Target Temp. (K) Surface	CL
cb: 2570 cn: 1626 me: 877 o: 1827 j: 1570	cb: 345 cn: 326 o: 398	me: 302 o: 355

Table 22 Comparison of Results for Part II, Case 13

Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
cb: 3170 o: 2400	cb: 358 o: 482 f: 421	f: 400 me: 352 o: 473

Table 23 Comparison of Results for Part II, Special Cases

	Peak HGL Temp. (K)	Peak Flux on Target (W/m^2)	Peak Target Temp. (K) Surface	CL
Case S1	cn: 457	cn: 2172	cn: 435	
Case S2	f: 489		f: 483	f: 458
Case S3	mc: 623		mc: 603	mc: 533
Case S4	me: 441	me: 4250	me: 408	me: 323
Case S5	me: 543		me: 531	

Case S1: Part II, Base Case with fire source at 1.8 m, and door open.
Case S2: Part II, Case 10 with fire source at 2.3 m (elevation of tray A).
Case S3, Part II, HRR = 3 MW; D = 3.1 m; door open and ventilation system on; fire source at 2.1 m, and LOL = 0 %.
Case S4: Part II, Base Case with LOL = 0 %.
Case S5, Part II, Case 10 with fire source at 1.0 m.

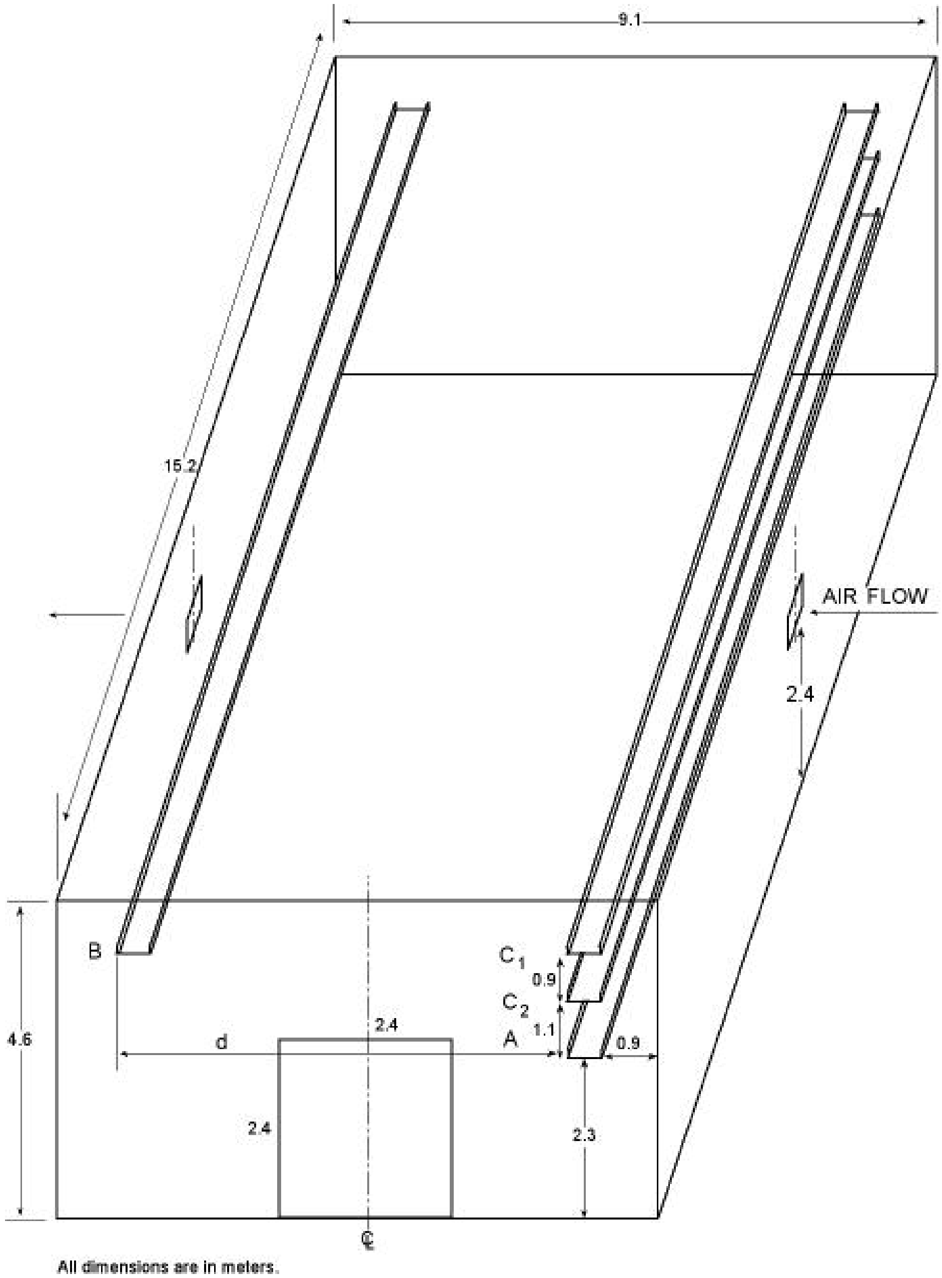


Figure 1 Representative PWR Room

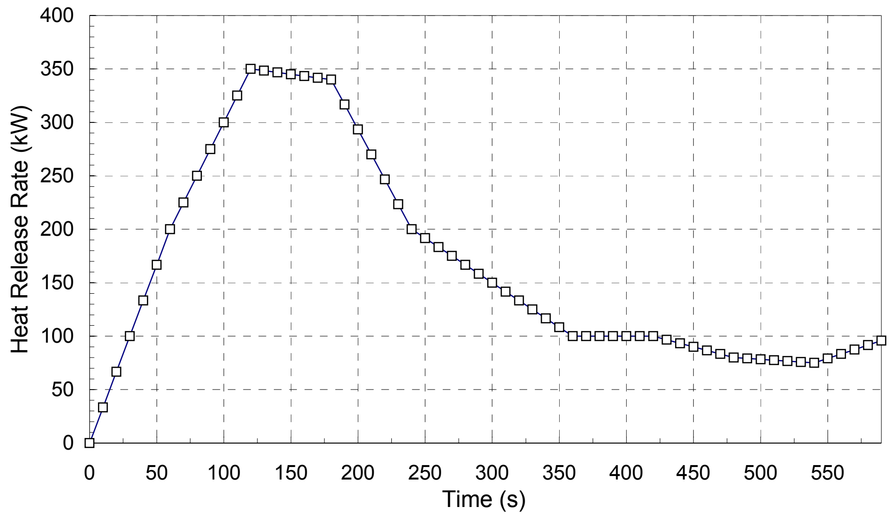


Figure 2 Trash Bag Fire (Part I)

