Nuclear Power Plant Fire Modeling Application Guide (NPP FIRE MAG)

Draft Report for Comment

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

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FOREWORD

Fire modeling and fire dynamics calculations are used in a number of nuclear power plant (NPP) fire hazards analysis (FHA) studies and documents, including fire risk analysis (FRA) calculations; compliance with and exemptions to the regulatory requirements for fire protection in 10 CFR Part 50; and the Significance Determination Process (SDP) used in the inspection program conducted by the U.S. Nuclear Regulatory Commission (NRC). More recently, the risk-informed performance-based (RI/PB) voluntary fire protection licensing basis established under 10 CFR 50.48(c) has allowed licensees to demonstrate compliance with safety requirements via fire modeling calculations. The RI/PB method is based on the National Fire Protection Association (NFPA) Standard 805, *Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants,* 2001 Edition.

This NUREG-series report provides technical documentation concerning the use and applicability of a specific set of fire dynamics calculation tools and fire models for the analysis of fire hazards in postulated NPP scenarios. Under a joint memorandum of understanding (MOU), the NRC Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) agreed to develop guidance on the use and review of fire modeling calculations, particularly in RI/PB applications. These activities would include creating a library of typical NPP fire scenarios and providing information on the ability of specific fire models to predict the consequences of those typical NPP fire scenarios.

Five commonly available fire modeling tools (FDT^s, FIVE-Rev1, CFAST, MAGIC, and FDS) were selected for this user's guide. These models were developed by nuclear power stakeholders, or have been applied to NPP fire scenarios. Previously, these models were the subject of a V&V study conducted by RES, EPRI, and the National Institute of Standards and Technology (NIST) as documented in NUREG-1824. NFPA 805 requires that models for use in analyzing NPP fire scenarios be verified and validated. This report is designed to help both the user performing the calculation and the person reviewing it, and includes guidance on selecting appropriate models for a given fire scenario and understanding the levels of confidence that can be attributed to the model results.

As with the V&V study, the analyses documented in this report represent the combined efforts of individuals from RES, EPRI, and NIST. These organizations supported this work by providing specialists in the use of fire models and other FHA tools; the results from this combined effort do not constitute either a regulatory position or regulatory guidance, but are intended to provide technical guidance regarding the best use of five fire dynamic calculation tools.

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REPORT SUMMARY

This report replaces EPRI 10002981, *Fire Modeling Guide for Nuclear Power Plant Applications*, August 2002, as guidance for fire modeling practitioners in nuclear power plants (NPPs). The report has benefited from the insights gained since 2002 on the predictive capability of selected fire models to improve confidence in the use of fire modeling in NPP decision-making.

Background

Since the 1990s, when the NRC adopted the policy of using risk-informed methods to make regulatory decisions whenever possible, the nuclear power industry has been moving from prescriptive rules and practices toward the use of risk information to supplement decision-making. Several initiatives have furthered this transition within the fire protection field, including risk-informed, performance-based fire protection programs (FPPs) that comply with Title 10, Section 50.48(c) of the *Code of Federal Regulations* (10 CFR 50.48(c)) and FPP change evaluation under the existing Title 10 Section 50.48 and Regulatory Guide 1.189. RI/PB fire protection often relies on fire modeling to determine the consequences of fires, necessitating an understanding of the level of confidence in their results.

Objectives

- To provide guidance on the application of specific fire models to NPP fire protection issues
- To provide guidance on estimating the quantitative confidence in the predictive capability of these fire models when they are used for NPP fire modeling applications

Approach

The project team reviewed and revised the fire scenarios of interest in NPPs. The five fire models used in the V&V study (NUREG-1824, EPRI 1011999)—(1) NRC's Fire Dynamics Tools (FDTs), (2) EPRI's Fire-Induced Vulnerability Evaluation Revision 1 (FIVE-Rev1), (3) the National Institute of Standards and Technology's (NIST) Consolidated Model of Fire Growth and Smoke Transport (CFAST), (4) Electricité de France's (EdF) MAGIC, and (5) NIST's Fire Dynamics Simulator (FDS)—were exercised for the fire scenarios of interest in NPPs. Finally, the project team developed guidance on the selection and application of each model and treatment of uncertainty and/or sensitivity as part of the fire modeling analysis.

Results

The results of this effort are presented in a step-by-step process for using fire modeling in nuclear power plant applications. The recommended methodology consists of six steps: (1) define the modeling objectives, (2) select and describe fire scenario(s), (3) select the appropriate fire model(s), (4) estimate the fire-generated conditions, (5) conduct sensitivity and/or uncertainty analysis, and (6) interpret and document the results.

EPRI Perspective

The use of fire models to support regulatory decision-making requires a good understanding of their limitations and predictive capabilities, and also presents challenges that should be addressed if the fire protection community is to realize the full benefit of fire modeling and performance-based fire protection. EPRI, with NRC support, will continue to provide training to the fire protection community, using this document to promote fire modeling and gain feedback

on how the results of this work may affect known applications of fire modeling. In the long term, model improvement and additional experiments should be considered.

Keywords

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

PREFACE

This report is the fifth in a series designed to assist those responsible for performing and reviewing fire modeling in nuclear power plant applications.

In August 2002, EPRI published EPRI 1002981, *Fire Modeling Guide for Nuclear Power Plant Applications*. This report offered step-by-step guidance that analysts could follow when using fire modeling to support nuclear power plant engineering calculations. It also included FIVE Rev 1, an Excel-based library of fire models previously documented by EPRI, and additional models available in fire protection literature.

In December 2004, the NRC published NUREG-1805, *Fire Dynamics Tools (FDTs) Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program*. This report provided an introduction to the principles of fire dynamics, and included an Excel-based library of fire models comparable to EPRI FIVE Rev 1.

In a follow-up effort, NRC-RES and EPRI jointly conducted a verification and validation of selected fire models for use in nuclear power plant fire modeling to gain insight into the predictive capabilities of these models. The results of this work were published in NUREG-1824, EPRI 1011999, *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*, May 2007. Using, in part, the findings of this work, NRC conducted a Phenomena Identification and Ranking Table (PIRT) study to evaluate the current state of knowledge for fire modeling for NPP applications. The results of this work were published in NUREG/CR-6978, *A Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire Modeling Applications*, November 2008.

This joint NRC-RES/EPRI report, *Nuclear Power Plant Fire Modeling Applications Guide*, replaces the EPRI Fire Modeling Guide by adding the insights gained in the studies since 2002 in order to form the foundation for future U.S. NPP fire modeling activities.

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LIST OF ACRONYMS

AGA	American Gas Association
AHJ	Authority Having Jurisdiction
ASET	Advanced Science and Engineering Technologies
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BE	Benchmark Exercise
BFRL	Building and Fire Research Laboratory
BRE	Building Research Establishment
BWR	Boiling-Water Reactor
CAROLFIRE	Cable Response to Live Fire
CDF	Core Damage Frequency
CFAST	Consolidated Fire Growth and Smoke Transport Model
CFD	Computational Fluid Dynamics
CFR	*Code of Federal Regulations*
CSR	Cable Spreading Room
ECCS	Emergency Core Cooling Systems
EdF	Electricité de France
EPRI	Electric Power Research Institute
ERFBS	Electrical raceway fire barrier system
FDS	Fire Dynamics Simulator
FDT^s	Fire Dynamics Tools (NUREG-1805)
FHA	Fire Hazard Analysis
FIVE-Rev1	Fire-Induced Vulnerability Evaluation, Revision 1
FFT	Fast Fourier Transform
FM/SNL	Factory Mutual & Sandia National Laboratories
FPA	Foote, Pagni, and Alvares
FPRA	Fire probabilistic risk assessment
FRA	Fire Risk Analysis
GRS	Gesellschaft fuer Anlagen-und Reaktorsicherheit (Germany)
HGL	Hot Gas Layer
HRR	Heat Release Rate
HRRPUA	Heat release rate per unit area
IAFSS	International Association of Fire Safety Science
iBMB	Institut für Baustoffe, Massivbau und Brandschutz
ICFMP	International Collaborative Fire Model Project
IEEE	Institute of Electrical and Electronics Engineers
IPEEE	Individual Plant Examination of External Events
LERF	Large Early Release Frequency
LES	Large eddy simulation
LFS	Limiting fire scenarios
LLNL	Lawrence Livermore National Laboratory
LOL	Low oxygen limit
MCC	Motor Control Center
MCR	Main Control Room
MEFS	Maximum expected fire scenarios
MOVs	Motor-operated valves

MQH	McCaffrey, Quintiere, and Harkleroad
MQH	McCaffrey, Quintiere, and Harkleroad
MOU	Memorandum of Understanding
NBS	National Bureau of Standards (now NIST)
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation (NRC)
PE	Polyethylene
PMMA	Polymethyl-Methacrylate
PRA	Probabilistic Risk Assessment
PVC	Polyvinyl chloride
PWR	Pressurized-Water Reactor
RCP	Reactor Coolant Pump
RES	Office of Nuclear Regulatory Research (NRC)
RI/PB	Risk-Informed, Performance-Based
RIS	Regulatory Issue Summary
RTE	Radiation Transport Equation
RTI	Response Time Index
SBDG	Stand-By Diesel Generator
SDP	Significance Determination Process
SFPE	Society of Fire Protection Engineers
SNL	Sandia National Laboratory
SWGR	Switchgear Room
THIEF	Thermally-Induced Electrical Failure
TP	Thermoplastic
TS	Thermoset
UL	Underwriters Laboratory
V&V	Verification & Validation
XPE	Cross-linked polyethylene and Neoprene

1
INTRODUCTION

1.1 Background

In 2001, the National Fire Protection Association (NFPA) completed its development of NFPA 805, *Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants*, 2001 Edition (NFPA 805, 2001). Effective July 16, 2004, the Nuclear Regulatory Commission (NRC) amended its fire protection requirements in Title 10, Section 50.48(c) of the *Code of Federal Regulations* (10 CFR 50.48(c)) to permit existing reactor licensees to voluntarily adopt fire protection requirements contained in NFPA 805 as an alternative to the existing deterministic fire protection requirements. One important element in supporting the use of performance-based applications is the availability of methods to assess the consequences of fire scenarios. Consequently, NFPA 805 allows fire modeling as a part of its performance-based requirements for regulatory applications.

NFPA 805 also allows the use of a fire probabilistic risk analysis (Fire PRA) in regulatory applications. Fire modeling is used in Fire PRAs to determine the consequences of postulated fire scenarios so that the associated risk can be quantified.

As part of its fire modeling requirements, NFPA 805 states that “fire models shall be verified and validated,” and “only fire models that are acceptable to the authority having jurisdiction (AHJ) shall be used in fire modeling calculations.” This is an important requirement since V&V of fire models are intended to ensure the correctness and suitability of the method. Specifically, verification is the process used to determine whether a model correctly represents the developer’s conceptual description, and whether it was “built” correctly; validation is the process used to determine whether a model is a suitable representation of the real world and is capable of reproducing phenomena of interest, and whether the right model was “built.”

In 2007, the NRC’s Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) completed a collaborative project for V&V of five select fire modeling tools to support RI/PB fire protection and implementation of the voluntary fire protection rule that adopts NFPA 805 as an RI/PB alternative. The results of this study are documented in NUREG 1824/EPRI 1011999 (NUREG-1824, 2007). The V&V effort was intended to increase the confidence of reviewers who evaluate fire models used in other programs, such as the Fire Protection Significance Determination Process (SDP). This collaboration brought together the information and knowledge generated in this area by the NRC and EPRI fire research programs. The National Institute of Standards and Technology (NIST) was also an important partner in this project, providing extensive fire modeling and experimentation expertise.

This report builds on the V&V research described earlier by incorporating the results into a set of guidelines and recommendations for conducting fire modeling studies in support of NFPA 805, Fire PRAs, Fire Protection SDPs, and/or other commercial nuclear industry applications.

1.2 Objectives

This guide has two objectives, the first being to describe the process of conducting a fire modeling analysis for commercial nuclear power plant applications. The process described in this guide addresses most of the technical elements relevant to fire modeling analysis, such as the selection and definition of fire scenarios, determination and implementation of input values, uncertainty and sensitivity analysis, and documentation.

The second objective is to provide guidance on incorporating the uncertainty associated with a fire modeling analysis in a Fire PRA. Currently, fire modeling results are incorporated as deterministic inputs in a Fire PRA (e.g., "the sprinkler activated before target damage occurred"). This guide provides an approach, based on verification and validation results documented in the seven volumes of NUREG-1824, for incorporating fire modeling results probabilistically (e.g., "the probability of sprinkler activation before target damage").

1.3 Scope

This guide should be used as a complement to, not a substitute for, fire dynamics textbooks, technical references, and "users' manuals" for specific fire modeling tools. This guide only compiles information and organizes it in a procedural way for NPP applications. Analysts are encouraged to review the references made throughout the guide for in-depth coverage of the advantages and limitations of specific models or assumptions.

Once a fire scenario has been selected, this guide will help the fire model user define the necessary modeling parameters, select an appropriate model, and interpret the fire modeling results. Since all models are merely approximations of reality, this guide will provide useful insights for translating real configurations into modeling scenarios. Due to the technical nature of this guide, users with the following characteristics will benefit the most:

- Understanding of algebraic equations.
- General knowledge of the behavior of compartment fires.
- General knowledge of basic engineering principles, specifically thermodynamics, heat transfer, and fluid mechanics.

This guide focuses on the capabilities of the models selected for V&V. However, some generic guidance is provided, and most of the discussion is applicable to any fire model of the respective type (hand calculation, zone model, or field model). Five specific models are discussed in this guide:

(1) NRC's Fire Dynamics Tools (FDT^S) (NUREG 1805, 2004)

(2) EPRI's Fire-Induced Vulnerability Evaluation, Revision 1 (FIVE-Rev1) (EPRI 1002981, 2002)

(3) National Institute of Standards and Technology's (NIST) Consolidated Model of Fire Growth and Smoke Transport (CFAST) Version (6) (Jones et al., 2004)

(4) Electricité de France's (EdF) MAGIC code Version (4.1.1) (Gay et al., 2005a)

(5) NIST's Fire Dynamics Simulator (FDS) Version (5) (McGrattan et al., 2009)

1.4 Organization

The guidance material provided in this document is divided into 11 chapters and a number of appendices, as outlined below.

- Chapter 2 presents a qualitative overview of the process for conducting fire modeling, including the basic principles of fire simulation, advantages and limitations of the technology, and brief descriptions of the five models.
- Chapter 3 provides specific guidance on selecting models to address typical scenarios in commercial nuclear power plants.
- Chapter 4 contains information on determining the sensitivity and uncertainty associated with fire modeling calculations.
- Chapters 5 and 6 discuss the relationship between this guide and other documents, such as NFPA 805 (NFPA 805, 2001) and NUREG/CR-6850 (NUREG-6850, 2005).
- Chapter 7 contains the list of references identified throughout this document.
- Appendices A through H provide detailed examples of fire modeling analyses of typical NPP scenarios.

2
THE FIRE MODELING PROCESS

This chapter provides a general step-by-step process for modeling fires in commercial nuclear power plants. The recommended methodology comprises six steps: (1) define the modeling objectives, (2) describe fire scenario(s), (3) select the appropriate model(s), (4) estimate the fire conditions, (5) conduct sensitivity and/or uncertainty analysis, and (6) document fire modeling analysis. These steps, shown in Figure 2-1, are described in detail in the following sections.

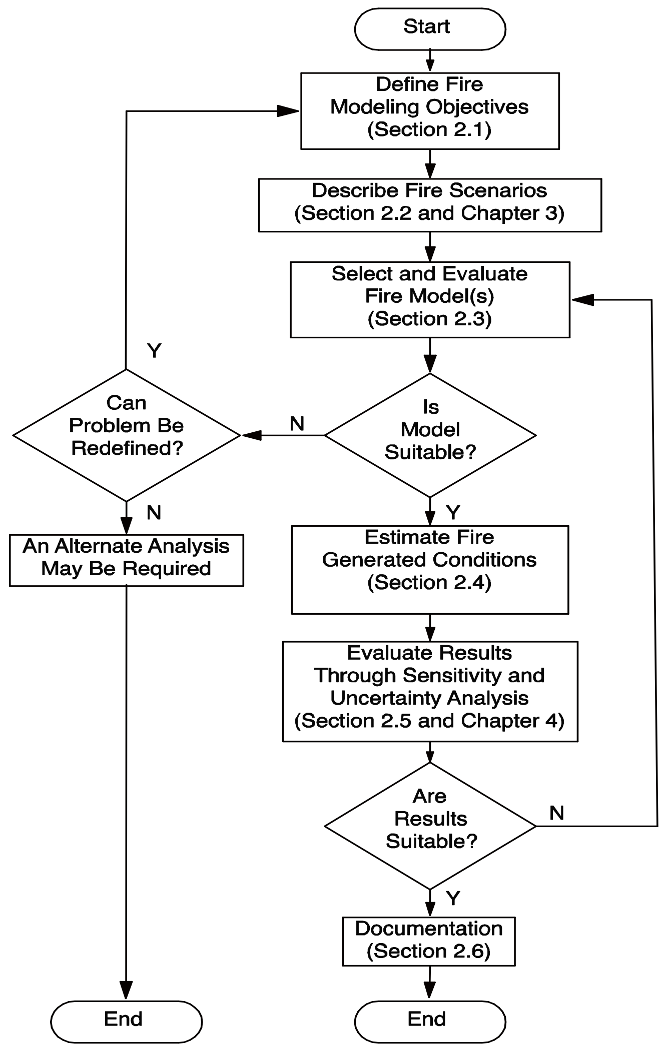

Figure 2-1. Fire Modeling Process

2.1 Step 1: Define Fire Modeling Objectives

The first step in the analysis is to identify and state the modeling objectives. Clearly defining the objectives is essential when selecting fire scenarios, describing the scenario, and selecting the appropriate model(s). The objectives should be specific when describing the end result of a fire modeling analysis in engineering terms.

In many nuclear power plant fire modeling applications, the analysis results are compared with a damage criterion in order to make fire safety-related decisions. These criteria are routinely expressed in terms of temperature or incident heat flux thresholds (see, for example, Appendix I of NUREG/CR-6850 (NUREG-6850, 2005)). Consequently, the modeling objectives should be stated in such a way that the analysis results can be effectively compared with the criteria, so that a decision can be reached.

Consider the following example: “Evaluate whether cable(s) can remain free of fire damage in a particular enclosure (i.e., fire area or fire zone).” The criterion for cable damage is a surface temperature exceeding 330°C (626°F); thus, an appropriate objective would be “to determine whether the surface temperature of a cable exceeds 330°C (626°F) when subjected to conditions generated by a predetermined fire." This last objective is stated in terms that can be achieved by a fire modeling analysis.

2.2 Step 2: Describe Fire Scenarios

Once the objectives of the fire modeling study are defined, there needs to be a description of at least one fire scenario that captures those technical elements that address the objectives. A fire scenario is a set of elements that describe a fire event, and is postulated to address the specific scenario objectives. These elements usually include the enclosure (i.e., compartment), boundary materials, ventilation, fire protection features, targets, intervening combustibles, and the fire (sometimes termed "ignition source").

Various documents provide guidance for describing fire scenarios from a technical and regulatory perspective. Most of these documents are "application"-specific; NFPA 805 (NFPA 805, 2001), for instance, defines two general categories of fire scenarios, limiting fire scenarios (LFSs) and maximum expected scenarios (MEFs). *LFSs* are scenarios "in which the inputs to the fire modeling calculations are varied to the point that the performance criteria is not met" (e.g., scenario evaluation results in target damage), while *MEFs* "represent the most challenging fires that could be reasonably anticipated for the occupancy type and conditions." The input values necessary to determine LFSs should remain within the range of probability, but can exceed values expected to be likely or even probable. The margin between LFSs and the MEFs can be used to identify those weaknesses in the analysis that could result in unacceptable consequences.

In a Fire PRA, for example, the objective is to quantify the risk contribution from individual scenarios and to identify potential risk-contributing scenarios (e.g., fires impacting important targets in the compartment). Although specific elements in the scenario selection process are "standardized" for guidance and completeness purposes, a certain degree of fire protection engineering judgment is also necessary. NUREG/CR-6850 (EPRI 1011989) (NUREG/CR-6850, 2005) contains information on fire frequency, cable (target) selection, heat release rate (HRR), damage criteria, and other information that would be useful in developing fire scenarios.

It should also be noted that not all the elements associated with a commercial nuclear plant fire scenario can be directly modeled using the tools within the scope of this guide (e.g., the effect of suppression activities by the fire brigade). It is important, however, not to limit the scenario selection and description to those elements that can be modeled.

2.2.1 General Considerations

In the scenario selection process, preliminary consideration should be given to (1) how many scenarios should be selected to address a given objective (i.e., how many scenarios are needed) and (2) which specific fire event characteristics each scenario should capture (i.e., which scenarios are needed). The following guidance may assist in answering these questions.

- Selecting appropriate scenarios is highly dependent on the objectives of the fire model. For example, when evaluating the performance of a fire barrier system, fire scenarios challenging the barriers are of interest; when conducting a risk analysis, fire scenarios impacting safety-related circuits may be of primary interest. The selected scenarios for these two applications may not be the same.

- Selected scenarios should represent a complete set of fire conditions that are important to the objective. For example, if the objective of the fire modeling is to predict whether specific cable(s) will remain free of fire damage, the analyst should examine fire scenarios that cover the range of fire conditions that could contribute to the damage of the cables of interest, including both fires that are small and close to the cable(s) of interest and fires that are larger and farther away. In other words, it may not always be appropriate to select, or at times even possible to define, the worst case fire scenario.

- The fire scenario should challenge the conditions being estimated. For example, if the objective is to evaluate flame irradiation to a target, locating the ignition source relatively far from the target may not provide the best representation of the fire hazards.
- Selection of fire scenarios is highly dependent on the fire area hazard profile (i.e., type, location and amount of fire source and combustibles, and the location and number of the targets). For example, in large enclosures with a limited number of targets to protect, such as a turbine building in a PWR when protection of a safety-related circuit is the objective, it is easier to locate the targets of interest and then identify those fire sources capable of affecting that target.

The following should also be considered when selecting fire scenarios:

- Which fire protection features can (or should) be credited in a scenario? This question usually requires a fire protection engineering evaluation of the system's effectiveness in performing its design objectives. The evaluation should determine whether the detection, suppression, and/or passive system is expected to protect the selected target from fire-generated conditions. Once the decision to credit a fire protection system is made, the analyst should specify the type of system selected for the scenario.
  - Fire detection systems: Smoke, heat detectors, or high sensitivity detection systems
  - Fire suppression systems: Automatically or manually activated fixed systems, fire extinguishers, and fire brigades
  - Passive fire protection systems: Structural fire barriers, fire doors, fire wraps, fire stops, etc.

  Notice that the fire modeling tools within the scope of this guide may not have the capability to model the impact of some of the fire protection features that may be credited in a given scenario. Nevertheless, fire protection features are designed to impact the outcome of a scenario, so their effects should be included in the analysis.
- Where is the fire located? Although identifying an ignition source is relatively easy (e.g., the fire will start in an electrical cabinet), identifying a fire location within the ignition source typically requires judgment. The following guidance may be useful in determining a fire location when judgment is required.
  - Targets in the fire plume or ceiling jet: Locating a source on top of a cabinet ignition source usually results in the most severe fire conditions since it assumes that cabinet walls will not affect fire-generated conditions. Furthermore, since the fire is located in the highest possible position, flames are expected to be higher, and temperatures in the plume and ceiling jet will also be high. The user should judge whether this is a conservative assumption based on the objective of the analysis. For example, this would not necessarily be a conservative assumption if detection of the fire was a critical objective of the analysis.

- Targets affected by flame radiation: The source should be located so that there is an unobstructed (assuming no passive fire protection system is credited) view between the source and the target. A horizontal path between flame and target is the most conservative configuration.
- Targets engulfed in flames: Flame height calculations should be performed to determine whether the selected location will result in targets engulfed in flames. Proper justification should be provided as to the location of the fire to ensure that the target is out of the flames. For example, consider the case where the analyst locates the fire on top of an enclosed cabinet, resulting in a cable tray engulfed in flames. This is a conservative scenario, since the fire is expected to start somewhere inside the cabinet. The analyst may choose to lower the fire's position and ignore the cabinet walls after a visual examination identifies the actual location of the combustibles.
- Targets immersed in the Hot Gas Layer (HGL): The fire's elevation may influence how far down the HGL will develop as predicted by some fire models, although other important scenario characteristics will also be influential.

- What type of fire conditions should be evaluated? It has been mentioned earlier that the postulated scenario should challenge the integrity of the target under evaluation. Thus, fire conditions, such as flame impingement, fire plume, ceiling jets, HGL, and/or flame radiation, should be considered based on the relative location of the ignition source, intervening combustibles, and targets. The analysis should quantify relevant fire conditions and properly disposition those that are not expected to affect the target.
- What ventilation conditions should be evaluated? "Ventilation conditions" refers to the operation of the mechanical ventilation system (e.g., the system will continue in normal operational mode, the system will transfer to smoke purge mode, the system will transfer off with close dampers, etc.) and the position of doors or other openings during the fire event (e.g., doors closed, doors open, doors opening at fire brigade arrival, etc.).
- What quantitative information should be collected for analysis? The analyst should become familiar with the information necessary to develop input files for the fire modeling tools. In practice, this information should be collected during the process of selecting and describing fire scenarios to minimize the number of walkdowns and document/drawing reviews.

Finally, plant walkdowns are an essential aspect of the scenario selection and description process. Many key decisions relevant to fire modeling, including those related to model selection and input parameters, are influenced by observations made during walkdowns.

2.2.2 Fire Scenario Elements

As mentioned earlier, the fire scenario is a set of elements that describe a fire event, and is postulated to address the specific scenario objectives. These elements usually include the enclosure (i.e., compartment), boundary materials, ventilation, fire protection features, targets, intervening combustibles, and the fire (sometimes termed "ignition source"). Each element is described in detail in Chapter 3.

2.3 Step 3: Select Fire Model(s)

A number of models are available for performing fire simulations. These models range from empirical correlations/hand calculations to sophisticated computational fluid dynamics (CFD) computer codes that require days to set up a scenario and perform the associated calculations. Given the availability of different models, the analyst is responsible for understanding the advantages and limitations of a particular model in a specific situation in order to achieve the established objectives. In general, fire models can be classified into three groups: (1) Empirical correlations/hand calculations, (2) zone models, and (3) field models. The level of effort required to describe a scenario and the computational time consumed by each group increase in the order in which they are listed.

In practical fire modeling applications, it is likely that a combination of all three types of models would be useful for analyzing a specific problem. For example, empirical correlations/hand calculations might be used to estimate the radiative flux to a target for determination of a zone of influence or minimum separation distance. A zone model would provide the temperature of the HGL and height as a function of time for evaluation of cable temperatures. Field model calculations could be used to provide more detailed information on fire-induced conditions in areas where the Empirical correlations/hand calculations and zone models are not conclusive. More complex models can also be used as a check against the “simpler” model results.

The first step in selecting a model is to determine whether the scenario can be analyzed using Empirical correlations/hand or spreadsheet calculations, zone models, or field models. This guide focuses on the models FDT^s (NUREG-1805, 2004), FIVE-Rev1 (), CFAST (Jones et al., 2004), MAGIC (Gay et al., 2005), and FDS (McGrattan et al., 2009). The FDT^s and FIVE-Rev1 are a set of relatively simple Empirical correlations/hand calculations codified in the form of electronic spreadsheets. CFAST and MAGIC represent the class of fire models commonly referred to as zone models. These models divide a compartment of interest into two zones, an elevated temperature upper layer and a cool lower layer. FDS is an example of a field model, or computational fluid dynamics (CFD) model. Models like FDS divide each compartment into thousands or millions of cells. Temperatures and other quantities of interest are calculated for each cell.

Empirical correlations/hand calculations can be solved by hand with a relatively small computational effort. In terms of fire modeling, empirical correlations/hand calculations have the following considerations:

- Equations predict quasi-steady conditions. Conditions are either assumed constant or estimated at a specific point in time.
- Most equations are semi-empirical correlations developed under experimental conditions that have to be considered in their applications.

Karlsson and Quintiere (2000) classify empirical correlations into three categories: (1) those that deal with combustion, (2) those that estimate resultant environmental conditions, and (3) those that address heat transfer. Empirical correlations/hand calculations related to the combustion process estimate fire intensity based on the flammability characteristics of the fuel. Equations that estimate fire-generated conditions include plume, ceiling jet, and compartment temperatures. Heat transfer equations deal with target temperatures and heat fluxes in the plume, ceiling jet, and lower and upper layer regions.

Computer zone models are algorithms that solve conservation equations for energy and mass. The fundamental assumption associated with zone models is that the enclosure is divided into a limited number of distinct gas zones of uniform properties. In fire applications, the enclosure is usually divided in two zones. The upper layer (i.e., hot or smoke layer) is the volume of smoke generated by the fire and accumulated below the ceiling of the enclosure. This layer is assumed to be homogeneous, and, therefore, to have uniform density and temperature. Its temperature and depth are affected by the amount of mass and energy entering or leaving the volume in each time step during the simulation. The lower layer, which can also experience a temperature increase, is characterized by colder fresh air between the floor and the bottom of the upper layer. This layer is also assumed to have uniform density and temperature.

CFD models are sophisticated algorithms that solve a simplified version of the Navier-Stokes equations. To run CFD codes, the enclosure must be divided into a large number of control volumes, and the equations solved for each control volume. CFD models then provide a detailed estimate of temperature profiles because calculations are performed for each control volume specified in the enclosure. CFD codes also handle turbulent gas flows. Another advantage of CFD models is their ability to simulate fire conditions in geometries other than rectangular floor compartments with flat ceilings. Some CFD codes also attempt to predict HRR values based on flammability properties of fuels provided by the analyst. The drawback of CFD models is the computational time and the level of effort required to set up a scenario, as computational times are usually on the order of days. The time required to set up a problem usually depends on the complexity of the geometry.

2.3.1 Fire Dynamics Tools (FDT^s)

Fire Dynamics Tools (FDT^s) is a set of algebraic empirical correlations preprogrammed into Microsoft® Excel® spreadsheets. The FDT^s library is documented in NUREG-1805, "Fire Dynamics Tools (FDT^s): Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program" (NUREG-1805, 2004). The primary objective of the FDT^s library and the accompanying documentation is to provide a methodology for NRC fire protection inspectors to use in assessing potential fire hazards in NRC-licensed NPPs. The methodology uses simplified, quantitative fire hazard analysis techniques to evaluate the potential hazard associated with credible fire scenarios.

The FDT^s library includes 23 distinct spreadsheets that can be used to calculate various fire parameters under varying conditions. Documentation of the theoretical bases underlying the equations used in the FDT^s spreadsheets helps to ensure that users understand the significance of the inputs that each spreadsheet requires, and why a particular spreadsheet should (or should not) be selected for a specific analysis. The governing equations and assumptions come primarily from the principles described in the *NFPA Fire Protection Handbook* (NFPA Handbook, 2007), the *SFPE Handbook of Fire Protection Engineering* (SFPE Handbook, 2008), and other fire science literature, and are generally accepted within the fire science community as state-of-the-art calculation methods for fire phenomena.

The complete list of spreadsheets included in the FDT^s library is shown in Table 2-1. A number of the calculation methods included in the FDT^s were part of the V&V study conducted by the NRC, EPRI, and NIST (NUREG-1824 Vol. 3, 2007). The NRC maintains a web site at http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/final-report/index.html, where both new and updated spreadsheets are posted.

Recently, a spreadsheet was added to the suite for predicting the temperature profile within a cable as a function of time, given a time-dependent exposure temperature or heat flux. The development of the Thermally-Induced Electrical Failure (THIEF) model has been documented in volume 3 of NUREG/CR-6931 (McGrattan, 2008).

Table 2-1. Routines included in the FDT^s

Function Name	Description
02.1_Temperature_NV.xls 02.2_Temperature_FV.xls 02.3_Temperature_CC.xls	**Chapter 2.** Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Compartment Fire with Natural Ventilation (Compartment with Thermally Thick/Thin Boundaries) Method of McCaffrey, Quintiere, and Harkleroad (MQH) **Chapter 2.** Predicting Hot Gas Layer Temperature in a Compartment Fire with Forced Ventilation (Compartment with Thermally Thick/Thin Boundaries) Method of Foote, Pagni, and Alvares (FPA) Method of Deal and Beyler **Chapter 2.** Predicting Hot Gas Layer Temperature in a Compartment Fire with Door Closed (Compartment has Sufficient Leaks to Prevent Pressure Buildup; leakage is Ignored) Method of Beyler
03_HRR_Flame_Height_Burning_ Duration_Calculation.xls	**Chapter 3.** Estimating Burning Characteristics of Liquid Pool Fire, HRR, Burning Duration and Flame Height
04_Flame_Height_Calculations.xls	**Chapter 4.** Estimating Wall Fire Flame Height, Line Fire Flame Height Against the Wall, and Corner Fire Flame Height
05.1_Heat_Flux_Calculations_Wind_Free.xls 05.2_Heat_Flux_Calculations_Wind.xls 05.3_Thermal_Radiation_From_ Hydrocarbon_Fireballs.xls	**Chapter 5.** Estimating Radiant Heat Flux from Fire to a Target Fuel *Wind-Free Condition* Point Source Radiation Model (Target at Ground Level) Solid Flame Radiation Model (Target at Ground Level) Solid Flame Radiation Model (Target Above Ground Level) *Presence of Wind* Solid Flame Radiation Model (Target at Ground Level) Solid Flame Radiation Model (Target Above Ground Level) Estimating Thermal Radiation from Hydrocarbon Fireballs
06_Ignition_Time_Calculations.xls	**Chapter 6.** Estimating the Ignition Time of a Target Fuel Exposed to a Constant Radiative Heat Flux Method of Estimating Piloted Ignition Time of Solid Materials Under Radiant Exposures Method of (1) Mikkola and Wichman, (2) Quintiere and Harkleroad, and (3) Janssens Method of Estimating Piloted Ignition Time of Solid Materials Under Radiant Exposures; Method of Toal, Silcock, and Shields Method of Estimating Piloted Ignition Time of Solid Materials Under Radiant Exposures; Method of Tewarson
07_Cable_HRR_Calculations.xls	**Chapter 7.** Estimating Full-Scale Heat Release Rate of a Cable Tray Fire
08_Burning_Duration_Soild.xls	**Chapter 8.** Estimating Burning Duration of Solid Combustibles
09_Plume_Temperature_Calculations.xls	**Chapter 9.** Estimating Centerline Temperature of a Buoyant Fire Plume

Function Name	Description
10_Detector_Activation_Time.xls	Estimating Detector Response Time **Chapter 10.** Estimating Sprinkler Response Time **Chapter 11.** Estimating Smoke Detector Response Time **Chapter 12.** Estimating Heat Detector Response Time
13_Compartment_ Flashover_ Calculations.xls	**Chapter 13.** Predicting Compartment Flashover Compartment Post-Flashover Temperature: Method of Law Minimum Heat Release Rate Required to Compartment Flashover: Method of (1) McCaffrey, Quintiere, and Harkleroad (MQH); (2) Babrauskas; and (3) Thomas
14_Compartment_Over_ Pressure_Calculations.xls	**Chapter 14.** Estimating Pressure Rise Attributable to a Fire in a Closed Compartment
15_Explosion_Claculations.xls	**Chapter 15.** Estimating the Pressure Increase and Explosive Energy Release Associated with Explosions
16_Battery_Compartment_Flammable_Gas_Conc.xls	**Chapter 16.** Calculating the Rate of Hydrogen Gas Generation in Battery Compartments Method of Estimating Hydrogen Gas Generation Rate in Battery Compartments Method of Estimating Flammable Gas and Vapor Concentration Buildup in Enclosed Spaces Method of Estimating Flammable Gas and Vapor Concentration Buildup Time in Enclosed Spaces
17.1_FR_Beams_Columns_ Substitution_Correlation.xls 17.2_FR_Beams_Columns_Quasi_ Steady_State_Spray_Insulated.xls 17.3_FR_Beams_Columns_Quasi_ Steady_State_Board_Insulated.xls 17.4_FR_Beams_Columns_Quasi_ Steady_State_Uninsulated.xls	**Chapter 17.** Calculating the Fire Resistance of Structural Steel Members Empirical Correlations Beam Substitution Correlation (Spray-Applied Materials) Column Substitution Correlation (Spray-Applied Materials) Heat Transfer Analysis using Numerical Methods Protected Steel Beams and Columns (Spray-Applied) Heat Transfer Analysis using Numerical Methods Protected Steel Beams and Columns (Board Materials) Heat Transfer Analysis using Numerical Methods Unprotected Steel Beams and Columns
18_Visibility_Through_Smoke.xls	**Chapter 18.** Estimating Visibility Through Smoke

2.3.2 FIVE-Rev1

In August 2002, the Electric Power Research Institute (EPRI) published the *Fire Modeling Guide for Nuclear Power Plant Applications* (EPRI 1002981, 2002) for the first time. Since then, it has provided fire protection engineers in the commercial nuclear industry with a broad overview of fire modeling theory and applications, including representative calculations performed with various state-of-the-art fire models. With this guide, EPRI included a library of preprogrammed Microsoft® Excel® equations, which are used to estimate some aspects of fire-induced conditions. This collection of Empirical correlations/hand calculations is referred to as the Fire-Induced Vulnerability Evaluation model (FIVE-Rev1). In general, the equations in the library are closed-form analytical expressions that can be solved by hand. The capabilities of the various equations in the library include predicting temperature and convective heat fluxes in the fire plume or ceiling jet, irradiated heat flux, upper-layer temperature, time to detection, and target heating, among others. Some of the equations in FIVE were included in the V&V study (NUREG-1824 vol. 4, 2007). Like the FDT^s, several of the equations used in the examples have not been subject to V&V. Subsequent efforts will be directed at V&V of these equations and models. The calculations included in the FIVE-Rev1 are summarized in Table 2-2.

Table 2-2. Routines included in FIVE-Rev1

Function	Description
Qf	Heat release rate profile considering t^2 growth and four stages
Firr	Estimates flame irradiation a distance r from the fire source. Point source approximation for REMOTE targets.
FHeight	Flame height based on Heskestad's flame height correlation
TpAlpert	Plume temperature at a specific height based on Alpert plume temperature correlation
TpMcCaffrey	Plume temperature at a specific height based on McCaffrey plume temperature correlation
TpHeskestad	Plume temperature at a specific height based on Heskestad plume temperature correlation
Plcflux	Estimates convective heat flux in the fire plume
VpAlpert	Plume velocity at a specific height based on Alpert's plume temperature correlation
VpMcCaffrey	Plume velocity at a specific height based on McCaffrey plume temperature correlation
VpHeskestad	Plume velocity at a specific height based on Heskestad plume temperature correlation
EpZukoski	Air entrainment into plume based on Zukoski plume entrainment correlation
EpThomas	Air entrainment into plume based on Thomas plume entrainment correlation
EpHeskestad	Air entrainment into plume based on Heskestad plume entrainment correlation
PdHeskestad	Estimates plume diameter based on Heskestad's plume correlation
TcjAlpert	Unconfined ceiling jet temperature based on Alpert ceiling jet correlation
TcjDelichatsios	Confined ceiling jet temperature based on Delichatsios ceiling jet correlation
Cjcflux	Estimates convective heat flux in the ceiling jet
VcjAlpert	Unconfined ceiling jet velocity based on Alpert ceiling jet correlation
MQHTemperature	Compartment temperature after a specified time given a steady HRR based on MQH approach
MQHFlashover	Heat release rate required for flashover after a specified time based on MQH approach
FiveTemp	Estimates compartment temperature using based on FIVE
Detact	Activation time of heat detection devices based on heat release rate profiles
Aset	Time required by hot gas layer to reach a specific height based on heat release rate profiles and openings at the bottom of the enclosure

Function	Description
CThrr	Estimate heat release rate from cable trays. The correlation is based in 14 experiments with a stack of 12 horizontal cable trays and 2 experiments with a combination of 12 horizontal cable trays and three vertical trays.
Visib	Estimate the length of a visible path in a smoke environment. The correlation applies to light reflecting signs.
Ttar	Estimation of target temperature under constant heat flux
Ttdam	Time to target damage under constant heat flux

2.3.3 Consolidated Fire Growth and Smoke Transport (CFAST) Model

CFAST is a classic two-zone computer fire model. For a given fire scenario, the model subdivides a compartment into two control volumes, which include a relatively hot upper layer and a relatively cool lower layer. In addition, mass and energy are transported between the layers via the fire plume. The lower layer is primarily fresh air. By contrast, combustion products accumulate via the plume in the hot upper layer (also known as the HGL). Each layer has its own energy and mass balances. The most important assumption for the model is that each zone has uniform properties, that is, that the temperature and gas concentrations are constant throughout the zone; they only change as a function of time. The CFAST model describes the conditions in each zone by solving equations for conservation of mass, species, and energy, along with the ideal gas law. The Technical Reference Guide for CFAST (Jones et al., 2004) provides a detailed discussion concerning the specific derivation of these conservation laws. Documentation for CFAST also includes a User's Guide (Peacock et al., 2008b), which details the use of the model, and a Model Development and Evaluation Guide (Peacock et al., 2008a), which presents the latest model V&V results.

For some applications, including long hallways or tall shafts, the two-zone assumption may not be appropriate. To address this, CFAST includes empirical algorithms to simulate smoke flow and filling in long corridors and for a single well-mixed volume in tall shafts. CFAST also includes several correlations (as sub-models), based on experimental data that are used to calculate various physical processes during a fire scenario: smoke production, fire plume dynamics, heat transfer by radiation, convection, conduction, natural flows through openings (vertical and horizontal), forced or natural ventilation, thermal behavior of targets, heat detectors, and water spray from sprinklers.

CFAST models horizontal flow through vertical vents (doors, windows, wall vents, etc.), vertical flow through horizontal vents (ceiling holes, hatches, roof vents, etc.), and mechanical ventilation through fans and ductwork. Natural flow is determined by the pressure difference across a vent, using Bernoulli's law for horizontal vent flow, and by empirical correlations for vertical vent flow. Mechanical ventilation is based on an analogy to electrical current flow in series and parallel paths where flow is split in parallel paths proportional to the flow resistance in each path and resistance to flow is additive for paths in series.

CFAST includes algorithms to account for radiation, convection, and conduction within a modeled structure. Radiative transfer occurs among the fire(s), gas layers, and compartment surfaces (ceiling, walls, and floor). It is a function of the temperature differences and emissivity of the gas layers, as well as the compartment surfaces. Convective heat transfer between gas layers and compartment or target surfaces is based on typical correlations available in the literature. CFAST uses a finite difference scheme that utilizes a non-uniform spatial mesh to advance the wall temperature solution consistent with the flux conducted into the wall (calculated using Fourier's law). The V&V results for CFAST are documented in volume 5 of

NUREG-1824 (NUREG-1824 vol. 5, 2007). Additional validation results, particularly for plume temperature predictions that were not included in the NUREG-1824 results, are included in the CFAST Model Development and Evaluation Guide (Peacock et al., 2008a).

2.3.4 MAGIC

MAGIC is a two-zone computer fire model, developed and maintained by Electricité de France (EdF), that predicts the environmental conditions resulting from a fire prescribed by the user within a compartmented structure. The space to be modeled is subdivided into two control volumes that represent upper and lower layers. The fundamental equations for conservation of energy and mass are solved in each control volume as the fire HRR develops over time. MAGIC is supported by three EdF publications, including (1) the technical manual, which provides a mathematical description of the model (Gay et al., 2005b); (2) the user's manual, which details how to use the graphical interface (Gay et al., 2005a); and (3) the validation studies, which compare MAGIC's results to experimental measurements (Gay et al., 2005c). These three proprietary publications are available through EPRI to EPRI members. In addition, V&V results for MAGIC are documented in Volume 6 of NUREG 1824 (NUREG 1824 vol. 6, 2007).

Once a given simulation is completed, MAGIC generates an output file with all of the solution variables. Through a "post-processor" interface, the user selects the relevant output variables for the analysis. Typical outputs include temperatures of hot and cold zones, concentrations of oxygen and unburned gases, smoke migration into each compartment, the mass flow rates of air and smoke through the openings and vents, the pressures at the floor level of each compartment, the temperatures at the surfaces of the walls, and the thermal fluxes (radiative and total) exchanged by the targets placed by the user.

The standard combustion model in MAGIC assumes a perfect oxidation reaction, that is, that the fire will burn at the specified HRR if oxygen is available. MAGIC tracks the amount of oxygen in the fuel (in the case of a premixed fuel), oxygen entrained by the fire, unburned fuel in the environment, and the predefined fuel source in order to determine whether complete combustion will occur. The chemical aspects of combustion are not considered. If the oxygen entrained into the plume is at least equal to the quantity necessary to burn all of the gaseous fuels in the plume, combustion is considered complete and controlled by the fuel flow rate. If not, the combustion is incomplete and controlled by the available oxygen. The user can also specify a low oxygen limit (LOL).

2.3.5 Fire Dynamics Simulator (FDS)

FDS (McGrattan et al., 2007) is a computational fluid dynamics (CFD) model of fire-driven fluid flow. The model numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow, with an emphasis on smoke and heat transport from fires. The partial derivatives of the equations for conservation of mass, momentum, and energy are approximated as finite differences, and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Lagrangian particles are used to simulate smoke movement and sprinkler discharge. FDS computes the temperature, density, pressure, velocity, and chemical composition within each numerical grid cell at each discrete time step. There are typically hundreds of thousands to several million grid cells, and thousands to hundreds of thousands of time steps. In addition, FDS computes the temperature, heat flux, mass loss rate, and various other quantities at solid surfaces.

Time histories of various quantities at a single point in space, or global quantities, such as the fire's HRR, are saved in simple, comma-delimited text files that can be plotted in a spreadsheet program. However, most field or surface data are visualized with a program called Smokeview, a tool specifically designed to analyze data generated by FDS. FDS and Smokeview are used in concert to model and visualize fire phenomena. Smokeview performs this visualization by presenting animated tracer particle flow, animated contour slices of computed gas variables, and animated surface data. Smokeview also presents contours and vector plots of static data anywhere within a scene at a fixed time. The FDS User's Guide (McGrattan et al., 2007) provides a complete list of FDS output quantities and formats. The Smokeview User's Guide (Forney, 2008) explains how to visualize the results of an FDS simulation. Volume 7 of NUREG 1824 contains the results of V&V efforts for FDS (NUREG-1824 vol. 7, 2007). Additional V&V results for FDS are contained in the FDS documentation series (McGrattan et al., 2007).

FDS solves conservation equations of mass, momentum, and energy for an expandable mixture of ideal gases in the low Mach number limit. This means that the equations do not permit acoustic waves, the result of which is that the time step for the numerical solution is bounded by the flow speed, rather than the sound speed. The assumption also reduces the number of unknowns by one, as density and temperature can be related to a known background pressure. Flow turbulence is treated by large eddy simulation (LES).

For most simulations, FDS uses a mixture fraction combustion model. The mixture fraction is a conserved scalar that represents, at a given point, the mass fraction of gases originating in the fuel stream. In short, the combustion is assumed to be controlled by the rate at which fuel and oxygen mix, and the reaction is instantaneous, regardless of temperature. The reaction occurs at an infinitely thin "flame sheet," for which the location in the flow is dictated by the basic stoichiometry of the reaction. Because the mixture fraction model assumes that fuel and oxygen react readily on contact, it is necessary to supplement the model with an empirical description of flame extinction in oxygen-limited compartments. A simple model uses the local temperature and oxygen concentration near the flame sheet to determine whether combustion can be sustained.

A numerical parameter is any input value that is needed for the mathematical solution of the equations, but has little or no physical meaning. For example, the time step with which the numerical solution of the HGL temperature is computed does have units of seconds, but it is not a value that has meaning outside of that particular algorithm; nevertheless, these numerical parameters can affect the solution, and their sensitivity should be assessed in some way. For the spreadsheet and zone models, this procedure is relatively straightforward because the calculations run in less than a minute. One simply varies the value and ensures that the solution does not change appreciably. Specifically, one should simply demonstrate that the solution *converges* towards a particular value as the parameter is varied; for instance, using a smaller and smaller time step ought to lead to convergence of any evolution equation.

Numerical parameters play a very important role in a computational fluid dynamics (CFD) model like FDS. Of these, the grid cell size is the most important. CFD models solve an approximate form of the conservation equations of mass, momentum, and energy on a numerical grid. The error associated with the discretization of the partial derivatives is a function of the size of the grid cells and the type of differencing used. FDS uses second-order accurate approximations of both the temporal and spatial derivatives of the Navier-Stokes equations, meaning that the discretization error is proportional to the square of the time step or cell size. In theory, reducing the grid cell size by a factor of 2 reduces the discretization error by a factor of 4; however, it also increases the computing time by a factor of at least 16 (a factor of 2 for the temporal and each spatial dimension). Clearly, there is a point of diminishing returns as one refines the numerical mesh. Determining which size grid cell to use in any given calculation is known as a *grid sensitivity study.*

Determining an optimal grid size in FDS is usually a matter of assessing the size of the fire. The physical diameter of the fire is not always a well-defined property; a compartment fire does not have a well-defined diameter, whereas a circular pan filled with a burning liquid fuel has an obvious diameter. Regardless, it is not the physical diameter of the fire that matters when assessing the "size" of the fire, but rather its characteristic diameter, D^*:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5}$$

In many instances, D^* is comparable to the physical diameter of the fire. FDS employs a numerical technique known as large eddy simulation (LES) to model the unresolvable or "sub-grid" motion of the hot gases. The effectiveness of the technique is largely a function of the ratio of the fire's characteristic diameter, D^*, to the size of a grid cell, δx. In short, the greater the ratio $D^*/\delta x$, the more the fire dynamics are resolved directly, and the more accurate the simulation. Past experience has shown that a ratio of 5 to 10 usually produces favorable results at a moderate computational cost.

As an example, suppose the HRR of the fire were 300 kW. Then we calculate

$$D^* = \left(\frac{300 \text{ kW}}{1.2 \text{ kg/m}^3 * 1.012 \text{ kJ/kg/K} * 293 \text{ K} \sqrt{9.81 \text{ m/s}^2}} \right)^{2/5} = 0.59 \text{ m}$$

To perform a grid sensitivity analysis, a good place to start might be 20 cm (8 in), which means that $D^*/\delta x = 3$. Then choose a grid of 10 cm (4 in), and then 5 cm (2 in). At this point, the calculation time will have increased by a factor of roughly 400, making it potentially impractical to compute; however, if it can be shown that there is little difference between the 5 cm and 10 cm grids, then the objective has been achieved. The meaning of "little difference" can be interpreted several ways. Given that NUREG-1824, the fire model V&V study, lists the relative error expected of the various models for the various quantities, it is reasonable to interpret the difference in results on different grids in light of what is expected of the model accuracy.

2.3.6 Verification and Validation

The use of fire models to support fire protection decision-making requires a good understanding of their limitations and predictive capabilities. The V&V study (NUREG-1824 vol. 1, 2007) conducted by the NRC, EPRI, and NIST provides valuable insight into the predictive capability of these five fire models. The validation results from the V&V are presented in the form of color-coded grades of the predictive capability of fire models for important parameters for NPP fire modeling applications. These grades are based on the quantitative relative differences between model predictions and applicable experimental measurements. The predictive capability considers the uncertainty in the experimental measurements. The experiments considered represent configurations that may be seen in NPP applications. Not all possible NPP scenarios were evaluated in the study. Users should independently decide whether the results of this study are applicable to their specific scenario. The results of the V&V effort are shown in Table 2-3.

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

The two-zone models performed well when compared with the experiments considered. An evaluation showed that they simulated the experimental results within experimental uncertainty for most of the parameters of interest, possibly because the relatively simple experimental configurations selected for this study conform well to the simple two-layer assumption that is the basis for these models. However, users must remain cautious when applying these models to more complex scenarios, or when predicting certain phenomena, such as heat fluxes.

Evaluation of the FDS model showed that the model simulated the experimental results within experimental uncertainty for most of the parameters of interest. The results of the field model, FDS, are comparable to the results of the two-zone models (CFAST and MAGIC), probably because the experimental configurations utilized in this study contained, in most cases, two distinct layers within the compartment of origin.

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

Like all predictive models, the best predictions come with a clear understanding of the limitations of the model and of the inputs provided for the calculations. For calculation of many attributes (see those attributes categorized as YELLOW in Table 2-3), caution should be exercised when applying these models. For the attributes categorized as GREEN, the models are accurate to within the experimental uncertainty associated with each particular attribute for the range of conditions represented by the experiments used in this study.

Validation studies are limited by the general characteristics of the fire experiments selected. Consequently, the validation results need to be identified as corresponding to specific NPP fire scenarios to determine their applicability. One method for determining the applicability of validation results to other specific NPP fire scenarios has been described in NUREG-1824 vol. 1. The applicability of the validation results is determined using normalized parameters traditionally used in fire modeling applications. Normalized parameters allow users to compare results from scenarios of different scales by normalizing physical characteristics of the scenarios.

Table 2-4 of NUREG-1824 vol. 1 lists selected normalized parameters that may be used to compare NPP fire scenarios with validation experiments. Table 2-4 is intended to provide guidance on which groups of validation experiments to consider when evaluating a certain attribute based on the validation results. These parameters may not be the only ones appropriate for evaluating the applicability of a specific experiment; Table 2-5 of NUREG-1824 vol. 1 lists the ranges of values for different physical characteristics and normalized parameters based on the experiments considered in the validation study.

For a given set of experiments and NPP fire scenarios, the user can calculate the relevant normalized parameters. If the fire scenario parameters fall within the ranges evaluated in the study, then the results of the study offer appropriate validation for the scenario. If they fall outside the range, then a validation determination cannot be made based on the results from the study. For any given fire scenario, more than one normalized parameter may be necessary for determining the applicability of the validation results.

