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Volume 5 of 5

Methods for Applying Risk Analysis to Fire Scenarios (MARIAFIRES)-2012

Volume 5
Module 5: Advanced Fire Modeling

Based on the Joint
NRC-RES/EPRI Training Workshops
Conducted in 2012

Weeks of July 16 and September 24, 2012

Bethesda, MD

U.S. Nuclear Regulatory Commission
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Methods for Applying Risk Analysis to Fire Scenarios (MARIAFIRES)-2012

NRC-RES/EPRI Fire PRA Workshop
Volume 5: Module 5: Advanced Fire Modeling

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) working under a memorandum of understanding (MOU) jointly conducted two sessions of the NRC– RES/EPRI Fire Probabilistic Risk Assessment (PRA) Workshop on July 16–20, 2012, and September 24–28, 2012, at the Bethesda Marriott in Bethesda, MD. The purpose of the workshop was to provide detailed, hands-on training on the fire PRA methodology described in the technical document, NUREG/CR-6850 (EPRI 1011989) entitled "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities." This fire PRA methodology document supports implementation of the risk-informed, performance-based rule in Title 10 of the *Code of Federal Regulations* (10 CFR) 50.48(c) endorsing National Fire Protection Association (NFPA) Standard 805, as well as other applications such as exemptions or deviations to the agency's current regulations and fire protection significance determination process (SDP) phase 3 applications.

RES and EPRI provided training in five subject areas related to fire PRA, namely: fire PRA, electrical analysis, fire analysis, fire human reliability analysis (HRA), and advanced fire modeling. Participants selected one of these subject areas and spent the duration of the course in that module. The HRA module reviewed guidance provided in NUREG-1921 (EPRI 1023001), "EPRI/NRC-RES Fire Human Reliability Analysis Guidelines," while the fire modeling module reviewed the fire modeling guidance provided in NUREG-1934 (EPRI 1019195), "Nuclear Power Plant Fire Modeling Application Guide." For each technical area, the workshop also included a 1-day module introducing the fundamentals of the subject. The purpose of the fundamentals modules was to assist students without an extensive background in the technical area in understanding the in-depth training modules that followed. Attendance in the fundamentals modules was optional. The workshop's format allowed for in-depth presentations and practical examples directed toward the participant's area of interest.

This NUREG/CP documents both of the two sessions of the NRC-RES/EPRI Fire PRA Workshop delivered in 2012 and includes the slides and handout materials delivered in each module of the course as well as video recordings of the training that was delivered. This NUREG/CP can be used as an alternative training method for those who were unable to physically attend the training sessions. This report can also serve as a refresher for those who attended one or more training sessions and could also be useful preparatory material for those planning to attend future sessions.

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ACRONYMS

ACB	Air-cooled Circuit Breaker
ACRS	Advisory Committee on Reactor Safeguards
AEP	Abnormal Event Procedure
AFW	Auxiliary Feedwater
AGS	Assistant General Supervisor
AOP	Abnormal Operating Procedure
AOV	Air Operated Valve
ASEP	Accident Sequence Evaluation Program
ATHEANA	A Technique for Human Event Analysis
ATS	Automatic Transfer Switch
ATWS	Anticipated Transient Without Scram
BAT	Boric Acid Tank
BNL	Brookhaven National Laboratory
BWR	Boiling-Water Reactor
CBDT	Cause-Based Decision Tree
CCDP	Conditional Core Damage Probability
CF	Cable (Configuration) Factors
CCPS	Center for Chemical Process Safety
CCW	Component Cooling Water
CDF	Core Damage Frequency
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CLERP	Conditional Large Early Release Probability
CM	Corrective Maintenance
CR	Control Room
CRS	Cable and Raceway (Database) System
CST	Condensate Storage Tank
CVCS	Chemical and Volume Control System
CWP	Circulating Water Pump
DC	Direct Current
ECCS	Emergency Core Cooling System
EDG	Emergency Diesel Generator
EDS	Electrical Distribution System
EF	Error Factor
EI	Erroneous Status Indicator
EOP	Emergency Operating Procedure
EPR	Ethylene-Propylene Rubber
EPRI	Electric Power Research Institute
ET	Event Tree
FEDB	Fire Events Database
FEP	Fire Emergency Procedure
FHA	Fire Hazards Analysis
FIVE	Fire-Induced Vulnerability Evaluation (EPRI TR 100370)

FMRC	Factory Mutual Research Corporation
FPRAIG	Fire PRA Implementation Guide (EPRI TR 105928)
FRSS	Fire Risk Scoping Study (NUREG/CR-5088)
FSAR	Final Safety Analysis Report
HCR	Human Cognitive Reliability
HEAF	High Energy Arcing Fault
HEP	Human Error Probability
HFE	Human Failure Event
HPI	High-Pressure Injection
HPCI	High-Pressure Coolant Injection
HRA	Human Reliability Analysis
HRR	Heat Release Rate
HTGR	High-Temperature Gas-cooled Reactor
HVAC	Heating, Ventilation, and Air Conditioning
ICDP	Incremental Core Damage Probability
ILERP	Incremental Large Early Release Probability
INPO	Institute for Nuclear Power Operations
IPE	Individual Plant Examination
IPEEE	Individual Plant Examination of External Events
IS	Ignition Source
ISLOCA	Interfacing Systems Loss of Coolant Accident
KS	Key Switch
LCO	Limiting Condition of Operation
LERF	Large Early Release Frequency
LFL	Lower Flammability Limit
LOC	Loss of Control
LOCA	Loss-of-Coolant Accident
LPG	Liquefied Petroleum Gas
LP/SD	Low Power and Shutdown
LWGR	Light-Water-cooled Graphite Reactors (Russian design)
MCB	Main Control Board
MCC	Motor Control Center
MCR	Main Control Room
MG	Motor-Generator
MFW	Main Feedwater
MOV	Motor-Operated Valve
MQH	McCaffrey, Quintiere, and Harkleroad’s Method
MS	Main Steam
MSIV	Main Steam Isolation Valve
NC	No Consequence
NEI	Nuclear Energy Institute
NEIL	Nuclear Electric Insurance Limited
NFPA	National Fire Protection Association
NPP	Nuclear Power Plant
NPSH	Net Positive Suction Head

NQ cable	Non-Qualified (IEEE-383) cable
NRC	U.S. Nuclear Regulatory Commission
ORE	Operator Reliability Experiments
P&ID	Piping and Instrumentation Diagram
PE	Polyethylene
PM	Preventive Maintenance
PMMA	Polymethyl Methacrylate
PORV	Power-Operated Relief Valve
PRA	Probabilistic Risk Assessment
PSF	Performance Shaping Factor
PTS	Pressurized Thermal Shock
PVC	Polyvinyl Chloride
PWR	Pressurized Water Reactor
Q cable	Qualified (IEEE-383) cable
RBMK	Reactor Bolshoy Moshchnosty Kanalny (high-power channel reactor)
RCIC	Reactor Core Isolation Cooling
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RDAT	Computer program for Bayesian analysis
RES	Office of Nuclear Regulatory Research (at NRC)
RHR	Residual Heat Removal
RI/PB	Risk-Informed / Performance-Based
RPS	Reactor Protection System
RWST	Refueling Water Storage Tank
SCBA	Self-Contained Breathing Apparatus
SDP	Significance Determination Process
SGTR	Steam Generator Tube Rupture
SI	Safety Injection
SMA	Seismic Margin Assessment
SNPP	Simplified Nuclear Power Plant
SO	Spurious Operation
SOV	Solenoid Operated Valve
SPAR-H	Standardized Plant Analysis Risk HRA
SRV	Safety Relief Valve
SSD	Safe Shutdown
SSEL	Safe Shutdown Equipment List
SST	Station Service Transformer
SUT	Start-up Transformer
SW	Service Water
SWGR	Switchgear
T/G	Turbine/Generator
T-H	Thermal Hydraulic
THERP	Technique for Human Error Rate Prediction
TGB	Turbine-Generator Building
TSP	Transfer Switch Panel

UAT	Unit Auxiliary Transformer
VCT	Volume Control Tank
VTT	Valtion Teknillinen Tutkimuskeskus (Technical Research Centre of Finland)
VVER	The Soviet (now Russian Federation) designation for light-water pressurized reactor
XLPE	Cross-Linked Polyethylene
ZOI	Zone of Influence

1

INTRODUCTION AND BACKGROUND

The U.S. Nuclear Regulatory Commission (NRC) approved the risk-informed and performance-based alternative regulation in Title 10 of the *Code of Federal Regulations* (10 CFR) 50.48(c) in July 2004, which allows licensees the option of using fire protection requirements contained in the National Fire Protection Association (NFPA) Standard 805, "Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants, 2001 Edition," with certain exceptions. To support licensees' use of that option, the NRC's Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) jointly issued NUREG/CR-6850 (EPRI 1011989), "Fire PRA Methodology for Nuclear Power Facilities," in September 2005. That report documents state-of-the art methods, tools, and data for conducting a fire probabilistic risk assessment (PRA) in a commercial nuclear power plant (NPP) application. This report is intended to serve the needs of a fire risk analysis team by providing a general framework for conducting the overall analysis, as well as specific recommended practices to address each key aspect of the analysis. Participants from the U.S. nuclear power industry supported demonstration analyses and provided peer review of the program. Methodological issues raised in past fire risk analyses, including the Individual Plant Examination of External Events (IPEEE), are addressed to the extent allowed by the current state-of-the-art and the overall project scope. Although the primary objective of the report is to consolidate existing state-of-the-art methods, in many areas, the newly documented methods represent a significant advance over previous methods.

NUREG/CR-6850 does not constitute regulatory requirements, and the NRC's participation in the study neither constitutes nor implies regulatory approval of applications based on the analysis contained in that document. The analyses and methods documented in that report represent the combined efforts of individuals from RES and EPRI. Both organizations provided specialists in the use of fire PRA to support this work. However, the results from that combined effort do not constitute either a regulatory position or regulatory guidance.

In addition, NUREG/CR-6850 can be used for risk-informed, performance-based approaches and insights to support fire protection regulatory decision making in general.

However, it is not sufficient to merely develop a potentially useful method, such as NUREG/CR- 6850, and announce its availability. It is also necessary to teach potential users how to properly use the method. To meet this need RES and EPRI have collaboratively conducted the NRC-RES/EPRI Fire PRA Workshops to train interested parties in the application of this methodology since 2005. The course is provided in five parallel modules covering tasks from NUREG/CR-6850.

These five training modules are:

- Module 1: PRA/Systems Analysis – This module covers the technical tasks for development of the system response to a fire including human failure events. Specifically, this module covers Tasks/Sections 2, 4, 5, 7, 14, and 15 of Reference [1].

- Module 2: Electrical Analysis – This module covers the technical tasks for analysis of electrical failures as the result of a fire. Specifically, this module covers Tasks/Sections 3, 9, and 10 of Reference [1].

- Module 3: Fire Analysis – This module covers technical tasks involved in development of fire scenarios from initiation to target (e.g., cable) impact. Specifically, this module covers Tasks/Sections 1, 6, 8, 11, and 13 of Reference [1].

- Module 4: Fire Human Reliability Analysis – This module covers the technical tasks associated with identifying and analyzing operator actions and performance during a postulated fire scenario. Specifically, this module covers Task 12 as outlined in Reference [1] based on the application of the approaches documented in Reference [2].

- Module 5: Advanced Fire Modeling – This module was added to the training in 2011. It covers the fundamentals of fire science and provides practical implementation guidance for the application of fire modeling in support of a fire PRA. Module 5 covers fire modeling applications for Tasks 8 and 11 as outlined in Reference [1] based on the material presented in Reference [3].

The first three modules are based directly on the "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities," EPRI 1011989, and NUREG/CR-6850 [1]. However, that document did not cover fire human reliability analysis (HRA) methods in detail. In 2010, the training materials were enhanced to include a fourth module based on a more recent EPRI/RES collaboration and the then draft guidance document, EPRI 1019196, NUREG-1921 [2] published in late 2009. The training materials are based on this draft document including the consideration of public comments received on the draft report and the team's responses to those comments. In 2011 a fifth training module on Advanced Fire Modeling techniques and concepts was added to the course. This module is based on another joint RES/EPRI collaboration and a draft guidance published in January 2010, NUREG-1934 EPRI 1019195 [3].

In 2012 an additional first day of training was included in the NRC-RES/EPRI Fire PRA Workshop to cover principal elements of each technical area covered in the Fire PRA course, i.e., PRA, HRA, Electrical Analysis, and Fire Analysis. This introductory module was intended to assist in preparing the students to understand the in-depth fire PRA training modules that followed. The introductory modules were not intended to be a substitute for education and/or training in the subject matter. The intent was that they would serve as a primer for those individuals who lacked such training or those who were cross-training in an area other than their primary area of expertise.

The four introductory modules listed below (referred to as Module 0) were offered in parallel on the first day of the workshop.

Module 0a: Principles of PRA

Module 0b: Principles of Electrical Analysis
Module 0c: Principles of Fire Science and Modeling
Module 0d: Principles of HRA

These sub-modules are included in the text and on the accompanying DVDs as a part of their related module.

1.1 About this text

"Methods for Applying Risk Analysis to Fire Scenarios (MARIAFIRES) – 2012", is a collection of the materials that were presented at the two sessions of the NRC-RES/EPRI Fire PRA conducted July 16–20, 2012, and September 24-28, 2012.

The 2012 workshop was video recorded and adapted as an alternative training method for those who were unable to physically attend the training sessions. This NUREG/CP is comprised of the materials supporting those videos and includes the five volumes below (the videos are enclosed on DVD in the published paper copies of this NUREG/CP). This material can also serve as a refresher for those who attended one or more of the training sessions, and would be useful preparatory material for those planning to attend a session.

MARIAFIRES is comprised of 5 volumes.

Volume 1 – Module 0a Principles of PRA and Module 1: PRA/Systems Analysis
Volume 2 – Module 0b Principles of Electrical Analysis and Module 2: Electrical Analysis
Volume 3 – Module 0c Principles of Fire Science and Modeling and Module 3: Fire Analysis
Volume 4 – Module 0d Principles of HRA and Module 4: Fire Human Reliability Analysis
Volume 5 – Module 5: Advanced Fire Modeling

Integral to Modules 1, 2 and 3 is a set of hands-on problems based on a conceptual generic nuclear power plant (NPP) developed for training purposes. This generic plant is referred to in this text and in classroom examples as SNPP (Simplified Nuclear Power Plant). The same generic NPP is used in all three modules. Chapter 2 of this document provides the background information for the problem sets of each module, including a general description of the sample power plant and the internal events PRA needed as input to the fire PRA. The generic NPP defined for this training is an extremely simplified one that in many cases does not meet any regulatory requirements or good engineering practices. For training purposes, the design features presented highlight the various aspects of the fire PRA methodology.

For Module 4 and 5, independent sets of examples are used to illustrate key points of the analysis procedures. The examples for these two modules are not tied to the simplified plant. Module 4 uses examples that were derived largely from pilot applications of the proposed fire HRA methods and on independent work of the EPRI and RES HRA teams. The examples for Module 5 were taken directly from Reference [3] and represent a range of typical NPP fire scenarios across a range of complexity and that highlight some of the computation challenges associated with the NPP fire PRA fire modeling applications.

A short description of the Fire PRA technical tasks is provided below. For further details, refer to the individual task descriptions in EPRI 1011989, NUREG/CR-6850, Volume 2. The figure presented at the end of this chapter provides a simplified flow chart for the analysis process and indicates which training module covers each of the analysis tasks.

Plant Boundary Definition and Partitioning (Task 1). The first step in applying the fire PRA methodology is to define the physical boundary of the analysis and to divide the area within that boundary into analysis compartments.

Fire PRA Component Selection (Task 2). The selection of components that are to be credited for plant shutdown following a fire is a critical step in any fire PRA. Components selected would generally include many, but not necessarily all, components credited in the 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix R, "Fire Protection Program for Nuclear Power Facilities Operating prior to January 1, 1979," post-fire safe shutdown (SSD) analysis. Additional components will likely be selected, potentially including most, but not all, components credited in the plant's internal events PRA. Also, the proposed methodology would likely introduce components beyond either the 10 CFR 50 Appendix R list or the internal events PRA model. Such components are often of interest because of concern for multiple spurious actuations that may threaten the credited functions and components, as well as from concerns about fire effects on instrumentation used by the plant crew to respond to the event.

Fire PRA Cable Selection (Task 3). This task provides instructions and technical considerations associated with identifying cables supporting those components selected in Task 2 above. In previous fire PRA methods (such as EPRI Fire-Induced Vulnerability Evaluation (FIVE) and Fire PRA Implementation Guide), this task was relegated to the SSD analysis and its associated databases. NUREG/CR-6850 (EPRI 1011989) offers a more structured set of rules for selection of cables.

Qualitative Screening (Task 4). This task identifies fire analysis compartments that can be shown, without quantitative analysis, to have little or no risk significance. Fire compartments may be screened out if they contain no components or cables identified in Tasks 2 and 3 and if they cannot lead to a plant trip because of either plant procedures, an automatic trip signal, or technical specification requirements.

Plant Fire-Induced Risk Model (Task 5). This task discusses steps for the development of a logic model that reflects plant response following a fire. Specific instructions have been provided for treatment of fire-specific procedures or plans. These procedures may impact availability of functions and components or include fire-specific operator actions (e.g., self- induced station blackout).

Fire Ignition Frequency (Task 6). This task describes the approach to develop frequency estimates for fire compartments and scenarios. Significant changes from the EPRI FIVE method have been made in this task. The changes generally relate to the use of challenging events, considerations associated with data quality, and increased use of a fully component-based ignition frequency model (as opposed to the location/component-based model used, for example, in FIVE).

Quantitative Screening (Task 7). A fire PRA allows the screening of fire compartments and scenarios based on their contribution to fire risk. This approach considers the cumulative risk associated with the screened compartments (i.e., the ones not retained for detailed analysis) to ensure that a true estimate of fire risk profile (as opposed to vulnerability) is obtained.

Scoping Fire Modeling (Task 8). This step provides simple rules to define and screen fire ignition sources (and therefore fire scenarios) in an unscreened fire compartment.

Detailed Circuit Failure Analysis (Task 9). This task provides an approach and technical considerations for identifying how the failure of specific cables will impact the components included in the fire PRA SSD plant response model.

Circuit Failure Mode Likelihood Analysis (Task 10). This task considers the relative likelihood of various circuit failure modes. This added level of resolution may be a desired option for those fire scenarios that are significant contributors to the risk. The methodology provided in NUREG/CR-6850 (EPRI 1011989) benefits from the knowledge gained from the tests performed in response to the circuit failure issue.

Detailed Fire Modeling (Task 11). This task describes the method to examine the consequences of a fire. This includes consideration of scenarios involving single compartments, multiple fire compartments, and the main control room. Factors considered include initial fire characteristics; fire growth in a fire compartment or across fire compartments; detection and suppression; electrical raceway fire barrier systems, and damage from heat and smoke. Special consideration is given to turbine generator (T/G) fires, hydrogen fires, high-energy arcing faults (HEAF), cable fires, and main control board (MCB) fires. Considerable improvements can be found in the method for this task over the EPRI FIVE and Fire PRA Implementation Guide in nearly all technical areas.

Post-Fire Human Reliability Analysis (Task 12). This task considers operator actions for manipulation of plant components. The analysis task procedure provides structured instructions for identification and inclusion of these actions in the fire PRA. The procedure also provides instructions for estimating screening human error probabilities (HEPs) before detailed fire modeling results (e.g., fire growth and damage behaviors) have necessarily been developed or detailed circuit analyses (e.g., can the circuit spuriously actuate as opposed to simply assuming it can actuate) have been completed. In a fire PRA, the estimation of HEP values with high confidence is critical to the effectiveness of screening. This report does not develop a detailed fire HRA methodology. A number of HRA methods can be adopted for fire with appropriate additional instructions that superimpose fire effects on any of the existing HRA methods such as the Technique for Human Error Rate Prediction (THERP), Causal Based Decision Tree (CBDT), A Technique for Human Event Analysis (ATHEANA), etc. This would improve consistency across analyses (i.e., fire and internal events PRA).

Seismic Fire Interactions (Task 13). This task is a qualitative approach to help identify the risk from any potential interactions between an earthquake and a fire.

Fire Risk Quantification (Task 14). The task summarizes what is to be done for quantification of the fire risk results.

Uncertainty and Sensitivity Analyses (Task 15). This task describes the approach to follow for identifying and treating uncertainties throughout the fire PRA process. The treatment may vary from quantitative estimation and propagation of uncertainties where possible (e.g., in fire frequency and non-suppression probability) to identification of sources without quantitative estimation. The treatment may also include one-at-a-time variation of individual parameter values or modeling approaches to determine the effect on the overall fire risk (i.e., sensitivity analysis).

Fire PRA Documentation (Task 16). This task describes the approach to follow for documenting the Fire PRA process and its results. Figure 1 shows the relationship between the above 16 technical tasks from EPRI 1011989, NUREG/CR-6850, Volume 2.

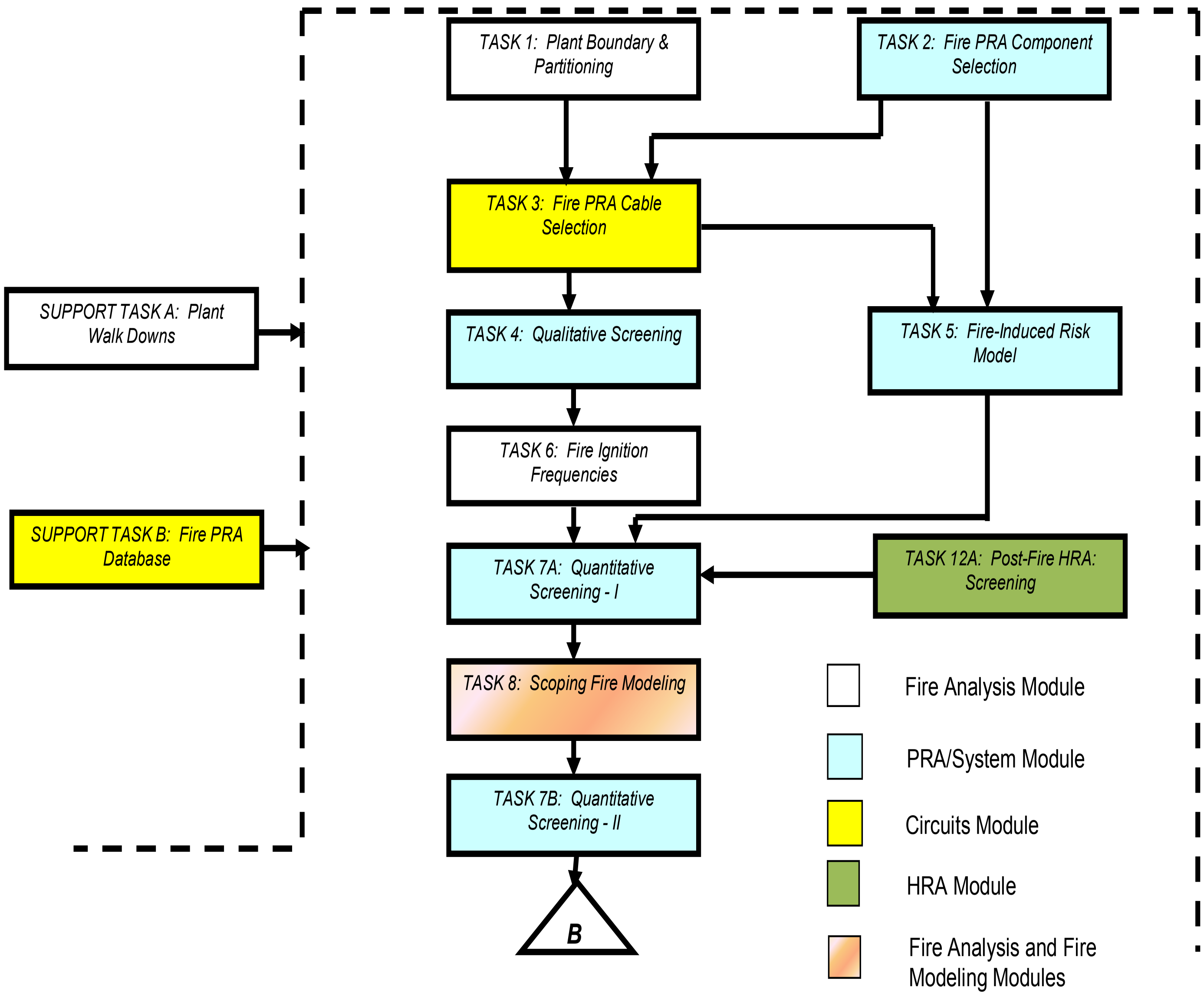


Figure 0-1 Relationship of Technical Tasks in NUREG/CR 6850 Volume 2

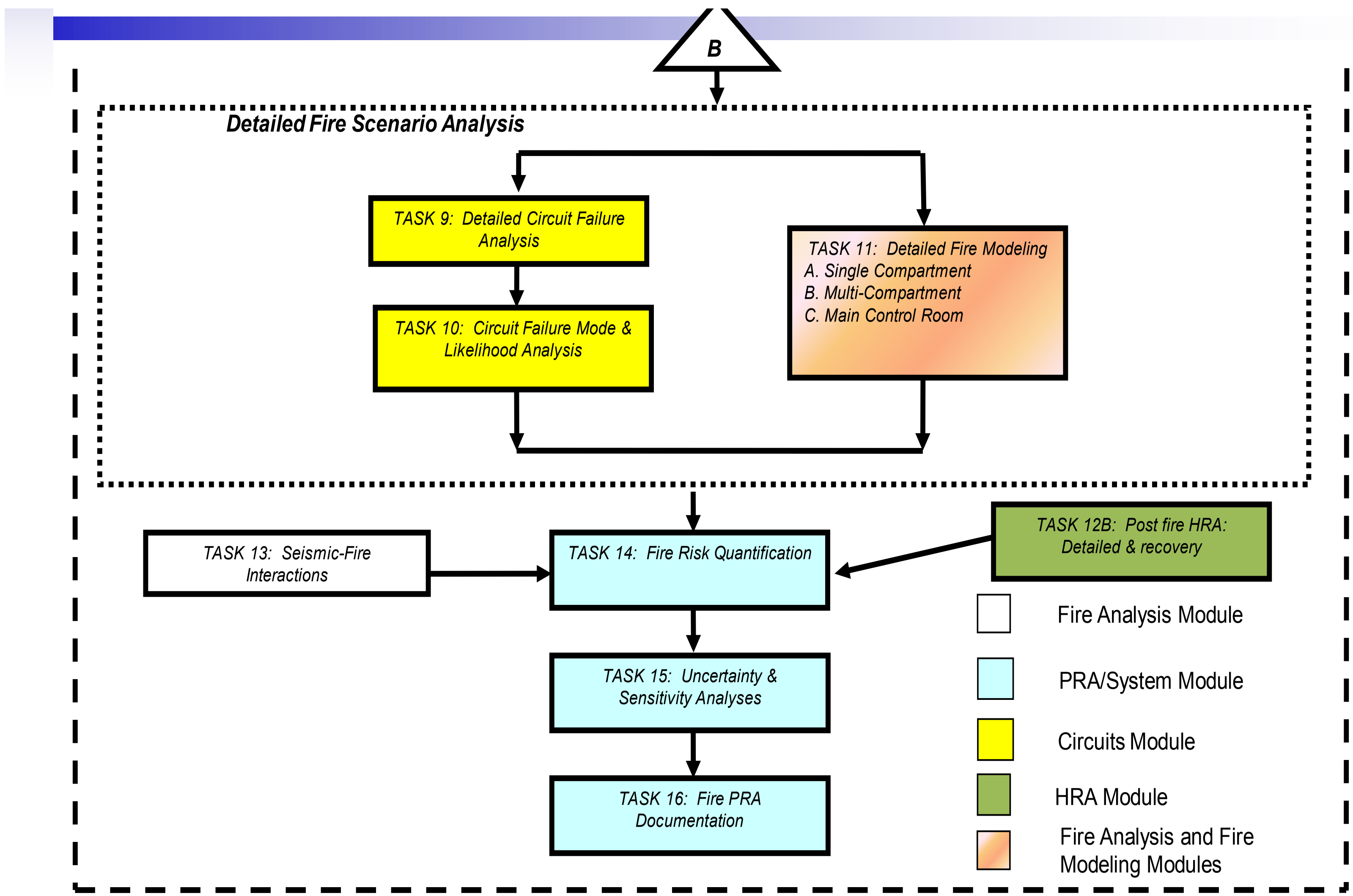


Figure 0-2 Note: "B" is from Task 7B (Previous Page)

1.2 References

1. NUREG/CR-6850, EPRI 1011989, *EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities*, September 2005.

2. NUREG-1921, EPRI 1023001, *EPRI/NRC-RES Fire Human Reliability Analysis Guidelines*, May 2012.

3. NUREG-1934, EPRI 1023259, *Nuclear Power Plant Fire Modeling Application Guide,* November 2012[1].

[1] At the time of the 2012 NRC-RES/EPRI Fire PRA Workshop, this final report had not yet been published. A draft for public comment was used to conduct the training.

2

MODULE 5: ADVANCED FIRE MODELING

NUREG/CR-6850, EPRI 1011989 did not provide detailed guidance on the application of fire modeling tools. Rather, the base methodology document assumes that the analyst will apply a range of computation fire modeling tools to support the analysis, provides recommended practice relative to the general development/definition of fire scenarios and provides recommendations for characterizing of various fire sources (e.g., heat release rate transient profiles and peak heat release rate distribution curves). The question of selecting and applying appropriate fire modeling tools was left to the analyst's discretion.

Module 5, Advanced Fire Modeling, is based on the joint EPRI/NRC-RES project documented in NUREG 1934, EPRI 1023259 "Nuclear Power Plant Fire Modeling Analysis Guidelines (NPP FIRE MAG)." NUREG 1934 was developed to provide guidance on the application of fire models to nuclear power plant fire scenarios and to serve as a teaching tool to support the Advanced Fire Modeling Module of the EPRI/NRC-RES fire PRA course.

The following is a short description of the Fire PRA technical tasks covered in Module 5. For further details relative to this technical task, refer to the individual task descriptions in Volume 2 of EPRI 1011989, NUREG/CR-6850.

- ***Scoping fire Modeling (Task 8).*** Scoping fire modeling is the first task in the Fire PRA framework where fire modeling tools are used to identify ignition sources that may impact the fire risk of the plant. Screening some of the ignition sources, along with the applications of severity factors to the unscreened ones, may reduce the compartment fire frequency previously calculated in Task 6.
- ***Detailed Fire Modeling (Task 11).*** This task describes the method to examine the consequences of a fire. This includes consideration of scenarios involving single compartments, multiple fire compartments, and the main control room. Factors considered include initial fire characteristics, fire growth in a fire compartment or across fire compartments, detection and suppression, electrical raceway fire barrier systems), and damage from heat and smoke. Special consideration is given to turbine generator (T/G) fires, hydrogen fires, high-energy arcing faults, cable fires, and main control board (MCB) fires.

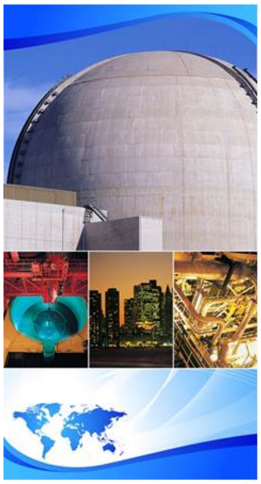
2.1 Fundamentals

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Sandia National Laboratories

SAIC Science Applications International Corporation
From Science to Solutions



EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5 – Advanced Fire Modeling
Fundamentals

Joint RES/EPRI Fire PRA Workshop
2012
Washington, D.C.

A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Advanced Fire Modeling

- **Course Objectives**
  - Fire modeling for nuclear power plant (NPP) applications
  - Fire model uncertainty estimation
- **Approach**
  - Evaluate fire scenarios relevant to NPPs
  - Use models evaluated in verification and validation (V&V) study
  - Demonstrate capability and limitations of each model type
  - Quantify uncertainty as part of the fire modeling analysis
  - Identify relevant sensitivity analyses to support use of results

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Background

- NFPA issued the first edition of NFPA 805 in 2001
- NRC amended 10 CFR 50.48(c) in 2004 to employ NFPA 805 as alternative to existing deterministic requirements
- NFPA 805 requires that
  - Fire models shall be verified and validated (section 2.4.1.2.3)
  - Only fire models that are acceptable to the authority having jurisdiction (AHJ) shall be used in fire modeling calculations (section 2.4.1.2.1)
- NRC/RES and EPRI completed V&V project for five fire modeling tools in 2007
- Results documented in NUREG-1824, EPRI 1011999

NUREG 1934 / EPRI 1023259 – NPP FIRE MAG

- The objective is to describe the process of conducting fire modeling analyses for commercial nuclear power plant applications
- The process addresses the following technical elements
  - Selection and definition of fire scenarios
  - Determination and implementation of input values
  - Sensitivity analysis
  - Uncertainty quantification
  - Documentation
- The document provides generic guidance, recommended best practices, and example applications

NUREG 1934 / EPRI 1023259 – NPP FIRE MAG

- Users with following expertise will benefit the most :
  - General knowledge of the behavior of compartment fires
  - General knowledge of basic engineering principles, specifically thermodynamics, heat transfer, and fluid mechanics
  - Ability to understanding the basis of mathematical models involving algebraic and differential equations
- Further training resources in Section 1.3.2
  - Academic courses
  - Short courses
  - Written materials

Fire Modeling Theory

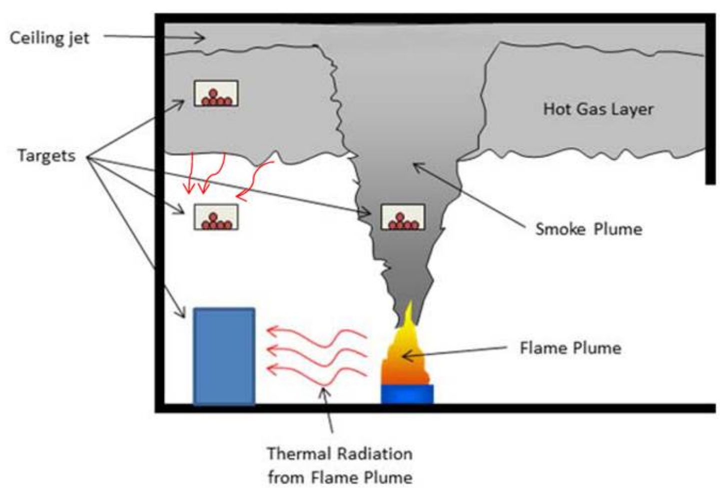


Figure 1-1. Characteristics of compartment fires.

Fire Modeling Theory

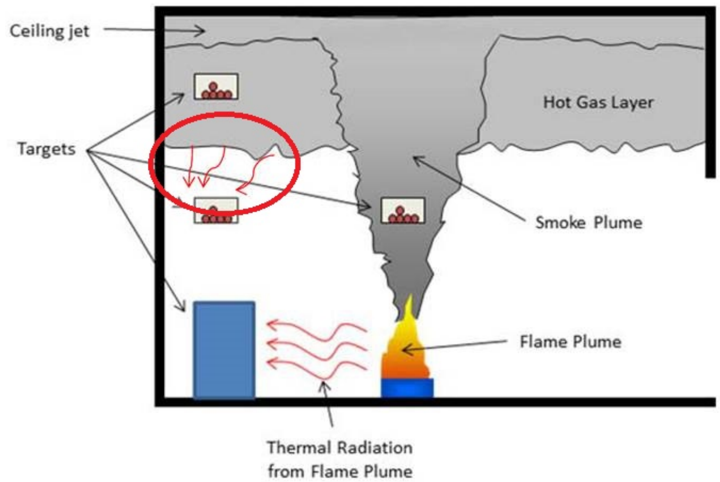


Figure 1-1. Characteristics of compartment fires.

Fire Modeling Theory

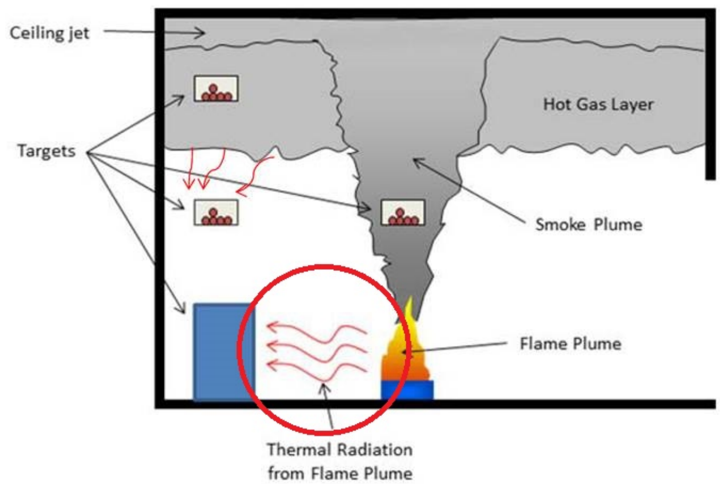


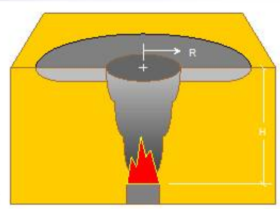
Figure 1-1. Characteristics of compartment fires.