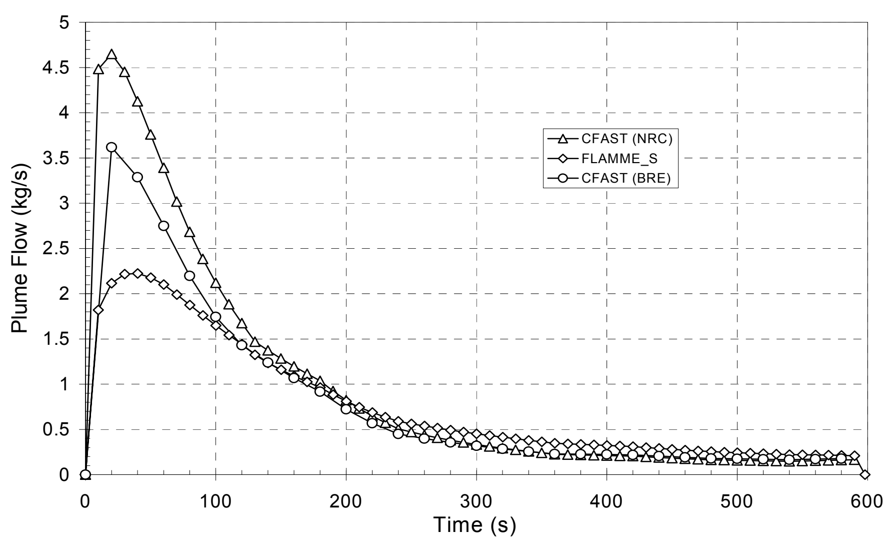


Figure 3 Plume Flow (Part I, Base Case)

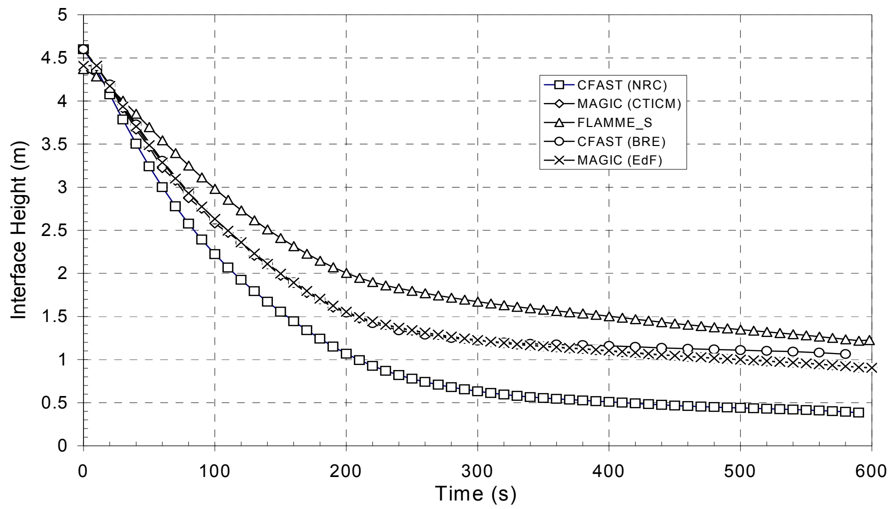


Figure 4 HGL Development (Part I, Base Case)

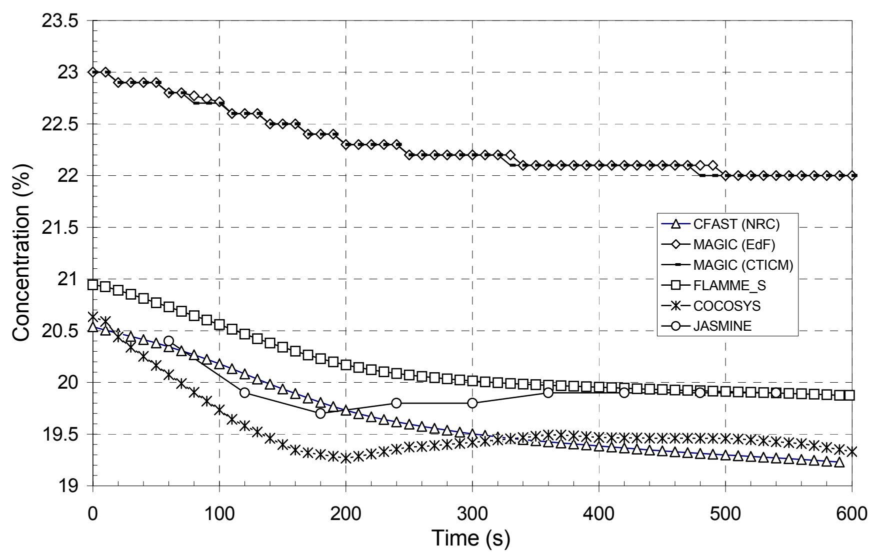


Figure 5 Oxygen Concentration (Part I, Base Case)

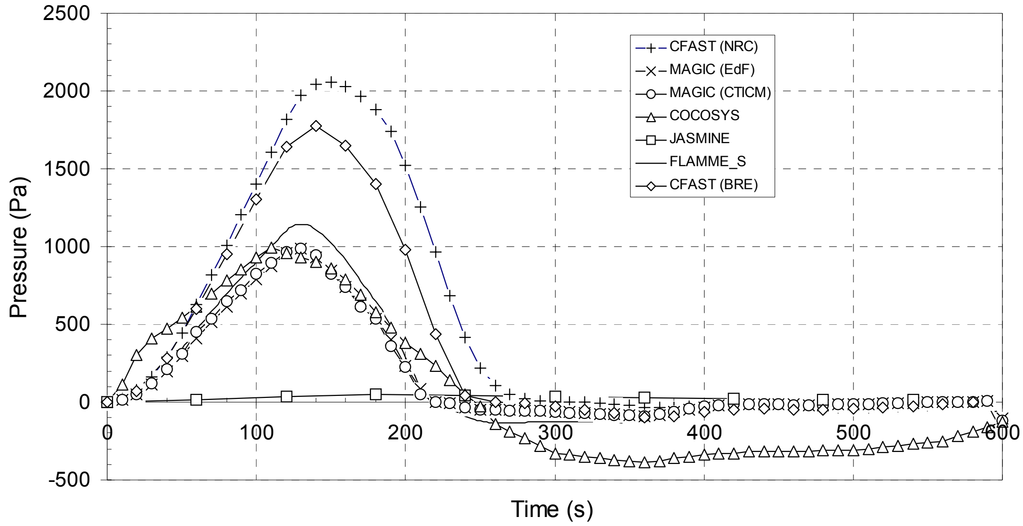


Figure 6 Pressure Development (Part I, Base Case)

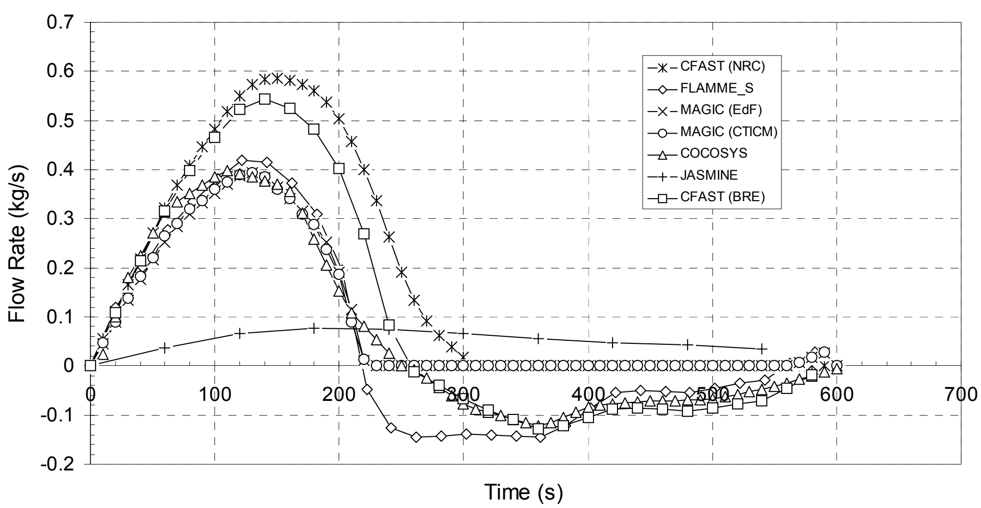


Figure 7 Flow from Crack (Part I, Base Case)