Table 2-3. Results of the Validation & Verification of the Selected Fire Models

Parameters[5]		Fire Model				
		FDT[s]	FIVE-Rev1	CFAST	MAGIC	FDS
Hot gas layer temperature ("upper layer temperature")	Compartment of Origin	YELLOW+	YELLOW+	GREEN	GREEN	GREEN
	Adjacent Compartment	N/A	N/A	YELLOW	YELLOW+	GREEN
Hot gas layer ("layer interface height")		N/A	N/A	GREEN	GREEN	GREEN
Ceiling jet temperature ("target/gas temperature")		N/A	YELLOW+[2]	YELLOW+	GREEN	GREEN
Plume temperature		YELLOW-	YELLOW+[2]	N/A	GREEN	YELLOW
Flame height[3]		GREEN	GREEN	GREEN	GREEN	YELLOW[1]
Oxygen concentration		N/A	N/A	GREEN	YELLOW	GREEN
Smoke concentration		N/A	N/A	YELLOW	YELLOW	YELLOW
Compartment pressure[4]		N/A	N/A	GREEN	GREEN	GREEN
Target temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Radiant heat flux		YELLOW	YELLOW	YELLOW	YELLOW	YELLOW
Total heat flux		N/A	N/A	YELLOW	YELLOW	YELLOW
Wall temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Total heat flux to walls		N/A	N/A	YELLOW	YELLOW	YELLOW

Notes:

1. FDS does not use an empirical correlation to predict the flame height; rather, it solves a set of equations appropriate for reacting flows and predicts the flame height as the uppermost extent of the combustion zone. This is a challenging calculation, and the Yellow emphasizes that caution should be exercised by users.
2. FIVE approximates the experimental plume temperature as the sum of hot gas layer temperature and the calculated plume temperature and experimental ceiling jet temperature as the sum of hot gas layer temperature and the calculated ceiling jet temperature. The calculated plume and ceiling jet temperatures were obtained from the correlations.
3. Flame height models compared with visual observations only.
4. Large experimental uncertainties for compartment pressure.
5. Refer to Table 2-3 for information on which experiments captured data for which parameter.
6. The + and – indicate whether the model overpredicts or underpredicts the V&V data.

2.4 Step 4: Estimate Fire-Generated Conditions

This step involves simply running the model(s). When running a computer model, the following general steps are recommended:

1. Prepare the input file. In this step, the analyst enters the input parameters into the model. The best way to enter input parameters is to follow the same guidelines described in the scenario description section. Each model has a user's manual with instructions on creating the respective input file. These files are created either through user-friendly menus and screens or through a text editor. If a text editor is used, it is strongly recommended that the analyst start with an example case prepared by code developers, and make appropriate changes to that file.

2. Determine the output parameters of interest. If the objective of the simulation is to estimate wall temperatures, for example, the analyst should be interested in internal and external wall temperatures. The analyst should ensure that the model will provide the output of interest, or at least the fire conditions that can help achieve the objectives. The output file should be labeled with a distinctive file name.

3. Run the computer model. The running time for zone models is on the order of minutes, depending on the complexity of the scenario and the speed of the computer. Calculations using a CFD model may take up to hours in complex scenarios, including multiple compartments, multiple fires, and mechanical ventilation systems.

For the FDT^s and FIVE-Rev1, the input data is entered directly into a spreadsheet, and the results are presented in the spreadsheet. Some of the FDT^s spreadsheets include graphical and tabular results. FIVE-Rev1 typically provides a single result for a given set of input data; however, many of the calculations in FIVE-Rev1 are implemented as Microsoft Excel functions. These functions can be called from any cell in the spreadsheet. It is possible, for example, to specify a heat release rate in one cell and the plume temperature at a specific location above the fire for that heat release rate. By entering a list of heat release rates that vary with time, the analyst could obtain the plume temperature or other calculations as a function of time.

CFAST, MAGIC, and FDS can handle user-specified transient heat release rates, as they calculate the results for each zone or cell at each time step. The time step required to maintain stable calculations is typically determined by the model. The interval at which results are presented is a user-specified value. CFAST, MAGIC, and FDS can output results as text files, which can be read or plotted using commercially available spreadsheet programs; CFAST and FDS can also output their results in a form appropriate for SMOKEVIEW (Forney, 2008). SMOKEVIEW is a software tool that visualizes smoke and other attributes of the fire using traditional scientific methods, such as displaying tracer particle flow, 2-D or 3-D shaded contours of gas flow data (e.g., temperature), and flow vectors showing flow direction and magnitude. MAGIC includes its own post processor for visually analyzing the results of a simulation.

2.5 Step 5: Sensitivity and Uncertainty Analysis

This guide recommends a comprehensive treatment of uncertainty and/or sensitivity analysis as part of a fire modeling analysis for the following reasons:

1. Models are developed based on idealizations of the physical phenomena and simplifying assumptions, which unavoidably introduces the concept of model uncertainty (i.e., model error) into the analysis.
2. A number of input parameters are based on available/generic data or on fire protection engineering judgment, which introduces the concept of parameter uncertainty into the analysis.

The concepts of model and parameter uncertainty have traditionally been addressed in fire modeling using uncertainty and/or sensitivity analysis. The uncertainty in a variable represents the lack of knowledge about the variable, and is often represented with probability distributions. Its objective is to assess the variability in the model output, that is, how uncertain the output is given the uncertainties related to the inputs and structure of the model. By contrast, the sensitivity of a variable in a model is defined as the rate of change in the model output with respect to changes in the variable. A model may be insensitive to an uncertain variable. Conversely, a parameter to which a model is very sensitive may not be uncertain.

Details of sensitivity and uncertainty analysis are included in Chapter 4 of this guide.

2.6 Step 6: Documentation

The amount of information required and generated by a fire modeling analysis can vary widely. Simple Empirical correlations/hand calculations may not require a large number of inputs, and the complete analysis, including output results, can be documented on a single piece of paper. On the other hand, some fire modeling exercises may require use of multiple computer models, where outputs from one are inputs to others. These cases, for the most part, will require a significant number of input parameters and will produce outputs requiring documentation. Regardless of the amount of information required or generated by the analysis, proper documentation is vital to identifying the important findings of the exercise and in providing clear, focused conclusions.

Documentation of the fire scenario selection and description process should include enough information so that the final report is useful in current and future applications. This is particularly relevant in the commercial nuclear industry, where compartment and equipment layouts or processes do not change much over time. It is likely that fire scenarios analyzed for one application may be useful for other applications as well; the key, however, is to develop and maintain good documentation of the selected fire scenarios, including all the technical elements discussed in this section.

It is likely that the information necessary for documenting the fire scenario selection will be gathered from a combination of observations made during engineering walkdowns and a review of existing plant documents and/or drawings. The documentation process then involves compiling the information from different sources into a well-organized package that can be used in future applications and for NRC regional inspections. The documentation package may consist of:

- Marked up plant drawings: Plant layout, detection, suppression, cable tray, and conduit drawings are often marked to highlight the location of the compartment, ignition sources, targets, and fire protection features. The drawings also serve as sources of fire model input values, such as compartment dimensions and relative locations of fire protection systems or targets.
- Sketches: Sketches are perhaps one of the most useful ways of documenting a fire scenario. A sketch typically consists of a drawing illustrating the ignition source, intervening combustibles, targets, and fire protection features. A first draft of the sketch is usually prepared during walkdowns. The analyst should take the opportunity to include details such as raceways and conduit IDs, and other information relevant to the fire modeling analysis. Pictures often supplement sketches.

- Write-ups and input tables: Write-ups and input tables are used to compile the information collected from drawings and walkdowns in an organized way. The write-up should include a brief scenario description and detailed documentation supporting quantitative inputs to the fire modeling analysis, as well as any relevant sketches or pictures associated with each scenario.

The following is a recommended structure for a fire modeling calculation file. The examples presented in Appendices A through H illustrate techniques for the proper documentation of fire modeling calculations.

1. 0 Purpose

Clearly state the purpose of the calculations being performed. What is being calculated, and why is this being done?

2. 0 References

Where did you get the input information included in the calculation? List references and identify them in the calculation (e.g., "This value for the density of concrete came from Ref. X").

3. 0 Design Input Data

List the design input data used in the calculation (e.g., "The compartment dimensions are X, Y, and Z from Ref. A. The wall thickness is B from Ref. C"). These are items commonly referred to as the "Givens" in college-type calculations. The "Givens" in the sample problems have been somewhat altered for example's sake.

4. 0 Fire Scenarios

List the fire scenarios used in the calculations. What is the assumed HRR from the oil fire that results from a pump spill? How much oil will spill? How big will the spill be? Is it in a curbed area (design input data), or do you have to make an assumption?

5. 0 Model Assumptions

What are the additional assumptions necessary to run the model? How was a circular geometry represented in a rectangular coordinate system?

6. 0 Summary of Results

List the results of your calculation and analysis. Here is where the tables, graphs, photos, drawings, etc. from the calculations are presented and discussed.

7. 0 Conclusion

List the conclusion of your calculation and analysis. Did the results address the purpose of the calculation?

8.0 Appendixes

Add any appendix material if appropriate.

9. 0 Attachments

Add any attachments if appropriate. A good example of this would be to attach a vendor cut sheet that contains a lot of material properties used in your calculation (k, □, c, etc.) as a material that you referenced, though the cut sheet is not commonly available (i.e., not in a common handbook).

2.7 Summary

This chapter described a recommended process for conducting and documenting a fire modeling process. Specific fire modeling examples are provided in Appendices A through H, and follow the process described above. In addition, Chapter 3 provides guidance on selecting the appropriate fire modeling tool for typical commercial nuclear power plant applications, and Chapter 4 details the treatment of model uncertainty in fire modeling applications.

3
DETAILED GUIDANCE ON FIRE MODEL SELECTION

This chapter has been designed to provide specific guidance and recommendations on modeling fire scenarios in the commercial nuclear industry using the fire modeling tools within the scope of this guide. In general, this chapter can be considered a catalogue of generic fire scenarios and corresponding modeling objectives for which a modeling strategy is discussed, relevant fire modeling elements are described, and model selection recommendations are offered.

The chapter begins with a general sketch depicting the fire scenarios and corresponding modeling elements. The sketch, presented in Figure 3-1, is intended to point the analyst to the specific section where the guidance is provided; the circled numbers represent a section number in this chapter as listed in the following table.

Table 3-1. Listing of generic fire scenarios described in this chapter

Number	Chapter Section	Scenario Description
1	3.1	Scenarios consisting of determining time to damage of cables above the ignition source located inside the flames or the fire plume
2	3.2	Scenarios consisting of determining time to damage of cables located inside or outside the hot gas layer
3	3.3	Scenarios consisting of determining time to damage of cables located in an adjacent room to the room of fire origin
4	3.4	Scenarios consisting of determining time to damage of cables located inside or outside hot gas layer in rooms with complex geometries
5	3.5	Scenarios consisting of determining time to untenability of the main control room or rooms
6	3.6	Scenarios consisting of determining the time to smoke or heat detector activation
7	3.7	Scenarios consisting of determining temperature of structural elements

Each of the sections listed above is organized as follows:

1. A scenario objective stating the purpose of the modeling exercise in engineering terms.
2. A description of the relevant technical fire scenario elements, such as mechanical ventilation, the room geometry, etc. Recall that fire scenario elements refer to the different characteristics of the fire scenario that are relevant to the analysis, and should be properly represented in the model.
3. A modeling strategy section summarizing the recommended steps for performing the calculation.
4. A section listing fire model recommendations for the analysis.
5. A section referencing relevant detailed fire modeling examples documented in the Appendix section of this guide.

Each section includes a sketch capturing most of the technical elements relevant to the analysis. A legend summarizing the different elements presented in the sketches is provided in Figure 3-2. In addition to the generic guidance provided in this chapter, detailed fire modeling examples are documented in the Appendix section of this guide, and are referenced throughout the generic guidance.

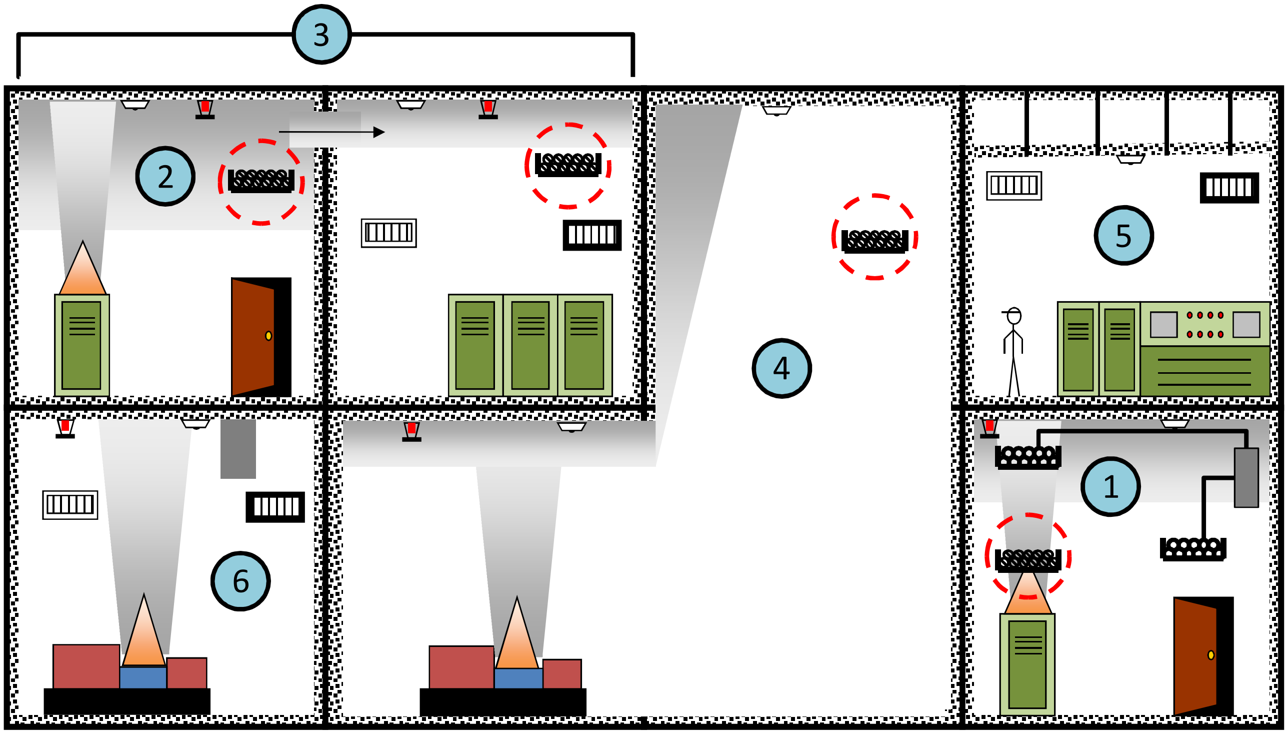

Figure 3-1. Pictorial representation of the fire scenario and corresponding technical elements described in this section

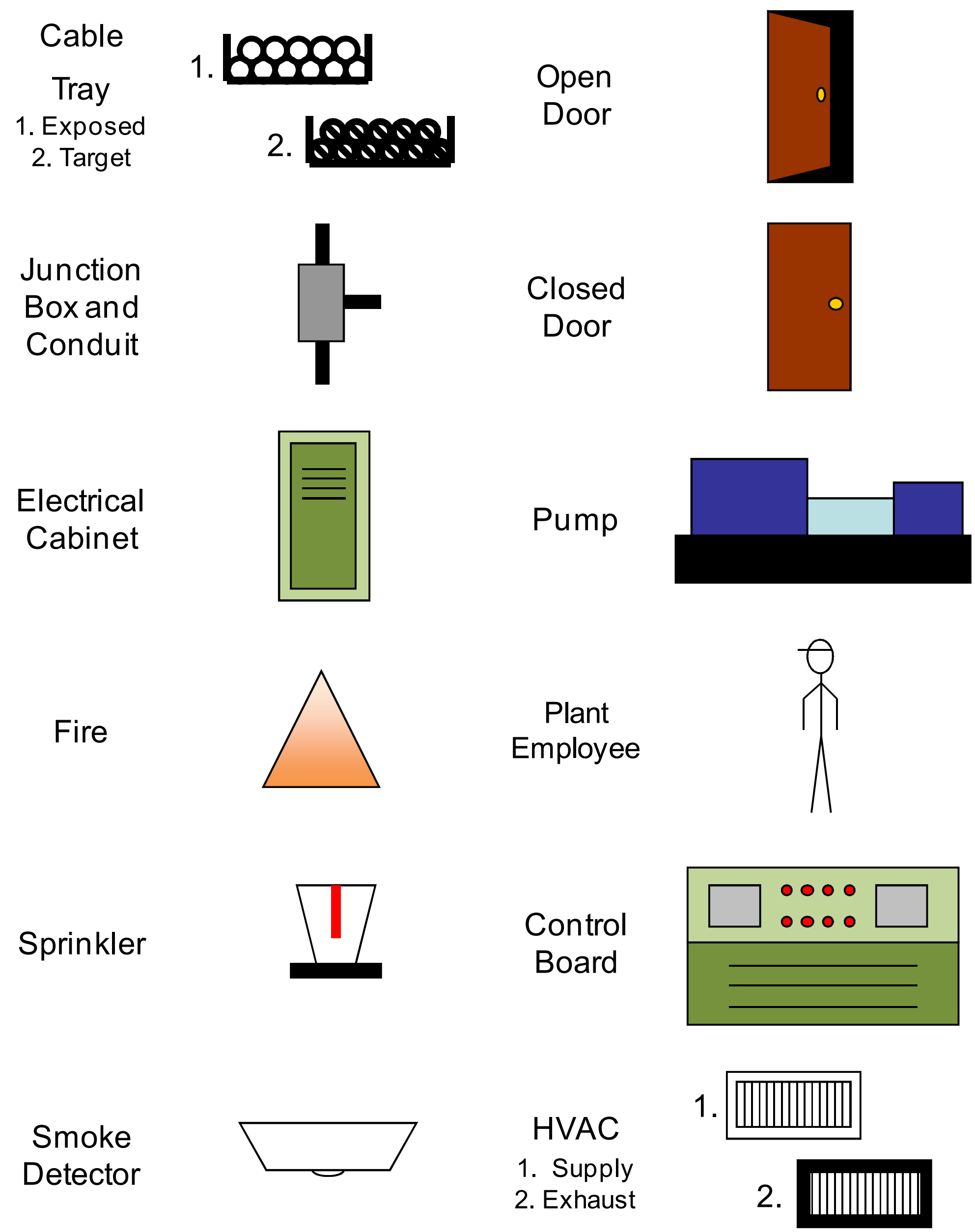

Figure 3-2. Legend for fire modeling sketches presented in this chapter

3.1 Scenario 1: Targets in the Flames or Plume

This scenario consists of a target electrical cable in a raceway immediately above an ignition source, which in this case is an electrical cabinet. This scenario is depicted in Figure 3-1, where the target is identified in the sketch with a dashed circle.

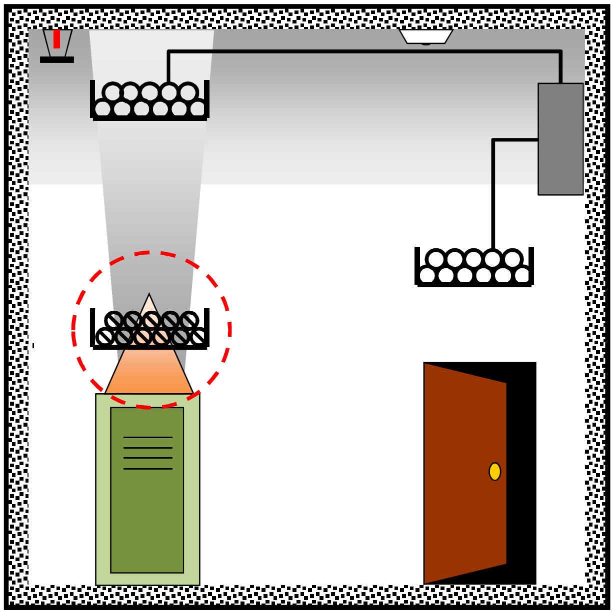

Figure 3-3. Pictorial representation of scenario 1

3.1.1 General Objective

Calculate the time to damage for an electrical cable in a raceway immediately above a fire starting in an electrical cabinet.

3.1.2 Fire Scenario Elements

Ignition Source (i.e., the fire)

The following elements associated with the ignition source are relevant to this scenario:

- Identify the fuel and assess the peak heat release rate value. For example, industry documents such as NUREG/CR-6850 would provide recommended heat release rate values for Fire PRA applications.
- Decide whether the fire will be modeled using a steady peak intensity or with an intensity varying as a function of time.
- Specify the fire location:
    a. Elevation: The fire elevation refers to the elevation of the base of the fire, measured from the floor. The fire elevation is a factor in two situations: (1) in scenarios involving targets in the fire plume where the relative distance between the fire and the target strongly influences the resulting plume temperature, and/or (2) in scenarios where the position of the hot gas layer is relevant, as the fire elevation may influence the air entrainment into the plume, and, consequently, the position of the layer.

    b. Fires located along a wall or in a corner. In scenarios where the fire is located along a wall and in the corner, the plume is expected to entrain less “fresh” air, resulting in higher plume temperatures.

- Assess the footprint area of the fire (optional—depends on model selection):
    a. Circular (e.g., pool fires specified by the diameter).
    b. Rectangular (e.g., bounded pool fires, electrical cabinets specified by length and width).
- Provide additional heat release rate characteristics:
    a. Total (or initial) fuel mass.
    b. Soot Yield. The soot yield is an important factor in radiative heat transfer (e.g., targets immersed in the hot gas layer) and visibility calculations.
    c. Irradiated fraction. Note that the irradiated fraction is the complement of the fraction of heat within the fire plume. Conservative values in terms of irradiated fractions will result in less conservative estimates in terms of the convective fraction of the HRR.

Targets

Generally, the technical specification of targets requires location, damage criteria, and thermophysical properties.

Location refers to the target position relative to the fire inside the compartment. The general location of a target with respect to the fire should be known. Targets may be exposed to distinct fire-generated conditions or fire-induced flows within a compartment, depending on their location (e.g., target subjected to plume temperatures, hot gas layer temperatures, etc.).

The damage criteria refer primarily to the characterization of the failure processes of each element interest (e.g., thermal damage, smoke, etc.) and the damage threshold or criteria (e.g., a failure temperature, etc.). In lieu of characterizing each individual target element, the analyst may select a single set of target characteristics to represent all elements of the target set. In this case, the selected characteristics should be based on the target element most vulnerable to failure given a particular failure mechanism. In general, the damage criteria for scenarios involving cable damage is expressed in terms of damage temperature or incidental heat flux.

Finally, the models within the scope of this guide require specification of the target's thermophysical properties (density (kg/m^3), specific heat (kg/kJ-K), and thermal conductivity (kW/m-K)) for the analysis. The estimated time for the gas temperature surrounding the target to reach a specific limit may not be the same as the time it takes the target to reach the same limit. Heat conduction to the inside of the target may delay the temperature rise at the surface during the heating process.

Intervening Combustibles

In most cases, commercial nuclear plant fire scenarios do not require modeling of burning targets. It is enough to determine when the target is affected (i.e., damaged or ignited) by fire. This is clearly not the case with intervening combustibles, whose flammability characteristics need to be incorporated into the model so that the fire progression is considered; thus, the necessary information for describing intervening combustibles should describe not only the relative proximities to the fire and the targets, but also the relevant thermophysical and flammability properties.

It is likely that fire propagation through cable trays will be an important element in a number of fire scenarios in NPP applications. At the same time, representing intervening combustibles in fire models will present technical challenges that the analyst should also consider, including (1) obtaining the necessary geometric and flammability information for representing the intervening combustible and (2) the ability of the computer tools to model the fire phenomena (e.g., fire propagation), among others. It should be noted that, due to these challenges, industry methodologies for applications (e.g., Fire PRAs) include a number of “special models” to predict fire-generated conditions that are currently outside the capabilities of the fire models within the scope of this guidance.

Room Geometry and/or Obstructions: Single Compartments

Compartment geometry refers to the physical layout of the scenario. Length, width, and height define the size of each compartment. The size of a compartment is an important factor in the volume used to solve the fundamental conservation equations. In terms of size, FDT^s, FIVE, MAGIC, and CFAST have similar input requirements: only the length, width, and height are required. While FDS requires the same length, width, and height information, the structure of the input is significantly different from that of the other models, as the different obstructions that make up the room geometry are individually specified in the computational domain.

Compartment Boundary Materials

Boundary (i.e., wall) materials are characterized with thermophysical properties. Thermophysical properties include the density, specific heat, and thermal conductivity of the material. In the majority of commercial nuclear power plant applications, the wall material is concrete. Other materials may include steel, gypsum board, etc. Properties for these materials are often available in “drop down” in the fire models or in fire protection engineering handbooks.

Natural Ventilation: Vertical Openings

The concept of vertical openings specifically refers to doors and/or windows. In some cases, a selected compartment will have more vertical openings than the number that can be specified in a specific model; for example, the MQH model for calculating room temperature available in FDTs and FIVE-Rev1 accept only one opening. The most important consideration in addressing the issue of vertical openings is to conserve the ventilation factor. If the number of vertical openings needs to be reduced in order to describe the scenario in a specific model, a weighted average for the vent factor needs to be estimated. The ventilation factor is defined as the product of the area of an opening and the square root of the height of the opening $\left(A_o\sqrt{H_o}\right)$ (Karlsson et al., 2000; Drysdale, 1996). The following steps can be followed for combining vertical openings:

1. Add the areas of the selected doors.
2. Divide the sum of the product of the area and height of each door by the total area calculated in step 1.

Mathematically, the process is summarized as:

$$A_o = \sum_{i=1}^{n} A_i \quad \text{and} \quad H_o = \frac{\sum_{i=1}^{n} A_i \cdot h_i}{A_o}$$

where A_i and h_i are the area and height of door i, respectively, and n is the total number of doors that need to be combined. A_o and H_o will be the effective area and height of the combined opening. To estimate the width of the combined opening, simply divide A_o by H_o.

Natural Ventilation: Leakage Paths

Many compartments in commercial NPPs have normally closed doors. However, they are not perfectly sealed. Consequently, the resulting pressure and the rate of pressure rise are often kept very small by gas leaks through openings in the walls and cracks around doors, or "leakage paths." Leakage paths must be specified in compartments with closed doors and windows during the fire event. By contrast, compartments with at least one open door or window can maintain pressure close to ambient during the fire event. Leakage paths therefore do not need to be specified, since the leakage opening area is negligible when compared with the opening areas of doors and windows.

Natural Ventilation: Horizontal Openings

Addressing horizontal openings is easier than addressing vertical openings because the pressure difference between the inside and outside of the enclosure is constant at the height of the openings. Thus, areas of horizontal openings can simply be added. Any zone model should provide similar answers with single or multiple horizontal openings as long as the total opening area is the same.

Mechanical Ventilation

Mechanical ventilation refers to any air injected into or extracted from a fire compartment by mechanical means. This has a number of practical applications, including, for example, extracting smoke from the hot gas layer (e.g., a smoke purge system). The ventilation rate and the vent position are the two most important mechanical ventilation parameters. These "mechanically" induced flows have the potential to alter the fire-induced flows described earlier in this section.

3.1.3 Modeling Strategy

The recommended modeling strategy is summarized in the following steps:

1. Determine whether the target cable, which is directly above the fire, is within the flame zone or within the fire plume. The target should be considered inside the flame zone if it is located directly above the base of the fire and its distance from the base of the fire is less than the flame height. If the target is above the fire but is not within the flame zone, then it is considered to be within the fire plume.
2. Calculate the time to damage by finding either:
    a. the time it takes the fire plume temperature to exceed the target damage temperature. This is achieved by calculating the plume temperature at the specified height as a function of time using the heat release rate profile (e.g., heat release rate as a function of time) as an input. This approach can be considered conservative, as it assumes cable damage occurs when the gas temperature surrounding the target reaches the damage temperature.
    b. the temperature inside the cable as a function of time, given a heat flux profile generated by the flame or plume.

If non-target raceways are located between the ignition source and the target, the contributions of intervening combustibles need to be considered in the analysis. Consider, for example, a panel fire that ignites the first of a stack of trays overhead. The fire involving the combination of the panel and first tray may then ignite the second tray in the stack, and the fire may progress to damaging the target raceway. Considerations of the intervening combustibles in the analysis include the heat release rate contribution and the corresponding effects on the target heating time.

In addition to following the guidance provided above, the analyst should determine whether hot gas layer effects are relevant in the scenario. In scenarios consisting of targets located relatively close to the ignition source, the hot gas layer effects on the plume temperature are generally not considered, as the time to target damage is expected to be relatively short. However, in scenarios involving targets in the fire plume, located relatively far from the ignition source, the hot gas layer effects on target heating should be considered. In the latter case, the room geometry and ventilation (both natural and mechanical) conditions should be captured by the analysis.

3.1.4 Recommended Modeling Tools

Engineering Calculations

Based on the above strategy, it is advisable to use engineering calculations in FIVE-REV1 or FDT^s for this scenario. Heskestad's flame height correlation is an alternative for determining flame height. Similarly, Heskestad's fire plume temperature correlation is an alternative for determining plume temperature (Heskestad, 2002).

The correlations listed above are particularly applicable for scenarios consisting of targets relatively closed to the ignition source, where hot gas layer effects are not considered in the analysis. However, in cases where hot gas layer effects are relevant, the use of hand calculations without appropriately considering the hot gas layer effects is not recommended.

Zone Models

Zone models can be used for this scenario as long as the target will be heated by flame or fire plume conditions. To do so, set up the necessary input file that includes a "target" in the location of the electrical cable of interest with the corresponding thermophysical properties so that the surface temperature of the cable can be tracked. Zone models have the ability to include hot gas layer effects in their calculation of plume temperature. Consequently, these models are particularly appropriate for scenarios where the hot gas layer temperature interacts with the fire plume at the location of the target.

CFD Model

Although a CFD model could be used for analyzing this scenario, the level of detail and resolution offered by a CFD calculation is usually not necessary. On the other hand, the model would be particularly applicable if the scenario involves obstructions between the fire and the target inside the fire plume. These obstructions are not captured by hand calculations or zone models.

3.1.5 Detailed Examples

Readers are referred to the following appendices for detailed examples of the generic scenario described in this section:

- Appendix B, which describes the analysis of an electrical cabinet fire in the switchgear room.
- Appendix E, which describes the analysis of a transient fire in a cable spreading room.

3.2 Scenario 2: Targets Inside or Outside the Hot Gas Layer

This scenario consists of an electrical cable target in a raceway located inside or outside the hot gas layer produced by a fire involving an electrical cabinet and propagating to nearby cable trays, and is depicted in Figure 3-4.

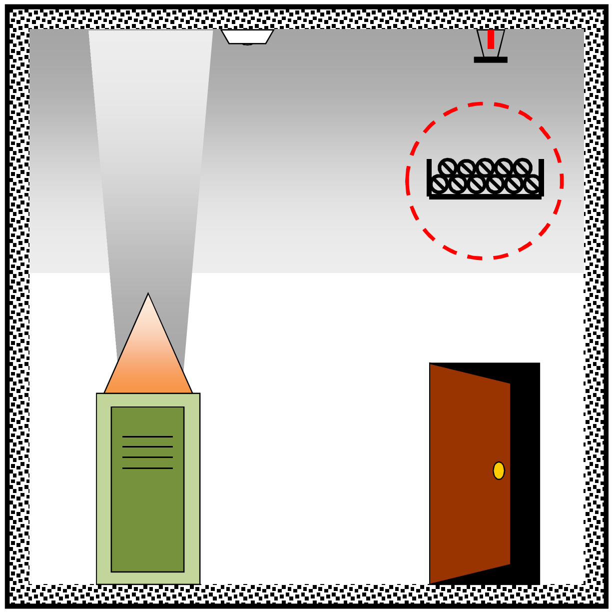

Figure 3-4. Pictorial representation of scenario 2

3.2.1 General Objective

Calculate the time to damage for an electrical cable in a raceway inside or outside the hot gas layer produced by a fire that starts in an electrical cabinet and propagates to secondary combustibles (e.g., nearby cable trays).

3.2.2 Fire Scenario Elements

Ignition Source (i.e., the fire)

The following elements associated with the ignition source are relevant to this scenario:

- Identify the fuel and assess the peak heat release rate value. For example, industry documents, such as NUREG/CR-6850, would provide recommended heat release rate values for Fire PRA applications.
- Decide whether the fire will be modeled with a steady peak intensity or with an intensity varying as a function of time.
- Specify the fire location:
    a. Elevation: The fire elevation refers to the elevation of the base of the fire measured from the floor. The fire elevation is a factor in two situations: (1) in scenarios involving targets in the fire plume where the relative distance between the fire and the target strongly influences the resulting plume temperature, and/or (2) in scenarios where the position of the hot gas layer is relevant, as the fire elevation

may influence the air entrainment into the plume, and, consequently, the position of the layer.

b. Fires located along a wall or in a corner. In scenarios where the fire is located along a wall and in the corner, the plume is expected to entrain less “fresh” air, resulting in higher plume temperatures.

- Assess the footprint area of the fire (optional—depends on model selection):
  a. Circular (e.g., pool fires specified by the diameter).
  b. Rectangular (e.g., bounded pool fires, electrical cabinets specified by length and width).
- Provide additional heat release rate characteristics:
  a. Total (or initial) fuel mass.
  b. Soot yield: The soot yield is an important factor in radiative heat transfer (e.g., targets immersed in the hot gas layer) and visibility calculations.
  c. Irradiated fraction. Note that the irradiated fraction is the complement of the fraction of heat within the fire plume. Conservative values in terms of irradiated fractions will result in less conservative estimates in terms of the convective fraction of the HRR.

Targets

Generally, the technical specification of targets requires location, damage criteria, and thermophysical properties.

Location refers to the target position relative to the fire inside the compartment. The general location of a target with respect to the fire should be known. Targets may be exposed to distinct fire-generated conditions or fire-induced flows within a compartment, depending on its location (e.g., target subjected to plume temperatures, hot gas layer temperatures, etc.).

The damage criteria refer primarily to the characterization of the failure processes of each element interest (e.g., thermal damage, smoke, etc.) and the damage threshold or criteria (e.g., a failure temperature, etc.). In lieu of characterizing each individual target element, the analyst may select a single set of target characteristics to represent all elements of the target set. In this case, the selected characteristics should be based on the target element most vulnerable to failure given a particular failure mechanism. In general, the damage criteria for scenarios involving cable damage is expressed in terms of damage temperature or incident heat flux.

Finally, the models within the scope of this guide require specification of the thermophysical properties (density (kg/m^3), specific heat (kg/kJ-K), and thermal conductivity (kW/m-K)) of the target for the analysis. The estimated time for the gas temperature surrounding the target to reach a specific limit may not be the same as the time it takes the target to reach the same limit. Heat conduction to the inside of the target may delay the temperature rise at the surface during the heating process.

Intervening Combustibles

In most cases, commercial nuclear plant fire scenarios do not require modeling of burning targets; it is enough to determine when the target is affected (i.e., damaged or ignited) by fire. This is clearly not the case with intervening combustibles, whose flammability characteristics need to be incorporated into the model so that the fire progression is considered. Thus, the necessary information for describing intervening combustibles should describe not only the relative proximities to the fire and the targets, but also the relevant thermophysical and flammability properties.

It is likely that fire propagation through cable trays will be an important element in a number of fire scenarios in NPP applications. At the same time, representing intervening combustibles in fire models will present technical challenges that the analyst should also consider, including (1) obtaining the necessary geometric and flammability information for representing the intervening combustible and (2) the ability of the computer tools to model the fire phenomena (e.g., fire propagation, among others). It should be noted that, due to these challenges, industry methodologies for applications (e.g., Fire PRAs) include a number of "special models" to predict fire-generated conditions that are currently outside the capabilities of the fire models within the scope of this guidance.

Room Geometry and/or Obstructions: Single Compartments

Compartment geometry refers to the physical layout of the scenario. Length, width, and height define the size of each compartment. The size of a compartment is an important factor in the volume used to solve the fundamental conservation equations. In terms of size, FDT^s, FIVE, MAGIC, and CFAST have simialr input requirements: only the length, width, and height are required. While FDS requires the same length, width, and height information, the structure of the input is significantly different from the other models, as the different obstructions that make up the room geometry are individually specified in the computational domain.

Compartment Boundary Materials

Boundary (i.e., wall) materials are characterized by thermophysical properties, including the density, specific heat, and thermal conductivity of the material. In the majority of commercial nuclear power plant applications, the wall material is concrete; other materials may include steel, gypsum board, etc. Properties for these materials are often available in "drop down" in the fire models or in fire protection engineering handbooks.

Natural Ventilation: Vertical Openings

The concept of vertical openings specifically refers to doors and/or windows. In some cases, a selected compartment will have more vertical openings than the number that can be specified in a specific zone model; for example, the MQH model for calculating room temperature available in FDT^s and FIVE-Rev1 accepts only one opening. The most important consideration in addressing the issue of vertical openings is to conserve the ventilation factor. If the number of vertical openings needs to be reduced in order to describe the scenario in a specific model, a weighted average for the vent factor needs to be estimated. The ventilation factor is defined as the product of the area of an opening times the square root of the height of the opening $\left(A_o\sqrt{H_o}\right)$ (Karlsson et al., 2000; Drysdale, 1996). The following steps can be followed for combining vertical openings:

1. Add the areas of the selected doors.
2. Divide the sum of the multiplication of the area and height of each door by the number calculated in step 1.

Mathematically, the process is summarized as:

$$A_o = \sum_{i=1}^{n} A_i \text{ , and } H_o = \frac{\sum_{i=1}^{n} A_i \cdot h_i}{A_o}$$

where A_i and h_i are the area and height of door i, respectively, and n is the total number of doors that need to be combined. A_o and H_o will be the effective area and height of the combined opening. To estimate the width of the combined opening, simply divide A_o by H_o.

Natural Ventilation: Leakage Paths

Many compartments in commercial NPPs have normally closed doors. However, they are not perfectly sealed. Consequently, the resulting pressure and the rate of pressure rise are often kept very small by gas leaks through openings in the walls and cracks around doors, referred to as “leakage paths.” Leakage paths must be specified in compartments with closed doors and windows during the fire event. By contrast, compartments with at least one open door or window can maintain pressure close to ambient during the fire event. Leakage paths therefore do not need to be specified, since the leakage opening area is negligible when compared with the opening areas of doors and windows.

Natural Ventilation: Horizontal Openings

Addressing horizontal openings is easier than addressing vertical openings because the pressure difference between the inside and outside of the enclosure is constant at the height of the openings; thus, areas of horizontal openings can simply be added. Any zone model should provide similar answers with single or multiple horizontal openings, as long as the total opening area is the same.

Mechanical Ventilation

Mechanical ventilation refers to any air injected into or extracted from a fire compartment by mechanical means. This has a number of practical applications, including, for example, extracting smoke from the hot gas layer (e.g., a smoke purge system). The ventilation rate and the vent position are the two most important mechanical ventilation parameters. These “mechanically” induced flows have the potential to alter the fire-induced flows described earlier in this section.

3.2.3 Modeling Strategy

Two strategies are available: (1) a first-order approximation using hand calculations for determining the room temperature as an indicator of the gas temperature surrounding the target, or (2) conducting a detailed heat transfer analysis for determining the target temperature.

The first strategy consists of determining the overall room temperature using a hand calculation (e.g., the MQH room temperature model) (McCaffrey et al., 1981). Such a calculation will indicate whether the target may be subjected to damaging temperatures and the time at which such temperatures may be observed. It should be noted that the room needs to be represented as a rectangular parallelepiped, where the area of all the surfaces in the room must be conserved.

The second strategy is best addressed with a model capable of capturing more than one room in a computational domain. A raceway outside the fire plume may be exposed to hot gas layer conditions if the smoke accumulating in the upper part of the room (i.e., the hot gas layer) eventually reaches the location of the raceway. Consequently, targets outside the fire plume are, during the course of the fire event, initially exposed to “lower layer” (i.e., below the hot gas layer) conditions; as the smoke continues to accumulate, the target is immersed in hot gas layer conditions. As heat transfer conditions will be different for each case, a model with the capability of tracking the relevant/applicable heat transfer interaction and calculations as a function of time, such as a zone model, should be selected to handle this scenario at the desired level of resolution.

Recall that the contribution of intervening combustibles needs to be considered in the analysis. Consider, for example, a panel fire that ignites raceways in an overhead stack. The fire involving the combination of the panel and first and the raceway stack now continues to heat up the room.

3.2.4 Recommended Modeling Tools

Engineering Calculations

Select the appropriate hot gas layer (or room temperature) model and then collect the required inputs, including room size, opening sizes, boundary material properties, and heat release rate. For screening purposes, the use of engineering calculations is recommended as long as the contribution of the first item ignited and intervening combustibles are considered. As mentioned earlier, this approach will provide a first-order approximation of the room temperature in which the target may be immersed.

Zone Models

Zone models provide a good alternative for modeling this scenario, as they provide the incident heat flux profile, the surface temperature, and the internal temperature of the target in one simulation. Set up the necessary input file with the required inputs, including room size, opening sizes, boundary material properties, heat release rate, and a target and fire location so that the cable’s surface temperature can be tracked.

CFD Model

The use of field models in this scenario is only recommended for complex geometries capable of affecting the location of the hot gas layer and the incident heat flux to the target. For instance, obstructions between the ignition source and the target will affect the heat balance at the surface of the target. Zone models may have limited capabilities for handling obstructions. The CFD model will require inputs similar to the ones collected for the zone models; however, the compartment geometry will need to be specified in detail.

3.2.5 Detailed Examples

Readers are referred to the following appendices for detailed examples of the generic scenario described in this section:

- Appendix C, which describes the analysis of a relatively large oil fire in a pump room, affecting a raceway in the room.
- Appendix E, which describes the analysis of a transient fire in a cable spreading room.

3.3 Scenario 3: Targets Located in Adjacent Rooms

This scenario consists of a target electrical cable in a raceway in a room adjacent to the room of fire origin. An opening in the wall (i.e., an open door or any other opening connecting the two rooms) allows combustion products to enter the adjacent room, as depicted in Figure 3-5.

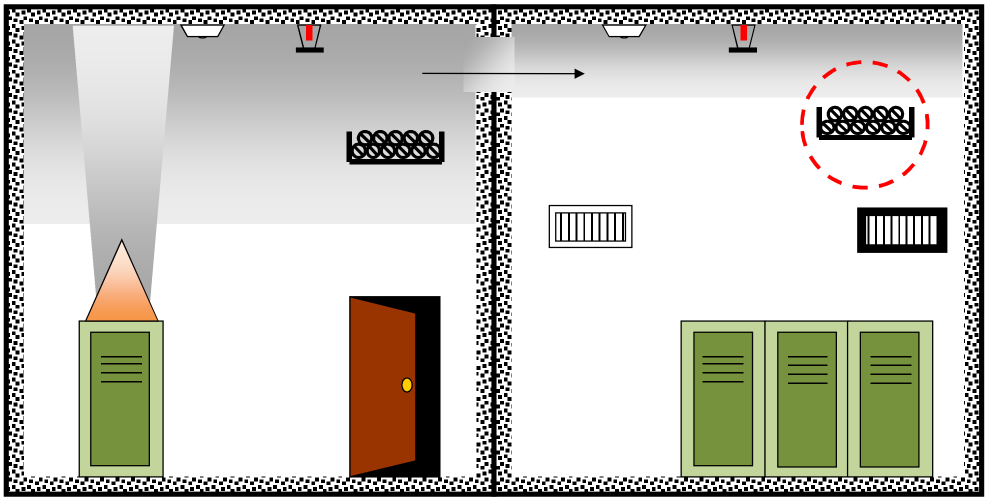

Figure 3-5. Pictorial representation of scenario 3

3.3.1 General Objective

The objective of this scenario is to calculate the time to damage for an electrical cable in a raceway in the hot gas layer in a room adjacent to the room of fire origin.

3.3.2 Fire Scenario Elements

Ignition Source (i.e., the fire)

The following elements associated with the ignition source are relevant to this scenario:

- Identify the fuel and assess the peak heat release rate value. For example, industry documents such as NUREG/CR-6850 would provide recommended heat release rate values for Fire PRA applications.
- Decide whether the fire will be modeled with a steady intensity or with an intensity varying as a function of time. It should be noted that the heat release rate should be represented as a function of time for scenarios consisting of determining "timing" results (e.g., time to target damage).
- Specify the fire location:
    a. Elevation: The fire elevation refers to the elevation of the base of the fire, measured from the floor. It is a factor in two situations: (1) in scenarios involving targets in the fire plume, where the relative distance between the fire and the target strongly influences the resulting plume temperature, and/or (2) in scenarios where the position of the hot gas layer is relevant, as the fire elevation may influence the air entrainment into the plume, and, consequently, the position of the layer.

b. Fires located along a wall or in a corner. In scenarios where the fire is located along a wall and in the corner, the plume is expected to entrain less "fresh" air, resulting in higher plume temperatures.

- Assess the footprint area of the fire (optional—depends on model selection):

  a. Circular (e.g., pool fires specified by the diameter).

  b. Rectangular (e.g., bounded pool fires, electrical cabinets specified by length and width).

- Provide additional heat release rate characteristics:

  a. Total (or initial) fuel mass

  b. Soot yield: The soot yield is an important factor in radiative heat transfer (e.g., targets immersed in the hot gas layer) and visibility calculations.

  c. Irradiated fraction. Note that the irradiated fraction is the complement of the fraction of heat within the fire plume. Conservative values in terms of irradiated fractions will result in less conservative estimates in terms of the convective fraction of the HRR.

Targets

Generally, the technical specification of targets requires location, damage criteria, and thermophysical properties.

Location refers to the target position relative to the fire inside the compartment. The general location of a target with respect to the fire should be known. Targets may be exposed to distinct fire-generated conditions or fire-induced flows within a compartment, depending on their location (e.g., target subjected to plume temperatures, hot gas layer temperatures, etc.).

The damage criteria refer primarily to the characterization of the failure processes of each element interest (e.g., thermal damage, smoke, etc.) and the damage threshold or criteria (e.g., temperature failure, etc.). In lieu of characterizing each individual target element, the analyst may select a single set of target characteristics to represent all elements of the target set. In this case, the selected characteristics should be based on the target element most vulnerable to failure given a particular failure mechanism. In general, the damage criteria for scenarios involving cable damage is expressed in terms of damage temperature or incident heat flux.

Finally, the models within the scope of this guide (FDT^s, FIVE-Rev1, CFAST, MAGIC, and FDS) require specification of the thermophysical properties (e.g., density (kg/m^3), specific heat (kg/kJ-K), and thermal conductivity (kW/m-K)) of the target for the analysis. The estimated time for the gas temperature surrounding the target to reach a specific limit may not be the same as the time it takes the target to reach the same limit. Heat conduction to the inside of the target may delay the temperature rise at the surface during the heating process.

Intervening Combustibles

In most cases, commercial nuclear plant fire scenarios do not require modeling of burning targets; it is enough to determine when the target is affected (i.e., damaged or ignited) by fire. This is clearly not the case with intervening combustibles, whose flammability characteristics need to be incorporated into the model so that the fire progression is considered. Thus, the necessary information for describing intervening combustibles should describe not only the relative proximities to the fire and the targets, but also the relevant thermophysical and flammability properties.

It is likely that fire propagation through cable trays will be an important element in a number of fire scenarios in NPP applications. At the same time, representing intervening combustibles in fire models will present technical challenges that the analyst should also consider, including (1) obtaining the necessary geometric and flammability information for representing the intervening combustible and (2) the ability of the computer tools to model the fire phenomena (e.g., fire propagation), among others. It should be noted that, due to these challenges, industry methodologies for applications such as Fire PRAs include a number of “special models” to predict fire-generated conditions that are currently outside the capabilities of the fire models within the scope of this guidance.

Recall that the contribution of intervening combustibles needs to be considered in the analysis. Consider, for example, a panel fire that ignites raceways in an overhead stack. The fire involving the combination of the panel and first tray in the raceway stack now continues to heat up the room.

Compartment Boundary Materials

Boundary (i.e., wall) materials are characterized by thermophysical properties (density (kg/m^3), specific heat (kg/kJ-K), and thermal conductivity (kW/m-K)). In the majority of commercial nuclear power plant applications, the wall material is concrete; other materials may include steel, gypsum board, etc. Properties for these materials are often available in “drop down” in the fire models, or in fire protection engineering handbooks.

Multiple Compartments in Horizontal Configurations

Multi-compartment scenarios refer to those where more than one enclosure is relevant in the analysis. These scenarios often involve determination of smoke migration routes or evaluation of fire conditions where the ignition source and the target are in different compartment. The particular case of a horizontal configuration refers to adjacent compartments on the same level, connected by open doors, windows, or other openings (e.g., a corridor connecting one or more compartments). Each compartment should be modeled following the guidance provided earlier for single compartment scenarios.

Multiple Compartments in Vertical Configurations

Vertical configurations refer to adjacent compartments on different levels that, for the purposes of this study, are connected by horizontal openings: for instance, a partial level between two floors, such as a mezzanine, will result in a horizontal opening between the two levels. The size of this opening needs to be accurately characterized so that the smoke migration process can be appropriately captured in the analysis. Each compartment should be modeled following the guidance provided earlier for single compartment scenarios.

Natural Ventilation: Vertical Openings

The concept of vertical openings specifically refers to doors and/or windows. In some cases, a selected compartment will have more vertical openings than the number that can be specified in a specific zone model: for example, the MQH model for calculating room temperature available in FDT[s] and FIVE-Rev1 would accept only one opening. The most important consideration in addressing the issue of vertical openings is to conserve the ventilation factor. If the number of vertical openings needs to be reduced in order to describe the scenario in a specific model, a weighted average for the vent factor needs to be estimated. The ventilation factor is defined as the product of the area of an opening times the square root of the height of the opening $\left(A_o\sqrt{H_o}\right)$(Karlsson et al., 2000; Drysdale, 1996). The following steps can be followed for combining vertical openings:

1. Add the areas of the selected doors.
2. Divide the sum of the multiplication of the area and height of each door by the number calculated in step 1.

Mathematically, the process is summarized as:

$$A_o = \sum_{i=1}^{n} A_i \text{ , and } H_o = \frac{\sum_{i=1}^{n} A_i \cdot h_i}{A_o}$$

where A_i and h_i are the area and height of door i, respectively, and n is the total number of doors that need to be combined. A_o and H_o will be the effective area and height of the combined opening. To estimate the width of the combined opening, simply divide A_o by H_o.

Natural Ventilation: Leakage Paths

Many compartments in commercial NPPs have normally closed doors. At the same time, these compartments are not sealed. Consequently, the resulting pressure and the rate of pressure rise are often kept very small by gas leaks through openings in the walls and cracks around doors, known as "leakage paths." Leakage paths must be specified in compartments with closed doors and windows during the fire event. By contrast, compartments with at least one open door or window can maintain pressure close to ambient during the fire event; thus, leakage paths do not need to be specified, since the leakage opening area is negligible when compared with the opening areas of doors and windows.

Natural Ventilation: Horizontal Openings

Addressing horizontal openings is relatively easier than addressing vertical openings because the pressure difference between the inside and outside of the enclosure is constant at the height of the openings, so areas of horizontal openings can simply be added. Any zone model should provide similar answers with single or multiple horizontal openings, as long as the total opening area is the same.

Mechanical Ventilation

Mechanical ventilation refers to any air injected into or extracted from a fire compartment by mechanical means. This has a number of practical applications, including, for example, extracting smoke from the hot gas layer. The ventilation rate and the vent position are the two most important mechanical ventilation parameters. These "mechanically" induced flows have the potential to alter the fire-induced flows described earlier in this section. Mechanical ventilation often consists of a supply and an exhaust system.

3.3.3 Modeling Strategy

The recommended strategy for determining the temperature of targets located in a room adjacent to the room of fire origin consists of four basic steps:

1. Determine the following characteristics for the hot gas layer in the room of fire origin and the adjacent compartment:
    a. Temperature as a function of time
    b. Depth as a function of time
2. Determine the incident heat flux surrounding the target cable.
3. Determine the surface and internal temperature of the target.
4. Compare the surface or internal temperature of the target with its damage temperature.

3.3.4 Recommended Modeling Tools

Engineering Calculations

Hand calculations are not recommended for this calculation, as a model capable of tracking fire conditions in adjacent rooms is necessary. Zone and field models will provide this capability.

Zone Models

The zone model is an appropriate tool for addressing this scenario. Zone models would provide an efficient tool for scenarios involving relatively simple geometries (i.e., geometries and openings that can be easily represented in rectangular parallelepipeds without compromising the technical elements in the analysis). Consequently, the room geometry should be represented as accurately as possible. One of the primary outputs of zone models is the height of the hot gas layer versus time in each of the rooms specified in the computational domain. Zone models are also capable of determining target temperature (as opposed to the temperature of the gases surrounding the target), given the boundary conditions generated by the fire and the thermophysical properties of the target.

CFD Model

A CFD model would be particularly appropriate for addressing targets located in adjacent rooms in scenarios with complex geometries (i.e., geometries that can't be easily represented as rectangular parallelepipeds). Field models will be able to describe the geometry of the compartment in detail, including the opening(s) providing smoke migration paths to the adjacent room.

3.3.5 Detailed Examples

Readers are referred to Appendix G, which describes the analysis of migrating smoke from a transient fire throughout a complex of rooms connected by a corridor, for detailed examples of the generic scenario described in this section.

3.4 Scenario 4: Targets in Rooms with Complex Geometries

This scenario was selected to provide guidance for conducting fire modeling calculations in a room with a complex geometry. In this particular example, the complex geometry is represented by an irregular ceiling height. The target in the scenario is a cable tray away from the ignition sources that may eventually be immersed in the hot gas layer. Figure 3-6 provides a pictorial representation for this scenario.