Fire Modeling Theory

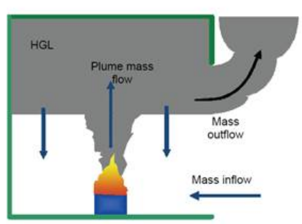
- Parameters of interest in fire modeling analyses:
  - Rate of smoke production
  - Rate of smoke filling
    - HGL interface position
  - Properties of the fire plume and ceiling jet
    - Temperatures / velocities
  - Properties of the HGL
    - Temperature / smoke concentration / visibility
  - Target response to incident heat flux
    - Nuclear safety targets (cables, equipment, operators …)
    - Fire protection targets (sprinklers, detectors …)

Fire Models In NUREG 1934 / EPRI 1023259

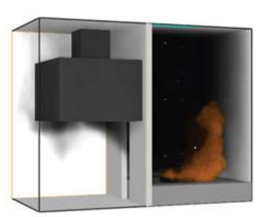
- **Algebraic models (1.4.1)**
  - FDTs
  - FIVE-rev1



- **Zone models (1.4.2)**
  - CFAST
  - MAGIC

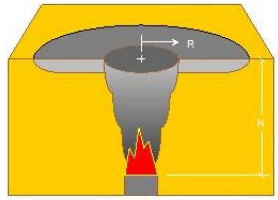


- **CFD models (1.4.3)**
  - FDS

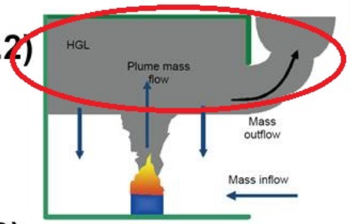


Fire Models In NUREG 1934 / EPRI 1023259

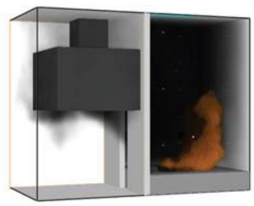
- **Algebraic models (1.4.1)**
  - FDTs
  - FIVE-rev1



- **Zone models (1.4.2)**
  - CFAST
  - MAGIC



- **CFD models (1.4.3)**
  - FDS



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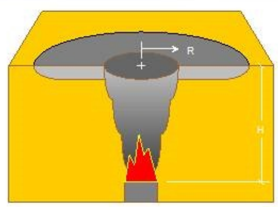
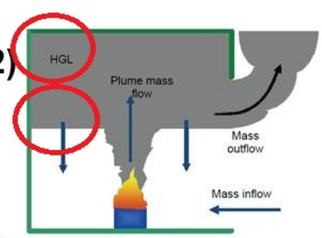
Fire Models In NUREG 1934 / EPRI 1023259

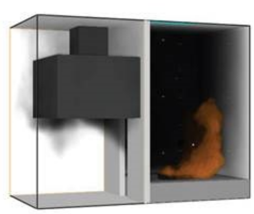
- **Algebraic models (1.4.1)**
  - FDTs
  - FIVE-rev1



- **Zone models (1.4.2)**
  - CFAST
  - MAGIC



- **CFD models (1.4.3)**
  - FDS



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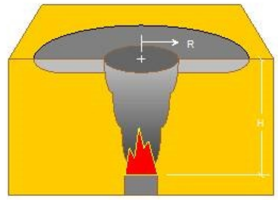
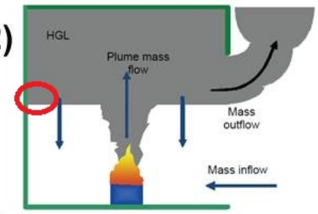
Fire Models In NUREG 1934 / EPRI 1023259

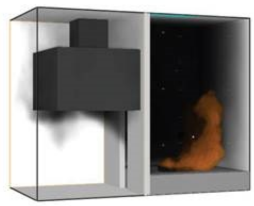
- **Algebraic models (1.4.1)**
  - FDTs
  - FIVE-rev1



- **Zone models (1.4.2)**
  - CFAST
  - MAGIC

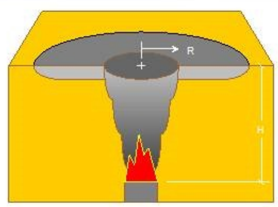


- **CFD models (1.4.3)**
  - FDS

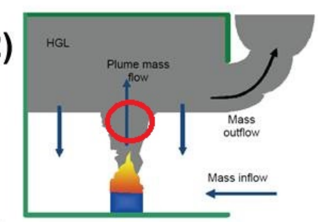


Fire Models In NUREG 1934 / EPRI 1023259

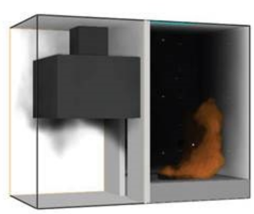
- **Algebraic models (1.4.1)**
  - FDTs
  - FIVE-rev1



- **Zone models (1.4.2)**
  - CFAST
  - MAGIC



- **CFD models (1.4.3)**
  - FDS



Fire Model V&V

- Fire models shall only be applied within the limitations of the given model and shall be verified and validated.
- Validation
  - Is the physics right?
  - Are the right equations being solved?
- Verification
  - Is the math right?
  - Are the selected equations being solved correctly?
- NUREG-1824, EPRI 1011999 - Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications

NFPA 805 Fire Modeling Applications

- NFPA 805 requirements associated with fire modeling are organized in two sections
  - Section 2.4.1.4 describes the requirements associated with the fire modeling tools selected for the analysis.
  - Section 4.2.4.1 describes requirements for the implementation of a performance-based fire modeling analysis.

NFPA 805 Fire Modeling Applications

- NFPA 805 Section 2.4.1.2 describes the requirements for the use of fire models, which include:
  - The use of fire models acceptable to the AHJ
  - The application of fire models within their range and limitations
- Chapter 2 of NUREG 1934, EPRI 1023259 provides guidance on
    - Ensuring the model is within the range of limitations
    - Ensuring specific fire model applications are within the scope of existing V&V studies
    - What steps should be taken if they are not

NFPA 805 Fire Modeling Applications

- NFPA 805 Section 4.2.4.1 describes the process to follow when using fire modeling to address variances from deterministic requirements (VFDRs):
  - Identify Targets (NFPA 805 § 4.2.4.1.1)
  - Establish Damage Thresholds (NFPA 805 § 4.2.4.1.2)
  - Determine Limiting Conditions (NFPA 805 § 4.2.4.1.3)
  - Establish Fire Scenarios (NFPA 805 § 4.2.4.1.4)
  - Protection of Required Nuclear Safety Success Paths (NFPA 805 § 4.2.4.1.5)
  - Operations Guidance (NFPA 805 § 4.2.4.1.6)

Fire Modeling in Support of Fire PRA

- Fire PRA applies fire modeling in the fire scenario development and analysis process
  - A fire scenario in a Fire PRA is often modeled as a progression of damage states over time
  - It is initiated by a postulated fire involving an ignition source
  - Each damage state is characterized by a time and a set of targets damaged within that time
  - Fire modeling is used to determine the targets affected in each damage state and the associated time at which this occurs

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Fire Modeling in Support of Fire PRA

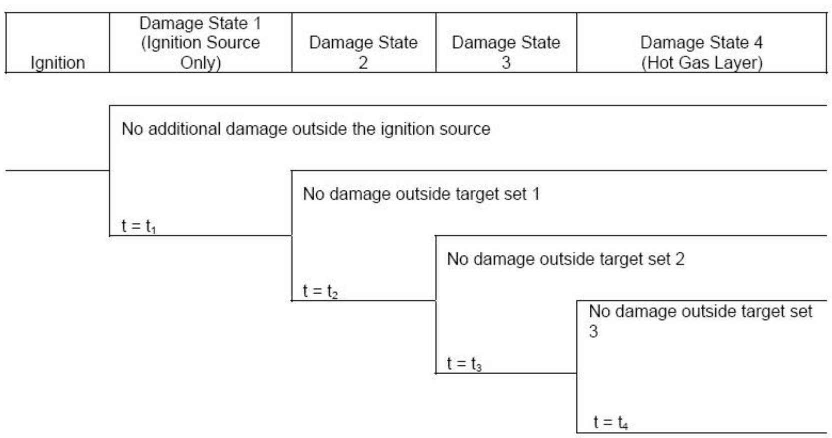

Figure 1-4: Event tree depicting scenario progression modeled in a Fire PRA

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Fire Modeling Process

- Step 1
  - Define modeling goals
- Step 2
  - Characterize fire scenarios
- Step 3
  - Select fire models
- Step 4
  - Calculate fire conditions
- Step 5
  - Sensitivity / uncertainty analyses
- Step 6
  - Document the analysis

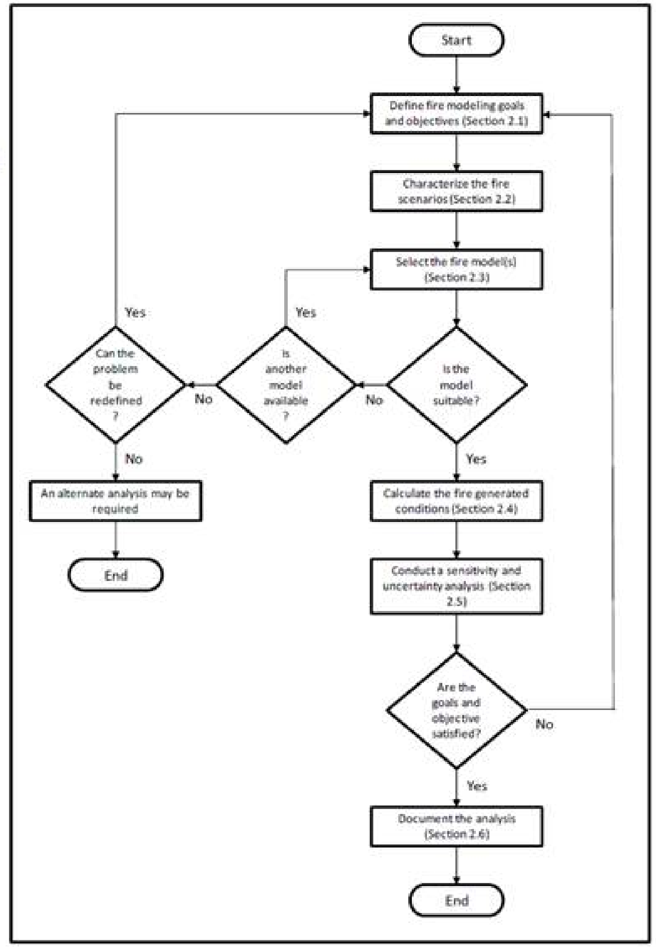


Figure 2-1. Fire modeling process.

Step 1 - Define Modeling Goals

- Establishment of general goals and performance objectives specific to the fire modeling application
- Example of a general goal
  - Demonstrate that targets required for safe shutdown remain free from fire damage (deterministic goal) … to a specified level of probability (probabilistic goal)
- Example of a specific performance objective
  - Evaluate if a fire in Fire Area "X" involving Panel "Y" could cause the surface temperature of Cable "Z" to exceed 330 °C (625 °F)

Step 1 - Define Modeling Goals

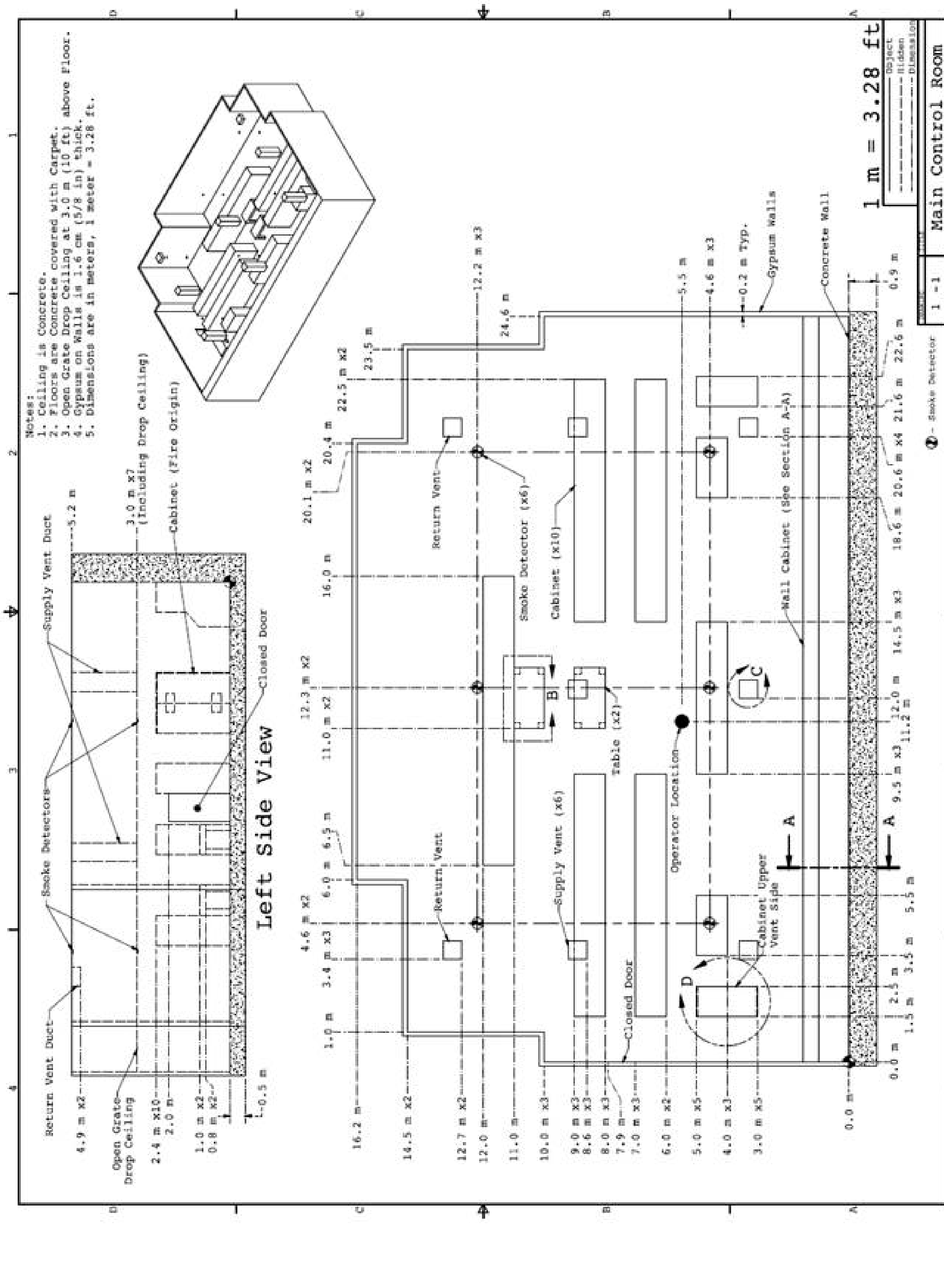
- Maximum acceptable surface temperature for a cable, component, secondary combustible, structural element, or fire-rated construction
- Maximum acceptable incident heat flux for a cable, component, structural element, or secondary combustible
- Maximum acceptable exposure temperature for a cable, component, structural element, or secondary combustible
- Maximum acceptable enclosure temperature
- Maximum smoke concentration or minimum visibility
- Maximum or minimum concentration of one or more gas constituents, such as carbon monoxide, oxygen, hydrogen cyanide

Step 2 - Characterize Fire Scenarios

- A fire scenario is defined as a set of elements needed to describe a fire incident
- These elements are typically specified in fire models
- These elements include the following:
  - Enclosure details
  - Fire location within the enclosure
  - Fire protection features that will be credited
  - Ventilation conditions
  - Target location(s)
  - Secondary combustibles
  - Source fire

Step 2 - Characterize Fire Scenarios

- **Enclosure details**
- Enclosure details include
  - The identity of the enclosures included in the fire model analysis
  - The physical dimensions of these enclosures
  - The boundary materials of each enclosure



Notes:
1. Ceiling is Concrete.
2. Floors are Concrete covered with Carpet.
3. Open Grate Drop Ceiling at 3.0 m (10 ft) above Floor.
4. Gypsum on Walls is 1.6 cm (5/8 in) thick.
5. Dimensions are in meters, 1 meter = 3.28 ft.
Left Side View
Return Vent Duct
Smoke Detectors
Supply Vent Duct
Cabinet (Fire Origin)
Closed Door
Open Grate Drop Ceiling
3.0 m x7 (Including Drop Ceiling)
5.2 m
4.9 m x2
2.4 m x10
2.0 m
1.0 m x2
0.8 m x2
0.5 m
Return Vent
Smoke Detector (x6)
Cabinet (x10)
Supply Vent (x6)
Table (x2)
Operator Location
Closed Door
Cabinet Upper Vent Side
Wall Cabinet (See Section A-A)
Gypsum Walls
Concrete Wall
0.2 m Typ.
Smoke Detector
1 m = 3.28 ft
Main Control Room
1 - 1
Object
Hidden
Dimension

Step 2 - Characterize Fire Scenarios

- **Fire location**
- The location depends on the fire modeling goal, the target location, and the fire modeling tool selected
- Examples:
  - Targets in the fire plume or ceiling jet
  - Targets affected by flame radiation
  - Targets engulfed in flames
  - Targets immersed in the Hot Gas Layer

Step 2 - Characterize Fire Scenarios

- **Credited fire protection**
- Fire protection features to be credited in a fire modeling analysis usually require a fire protection engineering evaluation of the system's effectiveness
  - Assessment of the system compliance with applicable codes, including maintenance and inspection
  - Assessment of the system performance against particular fire scenarios being considered.
- Fire modeling tools within this course may not be able to model the impact of some of the fire protection features credited in a given scenario.

Step 2 - Characterize Fire Scenarios

- **Ventilation conditions**
- Ventilation conditions include:
  - Mechanical ventilation
    - Normal HVAC / purge mode
  - Natural ventilation
    - Door / window / damper / vent positions

- **Target location(s)**
- The physical dimensions of the target relative to the source fire or the fire model coordinate system.

Step 2 - Characterize Fire Scenarios

- **Secondary combustibles**
- Any combustible materials that, if ignited, could affect the exposure conditions to the target set considered.
  - Intervening combustibles, which are those combustibles located between the source fire and the target, are examples of secondary combustibles
- Secondary combustibles include both fixed and transient materials
- Secondary combustibles take on the characteristics of a target prior to their ignition

Step 2 - Characterize Fire Scenarios

- **Source fire**
- The source fire is the forcing function for the fire scenario
- Common fuel packages include electrical panels and transformers, cables, transient combustible material, lubricant reservoirs, and motors
- The source fire is typically characterized by a heat release rate history
- Other important aspects include the physical dimensions of the burning object, its composition, and its behavior when burning

Step 3 - Select Fire Models

- Fire models can be classified into three groups:
  - Algebraic models
  - Zone models
  - CFD 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.
  - Combination of all three types of models may be useful for analyzing a specific problem.

Step 3 - Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

Fire Model Class	Examples	Typical Applications	Advantages	Disadvantages
Algebraic models	FDT[S] FIVE-Rev1	Screening calculations; zone of influence; target damage by thermal radiation, Hot Gas Layer, or thermal plume acting in isolation.	Simple to use; minimal inputs; quick results; ability to do multiple parameter sensitivity studies.	Limited application range; treats phenomena in isolation; typically applicable only to steady state or simply defined transient fires (e.g., proportional to the square of time or t^2 fires).

Step 3 - Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

Fire Model Class	Examples	Typical Applications	Advantages	Disadvantages
Zone Model	CFAST MAGIC	Detailed fire modeling in simple geometries; often used to compute hot gas temperatures and target heat fluxes.	Simple to use; couples Hot Gas Layer and localized effects; quick results; ability to do multiple parameter sensitivity studies.	Error increases with increasing deviation from a rectangular enclosure; large horizontal flow paths not well treated.

Step 3 - Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

Fire Model Class	Examples	Typical Applications	Advantages	Disadvantages
Computation Fluid Dynamics Model	FDS	Detailed fire modeling in complex geometries, including computing time to target damage and habitability (MCR abandonment or manual action feasibility).	Ability to simulate fire conditions in complex geometries and with complex vent conditions.	Significant effort to create input files and post-process the results; long simulation times; difficult to model curved geometry, smoke detector performance, and conditions after sprinkler actuation.

Step 3 - Select Fire Models

- **Fire Dynamics Tools (FDTs)**
- FDTs is a set of algebraic models preprogrammed into spreadsheets
- The FDTs library is documented in NUREG-1805 and Supplement 1 (2011)
- The NRC maintains a website where both new and updated spreadsheets are posted:

www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/finalreport/index.html

- See NUREG-1934, EPRI 1011999 Table 2-2 for complete list of FDTs routines

Step 3 - Select Fire Models

- **Fire-Induced Vulnerability Evaluation (FIVE)-Rev1**
- Five-Rev 1 is a set of algebraic models preprogrammed into spreadsheets
- The FIVE-Rev 1 library is documented in EPRI 1002981
- See NUREG-1934, EPRI 1011999 Table 2-3 for complete list of FIVE-Rev 1 routines

Step 3 - Select Fire Models

- **Consolidated Fire Growth and Smoke Transport (CFAST)**
- CFAST is a multi-room two-zone computer fire model
- The model subdivides a compartment into two control volumes
  - A relatively hot upper layer (i.e., the HGL)
  - A relatively cool lower layer
  - Conditions within each control volume are considered as uniform at any time, with no spatial variations within a control volume
- For some application the two-zone assumption may not be appropriate
  - Long hallways
  - Tall shafts

Step 3 - Select Fire Models

- **MAGIC**
- MAGIC is a two-zone computer fire model, developed and maintained by EdF specifically for use in NPP analysis
- MAGIC is fundamentally similar to CFAST and solves the same basic set of predictive differential equations

Step 3 - Select Fire Models

- **Fire Dynamics Simulator (FDS)**
- FDS is a 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
- FDS computes the temperature, density, pressure, velocity, and chemical composition within each grid cell at each time step
  - There are typically hundreds of thousands to several million grid cells, and thousands to hundreds of thousands of time steps in a FDS simulation

Table 2-5. Summary of selected normalized parameters for application of the validation results to NPP fire scenarios (NUREG-1824/EPRI 1011999, 2007).

Quantity	Normalized Parameter	General Guidance	Validation Range
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^2 \sqrt{gD}}$	Ratio of characteristic velocities. A typical accidental fire has a Froude number of order 1. Momentum-driven fire plumes, like jet flares, have relatively high values. Buoyancy-driven fire plumes have relatively low values.	0.4 – 2.4
Flame Length Ratio	$\frac{H_f + L_f}{H_c}$ $\frac{L_f}{D} = 3.7\,\dot{Q}^{*2/5} - 1.02$	A convenient parameter for expressing the "size" of the fire relative to the height of the compartment. A value of 1 means that the flames reach the ceiling.	0.2 – 1.0
Ceiling Jet Distance Ratio	$\frac{r_{cj}}{H_c - H_f}$	Ceiling jet temperature and velocity correlations use this ratio to express the horizontal distance from target to plume.	1.2 – 1.7
Equivalence Ratio	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2} \dot{m}_{O_2}}$ $\dot{m}_{O_2} = \begin{cases} 0.23 \times \frac{1}{2} A_0 \sqrt{H_0} & \text{(Natural)} \\ 0.23\,\rho_\infty \dot{V} & \text{(Mechanical)} \end{cases}$	The equivalence ratio relates the energy release rate of the fire to the energy release that can be supported by the mass flow rate of oxygen into the compartment, $\dot{m}_{O_2}$. The fire is considered over- or under-ventilated based on whether φ is less than or greater than 1, respectively. The parameter, r, is the stoichiometric ratio.	0.04 – 0.6
Compartment Aspect Ratio	L/H_c or W/H_c	This parameter indicates the general shape of the compartment.	0.6 – 5.7
Radial Distance Ratio	$\frac{r}{D}$	This ratio is the relative distance from a target to the fire. It is important when calculating the radiative heat flux.	2.2 – 5.7

Quantity	Normalized Parameter	General Guidance	Validation Range
Compartment Aspect Ratio	L/H_c or W/H_c	This parameter indicates the general shape of the compartment.	0.6 – 5.7
Radial Distance Ratio	$\frac{r}{D}$	This ratio is the relative distance from a target to the fire. It is important when calculating the radiative heat flux.	2.2 – 5.7

Step 3 - Select Fire Models

- Fire parameters may fall outside their validation range defined in NUREG-1824 , EPRI 1011999
- The predictive capabilities of the fire models in many scenarios can extend beyond the range
- Analyst is required to address these situations
- Sensitivity analyses can be used to address these scenarios

Step 4 - Calculate Fire Conditions

- This step involves running the model(s) and interpreting the results.
- The process includes
  - Determine the output parameters of interest
  - Prepare the input file
  - Run the computer model
  - Interpret the model results
  - Arrange output data in a form that is suitable for the goal

Step 5 - Sensitivity And Uncertainty Analyses

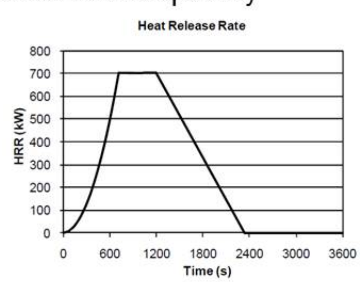
- A comprehensive treatment of uncertainty and sensitivity analyses are an integral part of a fire modeling analysis
- Model uncertainty
  - Models are developed based on idealizations of the physical phenomena and simplifying assumptions
- Parameter uncertainty
  - Many input parameters are based on available generic data or on fire protection engineering judgment

Step 6 - Document The Analysis

- Information needed to document 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
  - Marked up plant drawings.
  - Design basis documents (DBDs).
  - Sketches.
  - Write-ups and input tables.
  - Software versions, descriptions, and input files.
- A reviewer should be able to reproduce the results of a fire scenario analysis from the information contained within the documentation

Fire Modeling Elements – Heat Release Rate

- Three questions usually have to be answered to adequately assess the heat release rate of a fire:
  - How fast does the fire grow?
  - What is the peak intensity of the fire?
  - How long does the fire burn?



- Other factors:
  - Fire elevation
  - Fire location relative to targets or obstructions
  - Soot yield
  - Radiative fraction
  - Yield factors

Fire Modeling Elements – Area Configuration

- Compartment geometry
- Compartment Boundary materials

Table 3-1. Material Properties

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Source
Brick	0.8	2600	0.8	NUREG-1805, Table 2-3
Concrete	1.6	2400	0.75	NUREG-1805, Table 2-3
Copper	386	8954	0.38	SFPE Handbook, Table B.6
Gypsum	0.17	960	1.1	NUREG-1805, Table 2-3
Plywood	0.12	540	2.5	NUREG-1805, Table 2-3
PVC	0.192	1380	1.289	NUREG/CR-6850, Appendix R
Steel	54	7850	0.465	NUREG-1805, Table 2-3
XLP	0.235	1375	1.390	NUREG/CR-6850, Appendix R

Fire Modeling Elements – Ventilation Effects

- Ventilation openings
  - Vertical (doors / windows)
  - Horizontal (ceiling / floor vents)
- Leakage paths
- Mechanical ventilation
  - Injection
  - Extraction
  - Recirculation

Fire Modeling Elements – Targets

- Targets are objects of interest than can be affected by the fire-generated conditions
- Targets typically consist of
  - Cables in conduits
  - Cables in raceways
  - Plant equipment or
  - Plant personnel
- Targets are characterized by
  - Location,
  - Orientation (i.e. facing the fire, HGL, floor, etc.)
  - Damage criteria and
  - Thermophysical properties

Fire Modeling Elements – Secondary Combustibles

- Intervening combustibles should be described in terms of their locations as well as in terms of their relevant thermophysical and flammability properties
- Representing intervening combustibles in fire models presents technical challenges that the analyst should consider
  - Obtaining the necessary geometric and thermophysical properties representing the intervening combustible and
  - The ability of the computer tools to model the fire phenomena (e.g., fire propagation).

Representative Fire Scenarios

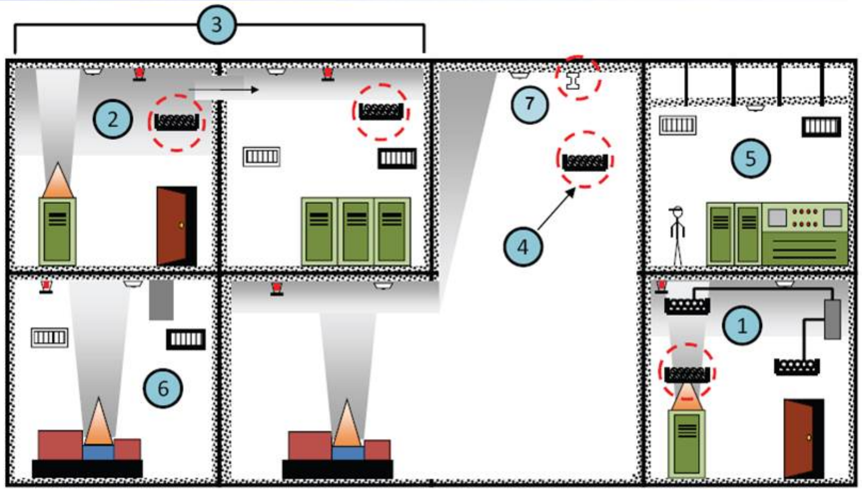


Figure 3-1. Pictorial representation of the fire scenario and corresponding technical elements described in this section.

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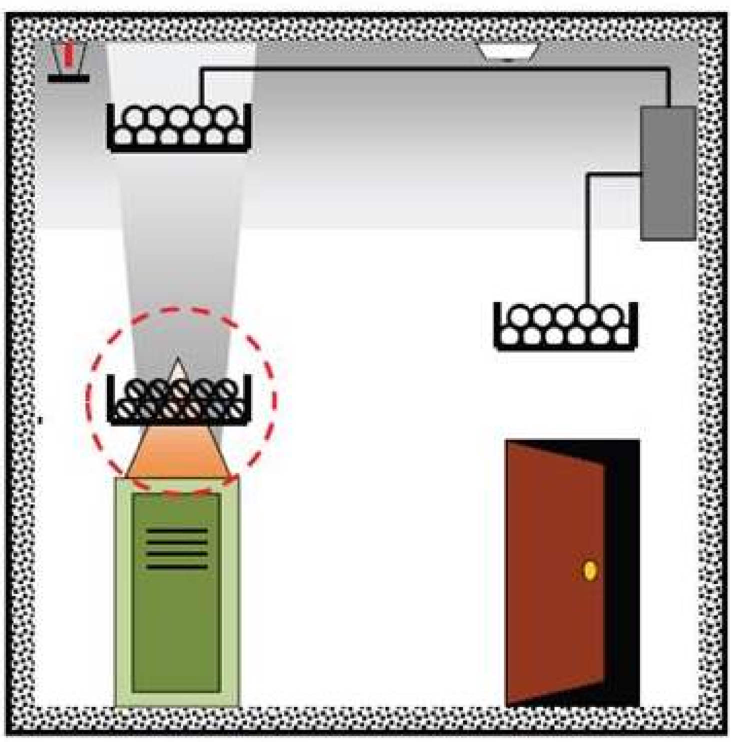


Figure 3-3. Pictorial representation of scenario 1

Scenario 2 - Targets Inside or Outside the Hot Gas Layer

- This scenario consists of a target, ignition source, and perhaps a secondary fuel source
- Objective: Calculate the time to damage for the target if it is inside or outside the Hot Gas Layer
- Examples C and E

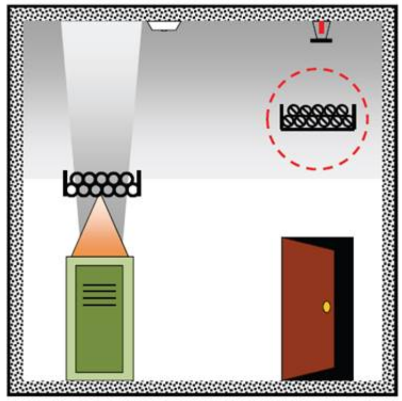


Figure 3-4 Pictorial representation of scenario 2

Scenario 3 - Targets Located in Adjacent Rooms

- This scenario consists of a target in a room adjacent to the room of fire origin
- Objective: Calculate the time to damage for a target in a room next to the room of fire origin
- Example G

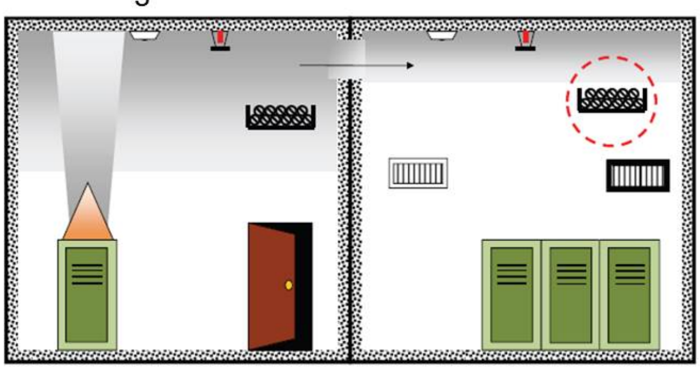


Figure 3-5. Pictorial representation of scenario 3

Scenario 4 - Targets in Rooms with Complex Geometries

- This scenario involves a room with an irregular ceiling height
- Objective: Calculate the time to damage for a target in a room with a complex geometry
- Examples D and H

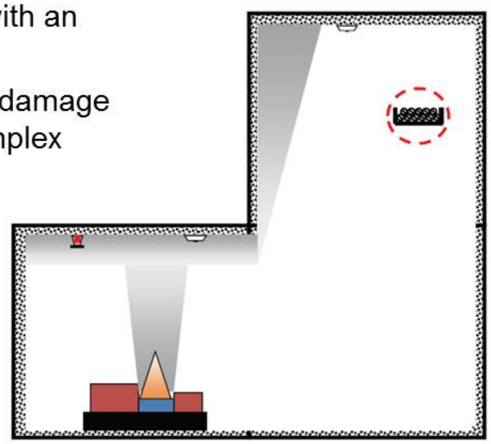


Figure 3-6. Pictorial representation of scenario 4

Scenario 5 - Main Control Room Abandonment

- This scenario consists of a fire (electrical cabinet fire within the main control board) that may force operators out of the control room
- Objective: Determine when control room operators will need to abandon the control room due to fire-generated conditions
- Example A

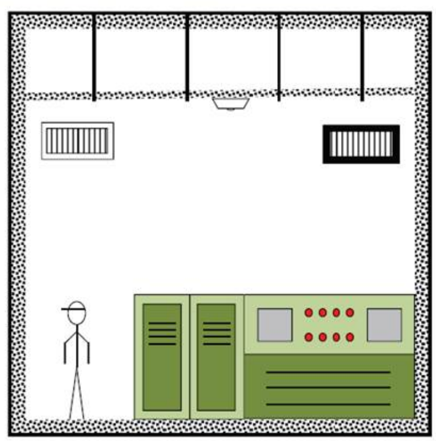
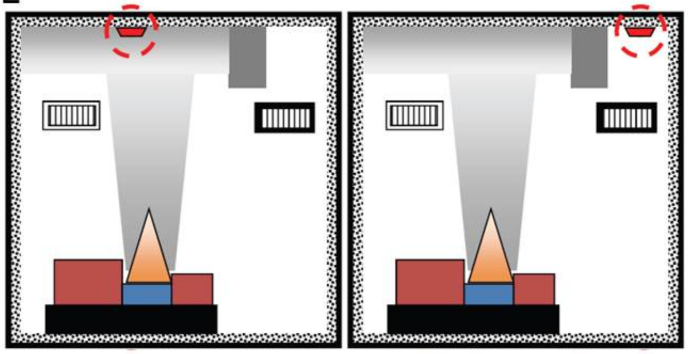


Figure 3-7. Pictorial representation of scenario 5

Scenario 6 - Smoke Detection and Sprinkler Activation

- This scenario addresses smoke/heat detector or sprinkler activation
- Objective: Calculate the response time of a smoke or heat detector that may be obstructed by ceiling beams, ventilation ducts, etc.
- Examples B and E



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Scenario 7 - Fire Impacting Structural Elements

- This scenario consists of fire impacting exposed structural elements
- Objective: Characterize the temperature of structural elements exposed to a nearby fire source
- Example F

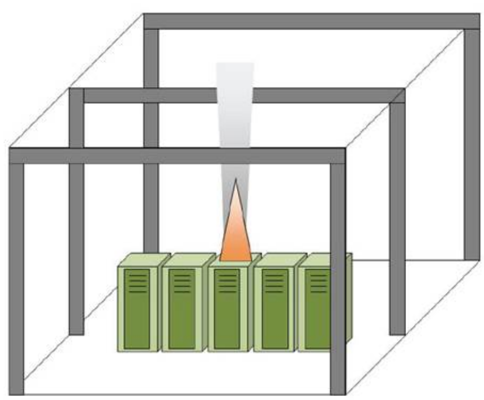

Figure 3-9. Pictorial representation of scenario 7

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Summary

- The purpose of this module has been to introduce the following concepts relevant to NPP applications:
  - The fire modeling process
  - The fire modeling tools
  - Representative fire modeling scenarios
  - Uncertainty / sensitivity analyses
- Over the next 2 days we will consider these representative fire modeling scenarios in more detail
- On Friday, you will perform your own analyses

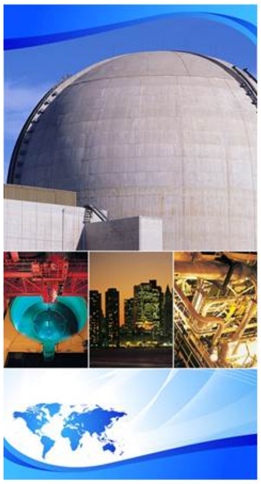
2.2 Fire Model Descriptions

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Sandia National Laboratories

SAIC Science Applications International Corporation
From Science to Solutions



EPRI/NRC-RES Fire PRA Methodology

Module 5: Advanced Fire Modeling
Fire Model Descriptions

Joint RES/EPRI Fire PRA Workshop
2012
Washington, D.C.