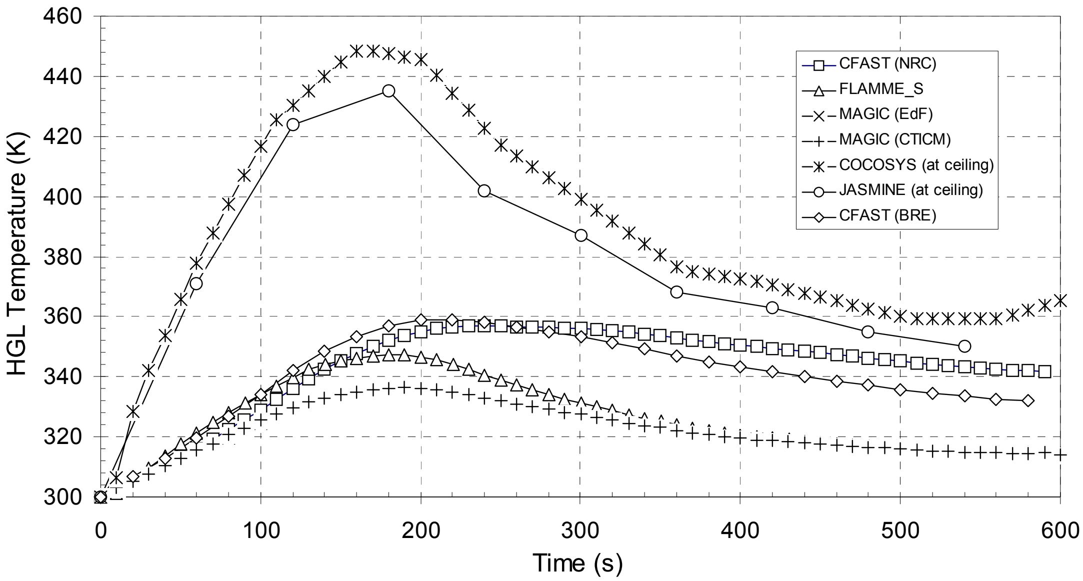


Figure 8 HGL Temperature (Part I, Base Case)

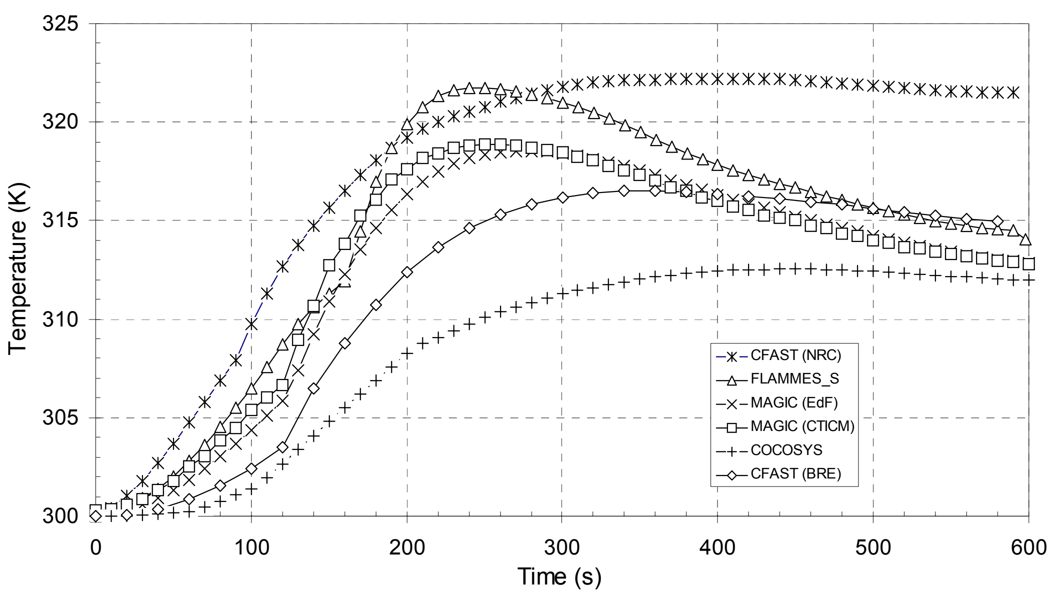


Figure 9 Target Surface Temperature (Part I, Base Case)

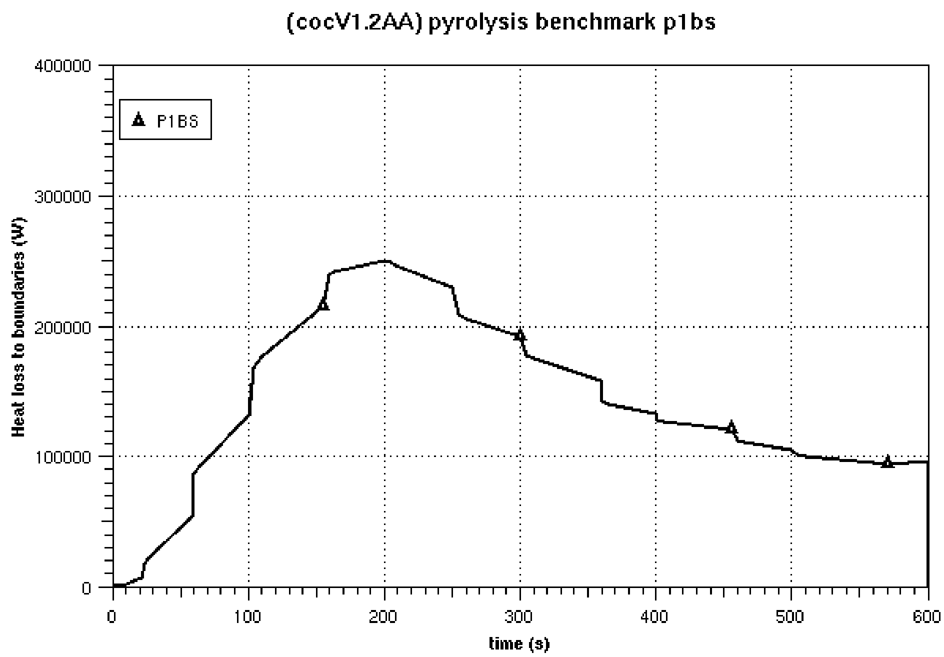


Figure 10 Total Heat Loss from Boundaries - COCOSYS
(from Klein-Hessling (Appendix F))