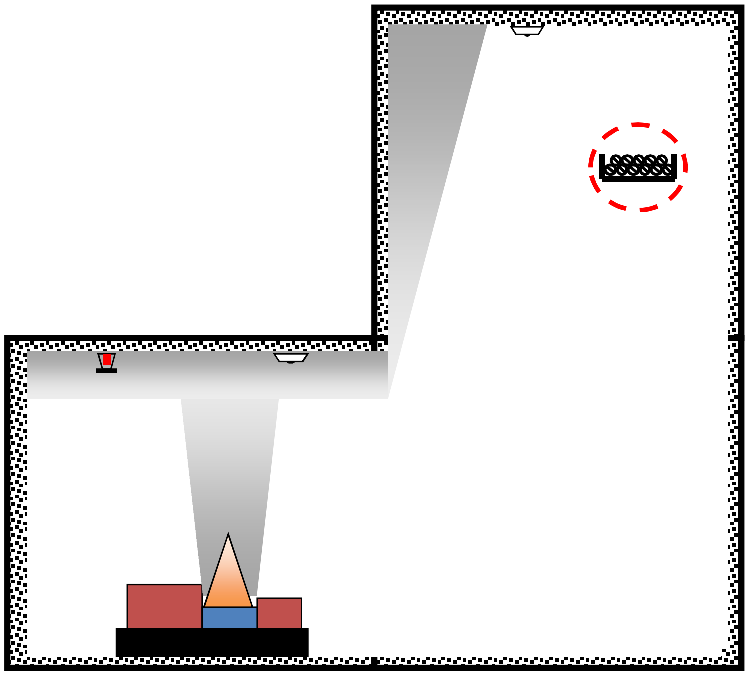

Figure 3-6. Pictorial representation of scenario 4

3.4.1 General Objective

The objective of this scenario is to calculate the time to damage for an electrical cable in a raceway in the hot gas layer in a room with a complex geometry.

3.4.2 Fire Scenario Elements

Ignition Source (i.e., the fire)

The following elements are associated with the ignition source, and are relevant to this scenario:

- Identify the fuel and assess the peak heat release rate value. For example, industry documents such as NUREG/CR-6850 would provide recommended heat release rate values for Fire PRA applications.
- Decide whether the fire will be modeled with a steady intensity or with an intensity varying as a function of time. It should be noted that the heat release rate should be represented as a function of time for scenarios consisting of determining “timing” results (e.g., time to target damage).

- Specify the fire location:
  a. Elevation: The fire elevation refers to the elevation of the base of the fire measured from the floor. The fire elevation is a factor in two situations: (1) in scenarios involving targets in the fire plume where the relative distance between the fire and the target strongly influences the resulting plume temperature, and/or (2) in scenarios where the position of the hot gas layer is relevant, as the fire elevation may influence the air entrainment into the plume, and, consequently, the position of the layer.
  b. Fires located along a wall or in a corner. In scenarios where the fire is located along a wall and in the corner, the plume is expected to entrain less “fresh” air, resulting in higher plume temperatures.
- Assess the footprint area of the fire (optional-depends on model selection):
  a. Circular (e.g., pool fires specified by the diameter).
  b. Rectangular (e.g., bounded pool fires, electrical cabinets specified by length and width).
- Provide additional heat release rate characteristics:
  a. Total (or initial) fuel mass.
  b. Yields of combustion products: Yields of combustion products describe the stoichiometric yield that a particular fuel produces during a combustion reaction. One of the most relevant ones in nuclear power plant fire scenarios is the soot yield, an important factor in radiative heat transfer (e.g., targets immersed in the hot gas layer) and visibility calculations.
  c. Irradiated fraction. Note that the irradiated fraction is the complement of the fraction of heat within the fire plume. Conservative values in terms of irradiated fractions will result in less conservative estimates in terms of the convective fraction of the HRR.

Targets

Generally, the technical specification of targets requires location, damage criteria, and thermophysical properties.

Location refers to the target position relative to the fire inside the compartment. The general location of a target with respect to the fire should be known. Targets may be exposed to distinct fire-generated conditions or fire-induced flows within a compartment, depending on their location (e.g., target subjected to plume temperatures, hot gas layer temperatures, etc.).

The damage criteria refer primarily to the characterization of the failure processes of each element interest (e.g., thermal damage, smoke, etc.) and the damage threshold or criteria (e.g., a failure temperature, etc.). In lieu of characterizing each individual target element, the analyst may select a single set of target characteristics to represent all elements of the target set. In this case, the selected characteristics should be based on the target element most vulnerable to failure given a particular failure mechanism. In general, the damage criteria for scenarios involving cable damage is expressed in terms of damage temperature or incident heat flux.

Finally, the models within the scope of this guide (e.g.,FDT^s, FIVE-Rev1, CFAST, MAGIC, and FDS) require specification of the thermophysical properties (density (kg/m^3), specific heat (kg/kJ-K), and thermal conductivity (kW/m-K)) of the target for the analysis. The estimated time for the gas temperature surrounding the target to reach a specific limit may not be the same as the time it takes the target to reach the same limit. Heat conduction to the inside of the target may delay the temperature rise at the surface during the heating process.

Room Geometry and/or Obstructions: Single Compartments

Compartment geometry refers to the physical layout of the scenario. Length, width, and height define the size of each compartment. The size of a compartment is an important factor in the volume used to solve the fundamental conservation equations. In terms of size, FDT^s, FIVE, MAGIC, and CFAST have similar input requirements: only the length, width, and height are required. While FDS requires the same length, width, and height information, the structure of the input is significantly different from the other models, as the different obstructions that make up the room geometry are individually specified in the computational domain.

Compartment Boundary Materials

Boundary (i.e., wall) materials are characterized by thermophysical properties (e.g., the density, specific heat, and thermal conductivity). In the majority of commercial nuclear power plant applications, the wall material is concrete; other materials may include steel, gypsum board, etc. Properties for these materials are often available in “drop down” in the fire models, or in fire protection engineering handbooks.

Compartments with Complex Geometries

In general, zone models simulate fires in compartments with rectangular floor areas and flat ceilings. If the selected compartment is not a rectangular parallelepiped, it needs to be represented as such. In general, to most accurately model the enclosure filling (which is based on the volume of the compartment) and the heat transfer (which is based on the enclosure surface area), the overall volume and height (and, thus, surface area) of the enclosure need to remain the same. To accomplish this, both the floor surface area and the length of the compartment perimeter must be unchanged for both the actual and modeled compartments. In mathematical terms, this means that $WD=A$ and $2W+2D=P$, where W is the effective width of the compartment, D is the effective depth, A is the floor surface area, and P is the perimeter. This provides two equations with two unknowns. Determining values for W and D gives the length and width of the equivalently sized rectangular parallelepiped.

Natural Ventilation: Vertical Openings

The concept of vertical openings specifically refers to doors and/or windows. In some cases, a selected compartment will have more vertical openings than the number that can be specified in a specific zone model; for example, the MQH model for calculating room temperature available in FDT^s and FIVE-Rev1 would accept only one opening. The most important consideration in addressing the issue of vertical openings is to conserve the ventilation factor. If the number of vertical openings needs to be reduced in order to describe the scenario in a specific model, a weighted average for the vent factor needs to be estimated. The ventilation factor is defined as the product of the area of an opening times the square root of the height of the opening $\left(A_o\sqrt{H_o}\right)$ (Karlsson et al., 2000; Drysdale, 1996). The following steps can be followed for combining vertical openings:

1. Add the areas of the selected doors.
2. Divide the sum of the multiplication of the area and height of each door by the number calculated in step 1.

Mathematically, the process is summarized as:

$$A_o = \sum_{i=1}^{n} A_i \text{ , and } H_o = \frac{\sum_{i=1}^{n} A_i \cdot h_i}{A_o}$$

where A_i and h_i are the area and height of door i, respectively, and n is the total number of doors that need to be combined. A_o and H_o will be the effective area and height of the combined opening. To estimate the width of the combined opening, simply divide A_o by H_o.

Natural Ventilation: Leakage Paths

Many compartments in commercial NPPs have closed doors, though they are not sealed; consequently, the resulting pressure and the rate of pressure rise are often kept very small by gas leaks through openings in the walls and cracks around doors, known as “leakage paths.” Leakage paths must be specified in compartments with closed doors and windows during the fire event. By contrast, compartments with at least one open door or window can maintain pressure close to ambient during the fire event. Thus, leakage paths do not need to be specified, since the leakage opening area is negligible when compared with the opening areas caused by doors and windows.

Natural Ventilation: Horizontal Openings

Addressing horizontal openings is easier than addressing vertical openings because the pressure difference between the inside and outside of the enclosure is constant at the height of the openings, so areas of horizontal openings can simply be added. Any zone model should provide similar answers with single or multiple horizontal openings, as long as the total opening area is the same.

Mechanical Ventilation

Mechanical ventilation refers to any air injected into or extracted from a fire compartment by mechanical means. This has a number of practical applications, including, for example, extracting smoke from the hot gas layer. The ventilation rate and the vent position are the two most important mechanical ventilation parameters. These “mechanically” induced flows have the potential to alter the fire-induced flows described earlier in this section. Mechanical ventilation often consists of a supply and an exhaust system.

3.4.3 Modeling Strategy

Two strategies are available: (1) a first-order approximation using hand calculations for determining the room temperature as an indicator of the gas temperature surrounding the target, or (2) conducting a detailed heat transfer analysis for determining the target temperature.

The first strategy consists of determining the overall room temperature with a hand calculation (e.g., the MQH room temperature model), which would indicate whether the target may be subjected to damaging temperatures and the time at which such temperatures may be observed.

The second alternative is best addressed with a model capable of capturing more than one room in a computational domain. A raceway outside the fire plume may be exposed to hot gas layer conditions if the smoke accumulating in the upper part of the room (i.e., the hot gas layer) eventually reaches the location of the raceway. Consequently, targets outside the fire plume are, over the course of the fire event, exposed to “lower layer” (i.e., below the hot gas layer) conditions. As the smoke continues to accumulate, they are immersed in hot gas layer conditions. Clearly, heat transfer conditions will be different for each case; a model with the capability of tracking the relevant/applicable heat transfer interaction and calculations as a function of time, such as a zone model, should be selected to handle this scenario to the desired level of resolution.

3.4.4 Recommended Modeling Tools

Engineering Calculations

Select the appropriate hot gas layer (or room temperature) model and then collect the required inputs, including room size, opening sizes, boundary material properties, and heat release rate. For screening purposes, the use of engineering calculations is recommended, as long as the contribution of the first item ignited and intervening combustibles are considered. As mentioned earlier, this approach will provide a first-order approximation of the room temperature in which the target may be immersed.

Zone Models

Zone models provide a good alternative for modeling this scenario, as they provide the incident heat flux profile, the surface temperature, and the internal temperature of the target in one simulation. Set up the necessary input file with the required inputs, including room size, opening sizes, boundary material properties, heat release rate, and a target and fire location so that surface temperature of the cable can be tracked.

CFD Model

The use of field models in this scenario is only recommended for complex geometries capable of affecting the location of the hot gas layer and the incident heat flux to the target. For example, obstructions between the ignition source and the target will affect the heat balance at the surface of the target. Zone models may have limited capabilities in handling obstructions. The CFD model will require inputs similar to the ones collected for the zone models; however, the compartment geometry will need to be specified in detail.

3.4.5 Detailed Examples

Readers are referred to the following appendices for detailed examples of the generic scenario described in this section:

- Appendix D, which consists of a switchgear fire in a room with a complex geometry.
- Appendix H, which consists of a fire inside the containment annulus.

3.5 Scenario 5: Main Control Room Abandonment

This scenario consists of an electrical cabinet fire within the main control board, which may force operators out of the control room, and is depicted in Figure 3-7. Notice the presence of a suspended ceiling in the control room.

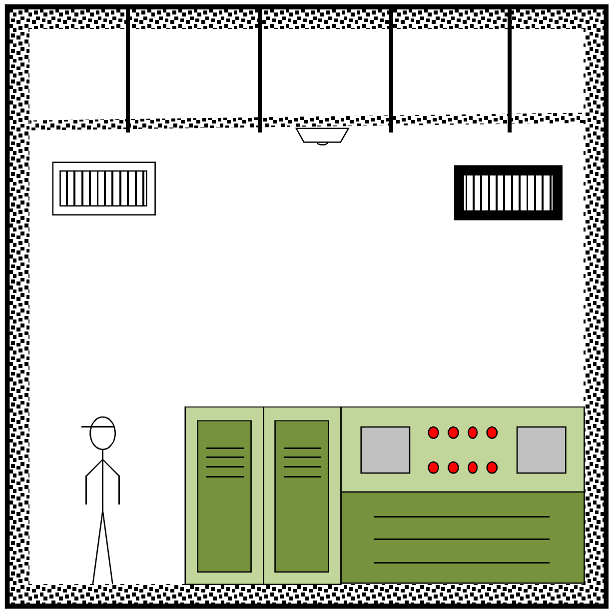

Figure 3-7. Pictorial representation of scenario 5

3.5.1 General Objective

Determine when control room operators will need to abandon the control room due to fire-generated conditions inside the room.

3.5.2 Fire Scenario Elements

Ignition Source (i.e., the fire)

The following elements are associated with the ignition source, and are relevant to this scenario:

- Identify the fuel and assess the peak heat release rate value. For example, industry documents such as NUREG/CR-6850 would provide recommended heat release rate values for Fire PRA applications.
- Decide with the fire will be modeled with a steady intensity or with an intensity varying as a function of time. It should be noted that the heat release rate should be represented as a function of time for scenarios consisting of determining "timing" results (e.g., time to target damage).
- Specify the fire location:
    a. Elevation: The fire elevation refers to the elevation of the base of the fire, measured from the floor. The fire elevation is a factor in two situations: (1) in scenarios involving targets in the fire plume, where the relative distance between the fire and the target strongly influences the resulting plume temperature, and/or (2) in

scenarios where the position of the hot gas layer is relevant, as the fire elevation may influence the air entrainment into the plume, and, consequently, the position of the layer.

   b. Fires located along a wall or in a corner. In scenarios where the fire is located along a wall and in the corner, the plume is expected to entrain less "fresh" air, resulting in higher plume temperatures.

- Assess the footprint area of the fire (optional—depends on model selection):
   a. Circular (e.g., pool fires specified by the diameter).
   b. Rectangular (e.g., bounded pool fires, electrical cabinets specified by length and width).
- Provide additional heat release rate characteristics:
   a. Total (or initial) fuel mass.
   b. Yields of combustion products: Yields of combustion products describe the stoichiometric yield that a particular fuel produces during a combustion reaction. Yields are the relevant inputs associated with toxicity and visibility calculations. In control room applications, one of the most relevant ones in nuclear power plant fire scenarios is the soot yield, an important factor in radiative heat transfer (e.g., targets immersed in the hot gas layer) and visibility calculations.
   c. Irradiated fraction. Note that the irradiated fraction is the complement of the fraction of heat within the fire plume. Conservative values in terms of irradiated fractions will result in less conservative estimates in terms of the convective fraction of the HRR.

Targets

In this particular scenario, the target consists of a control room operator, so a criteria for control room abandonment needs to be established; for instance, NUREG/CR-6850 recommends control room abandonment criteria due to fire-generated conditions for Fire PRA applications. These criteria may be expressed in terms of visibility, temperature, and toxicity levels that are untenable for the humans.

Room Geometry and/or Obstructions: Single Compartments

Compartment geometry refers to the physical layout of the scenario. Length, width, and height define the size of each compartment. The size of a compartment is an important factor in the volume used to solve the fundamental conservation equations. In terms of size, FDT^s, FIVE, MAGIC, and CFAST have similar input requirements; only the length, width, and height are required. While FDS requires the same length, width, and height information, the structure of the input is significantly different from the other models, as the different obstructions that make up the room geometry are individually specified in the computational domain. Most models ignore the effects of a suspended ceiling.

Compartment Boundary Materials

Boundary (i.e., wall) materials are characterized with thermophysical properties (density, specific heat, and thermal conductivity of the material). In the majority of commercial nuclear power plant applications, the wall material is concrete; other materials may include steel, gypsum board, etc. Properties for these materials are often available in "drop down" in the fire models, or in fire protection engineering handbooks.

Natural Ventilation: Vertical Openings

The concept of vertical openings specifically refers to doors and/or windows. In some cases, a selected compartment will have more vertical openings than the number that can be specified in a specific zone model: for example, the MQH model for calculating room temperature available in FDT[s] and FIVE-Rev1 would accept only one opening. The most important consideration in addressing the issue of vertical openings is to conserve the ventilation factor. If the number of vertical openings needs to be reduced in order to describe the scenario in a specific model, a weighted average for the vent factor needs to be estimated. The ventilation factor is defined as the product of the area of an opening times the square root of the height of the opening $\left(A_o\sqrt{H_o}\right)$ (Karlsson et al., 2000; Drysdale, 1996). The following steps can be followed for combining vertical openings:

1. Add the areas of the selected doors.
2. Divide the sum of the multiplication of the area and height of each door by the number calculated in step 1.

Mathematically, the process is summarized as:

$$A_o = \sum_{i=1}^{n} A_i \text{ , and } H_o = \frac{\sum_{i=1}^{n} A_i \cdot h_i}{A_o}$$

where A_i and h_i are the area and height of door i, respectively, and n is the total number of doors that need to be combined. A_o and H_o will be the effective area and height of the combined opening. To estimate the width of the combined opening, simply divide A_o by H_o.

Natural Ventilation: Leakage Paths

Many compartments in commercial NPPs have closed doors, though they are not sealed; consequently, the resulting pressure and the rate of pressure rise are often kept very small by gas leaks through openings in the walls and cracks around doors, known as “leakage paths.” Leakage paths must be specified in compartments with closed doors and windows during the fire event. By contrast, compartments with at least one open door or window can maintain pressure close to ambient during the fire event. Thus, leakage paths do not need to be specified, since the leakage opening area is negligible when compared with the opening areas of doors and windows.

Natural Ventilation: Horizontal Openings

Addressing horizontal openings is easier than addressing vertical openings because the pressure difference between the inside and outside of the enclosure is constant at the height of the openings, so areas of horizontal openings can simply be added. Any zone model should provide similar answers with single or multiple horizontal openings as long as the total opening area is the same.

Mechanical Ventilation

Mechanical ventilation refers to any air injected into or extracted from a fire compartment by mechanical means. This has a number of practical applications, including, for example, extracting smoke from the hot gas layer. The ventilation rate and the vent position are the two most important mechanical ventilation parameters. These “mechanically” induced flows have the potential to alter the fire-induced flows described earlier in this section. Mechanical ventilation often consists of a supply and an exhaust system.

3.5.3 Modeling Strategy

As mentioned in the previous sections, control room operators are considered “targets” in this scenario, so it is necessary to establish the fire conditions that would force operators out of the control room. This can be considered as the “abandonment criteria”; for example, visibility, temperature, heat flux, and toxicity are often the habitability indicators in these scenarios. Keeping regular track of these conditions may suggest the time at which the operator may need to abandon the control room. Once the criteria have been established, the fire-generated conditions in the room can be calculated so that the abandonment time can be determined.

3.5.4 Recommended Modeling Tools

Engineering Calculations

Engineering calculations are not recommended for conducting this analysis. Determining habitability and time to abandonment in a fire scenario often requires tracking numerous output variables simultaneously. Clearly, hand calculations do not provide this capability.

Zone Models

Unlike hand calculations, zone models are capable of simultaneously tracking a number of relevant output variables in this scenario. They are also a good alternative for analyzing this scenario, as long as the room geometry and ventilation conditions can be accurately represented.

CFD Model (FDS)

Field models are also a good alternative to address this scenario. In general, field models will have the added advantage of handling rooms with complex geometries or ventilation conditions.

3.5.5 Detailed Examples

Readers are referred to Appendix A, which describes the analysis of a fire in the main control room, for detailed examples of the generic scenario described in this section.

3.6 Scenario 6: Smoke Detection and Sprinkler Activation

This scenario consists of calculating smoke or heat detector (e.g., sprinkler) response in the room of the fire. In some scenarios, detection devices may be shielded from the combustion products by a ceiling obstruction. Failure of this detector to respond to the fire will delay the appropriate response of either the fire brigade or an automated suppression system. Such scenarios are depicted in Figure 3-8.

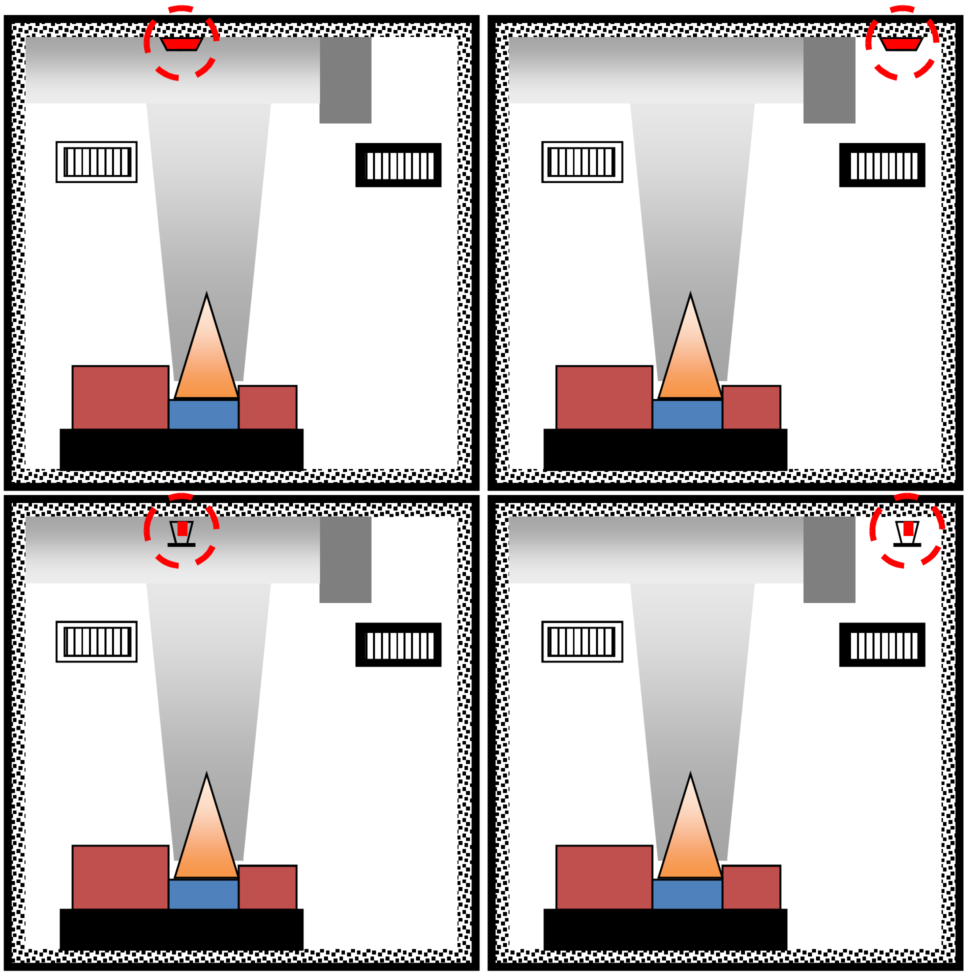

Figure 3-8. Pictorial representation of scenario 6

3.6.1 General Objective

Calculate the response time of a smoke or heat detector that may be obstructed by ceiling beams, ventilation ducts, etc.

3.6.2 Fire Scenario Elements

Ignition Source (i.e., the fire)

The following elements associated with the ignition source are relevant to this scenario:

- Identify the fuel and assess the peak heat release rate value. For example, industry documents such as NUREG/CR-6850 would provide recommended heat release rate values for Fire PRA applications.
- Decide whether the fire will be modeled with a steady intensity or with an intensity varying as a function of time. It should be noted that the heat release rate should be represented as a function of time for scenarios consisting in determining “timing” results (e.g., time to target damage).
- Specify the fire location:
    a. Elevation: The fire elevation refers to the elevation of the base of the fire measured from the floor. The fire elevation is a factor in two situations: (1) in scenarios involving targets in the fire plume where the relative distance between the fire and the target strongly influences the resulting plume temperature, and/or (2) in scenarios where the position of the hot gas layer is relevant, as the fire elevation may influence the air entrainment into the plume, and, consequently, the position of the layer.
    b. Fires located along a wall or in a corner. In scenarios where the fire is located along a wall and in the corner, the plume is expected to entrain less “fresh” air, resulting in higher plume temperatures.
- Assess the footprint area of the fire (optional—depends on model selection):
    a. Circular (e.g., pool fires specified by the diameter).
    b. Rectangular (e.g., bounded pool fires, electrical cabinets specified by length and width).
- Provide additional heat release rate characteristics:
    a. Total (or initial) fuel mass.
    b. Yields of combustion products: Yields of combustion products describe the stoichiometric yield which a particular fuel produces during a combustion reaction. One of the most relevant ones in nuclear power plant fire scenarios is the soot yield, an important factor in radiative heat transfer (e.g., targets immersed in the hot gas layer) and visibility calculations.
    c. Irradiated fraction. Note that the irradiated fraction is the complement of the fraction of heat within the fire plume. Conservative values in terms of irradiated fractions will result in less conservative estimates in terms of the convective fraction of the HRR.

Fire Detection Features

The inputs for heat detection are the location of the device with respect to the fire and the device’s response characteristics (activation temperature and the response time index (RTI)). Smoke detectors are often modeled with the same set of inputs as heat detectors, but assume low activation temperatures and low RTI values.

3.6.3 Modeling Strategy

For scenarios involving unobstructed smoke detector devices:

1. Determine the location of the detection device relative to the fire. Ideally, the detector will be immersed in fire plume or ceiling jet conditions.
2. Calculate the detection time using the appropriate model.

For scenarios involving obstructed smoke detector devices:

1. Determine the following characteristics of the hot gas layer using all the necessary inputs for a hot gas layer calculation, as described earlier in this chapter.
    a. Temperature as a function of time.
    b. Depth as a function of time. The smoke detector is expected to activate shortly after the hot gas layer reaches the bottom of the obstruction and spills into the location of the device.
2. Calculate the response time of the given smoke detector once the combustion products reach the detector.

The process is similar for heat detectors; the only difference is that the heat detector needs to be characterized with relevant parameters, such as activation temperatures and the RTI. In addition, the selected model should account for the heating process of thermally thin elements (i.e., the heat detector device).

3.6.4 Recommended Modeling Tools

Engineering Calculations

Hand calculations can be used to determine time to heat or smoke detection when the fire-induced flows are not obstructed before reaching the detection device. By contrast, engineering calculations are not recommended when fire-induced flows, such as fire plumes or ceiling jets, will be obstructed before reaching the detection device.

Zone Models

Zone Models can address the different scenario conditions presented in this section; for instance, CFAST and MAGIC have the capability of determining time to smoke or heat detection, assuming no obstructions. At the same time, they can calculate smoke accumulation so that the time for smoke detection activation can be estimated. This would provide a first order approximation, as zone models do not directly account for complex geometries, including obstructions. These models are not recommended for determining time to heat detection in obstructed geometries, since the velocity of the gases impacting the detector is not available in zone model calculations.

CFD Model

Field models are the best tool for estimating time to detection in complex geometries, including obstructions, as they can describe the compartment’s complex geometries and mechanical ventilation conditions in detail.

3.6.5 Detailed Examples

Readers are referred to Appendices B and D, which discuss the calculation of time to detection, for detailed examples of the generic scenario described in this section.

3.7 Scenario 7: Fire Impacting Structural Elements

This scenario consists of an electrical cabinet fire impacting exposed structural elements in the room, and is depicted in Figure 3-9.

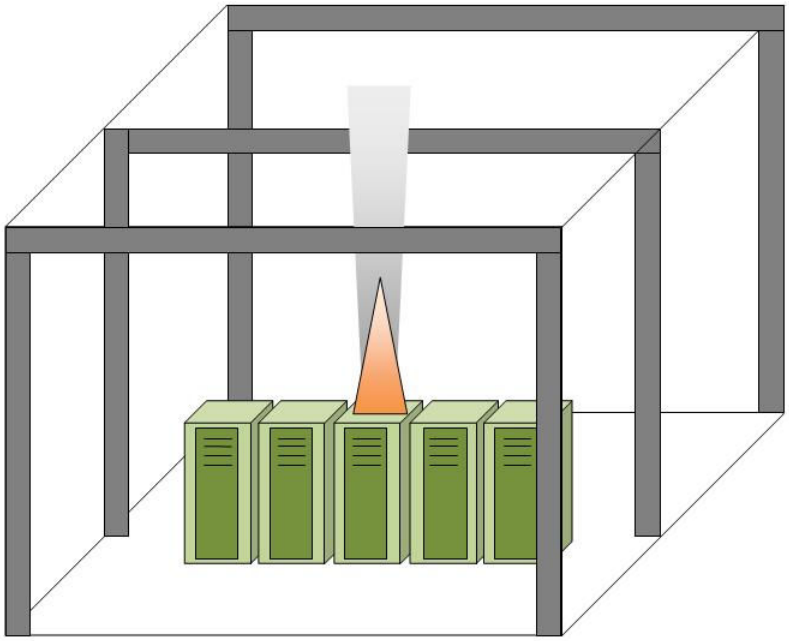

Figure 3-9. Pictorial representation of scenario 7

3.7.1 General Objective

Characterize the temperature of exposed structural elements subjected to a nearby electrical cabinet fire.

3.7.2 Fire Scenario Elements

Ignition Source (i.e., the fire)

The following elements associated with the ignition source are relevant to this scenario:

- Identify the fuel and assess the peak heat release rate value. For example, industry documents such as NUREG/CR-6850 would provide recommended heat release rate values for Fire PRA applications.
- Decide whether the fire will be modeled with a steady intensity or with an intensity varying as a function of time. It should be noted that the heat release rate should be represented as a function of time for scenarios consisting of determining “timing” results (e.g., time to target damage).
- Specify the fire location:
    a. Elevation: The fire elevation refers to the elevation of the base of the fire, measured from the floor. The fire elevation is a factor in two situations: (1) in scenarios

involving targets in the fire plume, where the relative distance between the fire and the target strongly influences the resulting plume temperature, and/or (2) in scenarios where the position of the hot gas layer is relevant, as the fire elevation may influence the air entrainment into the plume, and, consequently, the position of the layer.

b. Fires located along a wall or in a corner. In scenarios where the fire is located along a wall and in the corner, the plume is expected to entrain less "fresh" air, resulting in higher plume temperatures.

- Assess the footprint area of the fire (optional—depends on model selection):

  a. Circular (e.g., pool fires specified by the diameter).

  b. Rectangular (e.g., bounded pool fires, electrical cabinets specified by length and width).

- Provide additional heat release rate characteristics:

  a. Total (or initial) fuel mass.

  b. Soot Yield: The soot yield is an important factor in radiative heat transfer (e.g., targets immersed in the hot gas layer) and visibility calculations.

  c. Irradiated fraction. Note that the irradiated fraction is the complement of the fraction of heat within the fire plume. Conservative values in terms of irradiated fractions will result in less conservative estimates in terms of the convective fraction of the HRR.

Targets

Generally, the targets' technical specifications require location, damage criteria, and thermophysical properties.

Location refers to the target position relative to the fire inside the compartment. The general location of a target with respect to the fire should be known, as it may be exposed to distinct fire-generated conditions or fire-induced flows within a compartment (e.g., target subjected to plume temperatures, hot gas layer temperatures, etc.).

The damage criteria refer primarily to the characterization of the failure processes of each element of interest (e.g., thermal damage, smoke, etc.) and the damage threshold or criteria (e.g., a failure temperature, etc.). In lieu of characterizing each individual target element, the analyst may select a single set of target characteristics to represent all elements of the target set. In this case, the selected characteristics should be based on the target element most vulnerable to failure, given a particular failure mechanism. In general, the damage criteria for scenarios involving cable damage is expressed in terms of damage temperature or incident heat flux.

Finally, the models within the scope of this guide require specification of the thermophysical properties (density (kg/m^3), specific heat (kg/kJ-K), and thermal conductivity (kW/m-K)) of the target for the analysis. The estimated time for the gas temperature surrounding the target to reach a specific limit may not be the same as the time it takes the target to reach the same limit. Heat conduction to the inside of the target may delay the temperature rise at the surface during the heating process.

3.7.3 Modeling Strategy

The fire modeling tools within the scope of this guide should indicate whether the exposed structural element will reach damaging temperatures. However, this information is often not enough to determine whether the structural integrity of the compartment will be compromised by the exposing fire conditions. A full structural analysis may be necessary if such a determination is necessary.

Considering the limitations listed above, the following general guidance is provided:

1. Determine whether the structural element is directly above the fire, within the ceiling jet or the hot gas layer. The results of this determination will suggest which model or combination of models should be used.
2. Calculate the temperature of the structural element based on the fire conditions affecting it. This will require an initial estimate of the fire-generating conditions surrounding the structural element, and, subsequently, the temperature of the element itself.

3.7.4 Recommended Modeling Tools

Engineering Calculations

Provided that the fire conditions affecting the structural element are appropriately identified (e.g., fire plume, ceiling jet, flame radiation, hot gas layer), engineering calculations may be capable of determining whether the structural element will be exposed to damaging conditions. For example, plume temperature correlations can be used to determine the gas temperature surrounding an element inside the fire plume.

Zone Models (CFAST and MAGIC)

Zone models are an appropriate tool to address this scenario, as the input file can be developed to capture the relative location of the fire and the structural element. The structural element can be represented as a target, and the incident fire conditions can be tracked during the fire event; in addition, zone models are capable of performing conduction heat transfer calculations for the structural element, resulting in a prediction of the temperature of the element itself.

CFD Model (FDS)

Field models are the best tool for estimating temperature in structural elements in complex geometries, including obstructions, as they can describe the compartment’s complex geometries and mechanical ventilation conditions in detail.

3.7.5 Detailed Examples

Readers are referred to Appendix F, which describes the analysis of a lubricating oil fire’s effect on structural elements, for detailed examples of the generic scenario described in this section.

4
MODEL UNCERTAINTY

The fire models discussed in this Guide are classified as *deterministic* to distinguish them from *probabilistic* or *statistical* models. In essence, this means that each model takes as input a set of parameters that describe a specific fire scenario, and the model's algorithms then calculate the evolution of various quantities as a function of time. The calculated results are typically presented in terms of the peak values of the quantities of interest or the estimated time to target damage. In a sense, the model calculation is like a virtual experiment because the design of a model simulation often involves the same thought process as the design of an actual experiment. Likewise, the results of the calculation are expressed in terms similar to that of an experiment, including an estimate of the uncertainty of the results. Unlike an experiment, however, the uncertainty in a model calculation is caused by the following factors:

Model Error: Idealizations of physical phenomena lead to simplifying assumptions in the formulation of the model equations. In addition, the numerical solution of equations that have no analytical solution can lead to inexact results. Because of the complexity of the models, it is impractical to assess the model error by simply adding together the error of each of its components; rather, model error is estimated via the processes of *verification* and *validation*. The first seeks to quantify the error associated with the mathematical solution of the governing equations, typically through numerical analysis, while the second seeks to quantify the error associated with the simplifying physical assumptions, typically through comparison of model predictions and full-scale experiments.

Input Uncertainty: Input parameters are often chosen from statistical distributions or estimated from generic reference data. In either case, uncertainty is introduced into the resulting model prediction. The process of determining the extent to which the individual input parameters affect the results of the calculation is known as a *sensitivity analysis*.

In this chapter, the two sources of model uncertainty will be discussed, followed by a step-by-step process of evaluating the model uncertainty for a given predicted quantity.

4.1 Model Error

This section presents an approach for quantifying the model error with the results of the fire validation study documented in NUREG-1824. In that study, the predictions of five different fire models were assessed for thirteen different quantities using twenty-six full-scale fire experiments. The results of the study were presented in the form shown in Figure 4-1, which compares measured and predicted wall surface temperatures for the model FDS. The dashed diagonal lines indicate the experimental uncertainty. Roughly speaking, points within the dashed lines are said to be "within experimental uncertainty"; however, points outside of the lines indicate a certain degree of model error. To better quantify the error, it is assumed that the model error is normally distributed, with a different mean and standard deviation for each quantity and model. Table 4-1 displays these parameters for the five models and twelve of the thirteen quantities of interest; flame height is not listed because there was not sufficient data to develop statistics. Using these parameters, the "true" value of the predicted quantity, $M,$ is estimated as a normally distributed random variable with a mean of M/δ and a standard deviation of $\tilde{\sigma}_M(M/\delta)$. Details of the calculation methodology are shown in section 4.4.

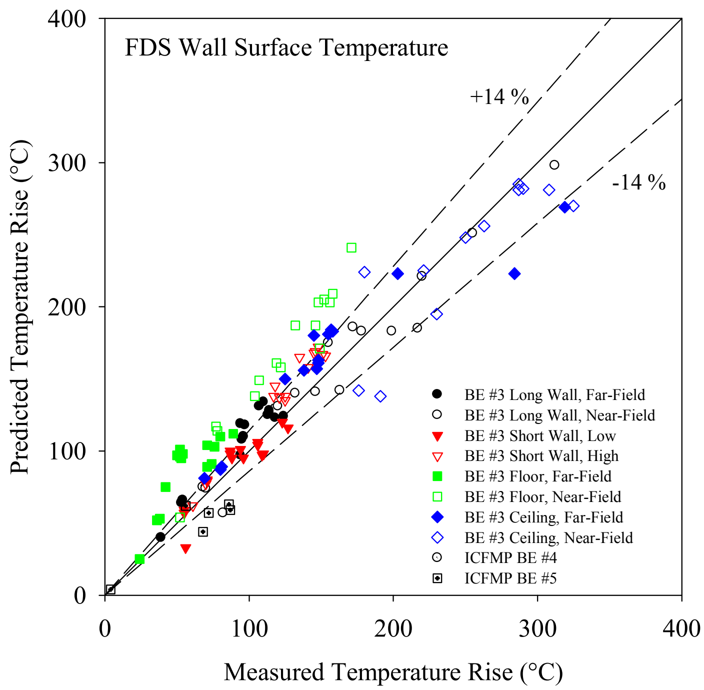

Figure 4-1. Sample plot from NUREG-1824.

The best way to explain the process is by way of example. Suppose that the model CFAST predicts that the HGL temperature rise due to a fire in a compartment is 330°C (ambient temperature is 20°C). Table 4-1 indicates that, on average, CFAST overpredicts the HGL temperature rise by a factor of 1.06. Figure 4-2 displays the distribution of the "true" value of the HGL Temperature, which has a mean of 20+330/1.06=331.3°C and a standard deviation of 0.12×330/1.06=37.4°C.

This estimate of the distribution of the true value only considers the effect of the model error: that is, CFAST, a zone model, assumes that the upper layer temperature is uniform. When comparing its predictions to experimental measurements, the procedure described above provides us with a way of estimating the effect of this assumption. However, there is also uncertainty in the CFAST prediction, due to the uncertainty in the input parameters. This issue is discussed in the next section.

Table 4-1. Bias factor and relative model error for the models evaluated in NUREG-1824

Quantity	FDTs		FIVE		CFAST		MAGIC		FDS	
	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$
HGL Temperature Rise	1.44	0.25	1.83	0.33	1.06	0.12	1.01	0.07	1.03	0.07
HGL Depth					1.04	0.14	1.16	0.20	0.99	0.07
Ceiling Jet Temperature Rise			1.96	0.29	1.15	0.24	1.01	0.08	1.04	0.07
Plume Temperature Rise	0.73	0.24	1.03	0.49	1.25	0.28	0.99	0.07	1.15	0.11
Oxygen Concentration					0.91	0.15	0.95	0.18	1.08	0.14
Smoke Concentration					2.65	0.63	2.18	0.53	2.70	0.55
Room Pressure Rise					1.13	0.37	0.98	0.39	0.95	0.51
Target Temperature Rise					1.00	0.27	1.27	0.27	1.02	0.13
Radiant Heat Flux	2.02	0.59	1.54	0.55	1.32	0.54	1.15	0.36	1.10	0.17
Total Heat Flux					0.81	0.47	1.27	0.35	0.85	0.22
Wall Temperature Rise					1.25	0.48	1.51	0.46	1.13	0.20
Wall Heat Flux					1.05	0.43	1.17	0.34	1.04	0.21

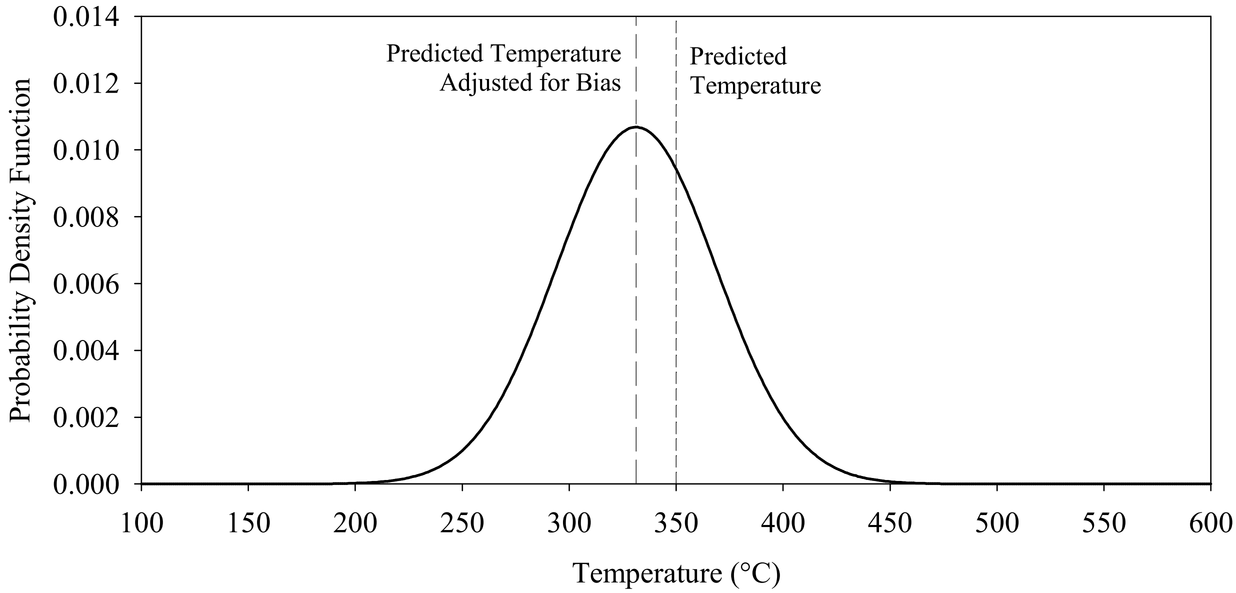

Figure 4-2. Normal distribution of the "true" value of the HGL Temperature of a postulated fire scenario

4.2 Input Uncertainty

The previous section outlines a method by which to quantify the model error. This section describes how to incorporate input parameter uncertainty into the final assessment of the model prediction uncertainty. Table 4-2 lists the most relevant output quantities calculated by fire models in NPP applications; for each of these output quantities, there are usually one or two input parameters that have the greatest influence on the result. The heat release rate is almost always one of these. In Volume 2 of NUREG-1824, Hamins quantifies these quantities' functional dependence on the key input parameters (see Table 4-2). These relationships are based either on the governing mathematical equations or on empirical correlations.

To understand how uncertainty in an input parameter can affect the predicted result of the model, consider the following example. According to the McCaffrey, Quintiere, Harkleroad (MQH) correlation, the HGL temperature rise in a compartment fire is proportional to the two-thirds power of the heat release rate:

$$T - T_0 = C\dot{Q}^{2/3}$$

It is not the value of the constant, C, that is important here, but rather the amount that the HGL temperature, $\Delta T,$ changes due to a shift in the HRR, $\Delta\dot{Q}$. It is the two-thirds power dependence, as found in Table 4-2, that matters. To see why, take the first derivative of T with respect to $\dot{Q}$ and write the result in terms of differentials:

$$\frac{\Delta T}{T - T_0} \approx \frac{2}{3}\frac{\Delta\dot{Q}}{\dot{Q}}$$

This is a simple formula with which one can readily estimate the relative change in the model output quantity, $\Delta T/(T - T_0)$, due to the relative change in the model input parameter, $\Delta\dot{Q}/\dot{Q}$.

Model Uncertainty

The following is an example of how to use such a formula. The uncertainty in a measured quantity is often expressed as a relative difference. Suppose that the uncertainty in the HRR of the fire, $\Delta\dot{Q}/\dot{Q}$, is 0.15, or 15 %. The expression above indicates that a 15 % increase in the HRR that is input into the fire model should lead to a 2/3 x 15 = 10 % increase in the prediction of the HGL temperature.

This relationship is based on an empirical correlation, and has nothing to do with any particular model; however, an effective way to check a fire model is to take a simple compartment fire simulation, vary the HRR, and ensure that the change in the HGL temperature agrees with the correlation. Consider the two curves shown in Figure 4-3. For Benchmark Exercise #3 of the International Collaborative Fire Model Project (ICFMP), Test 3 was simulated with FDS, using HRR values of 1000 kW and 1150 kW. An examination of the peak values confirms that the relative change in the HGL temperature (10 %) is two-thirds the relative change in the HRR (15 %), consistent with the empirical result of the MQH correlation. Even though FDS is a much more complicated model than the simple expression shown above, it still exhibits the same functional dependence on the HRR.

Table 4-2. Sensitivity of model outputs from Volume 2 of NUREG-1824

Quantity	Important Input Parameters	Power Dependence
HGL Temperature	HRR	2/3
HGL Depth	Door Height	1
Gas Concentration	HRR	1/2
Smoke Concentration	HRR Soot Yield	1 1
Pressure	HRR Leakage Rate Ventilation Rate	2 2 2
Heat Flux	HRR	4/3
Surface/Target Temperature	HRR	2/3

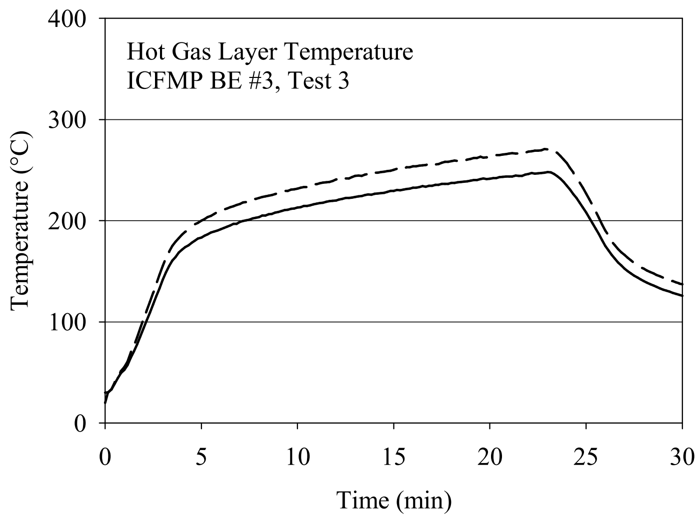

Figure 4-3. HGL Temperature as a function of time due to a 1000 kW fire (solid line) and an 1150 kW fire (dashed). Both predictions are by FDS. There is a 10 % increase in the temperature due to the 15 % increase in the HRR.

4.3 Combining Model Error and Input Uncertainty

The previous two sections have demonstrated how one can quantify the model error and input uncertainty individually, but how does one combine the two to estimate the total uncertainty of the final prediction of the model?

Consider again the example discussed in Section 4.1. The zone model CFAST has predicted a temperature rise of $M = 330$°C, caused by a postulated fire in a compartment. The results of a validation study indicate that CFAST overpredicts the HGL temperature by a factor of 1.06, on average, with a relative standard deviation of 0.12. It is postulated that the true value of the HGL temperature is a normally distributed random variable whose mean is approximately 6% less than the predicted value, and whose standard deviation is 0.12 times the mean. This is all due to the intrinsic error in CFAST, and has nothing to do with the uncertainty in the input parameters.

However, suppose now that the uncertainty in the HRR is to be considered. Assume that the HRR that was input into the model is actually the mean of a distribution whose relative standard deviation, $\tilde{\sigma}_I$, is 0.30. Using the argument type shown in Section 4.2, it can be proven that the relative standard deviation of the computed HGL temperature will have a relative standard deviation that is two-thirds times that of the input HRR. In this example, the relative standard deviation of the predicted HGL temperature rise, caused solely by the uncertainty in the HRR, is 2/3×0.30=0.20. We now have a relative standard deviation due to the model error (0.12) and another value (0.20) due to the input uncertainty. Assuming the model error is independent of the input uncertainty, the two values can be combined via quadrature to yield a combined uncertainty for the prediction:

$$\tilde{\sigma} = \sqrt{\tilde{\sigma}_M^2 + p^2\tilde{\sigma}_I^2} = \sqrt{0.12^2 + (2/3)^2 0.30^2} \cong 0.23$$

Model Uncertainty

Now consider the distribution shown in Figure 4-4. Both the model error and input uncertainty have been combined to indicate the likely range of the true temperature. In practice, this kind of information can be used to assign a probability to a particular event. Suppose, for example, that the cables within the compartment are known to fail electrically at a temperature of 400°C. The shaded area under the bell curve is the probability that the HGL temperature will exceed this value, in which case the probability is 0.25, or 25%. This means that even though the model predicts a temperature of 350°C, it is possible, with a probability of 17%, that the compartment temperature may still exceed 400°C due to model error and the uncertainty of the most important input parameter, the HRR.

To summarize, the procedure that has been outlined in this chapter. Given a model prediction, M, the true value of that quantity, θ, is assumed to be a normally distributed random variable:

$$\theta \sim N\left(\frac{M}{\delta}\ , (\tilde{\sigma}_M^2 + p^2 \tilde{\sigma}_I^2)\left(\frac{M}{\delta}\right)^2\right)$$

Notice in this notation that the second argument is the *variance*, or the square of the standard deviation. The terms $\tilde{\sigma}_M$ and δ are found in Table 4-1. The sensitivity factor p is found in Table 4-1 for the most important input parameter(s). The uncertainty of the input parameter, whose uncertainty is indicated by $\tilde{\sigma}_I^2$, is to be determined by the user.

The procedure outlined above is relatively simple, but it should be used with caution. There are several assumptions that ought to be considered carefully:

1. It has been assumed throughout that the model error and input uncertainty can be expressed in relative terms; that is, that the error/uncertainty is proportional to the predicted quantity.
2. It has been assumed that the true value of a given model output quantity can be expressed as a normally distributed random variable (Figure 4-4). In fact, there is no basis for assuming normal distributions for the input parameters or the error associated with the various model algorithms, and, therefore, no basis for assuming a normally distributed output. On the other hand, there is no basis for assuming any other distribution, either. However, it is necessary to express the results of the model in a form that can be used in a probabilistic framework.

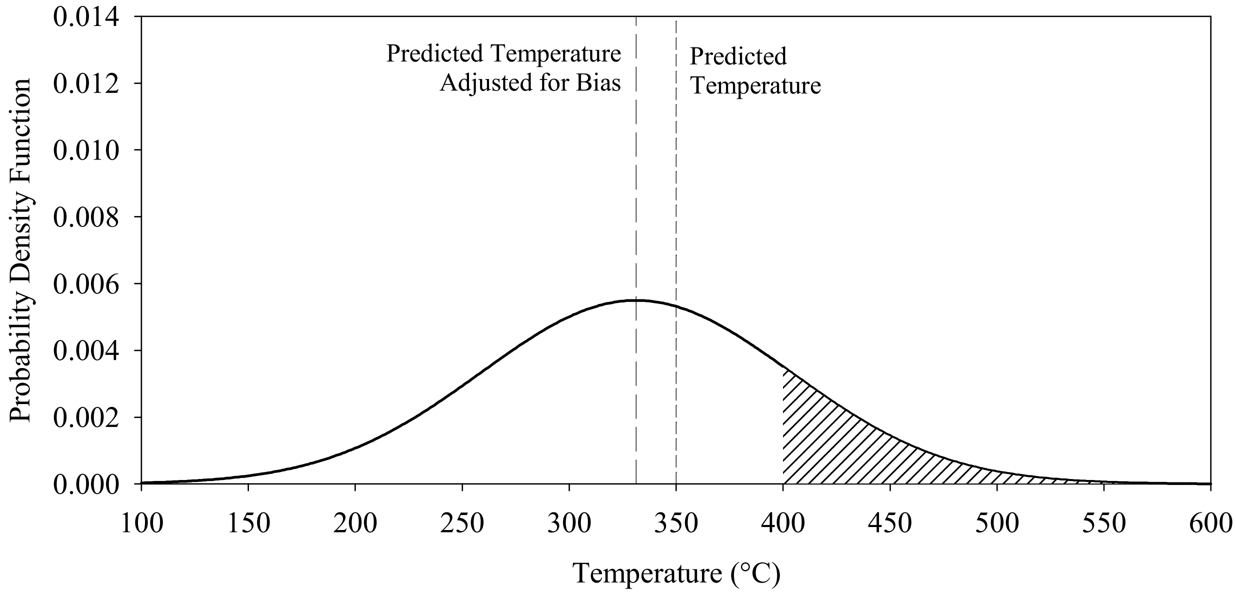

Figure 4-4. Normal distribution of the "true" value of the HGL Temperature of a postulated fire scenario. The shaded area represents the probability that the temperature exceeds 400 °C.

4.4 Calculating the Model Error

This section describes the method by which the model error was calculated from the results of the NRC/EPRI fire model validation study documented in NUREG-1824.

The starting point for the calculation is a set of measured and predicted values, along with an estimate of the experimental uncertainty. The purpose of the calculation is to "subtract off," in a statistical sense, the experimental uncertainty so that the model error can be estimated. Before describing the calculation, a few assumptions must be made:

1. The experimental measurements are assumed unbiased and their uncertainty is assumed to be normally distributed with a constant relative standard deviation, $\widetilde{\sigma}_E$ (that is, the standard deviation as a fraction of the measured value). Table 4-3 provides estimates of relative experimental uncertainties for the quantities of interest.

2. The model error is assumed to be normally distributed about the predicted value multiplied by a bias factor, δ. The relative standard deviation of the distribution is denoted as $\tilde{\sigma}_M$.