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FIVE (Fire-Induced Vulnerability Evaluation)

- EPRI TR-100443 "Methods of Quantitative Fire Hazards Analysis," May 1992.
- Mostly a collection of hand calculations to estimate fire-generated conditions.
- Capable of estimating smoke layer, height and temperatures.

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Slide 2

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About FIVE-Rev1

- More than 10 years after the start of FIVE, most of the equations are still used in practice
- A revision of the quantitative fire hazard techniques in FIVE.
- Most of the hand calculations are in the original EPRI publication and some other models available are in the fire protection engineering literature.
  - 4 stage heat release rate profile based on t^2 growth
  - Heskestad's flame height model
  - A radiation model from a cylindrical flame to targets
  - Models for velocity of plume and ceiling jet flows
  - Model for plume diameter as a function of height
  - MQH model for room temperature
  - Model for visibility through smoke

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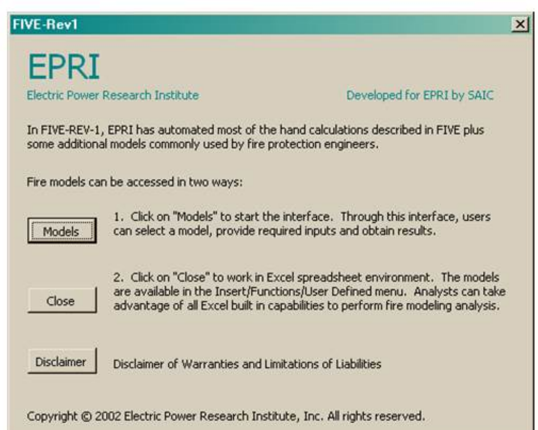
About FIVE-Rev1

- Excel spreadsheet
  - Graphical interface
  - Excel's equation library



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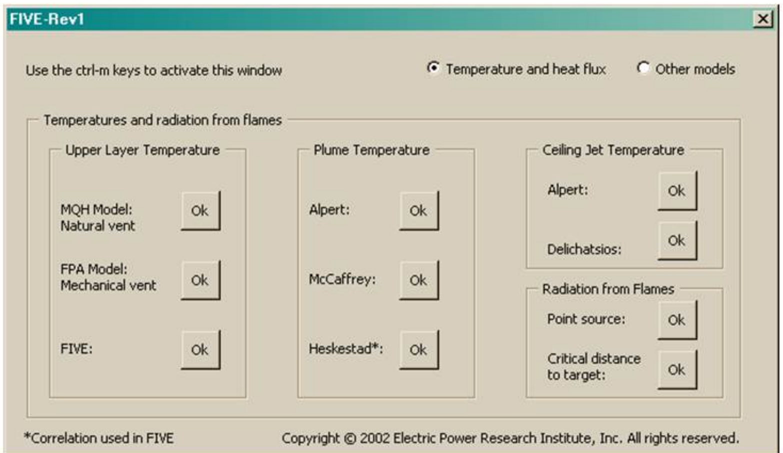
Graphical Interface

- Main menu screen: CTRL-m



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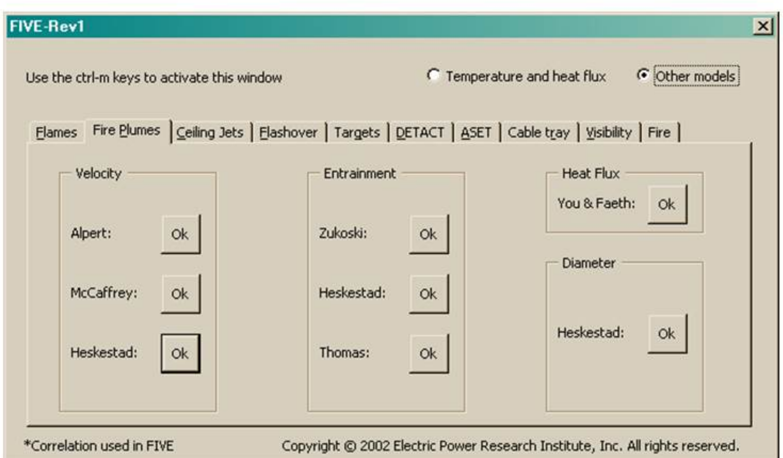
Graphical Interface

- Additional models screen:



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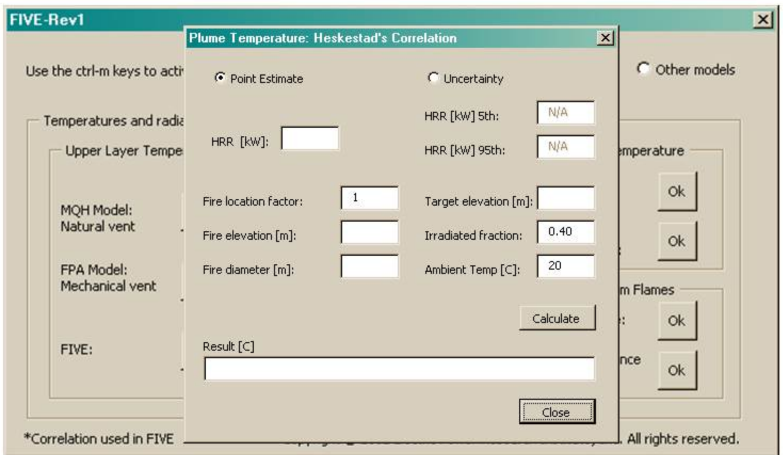
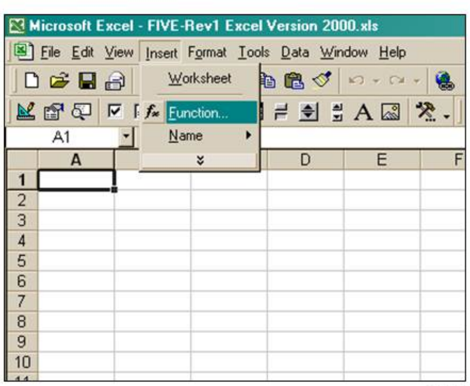
Graphical Interface

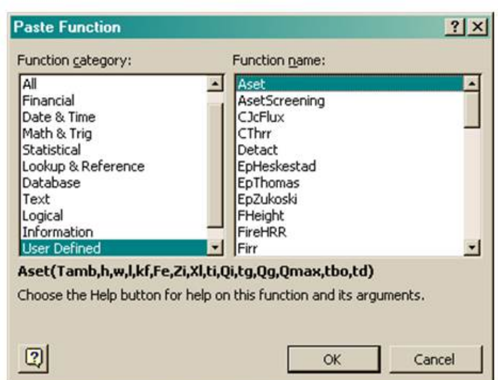
- Interface for models



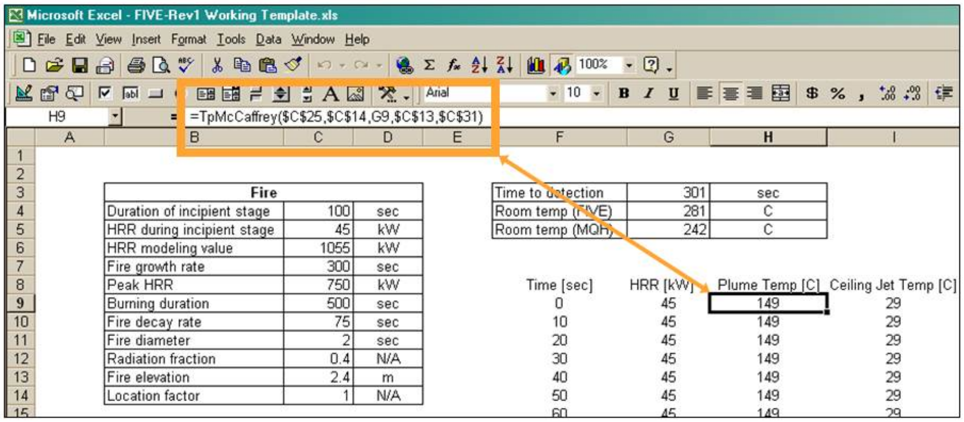
How to User FIVE-Rev1 Excel Function Library

- On a new Worksheet:
  - Click on: Insert/Function/User Defined
  - Use them as any other Excel built in functions





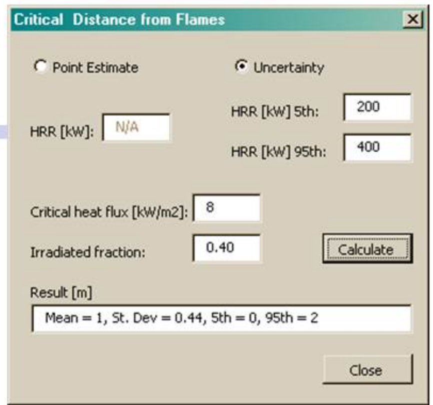
Excel Function Library

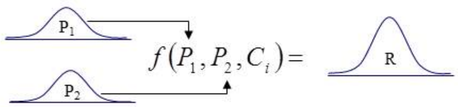


Excel Function Library

- Advantages:
  - Use in the fire modeling analysis all the Excel built-in capabilities
    - Charts, random number generation, statistical analyses
    - Create your own fire modeling templates, forms and reports
  - Uncertainty analysis
    - Propagation of parameter uncertainty
  - Sensitivity analysis
- However,
  - The graphical interface is the typical excel environment
  - Be familiar with Excel and the selected fire models

Technical Details Uncertainty





- Some models in the graphical interface can be solved with and without parameter uncertainty.
- If the uncertainty option is selected, the fire intensity is represented the 5th and 95th percentiles of the distribution.
- Both the input distribution and the output result are assumed to be normal.
- Uncertainty propagation is done using the Taylor expansion method.

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Fire Dynamic Tools (FDT^s)

- FDT^s are a series of Microsoft Excel® spreadsheets issued with NUREG-1805, "Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program."
- The primary goal of FDT^s was to be a training tool to teach NRC Fire Protection Inspectors an **Introduction to Fire Dynamics**.
- The secondary goal of FDT^s was to be used in plant inspections and support other programs that required Fire Dynamics knowledge such as, Significance Determination Process (SDP) and NFPA 805.
- NUREG-1805 provides a basic Introduction to Fire Dynamics for NPP applications. Available free download at: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/

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Fire Model Descriptions
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Development of NUREG-1805 FDT^s

- FDT^s are modeled after the Alcohol, Tobacco, Firearms, and Explosives (ATF&E) Fire and Arson Certified Fire Investigation Program
- Selected a series of state-of-the-art **Fire Dynamics Correlations** from ***SFPE Handbook of Fire Protection Engineering***, ***NFPA Fire Protection Handbook***, and other relevant **Fire Dynamics** text.
  - Customized for nuclear power plants applications
  - Appropriate physical properties
- New spreadsheets were added as a part of the review.

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Fire Model Descriptions

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Features of FDT^s

- User-friendly, **Pre-Programmed** Microsoft Excel® based on **Fire Dynamics** equation/correlations.
  - Quick application of **Fire Dynamics** principles found in state-of-the-art ***Fire Protection Handbooks***
  - Spreadsheets are protected to **Prevent Tampering**
  - **Automatic Unit Conversion**
  - Related **Material Fire Properties Data** for materials commonly found in nuclear power plants listed within each spreadsheet
  - **Reduces Input Errors** from inaccurate manual entries by using **Pull-Down Menus** which allow the user to select material fire property data
  - Provides for quick iterations with easy data entry in the spreadsheets to provide first order Fire Dynamics estimates.
- Spreadsheets are available in English and SI Units.

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Fire Model Descriptions

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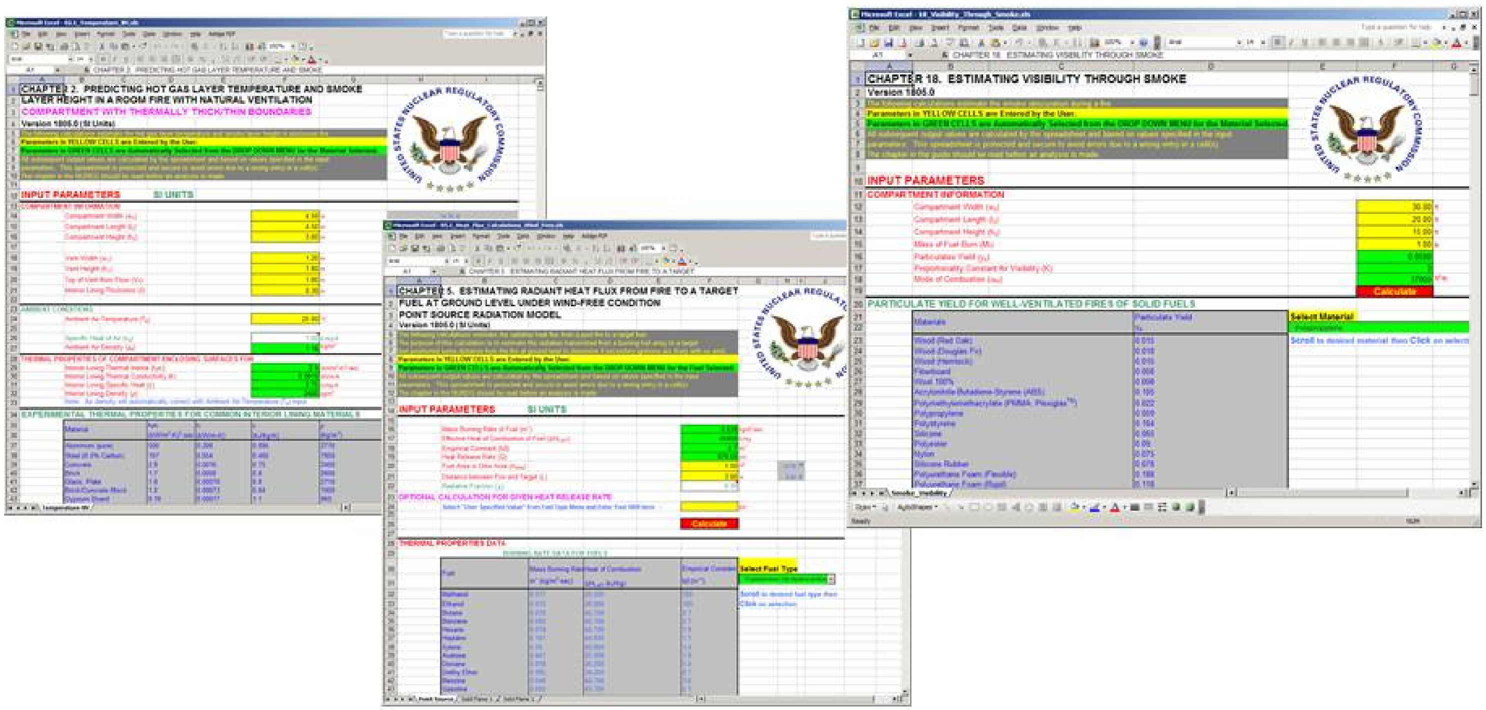
Features of FDTs



List of FDT^s Spreadsheets

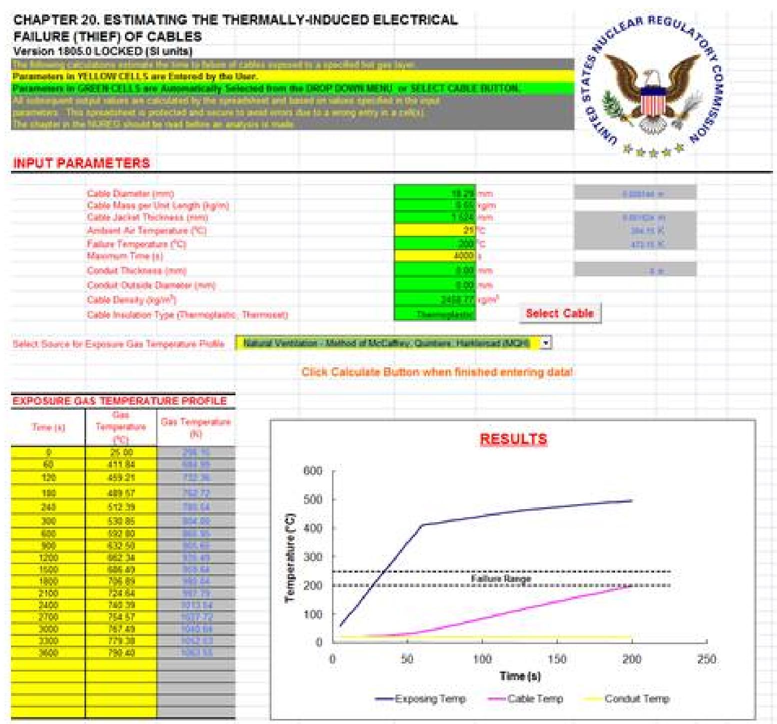
- 02.1_Temperature_NV.xls
- 02.2_Temperature_FV.xls
- 02.3_Temperature_CC.xls
- 03_HRR_Flame_Height_Burning_Duration_Calculation.xls
- 04_Flame_Height_Calculations.xls
- 05.1_Heat_Flux_Calculations_Wind_Free.xls
- 05.2_Heat_Flux_Calculations_Wind.xls
- 05.3_Thermal_Radiation_From_Hydrocarbon_Fireballs.xls
- 06_Ignition_Time_Calculations.xls
- 07_Cable_HRR_Calculations.xls
- 08_Burning_Duration_Soild.xls
- 09_Plume_Temperature_Calculations.xls
- 10_Detector_Activation_Time.xls
- 13_Compartment_Flashover_Calculations.xls
- 14_Compartment_Over_Pressure_Calculations.xls
- 15_Explosion_Claculations.xls
- 16_Battery_Room_Flammable_Gas_Conc.xls
- 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
- 18_Visibility_Through_Smoke.xls

New FDTs

THIEF – Cable Failure

- Flammable Liquid Spill Diameter
- Ceiling Jet Temperature & Velocity

THIEF Spreadsheet



THIEF Spreadsheet

CHAPTER 20. ESTIMATING THE THERMALLY-INDUCED ELECTRICAL FAILURE (THIEF) OF CABLES

Version 1805.0 LOCKED (SI units)

The following calculations estimate the time to failure of cables exposed to a specified hot gas layer.

Parameters in YELLOW CELLS are Entered by the User.

Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU or SELECT CABLE BUTTON.

All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).

The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

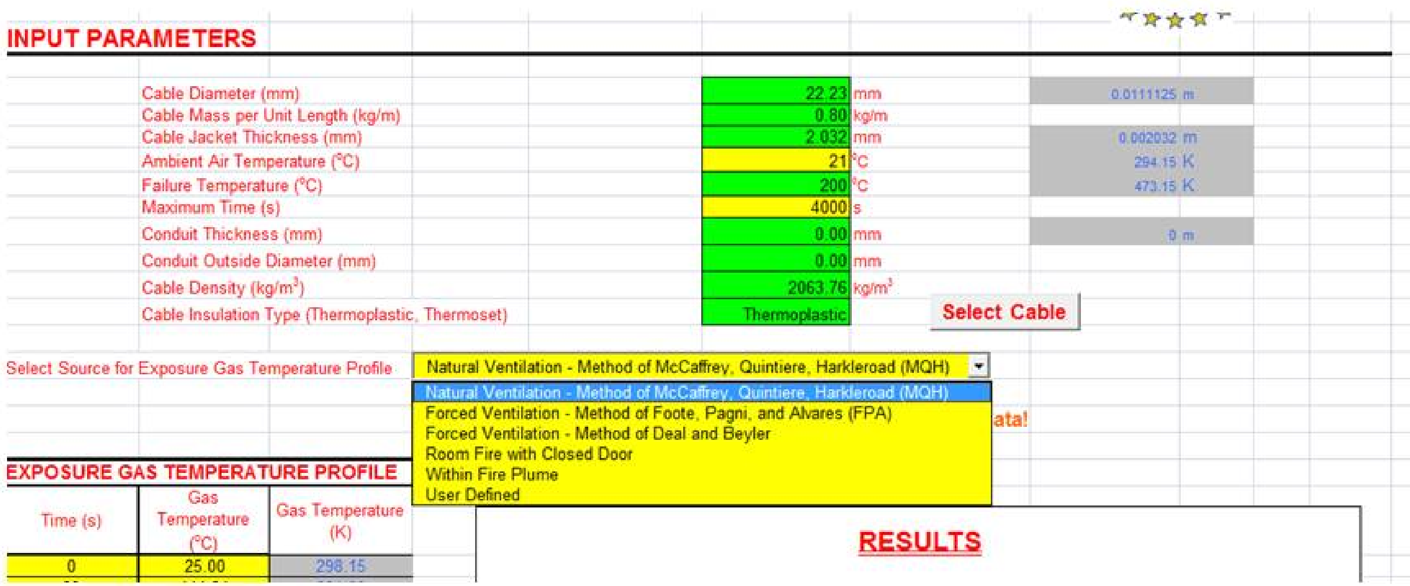
Cable Diameter (mm)	22.23	mm	0.0111125 m
Cable Mass per Unit Length (kg/m)	0.80	kg/m	
Cable Jacket Thickness (mm)	2.032	mm	0.002032 m
Ambient Air Temperature (°C)	21	°C	294.15 K
Failure Temperature (°C)	200	°C	473.15 K
Maximum Time (s)	4000	s	
Conduit Thickness (mm)	0.00	mm	0 m
Conduit Outside Diameter (mm)	0.00	mm	
Cable Density (kg/m³)	2063.76	kg/m³	
Cable Insulation Type (Thermoplastic, Thermoset)	Thermoplastic		

Select Cable

Select Source for Exposure Gas Temperature Profile: Natural Ventilation - Method of McCaffrey, Quintiere, Harkleroad (MQH)

Click Calculate Button when finished entering data!

Calculate Exposure



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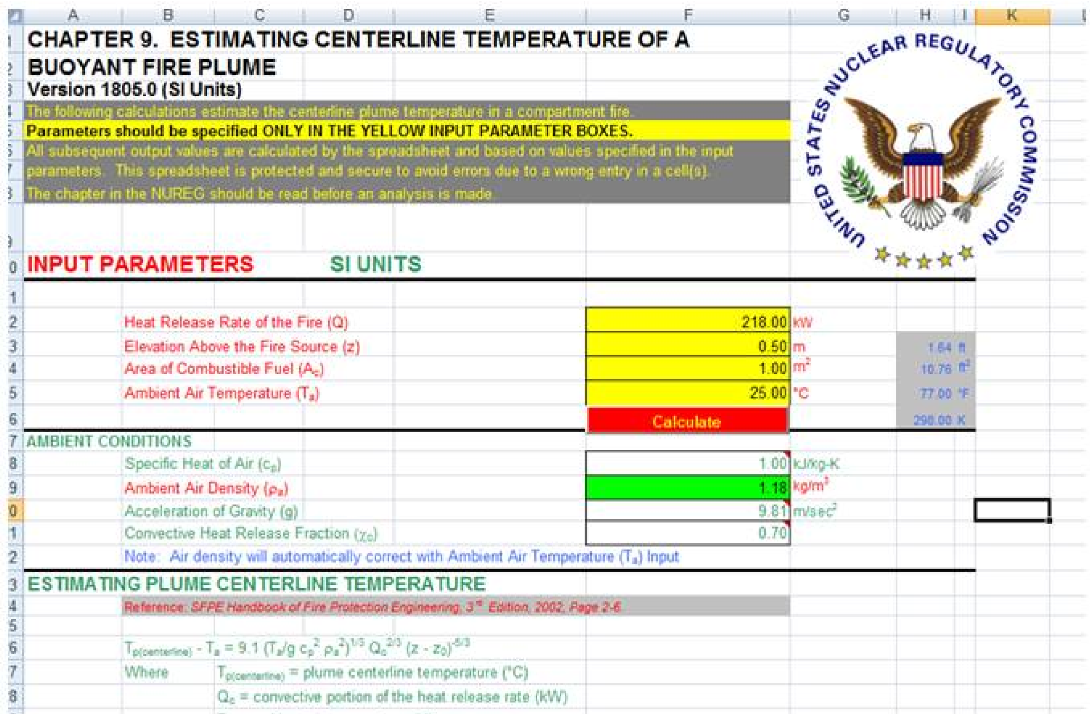
Plume-Calculations (Chap. 9)



Plume-Calculations Results

Centerline Plume Temperature Calculation

$T_{p(centerline)} - T_a = 9.1 (T_a/g\, c_p^2\, \rho_a^2)^{1/3}\, Q_c^{2/3}\, (z - z_0)^{-5/3}$

$T_{p(centerline)} - T_a =$	809.10	
$T_{p(centerline)} =$	1107.10	K
$T_{p(centerline)} =$	834.10 °C	1533.37 °F

Answer

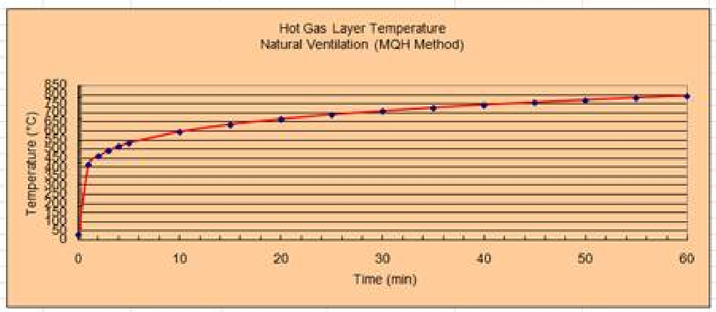
NOTE

Temperature-NV (Chap. 2)

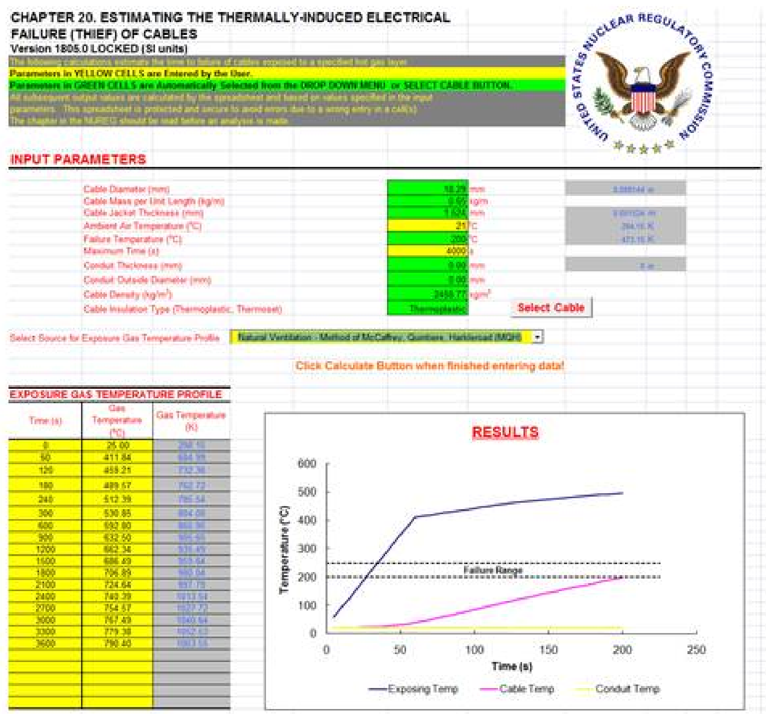
Temperature-NV Results

Results

Time After Ignition (t) (min)	(sec)	h_k (kW/m²-K)	ΔT_g (K)	T_g (K)	T_g (°C)	T_g (°F)
0	0.00	-	-	298.00	25.00	77.00
1	60	0.22	386.84	684.84	411.84	773.31
2	120	0.16	434.21	732.21	459.21	858.58
3	180	0.13	464.57	762.57	489.57	913.22
4	240	0.11	487.39	785.39	512.39	954.30
5	300	0.10	505.85	803.85	530.85	987.54
10	600	0.07	567.80	865.80	592.80	1099.04
15	900	0.06	607.50	905.50	632.50	1170.50
20	1200	0.05	637.34	935.34	662.34	1224.21
25	1500	0.04	661.49	959.49	686.49	1267.67
30	1800	0.04	681.89	979.89	706.89	1304.41
35	2100	0.04	699.64	997.64	724.64	1336.35
40	2400	0.03	715.39	1013.39	740.39	1364.69
45	2700	0.03	729.57	1027.57	754.57	1390.22
50	3000	0.03	742.49	1040.49	767.49	1413.49
55	3300	0.03	754.38	1052.38	779.38	1434.89
60	3600	0.03	765.40	1063.40	790.40	1454.72



THIEF Spreadsheet



Environment

EXPOSURE GAS TEMPERATURE PROFILE		
Time (s)	Gas Temperature (°C)	Gas Temperature (K)
0	25.00	298.15
60	411.84	684.99
120	459.21	732.36
180	489.57	762.72
240	512.39	785.54
300	530.85	804.00
600	592.80	865.95
900	632.50	905.65
1200	662.34	935.49
1500	686.49	959.64
1800	706.89	980.04
2100	724.64	997.79
2400	740.39	1013.54
2700	754.57	1027.72
3000	767.49	1040.64
3300	779.38	1052.53
3600	790.40	1063.55

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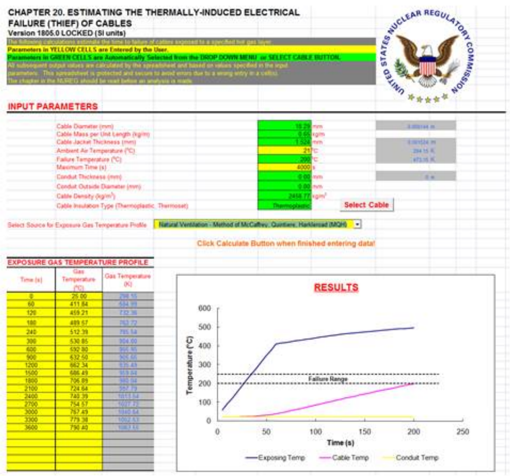
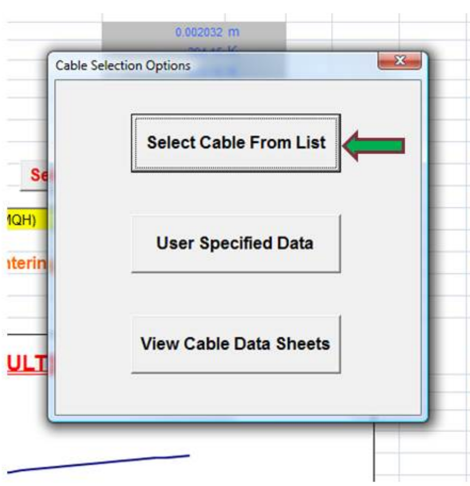
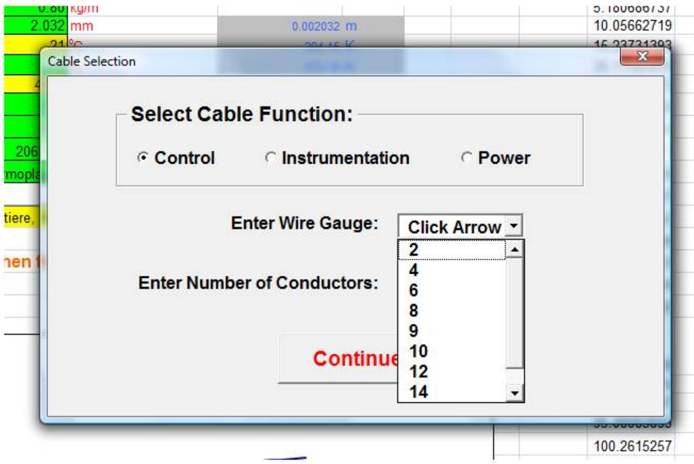
THIEF Spreadsheet



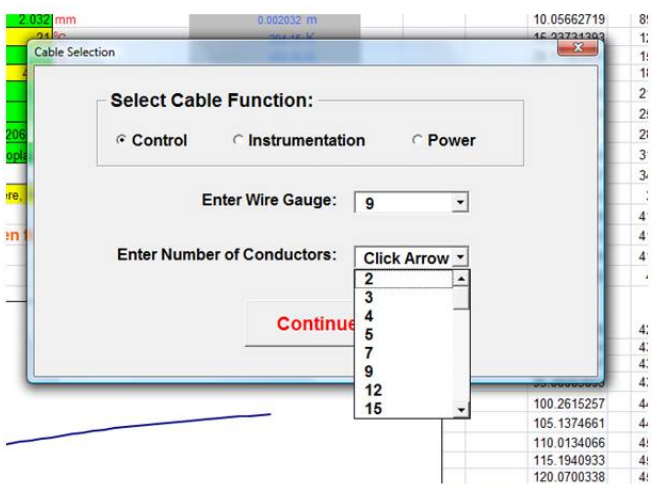
Select Cable



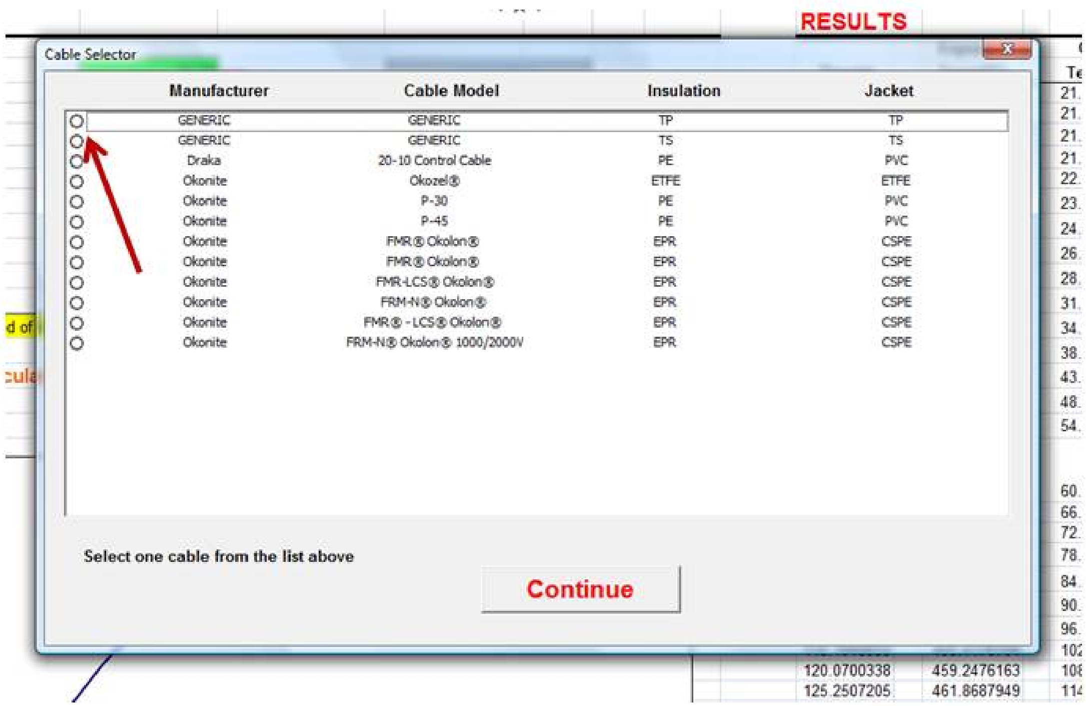
Cable Function & Gauge



Characteristics

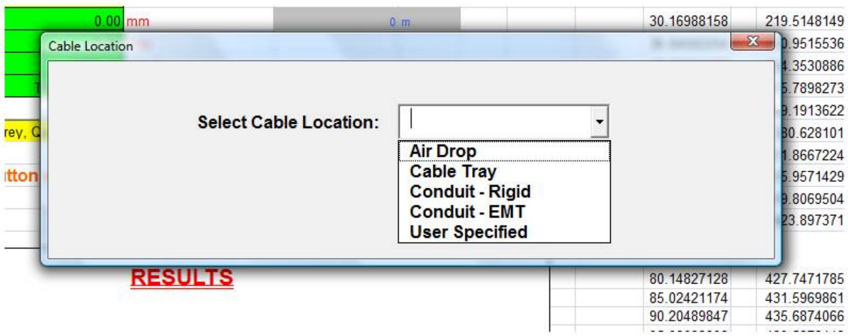


Cable List



RESULTS
Cable Selector
Manufacturer
Cable Model
Insulation
Jacket
GENERIC GENERIC TP TP
GENERIC GENERIC TS TS
Draka 20-10 Control Cable PE PVC
Okonite Okozel® ETFE ETFE
Okonite P-30 PE PVC
Okonite P-45 PE PVC
Okonite FMR® Okolon® EPR CSPE
Okonite FMR® Okolon® EPR CSPE
Okonite FMR-LCS® Okolon® EPR CSPE
Okonite FRM-N® Okolon® EPR CSPE
Okonite FMR® - LCS® Okolon® EPR CSPE
Okonite FRM-N® Okolon® 1000/2000V EPR CSPE
Select one cable from the list above
Continue
120.0700338
459.2476163
125.2507205
461.8687949

Location

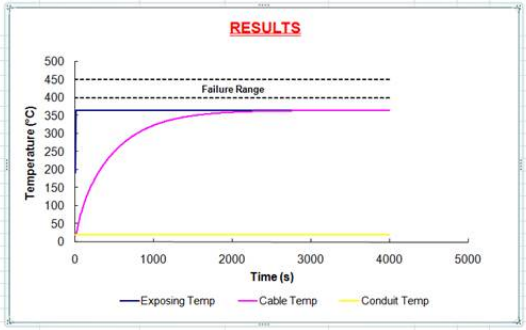


Results – Plume, TP

Results – Plume, TS

Click Calculate Button when finished entering data!