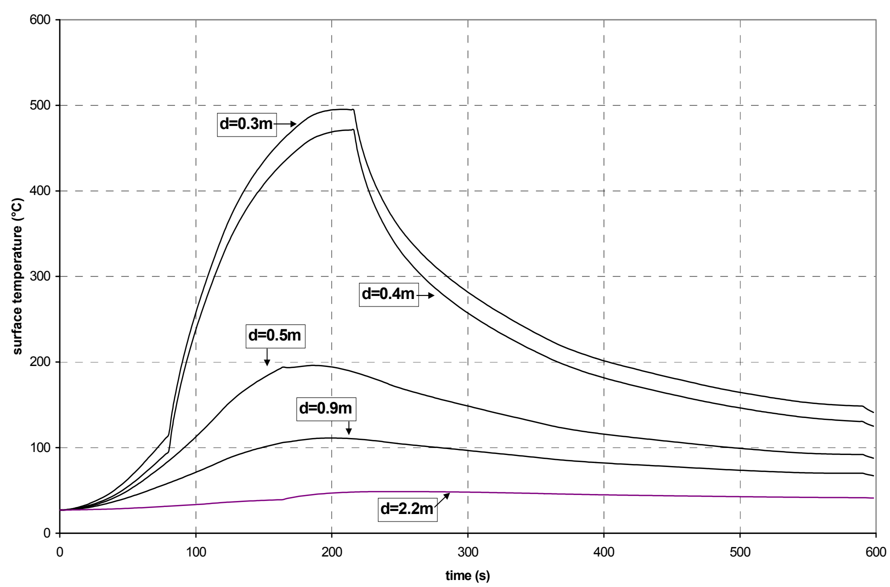


Figure 11 Effect of Distance between Fire and Target - FLAMME_S (from Bouton:Appendix A)

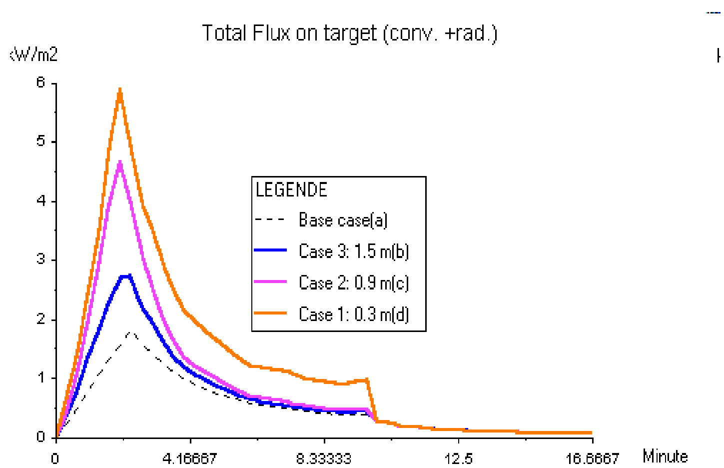


Figure 12 Effect of Distance on Radiative Flux - MAGIC **(from Gautier:Appendix C)**

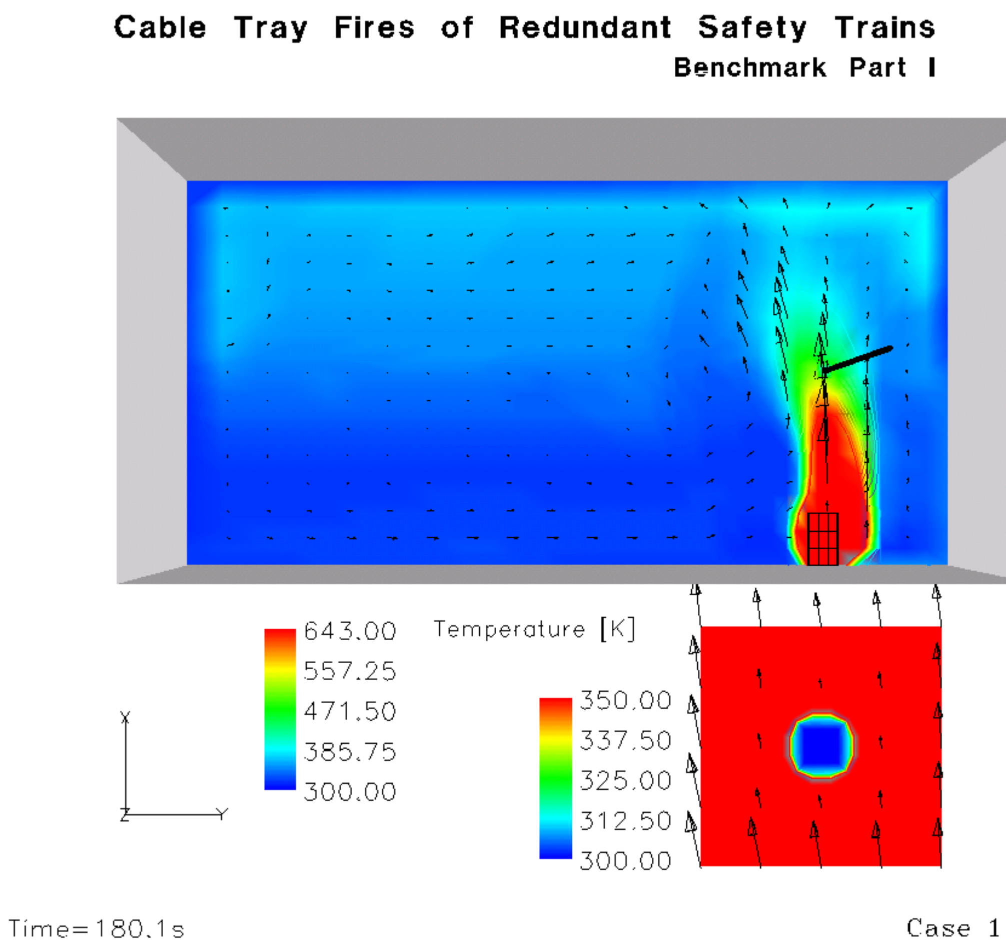


Figure 13 Target Exposure in Plume Region in CFD Analysis - CFX **(from Heitsch (Appendix D))**

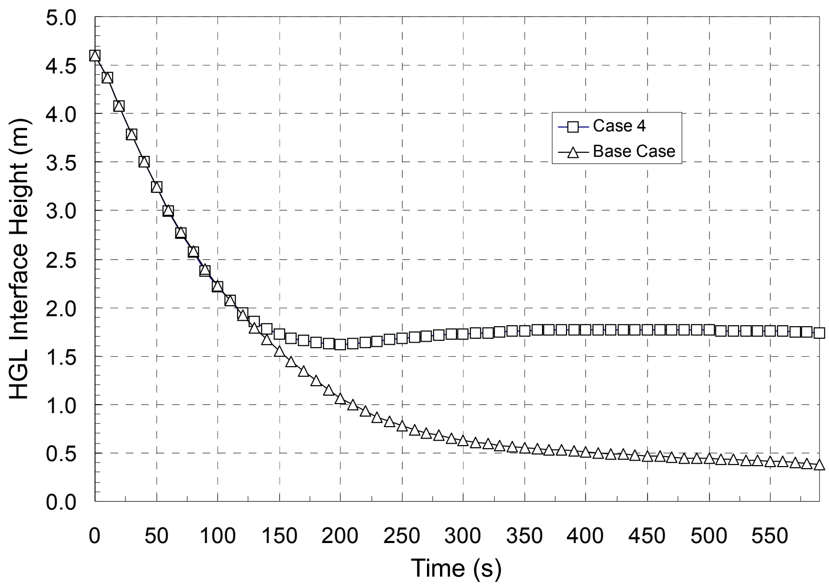


Figure 14 HGL Development (Part I) - CFAST
(from Dey (Appendix B))