The computation of the estimated bias and scatter associated with model error proceeds as follows. Given a set of n experimental measurements, E_i, and a corresponding set of model predictions, M_i, define the following quantities:

$$\overline{\ln M} = \frac{1}{n}\sum_{i=1}^{n} \ln M_i \quad ; \quad \overline{\ln E} = \frac{1}{n}\sum_{i=1}^{n} \ln E_i$$

The standard deviation of the model error, $\tilde{\sigma}_M$, can be computed from the following equation:

Model Uncertainty

$$\sqrt{\tilde{\sigma}_M^2 + \tilde{\sigma}_E^2} \cong \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left[\left(\ln(M_i) - \ln(E_i)\right) - \left(\overline{\ln M} - \overline{\ln E}\right)\right]^2}$$

The bias factor is:

$$\delta = \exp\left(\overline{\ln M} - \overline{\ln E} + \frac{\tilde{\sigma}_M - \tilde{\sigma}_E}{2}\right)$$

For a given model prediction, M, the “true” value of the quantity of interest is assumed to be a normally distributed random variable with a mean of M/δ and a standard deviation of $\tilde{\sigma}_M(M/\delta)$.

There are a few issues to consider when using this procedure:

1. All values need to be positive, and each value needs to be expressed as an increase over its ambient value. For example, the oxygen concentration should be expressed as a positive number (i.e., the decrease in concentration below its ambient value).

2. If the measurement uncertainty is overestimated, the model error will be underestimated. If ever the model error is less than the experimental uncertainty, the latter should be re-evaluated. The model cannot be shown to have less error than the uncertainty of the experiment with which it is compared.

Table 4-3. Experimental uncertainty of the experiments performed as part of the validation study in NUREG-1824

Quantity	$2\tilde{\sigma}_E$
HGL Temperature Rise	0.14
HGL Depth	0.13
Ceiling Jet Temperature Rise	0.16
Plume Temperature Rise	0.14
Gas Concentration	0.09
Smoke Concentration	0.33
Pressure (no forced ventilation)	0.40
Pressure (with forced ventilation)	0.80
Heat Flux	0.20
Surface or Target Temperature	0.14

5
FIRE MODELING IN NFPA 805 ANALYSES

5.1 NFPA 805 in Perspective

As noted in Section 1.1, the NFPA first issued NFPA 805, *Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants* (NFPA 805, 2001), in 2001. Effective July 16, 2004, the NRC amended its fire protection requirements in Title 10, Section 50.48(c), of the *Code of Federal Regulations* [10 CFR 50.48(c)] to permit existing reactor licensees to voluntarily adopt fire protection requirements contained in NFPA 805 (2001 edition) as an alternative to the existing deterministic fire protection requirements. The incorporation by reference of NFPA 805 into 10 CFR 50.48 includes some qualifications (exceptions, modifications, and supplementation). The following qualification pertains to fire modeling:

> Notwithstanding the prohibition against the use of performance-based methods (NFPA 805, Section 3.1), the fire protection program elements and minimum design requirements of Chapter 3 may be subject to the performance-based methods permitted elsewhere in the standard.

The pertinence of these qualifications to fire modeling will become clear as the application of fire modeling techniques to NFPA 805 analyses is described.

5.2 Verification and Validation of Fire Models

RI/PB fire protection may rely on fire modeling to determine the consequences of fires. NFPA 805 states that "fire models shall be verified and validated," and "only fire models that are acceptable to the authority having jurisdiction (AHJ) shall be used in fire modeling calculations" (NFPA 805, Section 2.4.1.2). NUREG-1824 (NUREG-1824, 2007) describes a V&V study of the five fire modeling tools that are addressed in this User's Guide (Chapter 5). These fire modeling tools may be acceptable for use in NFPA 805 analyses.

5.3 Fire Modeling in NFPA 805 Analyses

NFPA 805 (NFPA 805, 2001) addresses fire protection for existing light water NPPs during all phases of plant operation. The steps involved in complying with the NFPA 805 standard, and the potential role of fire modeling in each step, are summarized in Table 5-1.

Table 5-1. Applicability of Fire Modeling to NFPA 805 Analyses

Steps of the NFPA General Approach (NFPA 805 §2.2)		Pointers within NFPA 805	Applicability of Fire Modeling
Step	**Description**		
(a)	Establish the fundamental elements of a fire protection program.	§2.2.1 §3	These fundamental elements are generally prescriptive requirements for acceptable policies, procedures, training, and equipment to prevent, control, and mitigate the consequences of fires in nuclear power plants. Setting up a fire protection program in compliance with the prescriptive requirements, and verification that such a program has been adequately established, is not likely to involve fire modeling. However, fire modeling may be used if the licensee elects to address any fire protection program elements and minimum design requirements from Chapter 2 by using performance-based methods (see the qualification of NFPA 805 in 10 CFR 50.48 mentioned above in Section 5.1).
(b)	Identify fire areas and associated fire hazards.	§2.2.2 §A2.2.2 §3.11.3	Fire modeling is not normally required. However, if proposed fire area boundaries are not wall-to-wall, floor-to-ceiling, a performance-based analysis is required to assess the adequacy of the fire barrier and fire modeling may be needed.
(c)	Identify the performance criteria that apply to each fire area.	§1.5 §2.2.4	Not applicable.
(d)	Identify the systems structures and components in each fire area to which the selected performance criteria apply.	§2.2.5 §2.4.2	Not applicable.
(e)	Select the deterministic and/or performance-based approach for the applicable performance criteria.	§2.2.6 §A2.2.6 §2.2.8 §A2.2.8 §4.1	Not applicable.

Steps of the NFPA General Approach (NFPA 805 §2.2)		Pointers within NFPA 805	Applicability of Fire Modeling
Step	**Description**		
(f)	When applying a deterministic approach, demonstrate compliance with the deterministic requirements.	§2.2.6 §A2.2.6 §2.2.7 §A2.2.7	Not applicable.
(g)	When applying a performance-based approach, perform engineering analyses to demonstrate that performance-based requirements are satisfied.	§2.2.8 §A2.2.8 §2.4 §2.5 §4.2.4	Fire modeling is applicable because it can be used to address performance-based requirements.
(h)	For changes in risk, defense-in-depth, or safety margins, perform a plant change evaluation to demonstrate acceptability of the changes.	§2.2.9 §2.4.4 §A2.4.4	Fire modeling is applicable because it can be used in plant change evaluations to ensure that sufficient safety margins are maintained.
(i)	Establish a monitoring program to assess the continuing adequacy of the fire protection program in meeting the performance criteria.	§2.2.10 §2.6	Not applicable.
(j)	Provide documentation to ensure the quality of the analyses and maintain configuration control of the plant design and operation.	§2.2.11 §2.4.2.4 §2.7	The documentation that the fire modeler produces, as described in Chapter 2 of this *User's Manual* (Step 6: Documentation), will contribute to the documentation associated with NFPA 805 analysis.

The fire-modeling approach specified by NFPA 805 is outlined in Table 5-2, along with pointers to related chapters in this *User's Guide*. The pointers indicate how and where the *User's Guide* provides guidance for fire modeling.

Table 5-2. NFPA 805 Fire Modeling Approach

Item	Subsection of NFPA 805 §4.2.4.1		Pointers to this *User's Manual*
	Title	**Summary**	
1	Identify Targets	Identify and determine the locations of equipment and circuits needed to perform safety functions.	Chapter 2 (Step 1: Objectives) provides guidance on the establishment of objectives, which involve protection of the targets identified.
2	Establish Damage Thresholds	For the targets identified, establish damage thresholds (e.g., critical temperature, heat flux, smoke concentration).	Chapter 2 (Step 1: Objectives) provides guidance on establishing appropriately specific fire modeling objectives, which includes specification of damage thresholds.
3	Determine Limiting Conditions	The limiting conditions for a given fire area identify the most susceptible combination of equipment or circuits needed to perform a safety function.	Chapter 2 (Step 1: Objectives) provides guidance on formulating appropriately specific fire modeling objectives, which includes identification of susceptible equipment and circuits.
4	Establish Fire Scenarios	Establish the fire conditions for a given fire area.	Chapter 2 (Step 2: Selection and Description of Fire Scenarios) provides guidance on the selection, description, and assessment of fire scenarios. Chapter 4 (Uncertainty) provides guidance for understanding the ramifications of uncertainties in the results of fire modeling calculations.
5	Protection of Required Nuclear Safety Success Paths	Demonstrate that equipment and circuits needed to perform safety functions are protected.	Taken together, all of the steps in the fire modeling process described in the *User's Guide* contribute guidance and examples for ensuring that circuits in a safety success path in a given plant location are protected.
6	Operations Guidance	Provide guidance to plant personnel regarding credited success paths for each fire area.	Chapter 2 (Step 5: Interpretation) and Chapter 2 (Step 6: Documentation) provide guidance on translating numerical results into concrete actions to maintain safety success paths free of fire damage for equipment and circuits that are needed to perform safety functions.

5.4 Model Uncertainty Analysis

NFPA 805 (Section 2.4.1) permits the use of fire modeling to establish that the performance criteria under consideration are met. This modeling may be performed for an initial evaluation under performance-based criteria (Section 2.2.3) or for a plant change evaluation (Sections 2.4.4, A2.4.4.3). The set of fire scenarios to be considered in each plant area “shall include the following:

1. Maximum expected fire scenarios
2. Limiting fire scenario(s)”

The maximum expected fire scenarios (MEFS) for each fire area “represent the most challenging fire that could be reasonably anticipated for the occupancy type and conditions in the space” (Section 1.6.39). The environmental conditions that the MEFS would produce may be estimated using fire modeling, while the limiting fire scenarios (LFS) for each fire area may be generated from the MEFS by varying one or more inputs to the fire modeling calculation to the extent that a performance criterion is violated. It may be possible to generate an LFS by varying a single input to a very unlikely extent or by moderately varying multiple inputs to achieve a very unlikely combination of input values (Sections 1.6.37 and C3.3).

Whenever a limiting fire scenario can be generated from a maximum expected fire scenario by varying a single input to the extent needed to cause a performance criterion to be exceeded, a safety margin is implied for that input. Likewise, when multiple inputs are varied to the extent that they violate a performance criterion, a safety margin can be claimed based on the low likelihood that the postulated combination of input values could occur. Whether a safety margin is adequate to compensate for the uncertainties in the environmental conditions predicted by the fire model is a matter for uncertainty analysis. NFPA 805 states that “an uncertainty analysis shall be performed to provide reasonable assurance that the performance criteria have been met” (Section 2.7.3.5). The model uncertainty material described in Chapter 4 may be useful for judging the adequacy of the safety margins.

6
FIRE PROBABILISTIC RISK ASSESSMENT ANALYSIS

6.1 Purpose

NUREG/CR-6850, *EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities*, provides a comprehensive methodology for conducting a fire probabilistic risk assessment (PRA) of commercial nuclear power plants (NPPs) (NUREG/CR-6850, Vol. 1, p. xii). The intended audience for NUREG/CR-6850 comprises practitioners from various disciplines involved in conducting a fire PRA. The disciplines called upon in the performance of a fire PRA include (a) fire modeling, (b) general PRA modeling, (c) human reliability analysis, and (d) electrical circuit analysis; the reader of this *User's Guide* is likely to be engaged in fire modeling, but may not be familiar with the fire PRA context in which it may be conducted. The intent of this chapter is to introduce such a reader to the application of fire modeling in support of a fire PRA, as described in NUREG/CR-6850.

With regard to fire modeling, NUREG/CR-6850 includes:

- Instructions for identifying fire scenarios
- Descriptions of the types of fire modeling tools needed to support a fire PRA
- Recommended values for selected input parameters, including, in some cases, uncertainty distributions
- A framework for the incorporation of fire modeling results in fire risk quantification

6.2 Overview of Probabilistic Risk Assessment

Probabilistic risk assessment, in general, provides a systematic way to answer three basic questions:

1. What can go wrong?
2. How likely is it?
3. What are the consequences if it occurs?

These three questions can be used to define the notion of "risk" (NUREG/CR-6850, Vol. 2, Chapter 19). For a PRA of a commercial NPP, there are two important answers to the first question, "What can go wrong":

1. The rate of removal of heat from the reactor core might fall below the heat generation rate, with the result that fuel elements may suffer damage and release radioactivity. Core damage results in the release of radioactivity from the fuel, but not necessarily into the environment.
2. In the event of an accident that damages the reactor core, a further measure of what can go wrong involves the release of radioactivity into the environment. A core damage accident that leads to a large, unmitigated release of radioactivity from the reactor containment before effective evacuation of the nearby population is known as a large early release.

For the question "How likely is it," with regard to the two primary things that can go wrong, PRA can provide two quantitative answers:

1. The core damage frequency (CDF) is the expected number of core damage events per unit time. A PRA that limits itself to estimating the CDF is known as a Level 1 PRA.
2. The large early release frequency (LERF) is the expected number of large early release events per unit time. A PRA that estimates the LERF is known as a Level 2 PRA.

The systematic effort to answer the question "How likely is it?" implies a multitude of other little things that could go wrong (equipment failures, human failures, or natural events) and relates them in a logical structure that indicates which combinations of such occurrences would lead to core damage or a large early release. PRA practitioners call these potential occurrences "basic events," or, for those basic events that start an accident sequence, "initiating events." A great deal of effort goes into estimating the likelihoods of the basic events (for example, the probability of the failure of a pump to operate when called upon) and into building a logical structure of fault trees and event trees to determine what combinations of initiating events and basic events can lead to core damage or a large early release.

Answering the third question, "What are the consequences," is the province of a Level 3 PRA, or consequence analysis. The consequences to be addressed are the radioactive contamination of land and the health effects suffered by nearby human populations, brought on by a large early release of radioactivity from a NPP. Assessment of land contamination and health effects requires consideration of the nature of nearby populations, the timing and effectiveness of evacuation from the vicinity, and wind speed and direction and other weather conditions in the vicinity of the plant during the release.

6.3 Overview of Fire PRA

A fire PRA is a "collection of analyses, computer models and reports conducted and prepared for the purpose of estimating the risk associated with fire events in a NPP" (NUREG/CR-6850, Chapter 19). Thus, a fire PRA is a PRA that confines its consideration of initiating events to fire events.

The process described in NUREG/CR-6850 focuses on the assessment of CDF and LERF as risk indices.

Mathematically, the plant CDF (i.e., the fire risk associated with all the plant) is expressed as

$$CDF = \sum_{All-i} CDF_i = \sum_{All-i} \lambda_i \cdot ccdp_i$$

where:

- *λ* is the generic fire ignition frequency for plant compartment i, and
- *ccdp* is the conditional core damage probability for plant compartment i. The ccdp parameter captures the consequences of postulated fire scenarios in terms of plant shutdown capability. It's the probability of failing to safely shutting down the reactor given systems and components impacted by fire (in a fire risk application). In summary, this probability can be considered a consequence term.

For LERF calculations, the term ccdp is replaced by the conditional large early release probability (clerp). Notice that the CDF (or LERF) is the summation of the CDF_i or $LERF_i$

associated with the plant compartments within the scope of the fire risk assessment, which in turn is the multiplication of the frequency of a fire in a compartment and the probability of failing to safely shut down the plant.

The conditions generated by the postulated fire (the initiating event) are evaluated to determine whether plant equipment will be affected. The fire can affect the equipment by directly damaging nearby items or cables associated with components in different compartments; thus, a fire risk approach for determining CDF and LERF values considers the following elements:

1. The ignition sources with the corresponding ignition frequencies and secondary combustibles in the compartment.
2. The systems, components, cables, and human actions necessary for safely shutting down the reactor in the case of a fire event.
3. The electrical systems supporting the corresponding systems and components.
4. The plant layout/geometry in terms of buildings and compartment arrangement and characteristics.
5. The fire protection features available for detecting, controlling, and eventually suppressing fires.

Fire modeling is used within the above elements to determine the extent and timing of fire damage to relevant plant equipment or cables and the corresponding times to detection and suppression.

6.4 Fire Modeling for a Fire PRA

For the purposes of a fire PRA, the plant is divided into a number of fire compartments (NUREG/CR-6850 Section 1.1). The analysis then considers the impact of fires in a given compartment, and fires that might impact multiple compartments. A fire PRA will initially consider fire threats to safe shutdown primarily in the context of the defined fire compartments. The results of the fire PRA will be presented in terms of the risk contribution for fires confined to a single compartment and for fires that impact multiple adjacent compartments. The applicability of fire modeling to fire PRA analysis as described in NUREG/CR-1605 is outlined in Table 6-1.

Table 6-1. Fire Modeling in NUREG/CR-6850

NUREG/CR-6850 Tasks			
No.	**Title**	**Summary**	**Fire Modeling Applicability**
1	Plant Boundary Definition and Partitioning	Establish the global plant analysis boundaries relevant to the fire PRA and divide the plant into discrete physical analysis units (fire compartments). The fire compartments form the fundamental basis of the fire PRA.	Fire modeling is not applicable to establishing the global plant boundaries. The global boundaries are to include all locations with the potential to contribute substantially to fire risk. Fire compartments are bounded by non-combustible barriers where heat and products of combustion from a fire within the enclosure will be substantially confined. A fire compartment should substantially contain fire plume development, the development of a hot gas layer, direct radiant heating by the fire, and the actual spread of fire between contiguous or noncontiguous fuel elements. Though formal modeling is not likely to be used to establish "substantial containment," insight provided by an experienced fire modeler may be of use when defining fire compartments.
2	Fire PRA Component Selection	Determine the equipment for which cable identification and location are necessary. Include components credited in the 10 CFR 50 Appendix R fire safe shutdown analysis. Potentially include components credited in the plant's internal events PRA. Also include components of interest due to considerations of combined spurious actuations that may threaten the credited functions and components.	Not applicable.

NUREG/CR-6850 Tasks			Fire Modeling Applicability
No.	**Title**	**Summary**	
3	Fire PRA Cable Selection	Identify cables supporting those components selected in Task 2.	Not applicable.
4	Qualitative Screening	Identify compartments that can be shown, without quantitative analysis, to have little or no risk significance. A compartment may be screened out if it contains none of the components or cables identified in Tasks 2 and 3, and if a fire in the compartment cannot lead to a plant trip, due to either plant procedures, an automatic trip signal, or technical specification requirements.	Not applicable.
5	Plant Fire-Induced Risk Model	Using the internal events PRA model as a starting point, develop a fire PRA logic model that reflects plant response following a fire. The model indicates the plant response given a fire-initiated accident scenario. At this point, without information from subsequent tasks, the model does not contain information about the frequencies of fire-initiating events or the conditional probabilities of fire-induced equipment failures.	Not applicable.
6	Fire Ignition Frequency	Identify ignition sources within the unscreened fire compartments identified in Task 4 and estimate compartmental ignition frequencies.	Not applicable.

NUREG/CR-6850 Tasks			
No.	**Title**	**Summary**	**Fire Modeling Applicability**
7	Quantitative Screening	Screen out fire compartments based on their quantitative contribution to fire risk as determined using the fire PRA logic model from Task 5, human error probabilities determined in Task 12, the initiating event frequencies from Task 6, and setting the conditional probabilities of fire-induced equipment failure given a fire to TRUE. Consider the cumulative risk associated with the screened compartments to ensure an accurate estimate of fire risk.	Fire modeling is not directly applicable. However, information from Tasks 8 and 11 (for example, the potential for adverse environments and the timing of equipment damage relative to fire ignition) may influence the human error probabilities estimated in Task 12.
8	Scoping Fire Modeling	Screen out fixed ignition sources that do not pose a threat to the targets within a specific fire compartment, assign severity factors (estimates of the probability of target damage given a fire) to unscreened fixed ignition sources, and calculate revised compartment fire frequencies.	Fire modeling is used in this task to screen out fixed ignition sources that do not damage any nearby targets. For each ignition source examined, the analyst performs conservative fire modeling calculations to predict fire conditions near affected targets in order to assess whether target damage or ignition can occur. The screening may be performed using an automated zone of influence (ZOI) form. The analyst should be familiar with the calculations and use engineering judgment when interpreting the results. The analyst estimates severity factors for ignition sources that are not screened out.
9	Detailed Circuit Failure Analysis	Determine how the failure of the fire PRA cables identified in Task 3 would affect the fire PRA components identified in Task 2.	Not applicable.

NUREG/CR-6850 Tasks			Fire Modeling Applicability
No.	**Title**	**Summary**	
10	Circuit Failure Mode Likelihood Analysis	For the circuit failure modes requiring probabilistic assessment (as determined in Task 9), estimate conditional probabilities of circuit failure given fire-induced cable damage.	Not applicable.
11	Detailed Fire Modeling	Identify fire scenarios for each unscreened fire ignition source (Task 8) in each unscreened compartment (Tasks 4 and 7). Estimate frequencies of occurrence of fire scenarios, each of which involves a specific ignition source failing a predefined target before fire protection succeeds in protecting the target.	Task 11 encompasses the analyses of the physical fire scenarios. A fire scenario is a specific chain of events: fire ignition, propagation of the fire effects to other items, and the possibility of damaging a set of items identified as targets set before successful fire suppression. The fire analyst performs a detailed fire modeling analysis for each fire scenario in each unscreened fire compartment.
12	Post-Fire Human Reliability Analysis	Identify the human failure events to be included in the fire PRA. Perform screening, and, as needed, detailed human reliability analysis to estimate the corresponding human error probabilities.	Fire modeling is not directly applicable. However, information from Tasks 8 and 11 (for example, the potential for adverse environments and the timing of equipment damage relative to fire ignition) is needed to assess human error probabilities.
13	Seismic Fire Interactions	Qualitatively assess the risk from any potential interactions between an earthquake and a fire.	Fire modeling is not directly applicable. However, information from Task 8 (screening of ignition sources) may be used to assess the potential for seismically induced fires to compromise reactor shutdown capability.
14	Fire Risk Quantification	Quantify the final Fire PRA Model to generate the final fire risk results (core damage frequency and large early release frequency).	Fire modeling is not directly applicable. However, information from Task 11 (identified fire scenarios and fire scenarios frequencies) is needed to quantify the risk model for each fire ignition event.

NUREG/CR-6850 Tasks			
No.	**Title**	**Summary**	**Fire Modeling Applicability**
15	Uncertainty and Sensitivity Analyses	Identify and appropriately address uncertainties throughout the fire PRA process.	Fire modeling is not directly applicable. However, information from Task 11 (sources of uncertainty and the proposed approach for addressing the uncertainties) is needed for the uncertainty analysis.
16	Fire PRA Documentation	Document the fire PRA.	Fire modeling is not directly applicable. However, information from Tasks 8 and 11 (description of the fire modeling effort) is needed for the overall documentation.

6.5 Model Uncertainty Analysis

The model uncertainty methodology and quantification described in Chapter 4 of this guide was designed for and can be readily applied to a Fire PRA. As discussed earlier, fire modeling tools are used in a Fire PRA to determine the extent of fire damage and the time at which a target would be considered damage in a postulated fire scenario. The results of the model uncertainty quantification provide the analyst with the necessary information for assigning a probability to the deterministic results from a fire model.

The scope of the model uncertainty quantification effort does not cover all the fire modeling tools that are available and needed in a Fire PRA; it only covers selected capabilities of selected analytical fire models, so the application of the model uncertainty results in the Fire PRA will be restricted to those scenarios where the model is considered appropriate for analysis and model uncertainty values are available.

6.5.1 NUREG/CR-6850 Task 8, Scoping Fire Modeling

The scoping fire modeling tasks in the Fire PRA are intended to screen fixed ignition sources based on a zone of influence analysis. The zone of influence is a region near the fire, where targets are expected to be damaged. Fire modeling equations, primarily engineering (hand) calculations, are often used in developing the zone of influence.

The guidance for determining the zone of influence is based on conservative input parameters. The conservatism intentionally expressed in the input parameters serves as the justification for screening ignition sources without a detailed evaluation of their risk contributions; consequently, the model uncertainty quantification results in terms of error factors or biases may not be necessary. At the same time, the model uncertainty results can provide guidance on the conservatism that should be included for screening purposes or serve as a further justification of screening decision.

6.5.2 NUREG/CR-6850 Task 11, Detailed Fire Modeling

Detailed fire modeling is the Fire PRA task where the guidance provided in this report is most applicable. The guidance applies specifically in two areas: (1) conducting fire modeling analysis for determining damage times, etc., and (2) providing model uncertainty values to be included in the risk quantification of fire scenarios.

In terms of conducting fire modeling studies, the guide recommends steps to perform the analysis (e.g., selecting the appropriate model) and provides example calculations and guidance on interpreting the results.

In terms of incorporating model uncertainty into the risk quantification, the Fire PRA analyst can reflect the probability that the model is estimating the "real" value of the parameter in the analysis. The fire modeling results are usually reflected in the non-suppression probability term in the fire risk equation, which captures the fraction of fires that are not controlled or suppressed before target damage. To calculate this probability, various relevant timing results are necessary, including (but not limited to) time to smoke detection, time to start suppression activities, time to target damage, etc., which are often determined with fire modeling tools. As a conceptual example, Figure 6-1 illustrates a simplified fault tree that describes how the relevant fire scenario timings are incorporated into a non-suppression probability assessment:

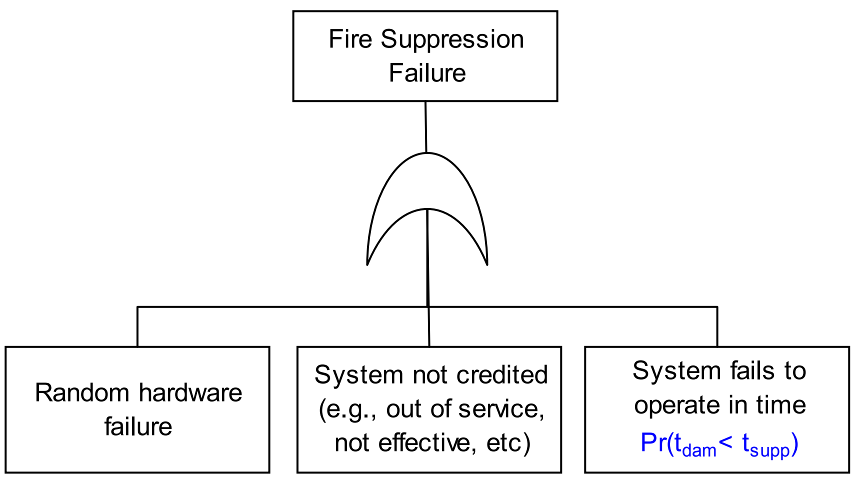

Figure 6-1. Generic fault tree depicting the logic for suppression failure

Notice that timing information (t_{dam} is the time to target damage, and t_{supp} is the time to suppression) resulting from fire modeling analysis is one of the considerations in quantifying a "failure to suppress the fire" event in a fire scenario. The logic presented in the fault tree suggests that suppression will not be successful if:

1. The suppression system randomly fails to operate as designed, which is represented by a failure probability or the system unavailability, OR
2. The system is not credited as an effective means of suppression for the postulated scenario, which is usually represented with a value of 0 for credited systems or 1 for non-credited systems, OR

3. The suppression does not start before target damage, in which case fire modeling results are used for determining this probability.

To determine a probability in the latter case (as opposed to a deterministic TRUE, FALSE answer to the question $t_{dam} < t_{supp}$), the model uncertainty should be considered in the analysis. Fire modeling results are often incorporated into the risk equation in the form of time values, necessitating a transformation from the fire modeling parameters for which model uncertainty quantification is available (e.g., HGL temperature, plume temperature, etc.) to the corresponding times.

Figure 6-2 presents a typical temperature versus time plot (red solid curve) from a fire model. An example of such a plot may be a HGL temperature versus time result. The plot also conceptually includes the model uncertainty results, which are represented by the dash curves. The center dashed line is the expected value corrected by the model bias, while the outer dashed lines represent the variability associated with the bias. The dashed lines therefore represent a probability distribution for the “real” value of the estimated parameter. Consequently, a distribution can be developed on the time by determining when the dashed temperature curves cross the damage temperature line (i.e., by transformation). The resulting time distribution is used to determine the probability that damage occurs before suppression, which corresponds to a failure to suppress event.

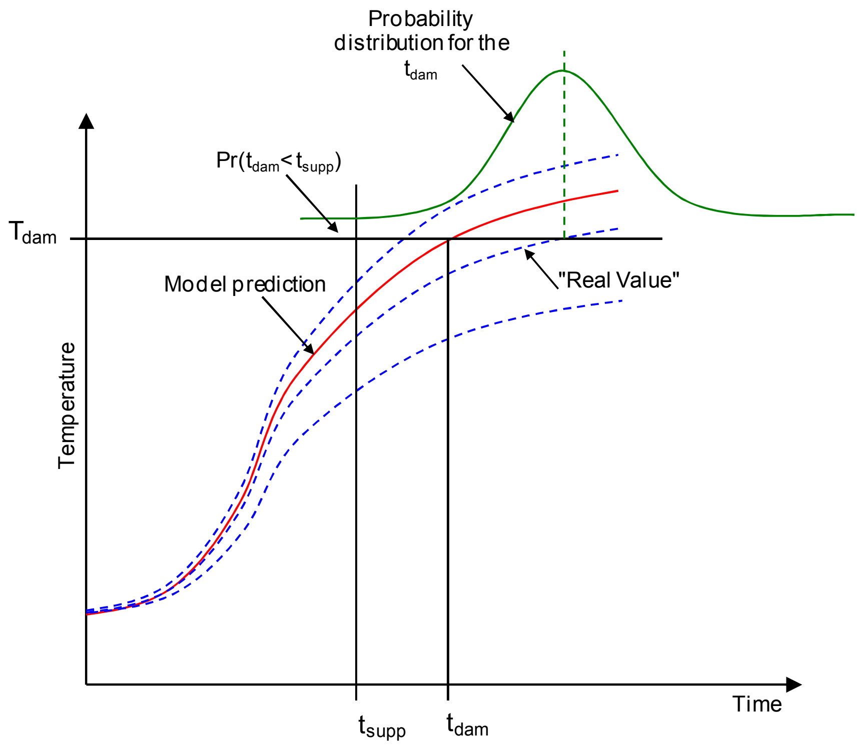

Figure 6-2. Conceptual representation of incorporating model uncertainty results in the risk quantification process

In summary, the model uncertainty quantification presented in Chapter 4 can be incorporated into the fire risk quantification process, specifically in the timing results used for determining non-suppression probabilities as described in Appendix P of NUREG/CR-6850.

7
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A
Cabinet Fire in Main Control Room

A.1 Purpose

The purpose of the calculations described in this section is to determine the length of time that the Main Control Room (MCR) remains habitable after the start of a fire within a low voltage (<600V) control cabinet.

A.2 References

1. ASTM E 84-05. *Standard Test Method for Surface Burning Characteristics of Building Materials.*
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A.3 Input Data

General Description: The MCR is manned 24 hours per day during normal plant operations. Operators typically stand in front of the various control boards or sit at workstations within the horseshoe.

Geometry: Details of the MCR are shown in Figure A-1 and Figure A-2. The compartment has a variety of control cabinets in addition to typical office equipment, such as computer monitors on workstations. There is an "open grate" ceiling above the floor which is shown in Figure A-3.

Construction: One wall of the compartment is made of concrete with no additional lining material. The other exterior walls are constructed of 5/8 in (1.6 cm) gypsum board supported by steel studs. The floor is a slab of concrete covered with low-pile carpet. The ceiling is a slab of concrete with the same thickness as the floor, but with no lining material.

Detection System: Smoke detectors are located as shown in Figure A-3 below the plenum space at the open grate ceiling level and on the upper concrete ceiling. The detectors are UL-listed with a nominal sensitivity of 1.5 %/ft (4.9 %/m).

Ventilation: During normal operation, the ventilation system provides 5 air changes per hour. As seen in Figure A-1, ventilation is provided via six supply diffusers, and two return vents of nominally the same size. A 120 Pa (0.0174 psi) over-pressure (relative to the adjacent compartments) is maintained in the MCR. Smoke purge mode may be manually actuated during smoky conditions to provide 25 air changes per hour.

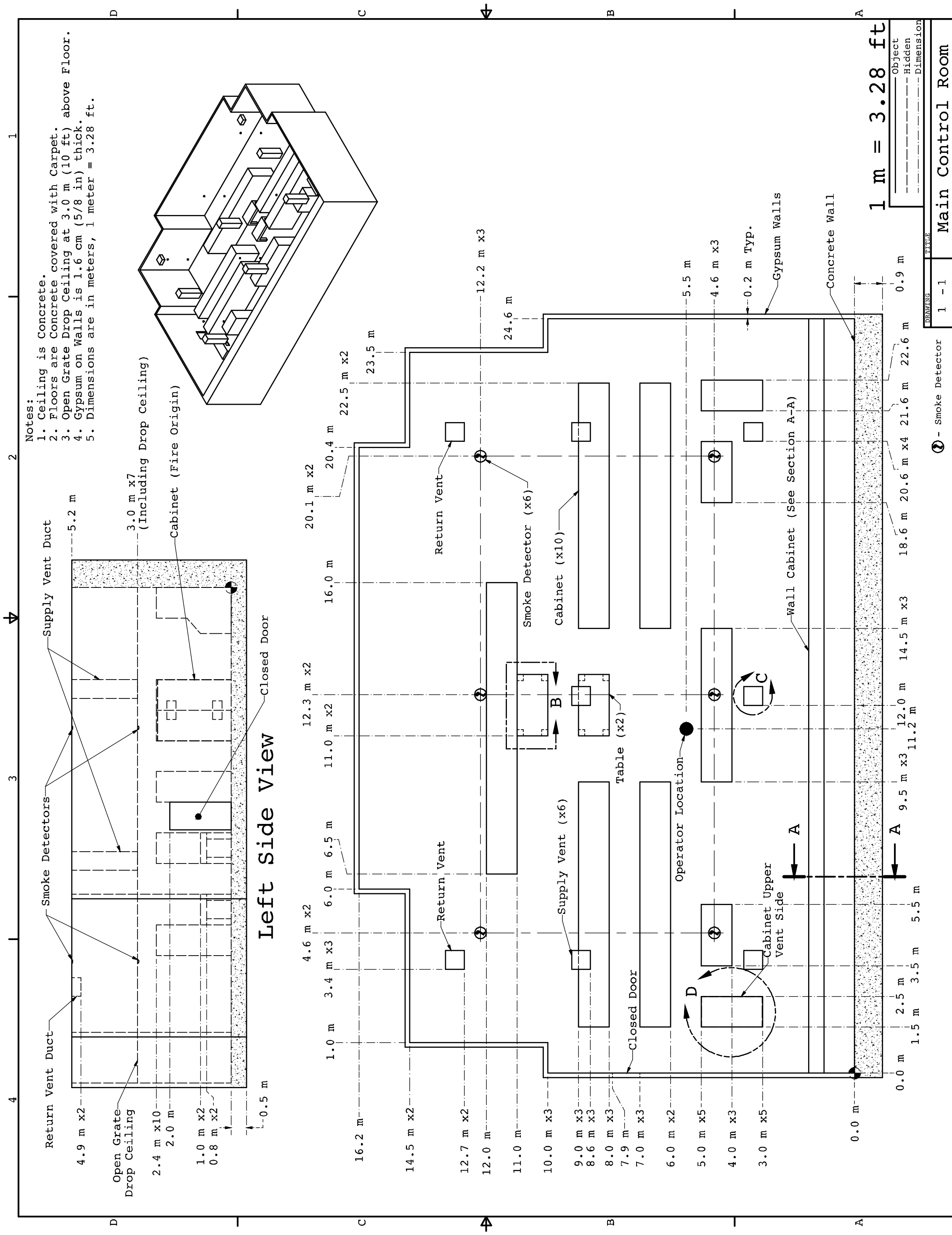

Figure A-1. Geometry of the Main Control Room.

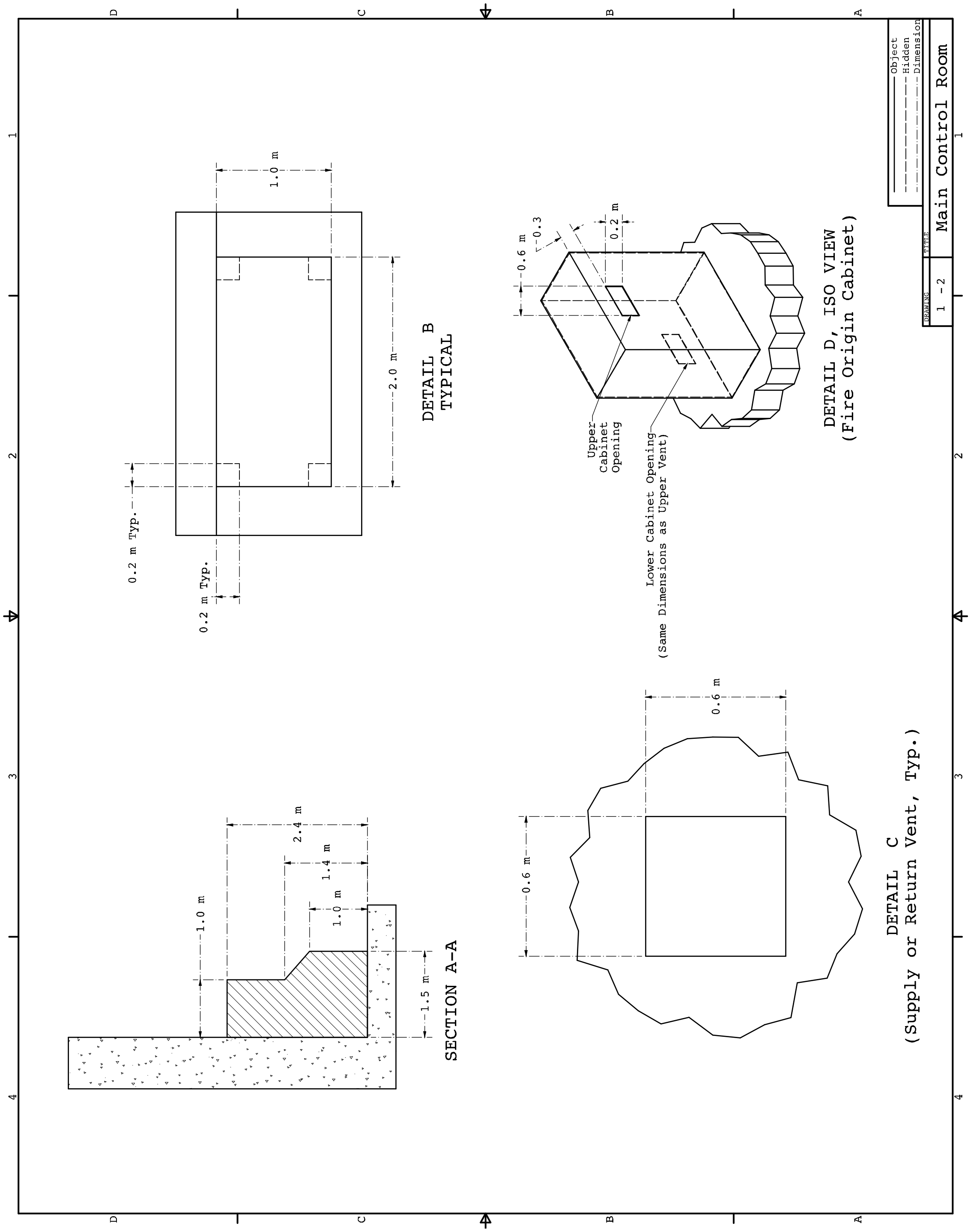

Figure A-2. Main Control Room Details.

Figure A-3. Photograph of a typical "open grate" ceiling.

Figure A-4. Photograph of a typical control cabinet.

A.4 Fire Scenario

This section contains a list of assumptions that define the fire scenario. This information is not typically obtained from plant design documents.

Fire: The control cabinet (Figure A-2), designated as the "Fire Origin" in Figure A-1, is assumed to have caught fire due an electrical malfunction. The fire is assumed to grow following a "t-squared" curve to a maximum value of 702 kW/m^2 in 12 min and remains steady for 8 additional minutes, consistent with NUREG/CR-6850, page G-5, for a low voltage cabinet fire propagating to more than one cable bundle of qualified cable. After 20 min, the fire's HRR is assumed to decay linearly to zero in 12 min. A peak fire intensity of 702 kW represents the 98^{th} percentile of the probability distribution for HRRs in cabinets with qualified cable in scenarios where flames are assumed to propagate through cable bundles. From a cabinet configuration perspective, this selection is appropriate for control cables where cable loading is typically higher than in other types of cabinets. From an applications perspective, the use of the 98^{th} percentile is consistent with the guidance provided in NUREG/CR-6850 for evaluating fire conditions with different fire intensities (including the 98^{th} percentile) within the probability distribution range.

None of the exterior panels of the cabinet are assumed to open before or during the fire. The fire is assumed to burn within the interior of the cabinet, and the smoke, heat, and possibly flames are assumed to exhaust from an air vent in the side of the cabinet. The top of the air vent is 0.3 m (1 ft) below the top of the cabinet. The air vent dimensions are 0.6 m (2 ft) wide and 0.3 m (1 ft) high. The cabinet is 2.4 m (8 ft) tall.

The heat of combustion of the burning cables is assumed to be 10.3 kJ/g (Table 2-4 of NUREG-1805). This number is appropriate for XPE/Neoprene cable. A mixture of polyethylene (C_2H_4) and Neoprene (C_2H_5Cl) would have an effective chemical formula of $C_2H_{4.5}Cl_{0.5}$.

The radiative fraction[1] of the fire is assumed to be 35 %, consistent with typical sooty fires (SFPE Handbook, Table 3-11.12).

For visibility calculations, soot yield[2] is a very important parameter. According to Tewarson's chapter in the *SFPE Handbook*, the soot yield for the various combustible materials within the cabinet ranges from 0.01 to 0.20. The soot yield for the combustion reaction is assumed to be 0.10, but the results of the calculation should be assessed in light of the wide variation in possible soot yields, and the fact that the fire could potentially be under-ventilated. This value of 0.10 is an estimate for a well ventilated fire close to an equivalency ratio of 1. The calculated optical density is directly proportional to this parameter, thus, the entire range of values can easily be assessed during post-processing of the results. The mass extinction coefficient is assumed to be 8.7 m^2/g, based on measurements made by Mulholland and Croarkin.

Materials: Nominal values for the thermal properties of various materials in the compartment have been taken from NUREG-1805 (Table 2-3) and are listed in Table A-1.

The carpet is assumed to have a flame spread rating of less than 25 as defined in ASTM E 84. Its thermal inertia ($k\rho c$) is assumed to have a value of 0.68 $(kW/m^2/K)^2 \cdot s$, an "Ignition Temperature" of 412 °C (774 °F), and a "Minimum Heat Flux for Ignition" of 18 kW/m^2, all

[1] The fraction of the fire's total energy emitted as thermal radiation.
[2] The soot yield is defined as the mass of smoke particulate generated per unit mass of fuel consumed.

obtained from NUREG-1805, Table 6-5, for “Carpet (Nylon/Wool Blend)”. It is not expected that the carpet would ignite as a result of the fire described above.

The properties of the cabling inside the control cabinet are not needed because the soot yield and HRR for the cabinet fire are assumed.

Ventilation: It is assumed that the supply air to the compartment is equally distributed among the six supply vents, and that the return air is drawn equally from the two returns. The supply air flow should exceed the return so that an over-pressure of 120 Pa (0.0174 psi) is maintained prior to the smoke purge. It is assumed that manual activation of the smoke purge system occurs 2 min following the ignition of the fire. Also, it is assumed that the only leakage from the compartment is via a 2.5 cm (1 in) high crack under the 0.91 m (3 ft) wide door on the west side of the compartment.

Habitability: For the purpose of assessing habitability of the compartment, it is assumed that an operator is standing at the position indicated in Figure A-1. According to NUREG/CR-6850, a space is considered uninhabitable if the gas temperature 2 m (6 ft) above the floor exceeds 95 °C (200 °F), or if the heat flux at the floor exceeds 1 kW/m^2, or if the optical density 1.5 m (5 ft) above the floor exceeds 3 m^{-1}.

Table A-1. Material Properties, Main Control Room (NUREG-1805)

Material	Thermal Conductivity, k (W/m/K)	Density, ρ (kg/m^3)	Specific Heat, c (kJ/kg/K)
Concrete	1.6	2400	0.75
Gypsum Board	0.17	960	1.1
Steel	54.	7850	0.465
Plywood	0.12	540	2.5

A.5 Model Assumptions

This section describes how each of the five fire model calculations is prepared. Note that a typical NPP fire modeling analysis would not require the use of all five models. However, for demonstration purposes, all five models are exercised to point out the different assumptions required of each beyond those listed in the previous section.

A.5.1 Empirical Models (FDT^s and FIVE)

General: The FDTs and FIVE have several equations that are useful for obtaining estimates of control room tenability. For the FDTs, the method of Deal and Beyler for predicting HGL temperature under forced ventilation conditions was used for this scenario. The other forced ventilation correlation (Method of Foote, Pagni, and Alvares) was used by FIVE. The equation for predicting heat flux to a target assuming the fire is a point source in the presence of no wind was used to estimate the radiant heat flux to the operator.

Geometry: The equations used in the FDT^s and FIVE to predict HGL temperature can only simulate fires in compartments with rectangular floor areas. For this example, the selected compartment is not a rectangular parallelepiped, so it needs to be represented as such with an effective width and depth. In general, to most accurately model the enclosure filling (which is based on the volume of the compartment) and the heat transfer (which is based on the enclosure surface area), the overall volume, height, (and thus surface area) of the enclosure needs to remain the same. The floor area is 371.7 m^2 (4001 ft^2) and the perimeter is 83.4 m (898 ft). Maintaining the total floor area and perimeter yields an effective compartment size of 28.8 m by 12.9 m (94 ft by 42 ft). The compartment height is maintained at 5.2 m (17 ft).

Fire: For the FDTs, a constant HRR of 702 kW was used; for FIVE the time dependant HRR was used. The fire was assumed to be located at the cabinet air vent. This assumption yields a fire height of 1.95 (6.4 ft) m above the floor. The distance from the fire to the operator is estimated to be approximately 8.9 m (29.2 ft).

Materials: The walls, ceiling and floor were all assumed to be 5/8 inch (1.6 cm) gypsum board. Typically, the FDT^s and FIVE equations can only account for one type of material at a time. The gypsum board was chosen because it is a better insulator and would lead to a higher HGL temperature, which for this scenario would be more likely to compromise human tenability.

Ventilation: The air flow was accounted for in the HGL correlation by assuming the ventilation remained constant at 5 air changes per hour. This yielded a total ventilation rate of 2.7 m^3/s (5700 cfm). Additional calculations with the appropriate ventilation rate could have been run to assess the impact of the air purge. This was not documented in this example.

Validation: NUREG-1824 contains experimental validation results for the FDT^s that are appropriate for this scenario. In particular, the FM/SNL (Factory Mutual/Sandia National Labs) test series was designed specifically as a mock-up of a real control compartment. One of the experiments (Test 21) actually has the fire within a hollow, steel cabinet. The ventilation, leakage, and heat flux to the target (the operator in this example) were validated in the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #3 test series.

A.5.2 Zone Models (CFAST and MAGIC)

Geometry: CFAST and MAGIC divide the geometry into one or more compartments connected by vents. For this simulation, the entire compartment was modeled as a single compartment. In general, zone models simulate fires in compartments with rectangular floor areas. The selected compartment is not a rectangular parallelepiped, so it needs to be represented as such with an effective width and depth. In general, to most accurately model the enclosure filling (which is based on the volume of the compartment) and the heat transfer (which is based on the surface area of the compartment), the overall volume, height, (and thus surface area) of the enclosure needs to remain the same. For this example, the actual floor area of 371.7 m^2 (4001 ft^2) and perimeter of 83.4 m (898 ft), calculated from the drawing, yields an effective compartment size of 28.79 m by 12.91 m (94.4 ft by 42.4 ft). Compartment height is maintained at 5.2 m (17 ft).

While there are numerous cabinets and tables in the compartment, most are well below the height of the fire (discussed below) and the key height for assessment of tenability, the head of the operator, here assumed to be 1.5 m (5 ft) above the floor. Thus, the cabinets and tables are ignored in the simulation. Likewise, the drop ceiling is not modeled because it is open and it is assumed that it represents a negligible resistance to heat and air that go through it.

Fire: In CFAST and MAGIC, a fire source is described as a source of heat placed at a specific point within a compartment that burns with user-specified combustion chemistry. Consistent with typical practice for the use of zone fire models for electrical cabinet fires, the fire is assumed to originate at the top of the air vent, 0.3 m (1 ft) below the top of the cabinet at the center of the cabinet. The air vent dimensions of 0.6 m (2 ft) wide and 0.3 m (1 ft) are assumed to represent the area of the burning fire, 0.2 m^2 (2 ft^2).

Combustion chemistry in CFAST is described, at a minimum, by the production rates of CO, CO_2, and soot. For a fuel effective chemical formula of $C_2H_{3.5}Cl_{0.5}$ and soot yield of 0.1 kg/kg), the CO yield can be estimated from the work of Köylu and Faeth:

$$y_{CO} = \frac{12x}{M_f \nu_f} 0.0014 + 0.37 y_S$$

Where x is the number of carbon atoms in a fuel molecule (2 in this example), M_f is the molecular weight of the fuel (45.26 g/mol, calculated from the effective chemical formula), y_S is the soot yield, and ν_f is the stoichiometric coefficient of the fuel, here taken to be 1 since all species yields are taken as a ratio to the mass of fuel consumed. For this example, the CO yield is calculated from the above equation to be 0.038 kg/kg. The CO_2 yield is 1.52 kg/kg. Direct inputs for species production rates CFAST are normalized to this CO_2 yield. Thus, the CFAST input of CO/CO_2 is 0.025 and C/CO_2 is 0.066. A final input is the ratio of the mass of hydrogen to the mass of carbon in the fuel or 0.15 kg/kg.

Materials: CFAST does not include the ability to model individual walls of different materials. For this example, the compartment walls were assumed to be entirely made of gypsum wallboard. The floors and ceilings were modeled as 0.5 m (18 in) thick concrete. MAGIC can assign different material properties to each of the bounding surfaces.

CFAST and MAGIC do not make use of the thermal inertia, $k\rho c$, directly, but rather require individual values of each. It is assumed that the density of the carpet is 200 kg/m^3 (12.5 lb/ft^3), the specific heat is 2 kJ/kg/K, and the thermal conductivity is 0.68/200/2=0.0017 kW/m/K.

Ventilation: It is assumed that air is supplied to the MCR via the six supply vents and exhausted through the two returns. The normal flow of air ramps up after the smoke purge system is activated, which is assumed to occur 120 s after ignition of the fire. The total ventilation rate of 5 air changes per hour, 9664 m^3/hr (2.69 m^3/s or 5700 cfm). With six supply vents, a flow of 0.48 m^3/s (1017 cfm) is used for each supply. Similarly, a flow of 1.34 m^3/s (2840 cfm) in each of the two return vents would result in a balanced inlet and outlet flow. Since the system design calls for a 120 Pa (0.0174 psi) overpressure, this return flow is slightly smaller in the CFAST and MAGIC input files. In essence, this smaller return flow simply reflects the real-world balancing of the ventilation system conducted as part of the system commissioning to meet design specifications. In CFAST and MAGIC, this return flow was achieved through a series of iterative simulations without a fire source until the desired overpressure was achieved.

Purge flow was included in the simulation by modifying the vent opening at the specified time of 120 s to yield five times the base flow.

Validation: NUREG-1824 contains experimental validation results for CFAST and MAGIC that are appropriate for this scenario. In particular, the FM/SNL (Factory Mutual/Sandia National Labs) test series was designed specifically as a mock-up of a real control compartment. One of the experiments (Test 21) actually has the fire within a hollow, steel cabinet. The ventilation, leakage, and heat flux to the target (the operator in this example) were validated in the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #3 test series.

A.5.3 CFD Model (FDS)

General: The fire scenario described above is a fairly typical application for FDS. To demonstrate the capability of the model, the fire was assumed to be within, rather than on top of, the cabinet. This shows that a CFD model has more flexibility in terms of modeling the actual fire and its immediate surroundings than zone models.

Geometry: The entire compartment is included in the computational domain. The exterior concrete wall coincides with the boundary of the computational domain, meaning that the inside surface of the concrete wall is flush with the boundary of the computational domain, and the properties of concrete (including its thickness) are applied to this boundary. The tables (made out of wood) and the electrical cabinets (made out of steel) are included in the simulation. Note that the drop ceiling is not modeled because it is open and is assumed to provide a negligible resistance to heat and air that go through it.

The computational mesh consists of a uniform grid of cells that are 0.2 m (8 in) on a side. A simple grid resolution study demonstrated that because the details of the fire (other than its specified heat and smoke production rates) within the cabinet were not of importance to the question asked, there was no need to further refine the grid in the vicinity of the cabinet. An explanation related to the choices of grid sizes appropriate for use can be found in NUREG-1824, Vol. 7.

Fire: The fire is assumed to burn within a hollow steel box that represents a cabinet. The box contains a single, solid obstruction that is 1 m wide by 0.2 m wide by 1 m high (3.3 x 0.66 x 3.3 ft). The obstruction does not contact the sides of the cabinet. It is assumed that this obstruction represents an electrical panel within the cabinet that is burning over an area of 1 m^2 (10.7 ft^2). The specified HRR curve is applied uniformly to this area. A hole is cut out of the side of the modeled cabinet consistent with the position of the air vent described above. Another hole is cut out of the back side of the cabinet to allow air to supply the fire with oxygen.

The fuel stoichiometry is input to the model as specified above. FDS requires the designation of a single gaseous fuel molecule via the number of carbon and hydrogen atoms assumed in the "surrogate" fuel, plus the number of "other" atoms in the molecule that play no role in the reaction. The soot yield and heat of combustion are input exactly as given.

Materials: The non-burning cabinets are assumed to be closed boxes with the properties of steel given in Table A-1. The tables are assumed to be made out of plywood that is 5 cm (2 in) thick. The table legs are not modeled because they would play little role in the fire or heat transfer calculation to the solids. Concrete and gypsum properties are applied to the walls and ceiling. The floor consists of an assumed 1 cm (0.4 in) thick carpet over a 0.5 m (1.64 ft) thick concrete slab. The concrete properties are taken directly from Table A-1. FDS does not make use of the thermal inertia, $k\rho c$, directly, but rather requires individual values of each. It is assumed that the density of the carpet is 200 kg/m^3 (12.5 lb/ft^3), the specific heat is 2 kJ/kg/K, and the thermal conductivity is 0.68/200/2=0.0017 kW/m/K, or 1.7 W/m/K as input for FDS.