EXPOSURE GAS TEMPERATURE PROFILE		
Time (s)	Gas Temperature (°C)	Gas Temperature (K)
0	0.00	273.15
10	364.95	638.10
2000	364.95	638.10
4000	364.95	638.10

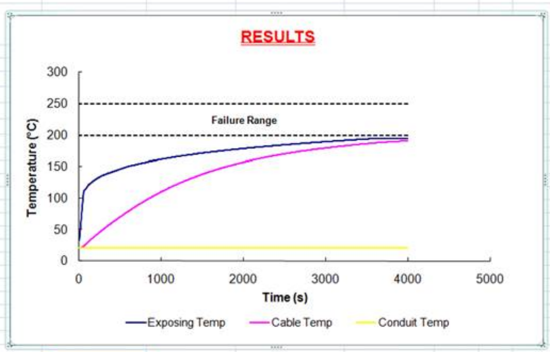


Click Calculate Button when finished entering data! Calculate

Answer: Cable does not reach failure temperature in 4000.2 seconds

Results – Layer, TP

EXPOSURE GAS TEMPERATURE PROFILE		
Time (s)	Gas Temperature (°C)	Gas Temperature (K)
0	25.00	298.15
60	110.95	384.10
120	121.48	394.63
180	128.23	401.38
240	133.30	406.45
300	137.40	410.55
600	151.16	424.31
900	159.99	433.14
1200	166.62	439.77
1500	171.98	445.13
1800	176.52	449.67
2100	180.46	453.61
2400	183.96	457.11
2700	187.11	460.26
3000	189.98	463.13
3300	192.62	465.77
3600	195.07	468.22



Click Calculate Button when finished entering data! Calculate

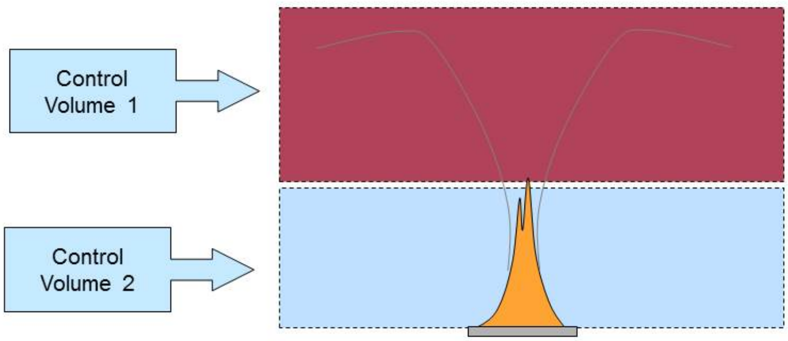
Answer: Cable does not reach failure temperature in 4000.4 seconds

MAGIC

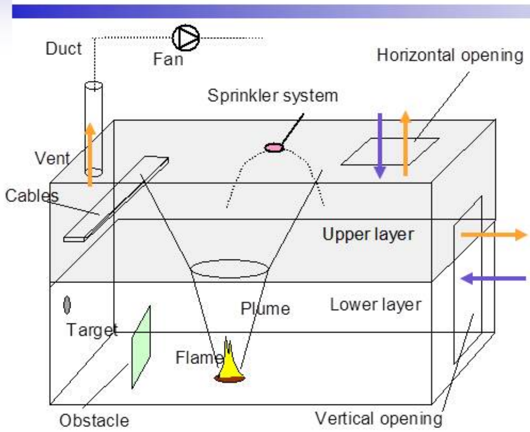
MAGIC is a two zone fire model developed by EDF.

The software solves conservation equations for **mass and energy in two control volumes.**

Local values of temperatures and fluxes are accessible with targets (flame, plume, ceiling-jet, relative distance from the fire).



Features



- Gaseous phase combustion, governed by pyrolysis rate and oxygen availability
- Heat transfer between flame, gases and smoke, walls and surrounding air, thermal conduction in multi-layer walls, obstacles to radiation
- Mass flow transfer: Fire-plumes, ceiling-jet, openings and vents
- Thermal behavior of targets and cables
- Secondary source ignition, unburned gas management
- Multi-compartment, multi-fire, etc.

Sub-Models

Semi empirical correlations for:
- Plume temperature and entrainment
- Ceiling jet temperature

Vertical openings: hydrostatics

Horizontal opening: Cooper's correlation

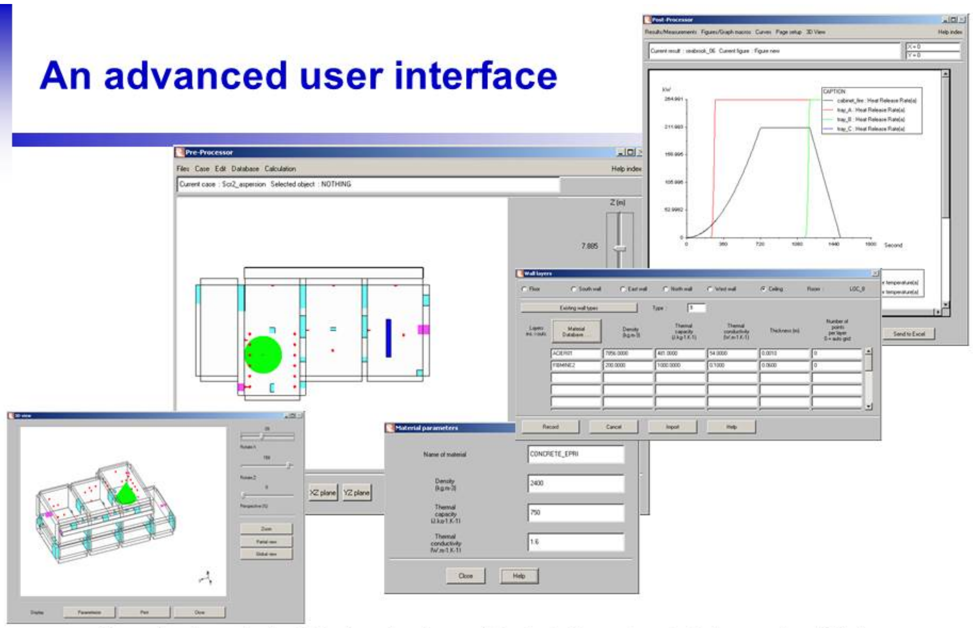
Wall and Target conduction: 1-D finite difference

Combustion: global balance – effect of oxygen depletion

Sprinkling system: integrated droplet approach

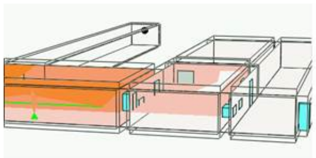
Ventilation: parabolic fan law (variable), head loss in ducts

An advanced user interface

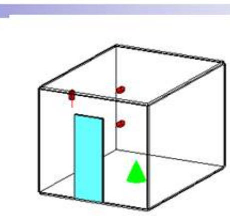


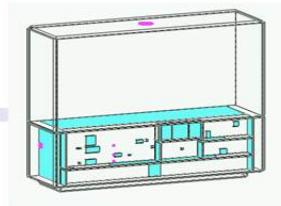
- Numerical controls, 3D visualization, wide data base (materials, combustible)
- Flexibility: user-friendly interface, PC English version, connection to Excel and Word, etc.

Examples
(EDF)

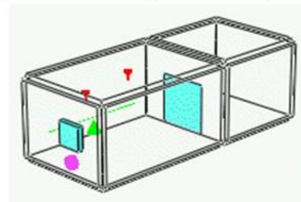


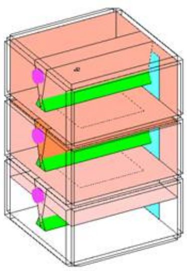
(electrical building – PWR 900)

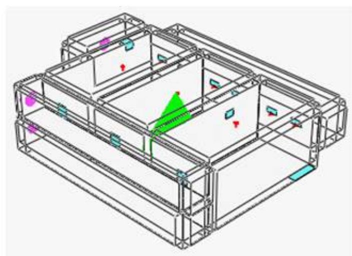




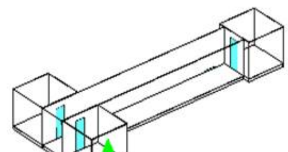
(electrical building – PWR 900)



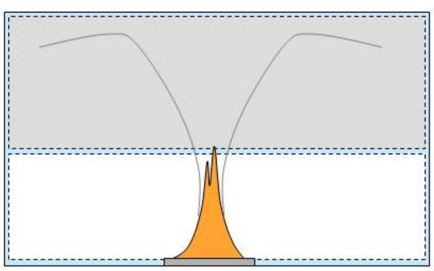




(CVCS pumps – PWR 900)

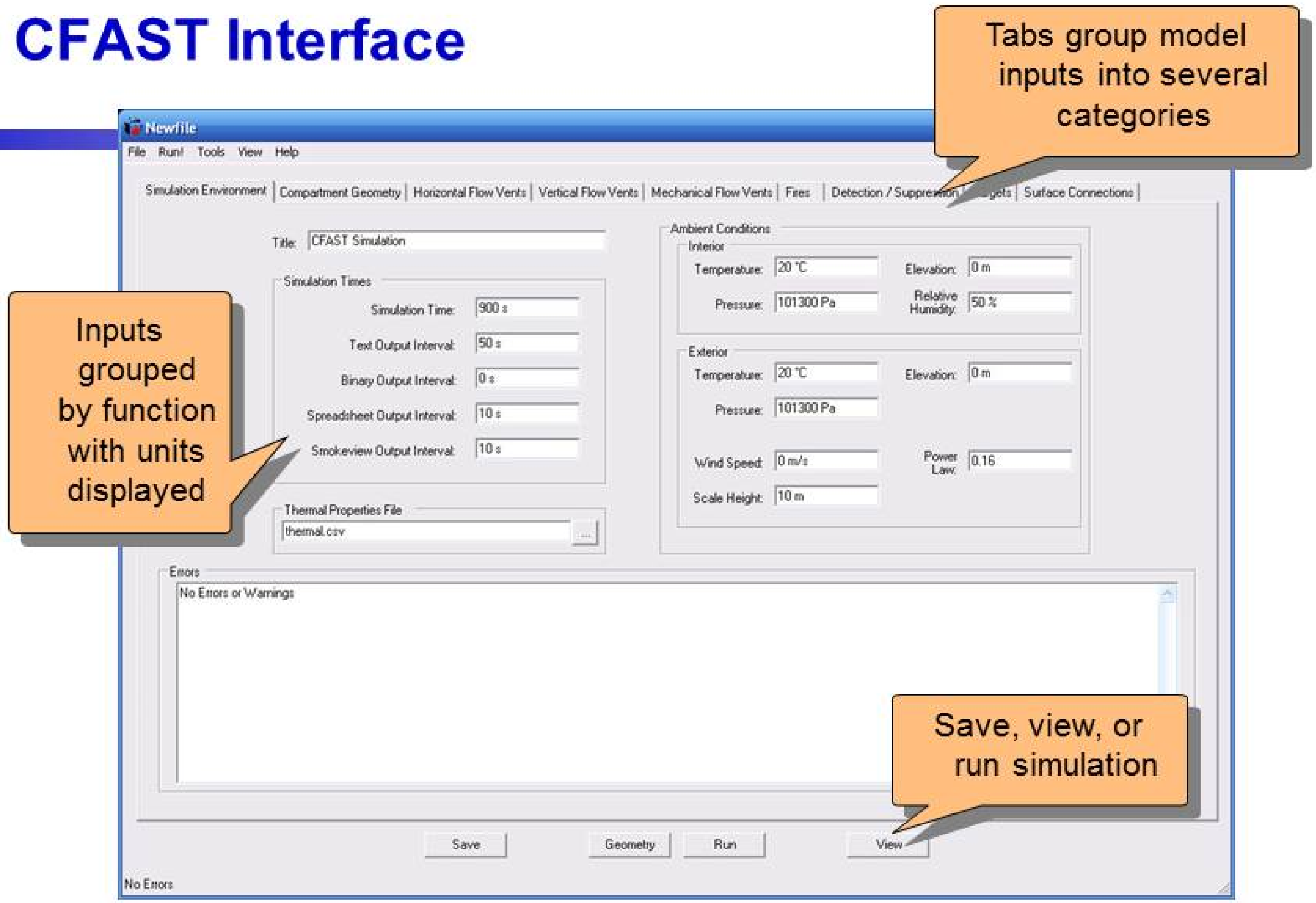


CFAST

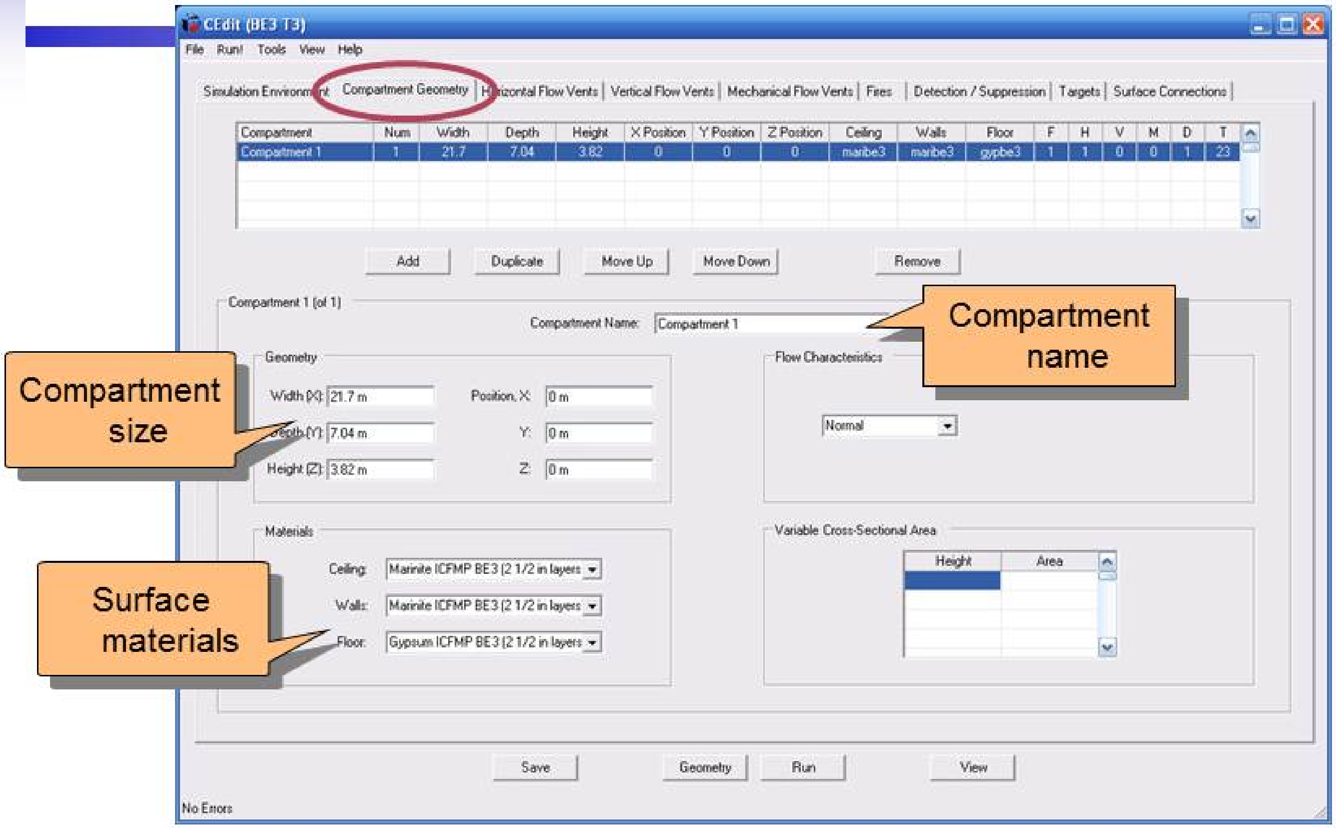


- CFAST is a two zone fire model developed by NIST
- The software solves conservation equations for mass and energy in two control volumes
- Accounts for the effects of
  - User specified fire(s) in multiple connected compartments
  - Natural flow between compartments through vents
  - Mechanical ventilation
  - Heating and ignition of objects

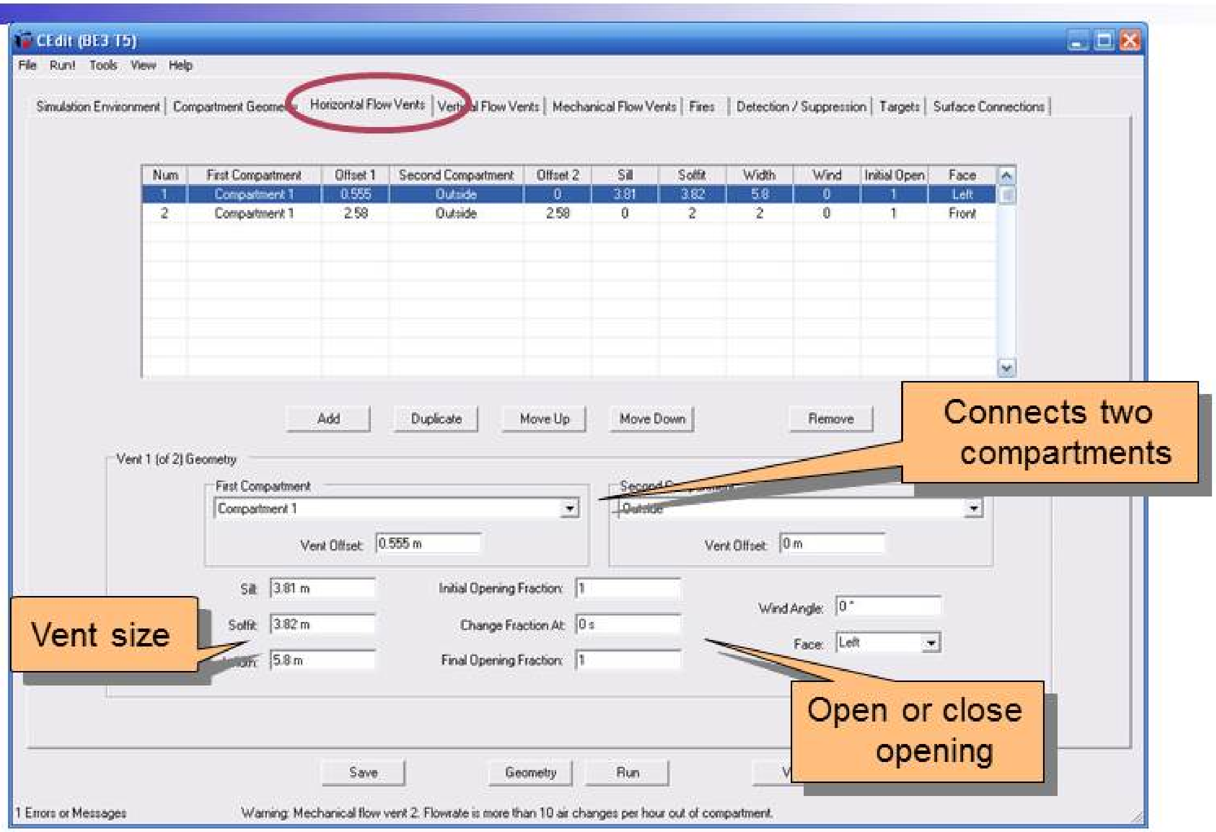
CFAST Interface



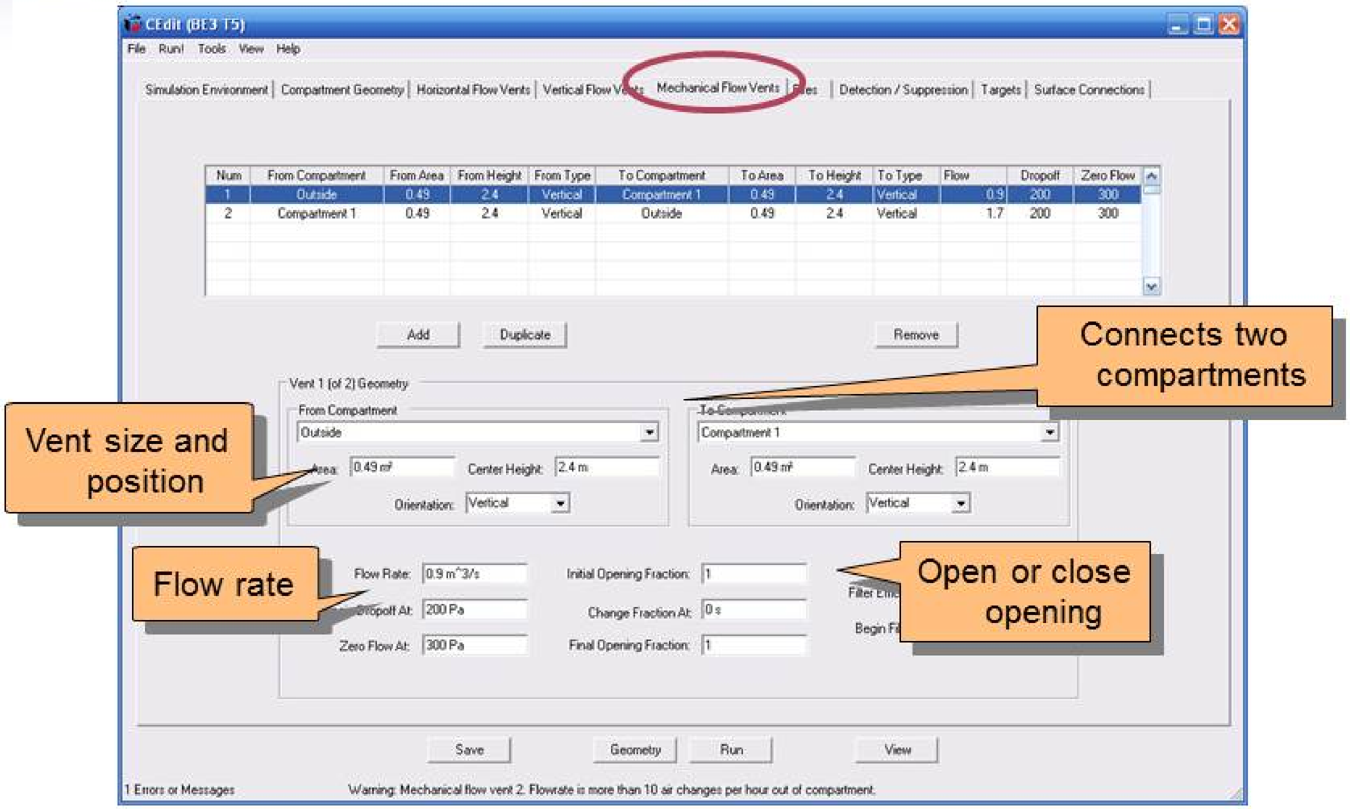
CFAST: Compartment Geometry



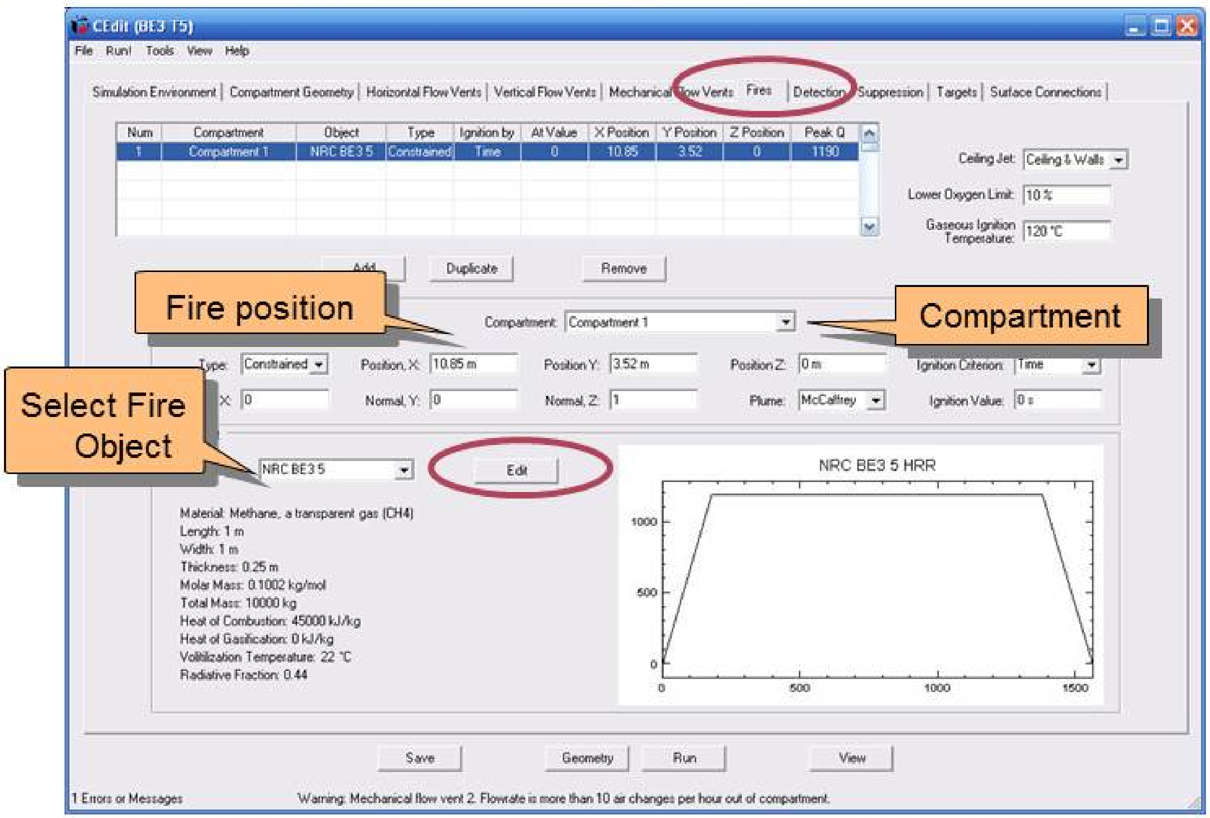
CFAST: Horizontal Flow Vents (Doors, Windows)



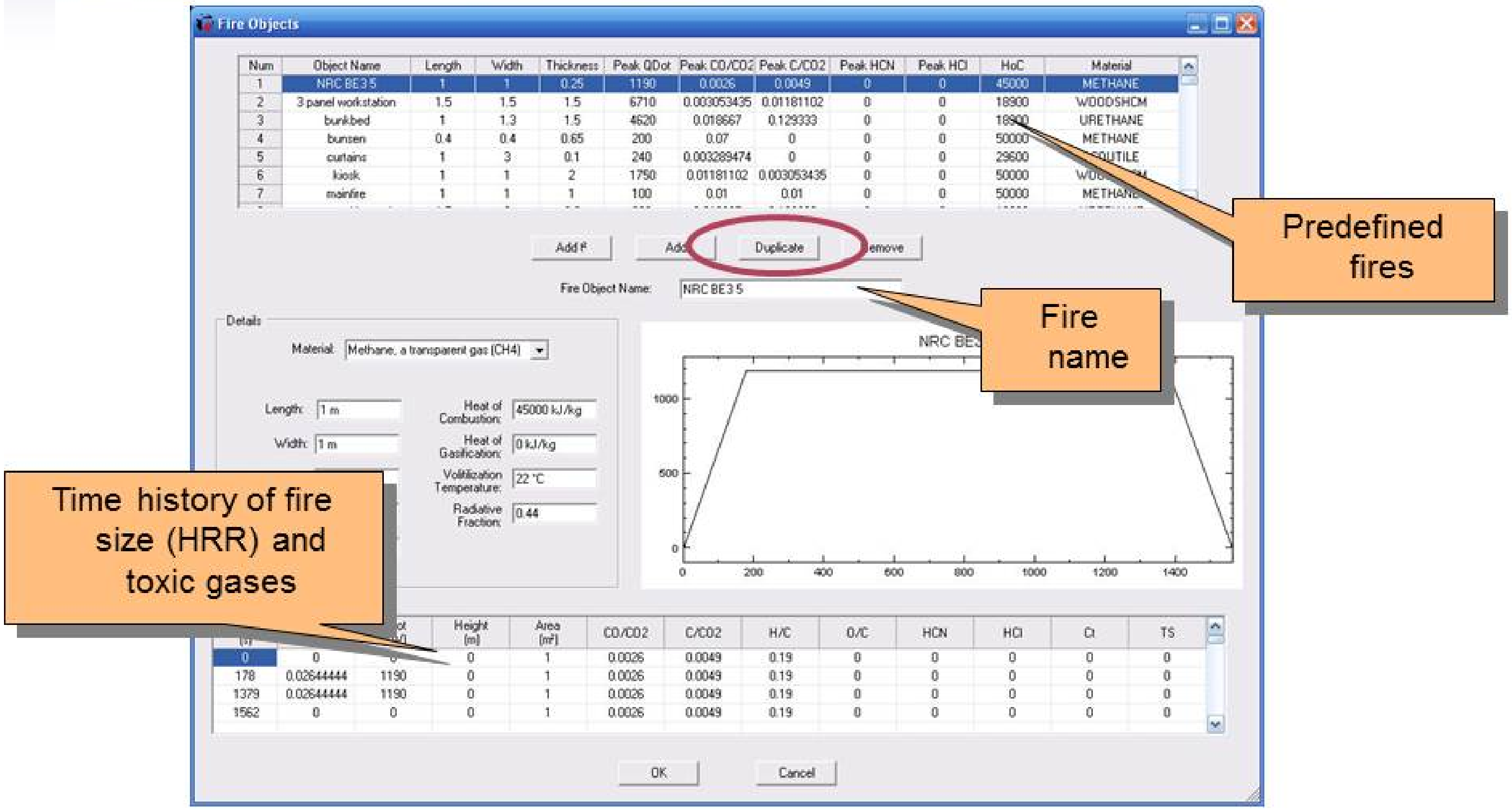
CFAST: Mechanical Flow Vents (HVAC)