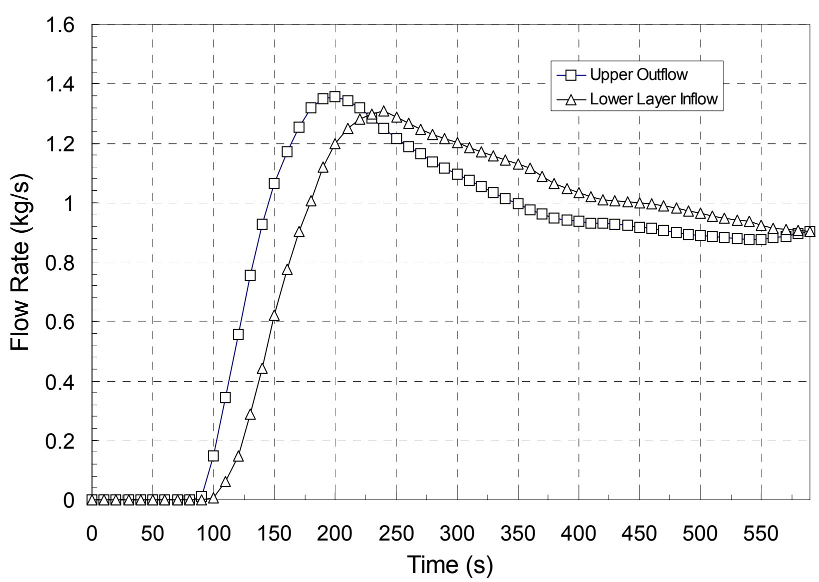


Figure 15 Door Flows (Part I, Case 4) - CFAST
(from Dey (Appendix B))

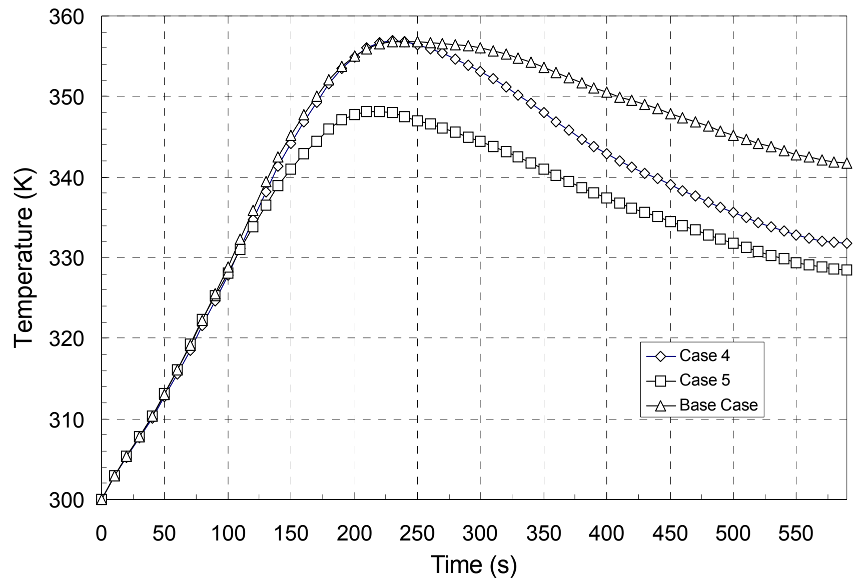


Figure 16 HGL Temperature (Part I) - CFAST
(From Dey (Appendix B))

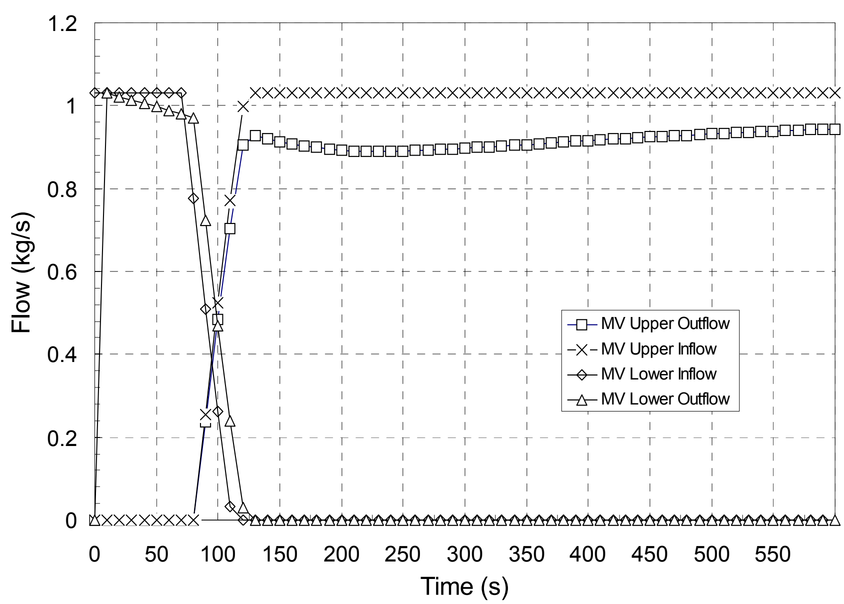


Figure 17 Mechanical Ventilation Flows (Part I, Case 5) - CFAST (from Dey (Appendix B))

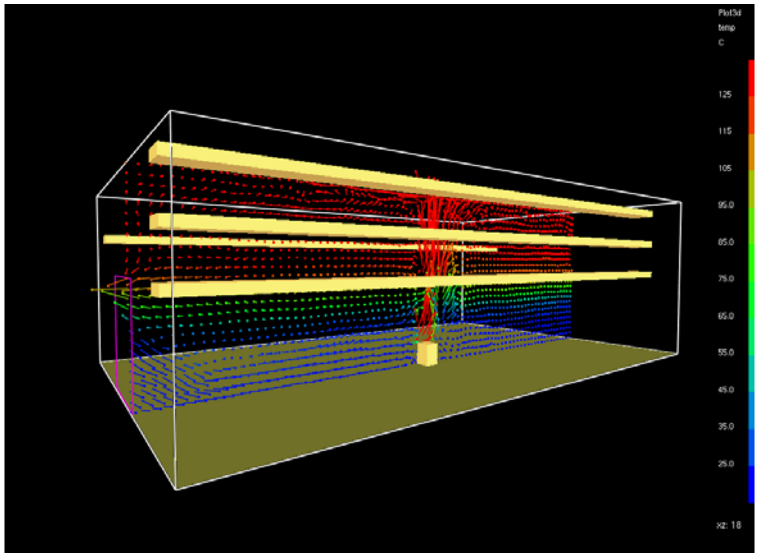
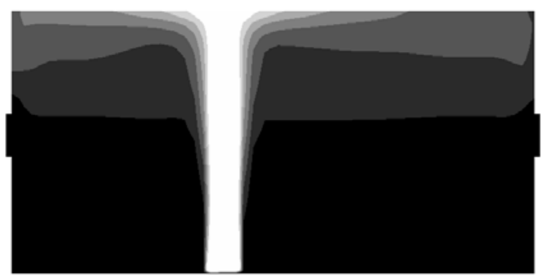
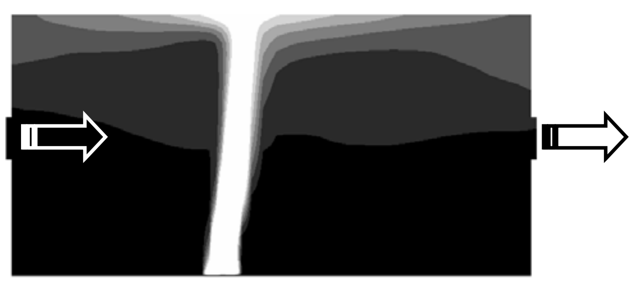