Ventilation: It is assumed that air is supplied to the MCR via the six supply vents and exhausted through the two returns. The normal flow of air ramped up after the smoke purge mode has been activated, which is assumed to occur 120 s after ignition of the fire. Steel plates are specified beneath the supply vent openings to mimic the effect of a diffusion grill. In other words, air is pushed downwards from the vent opening, but is then re-directed sideways by the plate. Because of the limited resolution of the numerical grid, this is the only way to account for the more detailed flow pattern of the real vent.

The leak from the compartment is modeled by specifying a small "vent" located at the base of the door through which air escapes at a rate determined by the pressure difference between the MCR and ambient. Note that the door crack itself is not modeled explicitly – the numerical grid is not fine enough. Rather, the leak is spread over a larger area. To achieve an over-pressure of 120 Pa (0.0174 psi), the supply volumetric flow rate is specified to be 2.88 m^3/s (6100 cfm), whereas the return flow rate is set to be 0.32 m^3/s (678 cfm) less because the volumetric flow rate through the crack is given by the following formula

$$\dot{V}_L = A_L \sqrt{\frac{2\,\Delta p}{\rho_\infty}}$$

where A_L is the leakage area (0.9 m by 0.025 m or 0.0225 m^2 (2.95x0.08 ft or 2.95x.074 ft) in this case), Δp is the pressure difference between the inside and outside of the compartment (120 Pa (0.0174 psi) in this case), and ρ_∞ is the ambient air density (1.2 kg/m^3 (0.075 lb/ft^3) in this case). The supply rate is divided equally among the six supply vents, and the return rate is divided equally among the two returns. Note that the FDS simulation is started 60 s prior to ignition to allow for the pressure to build up within the compartment.

Validation: NUREG-1824 contains experimental validation results for FDS that are appropriate for this scenario. In particular, the FM/SNL (Factory Mutual/Sandia National Labs) test series was designed specifically as a mock-up of a real control compartment. One of the experiments (Test 21) actually has the fire within a hollow, steel cabinet. The ventilation, leakage, and heat flux to the target (the operator in this example) were validated in the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #3 test series.

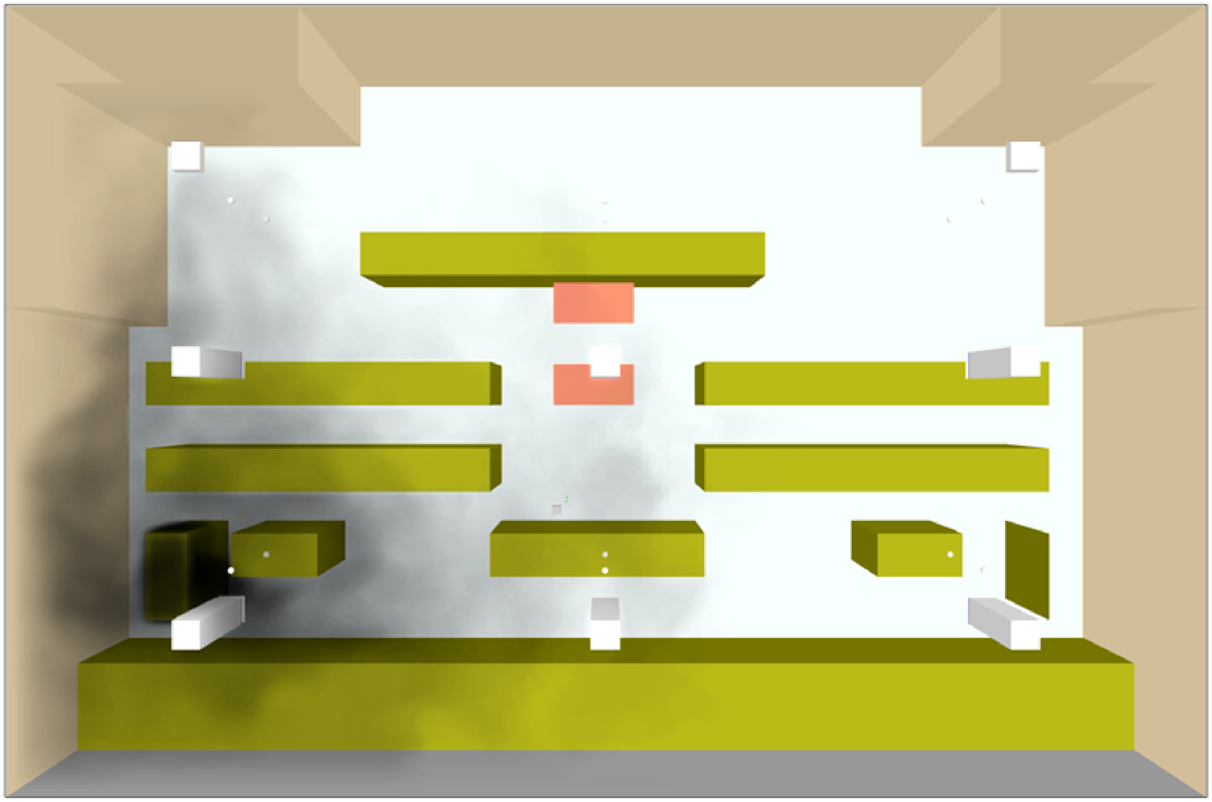

Figure A-5. FDS/Smokeview rendering of the Main Control Room, as seen from above.

A.6 Summary of Results

The results of the model simulations are shown in Figure A-6. The habitability of the control room depends on the temperature, heat flux, and smoke to which the operators would be exposed. As discussed above, a space is considered uninhabitable if the gas temperature 2 m (6 ft) above the floor exceeds 95 °C (200 °F) or the heat flux at the floor exceeds 1.0 kW/m^2 or the optical density 2 m (6 ft) above the floor exceeds 3 m^{-1}. Each of these three criteria is discussed in turn below.

A.6.1 Temperature Criterion

With the exception of the CFD model, FDS, the temperatures calculated by the models are the hot gas layer (HGL) temperatures. The calculated HGL depth for these models does not actually descend to the 1.5 m (4.9 ft) mark because of the smoke purging system. However, the substantial mixing of the gases that would actually occur in such a situation means that the two-layer assumption may not be appropriate. Thus, consideration of HGL temperature is appropriate to assess habitability.

The FDTs HGL calculation does not allow for a time-varying HRR, but rather assumes the maximum HRR is achieved instantly. As a result of this simplification, the calculations would show a temperature greater than what would be expected for a real fire scenario. It indicates that the operator would be exposed to untenable conditions in a matter of seconds. FIVE, on the other hand, does accept a time-varying HRR and predicts that the temperature would exceed 95 °C (200°F) in approximately 700 s.

Next, the two zone models, CFAST and MAGIC, predict that the temperature threshold is never reached and predict that the HGL is limited to a small layer near the ceiling of the control compartment. This is likely due to the fact that these models both include the impact of the high purging flow of the mechanical ventilation system. With the HGL located well above the operator, the near-ambient lower layer gas temperatures predicted by both CFAST and MAGIC would indicate that the temperature near the operator would not reach 95 °C (200°F).

Finally, the CFD model, FDS, does not predict that the temperature near the operator would ever reach 95 °C (200°F). FDS is better able to predict the impact of mixing of fire gases with ambient air due to the high purging flow since it models flow within the compartment in detail. The other models do not have the capability to model the enhanced mixing of the high flow rates caused by the purging flows. Finally, FDS, like any CFD model, allows greater flexibility in the specification of the fire. In this case, it was decided to model the fire within a steel cabinet rather than merely at its exterior as assumed by the simpler models. Consequently, the steel cabinet in the FDS calculation absorbs a fraction of the fire's heat output, and the plume is a bit cooler as a result.

A.6.2 Heat Flux Criterion

Like the gas temperature, the comparison of heat flux between models requires some clarification. Some of the models, like the FDTs and FIVE, assume that the fire is the only source of radiant heat flux to the operator. MAGIC and CFAST assume that the hot upper layer and the walls radiate thermal energy downwards to targets in the lower layer, in addition to the fire source. FDS also accounts for all sources of heat in more detail. In summary, all the models predict heat flux values that are well below the tenability criteria.

A.6.3 Visibility Criterion

The smoke optical density results are shown for CFAST and FDS. The other models do not make predictions of optical density. The CFAST prediction is based on its upper layer smoke concentration calculation, whereas that of FDS is based on the actual operator location. Consequently, the FDS prediction is lower because it accounts for the mixing of the upper layer smoke and lower layer air. In any case, both models predict visibility that is still considerably less than the tenability criterion of 3 m^{-1}.

A.7 Conclusion

Based on the discussion in the previous section, only the empirical models predict that the main control room would become untenable (because of temperature) in this scenario, mainly because neither accounts for the considerable effect of the smoke purging system and both base the assessment on the HGL temperature rather than the temperature at the exact location of the operator. Thus, it could be argued that no model actually predicts that the operator would be exposed to life-threatening conditions. It could be further argued that the CFD model prediction of a decrease in visibility, while not life-threatening, could have a more detrimental effect on the ability of the operators to remain within the control compartment.

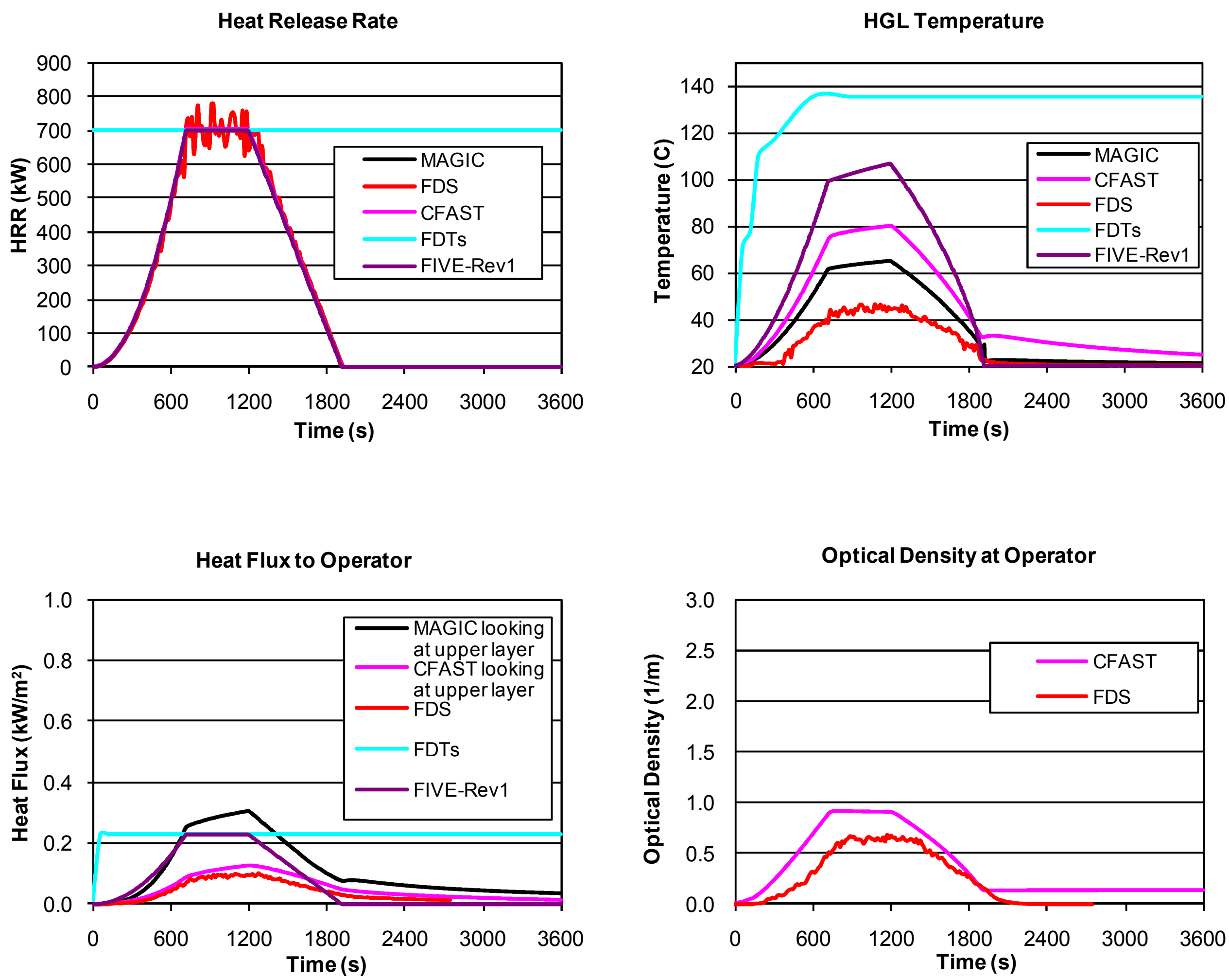

Figure A-6. Summary of the simulation results for the Main Control Room.

B
Cabinet Fire in Switchgear Room

B.1 Purpose

The calculations described in this example estimate the effects of fire in a cabinet in a Switchgear Room on nearby cable and cabinet targets. The Switchgear Room contains both Train A and Train B safety-related equipment that are not separated as required by Appendix R. The lack of separation between the two safety-related trains in this area has been identified as an unanalyzed condition. The purpose of the calculation is to analyze this condition, determine if these targets fail, and at what time failure occurs. The time to smoke detector activation is also estimated. The calculation will provide information for a decision on the hazard, risk, and potential mitigation strategies.

B.2 References

1. NUREG-1805. *Fire Dynamics Tool, 2004.*
2. NUREG/CR-6850. *Fire PRA Methodology for Nuclear Power Facilities*.
3. NUREG-1824. *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*, 2007.
4. *SFPE Handbook of Fire Protection Engineering*, 4th edition, 2008.
5. G.W. Mulholland and C. Croarkin. “Specific Extinction Coefficient of Flame Generated Smoke.” *Fire and Materials*, 24:227–230, 2000.
6. UL 217. Underwriters Laboratories, Inc., Single Station Fire Alarm Device.
7. U.O. Köylu and G.M. Faeth. Carbon Monoxide and Soot Emissions from Liquid-Fueled Buoyant Turbulent Diffusion Flames. Combustion and Flame, 87:61–76, 1991.
8. Jones, W., R. Peacock, G. Forney, and P. Reneke, “CFAST: An Engineering Tool for Estimating Fire Growth and Smoke Transport, Version 5 - Technical Reference Guide,” SP 1030, National Institute of Standards and Technology, Gaithersburg, MD, 2004.
9. Gay, L., C. Epiard, and B. Gautier “MAGIC Software Version 4.1.1: Mathematical Model,” EdF HI82/04/024/B, Electricité de France, France, November 2005.
10. NIST SP 1018-5. *Fire Dynamics Simulator (Version 5), Technical Reference Guide, Vol. 3, Experimental Validation*.

B.3 Input Data

General Description: The 4160 V Switchgear Room is located in the auxiliary building. The Switchgear Room contains 3 banks of cabinets. The center cabinet bank serves Train A equipment necessary for safe shutdown in the event of a fire. The cabinet bank on the north side of the compartment serves both non-safety and safety related Train A equipment. The cabinet bank on the south side of the compartment serves non-safety related equipment. In addition to the cabinets in the compartment, there are nine cable trays, three stacks of three trays each, which run west to east, directly above each of the cabinet banks. The lower two trays above the middle bank of cabinets contain control cables for safety-related Train B equipment. The compartment is not typically manned.

Geometry: A plan and side view of the Switchgear Room is shown in Figure B-1.

Cabinet Fire in Switchgear Room

Construction: The compartment floor, ceiling and walls are concrete. The cabinets and cable trays are made of steel, 1.5 mm (0.06 in) thick.

Cables: The cable trays are filled with PE insulated, PVC jacketed control cables. These cables have a diameter of approximately 1.5 cm (0.6 in), a jacket thickness of approximately 1.5 mm (0.06 in), and 7 conductors. They are contained in 9 stacked cable trays.

Fire Detection System: Two smoke detectors are located in the compartment at locations shown in the compartment drawing. The detectors are UL-listed with a nominal sensitivity of 1.5 %/ft (4.9 %/m).

Ventilation: There are three supply and three return registers located near the side walls. Each register has a rate of 0.472 m^3/s (1000 cfm). The mechanical ventilation is normally on. The compartment has only one door, and it is normally closed. The room temperature is maintained at 20°C (68°F) and the pressure is comparable to adjacent compartments.

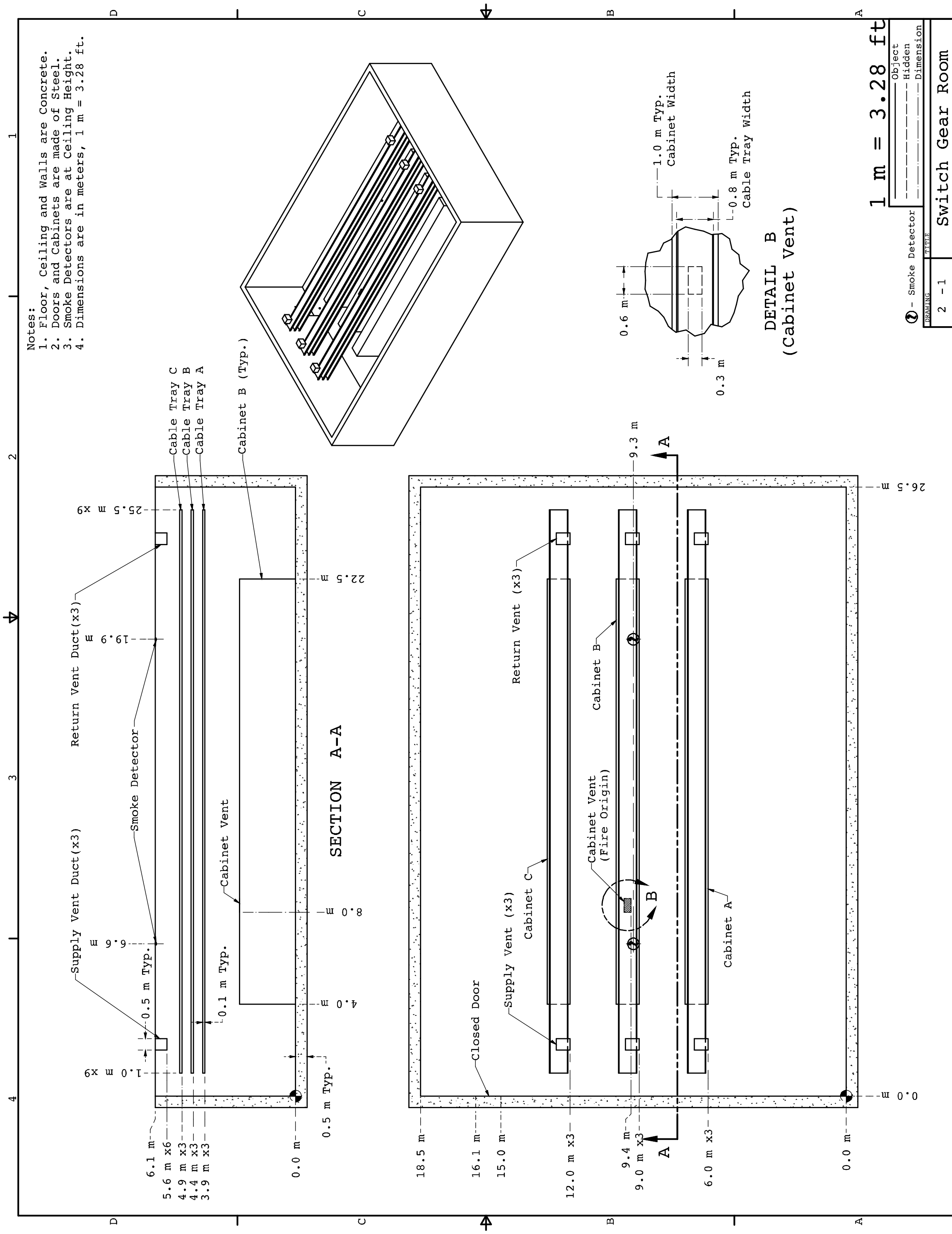

Figure B-1. Geometry of the Switchgear Room.

B.4 Fire Scenario

This section contains a list of assumptions that define the fire scenario. The information in this section is not typically obtained from plant design documents.

Fire: A fire is assumed to start in one electrical cabinet in the middle bank of cabinets, as specified in the drawing. It is assumed that the cabinet is closed and contains more than one bundle of unqualified cable. The fire is assumed to grow following a "t-squared" curve to a maximum value of 464 kW/m^2 in 12 min and remain steady for 8 additional minutes, consistent with NUREG/CR-6850, page G-5, for a cabinet with more than one cable bundle of unqualified cable. After 20 min, the HRR is assumed to decay linearly to zero in 12 min. A peak fire intensity of 464 kW represents the 98th percentile of the probability distribution for HRRs in cabinets with unqualified cable in scenarios where flames are assumed to propagate through cable bundles. From a cabinet configuration perspective, this selection is appropriate for control cables where cable loading is typically higher than in other types of cabinets. From an applications perspective, the use of the 98th percentile is consistent with the guidance provided in NUREG/CR-6850 for evaluating fire conditions with different fire intensities (including the 98th percentile) within the probability distribution range.

There is an air vent on the top the cabinet. The air vent dimensions are 0.6 m (2 ft) wide and 0.3 m (1 ft) long. The cabinet is 2.4 m (8 ft) tall. The fire is assumed to burn within the interior of the cabinet, and the smoke, heat, and possibly flames are assumed to exhaust from the air vent at the top of the cabinet.

The radiative fraction[3] of the fire is assumed to be 35 %, consistent with sooty fires. Burning cables in an electrical cabinet would produce a sooty fire (*SFPE Handbook*).

The heat of combustion of the burning cables is assumed to be 24 kJ/g (Table 2-4 of NUREG-1805). This number is appropriate for PE/PVC cable. It is assumed that a mixture of PE (C_2H_4) and PVC (C_2H_3Cl) would have an effective chemical formula of $C_2H_{3.5}Cl_{0.5}$.

For certain smoke detector activation calculations, soot yield[4] is necessary. According to Tewarson's chapter in the *SFPE Handbook*, the soot yield for the various combustible materials within the cabinet ranges from 0.01 to 0.20. The soot yield for this scenario is assumed to be 0.1, but the results of the calculation should be assessed in light of the wide variation in possible soot yields, and the fact that the fire could potentially be under-ventilated. The calculated optical density is directly proportional to this parameter; thus, the entire range of values can easily be assessed during post-processing of the results. The mass extinction coefficient is assumed to be 8.7 m^2/g, based on measurements made by Mulholland and Croarkin.

Materials: The concrete is assumed to have a thermal conductivity of 1.6 W/m/K, a density of 2400 kg/m^3 (150 lb/ft^3), and a specific heat of 0.75 kJ/kg/K (NUREG-1805, Table 2-3).

Cables: It is assumed that the cables above the switchgear cabinet have a density of 1380 kg/m^3 (86.2 lb/ft^3), a thermal conductivity of 0.192 W/m/K, and a specific heat of 1.289 kJ/kg/K. Cables are assumed damaged when the internal cable temperature reaches

[3] The fraction of the fire's total energy emitted as thermal radiation.
[4] The soot yield is defined as the mass of smoke particulate generated per unit mass of fuel consumed.

200 °C (392°F) or the exposure heat flux reaches 6 kW/m^2 (NUREG-1805, Appendix A). The damage criteria for the adjacent cabinet is assumed to be equal to that for PVC cable since the cables inside the cabinet are unqualified.

Ventilation: It is assumed that the supply air to the compartment is equally distributed among the supply vents, and that the return air is drawn equally from the returns. It is assumed that normal HVAC operations continue during the fire. The door is assumed closed throughout the scenario.

B.5 Model Assumptions

This section describes how each of the five fire model calculations was prepared. Note that a typical NPP fire modeling analysis would not necessarily require the use of all five models. However, for demonstration purposes, all five models were exercised to point out the different assumptions required of each beyond those listed in the previous section.

B.5.1 Empirical Models (FDT^s and FIVE)

General: The FDTs and FIVE spreadsheets have several algorithms that are useful for predicting the effects of fire on cables and other targets. A key difference between the two models, however, is the fact that the FDTs do not allow for a time-dependent HRR whereas FIVE does.

The FIVE analysis used Alpert's plume temperature correlations and Heskestad's flame height correlation, whereas the FDTs analysis used only those of Heskestad, to estimate the temperature to which the cables are exposed. Neither analysis included the effects of blockage due to the trays.

Geometry: The compartment in this example is rectangular; therefore the dimensions shown in the drawing are used directly.

Fire: The correlations used by the FDTs to estimate plume temperature and heat flux to a target use a steady-state HRR. A constant HRR of 464 kW was used. The FIVE analysis used the specified time-dependent HRR. Both analyses assumed the fire to be located at the cabinet top air vent, 2.4 m (7.9 ft) above the floor. Cable trays A, B, and C were assumed to be 1.5 m (4.9 ft), 2 m (6.6 ft), and 2.5 m (8.2 ft) above the fire, respectively. The radial distance from the closest smoke detector to the fire was assumed to be 1.7 m (5.6 ft), and 13.3 m (43.6 ft) to the farthest smoke detector.

Materials: The concrete property data is required for the HGL temperature estimates, but not for plume temperature or heat flux calculations.

Neither analysis used the specified properties of the adjacent cabinets as neither has a method of calculating the temperature of a heated solid. However, both analyses used the point source radiation model to estimate radiation heat flux to the cabinets. The distance between cabinets is 2.5 m (8.2 ft) (as measured from the center of the fire to the edge of the cabinets).

Both analyses used the specified properties of the cables. For the cables, the FIVE analysis used the plume temperature correlation as an estimate of the cable temperature. The FDTs used the THIEF (Thermally-Induced Electrical Failure) model, a new addition to the suite of spreadsheets, to estimate time to cable damage, using the plume temperature for the exposing temperature. THIEF is essentially a one-dimensional heat conduction calculation into a homogenous cylinder with assumed thermal properties. Electrical failure is assumed when the predicted temperature just inside the cable jacket exceeds a threshold value.

Ventilation: The empirical correlations selected for this scenario do not require that ventilation conditions be specified.

Fire/Smoke Detection: The smoke detector activation times in both analyses were based on Alpert's ceiling jet correlation with an assumed temperature increase of 10 °C (18 °F). This estimate is based on the Heskestad and Delichatsios correlation of a smoke temperature change of 10 °C (18 °F) from typical fuels (Section 11.5.1 from NUREG 1805).

Validation: NUREG-1824 contains experimental validation results for the FDTs that are appropriate for this scenario. In particular, the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #3 test series was designed specifically as a mock-up of a real Switchgear Room. These experiments include ventilation effects, heat fluxes to, and temperatures of, various targets, in particular, cables. Fire sizes in these experiments bound those used in this scenario.

B.5.2 Zone Models (CFAST and MAGIC)

General: The simple compartment geometry of this scenario lends itself well to the application of zone models. However, the relative position of the cabinet fire and cable trays make it a challenge because most of the algorithms used by the zone models to assess near-field target damage are similar to those used by the empirical models and have the same limitations.

Geometry: Both CFAST and MAGIC analyses assume the compartment to be a single rectangular parallelepiped with the specified dimensions. Neither assume that there are substantial obstructions that would require the volume be modified.

Fire: Both CFAST and MAGIC require a user-specified HRR and stoichiometry for the combustion of fuel and oxygen. In this scenario, both models assumed the fuel molecule to be $C_2H_{3.5}Cl_{0.5}$ and soot yield to be 0.1 kg/kg, as specified above. In addition, CFAST requires the specification of a CO yield. Gas yields for soot, CO, and other gases are best determined from testing of the materials of interest. In the absence of test results, the gas yields can be estimated. CO yields are available from the work of Köylu and Faeth:

$$y_{CO} = \frac{12x}{M_f v_f} 0.0014 + 0.37 y_S$$

where x is the number of carbon atoms in a fuel molecule (2 in this example), M_f is the molecular weight of the fuel (45.26 g/mol, calculated from the effective chemical formula), y_S is the soot yield, and v_f is the stoichiometric coefficient of the fuel, here taken to be 1 since all species yields are taken as a ratio to the fuel burned. Note that this correlation refers to well-ventilated fires, appropriate for this fire source. For this example, the CO yield is calculated from the above formula to be 0.038 kg/kg. The CO_2 yield is 1.52 kg/kg. Direct inputs for species production rates in CFAST are normalized to this CO_2 yield. Thus, CFAST input of

CO/CO2 is 0.025 and C/CO2 is 0.066. A final CFAST input is the ratio of the mass of hydrogen to the mass of carbon in the fuel or 0.15 kg/kg.

Both models used as input the specified time-dependent HRR curve. MAGIC uses an equivalent diameter based on the rectangular area while CFAST uses the fire area directly as an input.

Materials: Both models assume that the walls, floor, and ceiling are made of concrete, and both use the compartment drawing dimensions and target properties directly.

Ventilation: Both analyses assume normal HVAC operations continue during the fire and that the door to the compartment is closed.

Fire/Smoke Detection: In MAGIC and CFAST, there is no direct way of calculating smoke density for smoke detector activation. The recommended approach given by the developers is to model the smoke detector as a sprinkler with a low activation temperature and RTI. An activation temperature of 30 ^{o}C (86 ^{o}F) and an RTI of 5 $(m/s)^{1/2}$ was selected.

Cable Targets: In CFAST, target temperatures are calculated based on a one-dimensional heat transfer calculation that includes radiation from the fire, upper and lower gas layers, and bounding surfaces; convection from nearby gases; and conduction into the target. Radiation from the fire assumes a point source radiation calculation from the fire to the target. Cable targets were defined to be targets made of the jacketing material with a thickness equal to twice the jacketing thickness so that the center temperature of the target would be an estimate of the temperature at the inside surface of the jacketing material. This center temperature estimate was used to assess cable damage.

In MAGIC, cable target temperatures are calculated based on a heat transfer calculation that includes radiation exchanges between compartment surfaces, the upper and lower gas layers, and the nearby compartments fires; convective heat transfer that involves targets heat-up in the HGL, fire plume and ceiling jet sub-layers; and conduction into the target in a one-dimensional heat transfer calculation. Each cable is divided in 20 cm (8 in.) long segments and the maximum surface temperature calculated on all the segments is the criterion to cable ignition (at this time, the surface temperature remains constant to its last value and the cables behave like fires). Hence the relative location of the cables to the flame, plume, ceiling-jet or layers will affect the temperature calculation and the time to failure.

Validation: NUREG-1824 contains experimental validation results for MAGIC and CFAST that are appropriate for this scenario. In particular, the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #3 test series was designed specifically as a mock-up of a real Switchgear Room. These experiments include ventilation effects, heat fluxes to, and temperatures of, various targets, in particular, cables. Fire sizes in these experiments bound those used in this scenario.

B.5.3 CFD Model (FDS)

General: This scenario is a fairly typical application of FDS. Unlike the calculation performed for the Main Control Room, however, the model is applied here in much the same way that the zone models approach it, with the fire on top of the cabinet.

Cabinet Fire in Switchgear Room

Geometry: The compartment has a simple rectangular geometry which is assumed to coincide with the external boundary of the computational domain. In other words, the exterior walls are not explicitly declared, but rather are assumed to be the external boundaries of the domain with surface properties of concrete given above. The cabinets are modeled simply as boxes constructed of steel whose properties are specified above. No attempt is made to model the interior of the cabinets because the fire has been specified as originating at or near the top of one of the cabinets.

The numerical mesh consists of uniform grid cells, roughly 0.2 m (8 in) on a side. This is a relatively coarse mesh for scenario of this type.

Materials: The material properties are applied directly as specified to the walls, floor, ceiling and cabinet. The cabinet is assumed to be a hollow, steel box that is cold inside because details of the interior are not available and not of relevance to the question being asked.

Fire: The fire is specified via a "burner" atop the central cabinet with the specified HRR. This is meant to represent a fire burning near the top of the cabinet that exhausts through the vent. The fuel for the fire is assumed to be the PE/PVC cables within the cabinet. For the purpose of specifying the exhaust products of the fire, it is assumed that the fuel molecule is $C_2H_{3.5}Cl_{0.5}$. This is merely a simple way of accounting for the carbon and hydrogen within the cable materials. The chlorine is not assumed to be part of the reaction because FDS only assumes a simple one-step reaction between oxygen and a hydrocarbon fuel. The soot yield of the reaction is assumed to be 0.1, meaning that 10 % of the fuel mass is assumed to be converted to soot, which in turn is assumed to consist solely of carbon.

Ventilation: The door is included in the calculation merely as a surface of different properties from the default concrete wall. The supply and return vents are specified according to the drawing and given volume flow rates. Note that because of the relative coarseness of the underlying numerical grid, the ventilation rate is input directly in terms of the volume flow rate (m^3/s) rather than as a separate vent area (m^2) and velocity (m/s). The model automatically adjusts the dimensions of all objects to conform to the numerical mesh, and it also adjusts the velocity of the air stream to properly reflect the desired volume flow rate.

Validation: NUREG-1824 contains experimental validation results for FDS that are appropriate for this scenario. In particular, the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #3 test series was designed specifically as a mock-up of a real Switchgear Room. These experiments include ventilation effects, heat fluxes to, and temperatures of, various targets, in particular, cables.

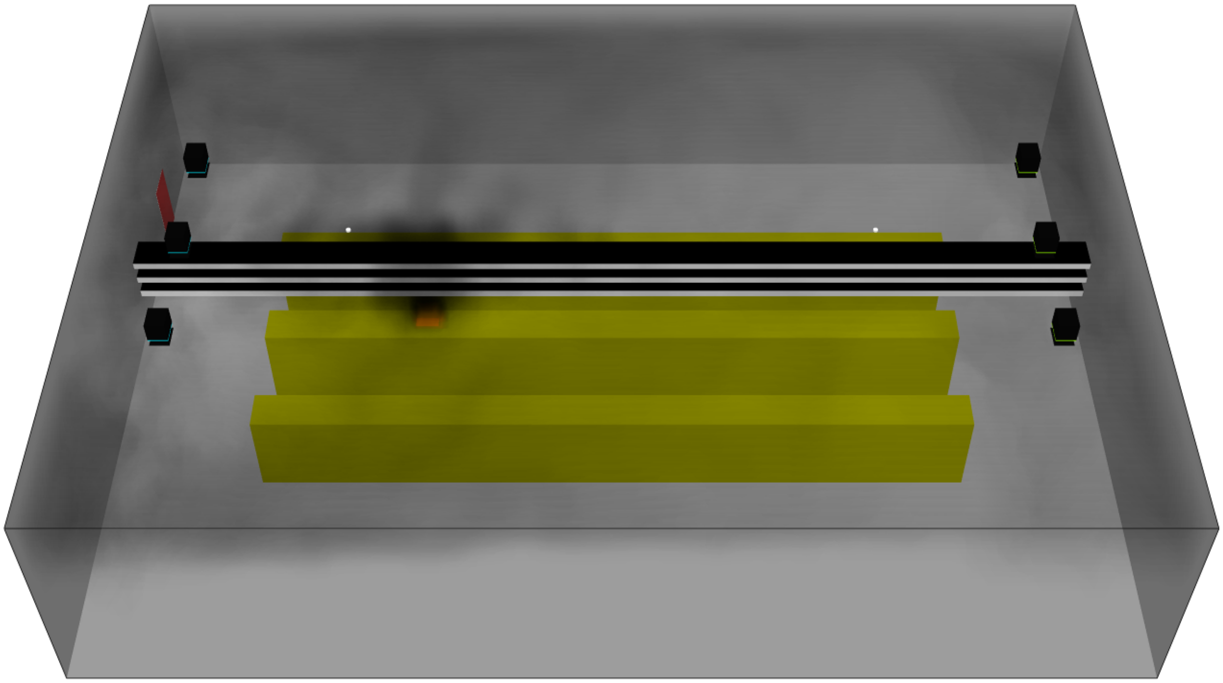

Figure B-2. FDS/Smokeview rendering of the Switchgear Room

B.6 Summary of Results

The purpose of the calculations is to assess (1) the potential damage of cables in trays above an electrical cabinet fire, and (2) the potential damage of adjacent cabinets. The results of all five models are shown in Figure B-3. The first plot shows the HRR used by the models. The FDTs require a constant HRR. FIVE uses the specified HRR of the cabinet only. CFAST, MAGIC, and FDS model the ignition and burning of the cables. NUREG/CR-6850 contains some guidance on modeling of cable ignition and flame spread based on a very limited set of fire test data. The differences in HRR between the three models results from variations in how this guidance is implemented. A research project is underway to develop additional data for cable ignition and fire spread. This new data should lead to improved cable HRR models.

B.6.1 Cable Damage

The empirical models cannot be used in this case to assess the damage to cables. FIVE does not have an algorithm that considers the thermal inertia of the cables. The FDTs do, but in this case the exposing temperature is assumed to be constant, rather than as specified.

The MAGIC, CFAST, and FDS temperature predictions for Tray A cables are shown in Figure B-3. Note that once the failure temperature is reached, MAGIC outputs that temperature from that point on. FDS continues to calculate the cable temperature past its point of assumed failure. Both models predict cable failure in Tray A at about 600 s.

As for Trays B and C, MAGIC and CFAST do not take into account the blockage effect of the trays; and, thus, its plume correlations is not applicable for an obstructed flow.

The CFD model, FDS, simulates the fire with a more realistic flow field and the inclusion of blocking obstructions. However, the specified fire scenario makes no mention of the amount of cable within the trays. Even if it were, there is considerable uncertainty associated with the calculation of flow through a pile of cables that have been arranged in no particular order.

B.6.2 Cabinet Damage

To assess potential damage to adjacent cabinets, both the predicted temperatures and heat fluxes are evaluated. Because the two adjacent cabinets are equidistant from the fire and have similar properties, only one is considered here. The critical damage thresholds are the same for these cabinets as the cables in trays.

The empirical models do not have the capability to estimate the temperature of a target such as an electrical cabinet, whereas the other models do. CFAST, MAGIC and FDS all predict similar peak temperatures of approximately 100 °C (212 °F), which is well below the threshold of 200 °C (392 °F). The slightly higher cabinet temperature predicted by MAGIC and CFAST is consistent with the fact that both models predicted a higher HRR of the fire due to the burning cables, and therefore the heat flux to the cabinet was slightly higher than that predicted by FDS. All models, including the empirical models, can estimate incident heat flux at the cabinets. The empirical models and zone models use simple point source estimates, whereas, FDS solves a three-dimensional radiation transport equation that essentially tracks thermal radiation via about 100 solid angles through a hot, smoky gas. All models predict an incident heat flux of approximately 2 kW/m^2, a factor of 3 lower than the threshold value.

B.6.3 Smoke Detector Activation

Table B-1 lists the smoke detection activation times for the various models. The FDTs are not included because it has assumed a steady-state HRR and consequently predicts detector activation in a few seconds, an unrealistic result. CFAST, MAGIC and FIVE base their activation estimates on a certain temperature rise, whereas FDS bases its prediction on the smoke concentration in the vicinity of the detector. The activation times based on temperature rise range from 3 to 5 min, whereas that based on smoke concentration is approximately 1 min. This is not a surprising result because the compartment is relatively large, and heat losses from the smoke plume to the ceiling cool the gases early in the fire, delaying the temperature-based activation estimate.

Table B-1. Smoke detector activation times, Switchgear Room cabinet fire

Model	Detector 1	Detector 2
FDT^s	N/A	N/A
FIVE-Rev1	185 s	515 s
MAGIC	280 s	330 s
CFAST	176 s	431 s
FDS	50 s	140 s

B.7 Conclusion

Based on the analysis above, the cabinet fire is likely to fail the electrical cables just overhead in approximately 10 min, based on the analyses of MAGIC and FDS. However, it is unlikely that the fire would damage the adjacent cabinets, based on all the predictions of all the models.

Cabinet Fire in Switchgear Room

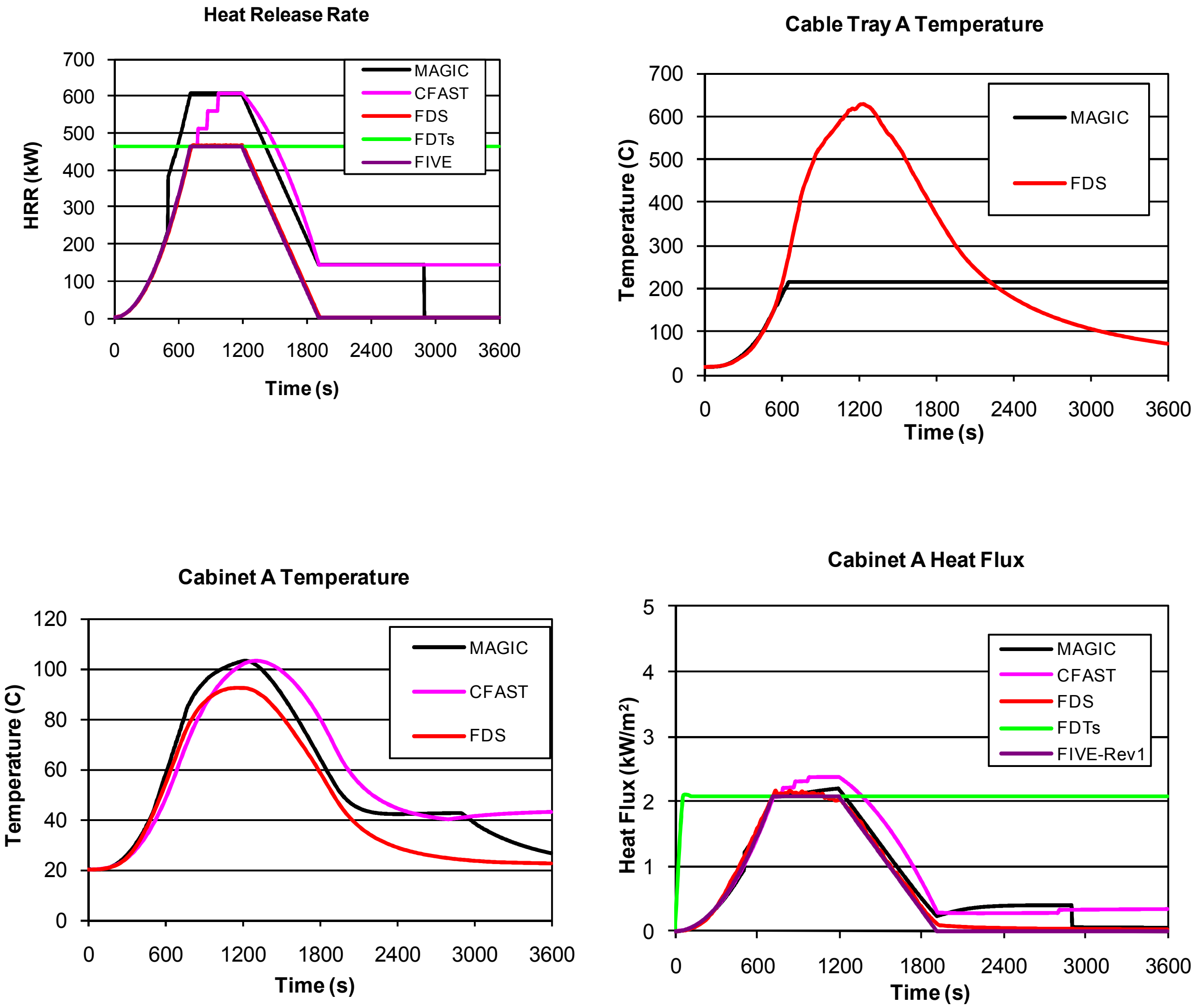

Figure B-3. Summary of simulation results for Switchgear Room cabinet fire.

C
Lubricating Oil Fire in Pump Compartment

C.1 Purpose

The calculations described in this example predict the effects of a large fire in a small compartment. The purpose of the calculation is to determine if important safe-shutdown targets fail, and at what time failure occurs. The integrity of fire barriers and boundaries and the activation of fire detection and suppression are also evaluated.

C.2 References

1. NUREG-1805. *Fire Dynamics Tools.*
2. NUREG/CR-6850. *Fire PRA Methodology for Nuclear Power Facilities*.
3. NUREG-1824. *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*, 2007.
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9. Gay, L., C. Epiard, and B. Gautier "MAGIC Software Version 4.1.1: Mathematical Model," EdF HI82/04/024/B, Electricité de France, France, November 2005.

C.3 Input Data

General Description: The compartment contains a Train A ECCS (Emergency Core Cooling System) pump and a protected cable tray containing Train B control cables. The pump is surrounded by a dike to contain any lube oil that may leak or spill. The pump has a maximum capacity of 190 L (50 gal) of lube oil. The compartment contains one smoke detector and one sprinkler.

Geometry: Figure C-1 contains a drawing of the pump compartment.

Construction: The walls, ceiling, floor and dike are made of concrete. The cable trays are made of steel.

Cables: The single cable tray in this compartment is filled with PVC insulated, PE jacketed cables. These cables have a diameter of approximately 1.5 cm (0.6 in), a jacket thickness of approximately 2 mm (0.079 in), and 7 conductors. See the drawing for the location of the cable tray. This cable tray is protected by an electrical raceway fire barrier system (ERFBS). The ERFBS is two layers of 1 in (2.54 cm) thick, 8 lb/ft^3 (128 kg/m3) Kaowool insulation blankets, covered in 1 mil foil. In qualification testing, under ASTM E 119 conditions using thresholds required in Generic Letter 86-10, Supplement 1, this ERFBS provided 24 minutes of protection. The thermal conductivity of this material is 0.06 W/m/K, the specific heat is 1.07 kJ/kg-K, and the emissivity is approximately 0.9.

Fire Protection Systems: As shown in the drawing, a smoke detector and sprinkler are mounted on the ceiling of the pump compartment. The detector is UL-listed with a nominal sensitivity of 1.5 %/ft (4.9 %/m). The sprinkler has a response time index (RTI) of 130 $(m\text{-}s)^{1/2}$ and activate at a temperature of 100 °C (212 °F) (NUREG-1805, Chap. 10).

Ventilation: There is one supply and one return register, each with an area of 0.5 m^2 (5.4 ft^3), providing a volume flow rate of 0.25 m^3/s (530 cfm). The locations are shown in the drawing. The pump compartment has only one door. It is 1.1 m (3.6 ft) wide and 2.1 m (6.9 ft) tall.

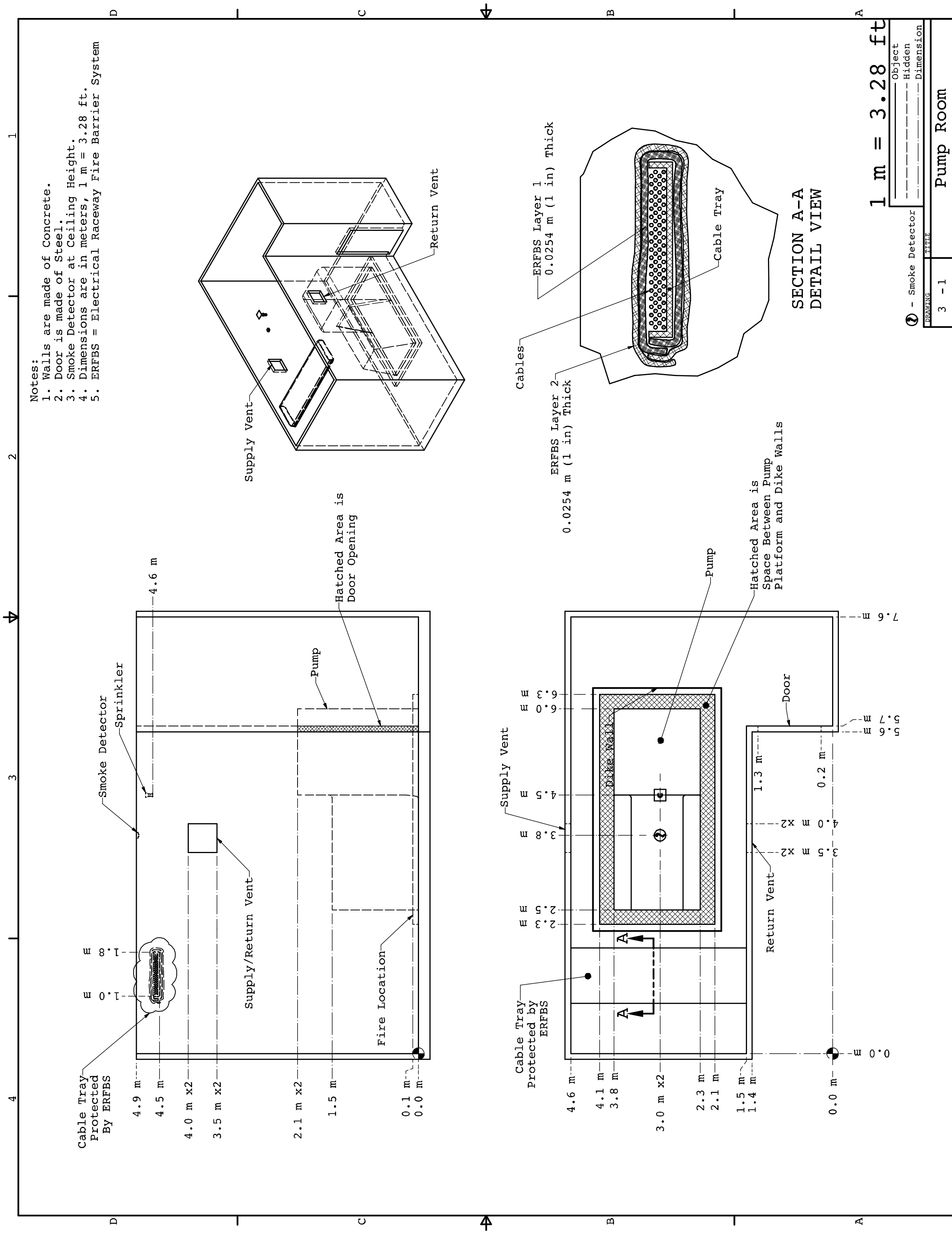


Figure C-1. Geometry of the Pump Room.

C.4 Fire Scenario

This section contains a list of assumptions that define the fire scenario. The information in this section is not typically obtained from plant design documents.

Fire: The fire is assumed to start following an accidental release of lube oil. The spill is contained by the dike. Using the values for transformer oil from NUREG-1805, the density is 760 kg/m^3 (47.4 lb/ft^3), the heat of combustion is 46,400 kJ/kg, the mass loss rate of the burning oil is 0.039 kg/m^2/s, and the empirical constant is 0.7 m^{-1}. Lube oil is a mixture of hydrocarbons. It is assumed that most are alkanes, which have a chemical formula of the form C_nH_{2n+2} with n ranging from 12 to 15.

The radiative fraction of the fire's HRR is assumed to be 35 %, a typical value for sooty fires (*SFPE Handbook*).

Materials: The walls, ceiling and floor are all assumed to be constructed of 0.9 m (3 ft) thick concrete with a density, specific heat and thermal conductivity of 2400 kg/m^3 (150 lb/ft^3), 0.75 kJ/kg/K, and 1.6 W/m/K, respectively (NUREG-1805).

Cables: The cable in the protected tray has a density of 1380 kg/m^3 (86.2 lb/ft^3), a thermal conductivity of 0.192 W/m/K, and a specific heat of 1.289 kJ/kg/K. Cables are assumed damaged when the internal cable temperature reaches 200 °C (392 °F) or the exposure heat flux reaches 6 kW/m^2 (NUREG-1805, Appendix A).

Fire Protection Systems: It is assumed that the sprinkler system fails.

Ventilation: The ventilation conditions are given above. In addition, it is assumed that the door is opened 10 min after ignition by the fire brigade. Before the door opens, it is assumed that the only leakage through the doorway is via a 2.5 cm (1 in) gap under the door. It is also assumed that the ventilation system continues to operate during the fire with no changes brought about by fire-related pressure effects. This does not imply that the fire does not impact the ventilation system, but rather that there is typically limited information about the ventilation network that feeds a given compartment.

C.5 Model Assumptions

This section describes how each of the five fire model calculations was performed. Note that a typical NPP fire modeling analysis would not require the use of all five models. The purpose is of this exercise is merely to point out the different assumptions made by each model.

C.5.1 Empirical Models (FDT^s and FIVE)

The FDTs and FIVE do not contain algorithms that are appropriate for an under-ventilated fire scenario, flashover, or the potential backdraft that could result from the opening of a door into an oxygen-starved, hot compartment. Consequently, neither model has been applied to this scenario.

C.5.2 Zone Models (CFAST and MAGIC)

Geometry: For MAGIC, the pump compartment was initially modeled as two compartments connected by an opening; however, difficulties were encountered in running the simulation the full time. Therefore, the two compartments were combined into a single compartment of the same total volume. Maintaining the total floor area and the length of the compartment perimeter unchanged for the actual and modeled compartment yields an effective compartment size of 9.4 m (30.8 ft) by 2.8 m (9.2 ft). CFAST modeled the space as two compartments with a completely open vent connecting the two compartments, sized to the width of the smaller entryway. While larger than typical for the entryway, this vent is appropriately sized in relation to the main pump compartment which is the compartment of primary interest in the simulation. For both models, the compartment height is maintained at 4.9 m (16.1 ft).

Fire: The fire size is based on the surface area of the dike around the pump. For flammable/combustible liquid spills or pools, fires are typically based on surface area and a unit-area mass loss rate. Although the dike is made up of four connected rectangles, the areas were reduced to a single equivalent area and the fire was modeled as a source of equal area. MAGIC models this as a single circular area of appropriate diameter and CFAST as an area input directly. It was assumed that the fire immediately involved the entire surface area of the dike. Based on these assumptions, an HRR of 4 MW for a total burn time of approximately 30 min was calculated. As noted previously, a radiant heat fraction of 35% was selected. A stochiometric ratio of 3.38 and an average specific area of 737.2 m^2/kg were taken from the MAGIC database for kerosene.