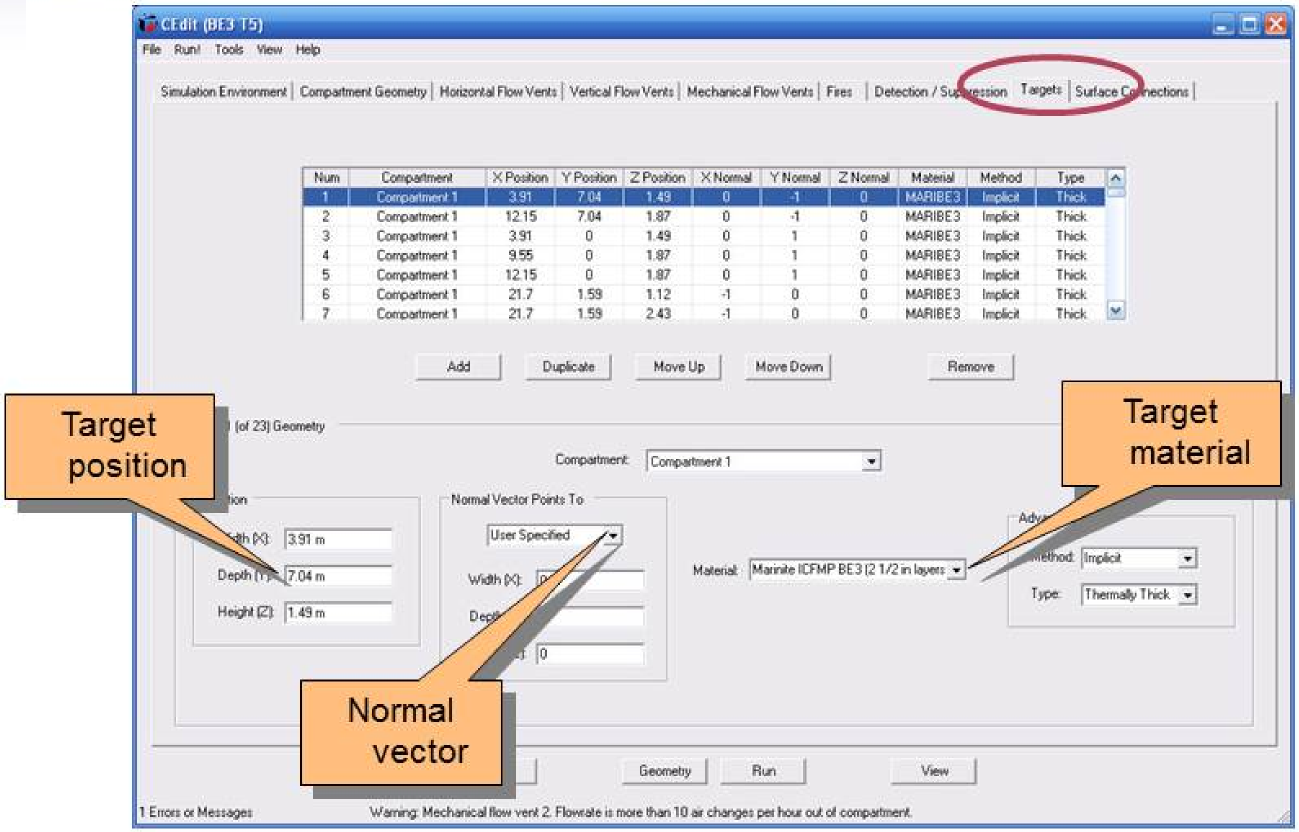
CFAST: Fire Placement



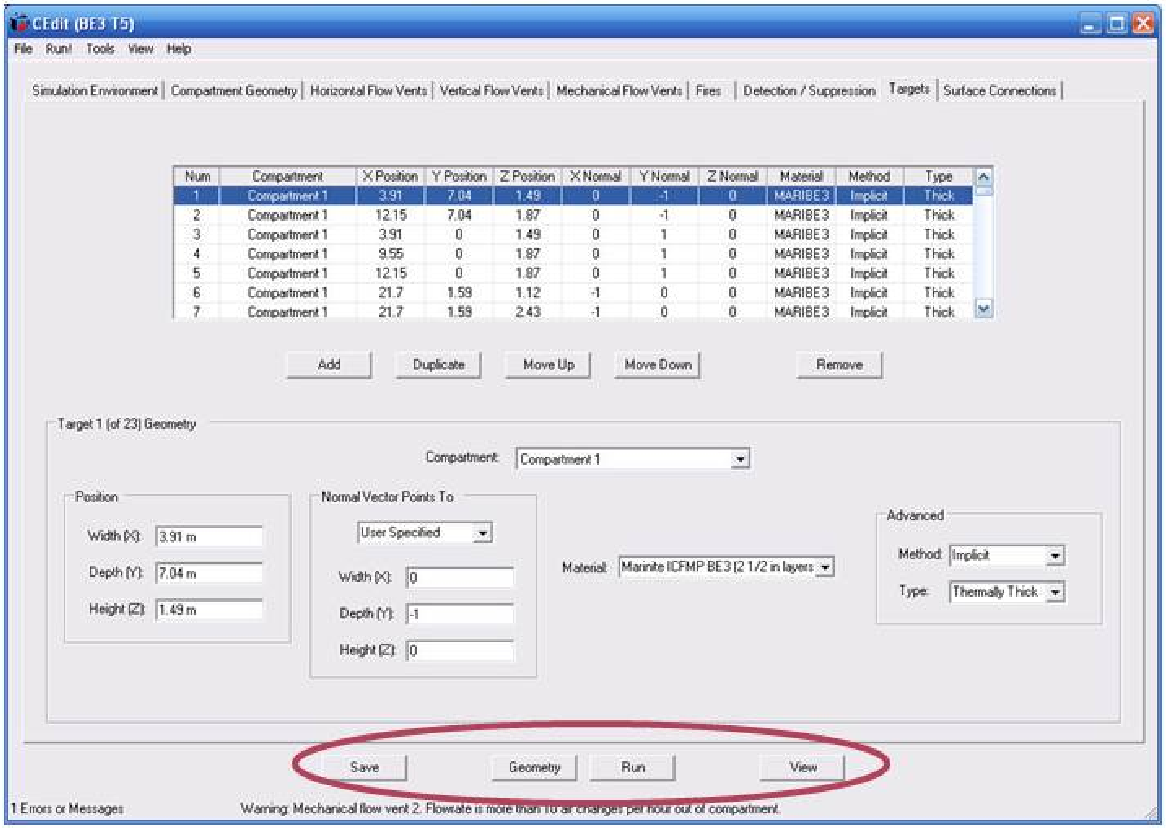
CFAST: Fire Object Definition



CFAST: Targets



Running and Viewing the Simulation



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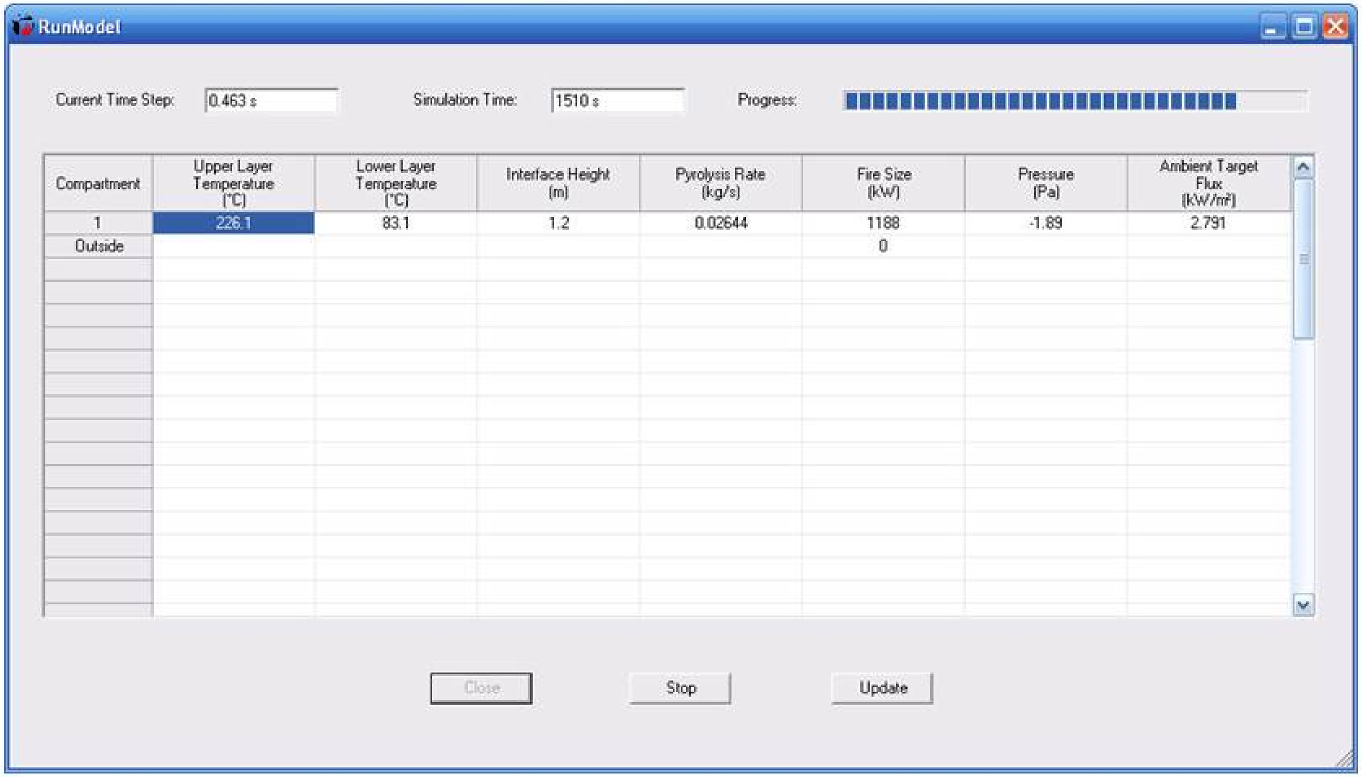
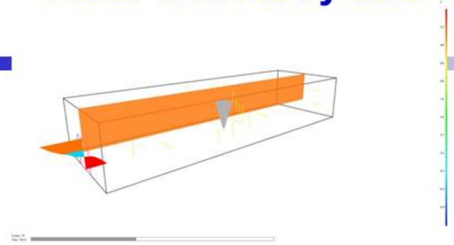
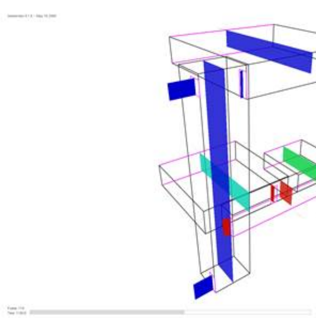
Run: Calculation and Results

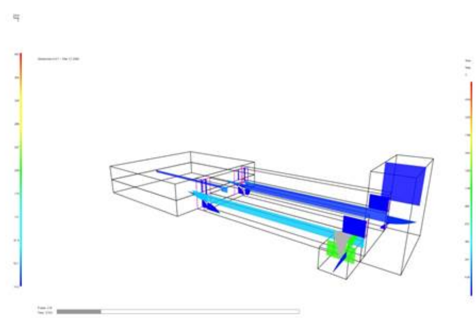


View: Geometry and Visualization of Results



- CFAST uses Smokeview to visualize scenario geometry, vents, fires, and targets.
- Visualization of model outputs also supported.





FDS (Fire Dynamics Simulator)

- Computational fluid dynamics (CFD) model of fire driven fluid flow
- The software solves a form of the Navier-Stokes equations
  - FDS was designed to study fire dynamics
  - Uses “Low Mach Number” approximation
  - Low speed, thermally driven flows
  - Emphasis on smoke and heat transport
- FDS vs. other CFD codes:
  - Low Mach Number assumptions
  - Large Eddy Simulation (LES) turbulence model
  - Relatively simple gridding

What is Smokeview?

- Software tool designed to visualize numerical predictions generated by FDS
- It is a post processing step after simulation is completed (not a graphical user interface for entering input data)
- Visualizations are performed by:
  - Displaying time dependent tracer particles
  - Animated contour slices of computed gas variables
  - Displaying time dependent surface data
  - Realistic smoke

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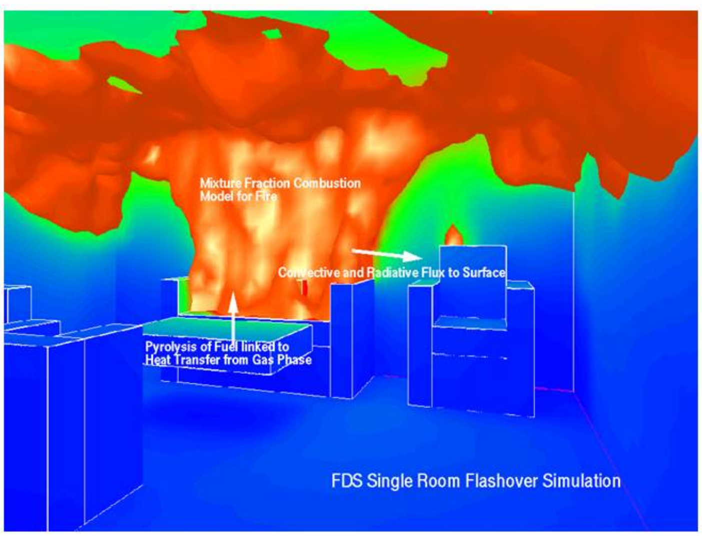
Basic Fire Physics in FDS



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Geometry

- Geometry is defined in FDS with:
  - Obstructions: rectangular solids within the flow domain
  - Vents: planes adjacent to obstructions or external walls
    - Open to the outside, simulating windows, or
    - Model fuel or mechanical ventilation flows
  - For full functionality, obstructions should be specified to be at least one grid cell thick
- Grid Size:
  - Best if grid cells are close to cubes

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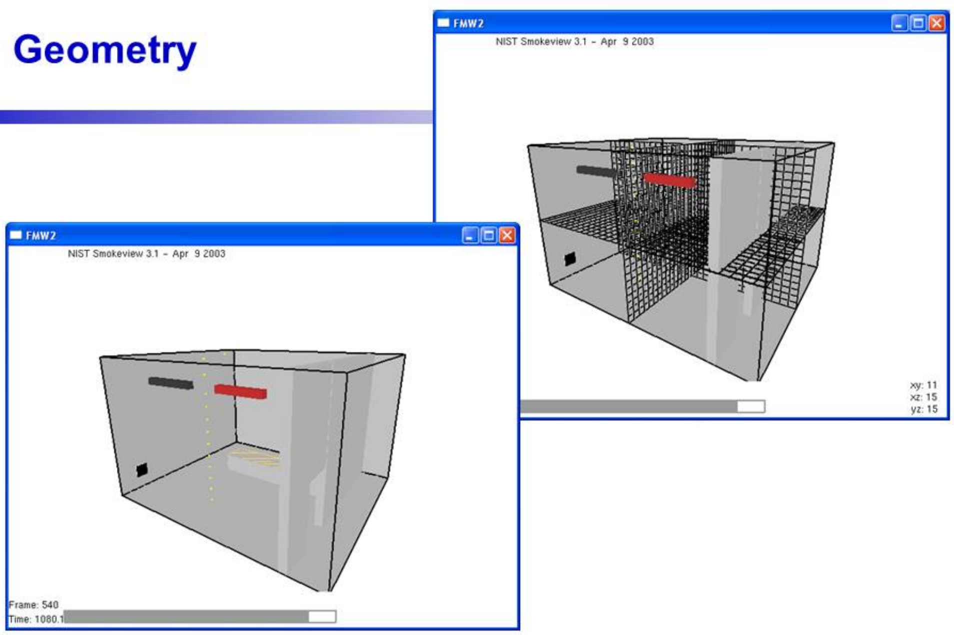
Geometry



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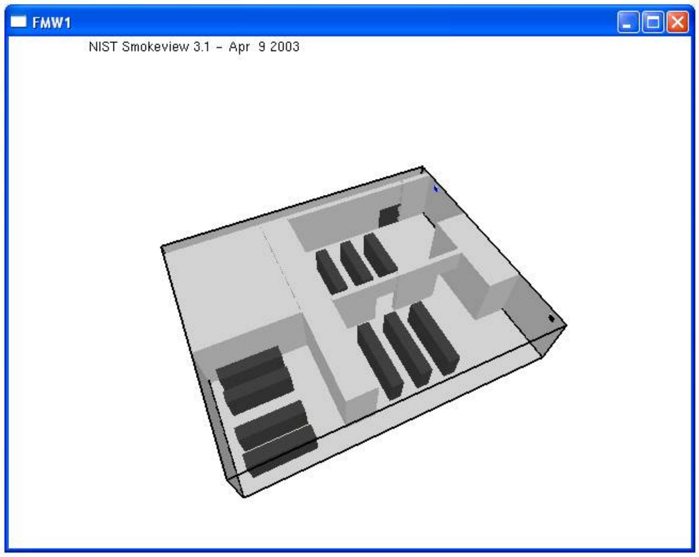
Geometry



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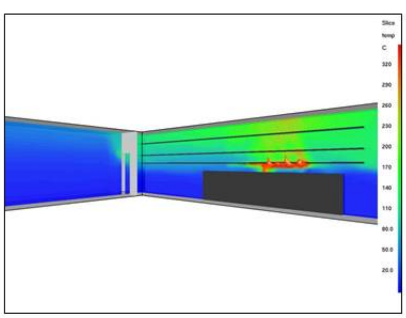
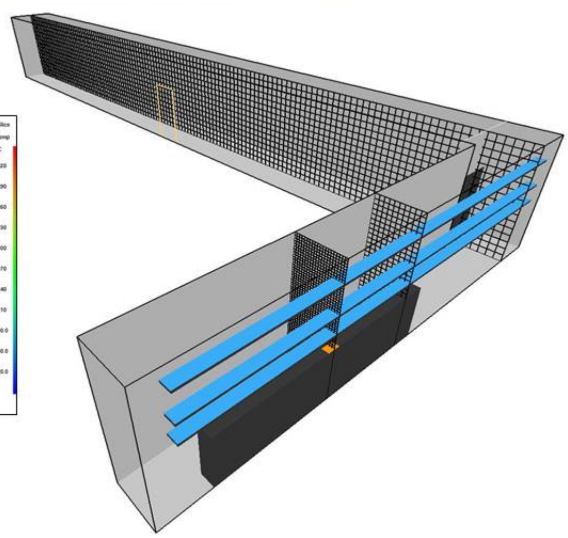
Geometry





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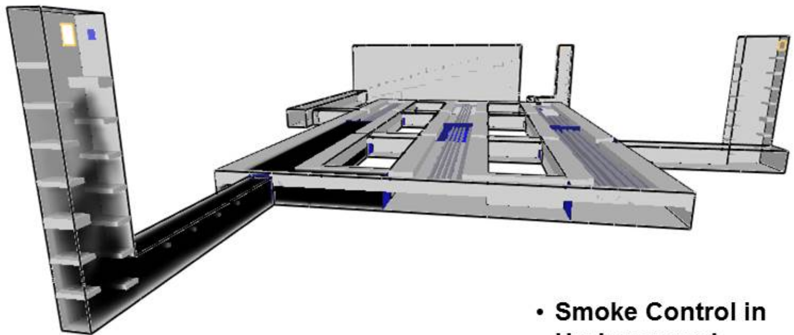

- **Smoke Control in Underground Parking Space**
- Mr. Simo Hostikka
  VTT Building and Transport
  Espoo, Finland

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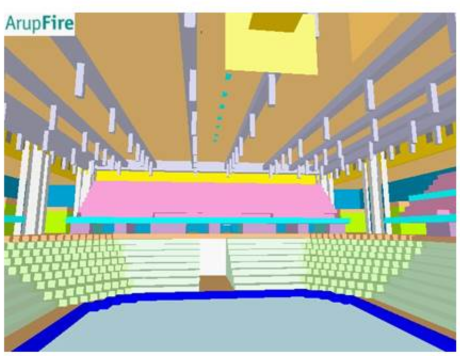
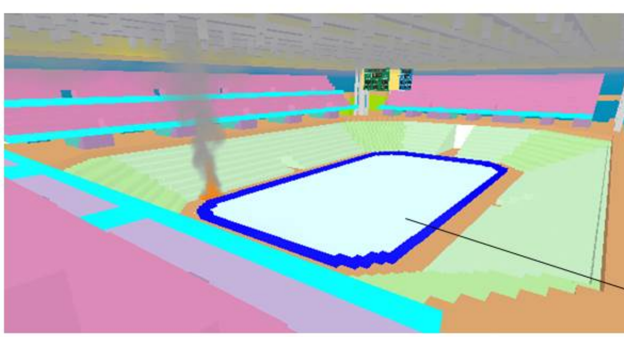
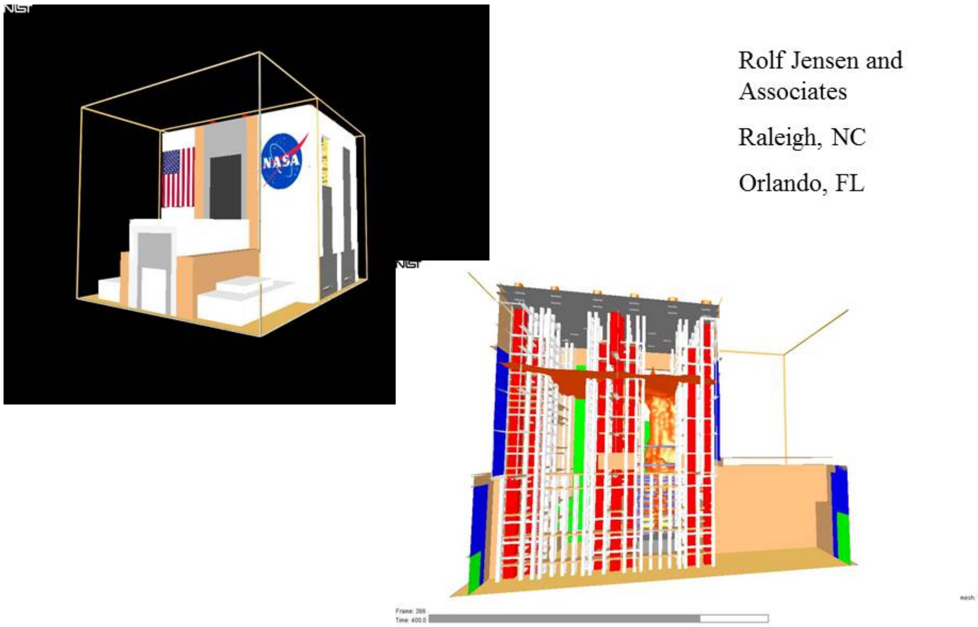


- **2006 Olympic Games Ice Hockey Stadium, Turin, Italy**
- Davy Leroy
- Ove Arup & Partners Ltd
- Leeds, West Yorkshire, UK



60

NASA Vehicle Assembly Building
Comparative Venting Scheme Analysis



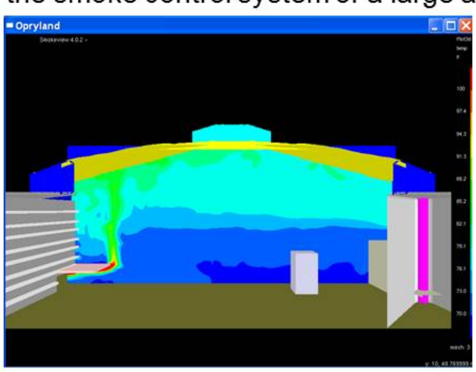
Rolf Jensen and Associates

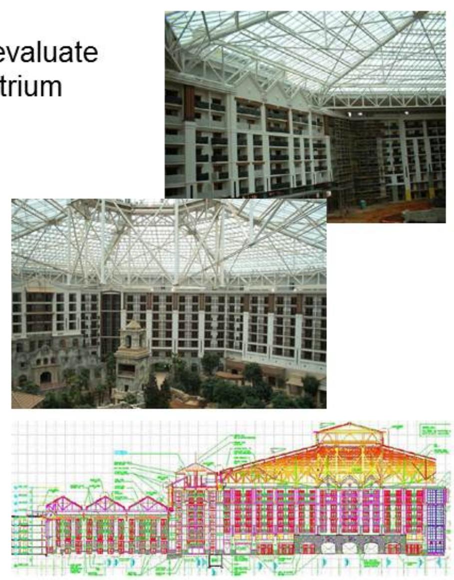
Raleigh, NC

Orlando, FL

Smoke Management In A Large Atrium

FDS fire modeling was performed to evaluate the smoke control system of a large atrium

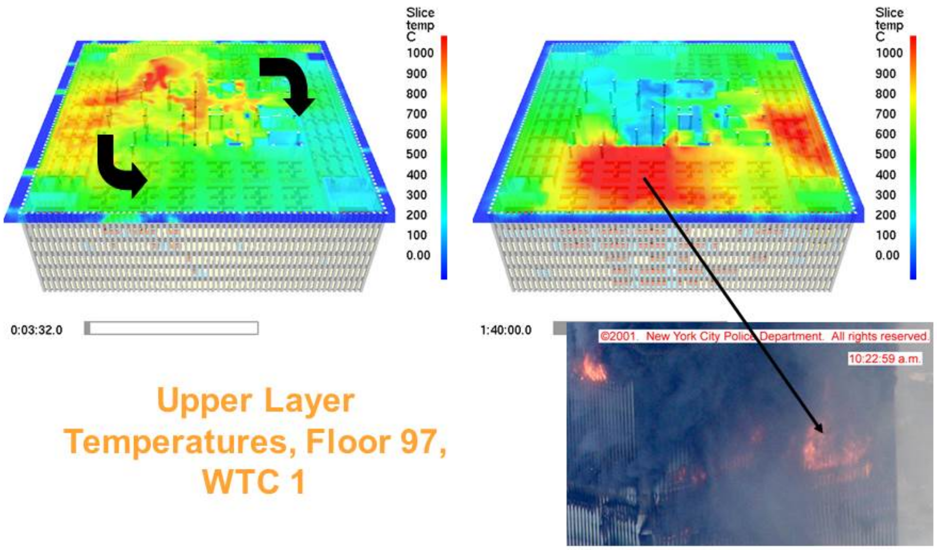




Ervin Cui, PhD, PE
Chen Su, PE
Warren Bonisch, PE
Dan O'Connor, PE

World Trade Center Investigation

Kevin McGrattan, Chuck Bouldin, Glenn Forney
Building and Fire Research Lab, NIST



Upper Layer Temperatures, Floor 97, WTC 1

Inputs

- FDS input is usually conveyed via a text file with .fds extension
- Recommended practice is to copy and sample file and edit it accordingly

Command Prompt

```
D:\FDS_Runs>fds5 couch.fds

 Fire Dynamics Simulator

 Compilation Date : Wed, 08 Apr 2009
 Version          : 5.3.1 Serial

 No OpenMP-Version

 SVN Revision No. : 3729

 Job TITLE        : Single Couch Test Case, SVN $Revision: 1995 $
 Job ID string    : couch

 Time Step:      1,   Simulation Time:      0.10 s
 Time Step:      2,   Simulation Time:      0.20 s
 Time Step:      3,   Simulation Time:      0.31 s
 Time Step:      4,   Simulation Time:      0.41 s
 Time Step:      5,   Simulation Time:      0.51 s
 Time Step:      6,   Simulation Time:      0.61 s
 Time Step:      7,   Simulation Time:      0.71 s
 Time Step:      8,   Simulation Time:      0.82 s
 Time Step:      9,   Simulation Time:      0.92 s
 Time Step:     10,   Simulation Time:      1.02 s
 Time Step:     20,   Simulation Time:      1.39 s
```

Input File Example

couch.fds - WordPad

Grid & Domain size

Fire

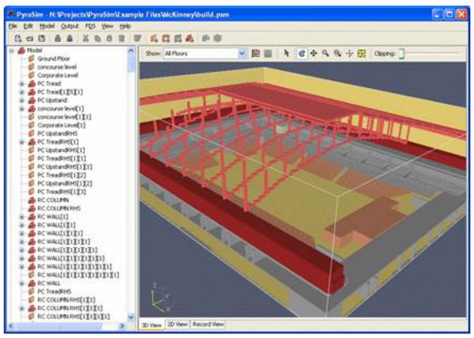
Open door

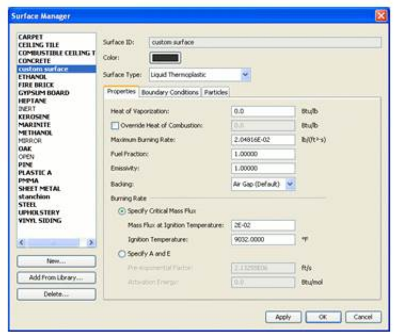
Outputs

```
&HEAD CHID='couch', TITLE='Single Couch Test Case'  /

&MESH IJK=24,10,24, XB=1.1,3.5,3.6,4.6,0.0,2.4 /

&TIME T_END=900. /

&MISC SURF_DEFAULT='WALL' /

&SURF ID='BURNER', HRRPUA=1000., PART_ID='smoke' /
.
.
.

&OBST XB= 1.50, 3.10, 3.80, 4.60, 0.00, 0.40 /
&OBST XB= 1.50, 3.10, 3.80, 4.60, 0.40, 0.60, SURF_ID='UPHOLSTERY' /
&OBST XB= 1.30, 1.50, 3.80, 4.60, 0.00, 0.90, SURF_ID='UPHOLSTERY' /
.
.
.

&VENT XB= 2.50, 2.60, 4.30, 4.40, 0.60, 0.60, SURF_ID='BURNER' /

&VENT MB='XMIN', SURF_ID='OPEN' /
&VENT MB='XMAX', SURF_ID='OPEN' /
&VENT MB='YMIN', SURF_ID='OPEN' /

&BNDF QUANTITY='RADIATIVE HEAT FLUX' /
&BNDF QUANTITY='CONVECTIVE HEAT FLUX' /

&SLCF PBX=2.60,QUANTITY='TEMPERATURE',VECTOR=.TRUE. /
&SLCF PBX=2.60,QUANTITY='HRRPUV' /


&TAIL /
```

Graphical User Interface (GUI)

- Third Party Software from Thunderhead Engineering
- Their product, PyroSim™, will not be free, but FDS and Smokeview will continue to be

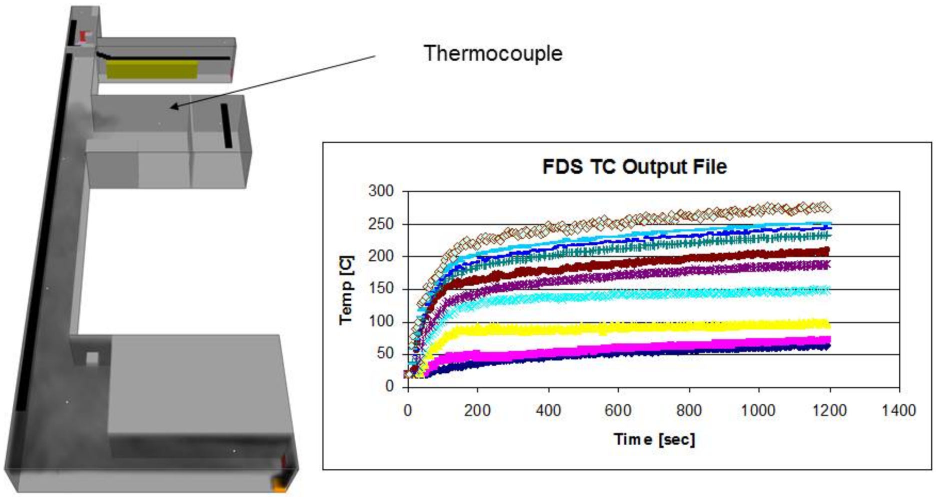




Outputs

- Devices
  - Virtual sensors located in the computational domain
  - Sensors record quantities of interest such as temperature, heat flux, flow velocity, etc.
  - Recorded values are dumped into a comma-delimited text file
- Slice Files
  - Animated contour plots “slicing” through the scene that show quantities of interest such as temperature, species concentration, etc.
- Boundary Files
  - Animated contour plots of surface quantities at all solid boundaries
- IsoSurfaces and Realistic Smoke/Fire
  - Animated 3D contours showing the fire dynamics

Outputs: Thermocouple for temperature



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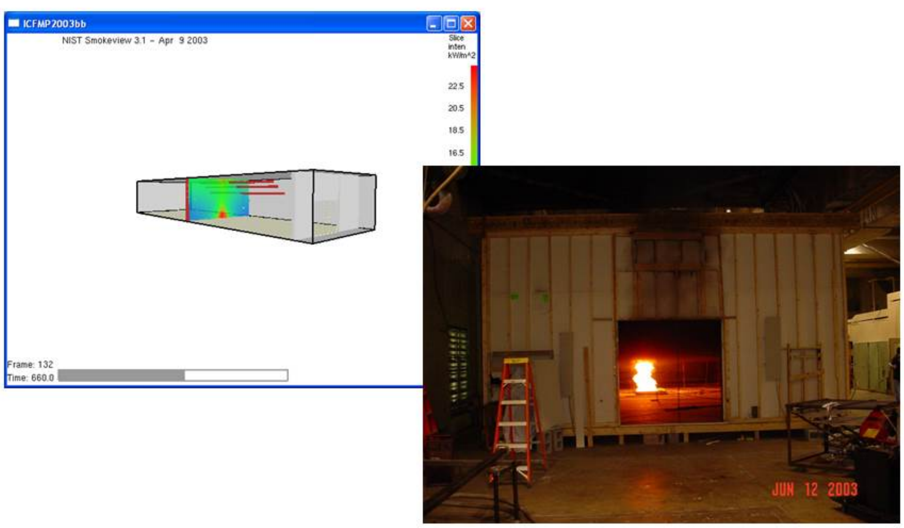
Outputs: Slice files for temp and heat flux



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Fire Model Descriptions

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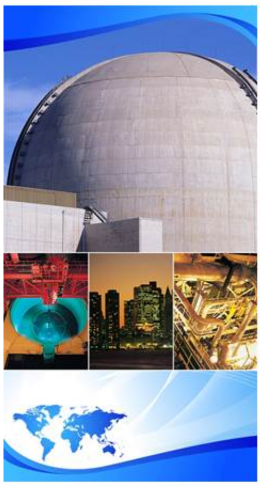
2.3 Special Topic: Validation



EPRI/NRC-RES Fire PRA Methodology

Module V: Advanced Fire Modeling

Special Topic: Validation

Joint RES/EPRI Fire PRA Workshop
2012
Washington, D.C.

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Verification and Validation

ASTM E 1355, Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models

- ***Verification:*** the process of determining that the implementation of a calculation method accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method. *Is the Math right?*
- ***Validation:*** the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method. *Is the Physics right?*
- This presentation focuses primarily on validation.

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Model Validation
Slide 2
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Important Measurements/ Parameters

- Room Temperature
  - Main control room abandonment study
  - Targets in room of fire origin or adjacent compartments
- Flame height, Plume & Ceiling jet temperature
  - Target heating and target temperature near the ignition source

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Important Measurements/ Parameters

- Oxygen & Smoke concentration
  - Main control room habitability
- Room pressure
  - Issues related to mechanical ventilation and/or smoke migration
- Target/Wall heating and Target/Wall temperature
  - Most fire scenarios throughout the plant

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How were the experiments selected?

Selection Criteria: High-Quality Experiments

- Large-scale experiments
- Availability of data
- Directly applicable to nuclear power plant applications
- Accurate measurement of the fire heat release rate
- Well documented
- Uncertainty analysis useful

- Selection Process
  - Extensive review of fire literature
  - Scarcity of high-quality large-compartment fire test data
  - Typical industry tests: proprietary, reduced-scale, not NPP related

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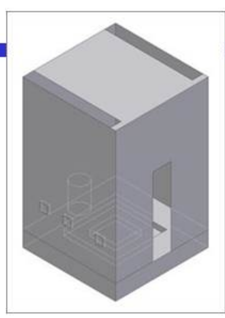
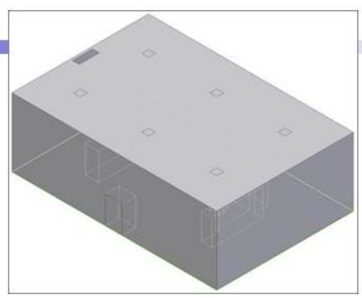
Pump Room

ICFMP BE #4, 5



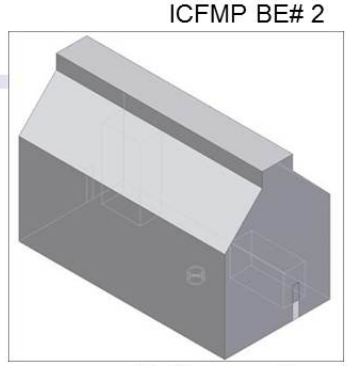
Main Control Room

FM/SNL



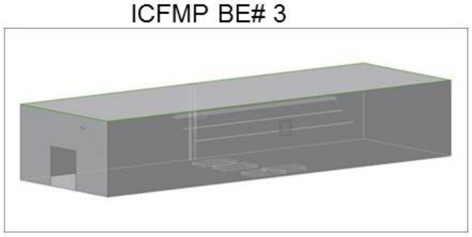
Turbine hall

ICFMP BE# 2



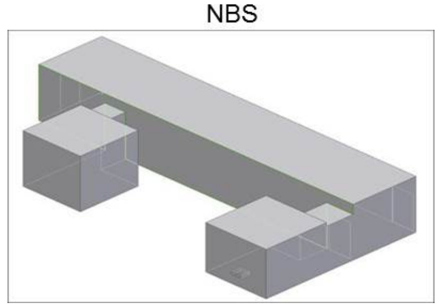
Misc.