Figure 18 Door Flows (Part I, Case 4) - FDS
(from Dey (Appendix B))



Part I base case – no mechanical



Part I case 5 - with mechanical ventilation

Figure 19 Effect of Mechanical Ventilation - JASMINE (from Miles (Appendix G))

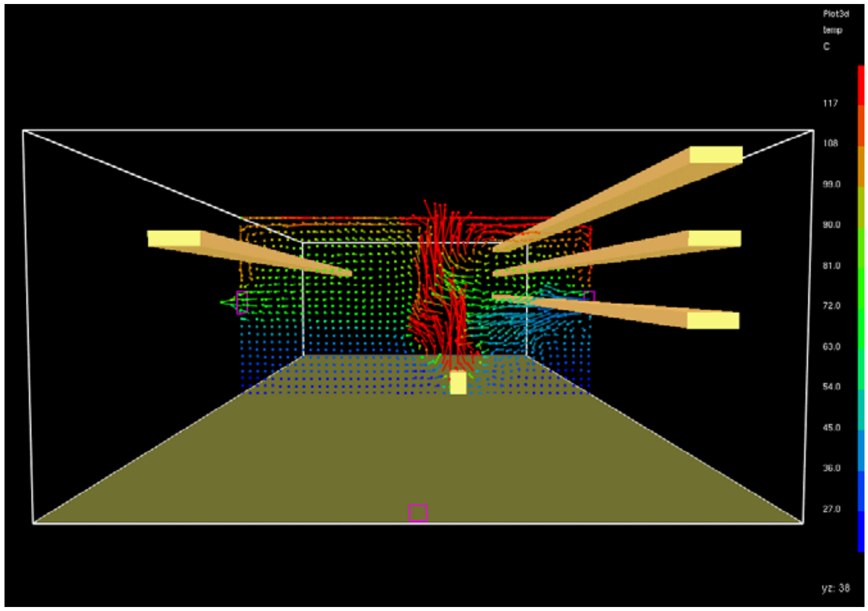


Figure 20 Effects of Mechanical Ventilation (Part I, Case 5) - FDS (from Dey (Appendix B))

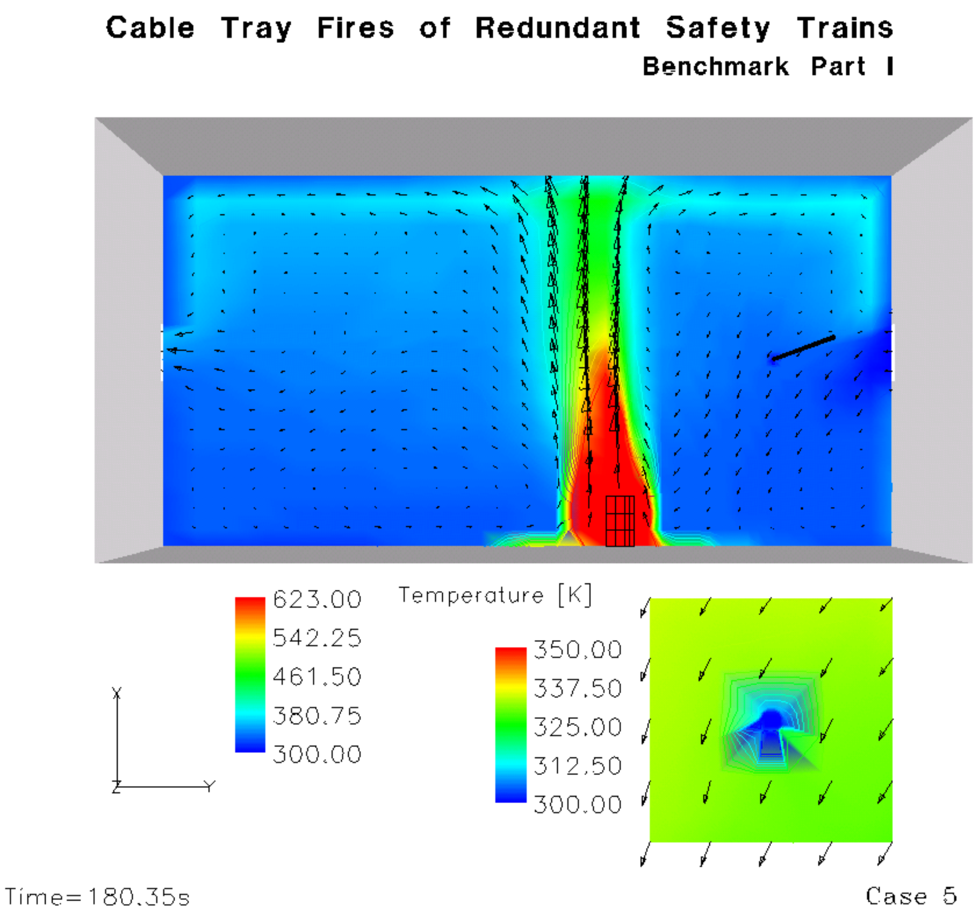


Figure 21 Effects of Mechanical Ventilation - CFX
(from Heitsch (Appendix D))

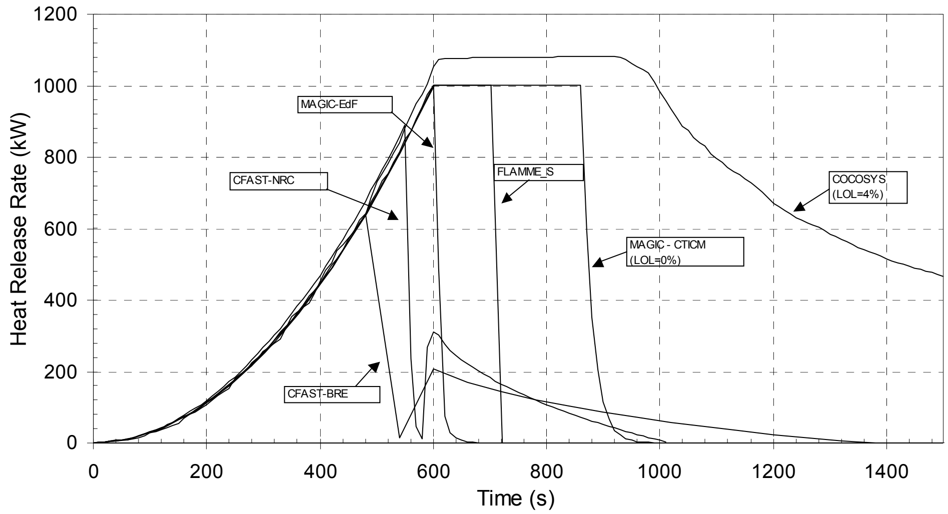


Figure 22 Heat Release Rate (Part II, Base Case)