Materials: The Kaowool and cable properties are taken as specified. The failure temperature for PVC cable was set at 205 ^oC (401 °F) per NUREG/CR-6850. Failure of the PVC cable protected by the Kaowool was based on a center temperature of the Kaowool exceeding 205 ^oC (401 °F). CFAST can only model a single uniform target material, and consequently the ERFBS-protected cable was not modeled in CFAST.

Ventilation: Mechanical ventilation is maintained constant during the simulation, and it is assumed that the door is opened 10 min after ignition.

Fire Protection Systems: In MAGIC and CFAST, there is no direct way of calculating smoke density for smoke detector activation. Consistent with NUREG-1805, the recommended approach given by the developers is to model the smoke detector as a sprinkler with a low activation temperature and RTI. An activation temperature of 30 ^oC (86 °F) and an RTI of 5

$(m/s)^{1/2}$ was selected. Due to the large fire and small area, the results were insensitive to the activation temperature and RTI selected.

Validation: The US NRC/EPRI sponsored fire model validation study (NUREG-1824) does not address a scenario of this type. For CFAST, additional validation data are available in the Software Development and Model Evaluation Guide for the model that includes small compartments with large under-ventilated fires. Predictions of gas temperatures in these experiments show accuracies comparable to those in NUREG-1824. Details of the experiments and CFAST simulations of them are included in the CFAST Software Development and Model Evaluation Guide, NIST SP 1086.

C.5.3 CFD Model (FDS)

General: This fire scenario is a challenging application, even for a CFD model. It involves relatively high temperatures, under-ventilated conditions, and flashover. Because of the limited amount of validation data available for scenarios of this type, and the considerable uncertainties involved, the approach taken is to *specify*, rather than attempt to *predict*, the burning rate of the fuel, even though the FDS model does provide the physical mechanisms to do it.

Geometry: The compartment is modeled as shown in the drawing, except the pump itself is modeled as two rectangular boxes. A single uniform, rectangular mesh spans the entire compartment, plus the hallway outside the door. It is important to capture the flow in and out of the compartment following the opening of the door.

The numerical mesh employed consists of 0.2 m (8 in) grid cells. A finer calculation with 0.1 m (4 in) cells was performed with similar results. The latter calculation required roughly a week of computing time on a single processor computer (2008 vintage), whereas the more coarsely-gridded calculation required about 10 hours.

Materials: The properties of the concrete walls are applied directly into the model. The protected cable tray is modeled as two layers – 5 cm (2 in) of Kaowool surrounding a 2.5 cm (1 in) thick “slab” consisting of 67 % copper and 33 % plastic (by mass). The heat conduction calculation is one-dimensional and in Cartesian (not cylindrical) coordinates.

Fire: The fire is specified in the diked area surrounding the pump. Although FDS has a liquid fuel burning model, it is not being used here because there is not enough information about the fuel and, more importantly, the exact geometry of the pump and diked area. FDS would assume that the oil has formed a relatively deep pool with relatively little influence by the surrounding solids. This is not the case here. Instead, the specified burning rate, 0.039 $kg/m^2/s$, is applied directly in the model over an area of 2.75 m^2 yielding a burning rate of 0.107 kg/s. The density of the oil is 0.76 kg/L, which means that the oil burns at a rate of 0.141 L/s. At this rate, 190 L will require 1348 s to burn out.

The vaporized fuel is a mixture of various hydrocarbons, but FDS assumes only one fuel molecule. It is assumed for this calculation that the fuel molecule is $C_{14}H_{30}$.

Ventilation: The volume flow rates are applied as specified.

Validation: The US NRC/EPRI sponsored fire model validation study (NUREG-1824) does not address a scenario of this type. However, work performed at NIST for the investigation of the

World Trade Center disaster provides an appropriate data set involving a fairly large fire in a relatively small compartment, limited ventilation, a liquid fuel spray fire, heat flux to and temperatures of insulated steel (similar to the cables protected by Kaowool blankets). These experiments and the FDS simulations of them are described in NIST SP 1018-5.

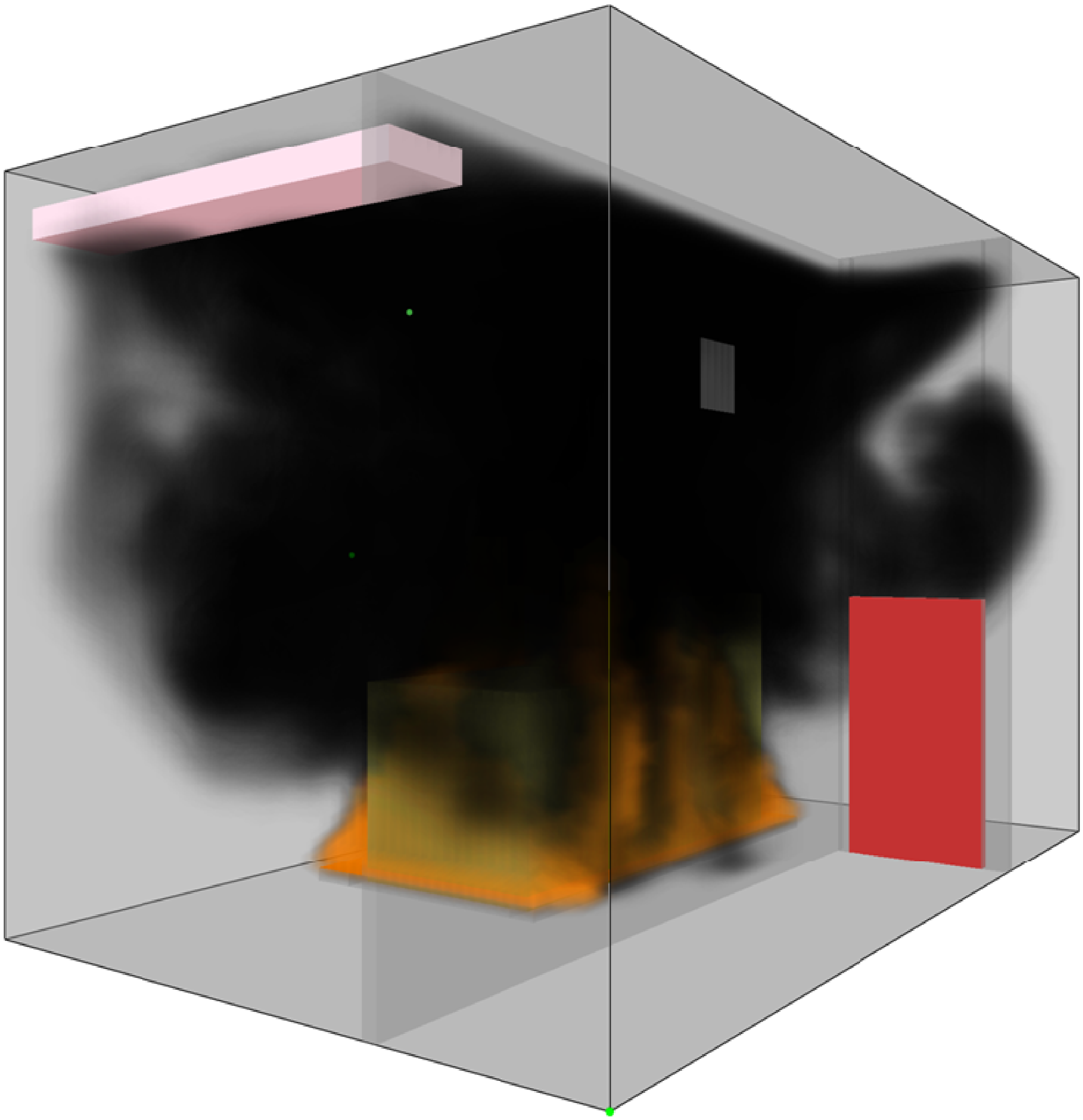


Figure C-2. FDS/Smokeview rendering of the Pump Room scenario at the early stage of the fire, before the compartment becomes under-ventilated.

C.6 Summary of Results

The purpose of the calculations discussed above is to assess whether critical cables within the pump room would be damaged in the event of a lube oil fire. In order to make the assessment, the gas temperatures and heat flux to the target tray need to be predicted. Although the burning rate of the lube oil spilled within a dike has been specified, it is clear from the results of the calculations that there would not be a sufficient amount of air within the compartment to sustain a large fire with the door closed for an extended period of time. The HRR curves predicted by the models are shown in Figure C-3.

The two empirical models, the FDTs and FIVE, do not account for the oxygen depletion effects, and as a result predict compartment temperatures that are significantly greater than the zone or CFD models. In particular, the FDT prediction is clearly beyond even theoretical limits for compartment fire temperatures. This over-prediction of temperature leads to an over-prediction of cable temperature as well, compounded by the fact that the cable temperature prediction is made without consideration of the protective thermal insulation wrapped around the tray.

The results of the zone and the CFD models are all consistent, in particular the HRR. This is not surprising because all three models use the same specified burning rate, the same assumed fuel stoichiometry, and the same basic rules of gas phase flame extinction based on oxygen and temperature levels in the vicinity of the fire. The HRR before the opening of the door drops to a level that can only be sustained by the ventilation system of the compartment, which is still assumed operational. Note that none of the models, not even the CFD model, has an algorithm capable of determining whether or not the fire would be sustained at this reduced burning rate until the door opening time. In fact, the substantial spike in the FDS prediction of HRR at 10 min results from its assumption that the fuel continues to pyrolyze in the dike, and burns rapidly following the door opening. This is what is known by fire fighters as a “backdraft,” and they have been known to cause serious injury and even death to those who open doors to compartments containing oxygen-deprived fires that suddenly flare up. The mechanisms that dictate how and when a backdraft occurs are still not understood well enough to allow for their reliable prediction. As a result, fire models typically make the assumption that fuel and oxygen burn on contact, ensuring that a backdraft will occur in the simulation, if not in reality.

Because the HRR predictions of the zone and CFD models are consistent, the predicted compartment gas temperatures are as well. The prediction of the cable temperature, however, is different for the zone and CFD models. CFAST currently has no algorithm to predict the heat penetration into a thermally-thick solid composed of multiple layers. MAGIC and FDS have heat conduction algorithms to account for the multiple layers of insulation and cable materials, but each has made its own separate prediction of the temperature and heat flux in the vicinity of the tray itself. Because the tray is in the back of the compartment, far from the door, FDS predicts a lower temperature there because the fire burns mainly in the vicinity of the open door following its opening after 10 min. MAGIC, on the other hand, assumes a uniform temperature throughout the compartment, and as a result, its temperature prediction towards the rear of the compartment exceeds that of FDS. Consequently, the MAGIC prediction of the cable temperature also exceeds that of FDS.

C.7 Conclusion

Based on the calculations above, the electrical raceway fire barrier system (ERFBS) is expected to protect the cables from reaching temperatures that would limit their functionality in the event of a fire of burning spilled lube oil. This conclusion is based on predictions of the zone model, MAGIC, and the CFD model, FDS. The zone model, CFAST, does not have a thermal conduction algorithm that is capable of predicting the temperatures within the ERFBS. However, its predictions of the overall thermal environment within the compartment are consistent with that of MAGIC and FDS.

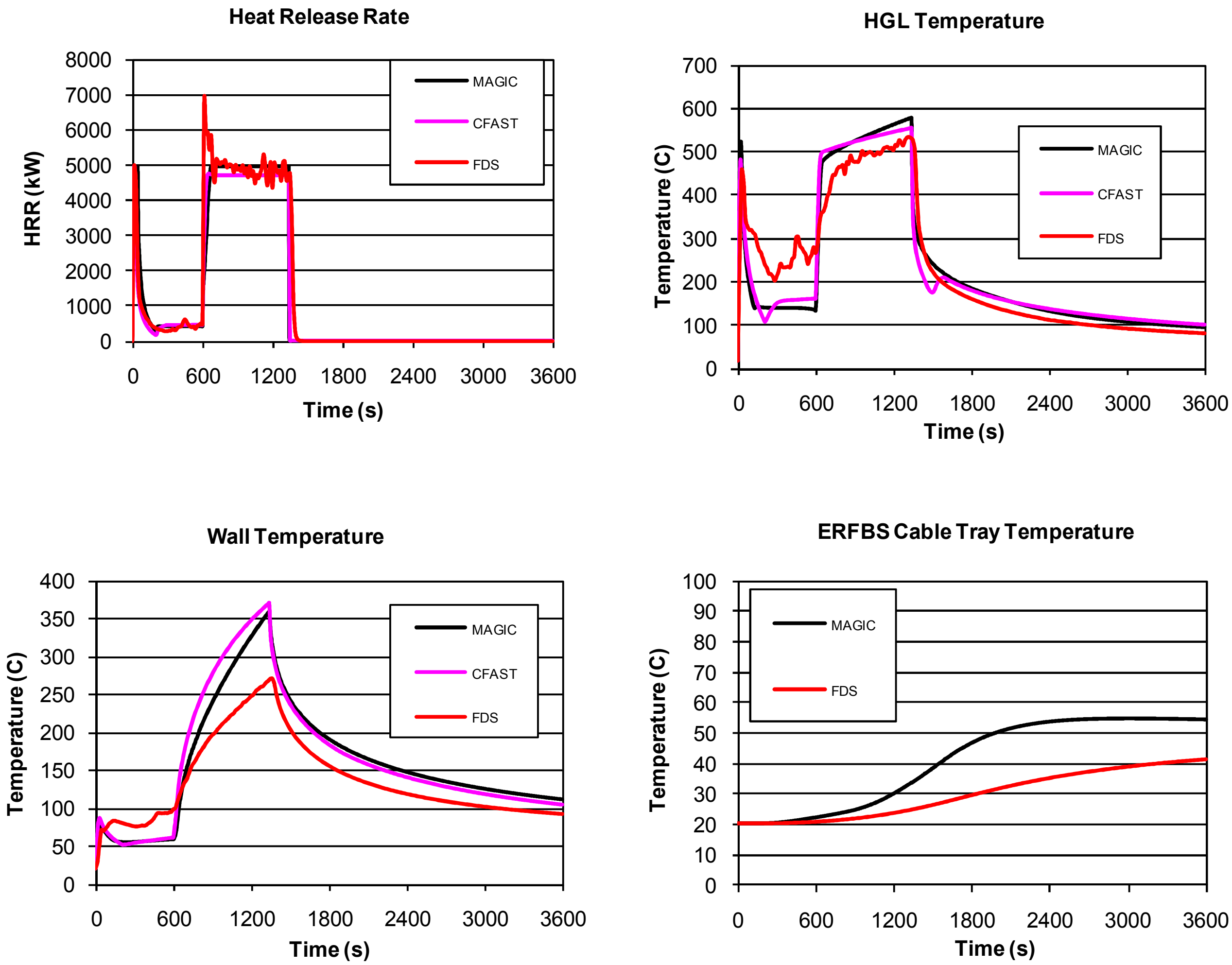


Figure C-3. Summary of results for the Pump Room fire scenario.

D
Motor Control Center Fire in Switchgear Room

D.1 Purpose

The calculations described in this example predict the effects of a fire in an MCC (Motor Control Cabinent) in a Switchgear Room on nearby cable and cabinet targets. The purpose of the calculation is to determine if these targets fail, and at what time failure occurs

D.2 References

1. NUREG/CR-6850. *Fire PRA Methodology for Nuclear Power Facilities.*
2. NUREG-1805. *Fire Dynamics Tools.*
3. NUREG-1824. *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*, 2007.
4. NUREG/CR-6931, *Cable Response to Live Fire (CAROLFIRE), Volume 2: Cable Fire Response Data for Fire Model Improvement.*
5. NUREG/CR-6931, *Cable Response to Live Fire (CAROLFIRE), Volume 3: Thermally-Induced Electrical Failure (THIEF) Model.*
6. UL 217. Underwriters Laboratories, Inc., Single Station Fire Alarm Device.
7. NIST SP 1086. *CFAST – Consolidated Model of Fire Growth and Smoke Transport (Version 6), Software Development and Model Evaluation Guide.*
8. NIST SP 1018-5. *Fire Dynamics Simulator (Version 5), Technical Reference Guide, Vol. 3, Experimental Validation*.
9. Gay, L., C. Epiard, and B. Gautier "MAGIC Software Version 4.1.1: Mathematical Model," EdF HI82/04/024/B, Electricité de France, France, November 2005.
10. *SFPE Handbook of Fire Protection Engineering*, 4th edition, 2008.

D.3 Input Data

General Description: The Switchgear Room is located in the reactor building. The compartment contains multiple motor control centers and some other switchgear cabinets.

Geometry: The layout of the compartment is shown in Figure D-1. Figure D-2 shows the equipment typically contained in the compartment, and Figure D-3 shows the significant elevation change between the “high” and “low” ceilings.

Construction: The walls, ceiling and floor are made of concrete. The cabinets and cable trays are made of steel.

Cables: The cable trays are filled with cross-linked polyethylene (XPE or XLPE) insulated cables with a Neoprene jacket. These cables have a diameter of approximately 1.5 cm (0.6 in.), a jacket thickness of approximately 2 mm (0.79 in.), and 7 conductors. The tray locations are shown the compartment drawing.

Detection System: There are two smoke detectors, centered on the ceilings at each level, located as shown in the drawing. The detectors are UL-listed with a nominal sensitivity of 1.5 %/ft (4.9 %/m).

Ventilation: The compartment is normally supplied with three air changes per hour. The supply and return vents are indicated on the drawing. The two doors are normally closed.

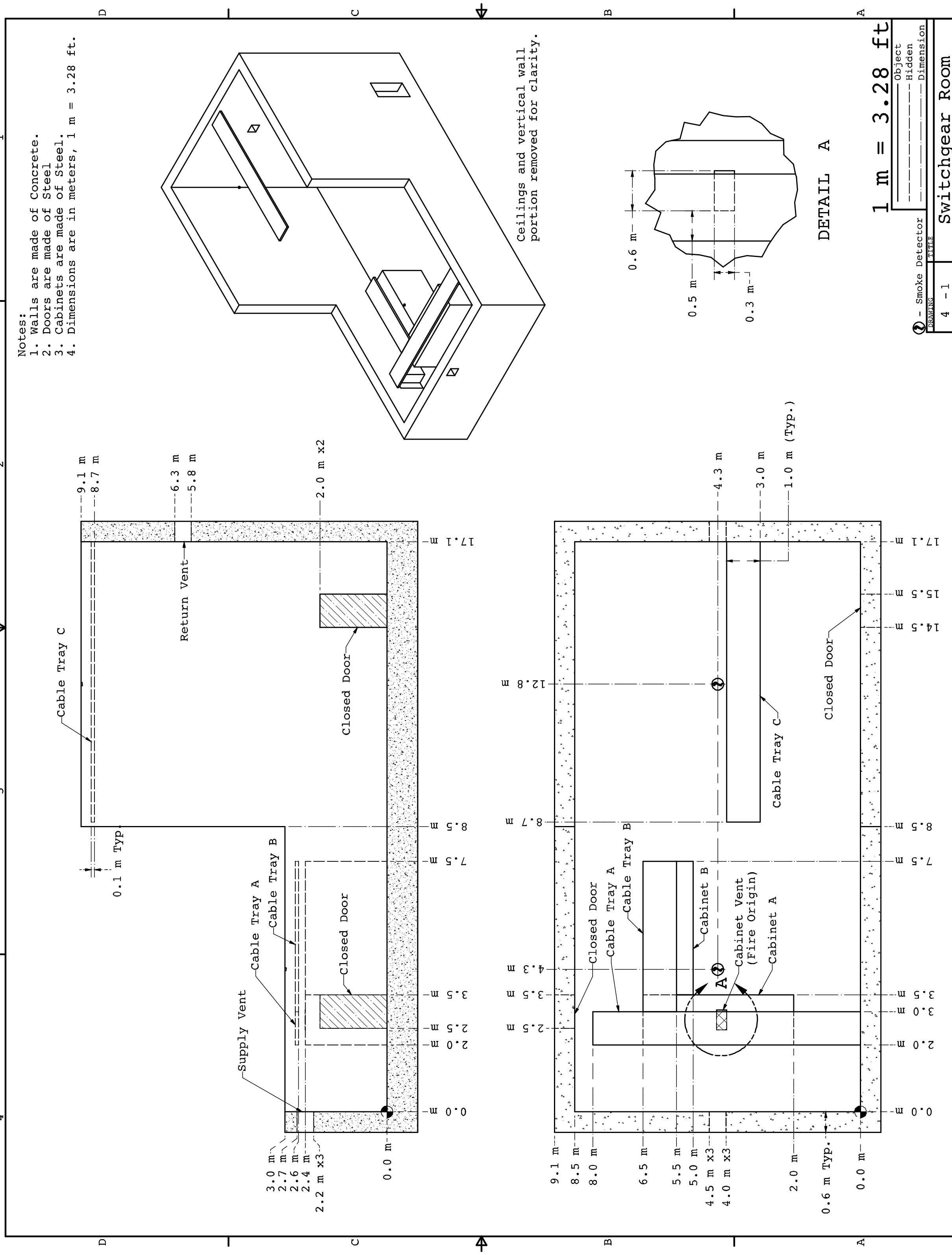


Figure D-1. Geometry of the MCC/Switchgear Room.

Figure D-2. Typical electrical cabinet in the lower part of the Switchgear Room.

Figure D-3. A view of the high ceiling.

D.4 Fire Scenario

This section contains a list of assumptions that define the fire scenario. The information in this section is not typically obtained from plant design documents.

Fire: A fire is assumed to start within a motor control center cabinet. It is assumed that the cabinet is closed and contains more than one bundle of qualified cable. The fire is assumed to grow following a “t-squared” curve to a maximum value of 702 kW in 12 min and remains steady for 8 additional minutes, consistent with NUREG/CR-6850, page G-5, for a cabinet with more than one cable bundle of qualified cable. After 20 min, the HRR is assumed to decay linearly to zero in 12 min. A peak fire intensity of 702 kW represents the 98th percentile of the probability distribution for HRR in cabinets with qualified cable in scenarios where flames are assumed to propagate through cable bundles. From a cabinet configuration perspective, this selection is appropriate for control cables where cable loading is typically higher than in other types of cabinets. From an applications perspective, the use of the 98th percentile is consistent with the guidance provided in NUREG/CR-6850 for evaluating fire conditions with different fire intensities (including the 98th percentile) within the probability distribution range.

It is assumed there is a louvered air vent on the top the cabinet. The air vent dimensions are 0.6 m (2 ft) wide and 0.3 m (1 ft) long. The cabinet is 2.4 m (8 ft) tall. The fire is assumed to burn within the interior of the cabinet, and the smoke, heat, and possibly flames are assumed to exhaust from the air vent at the top of the cabinet.

Materials: Assumed values for the relevant materials are listed in Table D-1. It is assumed that the cabinets are housed with 1.5 mm thick steel.

Cables: Assumed values for the cables in trays are listed in Table D-1. XPE cables are assumed damaged when the internal temperature just underneath the jacket reaches 400 °C (750 °F) (NUREG/CR-6931, Vol. 2, Table 5.10) or the exposure heat flux reaches 11 kW/m^2 (NUREG-1805, Appendix A). Damage criteria for the adjacent cabinets is assumed to be equal to that for XPE cable since the cables touching the heated metal will be damaged.

Ventilation: It is assumed normal HVAC operations continue during the fire. The doors are assumed closed. The volume of the compartment is 882 m^3 (31150 ft^3) meaning that three air changes per hour requires a volume flow rate of 0.735 m^3/s (1550 cfm).

Table D-1. Material Properties, MCC/Switchgear Room

Material	Thermal Conductivity, *k* (W/m/K)	Density, ρ (kg/m^3)	Specific Heat, *c* (kJ/kg/K)	Source
Concrete	1.6	2400	0.75	NUREG-1805[5]
Steel	54	7850	0.465	NUREG-1805
XPE Cables	0.235	0.235	1.39	NUREG/CR-6850

[5] The material property data is taken from Table 2-3 of NUREG-1805.

D.5 Model Assumptions

This section describes how each of the five fire model calculations was performed. Note that a typical NPP fire modeling analysis would not require the use of all five models. The purpose is of this exercise is merely to point out the different assumptions made by each model.

D.5.1 Empirical Models (FDT^s and FIVE)

General: The method of Foote, Pagni, and Alvares for predicting HGL temperatures under forced ventilation conditions was used for FDT^s analysis of the lower portion of the compartment. The HGL was not modeled in FIVE since FIVE cannot account for the two ceiling heights.

Geometry: The equations used in the FDT^s and FIVE to predict HGL temperature can only simulate fires in single compartments with a relatively uniform ceiling height. However, in this example, the FDTs calculation addresses the lower compartment with assumed dimensions of 8.5 m by 8.5 m by 3 m high (27.9 ft by 27.9 by ft by 9.8 ft).

Fire: The FDT^s correlations use a steady-state HRR to predict HGL temperature and target heat flux. A constant HRR of 702 kW was used as input for the calculation.

Materials: The walls, ceiling and floor were all assumed to be concrete.

Cables: The empirical models were not used to assess the possibility of cable damage because the HGL temperature calculation is invalid under multi-level ceiling, and the radiative heat flux calculation does not account for potential blocking by the cabinets.

Ventilation: The air flow was accounted for in the HGL correlation by assuming the ventilation remained constant at 0.735 m^3/s (1560 cfm).

Validation: The FDTs and FIVE-Rev1 have been shown to over-predict the HGL temperature (NUREG-1824) and thus provide conservative estimates of the layer temperatures exposing the cables in the lower portion of the compartment.

D.5.2 Zone Models (CFAST and MAGIC)

General: This scenario presents a challenge to the zone models because of the non-uniform ceiling height. Typically, the geometry would be modeled as two connected compartments. Alternatively, CFAST can model the space as a single compartment with a variable cross-sectional area to account for the extra volume of the high-ceiling space. Results from either approach should be similar.

Geometry: Zone fire models divide a calculation into one or more compartments connected by vents. For MAGIC, two compartments are modeled with a single vent connecting them sized to the entire width and height of one wall of the low-ceiling area. For CFAST, the two compartments are modeled as a larger compartment with a ceiling height of the lower space and a second compartment for the upper ceiling area. A single ceiling/floor vent connects the two spaces. Figure D-4 shows the geometry simulated with the CFAST model. Note for CFAST, two additional dummy compartments have been included in the calculation, not connected to any other compartment in the simulation, to visually represent the MCC cabinets within the Switchgear Room. These are included for visualization only and have no impact on the calculation.

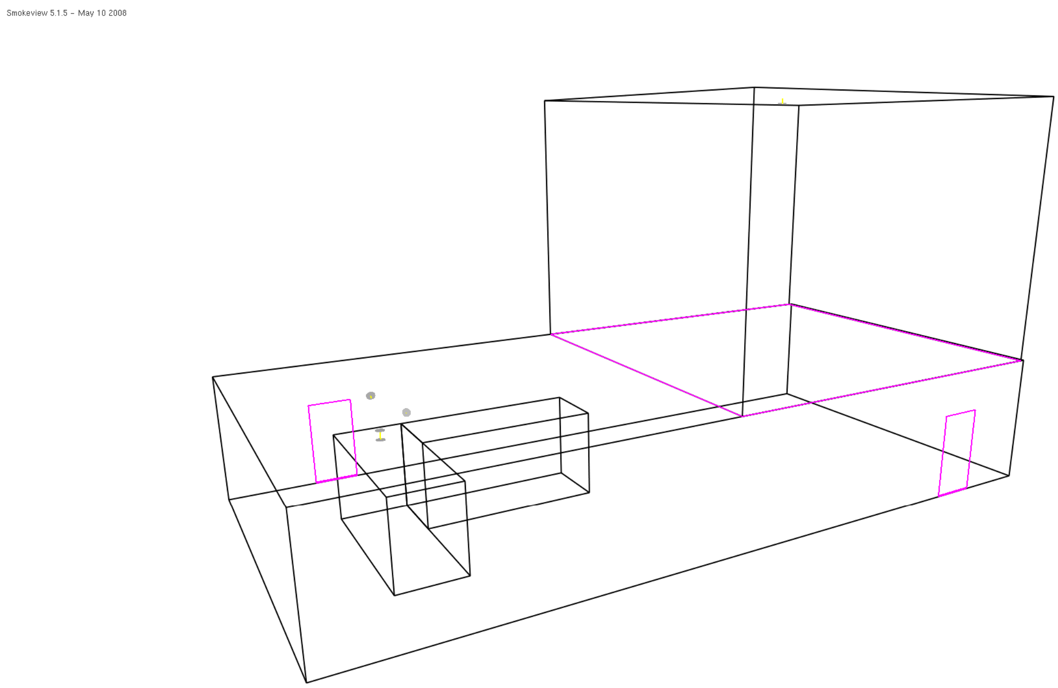


Figure D-4. Geometry two-height ceiling Switchgear Room as modeled in CFAST.

Fire: Consistent with NUREG CR-6850, the fire is placed near the top of the cabinet. It is positioned directly below the exposed cable tray to maximize exposure of the cable for the simulation. Fire area is assumed to be 0.18 m^2 (0.6 m by 0.3 m) or 1.94 ft^2 (2 ft by 1 ft) with a "t-squared" fire peaking at a HRR of 702 kW as specified. CFAST uses HRR and mass loss rate as input to describe the fire. MAGIC utilizes a mass loss rate coupled with a heat of combustion. Since no heat of combustion was specified, a value of 28.3 kJ/g was selected from the *SFPE Handbook* based on the cable types specified. MAGIC also requires a stochiometric mass-oxygen-to-fuel ratio and the average specific area for the fuel. The stochiometric mass-oxygen-to-fuel ratio can be estimated by dividing the fuels heat of combustion (28.3 kJ/g cited above) by 13.1 kJ/g – the net heat of combustion per unit mass of oxygen consumed (SFPE Handbook); this was found to be 2.16. An average specific area of 114 was calculated based on an average soot yield value for the cable type (*SFPE Handbook*).

Cables: CFAST and MAGIC include the ability to include one or more objects within a compartment that are heated or cooled by surrounding fires, gases, and bounding compartment surfaces. These target objects can be used to monitor the surface temperature of or incident heat flux to the objects. Each of three target cables is modeled in CFAST and MAGIC as a target object with uniform thermal properties. Target temperature is taken as the center temperature of the cable target. For CFAST, this target is modeled as XPE with a thickness of 2 mm (0.079 in) of XPE surrounding each side of the central conductor). For MAGIC, the target is modeled directly as a cable target. Placement of the objects is consistent with locations included in the compartment drawing. Since objects are not directly modeled as entire cable lengths, but rather as points within the compartment, exact location of each object is placed either directly above the fire source or at the point of nearest approach to a nearby object to maximize the thermal exposure to the object. For the object near the top of the high-ceiling area, the object is simply placed at the center of the space since zone models assume a horizontally uniform temperature within the surrounding gas layer (thus horizontal placement would have no impact on the resulting calculation).

Ventilation: The two compartments used to model the space are connected by a single large vent. Although the large size of this vent relative to the compartment size is not typical of a zone-model application, the simple two-compartment geometry of the space and the more dominant mechanical ventilation flow from one side of the Switchgear Room to the other should minimize any uncertainty in the calculation resulting from the large connecting vent. Mechanical ventilation is included at the specified height and with a constant volume flow of 0.735 m^3/s (1560 cfm) applied to the single supply (in the low-ceiling space) and return (in the high ceiling space) vents. Additionally, since zone fire models assume that compartments are completely sealed unless otherwise specified, a typical leakage vent, 25 mm (1 in) in height, is included at the bottom of each closed doorway to reflect the fact that the doorways are not totally airtight.

Validation: The basic smoke and heat transport algorithm used by CFAST and MAGIC to track the combustion products throughout a compartment, or throughout multiple compartments has been validated in the US NRC/EPRI-sponsored validation study, NUREG-1824. In particular, the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #2 was used to evaluate plumes of smoke and hot gases filling a fairly large, open hall with an angled roof. The NBS Multi-Compartment experiments demonstrated the ability of the models to predict conditions in a multi-compartment scenario. The fire size in this scenario is well within those studies in NUREG-1824.

D.5.3 CFD Model (FDS)

General: This scenario is a fairly typical application of FDS. Unlike the calculation performed for the Main Control Room, however, the model is applied here in much the same way that the zone models approach it, with the fire on top of the cabinet. The fact that there are two ceiling heights is not an issue with a CFD model like FDS – the compartment geometry is input as is with no need for further assumptions. In fact, it is very convenient in a case like this to use two rectangular meshes instead of one. Not only does it conform nicely to the actual geometry, but it also enables the calculation to be run in parallel on two processors instead of one. Figure D-5 is an FDS/Smokeview depiction of the scenario.

Geometry: The entire compartment is included in the computational domain. To avoid including a large portion of area outside the compartment, two separate meshes are used: one for the low-ceiling section and one for the high-ceiling section. The concrete walls are essentially the boundaries of these two meshes. The electrical cabinets and cables are included in the simulation as simple rectangular solids, and their dimensions have been approximated to the nearest 10 cm (4 in). There is no attempt made to model the details of either the cable trays or cabinets because the grid resolution is not fine enough. This is an appropriate assumption because the cables and cabinets are merely “targets” for which is sufficient to know their bulk thermal properties.

The numerical mesh consists of uniform grid cells, roughly 0.2 m (8 in) on a side. This is a relatively coarse mesh for scenario of this type, but finer meshes did not produce significantly different results. It should be noted, however, that there is considerable uncertainty in the exact nature of the fire relative to the cabinet and the cables just above. This uncertainty mainly has to do with the assumption that the fire originates directly atop the cabinet rather than deep within. It is a better use of computational resources to run multiple variations of the scenario on a relatively coarse mesh rather than perform only one with an extremely fine mesh.

Fire: The fire is assumed to burn over an area of 0.6 m by 0.3 m (2 ft by 1 ft) on top of the cabinet with a maximum HRR per unit area of 3900 kW/m^2, yielding a total HRR of 702 kW.

Cables: One of the objectives of the calculation is to predict the potential damage to the cables within three trays. FDS is limited to only 1-D heat transfer into either a rectangular or cylindrical obstruction. In this simulation, the cables are modeled as 1.5 cm (0.6 in) cylinders with uniform thermal properties given in Table D-1. Following the THIEF (Thermally-Induced Electrical Failure) methodology in NUREG/CR-6931, Vol. 3, electrical functionality is assumed lost when the temperature just inside of the 2 mm (0.079 in) jacket reaches 400 °C (750 °F). Note that no attempt is made in the simulation to predict ignition and spread of the fire over the cables, which is why the in-depth heat penetration calculation is focused on a single cable. It is assumed that at least one cable per tray is relatively free of its neighbors and would heat up more rapidly than those buried deeper within the pile.

Ventilation: Three air changes per hour are achieved with a volume flow of 0.735 m^3/s (1560 cfm) applied to the single supply and return vents.

Validation: The basic smoke and heat transport algorithm used by FDS to track the combustion products throughout a compartment that does not have a flat ceiling, or throughout multiple compartments has been validated in the US NRC/EPRI-sponsored validation study, NUREG-1824. In particular, the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #2 was used to evaluate plumes of smoke and hot gases filling a fairly large, open hall with an angled roof.

D.6 Summary of Results

The purpose of the calculations described above is to predict if and when cables and cabinets within a compartment become damaged due to a fire in the MCC. There are three cable trays and a cabinet of interest in the compartment, A, B, and C. Tray A is within the fire plume itself, and predicted damage is based on an analysis of the plume, rather than the compartment, temperatures. Trays B and C are largely subjected to the gas temperatures under the low and high ceilings, respectively. The cabinet is located in the portion of the compartment with the lower ceiling.

Figure D-6 and Figure D-7 present the results of the simulations. The HRR and HGL predictions are shown first followed by the cabinet and cable heat flux and temperature predictions. XPE cables are assumed damaged when the internal temperature just underneath the jacket reaches 400 °C (750 °F) (NUREG/CR-6931, Vol. 2, Table 5.10) or the exposure heat flux reaches 11 kW/m^2 (NUREG-1805, Appendix A). Damage criteria for the adjacent cabinets is assumed equal to that for XPE cable since he cables touching the heated metal will be damaged.

D.6.1 Damage to Cabinet

There are safety related cabinets near the one that is actually burning that must be evaluated to determine damage. Both temperature and heat flux are evaluated. The critical thresholds are the same for these cabinets as the cables in trays. Cabinet B is located adjacent to Cabinet A and approximately 1 m (3.3 ft) from the fire source. However, there is no direct line of site from the nearest part of Cabinet B.

The empirical models do not have the capability to estimate temperature at a specific location in the lower layer. Both zone models and FDS are able to provide estimates of temperatures at the cabinet locations. CFAST and FDS both predict peak cabinet temperatures of approximately 160 °C (320 °F), with peak heat fluxes in the range of 4 kW/m^2 to 5 kW/m^2. The MAGIC predictions of both cabinet temperature and heat flux are significantly lower. All of the model predictions of heat flux and temperature are considerably lower than the damage criteria.

D.6.2 Cable Damage Based on Temperature

The burning cabinet is directly under cable tray A. Neither the empirical nor the zone models explicitly define the geometry of the cabinet and trays. Instead, they use either an empirical flame height or plume temperature correlation to estimate the gas temperature at the elevation of the trays of interest.

CFAST and FDS were used in this example to predict cable temperatures using the THIEF methodology (NUREG/CR-6931). Generally speaking, the FDS predictions of both heat flux and temperature are greater than those of CFAST. Both predict that the cables in Tray A are likely to fail, but FDS predicts a failure time of approximately 5 minutes, while CFAST predicts 10 minutes. Neither model predicts that the cables in Tray B are likely to reach the failure temperature of 400 °C (750 °F), but FDS does predict that these cables could reach as high as 350 °C (660 °F). The chapter on Model Uncertainty provides guidance on how to express the uncertainty of this prediction.

The predicted temperatures of the cables in Tray C indicate that they are unlikely to fail.

D.6.3 Cable Damage Based on Incident Heat Flux

The cable damage predictions discussed above require information about the thermal properties of the cables themselves. However, the cables in any given tray within a plant may have a range of sizes and thermal properties making it impractical to predict the temperature within each and every one. For this reason, an alternative predictor for cable damage is simply the incident heat flux to the cable surface, which does not require more detailed information about the cables themselves. In this scenario, the damage threshold has been defined to be when the heat flux exceeds 11 kW/m^2 at some point during the fire.

The heat flux predictions of CFAST and FDS, like the temperature predictions, indicate that the cables in Tray A are highly likely to fail, that the cables in Tray B might fail, and that the cables in Tray C are unlikely to fail. For the interesting case, Tray B, FDS predicts a maximum (sustained) heat flux of approximately 12 kW/m^2. This exceeds the damage criterion of 11 kW/m^2. Because the temperature prediction is slightly under, and the heat flux slightly over, there is a reasonable chance that these cables may fail.

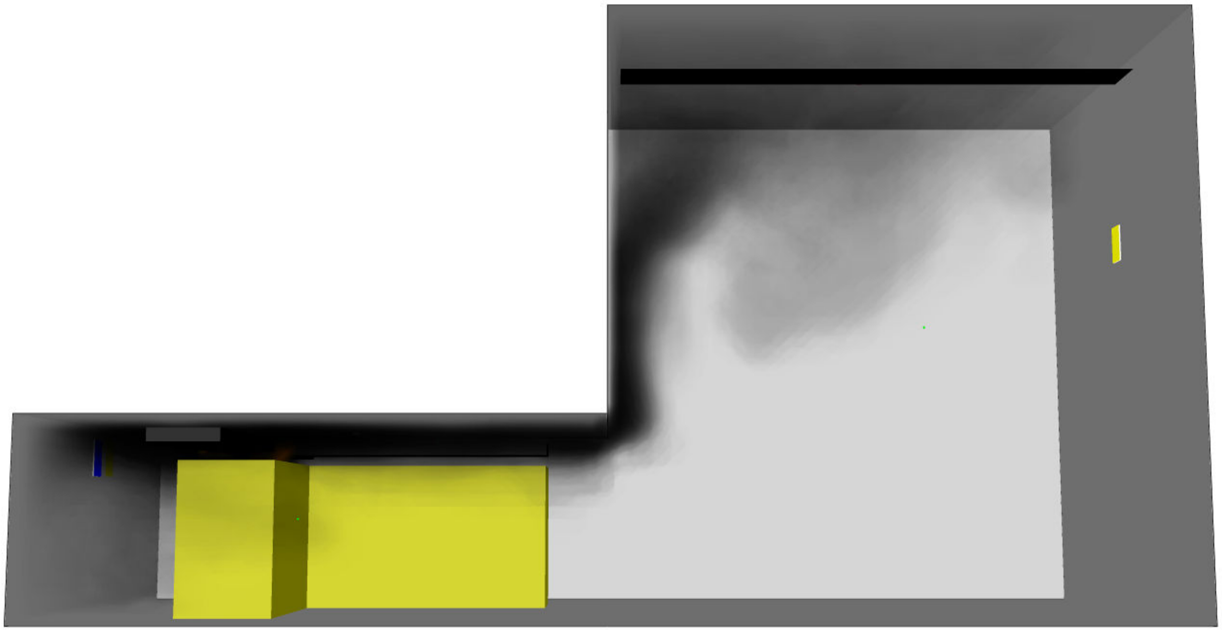


Figure D-5. FDS/Smokeview representation of the MCC/Switchgear Room scenario.

D.7 Conclusions

The calculations described in this example were designed to assess the effects of a fire in an MCC (Motor Control Cabinet) in a Switchgear Room on nearby cable and cabinet targets. The models indicate that the cables in Tray A, directly over the cabinet fire, are likely to fail due to excessive temperature and heat flux. The models indicate that the temperature and heat flux of the cables in Tray B are too close to the failure criteria to draw any firm conclusion. The models indicate that the cables in Tray C are unlikely to fail due to either excessive temperature or heat flux.

The models also indicate that the temperature of, and heat flux to, a nearby cabinet are significantly lower than the failure thresholds.

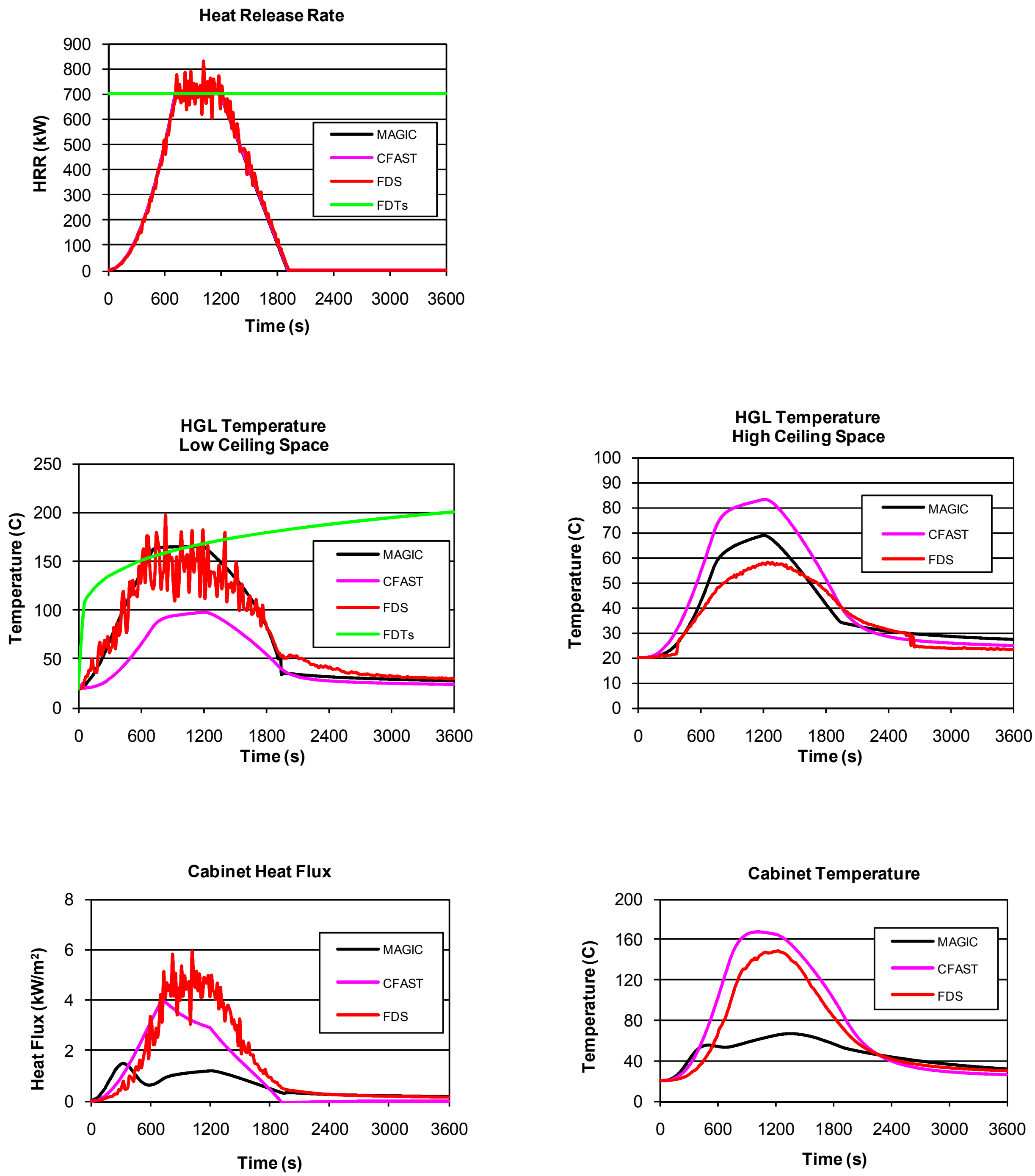


Figure D-6. Summary of simulation results for the MCC/Switchgear Room.

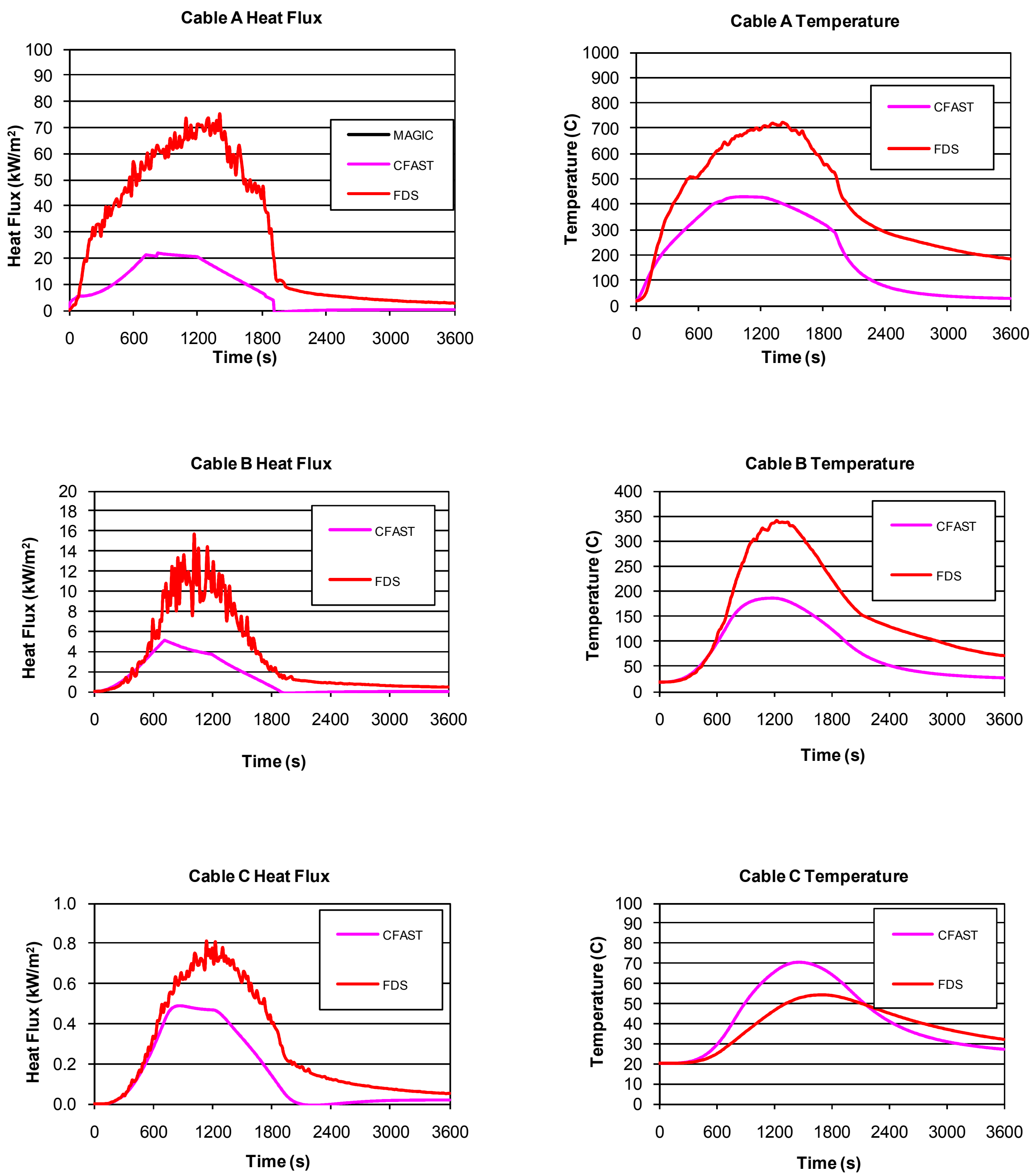


Figure D-7. Summary of cable results for the MCC/Switchgear Room.

E
Trash Fire in Cable Spreading Room

E.1 Purpose

The purpose of this calculation is to determine if important safe-shutdown cables would fail due to a fire in a trash bin inside a Cable Spreading Room. The time to smoke detector activation is also estimated.

E.2 References

1. NUREG-1805. *Fire Dynamics Tools.*
2. NUREG/CR-6850. *Fire PRA Methodology for Nuclear Power Facilities*.
3. NUREG-1824. *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*, 2007.
4. *SFPE Handbook of Fire Protection Engineering*, 4th edition, 2008.
5. EPRI Fire PRA Guide.
6. NUREG/CR-4680. *Heat and Mass Release Rate for Some Transient Fuel Source Fires: A Test Report.*
7. NUREG/CR-6931. *Cable Response to Live Fire (CAROLFIRE) Volume 3: Thermally-Induced Electrical Failure (THIEF) Model*.
8. UL 217. Underwriters Laboratories, Inc., Single Station Fire Alarm Device.
9. *SFPE Engineering Guide to the Evaluation of the Computer Model DETACT-QS*
10. NIST SP 1086. *Consolidated Model of Fire Growth and Smoke Transport, CFAST (Version 6), Software Development and Model Evaluation Guide*
11. NIST SP 1018-5. *Fire Dynamics Simulator (Version 5), Technical Reference Guide, Vol. 3, Experimental Validation*.
12. Gay, L., C. Epiard, and B. Gautier "MAGIC Software Version 4.1.1: Mathematical Model," EdF HI82/04/024/B, Electricité de France, France, November 2005.

E.3 Input Data

General Description: The Cable Spreading Room (CSR) contains a large quantity of redundant instrumentation and control cables needed for plant operation. The cables are either situated in ladder-back trays or conduits.

Geometry: Figure E-1 illustrates the CSR. In addition to cables, the CSR contains a fully enclosed computer compartment, ductwork, and large structural beams. There is no high or medium voltage equipment (switchgears or transformers) in the compartment. Figure E-2 presents a photograph of a typical CSR. As indicated in Figure E-3, the top 2 m (6.6 ft) of the compartment is filled with cable trays containing cables, or ductwork, or large structural beams.

Construction: The walls, floor, and ceiling of the CSR are constructed of concrete.

Cables: The third and sixth cable trays above the fire source are filled with PE insulated, PVC jacketed control cables that are important to safe shutdown. These cables have a diameter of approximately 1.5 cm (0.6 in), a jacket thickness of approximately 1.5 mm (0.06 in), and 7 AWG 12 conductors.

Ventilation: The CSR has two doors on the east wall that are normally closed. Each door is 2 m (6.6 ft) wide by 2 m (6.6 ft) tall, with a 1 cm (0.4 in) gap along the floor. There are two supply and two return vents, each with an area of 0.25 m^2 (2.7 ft^2). The total air supply rate is 1.4 m^3/s (3000 cfm). All vents are 2.4 m (8 ft) above the floor. Once the fire is detected, the fans stop and the dampers close.

Detection: Smoke detectors are located on the ceiling, as specified in the drawing. The detectors are UL-listed with a nominal sensitivity of 1.5 %/ft (4.9 %/m).

Suppression: An automatic CO_2 system is initiated by smoke detection in the compartment or operated manually. A CO_2 discharge causes fire dampers to close and mechanical ventilation fans to stop to maintain a proper concentration of suppression agent.