ICFMP BE# 3



Multi-compartment

NBS



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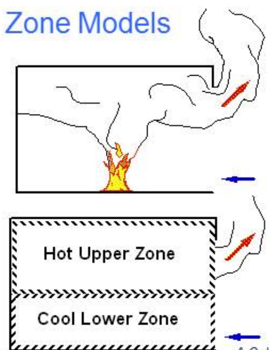
Slide 6

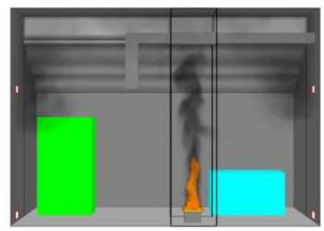
Fire Models Selected

Fire Dynamics Tools (FDT^s^)	NRC Spreadsheets
FIVE-Rev1	EPRI Spreadsheets
Cons. Fire & Smoke Transport (CFAST)	NIST zone model
MAGIC	Electricite de France zone
Fire Dynamics Simulator (FDS)	NIST CFD Model

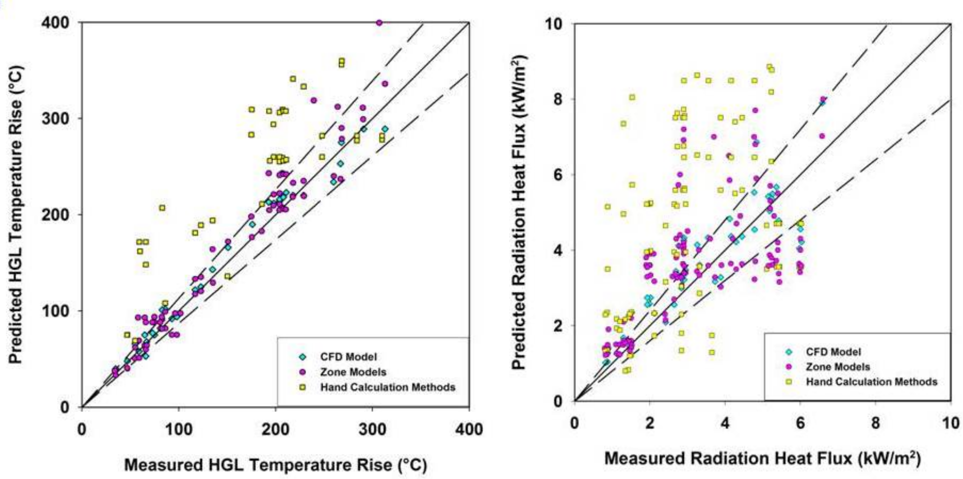
Spreadsheets | Zone Models | Field Models

$$L_f = 0.23\dot{Q}^{2/5} - 1.02D$$

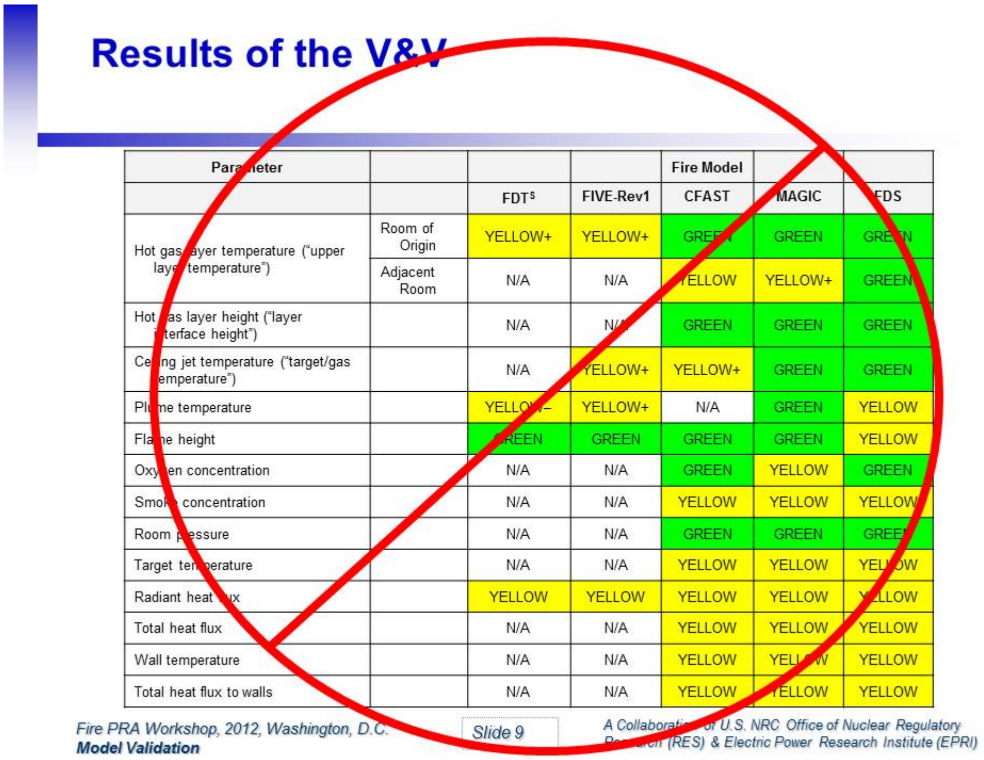




Quantitative V&V Results



Measured vs. Predicted Hot Gas Layer Temperature Rise (left) and Measured vs. Predicted Heat Flux (right)



Results of the V&V

Parameter				Fire Model		
		FDTs	FIVE-Rev1	CFAST	MAGIC	FDS
Hot gas layer temperature ("upper layer temperature")	Room of Origin	YELLOW+	YELLOW+	GREEN	GREEN	GREEN
	Adjacent Room	N/A	N/A	YELLOW	YELLOW+	GREEN
Hot gas layer height ("layer interface height")		N/A	N/A	GREEN	GREEN	GREEN
Ceiling jet temperature ("target/gas temperature")		N/A	YELLOW+	YELLOW+	GREEN	GREEN
Plume temperature		YELLOW–	YELLOW+	N/A	GREEN	YELLOW
Flame height		GREEN	GREEN	GREEN	GREEN	YELLOW
Oxygen concentration		N/A	N/A	GREEN	YELLOW	GREEN
Smoke concentration		N/A	N/A	YELLOW	YELLOW	YELLOW
Room pressure		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

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Model Validation

Slide 9

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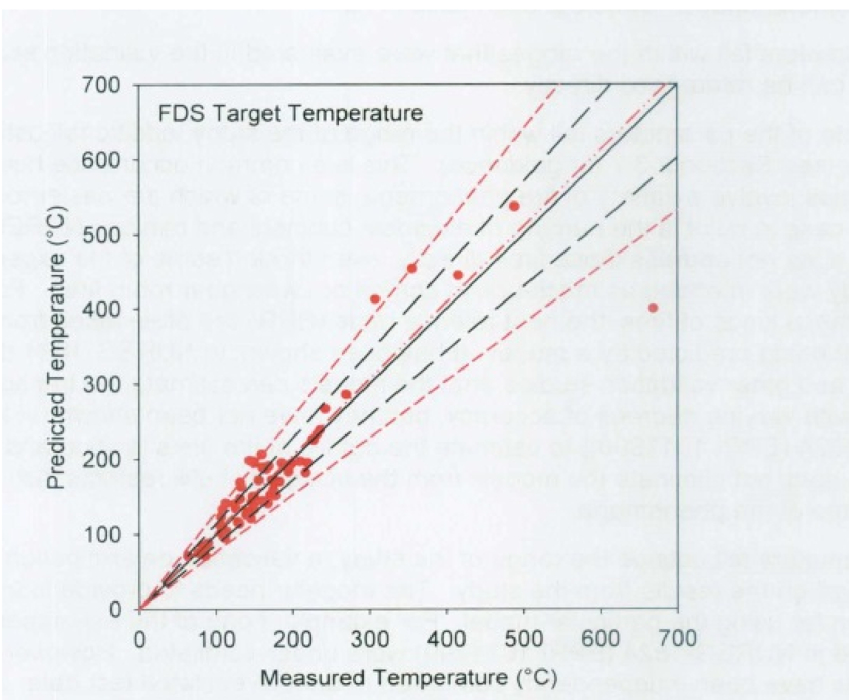
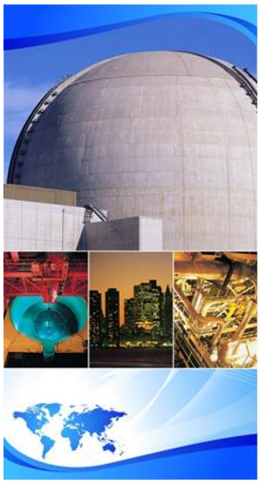


Figure 4-1. Sample set of results from NUREG-1824 (EPRI 1011999).

2.4 Model Uncertainty



EPRI/NRC-RES Fire PRA Methodology

Module 5: Advanced Fire Modeling
Model Uncertainty

Joint RES/EPRI Fire PRA Workshop
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What is Uncertainty?

- Parameter Uncertainty – refers to the contribution of the uncertainty in the input parameters to the total uncertainty of the simulation
- Model Uncertainty – refers to the effect of the model assumptions, simplified physics, numerics, etc.
- Completeness Uncertainty – refers to physics that are left out of the model. For most, this is a form of Model Uncertainty.

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Model Uncertainty

Slide 2

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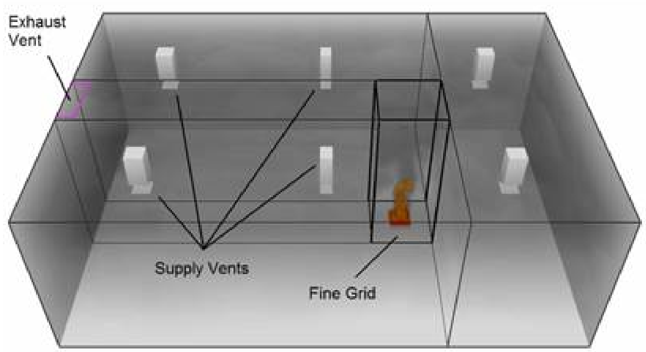
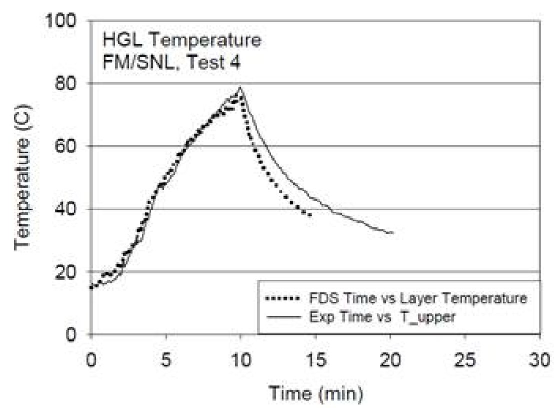
Fire Model Validation Study, NUREG-1824





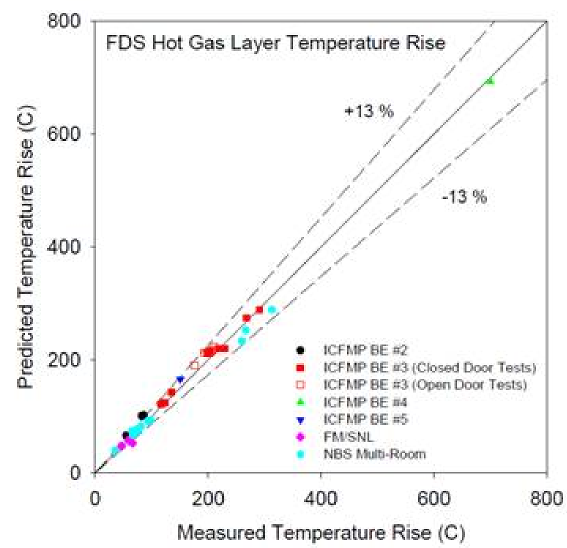


Table 4-1. Results of the V&V study, NUREG-1824 (EPRI 1011999).

Output Quantity	FDTs		FIVE		CFAST		MAGIC		FDS		Exp
	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	$\tilde{\sigma}_E$
HGL Temperature Rise*	1.44	0.25	1.56	0.32	1.06	0.12	1.01	0.07	1.03	0.07	0.07
HGL Depth*	N/A		N/A		1.04	0.14	1.12	0.21	0.99	0.07	0.07
Ceiling Jet Temp. Rise	N/A		1.84	<u>0.29</u>	1.15	<u>0.24</u>	1.01	0.08	1.04	0.08	0.08
Plume Temperature Rise	0.73	<u>0.24</u>	0.94	<u>0.49</u>	1.25	0.28	1.01	0.07	1.15	<u>0.11</u>	0.07
Flame Height**	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.	I.D.
Oxygen Concentration	N/A		N/A		0.91	<u>0.15</u>	0.90	0.18	1.08	0.14	0.05
Smoke Concentration	N/A		N/A		2.65	<u>0.63</u>	2.06	<u>0.53</u>	2.70	<u>0.55</u>	0.17
Room Pressure Rise	N/A		N/A		1.13	0.37	0.94	0.39	0.95	0.51	0.20
Target Temperature Rise	N/A		N/A		1.00	0.27	1.19	0.27	1.02	0.13	0.07
Radiant Heat Flux	2.02	<u>0.59</u>	1.42	0.55	1.32	0.54	1.07	0.36	1.10	0.17	0.10
Total Heat Flux	N/A		N/A		0.81	0.47	1.18	0.35	0.85	0.22	0.10
Wall Temperature Rise	N/A		N/A		1.25	0.48	1.38	0.45	1.13	0.20	0.07
Wall Heat Flux	N/A		N/A		1.05	0.43	1.09	0.34	1.04	0.21	0.10

I.D. indicates insufficient data for the statistical analysis.
N/A indicates that the model does not have an algorithm to compute the given Output Quantity.
Underlined values indicate that the data failed a normality test because of the relatively small sample size.
* The algorithm used to compute the layer temperature and depth for the model FDS is described in NUREG-1824.
** All of the models except FDS use the Heskestad Flame Height Correlation (Heskestad, *SFPE Handbook*). These models were shown to be in qualitative agreement with the experimental observations, but there was not enough data to further quantify this assessment.

Procedure for Calculating Model Uncertainty

1. Express the predicted value in terms of a rise above ambient. For example, subtract the ambient temperature from the predicted temperature. Call this value M.
2. Find the values of model bias and relative standard deviation from table on previous slide. Compute the mean and standard deviation of normal distribution:

$$\mu = M/\delta \qquad \sigma = \tilde{\sigma}_M(M/\delta)$$

3. Compute the probability of exceeding the critical value:

$$P(x > x_c) = \frac{1}{2}\,\text{erfc}\left(\frac{x_c - \mu}{\sigma\sqrt{2}}\right)$$

4.3.1 Example 1: Target Temperature

Suppose that cables within a compartment are assumed to fail if their surface temperature reaches 330 °C (625 °F). The model FDS predicts that the maximum cable temperature due to a fire in an electrical cabinet is 300 °C (570 °F). What is the probability that the cables could fail?

Step 1: Subtract the ambient value of the cable temperature, 20 °C (68 °F) to determine the predicted temperature <u>rise</u>. Refer to this value as the *model prediction*:

$$M = 300 - 20 = 280°\mathrm{C} \tag{4-6}$$

Step 2: Refer to Table 4-1, which indicates that, on average, FDS overpredicts Target Temperatures with a bias factor, δ, of 1.02. Calculate the *adjusted model prediction*:

$$\mu = \frac{M}{\delta} = \frac{280}{1.02} = 275°\mathrm{C} \tag{4-7}$$

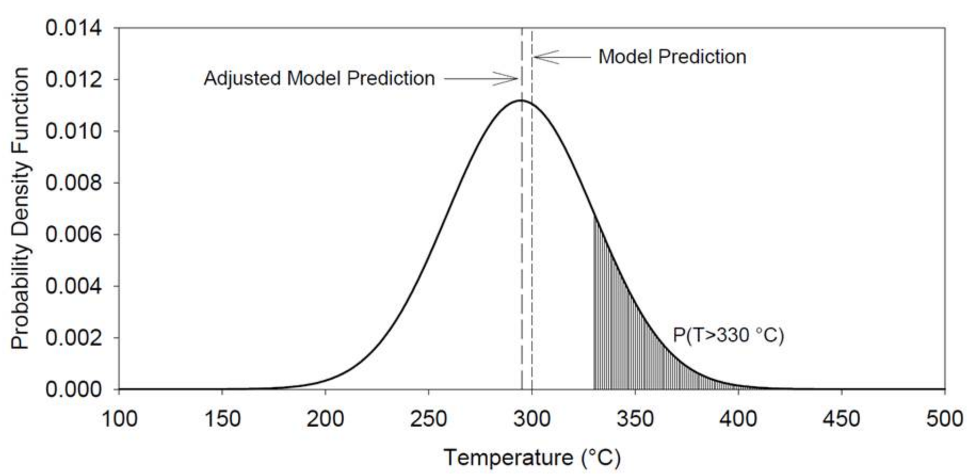
Referring again to Table 4-1, calculate the standard deviation of the distribution:

$$\sigma = \tilde{\sigma}_M \left(\frac{M}{\delta}\right) = 0.13 \left(\frac{280}{1.02}\right) = 36°\mathrm{C} \tag{4-8}$$

Step 3: Calculate the probability that the actual cable temperature would exceed 330°C:

$$P(T > 330) = \frac{1}{2}\ \mathrm{erfc}\left(\frac{T - T_0 - \mu}{\sigma\sqrt{2}}\right) = \frac{1}{2}\ \mathrm{erfc}\left(\frac{330 - 20 - 275}{36\sqrt{2}}\right) = 0.16 \tag{4-9}$$

The process is shown graphically in Figure 4-3. The area under the "bell curve" for temperatures higher than 330 °C (625 °F) represents the probability that the actual cable temperature would exceed that value. Note that this estimate is based only on the model uncertainty.



4.3.2 Example 2: Critical Heat Flux

As part of a screening analysis, the model MAGIC is used to predict the radiant heat flux from a fire to a nearby group of thermoplastic cables. According to NUREG/CR-6850 (EPRI 1011989), Appendix H, one of the damage criteria for thermoplastic cables is a radiant heat flux to the target cable that exceeds 6 kW/m^2. The model, by coincidence, predicts a heat flux of 6 kW/m^2. What is the probability that the actual heat flux from a fire will be 6 kW/m^2 or greater? Assume for this exercise that the model input parameters are not subject to uncertainty, only the model itself.

Step 1: Unlike in the previous example, there is no need to subtract an ambient value of the heat flux (it is zero). Thus, the *model prediction* is:

$$M = 6 \text{ kW/m}^2 \tag{4-10}$$

Step 2: Refer to Table 4-1, which indicates that, on average, MAGIC overpredicts Radiant Heat Flux with a bias factor, δ, of 1.15. Calculate the *adjusted model prediction*:

$$\mu = \frac{M}{\delta} = \frac{6}{1.15} \approx 5.2 \text{ kW/m}^2 \tag{4-11}$$

Referring again to Table 4-1, calculate the standard deviation of the distribution:

$$\sigma = \tilde{\sigma}_M \left(\frac{M}{\delta}\right) = 0.36\left(\frac{6}{1.15}\right) \approx 1.9 \text{ kW/m}^2 \tag{4-12}$$

Step 3: Calculate the probability that the actual heat flux, $\dot{q}''$, will exceed the critical value of the heat flux, $\dot{q}''_c = 6$ kW/m^2:

$$P(\dot{q}'' > 6) = \frac{1}{2}\,\text{erfc}\left(\frac{\dot{q}''_c - \mu}{\sigma\sqrt{2}}\right) = \frac{1}{2}\,\text{erfc}\left(\frac{6 - 5.2}{1.9\sqrt{2}}\right) \approx 0.34 \tag{4-13}$$

This is a somewhat surprising result. Even though the model predicts a peak radiant heat flux equal to the critical value, there is only a one in three chance that the actual heat flux would exceed this value. This is mainly due to the fact that MAGIC has been shown to over-predict the heat flux by about 15%.

Sensitivity Analysis to Address Parameter Uncertainty

Output Quantity = Constant × (Input Parameter)$^{\text{Power}}$

Example: MQH correlation states that the HGL temperature rise is proportional to the HRR to the 2/3 power:

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

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

Table 4-3. Sensitivity of model outputs from Volume 2 of NUREG-1824 (EPRI 1011999).

Output Quantity	Important Input Parameters	Power Dependence
HGL Temperature	HRR Surface Area Wall Conductivity Ventilation Rate Door Height	2/3 -1/3 -1/3 -1/3 -1/6
HGL Depth	Door Height	1
Gas Concentration	HRR Production Rate	1/2 1
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

Suppose, for example, that as part of an NFPA 805 analysis the problem is to determine the Limiting Fire Scenario for a particular compartment whose HGL temperature is not to exceed 500 °C (930 °F). Assume that the geometrical complexity of the compartment rules out the use of the empirical and zone models, and that FDS has been selected for the simulation.

Step 1: Determine an appropriate maximum expected fire heat release rate. For this example, suppose that a 98th percentile HRR for the electrical cabinet fire, 702 kW, has been determined to be the MEFS. Choose a model and calculate the peak HGL temperature.

Step 2: Assume that FDS predicts 450 °C (840 °F) for the selected fire scenario. Adjust the prediction to account for the model bias, δ (See Table 4-1):

$$T_{\mathrm{adj}} = T_0 + \frac{T - T_0}{\delta} = 20 + \frac{450 - 20}{1.03} \approx 437°\mathrm{C} \qquad (4\text{-}17)$$

Step 3: Calculate the change in HRR required to increase the HGL temperature to 500 °C (930 °F):

$$\Delta\dot{Q} \approx \frac{3}{2}\dot{Q}\frac{\Delta T}{T_{\mathrm{adj}} - T_0} = \frac{3}{2}702\frac{500 - 437}{417} = 159\ \mathrm{kW} \qquad (4\text{-}18)$$

This calculation suggests that adding an additional 159 kW to the original 702 kW will produce an HGL temperature in the vicinity of 500 °C (930 °F). This result can be double-checked by re-running the model with the modified input parameters.

Propagating Uncertainty

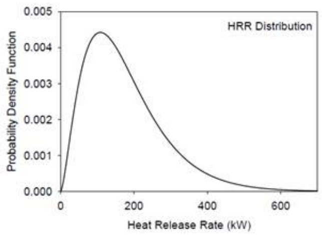
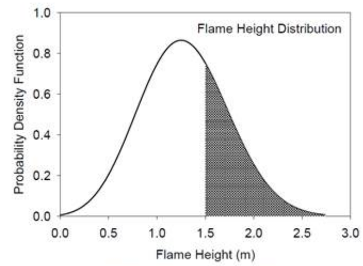


Figure 4-4. Distribution of HRR for an electrical cabinet fire.

$$L_\mathrm{f} = 0.235\,\dot{Q}^{2/5} - 1.02\,D$$

$$f(L_\mathrm{f}) = \frac{g(\dot{Q};\alpha,\beta)}{\left|\frac{dL_\mathrm{f}}{d\dot{Q}}\right|} = g(\dot{Q};\alpha,\beta)\,\frac{\dot{Q}^{3/5}}{0.094}$$



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Model Uncertainty

Slide 12

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2.5 Development of a Cable Response Model and Fire Model Verification and Validation

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Fire Branch Research

Development of a Cable Response Model and Fire Model Verification and Validation

Kevin McGrattan
National Institute of Standards and Technology

Office of Nuclear Regulatory Research

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

CAROLFIRE (Cable Response to Live Fire)

- ***Penlight*** heats target cables via grey-body radiation from a heated shroud
- Well controlled, well instrumented tests
- Allows for many experiments in a short time
- Thermal response and failure for single cables and small cable bundles (up to six cables)
- Cable trays, air drops, conduits

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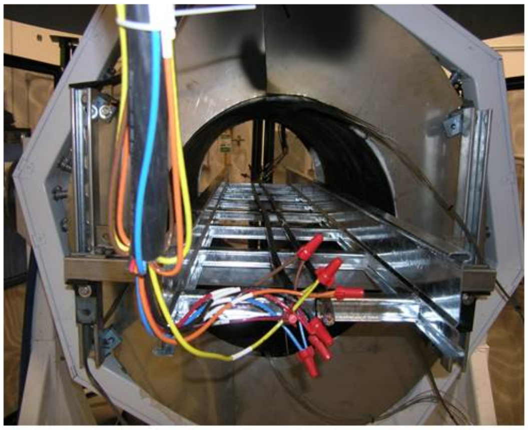
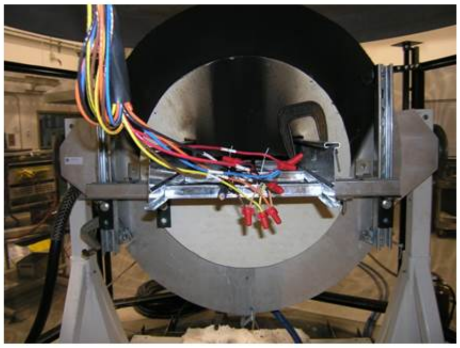
Typical Penlight setup





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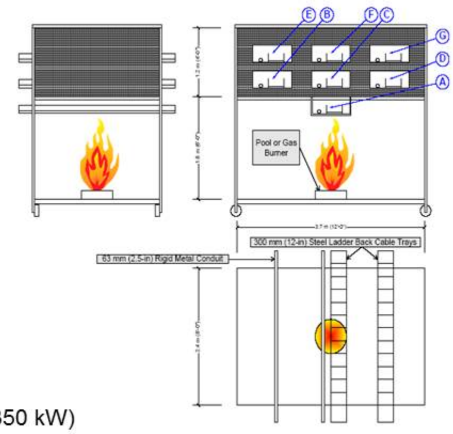
Intermediate-Scale Tests

Courtesy Steve Nowlen and Frank Wyant, Sandia National Labs



- Less controlled, but a more realistic scale
- Hood is roughly the size of a typical ASTM E 603 type room fire test facility
- Propene (Propylene) burner fire (200 kW to 350 kW)
- Cables in trays, conduits and air drop

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Simple Response Models in Fire

$$\frac{dT_l}{dt} = \frac{\sqrt{|\mathbf{u}|}}{\mathrm{RTI}}(T_g - T_l)$$

Solve for link temperature using velocity **u** and gas temperature from Fire Model. The RTI (Response Time Index) is unique to each sprinkler.
Source: Gunnar Heskestad, Factory Mutual

$$\frac{dY_c}{dt} = \frac{Y_e(t) - Y_c(t)}{L/\mathbf{u}}$$

Solve for smoke chamber concentration using external smoke concentration and velocity **u** from Fire Model. L is a length scale unique to each detector.

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Cable Failure Model

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{k_s}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_s}{\partial r}\right)$$

$$-k_s \frac{\partial T_s}{\partial r} = \dot{q}_c'' + \dot{q}_r''$$

1-D heat conduction into homogenous cylinder. Thermal conductivity (k) and specific heat (c) assumed constant for all cables. Density (ρ) obtained from cable diameter and mass per unit length. Failure temperature obtained experimentally.

The Fire Model provides the convective and radiative heat flux at the cable surface.

Source: Andersson and Van Hees, SP Fire, Sweden.

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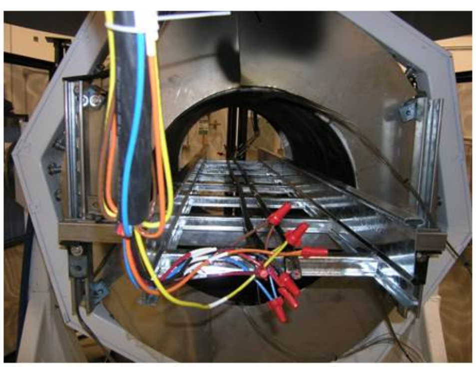
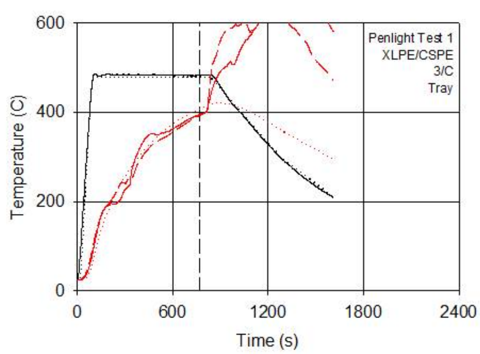
Single Cable



Courtesy Steve Nowlen and Frank Wyant
Sandia National Laboratory



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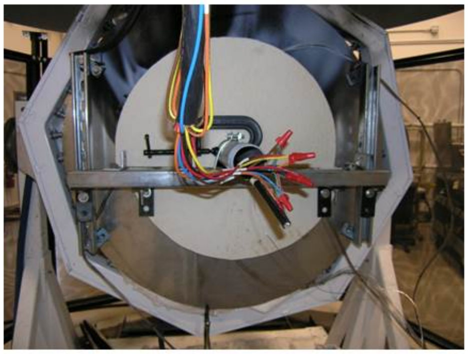
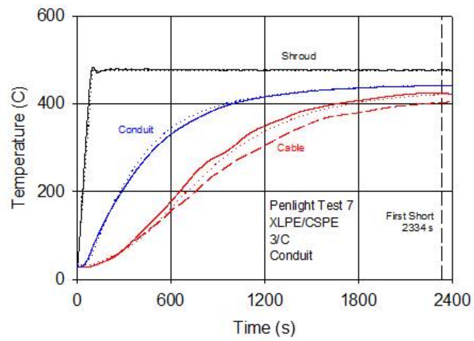
Cable in a Conduit





Courtesy Steve Nowlen and Frank Wyant
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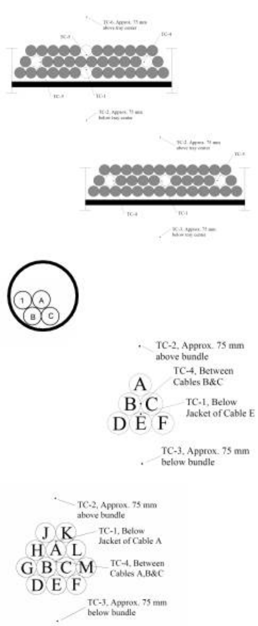
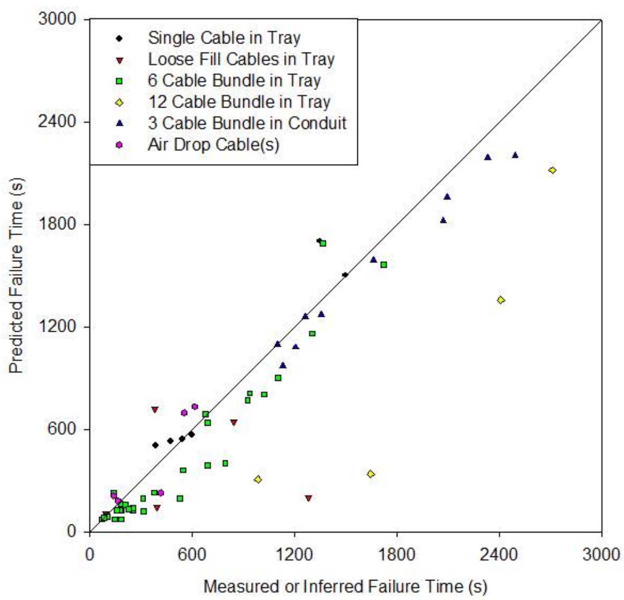
Intermediate-Scale Experiments





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3
EXAMPLES

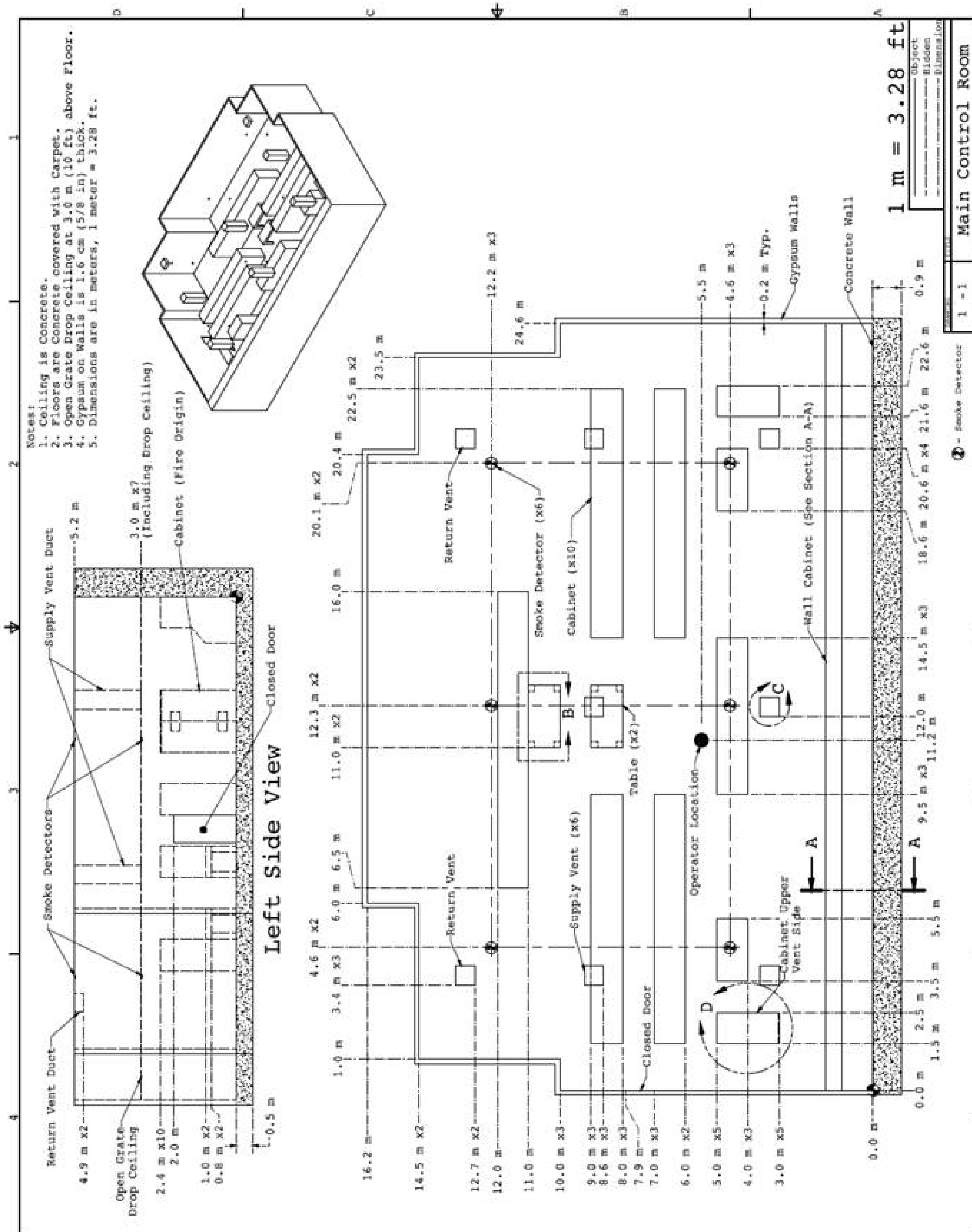
3.1 Example A: Control Room Fire

Step 1. Define Fire Modeling Goals

- Determine the length of time that the Main Control Room (MCR) remains habitable after the start of a fire within a low-voltage control cabinet.
- Follow guidance provided in Chapter 11 of NUREG/CR-6850 (EPRI 1011989), Volume 2, "Detailed Fire Modeling (Task 11)."
- Note that MCR fire scenarios are treated differently than fires within other compartments, mainly because it is necessary to consider and evaluate forced abandonment in addition to equipment damage.

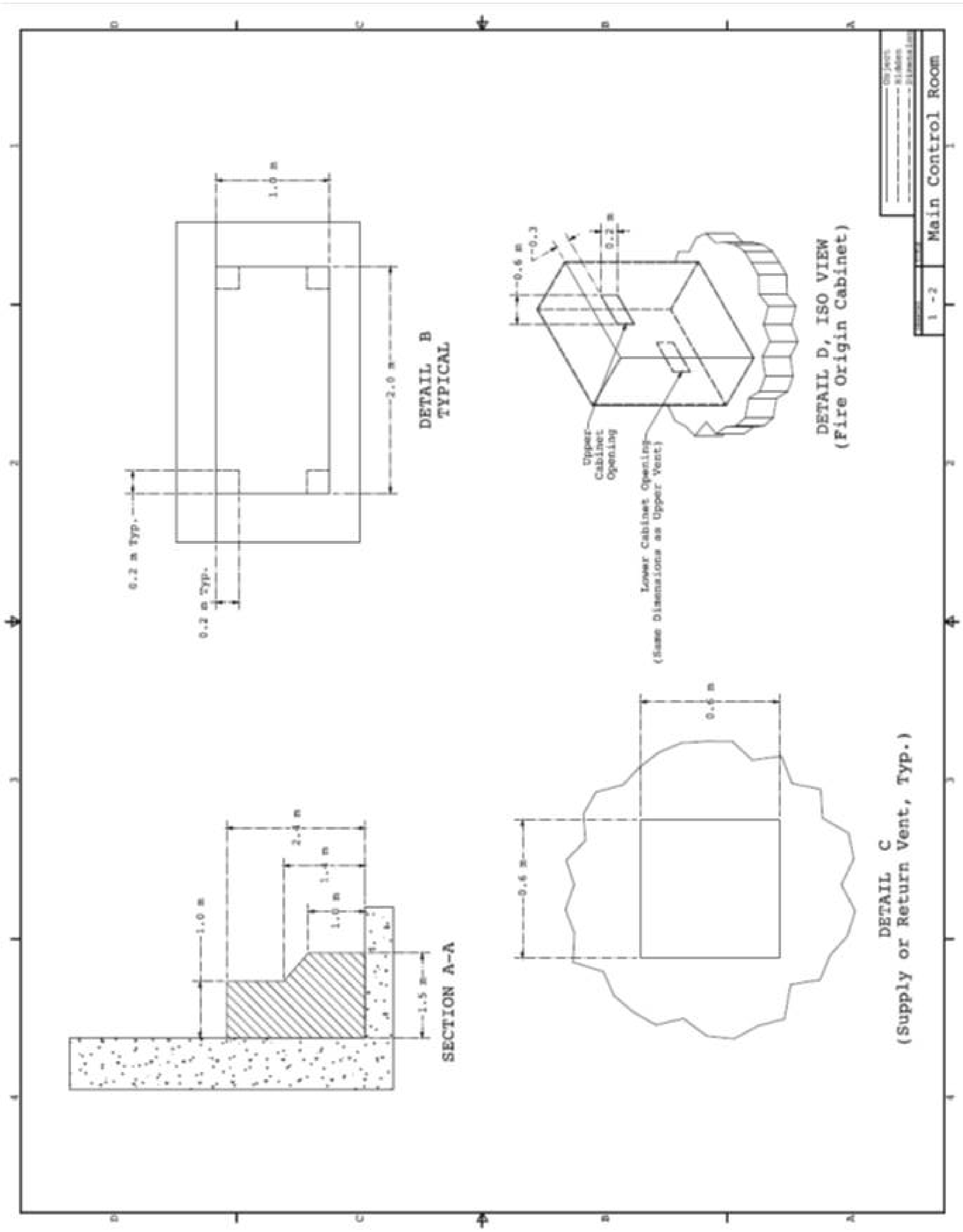
Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire
- Habitability and Human Factors


Notes:
1. Ceiling is Concrete.
2. Floors are Concrete covered with Carpet.
3. Open Grate Drop Ceiling at 3.0 m (10 ft) above Floor.
4. Gypsum on Walls is 1.6 cm (5/8 in) thick.
5. Dimensions are in meters, 1 meter = 3.28 ft.
Left Side View
Supply Vent Duct
Smoke Detectors
Return Vent Duct
Open Grate Drop Ceiling
Cabinet (Fire Origin)
Closed Door
Return Vent
Smoke Detector (x6)
Cabinet (x10)
Supply Vent (x6)
Table (x2)
Operator Location
Closed Door
Wall Cabinet (See Section A-A)
Cabinet Upper Vent Side
Gypsum Walls
Concrete Wall
Smoke Detector
1 m = 3.28 ft
Main Control Room

Typical “open grate” ceiling

Typical Control Room Cabinet


DETAIL B
TYPICAL
1.0 m
2.0 m
0.2 m Typ.
0.2 m Typ.
DETAIL D, ISO VIEW
(Fire Origin Cabinet)
Upper
Cabinet
Opening
Lower Cabinet Opening
(Same Dimensions as Upper Vent)
0.6 m
0.2 m
SECTION A-A
2.4 m
1.4 m
1.0 m
1.0 m
1.5 m
DETAIL C
(Supply or Return Vent, Typ.)
0.6 m
0.6 m
Main Control Room

Material Properties

- For non-burning materials, the most important properties are thermal conductivity, *k*, density, ρ, and specific heat, *c*

- For specified burning rates, you need:
  - Heat Release Rate (HRR)
  - Heat of Combustion – energy released per unit mass consumed. This is needed if you specify the yields of products of combustion, like soot.