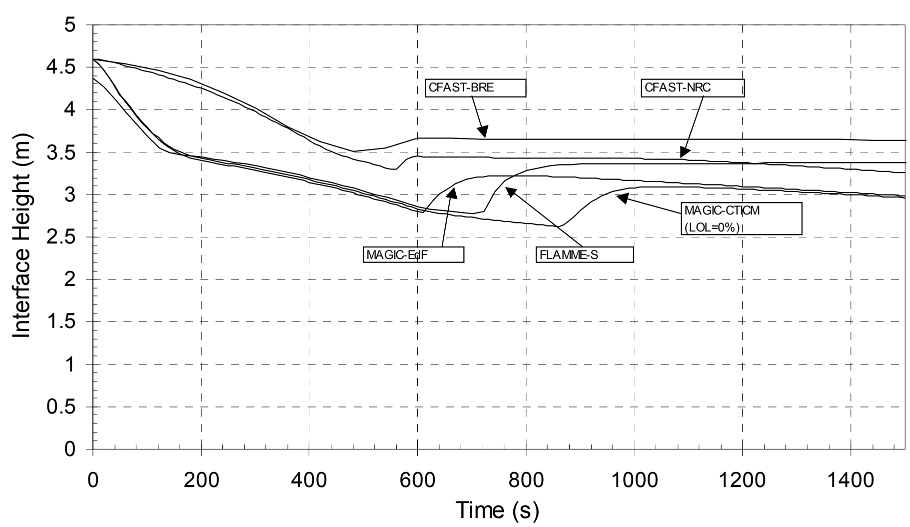


Figure 23 HGL Development (Part II, Base Case)

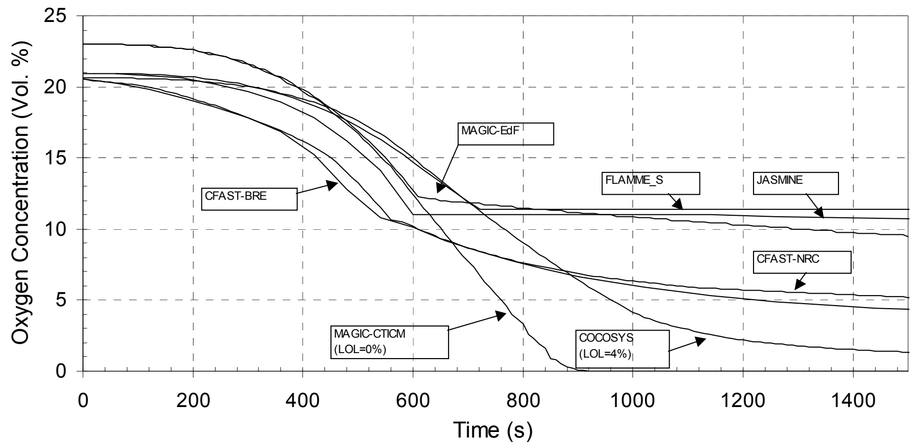


Figure 24 Oxygen Concentration (Part II, Base Case)

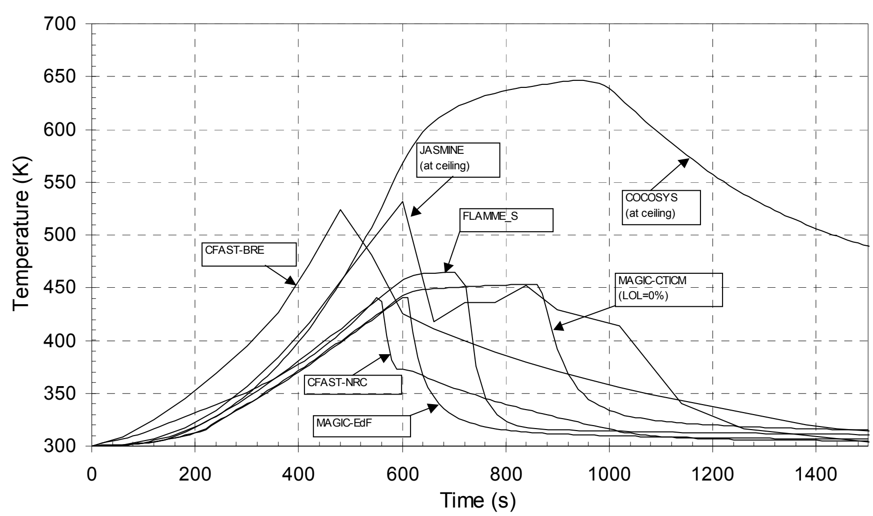


Figure 25 HGL Temperature (Part II, Base Case)

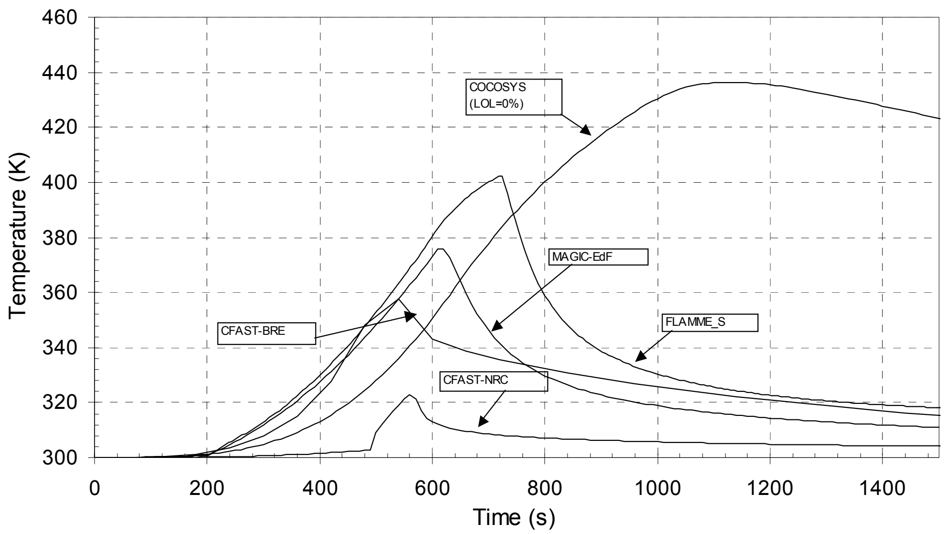


Figure 26 Target Surface Temperature (Part II, Base Case)

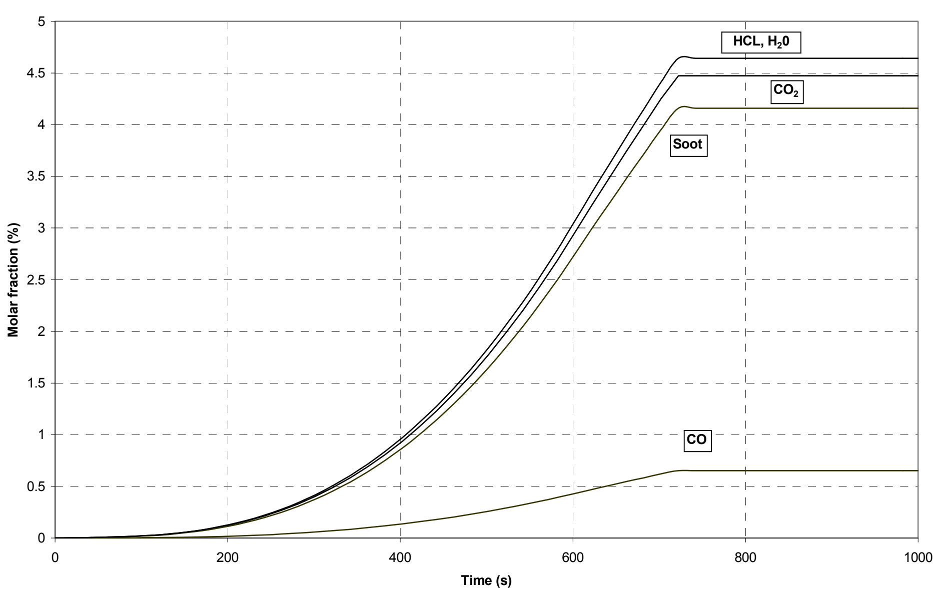


Figure 27 Species Concentration (Part II, Base Case)
(from Bouton (Appendix A))