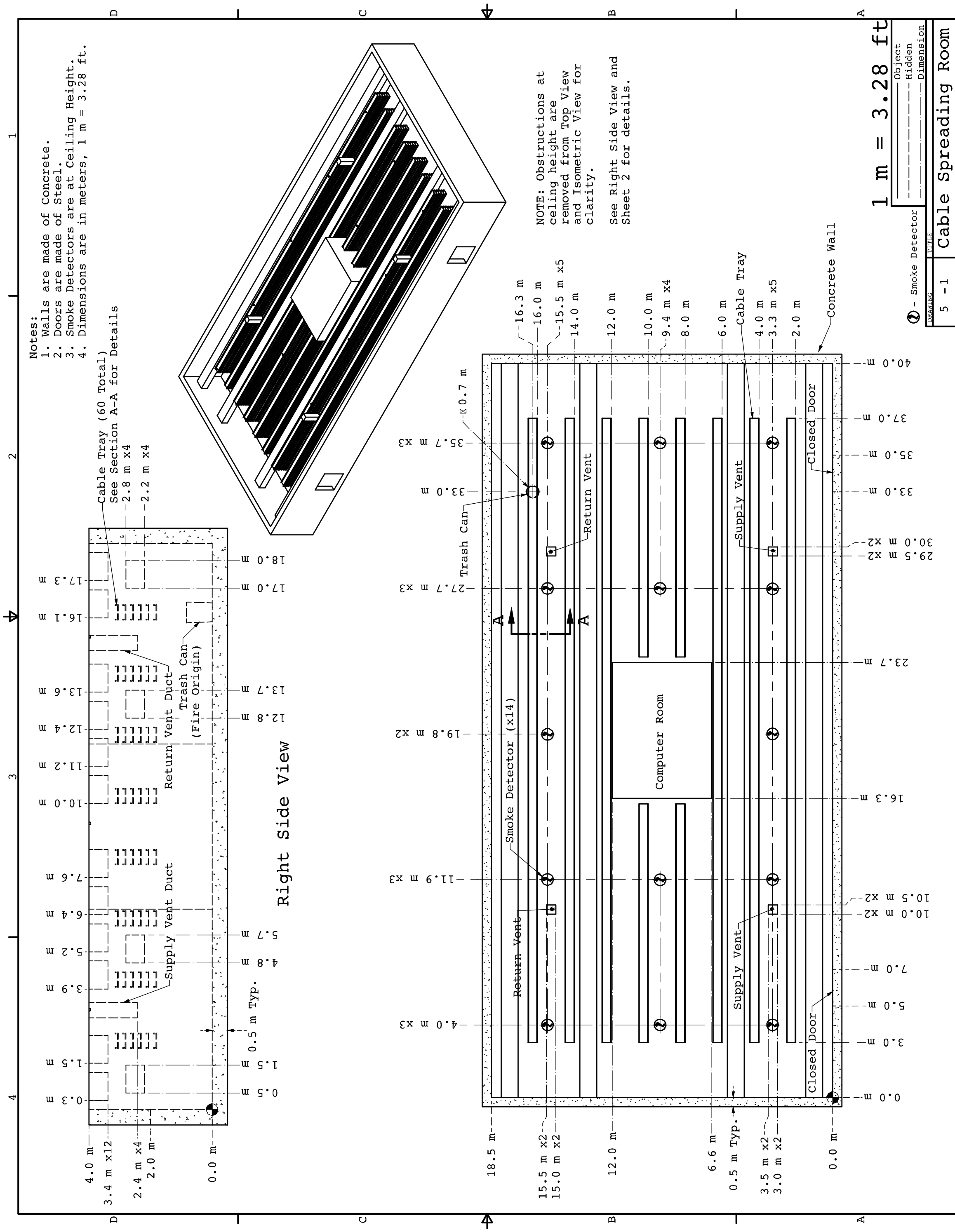


Figure E-1. Geometry of Cable Spreading Room

Trash Fire in Cable Spreading Room

Figure E-2. Photograph of typical Cable Spreading Room

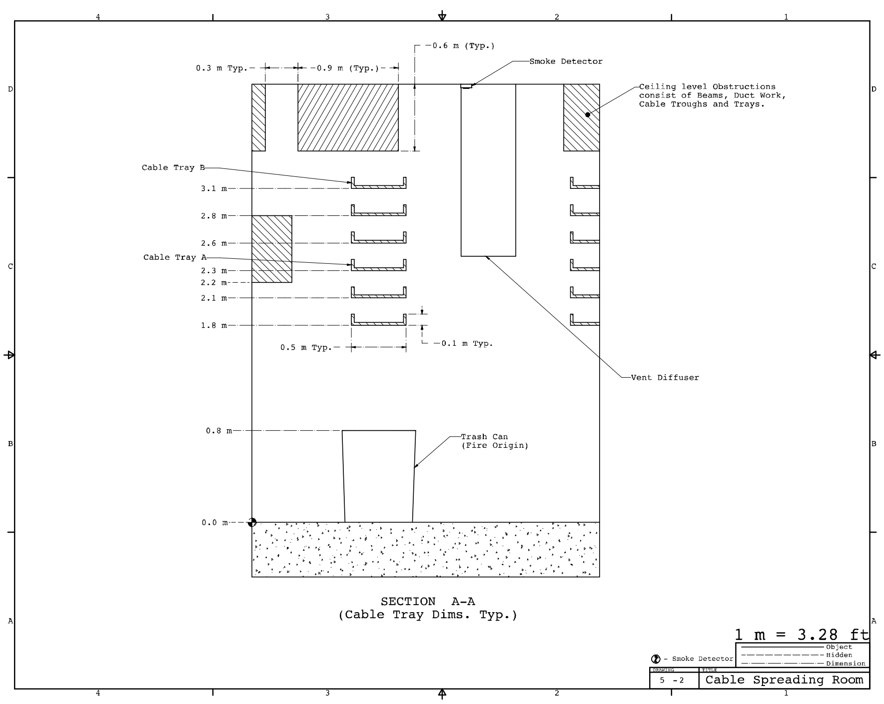


Figure E-3. Geometric detail of the Cable Spreading Room.

E.4 Fire Scenario

This section contains a list of assumptions that define the fire scenario. The information in this section is not typically obtained from plant design documents.

Fire: A trash fire is assumed to burn within a cylindrical steel waste bin 0.8 m (2.6 ft) high and 0.6 m (2.0 ft) in diameter. The HRR of the transient fire is estimated using NUREG/CR-4680. It is assumed that there is 5 kg (11 lb) of trash. The heat of combustion of the trash is assumed to be 20 kJ/g (*SFPE Handbook*; based on an average for various items that could be encountered in a trash can). The fire is assumed to grow following a "t-squared" curve to a maximum value of 130 kW in 600 s. The fire is assumed to burn at its maximum value until the trash is consumed. The radiative fraction[6] of the fire is assumed to be 35%, consistent with typical sooty fires. The soot yield of the fire is assumed to be 1.5 %, typical for wood and other cellulosic materials (Tewarson chapter, *SFPE Handbook*).

As a simplification, it is assumed that none of the cable trays ignite and, therefore, do not contribute to the overall HRR within the compartment. The currently available theory and models of cable tray ignition, flame spread and HRR (e.g., Appendix R of NUREG/CR-6850) would not provide any insights for this example calculation.

Materials: The properties of concrete are assumed to be as follows: density 2240 kg/m^3 (140 lb/ft^3), specific heat 1.2 kJ/kg/K, and thermal conductivity 1.4 W/m/K. The concrete is 0.5 m (1.6 ft) thick.

Cables: The important cables for this calculation are located in the third and sixth trays above the fire source. The properties of the PE-insulated, PVC-jacketed (PE/PVC) cables are assumed to be as follows: density 1380 kg/m^3 (86.2 lb/ft^3), specific heat 1.289 kJ/kg/K, and a thermal conductivity 0.192 W/m/K (NUREG/CR-6850). It is assumed that these thermoplastic cables fail when the temperature inside the outer jacket reaches 200 °C (392 °F) (NUREG/CR-6931).

Ventilation: It is assumed that one of the doors on the east wall is opened by an operator investigating a fire alarm 600 s (10 min) after the fire starts. Also, upon smoke detector activation, the mechanical ventilation fans stop and dampers close.

Suppression: The CO_2 system is not modeled.

[6] The fraction of the fire's total energy emitted as thermal radiation.

E.5 Model Assumptions

This section describes how each of the five fire model calculations was performed. Note that a typical NPP fire modeling analysis would not require the use of all five models. The purpose is of this exercise is merely to point out the different assumptions made by each model.

E.5.1 Empirical Models (FDT^s and FIVE)

General: The FDTs and FIVE were both used to estimate the HGL temperature, and FIVE was also used to estimate the smoke detector activation time.

Geometry: There are significant obstructions (computer compartment, cable trays, ductwork, beams) in this space that may have an effect on the HGL temperature. The FDTs and FIVE correlations do not have a specific mechanism to account for these effects.

Fire: The FDT correlations used to predict hot plume temperature assume a steady-state HRR. A constant HRR of 130 kW is used as input for the plume temperature calculations. For FIVE, a time-dependant HRR was used. The calculations assume the fire is located at the top of the trash can. This assumption yields a fire height of 0.8 m (2.6 ft) above the floor.

Materials: The walls, ceiling, and floor were all assumed to be concrete as specified above.

Cables: FIVE does not have an algorithm to predict a cable temperature. The FDTs do have an algorithm, but its exposing temperature would be based on a constant HRR, and therefore would significantly under-predict the cable failure time.

Ventilation: For both FIVE and the FDTs, the detector activation model does not account for ventilation effects.

Fire Detection: For FIVE, Alpert's ceiling jet correlation was used, and a temperature rise of 10 °C (18 °F) at the detector was used as an approximation of detector activation time. The radial distance from the smoke detector to the fire is based on the closest detector to the fire.

Validation: The plume temperature calculation has been validated in NUREG-1824. The detector activation algorithm used by FIVE was validated in the SFPE validation study of the model DETACT-QS.

E.5.2 Zone Models (CFAST and MAGIC)

Geometry: Since zone models are concerned with volumes and not physical length and width dimensions, the volume of the computer compartment, as well as the numerous cable trays, ductwork and beams was subtracted from the volume of the Cable Spreading Room and an equivalent square rectangle was used for the compartment geometry. For MAGIC, this resulted in a compartment 35.0 m by 18.5 m (115 ft x 61 ft). The ceiling height was maintained as specified. Objects were then placed in the enclosure in a manner that best approximated the location of each object with respect to the others (i.e., vertical and horizontal separations between the fire and objects of interest were maintained).

Fire: The specified fire was used for both zone models. In addition, MAGIC requires the stochiometric mass-oxygen-to-fuel ratio in order to determine under- or over-ventilated conditions. This ratio can be estimated by dividing the fuel's heat of combustion (20 kJ/g cited above) by 13.1 kJ/g – the net heat of combustion per unit mass of oxygen consumed (*SFPE Handbook*); the stochiometric ratio for this scenario is 1.53. An average specific area of 114 was calculated based on the assumed soot yield. This value is used in the soot concentration calculation of MAGIC, which relates to the radiation heat transfer. To determine the duration of the fire, the total energy of the fuel is calculated: (5 kg)×(20,000 kJ/kg) = 100,000 kJ. The area under the HRR curve is calculated to determine the burn time necessary to exhaust the fuel. This was found to be approximately 1180 s.

Materials: The material properties listed above were used for the zone models.

Cables: Following the THIEF (Thermally-Induced Electrical Failure) methodology in NUREG/CR-6931, Vol. 3, electrical functionality is assumed lost when the temperature just inside of the jacket of a thermoplastic cable reaches 200 °C (392 °F). For CFAST, the cable targets were defined with thermal properties as defined above with a thickness twice the jacket thickness. With this thickness, the center temperature of the target provides an estimate of the inner surface temperature of the jacketing consistent with the THIEF methodology. To account for the blockage of the two cable trays beneath Tray A, the CFAST simulation positioned the front face of the cable targets so that they were pointed away from the fire. This has the effect of blocking the target from radiative heating by the fire. Convective heating from the elevated temperature of the fire plume is still included in the heat transfer calculation.

Ventilation: Upon smoke detector activation, mechanical ventilation fans stop and dampers close to allow fire suppression via the CO_2 system. Therefore, before a stop time for the fans could be specified, the time to smoke detector activation was needed. This requires that MAGIC be run with the fans on for the entire time to find the first smoke detector activation. MAGIC is then re-run using the smoke detector activation time as the fan-stop time.

Fire Detection: Although there are multiple smoke detectors in the space, it was assumed the closest detector is the only one that needs to be modeled to determine time to detection. In CFAST and MAGIC, there is no direct way of calculating smoke density for smoke detector activation. Instead the smoke detector is modeled as a sprinkler with a low activation temperature and RTI. An activation temperature of 30 ^{o}C and an RTI of 5 $(m/s)^{1/2}$ were assumed. For MAGIC the smoke detector activation time was based on Alpert's ceiling jet correlation with an assumed temperature increase of 10 °C (18 °F). This estimate is based on the Heskestad and Delichatsios correlation of a smoke temperature change of 10 °C (18 °F) from typical fuels (Section 11.5.1 from NUREG 1805).

Validation: The ability of CFAST and MAGIC to calculate the smoke and heat transport from the fire in the presence of a ventilation system has been validated in NUREG-1824. The experimental test series that is most applicable is the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #3. For CFAST, plume temperature calculations have been validated for a broad range of fire sizes and distances above the fire source in the CFAST Software Development and Model Evaluation Guide, NIST SP 1086.

E.5.3 CFD Model (FDS)

General: This scenario is notable because it includes a considerable amount of "clutter," that is, the space has a relatively large number of obstructions. Because the cable trays are regularly spaced in both the horizontal and vertical directions, it is easy in FDS to simply replicate a single tray as many times as necessary. Another interesting feature of the scenario is the automatic activation of the ventilation system at the time of any smoke detector activation. FDS models this by associating the creation or removal of obstructions or the activation/deactivation of a vent to actions taken by any number of fire protection devices.

Geometry: The interior of the compartment is modeled, and all obstructions have been included. To get increased resolution in the area of interest, multiple meshes are used. The finest mesh has 10 cm (4 in) resolution and spans a volume surrounding the trash can that is 6 m (20 ft) long, 3 m wide (10 ft), and 4 m (13 ft) high. Coarse meshes cover the remainder of the compartment and adjacent hallway with cells of 20 cm (8 in). Because the objective of the calculation is to predict time to failure for cables within stacked trays, it is important to have at least 10 cm (4 in) resolution, the typical dimension of the rails of conventional cable trays.

Fire: The trash can is modeled by assuming a square, rather than round, cross section with equivalent area and the same height as specified. The specified HRR is applied to the top of this obstruction. The duration of the fire is assumed to be 1180 s, the same assumption as is made for the zone models. No attempt is made to model the interior of the can.

Materials: The thermal properties of the walls are applied directly as specified.

Cables: One of the objectives of the calculation is to predict the potential damage to the cables within the trays. FDS is limited to only 1-D heat transfer into either a rectangular or cylindrical obstruction. In this simulation, the cables are modeled as 1.5 cm (0.6 in) cylinders with uniform thermal properties given above. Following the THIEF (Thermally-Induced Electrical Failure) methodology in NUREG/CR-6931, Vol. 3, electrical functionality is assumed lost when the temperature just inside of the jacket of a thermoplastic cable reaches 200 °C (392 °F). Note that no attempt is made in the simulation to predict ignition and spread of the fire over the cables. The THIEF methodology does not account for the effects of bundled cables, which may reduce the overall heat-up of a single cable.

Detection: In addition, FDS has a smoke detection algorithm that predicts the smoke obscuration within the detection chamber based on the smoke concentration and air velocity in the grid cell within which the detector is located. The detector itself is not modeled – it is merely a point within the computational domain. The two parameters needed for the model are the obscuration at alarm, which is given by the manufacturer, and an empirically determined length scale from which a smoke entry time lag is estimated from the outside air velocity. The *SFPE Handbook* provides a nominal value of 1.8 m (5.9 ft) for this length scale. The obscuration at alarm is 4.9 %/m (1.5 %/ft, a typical sensitivity for smoke detectors).

Ventilation: The supply and return air flow rates are input directly into FDS. The ducts are represented by rectangular obstructions with thin plates just below (one grid cell) the vent itself to represent the diffusing effect of the grill. The resolution of the grid is not fine enough to capture this effect directly. FDS has the capability to stop the ventilation system upon the activation of any smoke detector.

Validation: The ability of FDS to calculate the smoke and heat transport from the fire in the presence of a ventilation system has been validated in NUREG-1824. The experimental test series that is most applicable is the ICFMP (International Collaborative Fire Model Project) Benchmark Exercise #3. Smoke detection is not included in NUREG-1824, but papers and articles on the subject are cited in NIST SP 1018-5.

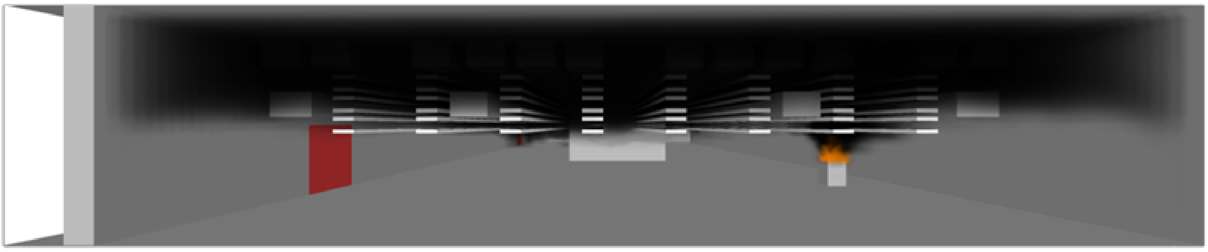


Figure E-4. FDS/Smokeview rendering of the Cable Spreading Room scenario.

E.6 Summary of Results

The purpose of the calculations described above is to predict smoke detector activation times and potential cable damage from a trash can fire in the Cable Spreading Room. The compartment itself is relatively large and the relatively small fire (130 kW) does not substantially heat it up. The HRR curves and other outputs are shown in Figure E-5.

E.6.1 Smoke Detection

Table E-1 shows the results for smoke detection activation for the various models. Except for FDS, the models assume that a smoke detector can be treated like a heat detector with a relatively low thermal inertia and activation temperature. However, there is no consensus in the fire literature for the appropriate RTI (Response Time Index) value and activation temperature. In addition, some models use the computed HGL temperature (FDTs and CFAST), and others use a ceiling jet correlation (FIVE and MAGIC). For a weak, slowly growing fire in a large space, these different assumptions lead to a wide variety of results. Given the presence of beam pockets and obstructions, even a CFD model like FDS that uses actual smoke concentration rather than temperature in its detector algorithm is subject to significant uncertainty.

Table E-1. Smoke detector activation times, Cable Spreading Room

Model	Time (s)
FDTs	N/A
FIVE-Rev1	325 s
MAGIC	525 s
CFAST	280 s
FDS	165 s

E.6.2 Cable Damage

CFAST and FDS make similar predictions of the cable temperature. The predicted heat flux by CFAST is slightly higher than FDS because CFAST does not account for the fact that the cable trays of interest are shielded by trays below. For Cable Tray A, CFAST predicts a slightly lower cable temperature than FDS, even though its heat flux prediction is greater. This is most likely due to the fact that FDS assumes the cable to be a cylinder, whereas CFAST assumes it to be a slab of comparable thickness. In any event, neither model predicts that the cables will reach the damage temperature.

E.7 Conclusions

The analysis have shown that a 130 kW trash can fire beneath a vertical array of cable trays is unlikely to damage cables in the trays three and six levels above the fire. Both CFAST and FDS predict peak temperatures of approximately 100 °C (212 °F) for cables in the third tray from the bottom. However, this analysis has not included any consideration of the ignition and burning of the cables themselves. Depending on the duration of the fire, it is possible that cables in the first two trays from the bottom could add to the HRR and consequently damage cables above.

Because of the uncertainty in the smoke detector activation prediction of all the models and the uncertainty associated with the possible ignition of cables in the trays just above the fire, it is difficult to predict whether or not the CO_2 suppression system would be activated in time to prevent possible cable ignition.

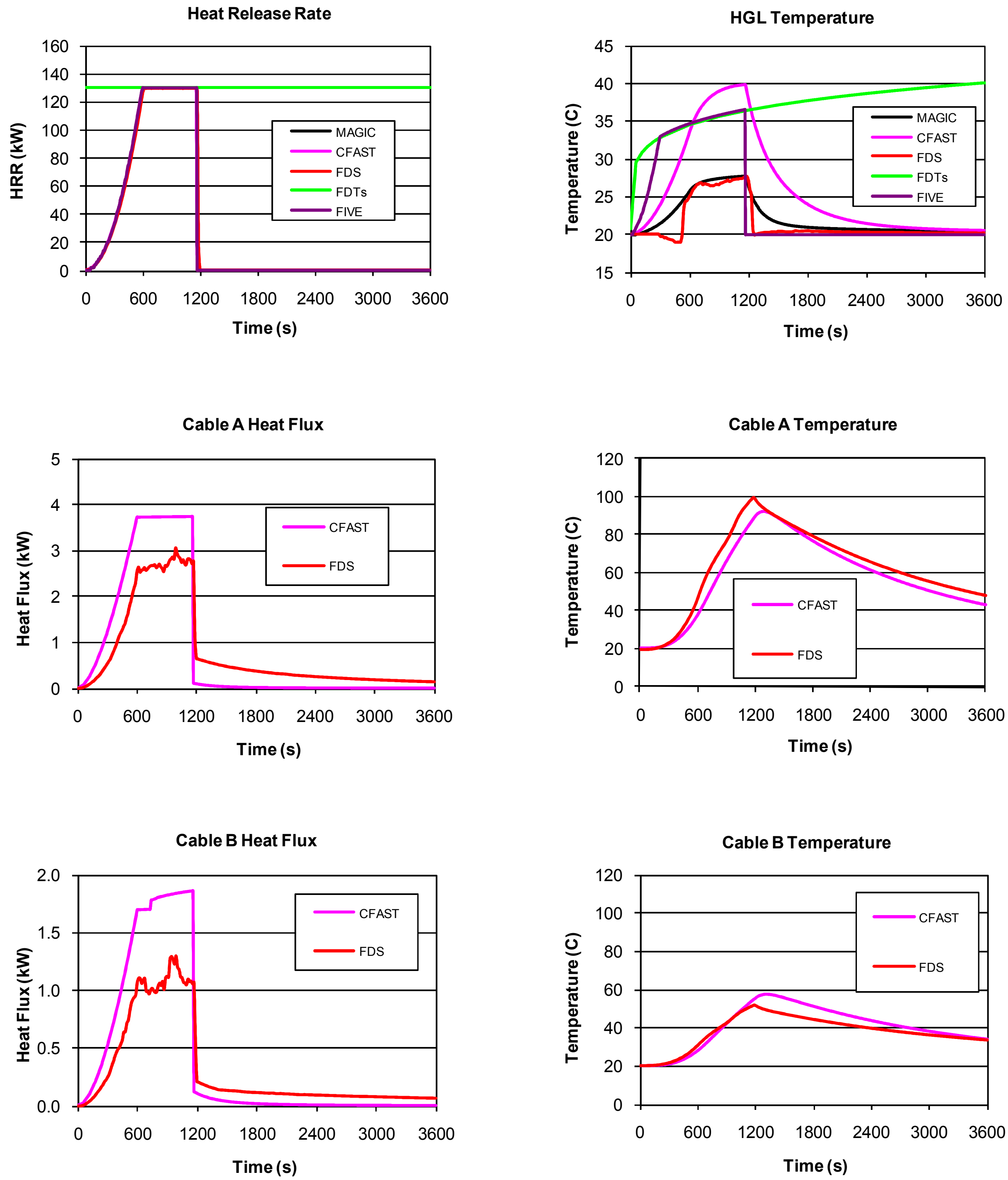


Figure E-5. Summary of simulation results for the Cable Spreading Room.

F
Lubricating Oil Fire in Turbine Building

F.1 Purpose

The calculations described in this example predict the effects of a very large fire in a turbine building. The purpose of these calculations is to determine the structural integrity of the turbine building columns during a large lube oil fire.

F.2 References

1. NUREG/CR-6850. *Fire PRA Methodology for Nuclear Power Facilities.*
2. NUREG-1805. *Fire Dynamics Tools.*
3. NUREG-1824. *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*, 2007.
4. *SFPE Handbook of Fire Protection Engineering*, 4th edition, 2008.
5. NIST SP 1018-5. *Fire Dynamics Simulator (Version 5), Technical Reference Guide, Vol. 3, Experimental Validation*.
6. NIST NCSTAR 1-5F. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Computer Simulation of the Fires in the World Trade Center Towers*, 2005.
7. NIST SP 1086. *Consolidated Model of Fire Growth and Smoke Transport, CFAST (*Version 6*), Software Development and Model Evaluation Guide*
8. Gay, L., C. Epiard, and B. Gautier "MAGIC Software Version 4.1.1: Mathematical Model," EdF HI82/04/024/B, Electricité de France, France, November 2005.

F.3 Input Data

General Description: The turbine building houses two turbines and other equipment important to safely shutting down the reactor in the event of a fire. The lube oil tank is located one level below the turbine deck.

Geometry: A plan view of the turbine building and is shown in Figure F-1. This calculation involves the two upper levels, which are separated by a concrete slab. There are stairwells, hatches and exhaust vents penetrating the slab. The items labeled '**P**' in the drawing are penetrations through the turbine deck to the level below, areas labeled '**S**' are stairwells to the lower level, and there are 18 exhaust vents to the outside around the perimeter of the turbine deck level.

Construction: The turbine deck is made of concrete. Some areas and landings in the turbine building are made of metal grating. The floor in the area of the lube oil tank is 1m (3.3 ft) thick concrete. The walls and ceiling of the upper level of the turbine building are made of corrugated steel. There are 40 unprotected steel support columns (W14x145 see Detail A in the drawing) in a rectangular configuration (4 rows of 10 each) around the lube oil tank.

Detection System: None.

Ventilation: The calculated area is an open configuration, with no forced ventilation or openings other than those specified in the drawings

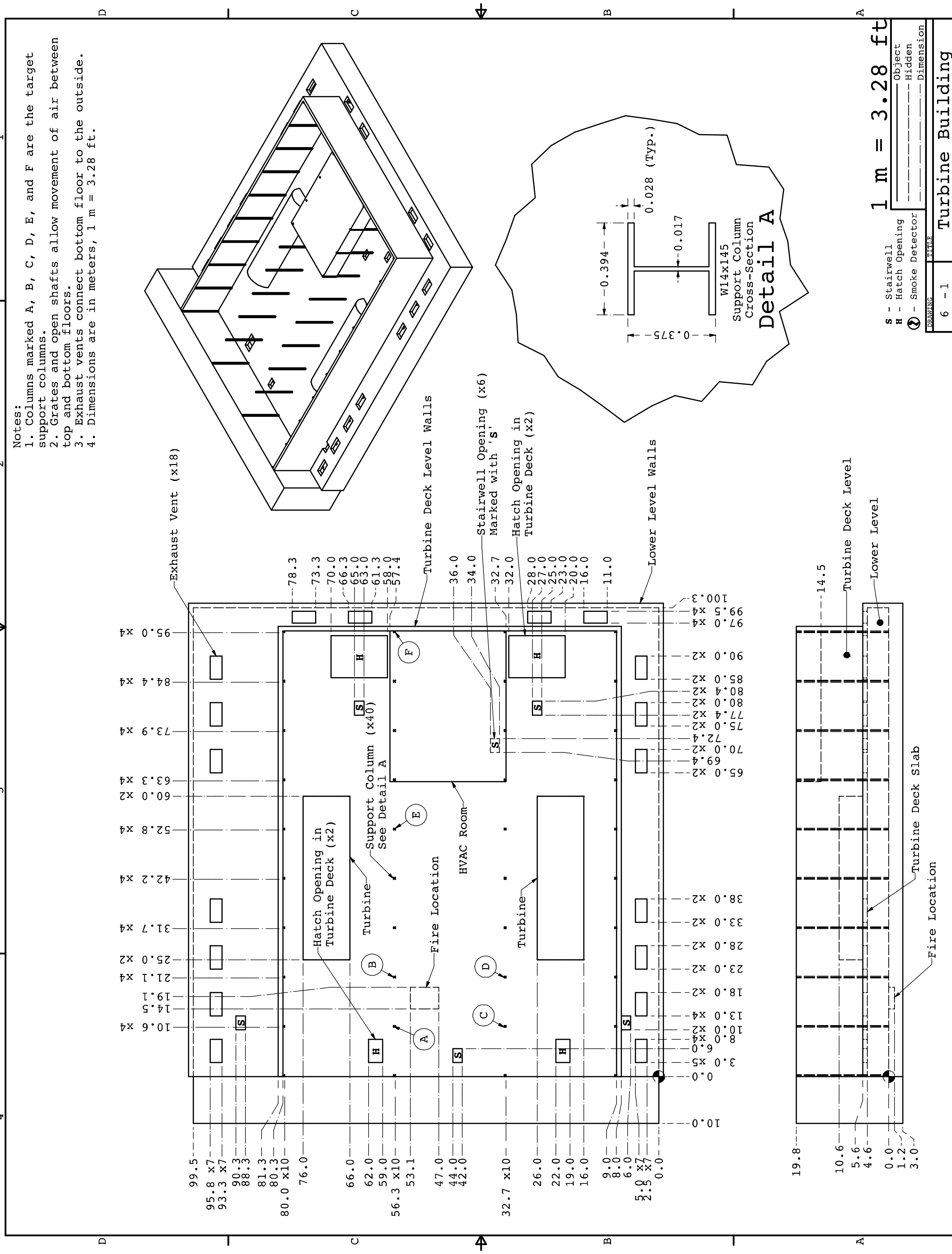


Figure F-1. Geometry of the Turbine Building

Figure F-2. Typical support column in the Turbine Building.

Figure F-3. The lube oil tank below the turbine deck.

F.4 Fire Scenario

This section contains a list of assumptions that define the fire scenario. The information in this section is not typically obtained from plant design documents.

Fire: The fire is assumed to be a large turbine lube oil fire as a result of a rupture of the line between the lube oil tank and the pump. Prior to ignition, approximately 3000 L (800 gal) of lube oil from the tank has spilled into the catch basin around the tank. The area of the spill is indicated in the drawing. The entire area of the pool of lube oil is assumed to ignite instantaneously, producing a HRR per unit area (HRRPUA) of 1795 kW/m^2 (NUREG-1805, page 2-21).

Using the values for transformer oil from NUREG-1805, the density is 760 kg/m^3 (47.5 lb/ft^3), the heat of combustion is 46,400 kJ/kg, the mass loss rate of the burning oil is 0.039 kg/m^2/s, and the empirical constant is 0.7 m^{-1}. Lube oil is a mixture of hydrocarbons. It is assumed that most are alkanes, which have a chemical formula of the form C_nH_{2n+2} with n ranging from 12 to 15.

The radiative fraction of the fire's HRR is assumed to be 35 %, a typical value for sooty fires (*SFPE Handbook*).

Materials: Assumed values for the thermal properties of various materials in the turbine building are listed in Table F-1.

Support Columns: The cross sectional dimensions of the columns are indicated in the drawing, Detail A. The steel support columns are assumed to fail when the temperature of the steel at a single point reaches 649 °C (1200 °F). This is the endpoint criteria for steel columns as defined in ASTM E 119, as referenced by NUREG-1805.

Ventilation: Leakage areas in the domain of this calculation are enough to prevent significant over-pressurization due to this fire scenario.

Table F-1. Material Properties, Turbine Building

Material	Thermal Conductivity, *k* (W/m/K)	Density, *ρ* (kg/m^3)	Specific Heat, *c* (kJ/kg/K)	Source
Concrete	1.6	2400	0.75	NUREG-1805
Steel	54.	7850	0.465	NUREG-1805

F.5 Model Assumptions

This section describes how each of the five fire model calculations was performed. Note that a typical NPP fire modeling analysis would not require the use of all five models. The purpose is of this exercise is merely to point out the different assumptions made by each model.

F.5.1 Empirical Models (FDT^s and FIVE)

General: The FDTs and FIVE calculate the radiant heat flux to each column within the turbine building by assuming the fire is a point source in the presence of no wind.

Geometry: The only geometric parameter needed by the empirical models is the distance between the fire and respective columns, A, B, C, D, E, and F, which were calculated to be 10.7 m (35.1 ft), 7.6 m (24.9 ft), 18.4 m (60.4 ft), 17.9 m (58.7 ft), 36.5 m (119.7 ft), and 78.4 m (257.2 ft), respectively.

Fire: A constant HRR of 50 MW was used as input for the calculations. No estimate or correction for oxygen starvation is provided in the FDTs or FIVE; therefore, the fire was assumed to have sufficient oxygen for continued combustion. The radiative fraction of the fire is assumed to be 35 %.

Materials: No material property data is required.

Ventilation: The air flow is not required.

Validation: The point source radiation model was used extensively in the US NRC/EPRI V&V study (NUREG-1824) to predict heat fluxes less than 20 kW/m^2. The method is not being used to predict the heat flux to targets in the immediate vicinity of the fire.

F.5.2 Zone Models (CFAST and MAGIC)

General: This is a particularly challenging simulation for a zone fire model, with very large compartments and numerous connections between the compartments and to the outside. With such large compartment sizes, local variations in temperatures can be expected within the lower compartment that contains the fire source. Results of calculations that depend on the uniform gas layer assumption inherent in all zone fire models should be evaluated with care.

Geometry: The entire turbine hall is included in the simulation. Two compartments are used in MAGIC; one for the lower deck, and one the upper turbine deck. The two compartments are connected by hatches and stairs. The columns are approximated as steel plates with the given thickness of the actual columns. To determine the location of highest temperature, initial simulations with targets from floor to ceiling were conducted. For MAGIC, a location near the ceiling was selected as the location for evaluating steel temperatures. For CFAST, the simple point source model for the fire led to the highest temperature on nearby steel columns being near the floor level.

Materials: For the lower area, the walls, ceiling and floor were all assumed to be concrete as specified. The walls and ceiling of the upper level of the turbine building are made of corrugated steel. The properties are all taken as specified. However, it is assumed the corrugated steel is 3 mm (0.12 in) thick.

Fire: The fire is assumed to burn within the specified area with the specified HRR per unit area. This leads to a roughly 50 MW fire, assuming that enough oxygen is drawn into the lower deck via the vents to the outside located around the periphery of the lower level. The duration of the fire is calculated by first calculating the burning rate, which is the HRR divided by the heat of combustion, 50 MW/43 MJ/kg =1.16 kg/s. The density of the oil is 0.88 kg/L; thus, the burning rate can be expressed as 1.32 L/s. At this rate, it would take about 2270 s to consume 3000 L. It is assumed that the fuel molecule is $C_{14}H_{30}$.

Ventilation: There are 18 vents from the lower level. These are assumed open to the atmosphere. To simplify the numerous vents, MAGIC used six vents of equal total area spaced approximately where the actual vents are located. The two large hatch openings that connect the lower level with the upper deck were modeled as two openings of the same equivalent area. The smaller hatches and stairs were combined into two equivalent area openings. Since MAGIC is a zone model, the area of the various openings is important, but the location is not. In CFAST, each vent was simulated individually. To account for normal building leakage, a long opening was placed in an exterior wall at floor level in both models.

Validation: The fire scenario described above falls outside of the parameter space of the NRC/EPRI V&V study (NUREG-1824). However, the plume algorithm used in both MAGIC and CFAST has been subjected to extensive validation for a wide range of fire sizes up to more than 30 MW. The CFAST Software Development and Model Evaluation Guide includes details of this validation. For large fire sizes (up to 33 MW) in large compartments (up to 60,000 m^3), CFAST has been subjected to validation studies that show a larger uncertainty in the calculation compared to smaller fire size simulation. Still, with these large fires in large compartments, care should be taken in evaluating the results of the calculations since local variations in temperature can be expected in the larger compartment sizes.

F.5.3 CFD Model (FDS)

General: This scenario is challenging because it involves a very large fire in a very large space. However, the fact that the objective of the calculation is to estimate the temperature increase of steel columns that are not located within the fire itself makes it less subject to error. Predicting the heat flux to a column engulfed in fire is more difficult because it requires more details of the fuel and exhaust products, including soot, within the flame region.

Geometry: The entire turbine hall is included in the simulation. One mesh covers the lower deck, and one the upper turbine deck, with a resolution of 1 m (3.3 ft). While this mesh appears to be fairly coarse, the fire is so large that the ratio of D^* (the characteristic fire diameter) to the cell size is about 5. This is sufficient resolution to simulate the fire and its impact on the overall space. The main focus is the heat flux to nearby columns, not necessarily columns within the fire itself.

The columns cannot be resolved on the relatively coarse grid, and are approximated as steel plates with the given thickness of the actual columns. FDS only performs a one-dimensional heat transfer calculation within solid obstructions, which is why there is little to be gained by resolving the column. The neglect of lateral heat conduction within the solid tends to produce a slight over-prediction of the column temperature, but because the heat flux from the fire is expected to be fairly uniform over the width of the column, a more detailed thermal conduction calculation is not warranted.

Materials: The support columns are assumed to be made out of 2.5 cm (1 in) thick steel, and the walls are assumed to be made out of 0.9 m (3 ft) thick concrete.

Fire: The fire is assumed to burn within the specified area with the specified HRR per unit area. This leads to a roughly 50 MW fire, assuming that enough oxygen is drawn into the lower deck via the vents to the outside located around the periphery of the lower level. The duration of the fire is calculated by first calculating the burning rate, which is the HRR divided by the heat of combustion, 50 MW/43 MJ/kg=1.16 kg/s. The density of the oil is 0.88 kg/L; thus, the burning rate can be expressed as 1.32 L/s. At this rate, it would take about 2270 s to consume 3000 L. It is assumed that the fuel molecule is $C_{14}H_{30}$.

Ventilation: There are no explicit openings to the outside on the turbine deck, but the scenario description indicates that there is sufficient leakage to prevent any appreciable build-up in pressure. It should be noted that the point of including the lower and upper levels of the turbine building in the simulation is to check whether there would be sufficient make-up air drawn through the various vents to sustain a steady-state 50 MW fire.

Validation: The fire scenario described above falls outside of the parameter space of the NRC/EPRI V&V study (NUREG-1824). However, FDS was used to predict upper layer temperatures for fully-engulfed compartment fires as part of the NIST World Trade Center Investigation. Details can be found in NIST NCSTAR 1-5F. In particular, six experiments were conducted in a mock-up of a section of a floor in one of the towers. In each experiment, the fire flashed over the compartment, producing temperatures near the ceiling on the order of 1100 °C (2000 °F) and HRRs on the order of 10 MW under a ceiling height of 3.6 m (12 ft). In the turbine building fire scenario described above, temperatures of similar magnitude are predicted.

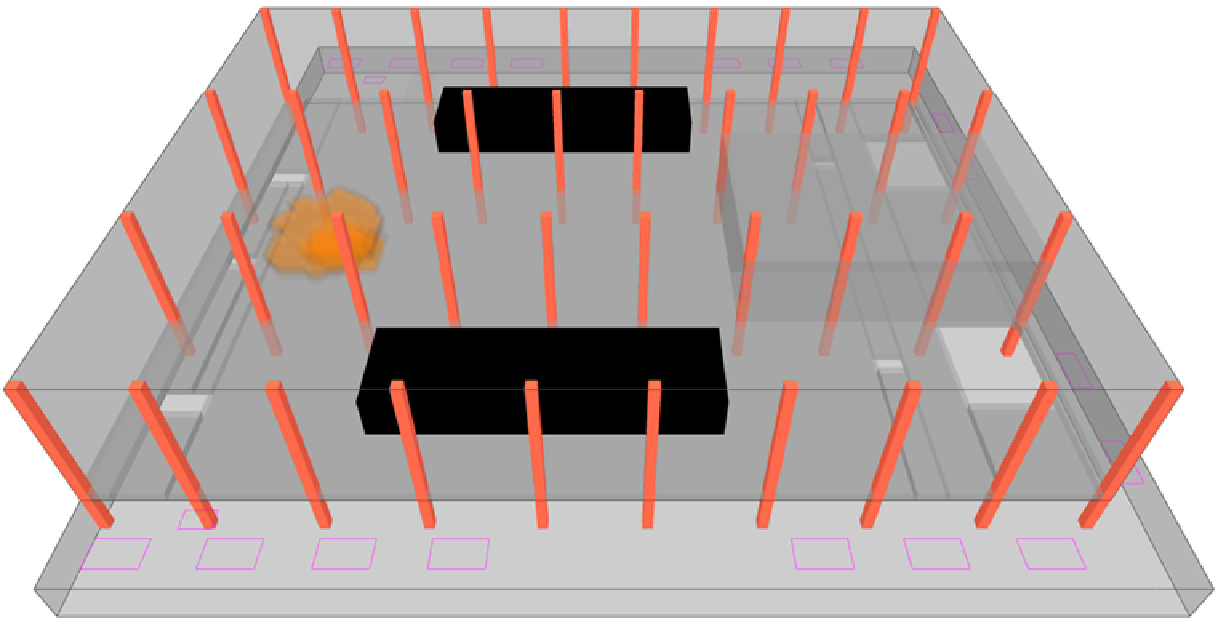


Figure F-4. FDS/Smokeview rendering of the Turbine Building scenario.

F.6 Summary of Results

The purpose of the calculations described above is to estimate the steel temperature of six large columns in the turbine building to determine if any would lose the ability to carry its design load in the event of a large fire in the dike of a lube oil tank. The HRR curves are all the same (50 MW for 40 min) and are not shown.

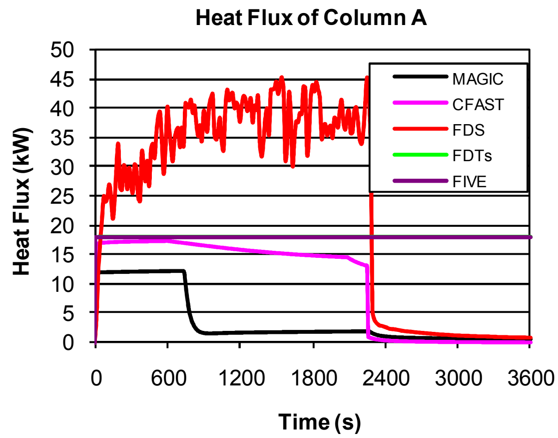
The temperature and heat flux predictions for the six columns are shown in Figure F-5. The FDTs and FIVE do not have an algorithm appropriate for predicting the temperatures of these exposed columns in this large space. However, they both use the same point source calculation for the radiative heat flux. Assuming a radiative fraction of 35 %, the heat fluxes from a 50 MW fire would be 18.4 kW/m^2, 12.2 kW/m^2, 4.1 kW/m^2, 4.4 kW/m^2, 1.1 kW/m^2, and 0.2 kW/m^2, respectively.

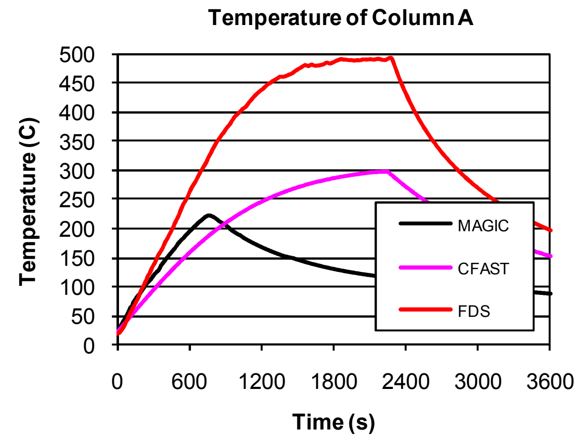
CFAST and MAGIC, the zone models, do not produce consistent estimates of heat flux, even though both either use the point source radiation model, the HGL temperature, or both. It is unclear why the heat flux estimates are different because the HGL temperature is similar. In addition, for Column A, the MAGIC prediction of column temperature is inconsistent with its heat flux estimate. The heat flux estimate is only 12 kW/m^2, a flux which would make the column temperature increase initially at a rate of approximately 0.2 °C/s. However, it appears to increase at about twice that rate. The Column A temperature predicted by CFAST is consistent with its predicted heat flux, but this value is too low based on the point source estimate given above.

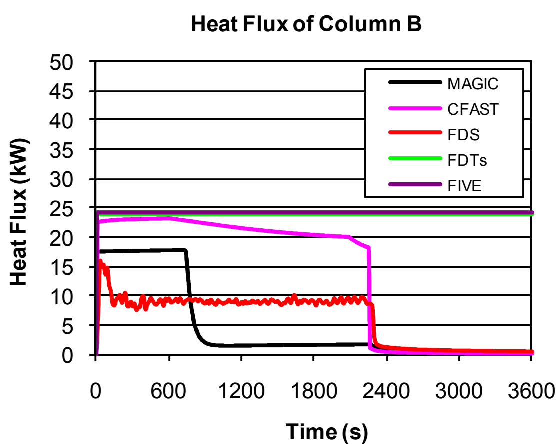
The FDS predictions of heat flux are based on the solution of a three-dimensional radiation transport equation with 100 angular directions. This model accounts for both the fire and the hot smoke as sources of heat flux at the columns. FDS predicts a maximum heat flux and temperature for Column A because the simulated fire leans in the direction of this column because of the proximity of a large hatch nearby that draw the hot gases, and as a result the fire, upwards.

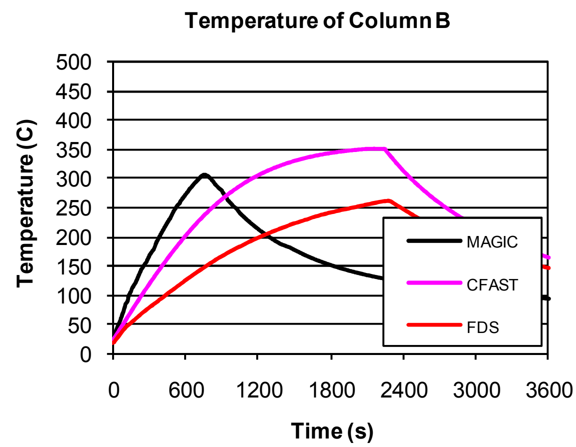
F.7 Conclusion

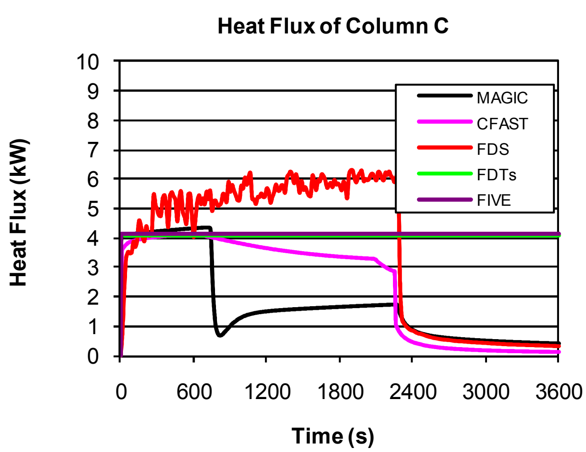
The peak column temperature as calculated by FDS is nearly 500 °C (930 °F). This is lower than the critical temperature of 649 °C (1200 °F) as set out in the problem description. Because this temperature occurs at Column A, and A is closest to the fire, it is not expected that any other column would reach this temperature.

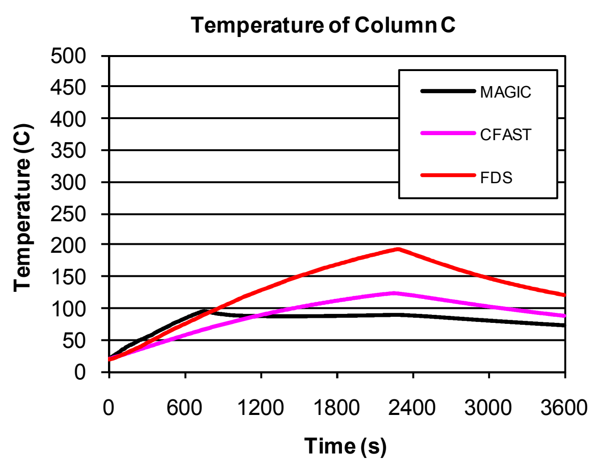

Heat Flux of Column A
Heat Flux (kW)
Time (s)
MAGIC
CFAST
FDS
FDTs
FIVE


Temperature of Column A
Temperature (C)
Time (s)
MAGIC
CFAST
FDS


Heat Flux of Column B
Heat Flux (kW)
Time (s)
MAGIC
CFAST
FDS
FDTs
FIVE


Temperature of Column B
Temperature (C)
Time (s)
MAGIC
CFAST
FDS


Heat Flux of Column C
Heat Flux (kW)
Time (s)
MAGIC
CFAST
FDS
FDTs
FIVE


Temperature of Column C
Temperature (C)
Time (s)
MAGIC
CFAST
FDS

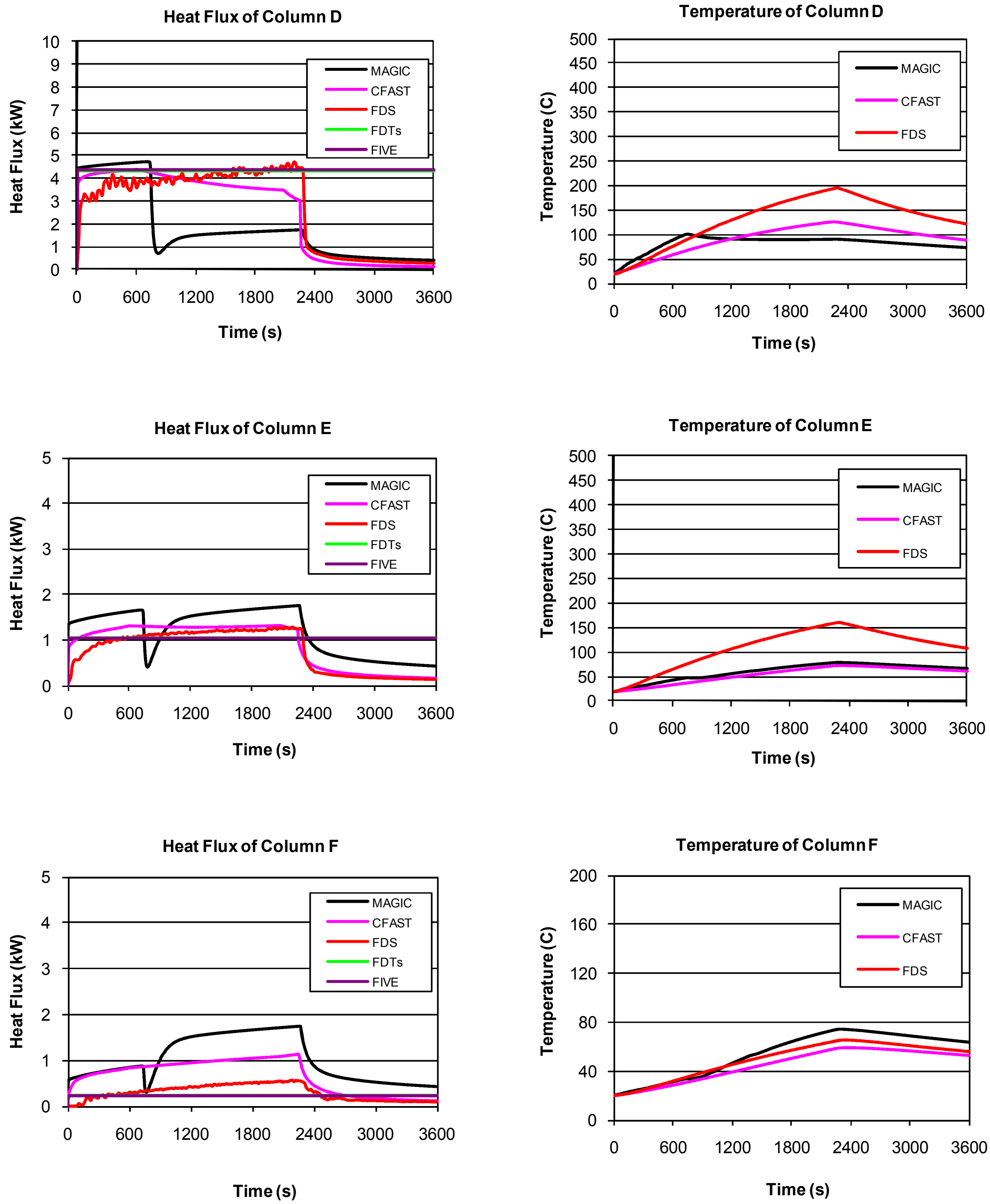


Figure F-5. Summary of simulation results for the Turbine Building.

G
Transient Fire in a Multi-Compartment Corridor

G.1 Purpose

The calculations described in this example predict the transport of smoke and heat from a stack of burning pallets through multiple compartments with different door heights and soffits. The purpose of the calculation is to determine if important safe-shutdown equipment fails, and at what time failure occurs. The time to smoke detector activation is also estimated.

G.2 References

1. NUREG-1805. *Fire Dynamics Tools.*
2. NUREG-1824. *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications*, 2007.
3. NUREG/CR-6850. *Fire PRA Methodology for Nuclear Power Facilities*.
4. *SFPE Handbook of Fire Protection Engineering*, 4th edition, 2008.
5. NUREG/CR-6931, *Cable Response to Live Fire (CAROLFIRE), Volume 2: Cable Fire Response Data for Fire Model Improvement*.
6. NUREG/CR-6931, *Cable Response to Live Fire (CAROLFIRE), Volume 3: Thermally-Induced Electrical Failure (THIEF) Model.*
7. UL 217. Underwriters Laboratories, Inc., Single Station Fire Alarm Device.
8. NIST SP 1018-5. *Fire Dynamics Simulator (Version 5), Technical Reference Guide, Vol. 3, Experimental Validation*.
9. NIST SP 1086. *Consolidated Model of Fire Growth and Smoke Transport, CFAST (Version 6), Software Development and Model Evaluation Guide*
10. Gay, L., C. Epiard, and B. Gautier “MAGIC Software Version 4.1.1: Mathematical Model,” EdF HI82/04/024/B, Electricité de France, France, November 2005.

G.3 Input Data

General Description: The corridor provides access to a variety of spaces and contains support equipment. Certain important cables are routed through these connecting spaces.

Geometry: This multi-compartment area consists of interconnected compartments and corridors on the same level. Figure G-1 illustrates the geometry.

Construction: The walls, ceiling and floor are made of concrete. The cabinets and cable trays are made of steel.

Cables: The cable trays contain cross-linked polyethylene (XPE or XLPE) insulated cables with a Neoprene jacket. These cables have a diameter of approximately 1.5 cm (0.6 in), a jacket thickness of approximately 2 mm (0.079 in), and 7 conductors. The tray locations are shown in Figure G-2.

Detection System: There are nine smoke detectors, located as shown in Figure G-1. The detectors are UL-listed with a nominal sensitivity of 1.5 %/ft (4.9 %/m).

Ventilation: The ventilation system supplies the space at a rate of 1.67 m^3/s (3540 ft^3/min). The vents are shown in the drawing. There are three doors leading into the space, all of which are closed during normal operation.