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Example A: Control Room Fires

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Table 3-1. Material Properties

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Source
Brick	0.8	2600	0.8	NUREG-1805, Table 2-3
Concrete	1.6	2400	0.75	NUREG-1805, Table 2-3
Copper	386	8954	0.38	SFPE Handbook, Table B.6
Gypsum	0.17	960	1.1	NUREG-1805, Table 2-3
Plywood	0.12	540	2.5	NUREG-1805, Table 2-3
PVC	0.192	1380	1,289	NUREG/CR-6850, Appendix R
Steel	54	7850	0.465	NUREG-1805, Table 2-3
XLP	0.235	1375	1,390	NUREG/CR-6850, Appendix R

Typical material properties for common construction and cable materials

Ventilation

- 25 Air Changes Per Hour (ACH) for purge mode
- Two scenarios – purge mode or ventilation inoperative
- Leakage – often the "leakage area" is the area of the crack under the door
- Exact supply and exhaust location only important for CFD
- Zone models usually only consider height of mechanical ventilation injection and extraction grilles

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Example A: Control Room Fires

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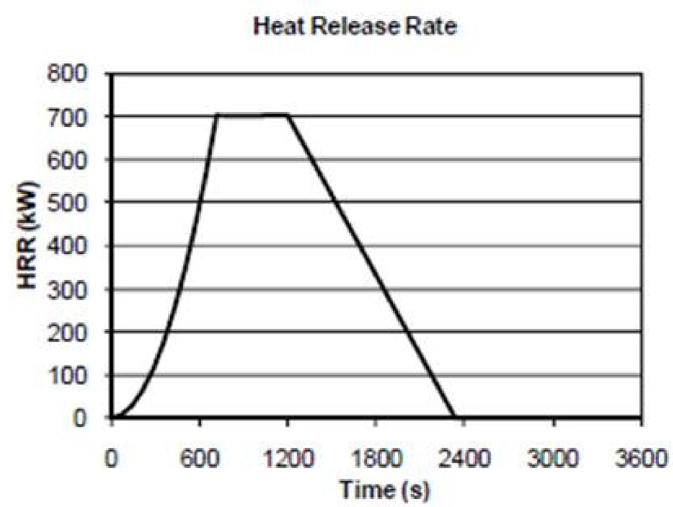
Fire

Table G-1
Recommended HRR Values for Electrical Fires

Ignition Source	HRR kW (Btu/s)		Gamma Distribution	
	75th	98th	α	β
Vertical cabinets with qualified cable, fire limited to one cable bundle	69 [1] (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Vertical cabinets with qualified cable, fire in more than one cable bundle	211 [2] (200)	702 [3] (665)	0.7 (0.7)	216 (204)
Vertical cabinets with unqualified cable, fire limited to one cable bundle	90 [4] (85)	211 [2] (200)	1.6 (1.6)	41.5 (39.5)
Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	232 [5] (220)	464 [6] (440)	2.6 (2.6)	67.8 (64.3)
Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	232 [5] (220)	1002 [7] (950)	0.46 (0.45)	386 (366)
Pumps (electrical fires) [8]	69 (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Motors [8]	32 (30)	69 (65)	2.0 (2.0)	11.7 (11.1)
Transient Combustibles [9]	142 (135)	317 (300)	1.8 (1.9)	57.4 (53.7)



HRR taken from Appendix G, NUREG/CR 6850 (EPRI 10111989)

Fire

What is burning?

Cables made of polyethylene (C_2H_4) and neoprene (C_4H_5Cl)

Assume effective fuel: $C_3H_{4.5}Cl_{0.5}$

Table A-1. Data for MCR fire based on XPE/neoprene electrical cable.

Parameter	Value	Source
Effective Fuel Formula	$C_3H_{4.5}Cl_{0.5}$	Combination of polyethylene and neoprene
Peak HRR	702 kW	NUREG/CR-6850 (EPRI 1011989), App. G
Time to reach peak HRR	720 s	NUREG/CR-6850 (EPRI 1011989), App. G
Heat of Combustion	10,300 kJ/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
CO_2 Yield	0.63 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
Soot Yield	0.175 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
CO Yield	0.082 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
Radiative Fraction	0.53	*SFPE Handbook,* 4th ed., Table 3-4.16
Mass Extinction Coefficient	8700 m^2/kg	Mulholland and Croarkin (2000)

Habitability

Criteria for habitability (NUREG/CR-6850, Vol 2, Chap 11)

- Gas Temperature 2 m off the floor is 95 °C
- Heat Flux exceeds 1 kW/m^2
- Optical Density exceeds 3 m^{-1}

What is Optical Density? $D \equiv -\frac{1}{L}\log_{10}\left(\frac{I}{I_0}\right) = K \log_{10} e$

Mass Extinction Coefficient (8700 m^2/kg)

$$K = K_m \rho Y_s$$

Smoke Concentration (kg/m^3)

Step 3. Select Fire Models

- Algebraic Models: FPA algorithm in FIVE and FDTs provides estimate of HGL temperature within a closed, ventilated compartment.
  - FDTs do not allow for time-dependent HRR
- Zone Models: CFAST includes smoke obscuration. MAGIC does not.
- CFD: Provides more detailed information at exact location of operators

Table A-2. Normalized parameter calculations for the MCR fire scenario. See Table 2-5 for further details.

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{702\ \mathrm{kW}}{(1.2\ \mathrm{kg/m^3})(1.0\ \mathrm{kJ/kg/K})(293\ \mathrm{K})(0.4^{2.5}\ \mathrm{m^{2.5}})\sqrt{9.8\ \mathrm{m/s^2}}} \cong 6.2$	0.4 – 2.4	No
Flame Height, $H_f + L_f$, relative to the Ceiling Height, H_c	$\frac{H_f + L_f}{H_c} = \frac{2.1\ \mathrm{m} + 2.7\ \mathrm{m}}{5.2\ \mathrm{m}} \cong 0.9$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 0.4\ \mathrm{m}\,(3.7 \times 6.2^{0.4} - 1.02) \cong 2.7\ \mathrm{m}$	0.2 – 1.0	Yes
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H_c	N/A – Ceiling jet targets are not included in simulation.	1.2 – 1.7	N/A
Equivalence Ratio, φ, of the room, based on Forced Ventilation of Purge Mode	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\dot{m}_{O_2}} = \frac{702\ \mathrm{kW}}{13{,}100\ \mathrm{kJ/kg} \times 3.7\ \mathrm{kg/s}} \cong 0.014$ $\dot{m}_{O_2} = Y_{O_2}\,\rho_\infty \dot{V} = 0.23 \times 1.2\ \mathrm{kg/m^3} \times 13.4\ \mathrm{m^3/s} \cong 3.7\ \mathrm{kg/s}$	0.04 – 0.6	No
Compartment Aspect Ratio	$\frac{L}{H_c} = \frac{24.6\ \mathrm{m}}{5.2\ \mathrm{m}} \cong 4.7$; $\frac{W}{H_c} = \frac{16.2\ \mathrm{m}}{5.2\ \mathrm{m}} \cong 3.1$	0.6 – 5.7	Yes
Target Distance, r, relative to the Fire Diameter, D	$\frac{r}{D} = \frac{8.8\ \mathrm{m}}{0.4\ \mathrm{m}} \cong 22$	2.2 – 5.7	No

Applicability of Validation

- For the scenario with no ventilation, the classic definition of the Equivalence Ratio does not apply because there is no supply of oxygen in the room.
- However, it can be shown that there is sufficient oxygen in the room to sustain the specified fire.

$$m_{O_2,\mathrm{tot}} = \rho V Y_{O_2} = 1.2\ \mathrm{kg/m^3} \times 1945\ \mathrm{m^3} \times 0.23 \cong 537\ \mathrm{kg}$$

$$m_{O_2,\mathrm{req}} = \frac{Q}{\Delta H_{O_2}} \cong \frac{702\ \mathrm{kW} \times 60\ \mathrm{s/min} \times \left(\frac{12}{3} + 8 + \frac{19}{2}\right)\ \mathrm{min}}{13{,}100\ \mathrm{kJ/kg}} \cong 69\ \mathrm{kg}$$

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Example A: Control Room Fires

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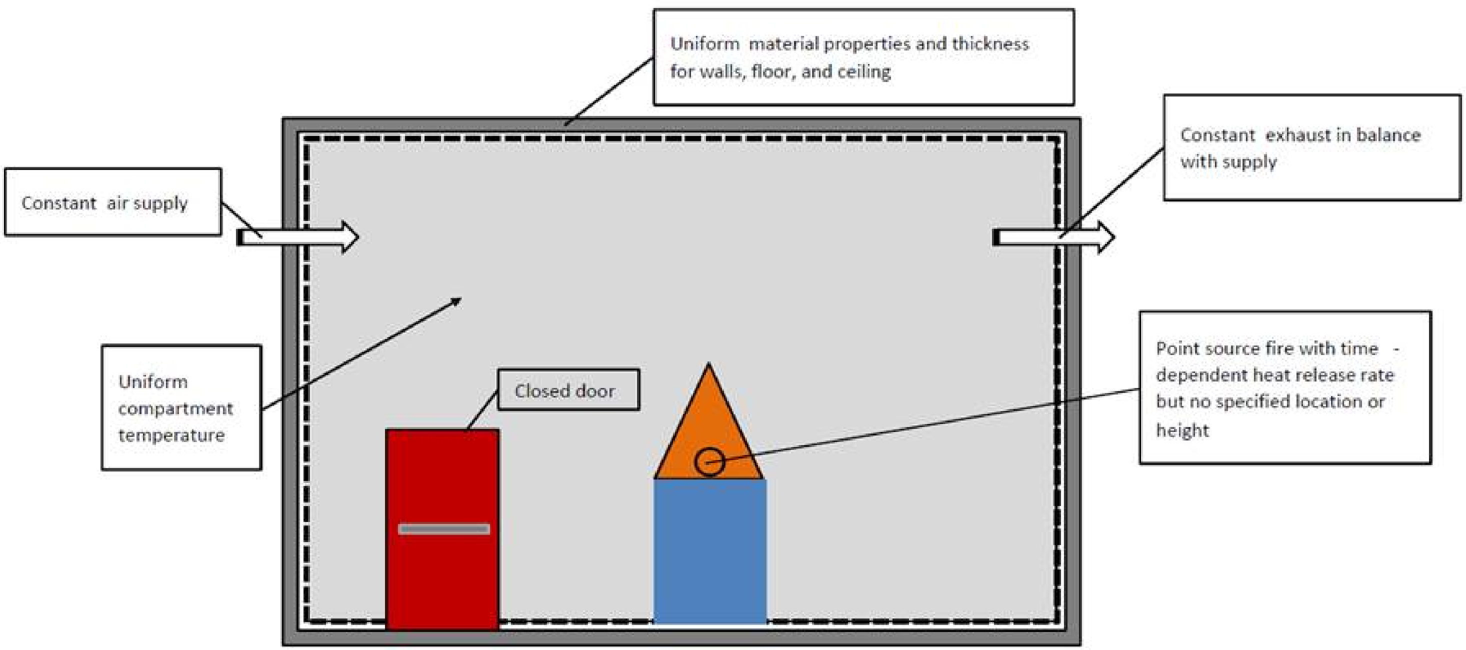
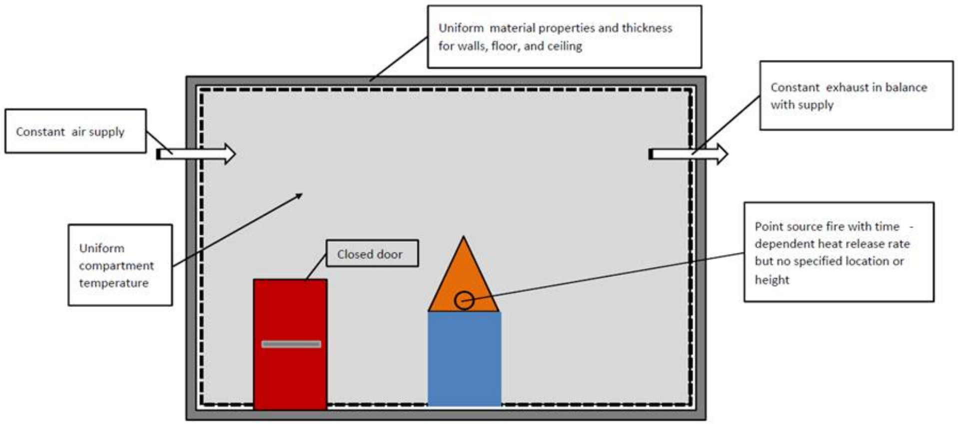
Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions

- Temperature in smoke purge scenario
  - Use FPA correlation in FIVE-rev1 or FDTs
- Need equivalent length / width of non-rectangular rooms

$$A_{\text{fl}} = L_e \times W_e \quad ; \quad P = 2 \times (L_e + W_e)$$

- Other input parameters

Table A-3. Summary of input parameters for the FPA calculation of the MCR.

Parameter	Value	Source
Room height (H)	5.2 m	Figure A-1
Room effective length (L_e)	27.1 m	Equation (A-3)
Room effective width (W_e)	13.8 m	Equation (A-3)
Room boundary material	Gypsum board	Table 3-1
Mech. ventilation rate ($\dot{V}$)	13.4 m^3/s	Specified (25 ACH)
Ambient temperature (T_a)	20 °C	Specified
Fire parameters		Table A-1

Step 4. Calculate Fire-Generated Conditions

Heat Flux

The point source model is used to estimate the heat flux from the flames to the operator when the fire is at its peak HRR. The peak HRR, $\dot{Q}$, is 702 kW, the radiative fraction, χ_r, is 0.53, and the distance from the cabinet vent to the operator is approximately 8.8 m (29 ft). The heat flux is calculated:

$$\dot{q}'' = \frac{\chi_r \, \dot{Q}}{4\pi \, r^2} = \frac{0.53 \times 702 \text{ kW}}{4\pi \times 8.8^2 \text{ m}^2} \cong 0.38 \text{ kW/m}^2 \quad \text{(A-4)}$$

While this heat flux prediction is well below the critical value of 1 kW/m^2, it does not account for the thermal radiation from the HGL. Thus, the point source method can be used as a screening tool, and further analysis can be performed by CFAST and FDS.

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Example A: Control Room Fires

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Smoke concentration and visibility

Neither the FDT^s nor FIVE include methods to calculate smoke concentrations or visibility in mechanically ventilated enclosure fires, but calculation methods provided in Section 3, Chapter 9, of the *SFPE Handbook* are relatively simple to apply and are based on the same principles and concepts embodied in zone models. These hand calculations provide an estimate of the fire-generated smoke concentrations and visibility conditions for this scenario and will indicate if more detailed modeling is warranted.

The soot mass generation rate, $\dot{m}_s$, is the product of the soot yield, y_s, and the mass burning rate of fuel, $\dot{m}_f$. The latter quantity is obtained by dividing the HRR, $\dot{Q}$, by the heat of combustion, ΔH:

$$\dot{m}_s = y_s \dot{m}_f = y_s \frac{\dot{Q}}{\Delta H} = 0.175 \times \frac{702 \text{ kW}}{10{,}300 \text{ kJ/kg}} \cong 0.012 \text{ kg/s} \quad \text{(A-5)}$$

The soot mass fraction in the smoke layer, Y_s, is then calculated:

$$Y_s = \frac{\dot{m}_s}{\dot{m}_{\text{tot}}} \cong \frac{\dot{m}_s}{\dot{m}_a} = \frac{\dot{m}_s}{\rho \dot{V}} = \frac{0.012 \text{ kg/s}}{1.2 \text{ kg/m}^3 \times 13.4 \text{ m}^3\text{/s}} \cong 0.00075 \text{ kg/kg} \quad \text{(A-6)}$$

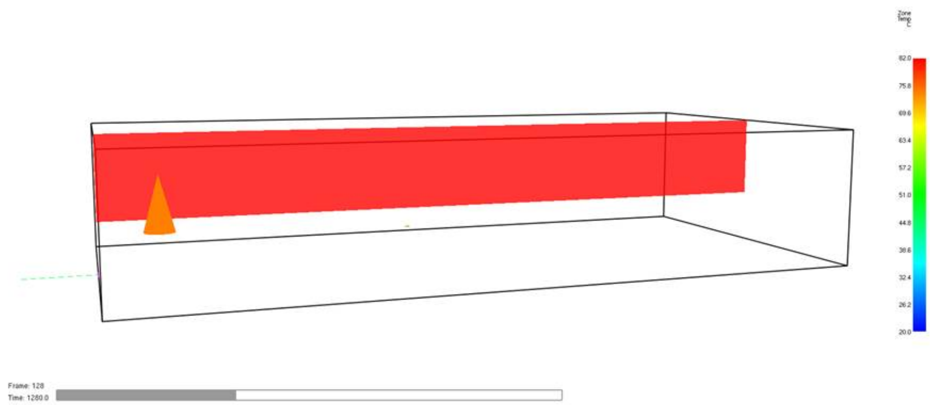
The extinction coefficient of the smoke, K, is calculated:

$$K = K_m \rho Y_s = 8700 \text{ m}^2\text{/kg} \times 1.2 \text{ kg/m}^3 \times 0.00075 \text{ kg/kg} \cong 7.8 \text{ m}^{-1} \quad \text{(A-7)}$$

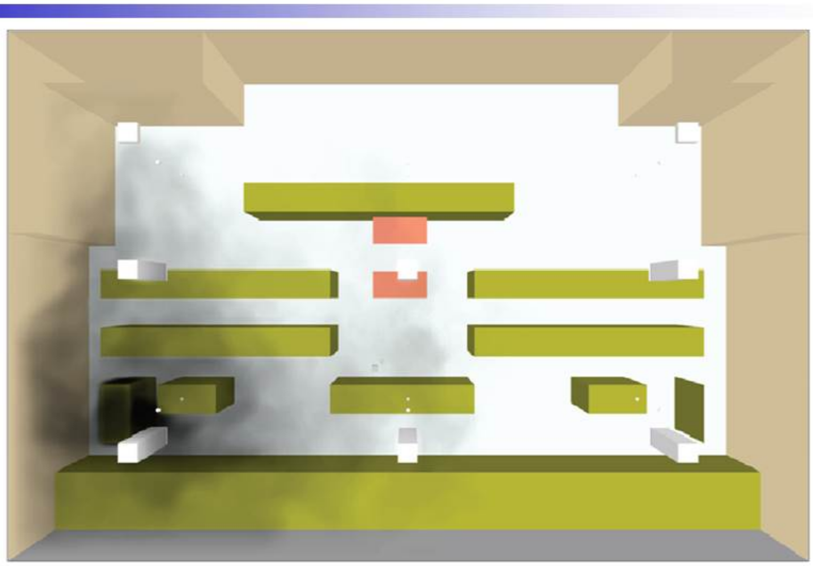
Here K_m is the mass specific extinction coefficient listed in Table A-1. By definition, the optical density of the smoke is related to the extinction coefficient via the expression:

$$D = \frac{K}{\ln 10} \cong \frac{7.8 \text{ m}^{-1}}{2.3} \cong 3.4 \text{ m}^{-1} \quad \text{(A-8)}$$

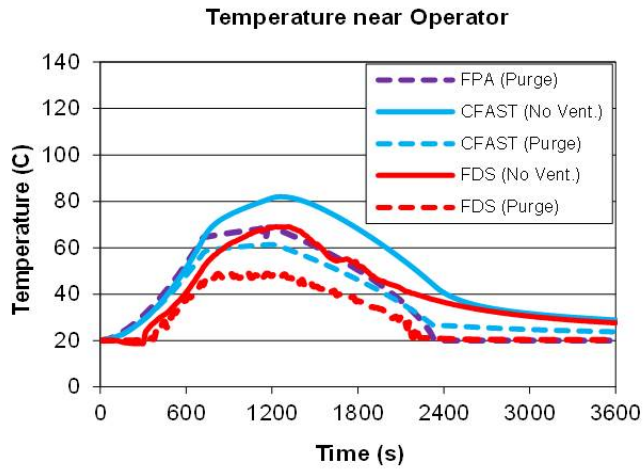
CFAST – Smokeview rendering of MCR fire



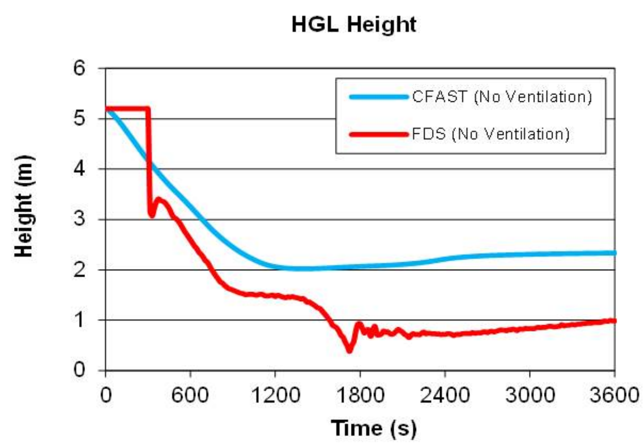
FDS – Smokeview rendering of MCR fire



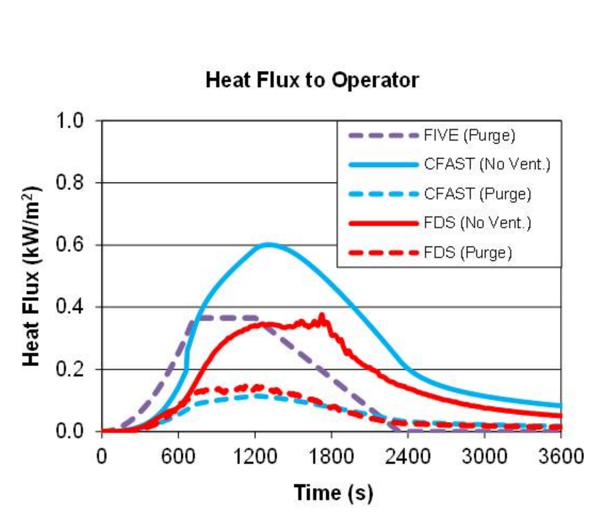
Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions



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Example A: Control Room Fires

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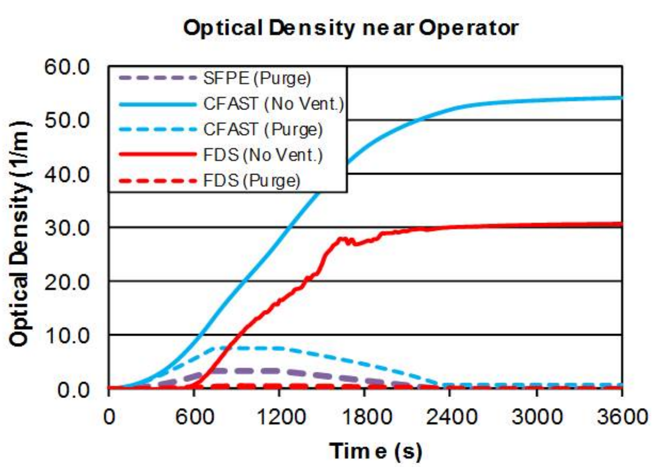
Step 4. Calculate Fire-Generated Conditions



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Example A: Control Room Fires

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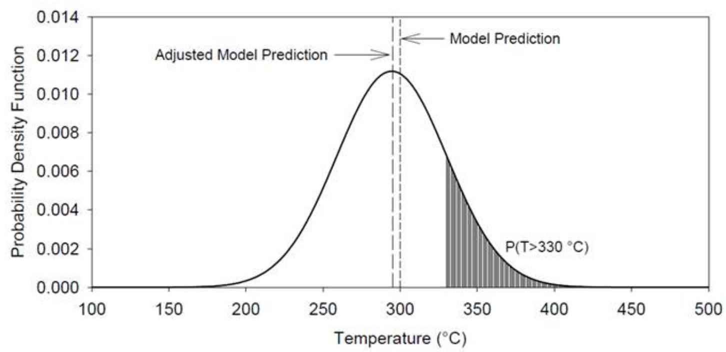
Step 5. Sensitivity and Uncertainty Analysis

- Uncertainty Analysis quantifies the **model** uncertainty
  - List the predicted quantities and the critical values of these quantities
- Sensitivity Analysis can be used to assess parameter uncertainty



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Example A: Control Room Fires

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Step 5. Sensitivity and Uncertainty Analysis

Table A-4. Summary of the model predictions of the MCR scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Ventilation	Predicted Value	Critical Value	Probability of Exceeding
Temperature (°C), Initial Value = 20 °C						
FIVE-Rev1 (FPA)	1.56	0.32	Purge	70	95	0.000
CFAST	1.06	0.12		61	95	0.000
FDS	1.03	0.07		48	95	0.000
CFAST	1.06	0.12	No Vent.	82	95	0.009
FDS	1.03	0.07		70	95	0.000
Heat Flux (kW/m^2)						
FIVE-Rev1	1.42	0.55	Purge	0.4	1	0.000
CFAST	0.81	0.47		0.1	1	0.000
FDS	0.85	0.22		0.2	1	0.000
CFAST	0.81	0.47	No Vent.	0.6	1	0.228
FDS	0.85	0.22		0.4	1	0.000
Optical Density (m^{-1})						
CFAST	2.65	0.63	Purge	7.6	3	0.471
FDS	2.7	0.55		0.5	3	0.000
CFAST	2.65	0.63	No Vent.	54	3	0.912
FDS	2.7	0.55		31	3	0.909

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Example A: Control Room Fires

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Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

Step 6. Document the Analysis

A.6 Conclusion

A fire modeling analysis has been performed to assess the habitability of the MCR in the event of a fire within an isolated electrical cabinet. The fire is not expected to spread to other cabinets. Of the three MCR abandonment criteria, it is most likely that the operators would be forced to abandon the MCR because the optical density would surpass 3 m^{-1} approximately 12 minutes after the fire ignites if the smoke purge system is not activated before this time, according to the FDS analysis. A simple analytical method and the zone model CFAST indicate that the optical density would exceed the critical value with the smoke purge system on and with the ventilation system turned off. However, these analyses are based on the use of several important conservative parameters. For the smoke purge case, the analytical method predicts that the smoke fills the entire compartment uniformly, even though the FDS analysis shows that the supply vents maintain visibility in the vicinity of the operator location. CFAST reports the optical density of the upper layer, but does not predict that the upper layer would descend to the level of the operator in either the purge or no-ventilation scenario based on the conservative specifications, at least for a fire having a base height of 2 m (6.6 ft).

3.2 Example B: Cabinet Fire in Switchgear Room

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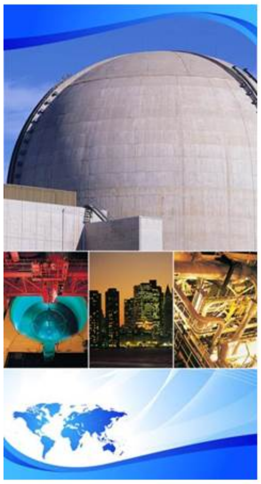

EPRI/NRC-RES Fire PRA Methodology

Module V:
Advanced Fire Modeling
Example B: Cabinet Fire in Switchgear Room

Joint RES/EPRI Fire PRA Workshop
2012
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Step 1. Define Fire Modeling Goals

- Estimate the effects of fire in a cabinet in a Switchgear Room on nearby cable and cabinet targets.
- Switchgear Room contains safety-related equipment for both Train A and Train B that are not separated as required by Appendix R.
- The purpose of the calculation is to analyze this condition and determine whether these targets fail, and, if so, at what time failure occurs.
- Follow guidance provided in Chapter 11 of NUREG/CR-6850 (EPRI 1011989), Volume 2, "Detailed Fire Modeling (Task 11)."

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Example B: Switchgear Room
Slide 2
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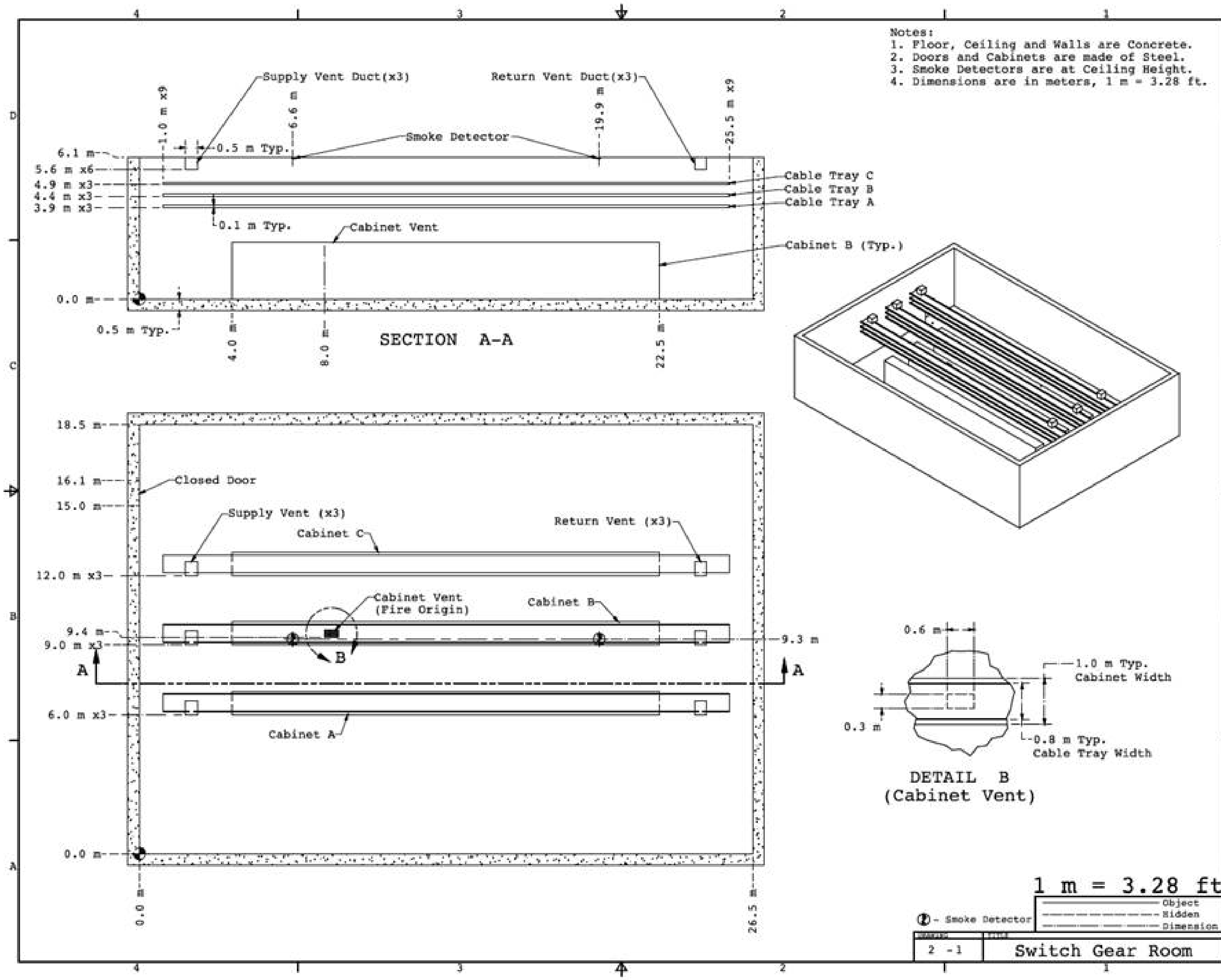
Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Ventilation
- Fire
- Fire Protection Systems
  - None credited for this scenario


Notes:
1. Floor, Ceiling and Walls are Concrete.
2. Doors and Cabinets are made of Steel.
3. Smoke Detectors are at Ceiling Height.
4. Dimensions are in meters, 1 m = 3.28 ft.
Supply Vent Duct(x3)
Return Vent Duct(x3)
Smoke Detector
0.5 m Typ.
1.0 m x9
6.6 m
19.9 m
25.5 m x9
6.1 m
5.6 m x6
4.9 m x3
4.4 m x3
3.9 m x3
Cable Tray C
Cable Tray B
Cable Tray A
0.1 m Typ.
Cabinet Vent
Cabinet B (Typ.)
0.0 m
0.5 m Typ.
4.0 m
8.0 m
22.5 m
SECTION A-A
18.5 m
16.1 m
Closed Door
15.0 m
Supply Vent (x3)
Cabinet C
Return Vent (x3)
12.0 m x3
Cabinet Vent
(Fire Origin)
Cabinet B
9.4 m
9.0 m x3
9.3 m
A
B
6.0 m x3
Cabinet A
0.0 m
26.5 m
0.6 m
1.0 m Typ.
Cabinet Width
0.3 m
0.8 m Typ.
Cable Tray Width
DETAIL B
(Cabinet Vent)
1 m = 3.28 ft
Object
Hidden
Dimension
Smoke Detector
2 -1
Switch Gear Room

Material Properties

Table 3-1. Material properties.

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Source
Brick	0.8	2600	0.8	NUREG-1805, Table 2-3
Concrete	1.6	2400	0.75	NUREG-1805, Table 2-3
Copper	386	8954	0.38	SFPE Handbook, Table B.6
Gypsum	0.17	960	1.1	NUREG-1805, Table 2-3
Plywood	0.12	540	2.5	NUREG-1805, Table 2-3
PVC	0.192	1380	1.289	NUREG/CR-6850, Appendix R
Steel	54	7850	0.465	NUREG-1805, Table 2-3
XLP	0.235	1375	1.390	NUREG/CR-6850, Appendix R

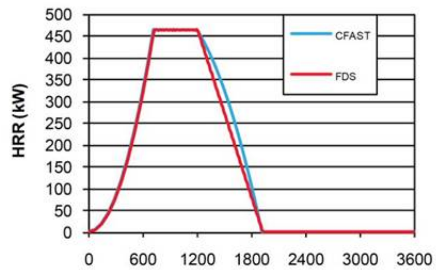
Ventilation

- Design flowrate specified for each of three supply and return registers.
- Normal operation continues during the fire.
- Leakage – often the "leakage area" is the area of the crack under the door.
- Exact supply and exhaust location only important for CFD.
- Zone models usually only consider height of ducts off floor and orientation of the vent.

Fire

Table G-1
Recommended HRR Values for Electrical Fires

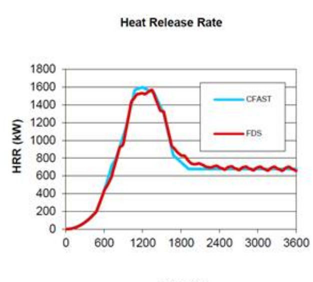
Ignition Source	HRR kW (Btu/s)		Gamma Distribution	
	75th	98th	α	β
Vertical cabinets with qualified cable, fire limited to one cable bundle	69 [1] (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Vertical cabinets with qualified cable, fire in more than one cable bundle	211 [2] (200)	702 [3] (665)	0.7 (0.7)	216 (204)
Vertical cabinets with unqualified cable, fire limited to one cable bundle	90 [4] (85)	211 [2] (200)	1.6 (1.6)	41.5 (39.5)
Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	232 [5] (220)	464 [6] (440)	2.6 (2.6)	67.8 (64.3)
Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	232 [5] (220)	1002 [7] (950)	0.46 (0.45)	386 (366)
Pumps (electrical fires) [8]	69 (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Motors [8]	32 (30)	69 (65)	2.0 (2.0)	11.7 (11.1)
Transient Combustibles [9]	142 (135)	317 (300)	1.8 (1.9)	57.4 (53.7)



HRR taken from Appendix G, NUREG/CR 6850 (EPRI 10111989)

Fire

- Original fire source is specified atop the central cabinet.
- FLASH-CAT model (NUREG/CR-7010, Volume 1) is used to determine the ignition, flame spread and extinction of the cables above the original fire source.



Fire

What is burning?

Cables made of polyethylene (C_2H_4) and polyvinylchloride (C_2H_3Cl).

Assume effective fuel: $C_2H_{3.5}Cl_{0.5}$

Table B-1. Products of combustion for switchgear room cabinet and cable fire.