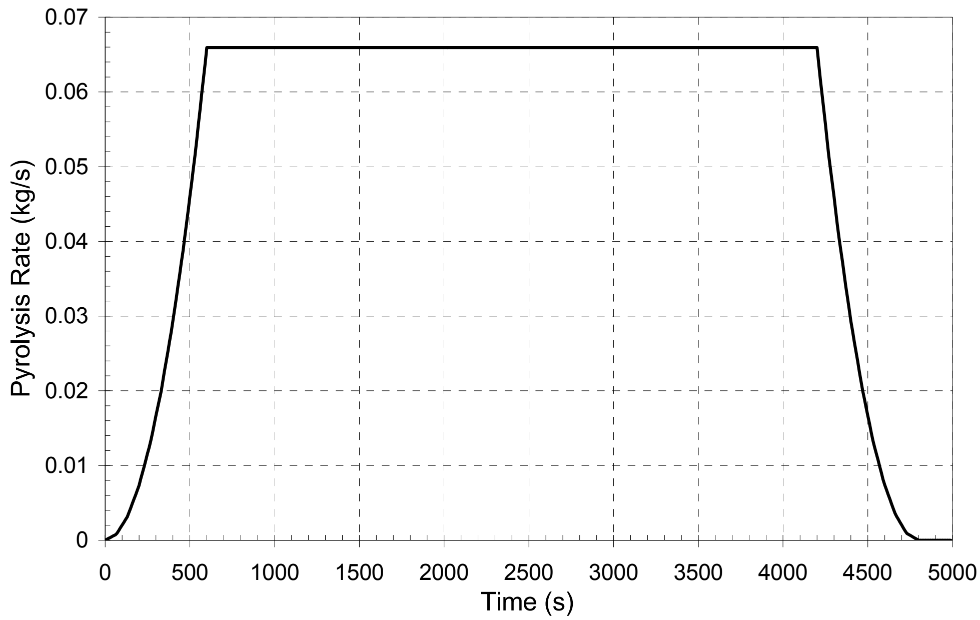


Figure 28 Pyrolysis Rate (Part II, Base Case)
(from Dey (Appendix B))

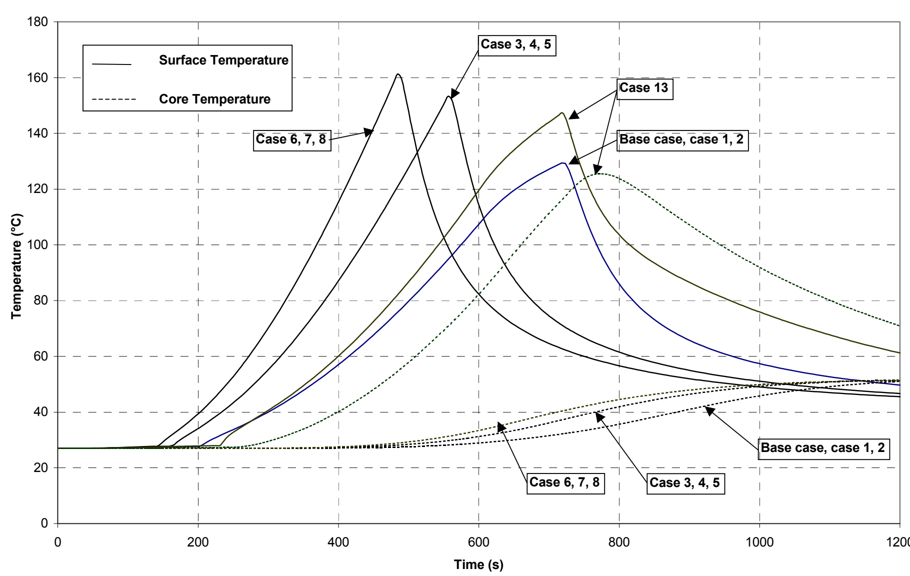


Figure 29 Effect of Cable Structure
(from Bouton (Appendix A))

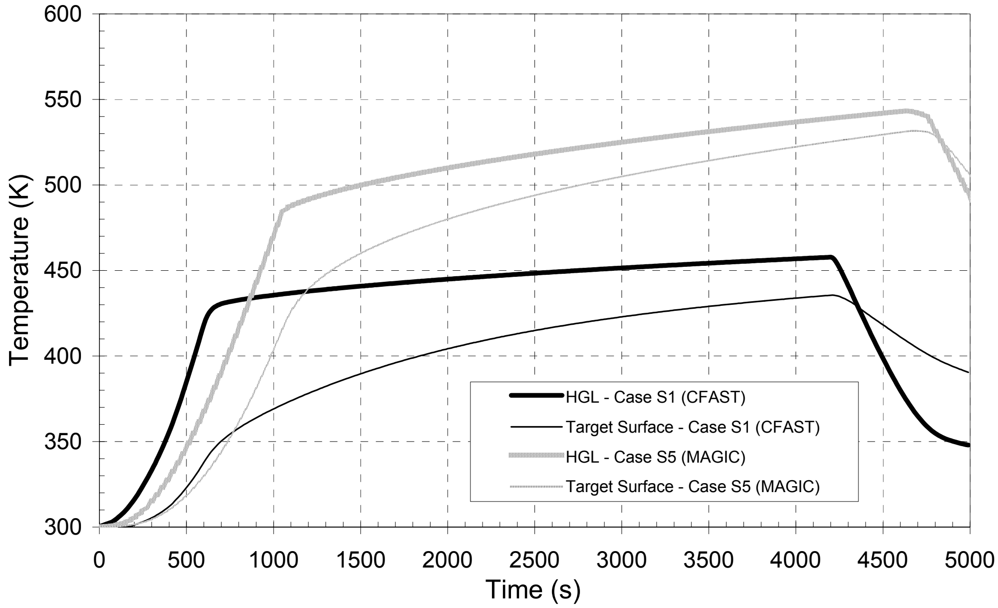


Figure 30 Temperature Development (Special Cases)

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Appendix A: Benchmark Analysis with FLAMME_S, Eric BOUTON, and Bruno TOURNIAIRE, IPSN, France

Appendix B: Benchmark Analysis with CFAST and FDS, Monideep DEY, NRC/NIST, USA

Appendix C: Benchmark Analysis with MAGIC, Bernard GAUTIER, Helene ERNANDORENA, and Maurice KAERCHER, EdF, France

Appendix D: Benchmark Analysis with CFX, Matthias HEITSCH, GRS, Germany

Appendix E: Benchmark Analysis with MAGIC, Daniel JOYEUX, and Olivier LECOQ-JAMMES, CTICM, France

Appendix F: Benchmark Analysis with COCOSYS, Walter KLEIN-HESSLING, GRS, Germany

Appendix G: Benchmark Analysis with JASMINE and CFAST, Stewart MILES, BRE, UK

Appendix H: Benchmark Analysis with CFAST, Juergen WILL, GRS, Germany