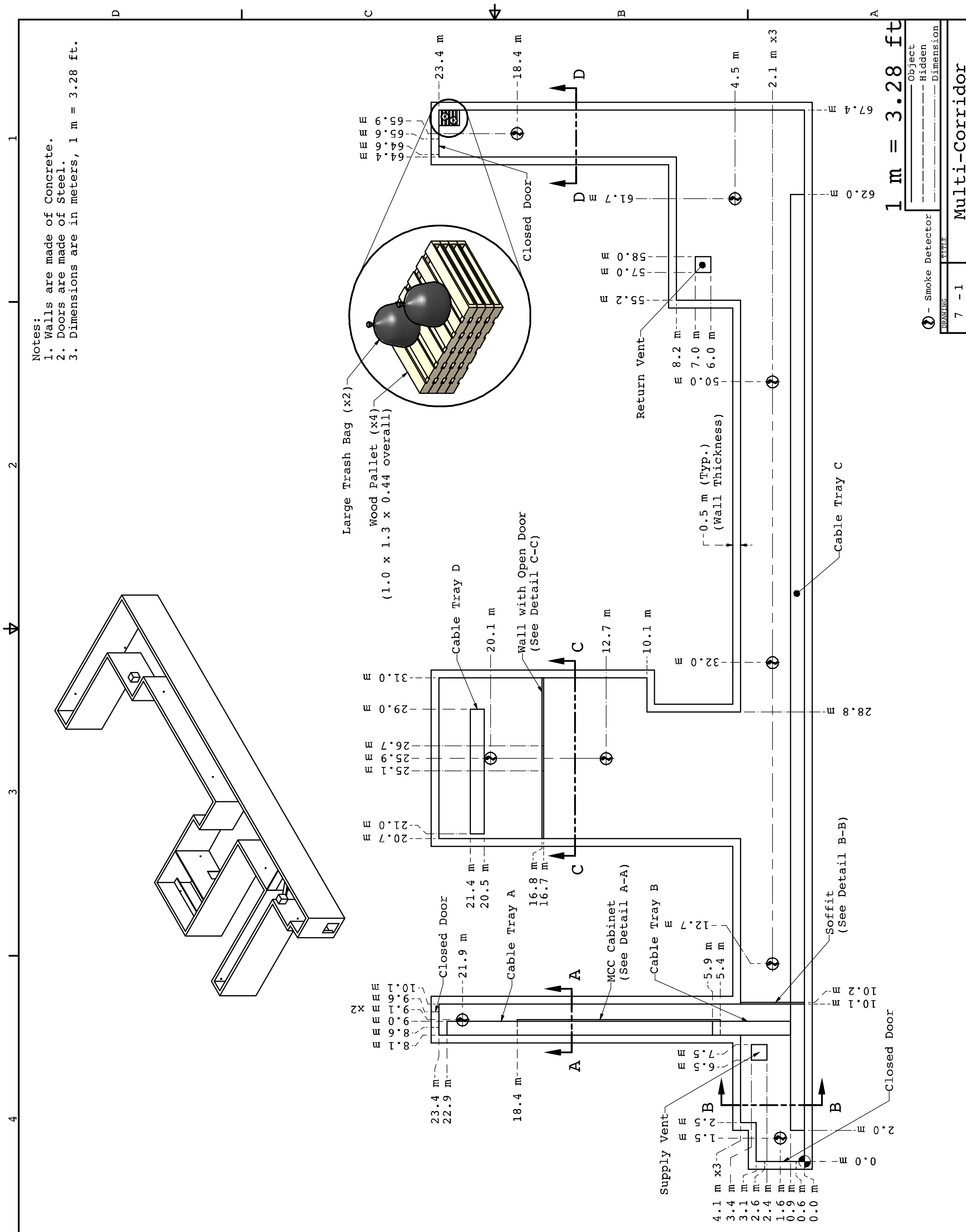


Figure G-1. Geometry of the Multi-Compartment Corridor

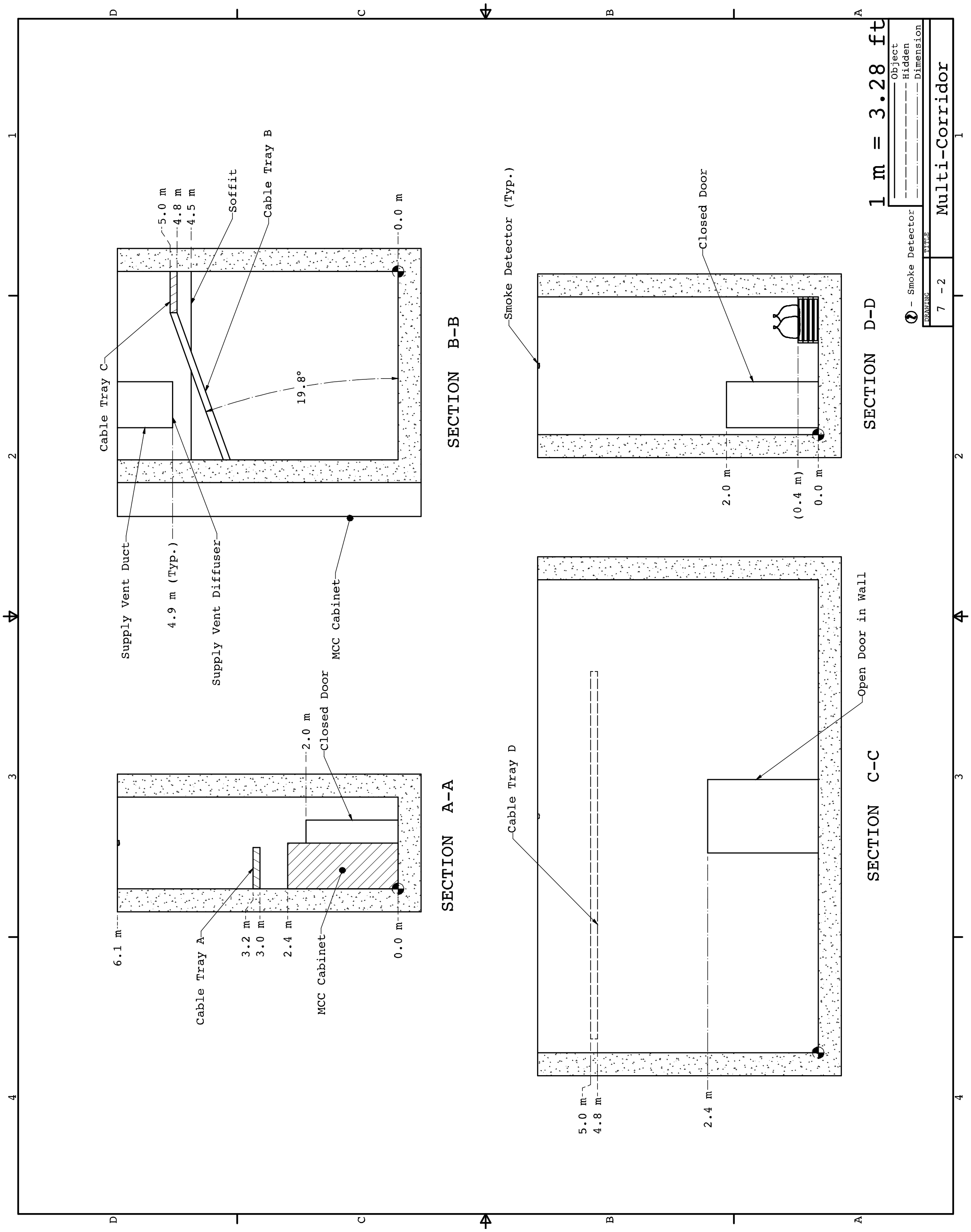


Figure G-2. Geometry Details of the Multi-Compartment Corridor

G.4 Fire Scenario

This section contains a list of assumptions that define the fire scenario. The information in this section is not typically obtained from plant design documents.

Fire: It is assumed that the fire source is a stack of four wood pallets with two trash bags located in the corner shown in Figure G-1. The fire is assumed to grow following a “t-squared” curve to a maximum value of 2500 kW/m^2 in 7 minutes and remains steady for 8 additional minutes. This HRR is estimated by combining separate estimates for a 0.4 m stack of wood pallets and 2 trash bags filled with paper. After that, the fire’s HRR is assumed to decay linearly to zero in 8 minutes.

The radiative fraction[7] of the fire is assumed to be 35 %, a value typical of sooty fires (*SFPE Handbook*). It is assumed that the soot yield is 1.5 %, typical of cellulosic materials like wood and paper (*SFPE Handbook*). The gaseous fuel from the burning pallets and rubbish is assumed to have the same atomic structure of Douglas Fir, $CH_{1.7}O_{0.74}N_{0.002}$, and a heat of combustion of 16400 kJ/kg (*SFPE Handbook*). The molecular weight of the fuel molecule is inferred from its chemical formula, even though the formula only indicates the relative number of atoms.

Materials: Walls, ceiling and floor are all assumed to be concrete with density, specific heat and thermal conductivity of 2400 kg/m^3 (150 lb/ft^3), 0.75 kJ/kg/K, and 1.6 W/m/K, respectively. The cabinets are constructed of steel with an assumed density, specific heat and thermal conductivity of 7850 kg/m^3 (490 lb/ft^3), 0.465 kJ/kg/K, and 54 W/m/K, respectively (NUREG-1805).

Cables: The cables are assumed to have a density of 1375 kg/m^3 (85.8 lb/ft^3), a specific heat of 1.39 kJ/kg/K, a thermal conductivity of 0.235 W/m/K, and an emissivity of 0.95 (NUREG/CR-6850). The cables are assumed damaged when the internal temperature just underneath the jacket reaches 400 °C (750 °F) (NUREG/CR-6931, Vol. 2, Table 5.10) or the exposure heat flux reaches 11 kW/m^2 (NUREG-1805, Appendix A).

Ventilation: The ventilation rate is given above. Also, it is assumed that the only leakage from the space is via a 2.5 cm (1 in) crack under each of the three doors.

[7] The fraction of the fire’s total energy emitted as thermal radiation.

G.5 Model Assumptions

This section describes how each of the five fire model calculations is prepared. Note that a typical NPP fire modeling analysis would not require the use of all five models. However, for demonstration purposes, all five models are exercised to point out the different assumptions required of each beyond those listed in the previous section.

G.5.1 Empirical Models (FDT^s and FIVE)

The FDT^s and FIVE were not used for this scenario.

G.5.2 Zone Models (CFAST and MAGIC)

General: This is a classic application of a zone fire model with a fire in one compartment connected to a number of additional compartments with doorway-like vents. Outputs of primary interest in the simulation include temperatures in the compartments, activation of smoke detectors in the compartments, and the temperature of cable targets in the compartments.

Geometry: To simplify the process of modeling the multi-compartment, the layout is divided into eight areas, as illustrated in Figure G-3. Note the small indentation in compartment 1 was ignored for the MAGIC calculations. Connections between compartments was by door (compartment 5 to 6), by soffit (compartment 2 to 3), or left open by using a full-wall opening. Table G-1 summarizes the compartment dimensions used for zone modeling.

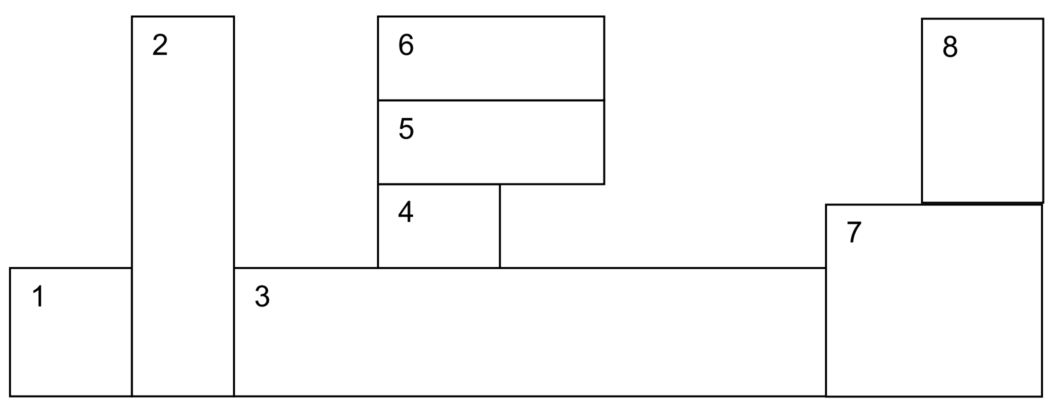


Figure G-3. Effective corridor layout for implementation in zone models (not to scale)

Table G-1. Compartment dimensions for Corridor scenario.

Comp.	Length (m)	Width (m)	Area (m^2)
1	8.1	4.1	33.21
2	2.0	23.4	46.80
3	45.1	4.1	184.91
4	8.1	6	48.6
5	10.3	6.6	67.98
6	10.3	6.6	67.98
7	12.2	8.2	100.04
8	3	15.2	45.6

Materials: It is assumed that all walls, ceiling and floor are made of the specified concrete. Cables and their associated damage criteria are as specified.

Fire: MAGIC uses a mass loss rate to determine the HRR. CFAST uses a specified HRR and either a corresponding mass loss rate or heat of combustion. The heat of combustion of the fire is assumed to be 17.1 kJ/g; this is an average for three "wood" values from the *SFPE Handbook*. The fire was modeled as a 1 m^2 (11 ft^2) source. It was assumed the fire was at an elevation of 0.1 m (0.33 ft). For MAGIC, an oxygen-fuel stochiometric ratio of 1.3 was used and is based on the heat of combustion of the fuel and a conversion value of 13.1 kJ/g (*SFPE Handbook*). An average specific area of 114 was calculated based on an average soot yield value for wood (*SFPE Handbook*).

Ventilation: The specified ventilation rates are used by both MAGIC and CFAST. The vents in Figure G-1 are square; but because MAGIC uses round vents, an equivalent diameter of 1.13 m (3.7 ft) was used as input. In CFAST, the vent area is input directly.

Each of the three doorways from the compartments in the simulation to the exterior spaces was modeled as closed doorways with a 25 mm (1 in) undercut to represent typical leakage areas.

Fire/Smoke Detection: In CFAST and MAGIC, there is no direct way of calculating smoke density for smoke detector activation. Consistent with NUREG 1805, the recommended approach given by the developers is to model the smoke detector as a sprinkler with a low activation temperature and RTI. An activation temperature of 30 ^{o}C and an RTI of 5 $(m/s)^{1/2}$ was selected.

Validation: The input parameters for this scenario are within the range of parameters used in the NRC/EPRI V&V study (NUREG-1824). In particular, the NBS Multi-Compartment test series is an appropriate surrogate. Temperature of and heat flux to cable targets is included in the ICFMP Benchmark Exercise 3 test series in NUREG 1824.

G.5.3 CFD Model (FDS)

General: The scenario is simulated in FDS using 4 meshes for each of the corridors, all run in parallel. Otherwise, this is a fairly common application of the model.

Transient Fire in a Multi-Compartment Corridor

Geometry: The overall space is modeled using four rectangular meshes, one for the long corridor, and one for each of the adjacent spaces. In general, the external walls of the compartments correspond to the boundaries of the numerical meshes. The dimensions of the compartments have been approximated to the nearest 20 cm (8 in) to conform to the numerical meshes. This is important in a multiple mesh calculation because FDS requires that meshes align precisely. In other words, FDS does not allow a mesh with 19 cm (7.5 in) grid cells to abut a mesh with 20 cm (8 in) grid cells.

Materials: It is assumed that all walls, ceiling and floor are made of the specified concrete. This is applied in the input file as a default surface, meaning that FDS assumes all solid surfaces to be the given concrete type unless otherwise indicated. The cabinets are introduced into the model simply as rectangular boxes constructed of steel with the given properties and thickness. The purpose of the cabinets in the calculation is to occupy space and absorb heat at a different rate than the concrete walls. The doors are also assumed to be made of steel, 1.5 mm (0.06 in) thick. This has not been explicitly specified above, and it is done mainly to identify the locations of the doors in the graphical representation of the geometry.

Cables: One of the objectives of the calculation is to predict the potential damage to the cables. FDS is limited to only 1-D heat transfer into either a rectangular or cylindrical obstruction. In this simulation, the cables are modeled as 1.5 cm (0.6 in) cylinders with uniform thermal properties. Following the THIEF (Thermally-Induced Electrical Failure) methodology in NUREG/CR-6931, Vol. 3, electrical functionality is assumed lost when the temperature just inside of the 2 mm (0.079 in) jacket reaches 400 °C (750 °F). Note that no attempt is made in the simulation to predict ignition and spread of the fire over the cables, which is why the in-depth heat penetration calculation is focused on a single cable. It is assumed that at least one cable per tray is relatively free of its neighbors and would heat up more rapidly than those buried deeper within the pile.

Fire: The pallets and trash bags are modeled simply as a single rectangular obstruction lying on the floor with the specified burning rate applied evenly to the five exposed sides. The chemical composition of the pyrolyzed wood and rubbish has been specified, along with the soot yield. Because the fire's HRR has been specified, the heat of combustion and stoichiometry of the fuel is not important. However, the smoke yield is important if a detector algorithm is used that is based on the smoke concentration inside and outside of the sensing chamber. In this calculation, FDS predicts smoke detector activation using both a temperature-based criterion given above, and a smoke detection algorithm described below.

Ventilation: The supply and exhaust vents are positioned to the nearest 20 cm (8 in) to conform to the numerical mesh. The flow rates are applied directly. It is assumed that the ventilation ducts are constructed of steel with the given properties and thickness of 2 mm (0.079 in). The three doors leading into the space are all assumed closed, but a row of grid cells is left open at the bottom of each to represent leakage. The areas of the openings in the FDS calculations are larger than the actual door cracks, but it is assumed that the space has other leakage paths that are unaccounted for. It is not expected that leakage plays an important role in the scenario.

Detection: FDS uses a simple algorithm to estimate the temperature and depth of the HGL. In addition, FDS has a smoke detection algorithm that predicts the smoke obscuration within the detection chamber based on the smoke concentration and air velocity in the grid cell within which the detector is assumed located. The detector itself is not modeled – it is merely a point within the computational domain. The two parameters needed for the model are the obscuration at alarm, which is given by the manufacturer, and an empirically determined length scale from which a smoke entry time lag is estimated from the outside air velocity. The SFPE Handbook provides a nominal value of 1.8 m (5.9 ft) for this length scale. The obscuration at alarm is 4.9 %/m (1.5 %/ft, a typical sensitivity for smoke detectors).

Validation: The input parameters for this scenario are within the range of parameters used in the NRC/EPRI V&V study (NUREG-1824). In particular, the NBS Multi-Compartment test series is an appropriate surrogate. The exception is the ceiling jet radius as a function of the ceiling height, r_{cj}/H. However, the FDS Validation Guide (NIST SP 1018-5) contains experimental data where this parameter is smaller than those used in NUREG-1824.

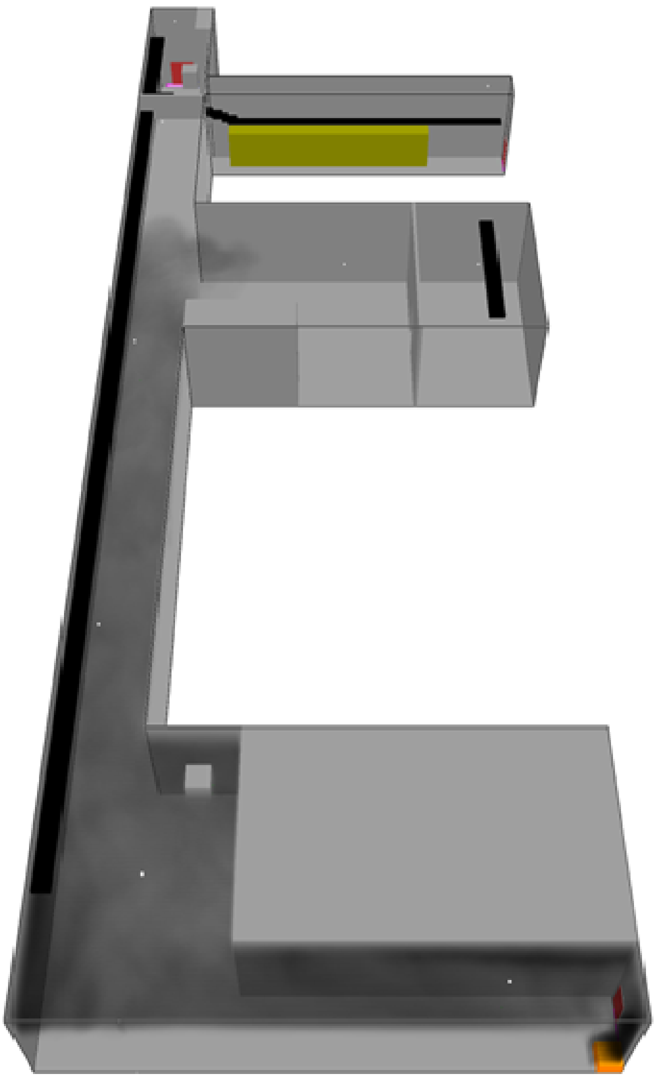


Figure G-4. FDS/Smokeview rendering of the Corridor scenario.

G.6 Summary of Results

The purpose of the calculations described above is to determine if a stack of burning pallets in a corridor could generate gas temperatures in adjacent compartments capable of damaging cables and electrical equipment. The results of the simulations are shown in Figure G-5. Only the zone and CFD models are used for this scenario. All of the models use the specified HRR for the stack of pallets.

G.6.1 HGL Temperature

CFAST, MAGIC and FDS predict similar temperatures in the upper layer. Both MAGIC and CFAST predict comparable temperatures (about 200 °C (392 °F), peak) in the corridor where the fire is located. The CFD model, FDS, predicts a lower temperature in this corridor. The reason is that FDS is reporting its upper layer temperature at a point that is roughly halfway along the corridor. A CFD model does not predict average layer temperatures; thus, it is somewhat difficult to compare its results directly with a zone model when the compartment is long and narrow and the smoke layer interface is not expected to be horizontal.

G.6.2 Smoke Detection

Smoke detector activation times in the corridor containing the burning pallets range from 40 s to 105 s. FDS predicteds 40 s. most likely because its prediction is based on smoke concentration, not temperature rise. Detection time in the connected spaces away from the fire was considerably longer.

Table G-2. Smoke detector activation times for the Corridor scenario.

Model	Detector Activation Time (s)
FDTs	N/A
FIVE-Rev1	105
MAGIC	100
CFAST	84
FDS	40

G.7 Conclusions

The models do not predict HGL temperatures capable of cable damage in any compartment or corridor, including the corridor containing the burning pallets. Based on a simplified method for smoke detector activation, smoke detectors only activate in the fire compartment and immediately adjacent space, beginning as early as 40 s.

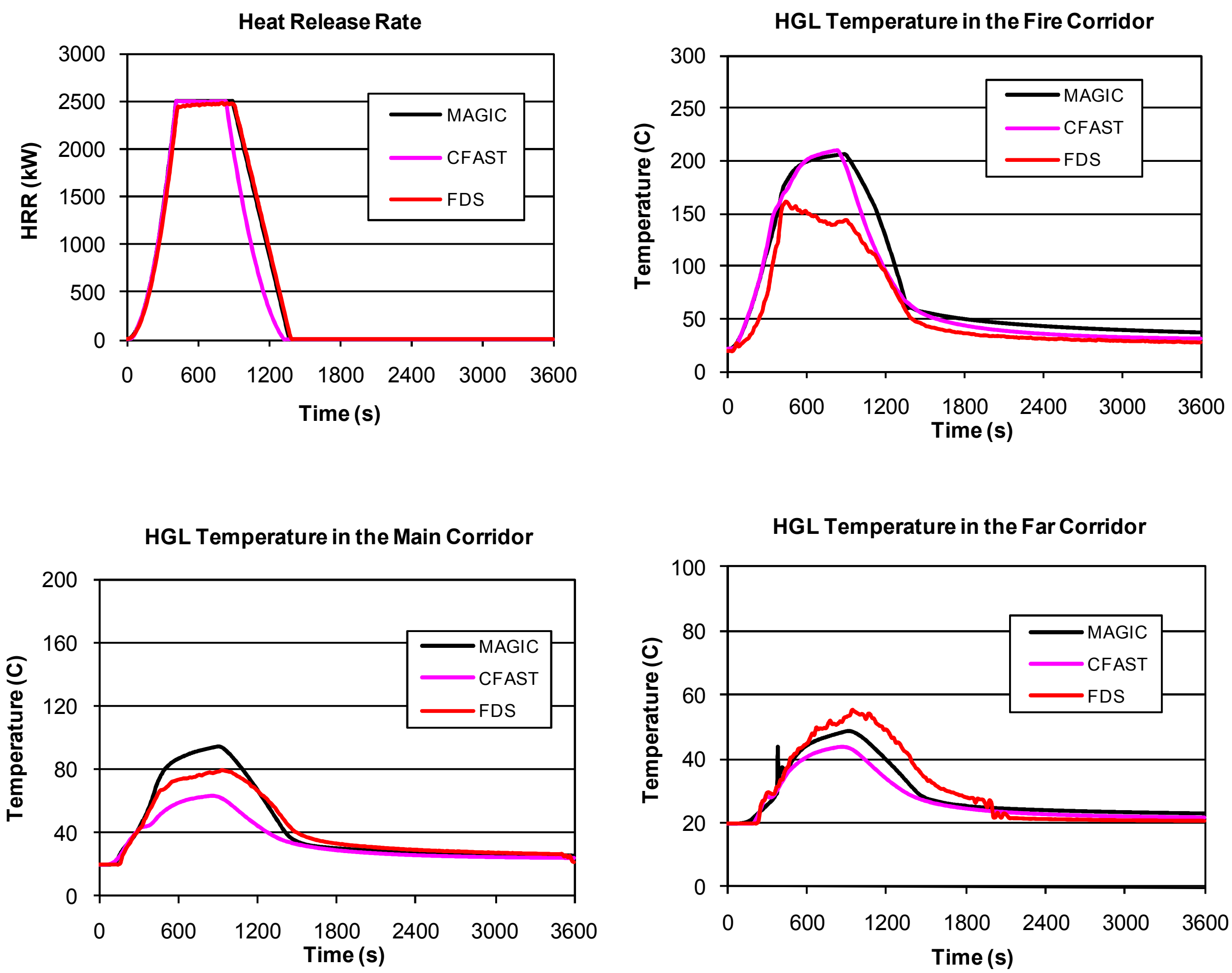


Figure G-5. Summary of modeling results for the Corridor scenario.

H
Cable Tray Fire in Annulus

H.1 Purpose

The calculations described in this example predict the effects of a cable tray fire in the annulus. The purpose of the calculation is to determine if nearby, redundant safe-shutdown cables fail, and at what time failure occurs.

H.2 References

1. NUREG/CR-6850. *Fire PRA Methodology for Nuclear Power Facilities.*
2. NUREG-1805. *Fire Dynamics Tools.*
3. SFPE Handbook, 4th edition, 2008.
4. NUREG/CR-6931, *Cable Response to Live Fire (CAROLFIRE), Volume 2: Cable Fire Response Data for Fire Model Improvement.*
5. NUREG/CR-6931, *Cable Response to Live Fire (CAROLFIRE), Volume 3: Thermally-Induced Electrical Failure (THIEF) Model.*
6. NFPA 70 (NEC 2008). *National Electric Code.*
7. UL 217. Underwriters Laboratories, Inc., Single Station Fire Alarm Device.
8. NIST SP 1018-5. *Fire Dynamics Simulator (Version 5), Technical Reference Guide, Vol. 3, Experimental Validation*.

H.3 Input Data

General Description: The annulus is the region between the primary containment structure and the secondary containment (shield) building. The primary and secondary containments are cylindrical with domes on top. The annulus space contains a variety of penetrations from the reactor to the external support systems. One of these penetrations contains two cable trays with cables that control systems in both trains of safety equipment.

Geometry: A drawing of the annulus is shown in Figure H-1.

Construction: The exterior wall is made of concrete. The interior wall and cable trays are made of steel. The wall thicknesses are indicated in the drawing. The tray steel is approximately 2 mm (0.079 in) thick.

Cables: The tray locations are shown in Figure H-2. The cable trays are filled with PE insulated, PVC jacketed control cables. These cables have a diameter of approximately 1.5 cm (0.6 cm), a jacket thickness of approximately 1.5 mm (0.06 in), and 7 conductors. There are approximately 120 cables in each tray. The mass of each cable is 0.4 kg/m (0.27 lb/ft). The mass fraction of copper is 0.67.

Detection and Suppression System: Smoke detectors are located on the wall of the shield building 15 m (50 ft) above grade. The detectors are UL-listed with a nominal sensitivity of 1.5 %/ft (4.9 %/m). Standard response sprinklers are located on the inner wall as shown in the drawing. The sprinklers have a response time index (RTI) of 130 $(m\ s)^{1/2}$ and activate at a temperature of 100 °C (212 °F) (NUREG-1805, Chap. 10). Each sprinkler is topped by heat collectors that are designed to trap heat from a fire.

Ventilation: None.

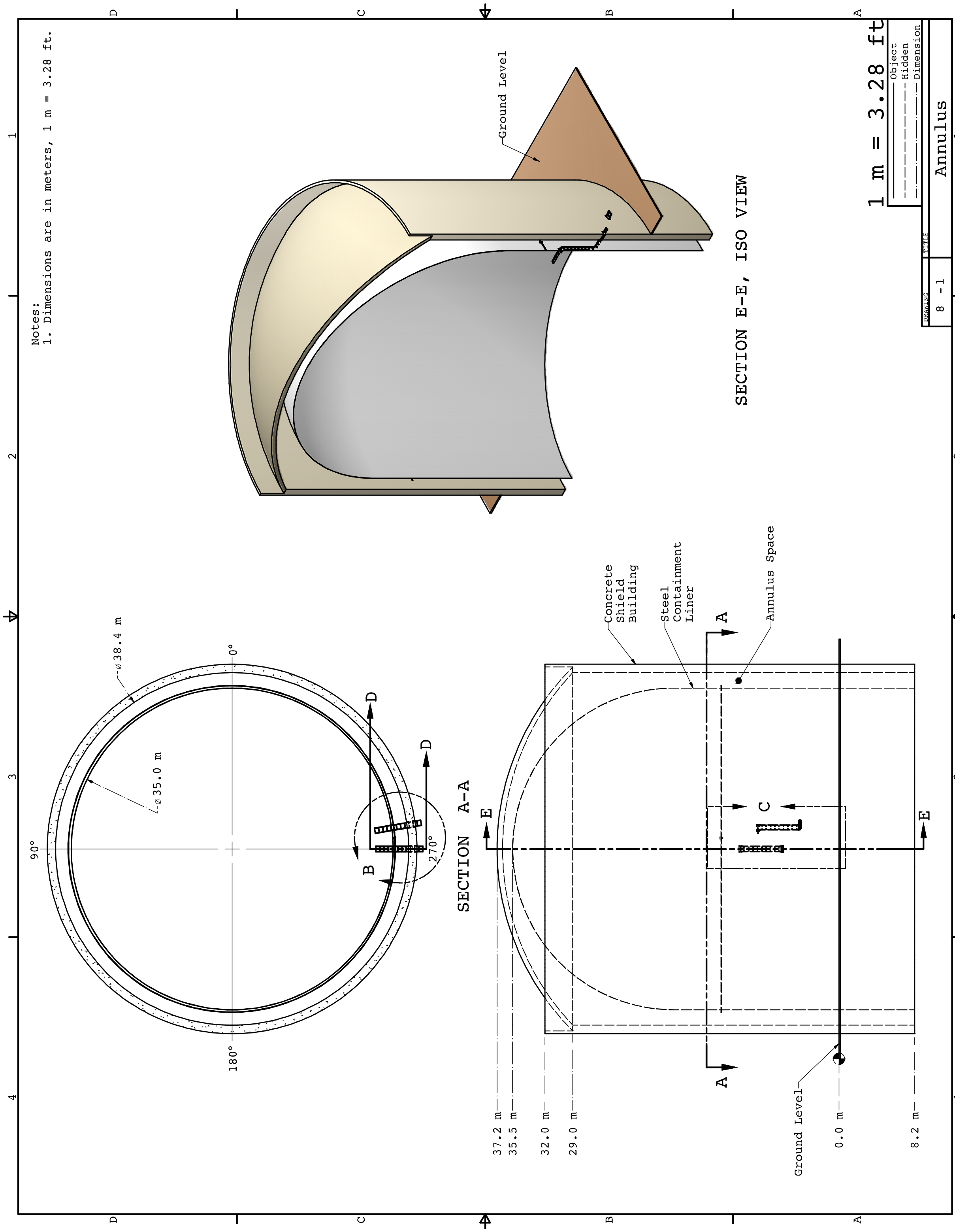


Figure H-1. Geometry of the Annulus.

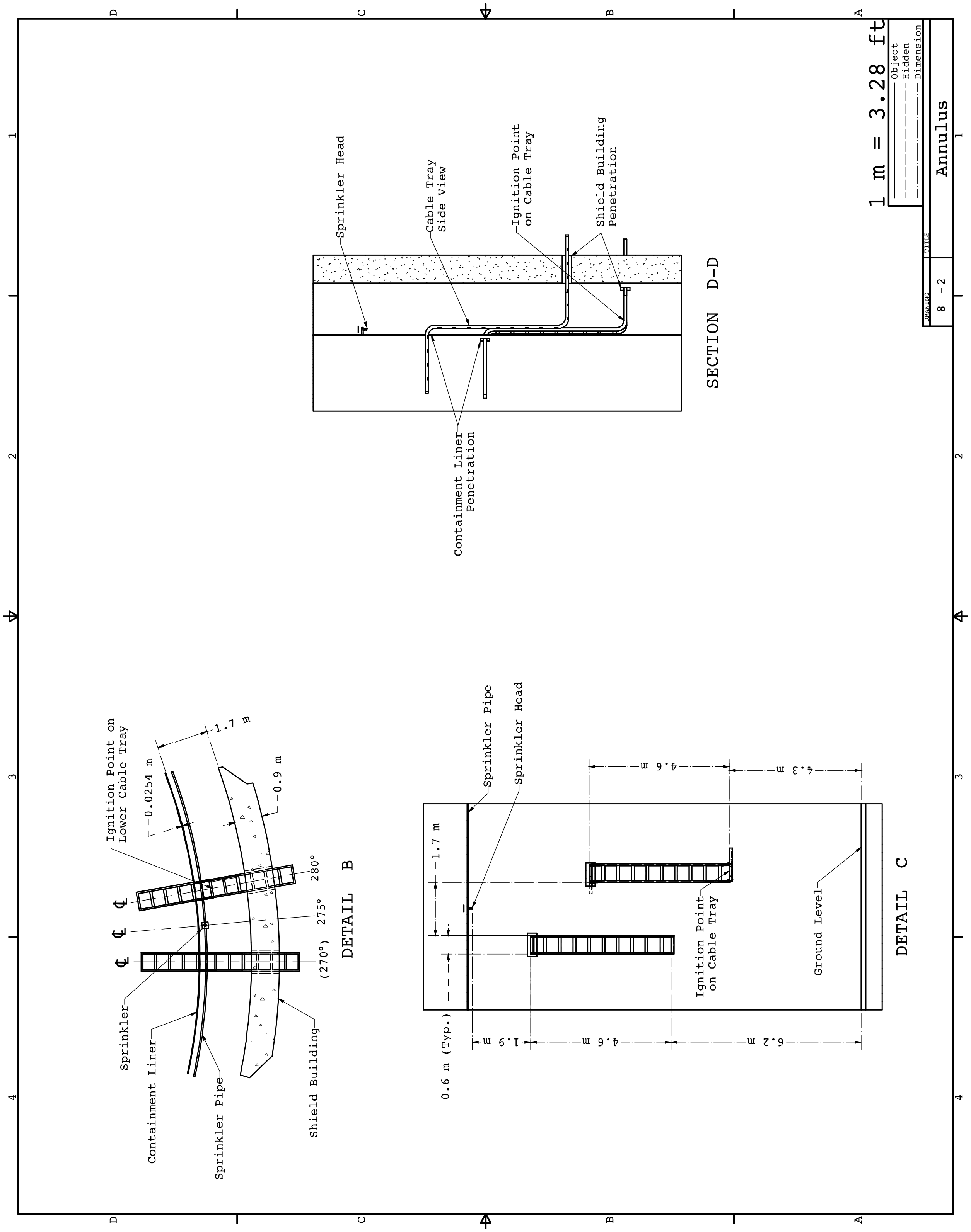


Figure H-2. Geometry details of the Annulus

H.4 Fire Scenario

This section contains a list of assumptions that define the fire scenario. The information in this section is not typically obtained from plant design documents.

Fire: It is assumed that the fire ignites at the base of the lower cable train in the vicinity of the bend at the inner wall. The fire is assumed to spread vertically at a rate of 25 mm/s and horizontally at a rate of 0.9 mm/s. The highest reported bench-scale burning rate of PVC cable is 589 kW/m^2. It is recommended that this value be multiplied by 0.45 for full-scale applications (NUREG/CR-6850).

The heat of combustion of the burning cables is assumed to be 24 kJ/g (Table 2-4 of NUREG-1805). This number is appropriate for PE/PVC cable. A mixture of PE (C_2H_4) and PVC (C_2H_3Cl) would have an effective chemical formula of $C_2H_{3.5}Cl_{0.5}$.

It is assumed that the soot yield of the burning cable is 0.1; that is, 10 % of the cable mass consumed is converted into smoke particulate. It is also assumed that the radiative fraction of the fire is 35 %, typical of sooty fires (*SFPE Handbook*).

Materials: Nominal values for the thermal properties of the materials in the annulus region are given in Table H-1.

Cables: Cables are assumed damaged when the internal cable temperature reaches 200 °C (392 °F) or the exposure heat flux reaches 6 kW/m^2 (NUREG-1805, Appendix A).

Table H-1. Table of material properties, Annulus.

Material	Thermal Conductivity, *k* (W/m/K)	Density, *ρ* (kg/m^3)	Specific Heat *c* (kJ/kg/K)	Source
Concrete	1.6	2400	0.75	NUREG-1805
PVC Cable	0.192	1380	1.29	NUREG/CR-6850

H.5 Model Assumptions

This section describes how each of the five fire model calculations is prepared. Note that a typical NPP fire modeling analysis would not require the use of all five models. However, for demonstration purposes, all five models are exercised to point out the different assumptions required of each beyond those listed in the previous section.

H.5.1 Empirical Models (FDT^s and FIVE)

The FDTs and FIVE were not used for this scenario.

H.5.2 Zone Models (CFAST and MAGIC)

General: The geometry of this scenario is quite unique for application of a zone model that is typically used with mostly rectangular compartments where a HGL forms from a fire source. Still, since the containment building is so large such that the curvature of the walls will have little effect, a smaller compartment can be defined with a tall ceiling height and vent connections size to the cross-sectional area of the annulus so that any layer that forms will flow out into rest of the annulus without impacting the region directly around the fire source and redundant cable tray target.

Geometry: Only the section of the annulus directly enclosing the cables and relevant targets is included in a single compartment simulation. A taller ceiling was included to allow the HGL to form well away from the targets since the much larger volume of the whole annulus would have to fill before any HGL would form near the fire source and targets. Horizontal vents on each side of the annulus section were included and sized to the full cross-section of the annulus to simulate flow from the simulation region to the rest of the annulus. Surfaces of this section of the annulus were assumed to be constructed of concrete of the specified thickness.

Fire: It is assumed that the fire originates near the base of the vertical portion of the cable train and quickly spreads to the entire vertical surface (4.6 m high by 0.6 m wide) (15.1 ft by 2.0 ft). With the specified HRR of 265 kW/m^2, this results in a peak HRR of approximately 1000 kW.

Cables: One of the objectives of the calculation is to predict the potential damage to the cables within the redundant train. CFAST calculates target temperature using a 1-D heat transfer calculation into a rectangular target. In this simulation, the cables are modeled with uniform thermal properties given above. Following the THIEF (Thermally-Induced Electrical Failure) methodology in NUREG/CR-6931, Vol. 3, electrical functionality is assumed lost when the temperature just inside of the 1.5 mm (0.06 in) jacket reaches 200 °C (392 °F). Thus, the target thickness is assumed to be 3 mm (0.12 in) so that the calculated center temperature of the target represents the temperature of the inside surface of the jacket insulation. Note that no attempt is made in the simulation to predict ignition and spread of the fire over the cables, which is why the in-depth heat penetration calculation is focused on a single cable. It is assumed that at least one cable per tray is relatively free of its neighbors and would heat up more rapidly than those buried deeper within the pile.

Sprinkler Activation: CFAST uses the conventional Response Time Index (RTI) concept to predict sprinkler activation for a sprinkler placed at the specified location.

Validation: The geometry of this scenario is outside the validation exercises included in the NRC/EPRI V&V study in NUREG 1824. Calculation of target temperature and heat flux are included in NUREG 1824 for a range of fire sizes.

H.5.3 CFD Model (FDS)

General: Although the geometry of this scenario is unlike the mostly rectangular compartments found in a nuclear plant, it is not particularly difficult to model in FDS. In fact, the containment building is so large that the curvature of the walls has little effect on the results of the calculation.

Geometry: Only the section of the annulus encompassing the cables and relevant targets is included in the computational domain. This volume is 9.6 m (31 ft) wide, 2.5 m (8 ft) deep, and 12.8 (42 ft) high. Extra depth is needed to accommodate the slight curvature of the bounding walls. The top, bottom and sides of the computational domain are assumed “open,” that is, open to an infinitely large volume. This assumption is based on the fact that the volume of the annulus is very large and neither smoke build-up nor pressure effects should influence the region near the cables. Both the internal and external walls of the annulus are included in the model. Since FDS only allows rectilinear obstructions, a series of obstructions 20 cm (8 in) thick approximate the curved walls. The numerical grid conforms to this “stair-stepped” geometry.

Fire: It is assumed that the fire ignites near the base of the vertical portion of the cable train near the shielding, or inner wall. The spread rates of 25 mm/s in the vertical direction and 0.9 mm/s in the horizontal are input by using a feature of FDS whereby a surface is designated as having a fire spread over it at a designated rate. In this case, a surface is specified along the side of the vertical tray and along the top of the horizontal tray with the respective spread rates. The HRR per unit area of the fire is taken directly from the Assumptions section above. To determine the duration of the fire, it is calculated that 120 cables per tray multiplied by 0.4 kg/m equals 48 kg/m total mass per unit length of tray. One-third (0.33) of this mass is assumed to be combustible plastic, or 15.8 kg/m. Since the tray is 0.6 m (24 in) wide, the mass of combustibles per unit area of burning surface is 15.8/0.6=26.3 kg/m^2. The heat of combustion for PE/PVC has been specified to be 24 000 kJ/kg, thus, the combustible “load” is 631200 kJ/m^2. The HRR per unit area is estimated to be 265 kW/m^2, which means that the duration of the fire at any particular location along the tray is 631200/265=2382 s. FDS accepts as input the combustible load as a “surface density” and computes the burn-out of fuel automatically.

Cables: One of the objectives of the calculation is to predict the potential damage to the cables within the redundant train. FDS is limited to only 1-D heat transfer into either a rectangular or cylindrical obstruction. In this simulation, the cables are modeled as 1.5 cm (0.6 in) cylinders with uniform thermal properties given in Table H-1. Following the THIEF (Thermally-Induced Electrical Failure) methodology in NUREG/CR-6931, Vol. 3, electrical functionality is assumed lost when the temperature just inside of the 1.5 mm (0.06 in) jacket reaches 200 °C (392 °F). Note that no attempt is made in the simulation to predict ignition and spread of the fire over the cables, which is why the in-depth heat penetration calculation is focused on a single cable. It is assumed that at least one cable per tray is relatively free of its neighbors and would heat up more rapidly than those buried deeper within the pile.

Smoke Detection: FDS has a smoke detection algorithm that predicts the smoke obscuration within the detection chamber based on the smoke concentration and air velocity in the grid cell within which the detector is assumed located. The detector itself is not modeled – it is merely a point within the computational domain. The two parameters needed for the model are the obscuration at alarm, which is given by the manufacturer, and an empirically determined length scale from which a smoke entry time lag is estimated from the outside air velocity. The SFPE Handbook provides a nominal value of 1.8 m (5.9 ft) for this length scale. The obscuration at alarm is 4.9 %/m.

Sprinkler Activation: FDS uses the conventional Response Time Index (RTI) concept to predict sprinkler activation. In this scenario, a steel plate has also been added just above the location of the sprinkler to simulate the affect of the actual deflector. Note that the sprinkler itself is just a point in the model, and its activation is determined by the time history of the temperature and velocity of hot gases within the numerical grid cell in which it is assumed the sprinkler exists.

Validation: Examples of validation work by NIST and others for sprinklers and smoke detectors is included in the FDS Validation Guide (NIST SP 1018-5). The THIEF cable failure algorithm is developed and validated in NUREG/CR-6931, Vol. 3.

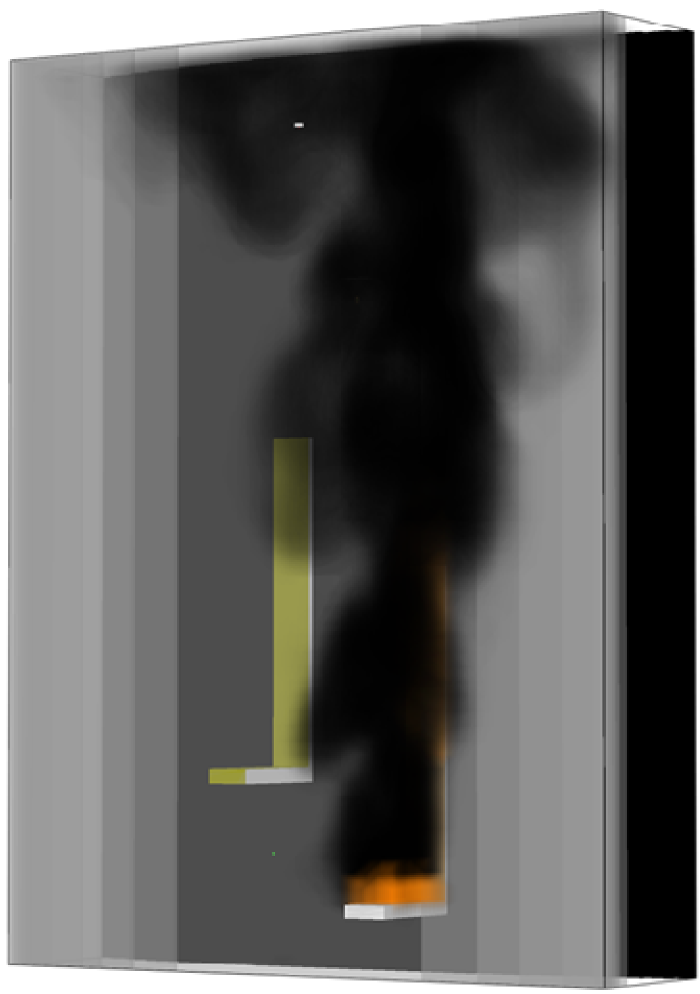


Figure H-3. FDS/Smokeview rendering of the Annulus scenario.

H.6 Summary of Results

The results of the simulations are shown in Figure H-4. Only CFAST and FDS have been used in the calculations. The HRR for this scenario was specified for CFAST. Although FDS does have an algorithm to predict flame spread, it was decided to use the specified burning and spread rates as given above. As a result, the HRR increases fairly rapidly to approximately 750 kW following ignition and the spread of the fire upwards, and it continues to increase, but not as rapidly, as the fire spreads horizontally. The peak HRR is about 1 MW.

The heat flux from the burning cable to the redundant cable tray is predicted by CFAST to peak just above 2 kW/m^2 and for FDS just below 2. However, FDS predicts a higher temperature in the cable, most likely due to the fact that FDS computes the heat conduction equation for a cylinder rather than a slab. The cable temperature rises to approximately 120 °C (248 °F) in the FDS simulation, well below the damage temperature.

Neither CFAST nor FDS predict sprinkler activation in this case because the link temperature is only predicted to increase to approximately 90 °C (194 °F) by FDS, less than the activation temperature of 100 °C (212 °F). Sprinkler heating in CFAST is assumed to occur only from convective heating from the surrounding gases. For this scenario, this gas temperature is near ambient so that the sprinkler does not heat significantly. Thus, predictions from the more detailed FDS calculation are likely more accurate.

FDS predicts smoke detection at about 900 s. It should be noted, however, that both the sprinkler and smoke detector are located just outside the fire plume. It is expected that for a real fire of this type, the natural air movements within such a large space as the containment annulus would almost certainly bend the plume from the vertical in a way that would be difficult to replicate with a model that is not accounting for the air movements throughout the entire facility.

H.7 Conclusions

Based on the model calculations, it is not expected that a fire in one cable tray within the annulus region of the containment building would damage cables in an adjacent train. However, the models cannot predict conclusively whether a sprinkler would activate above the fire, or at what time a smoke detector might activate. These predictions are extremely sensitive to the exact locations of the devices relative to a fire plume that may be subject to unpredictable air movements throughout the entire facility.

Cable Tray Fire in Annulus

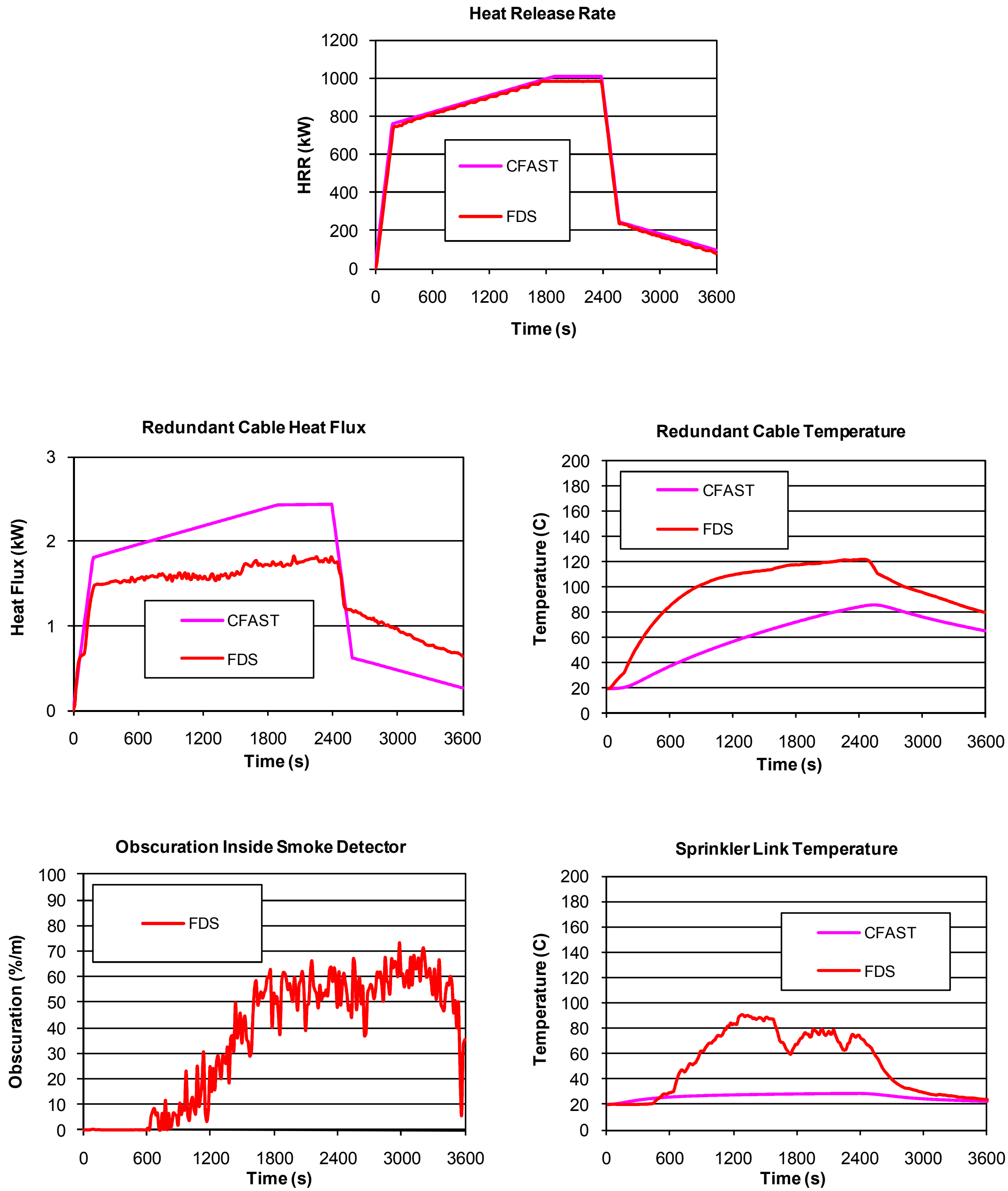


Figure H-4. Summary of simulation results for the Annulus.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

There is a movement to introduce risk-informed and performance-based analyses into fire protection engineering practice. This movement exists in the general fire protection community, as well as the nuclear power plant (NPP) fire protection community. The U.S. Nuclear Regulatory Commission (NRC) has used risk-informed insights as part of its regulatory decision making since the 1990s. In 2002, the National Fire Protection Association developed NFPA 805, Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants. In July 2004, the NRC amended its fire protection requirements in Title 10, Section 50.48 of the Code of Federal Regulations to permit existing reactor licensees to voluntarily adopt fire protection requirements contained in NFPA 805 as an alternative to the existing deterministic requirements. One key tool needed to further the use of risk-informed and performance-based fire protection is the availability of verified and validated (V&V) fire models that can reliably predict the consequences of fires. The U.S. NRC together with the Electric Power Research Institute (EPRI) and the National Institute of Standards and Technology (NIST) conducted a research project to verify and validate five fire models for NPP applications, NUREG-1824 (EPRI 1011999). This report provides guidance on the use of the five fire models in analyzing NPP fire protection issues. The features and limitations of the models and the implications of the V&V results for fire model users and reviewers are discussed.

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