Parameter	Value	Source
Effective Fuel Formula	$C_2H_{3.5}Cl_{0.5}$	Combination of polyethylene and PVC
Peak HRR	464 kW	NUREG/CR-6850 (EPRI 1011989), App. G
Heat of Combustion	20,900 kJ/kg	*SFPE Handbook,* 4th Ed., Table 3-4.16
CO_2 Yield	1.29 kg/kg	*SFPE Handbook,* 4th Ed., Table 3-4.16
Soot Yield	0.136 kg/kg	*SFPE Handbook,* 4th Ed., Table 3-4.16
CO Yield	0.147 kg/kg	*SFPE Handbook,* 4th Ed., Table 3-4.16
Radiative Fraction	0.49	*SFPE Handbook,* 4th Ed., Table 3-4.16

Step 3. Select Fire Models

- Algebraic Models: FPA algorithm in FIVE provides estimate of HGL temperature within a closed, ventilated compartment. FDTs do not allow for time-dependent HRR. Both FIVE and FDTs can estimate heat flux from a fire to a target.
- Zone Models: Both CFAST and MAGIC include algorithms to estimate the heat flux to and temperature of cable targets.
- CFD: Typical application of FDS. The primary advantage of a CFD model for this fire scenario is that the CFD model can predict local conditions at the specific location of the target cables and adjacent cabinet.

Applicability of Validation

Table B-2. Key parameters and their ranges of applicability to NUREG-1824 (EPRI 1011999).

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{464\ \text{kW}}{(1.2\ \text{kg/m}^3)(1.0\ \text{kJ/kg/K})(293\ \text{K})(0.48^{2.5}\ \text{m}^{2.5})\sqrt{9.8\ \text{m/s}^2}} \cong 2.6$ $\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{1600\ \text{kW}}{(1.2\ \text{kg/m}^3)(1.0\ \text{kJ/kg/K})(293\ \text{K})(1^{2.5}\ \text{m}^{2.5})\sqrt{9.8\ \text{m/s}^2}} \cong 1.4$	0.4 – 2.4	No
Flame Length, L_f, relative to the Ceiling Height, H_c	$\frac{H_f + L_f}{H_c} = \frac{2.4\ \text{m} + 2.1\ \text{m}}{6.1\ \text{m}} \cong 0.7$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 0.48\ \text{m}\,(3.7 \times 2.6^{0.4} - 1.02) \cong 2.1\ \text{m}$	0.2 – 1.0	Yes
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H_c	N/A – Ceiling jet targets are not included in simulation.	1.2 – 1.7	N/A
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\,\dot{m}_{O_2}} = \frac{1{,}600\ \text{kW}}{13{,}100\ \text{kJ/kg} \times 0.4\ \text{kg/s}} \cong 0.31$ (based on peak fire size) $\dot{m}_{O_2} = 0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2\ \text{kg/m}^3 \times 1.4\ \text{m}^3/\text{s} \cong 0.4\ \text{kg/s}$	0.04 – 0.6	Yes
Compartment Aspect Ratio	$\frac{L}{H_c} = \frac{26.5\ \text{m}}{6.1\ \text{m}} \cong 4.3$ $\frac{W}{H_c} = \frac{18.5\ \text{m}}{6.1\ \text{m}} \cong 3.0$	0.6 – 5.7	Yes
Target Distance, r, relative to the Fire Diameter, D	$\frac{r}{D} = \frac{1.5\ \text{m}}{0.48\ \text{m}} \cong 3.1$	2.2 – 5.7	Yes

Step 4. Calculate Fire-Generated Conditions

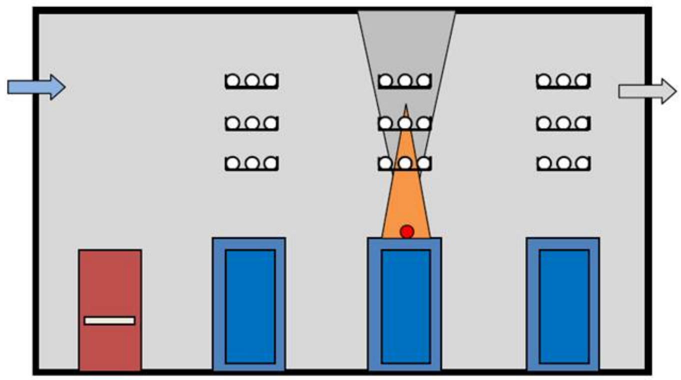


Figure B-2. Schematic diagram of cabinet fire in switchgear room.

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Example B: Switchgear Room

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Step 4. Calculate Fire-Generated Conditions

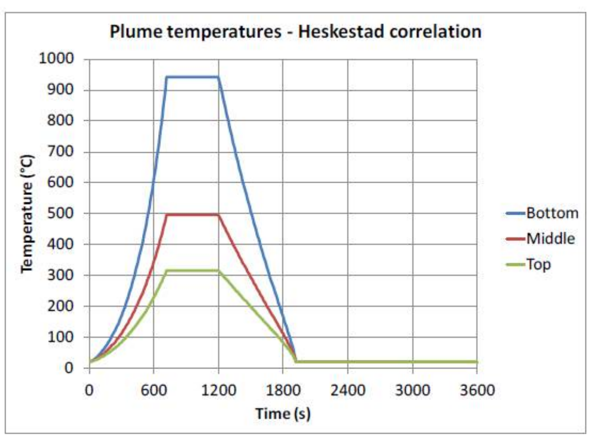

Figure B-3. Plume temperatures at cable trays located above cabinet fire.

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Example B: Switchgear Room

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Step 4. Calculate Fire-Generated Conditions

Table B-3. Summary of input parameters for FPA analysis of switchgear room scenario.

Parameter	Value	Source
Room height (H)	5.2 m	Figure B-1
Room length (L)	26.5 m	Figure B-1
Room effective width (W_e)	18.5 m	Calculation
Room boundary material	Concrete	Figure B-1. See Table 3-1 for properties.
Mech. Ventilation rate ($\dot{V}$)	1.42 m^3/s	From scenario description
Fire elevation (H_f)	2.4 m	From scenario description of cabinet height and vent location.
Ambient temperature (T_a)	20°C	Specified
Fire parameters	See Table B-1	

Temperature: The FPA HGL temperature correlation for mechanically ventilated spaces is expressed in non-dimensional terms as:

$$\frac{\Delta T_g}{T_\infty} = 0.63\left(\frac{\dot{Q}}{\dot{m}c_pT_\infty}\right)^{0.72}\left(\frac{h_kA_T}{\dot{m}c_p}\right)^{-0.36} \quad \text{(B-4)}$$

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Example B: Switchgear Room

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Step 4. Calculate Fire-Generated Conditions

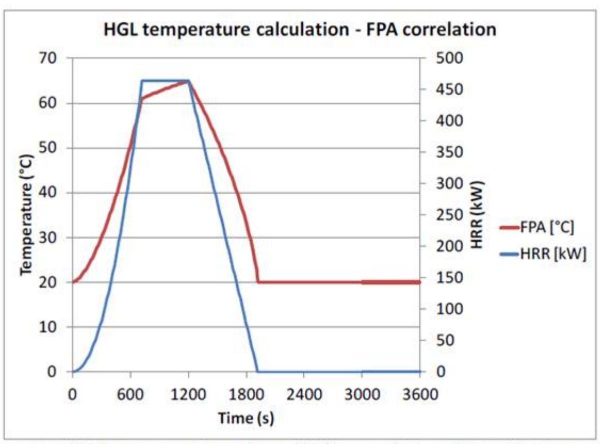

Figure B-4. Average HGL temperature from FPA correlation for switchgear room cabinet fire scenario.

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Example B: Switchgear Room

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CFAST – Smokeview rendering of SWGR fire

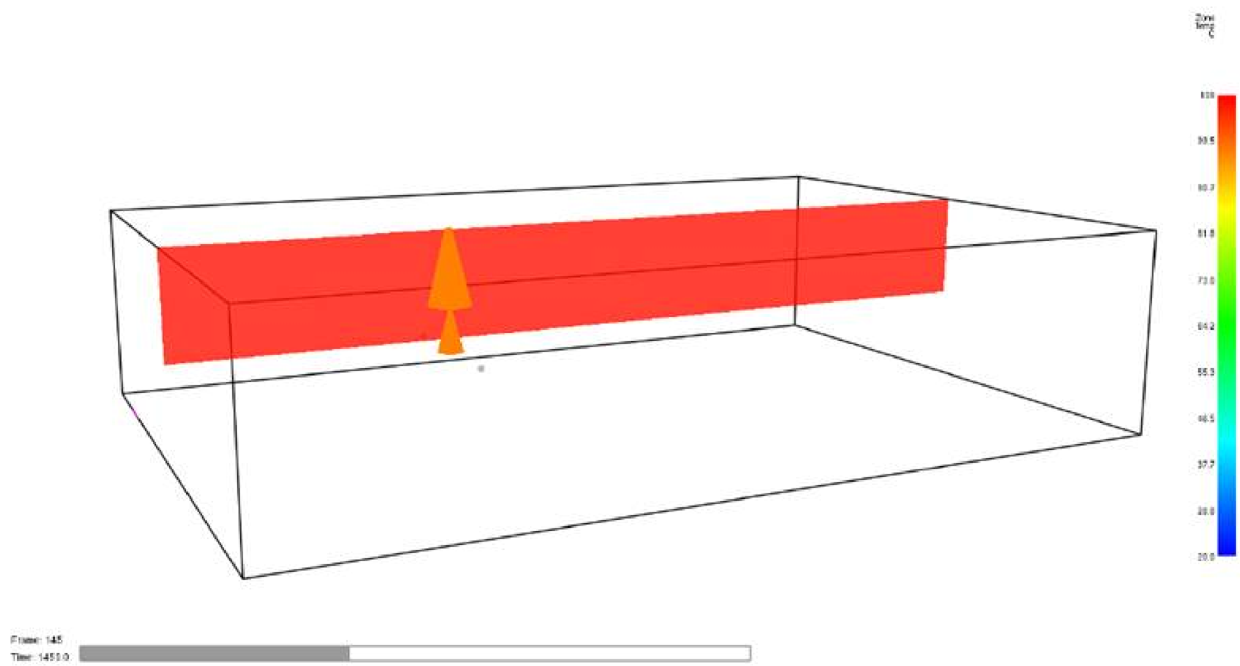

Figure B-5. Average CFAST/Smokeview rendering of Switchgear Room.

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Example B: Switchgear Room

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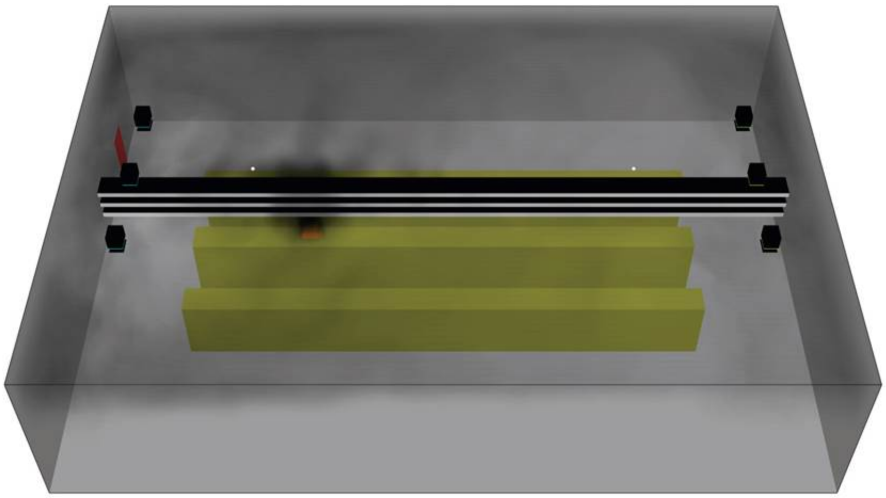
FDS – Smokeview rendering of SWGR fire



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Example B: Switchgear Room

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FDS – Smokeview rendering of SWGR fire

- Initial fire modeled as a "gas burner" on top of the central cabinet with the specified HRR for this type of cabinet
  - Represents a fire exhausting through the upper cabinet vent
- Ignition / growth of cable fire based on FLASH-CAT model

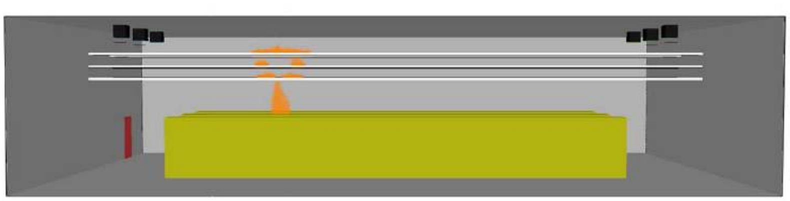

Figure B-11. FDS/Smokeview rendering of the SWGR fire showing localized ignition of extinction of secondary cable fires resulting from initial cabinet fire.

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Example B: Switchgear Room

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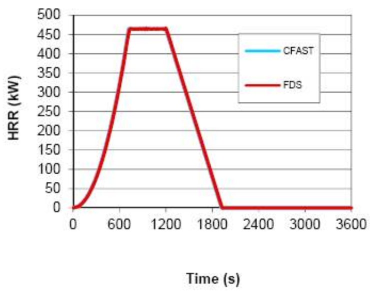
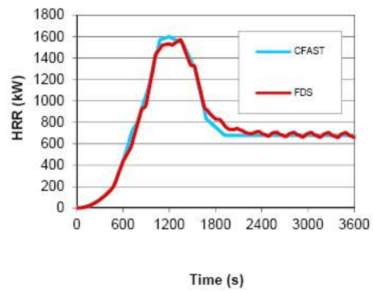
Step 4. Calculate Fire-Generated Conditions



(a) Initial cabinet fire only



(b) Initial cabinet fire and ignited cables

Figure B-12. Heat release rate inputs to CFAST and FDS for a SWGR cabinet fire scenario.

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Example B: Switchgear Room

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Step 4. Calculate Fire-Generated Conditions

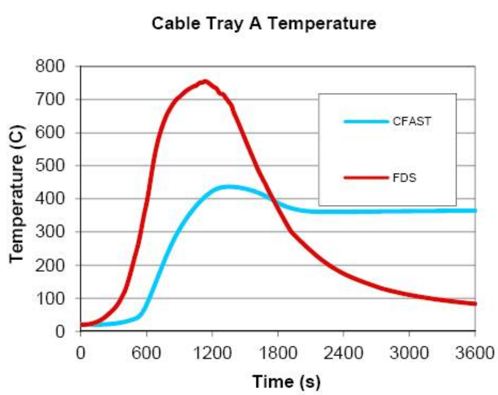

Figure B-13. Estimated temperatures for Cable Tray A directly above the fire source for a SWGR cabinet fire scenario.

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Example B: Switchgear Room

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Step 4. Calculate Fire-Generated Conditions

Table B-5. Estimated time to ignition of lowest cable tray by CFAST for the SWGR cabinet fire.

Ignition Criterion	Time
Gas temperature ≥ 205 °C	270 s
Cable temperature ≥ 205 °C	860 s
Heat flux ≥ 6 kW/m^2	490 s
Heat flux ≥ 15 kW/m^2	740 s
Flame impingement	490 s

Step 4. Calculate Fire-Generated Conditions

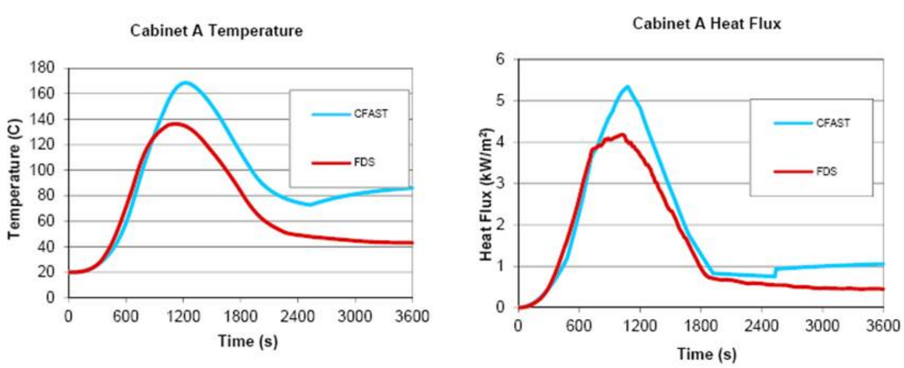

Figure B-14. Estimated temperature and heat flux to a cabinet adjacent to the fire source in a SWGR cabinet fire scenario.

Step 5. Sensitivity and Uncertainty Analysis

Table B-4. Summary of the model predictions of the cabinet fire scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Location	Predicted Value	Critical Value	Probability of Exceeding
Temperature (°C), Initial Value = 20 °C						
CFAST	1.00	0.27	Cable Tray A	335	205	0.937
FDS	1.02	0.13		755	205	1.000
CFAST	1.00	0.27	Cabinet A	168	205	0.177
FDS	1.02	0.13		136	205	0.000
Heat Flux (kW/m²)						
CFAST	0.81	0.47	Cabinet A	5.3	6	0.576
FDS	0.85	0.22		4.2	6	0.159

Step 5. Sensitivity and Uncertainty Analysis

B.5.3 Parameter Uncertainty Propagation

The analysis above has shown that a 98th percentile cabinet fire is likely to damage cables in the tray above the cabinet but unlikely to damage adjacent cabinets. However, for some PRA applications, it may be necessary to calculate the probability of cable damage for *any* fire within the cabinet, not just the 98th percentile fire.

Figure B-15 displays the distribution[17] of peak heat release rates for cabinets with more than one bundle of unqualified cable (NUREG/CR-6850, Appendix G). The analysis described above made use of the 98th percentile fire from this distribution, whose peak is 464 kW.

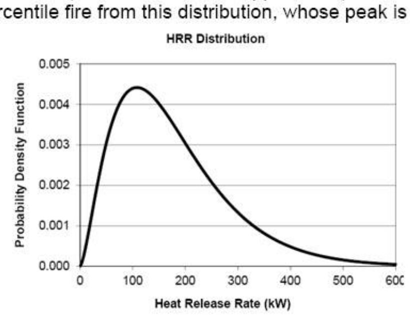

Figure B-15. Distribution of HRR for an electrical cabinet fire.

Step 5. Sensitivity and Uncertainty Analysis

Applying Heskestad's flame height correlation to the entire range of HRR, now taken as a random variable, leads to a distribution of flame height shown in Figure B-16.

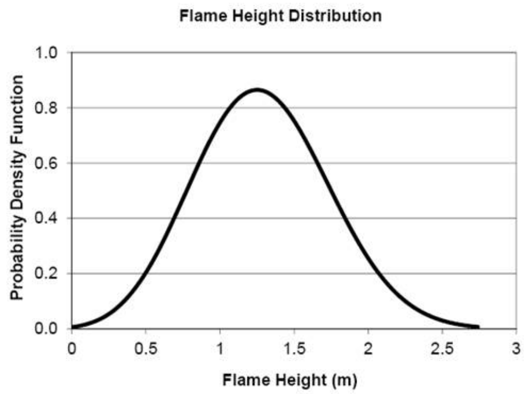

Figure B-16 Distribution of flame heights for the entire range of cabinet fires.

Step 5. Sensitivity and Uncertainty Analysis

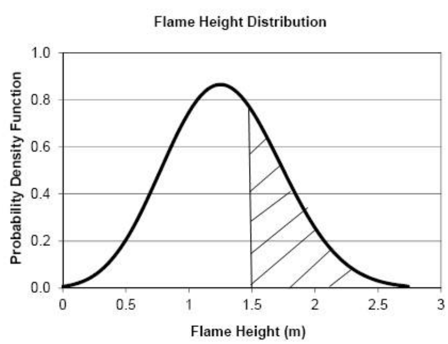

Figure B-16 Distribution of flame heights for the entire range of cabinet fires.

The cable tray is 1.5 m (4.9 ft) above the top of the cabinet. The probability that the flames from a randomly chosen fire will reach the cables is equal to the area beneath the curve in Figure B-16 for flame heights greater than 1.5 m (4.9 ft), or approximately 0.31. Consistent with the guidance in NUREG/CR-6850, this resulting probability can be used as the "severity factor" for the quantification of corresponding fire ignition frequencies.

Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

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Example B: Switchgear Room

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Step 6. Document the Analysis - Conclusions

- Analysis based on 98th percentile HRR in electrical cabinet in 4160 V SWGR used to evaluate potential for damage to overhead cables and adjacent cabinets
  - Screening calculations using algebraic equations for plume temperatures and flame heights demonstrate potential for damage and ignition of overhead cables
  - More detailed analyses with CFAST and FDS demonstrate that the 98th percentile cabinet fire is likely to fail the electrical cables in the lowest cable tray in approximately 10 minutes
  - CFAST analysis also demonstrates a 58% probability of damaging the adjacent cabinet as a result of heat flux, while FDS analysis shows a 16% probability

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Example B: Switchgear Room

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Step 6. Document the Analysis - Conclusions

- Uncertainty analysis based on the HRR distribution for the electrical cabinet shows a 31% probability of flames from the electrical cabinet reaching the lowest cable tray and igniting cables in this tray

- Question: How would you evaluate the probability of the electrical cabinet fire damaging cables in the lowest cable tray rather than igniting them?

3.3 Example C: Lubricating Oil Fire in Pump Compartment

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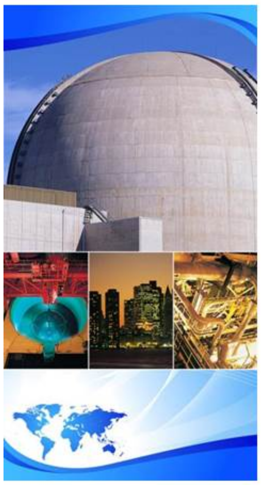

EPRI/NRC-RES Fire PRA Methodology

Module V:
Advanced Fire Modeling
Example C: Lubricating Oil Fire in Pump Compartment

Joint RES/EPRI Fire PRA Workshop
2012
Washington, D.C.

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Step 1. Define Fire Modeling Goals

- Determine whether important safe-shutdown equipment within a pump room will fail, and at what time failure occurs
- Cables in pump room are protected by an Electrical Raceway Fire Barrier System (ERFBS), but there is concern that existing ERFBS will not provide required protection
- Impact of opening door to pump room during fire is also investigated

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Example C: Lube Oil Fire in Pump Room

Slide 2

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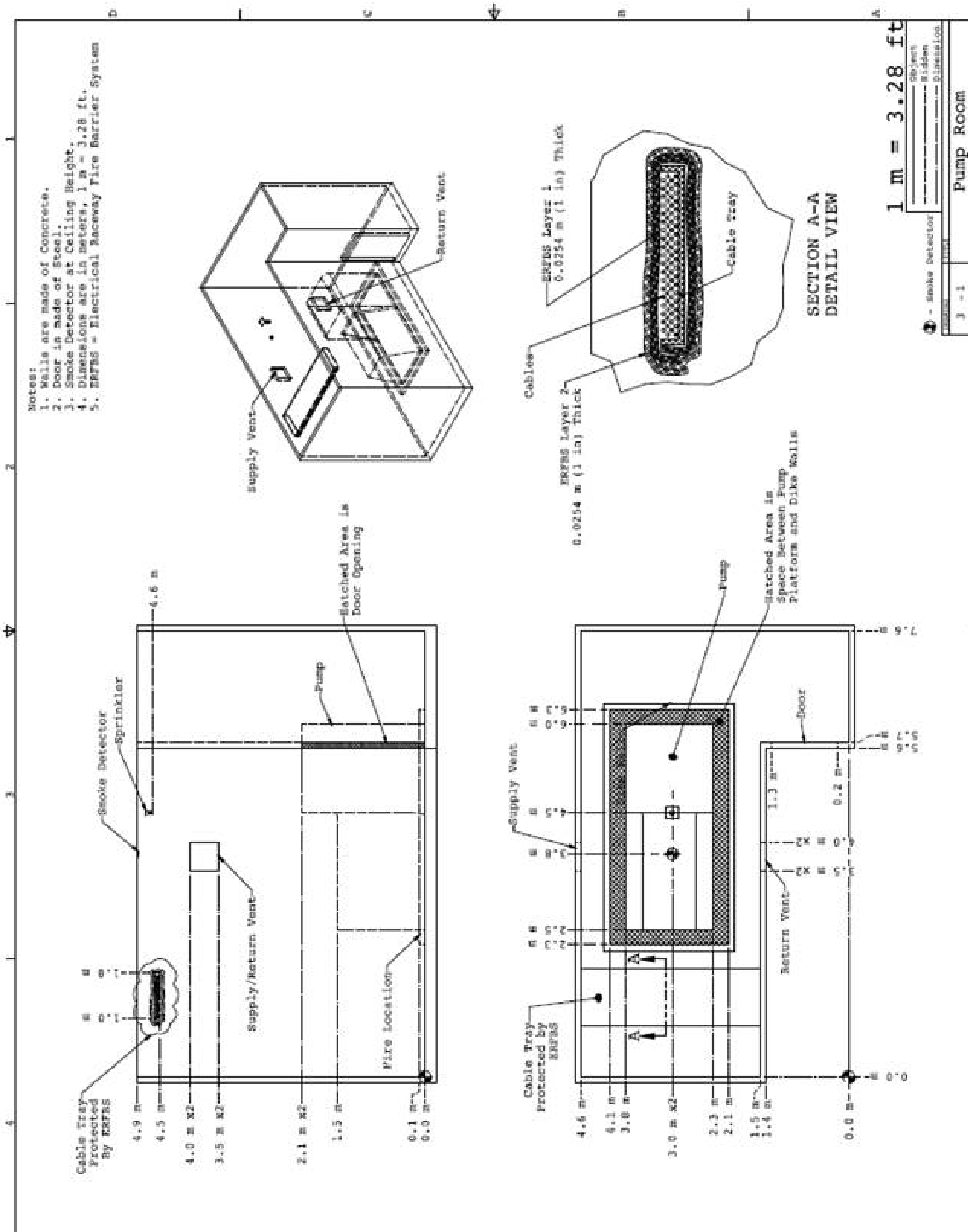
Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
  - Detection / suppression not credited for analyzed scenario
- Ventilation
- Fire


Notes:
1. Walls are made of Concrete.
2. Door is made of Steel.
3. Smoke Detector at Ceiling Height.
4. Dimensions are in meters, 1 m = 3.28 ft.
5. ERFBS = Electrical Raceway Fire Barrier System
Cable Tray Protected By ERFBS
Smoke Detector
Sprinkler
4.9 m
4.5 m
4.0 m x2
3.5 m x2
2.1 m x2
1.5 m
0.1 m
0.0 m
1.0 m
1.8 m
4.6 m
Supply/Return Vent
Pump
Hatched Area is Door Opening
Fire Location
Supply Vent
Return Vent
Cable Tray Protected by ERFBS
4.6 m
4.1 m
3.8 m
3.0 m x2
2.3 m
2.1 m
1.5 m
1.4 m
0.0 m
2.3 m
2.5 m
3.8 m
4.5 m
6.0 m
6.3 m
1.3 m
0.2 m
3.5 m x2
4.0 m x2
5.6 m
5.7 m
7.6 m
Pump
Hatched Area is Space Between Pump Platform and Dike Walls
Return Vent
Door
Cables
ERFBS Layer 1 0.0254 m (1 in) Thick
ERFBS Layer 2 0.0254 m (1 in) Thick
Cable Tray
SECTION A-A DETAIL VIEW
1 m = 3.28 ft
Object
Hidden
Dimension
- Smoke Detector
3 -1
Pump Room

ERFBS and cable insulation data

Table C-1. Data for ERFBS and cable insulation.

Material	Parameter	Value*
Ceramic Fiber Insulation	Thickness (2 layers)	5 cm
	Thermal conductivity	0.06 W/m/K
	Density	128 kg/m^3
	Specific heat	1.07 kJ/kg/K
	Emissivity	0.9
Cable	Diameter	15 mm
	Jacket thickness	2 mm
	Insulation/jacket conductivity	0.192 W/m/K
	Insulation/jacket density	1380 kg/m^3
	Insulation/jacket specific heat	1.289 kJ/kg/K
	Mass per unit length	0.4 kg/m
	Conductor mass fractions	33% PE/PVC, 67% copper

*Source: Product literature (ERFBS) and NUREG/CR-6850 (EPRI 1011989), Volume 2, Appendix R (PVC cable insulation).

Fire

- Fire starts following accidental release of 190 L (50 gal) of lubricating oil; spill contained by dike
  - Oil is mix of hydrocarbons, assumed to be $C_{14}H_{30}$
  - Fuel properties summarized in Table C-2 from NUREG-1805

Table C-2. Data for lubricating oil fire.

Parameter	Value	Source
Effective Fuel Formula	C_nH_{2n+2}	Specified as $C_{14}H_{30}$
Mass burning rate	0.039 kg/s.m^2	NUREG-1805 Table 3-4
Fuel volume	190 L	Specified
Fuel density	760 kg/m^3	NUREG-1805 Table 3-4
Heat of Combustion	46,000 kJ/kg	NUREG-1805 Table 3-4
Heat of Combustion per unit mass of oxygen consumed	13,100 kJ/kg	Huggett 1980, Average value
CO_2 Yield	2.64 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16*
Soot Yield	0.059 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16*
CO Yield	0.019 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16*
Radiative Fraction	0.34	*SFPE Handbook*, 4th ed., Table 3-4.16*
Mass Extinction Coefficient	8700 m^2/kg	Mulholland and Croarkin (2000)

*Material identified as "Hydrocarbon" in SFPE Handbook was used to derive the properties.

Ventilation

- One supply and one return, each 0.5 m^2
- Flow rate is 0.25 m^3/s
- One closed door, 1.1 m by 2.1 m
  - Leakage – 1.3 cm (1/2 in) gap under door
- Door opens after 10 min

Step 3. Select Fire Models

- Algebraic Models: Nothing to estimate HGL temperature in a flashed over compartment. Hand calculation used to evaluate oxygen availability in closed ventilated room
- Zone Models: In flashover situation, zone models transition from 2 zones to 1.
- CFD: Challenging scenario because of under-ventilated conditions

Table C-3. Normalized parameter calculations for the pump room fire scenario.

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{4934 \text{ kW}}{(1.2 \text{ kg/m}^3)(1.0 \text{ kJ/kg/K})(293 \text{ K})(1.9^{2.5} \text{ m}^{2.5})\sqrt{9.8 \text{ m/s}^2}} \cong 0.9$	0.4 – 2.4	Yes
Flame Length, L_f, relative to the Ceiling Height, H_c	$\frac{L_f}{H_c} = \frac{4.8 \text{ m}}{4.9 \text{ m}} \cong 0.99$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 1.9 \text{ m}\,(3.7 \times 0.93^{0.4} - 1.02) \cong 4.8 \text{ m}$	0.2 – 1.0	Yes
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H_c	N/A	1.2 – 1.7	N/A
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\,\dot{m}_{O_2}} = \frac{4934 \text{ kW}}{13{,}100 \text{ kJ/kg} \times 0.07 \text{ kg/s}} \cong 5.5$ $\dot{m}_{O_2} = 0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2 \text{ kg/m}^3 \times 0.25 \text{ m}^3\text{/s} \cong 0.07 \text{ kg/s}$	0.04 – 0.6	No
Equivalence Ratio, φ, as an indicator of the Opening Ventilation	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\,\dot{m}_{O_2}} = \frac{4934 \text{ kW}}{13{,}100 \text{ kJ/kg} \times 0.38 \text{ kg/s}} \cong 0.99$ $\dot{m}_{O_2} = 0.23 \cdot 0.5 A_o \sqrt{h_o} = 0.23 \times 0.5 \times 2.31 \text{ m}^2\,\sqrt{2.1 \text{ m}} \cong 0.38 \text{ kg/s}$	0.04 – 0.6	No
Compartment Aspect Ratios	$\frac{L}{H_c} = \frac{9.4 \text{ m}}{4.9 \text{ m}} \cong 1.9$ $\quad \frac{W}{H_c} = \frac{2.8 \text{ m}}{4.9 \text{ m}} \cong 0.6$	0.6 – 5.7	Yes
Target Distance, r, relative to the Fire Diameter, D	N/A	2.2 – 5.7	N/A

Notes:

(1) The non-dimensional parameters are explained in Table 2-5.

(2) The equivalent fire diameter, $D = \sqrt{4A/\pi}$, where A is the area of the spilled lubricating oil.

C.4.1 Calculation of Oxygen Availability

At the start of the scenario, the mechanical ventilation is operational, the door is closed, and the fire output immediately jumps to the peak heat release rate (HRR) with a total spill area of approximately 2.75 m^2 (29.6 ft^2), as shown in the hatched area of Figure C-1. The peak HRR, $\dot{Q}$, is computed from the fuel mass burning rate, $\dot{m}''$, the heat of combustion, ΔH, and the specified area of the spill, A:

$$\dot{Q} = \dot{m}''\,\Delta H\,A = 0.039 \text{ kg/m}^2\text{/s} \times 46{,}000 \text{ kJ/kg} \times 2.75 \text{ m}^2 \cong 4{,}934 \text{ kW} \qquad \text{(C-1)}$$

The oxygen needed to sustain the fire is calculated from the following equation:

$$\frac{\dot{Q}}{\Delta H_{O_2}} = \frac{4934 \text{ kW}}{13{,}100 \text{ kJ/kg}} = 0.377 \text{ kg/s} \qquad \text{(C-2)}$$

where ΔH_{O_2} is the heat of combustion per unit mass of oxygen consumed. The quantity of oxygen provided by the ventilation system is calculated by multiplying the oxygen content (0.23) by the density and the ventilation rate of the air:

$$0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2 \text{ kg/m}^3 \times 0.25 \text{ m}^3\text{/s} = 0.069 \text{ kg/s} \qquad \text{(C-3)}$$

The oxygen provided by the ventilation system is much lower than the amount needed to sustain the fire. The oxygen initially in the room can provide the additional oxygen needed for combustion for a short time. The available oxygen in the room, calculated from the room dimensions (Table C-4), is:

$$0.23\,\rho_\infty L W H_c = 0.23 \times 1.2\ \text{kg/m}^3 \times (2.81 \times 9.39 \times 4.9)\ \text{m}^3 = 35.7\ \text{kg} \qquad \text{(C-4)}$$

The oxygen initially in the room can sustain the fire for an amount of time equal to the oxygen quantity in the room divided by the consumption rate minus the ventilation supply rate, as shown below:

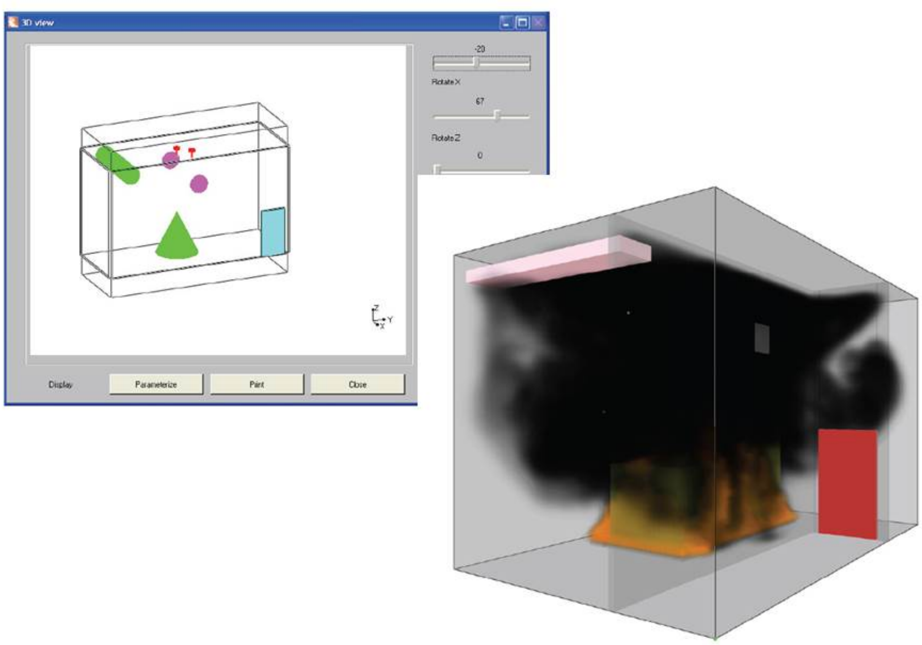
$$\frac{35.7\ \text{kg}}{(0.377\ \text{kg/s}\ - 0.069\ \text{kg/s})} = 116\ \text{s} \qquad \text{(C-5)}$$

Equation C-4 assumes that all the oxygen within the room can be consumed by the fire. This establishes an upper limit to the burning duration before the fire becomes ventilation-limited. After 116 s, the size of the fire is maintained only by the ventilation system and is limited to:

$$0.069\ \text{kg/s} \times 13{,}100\ \text{kJ/kg}\ = 904\ \text{kW} \qquad \text{(C-6)}$$

These results show that the oxygen supply available to the room will only allow a fire of reduced size to burn until the door is opened (under-ventilated condition).

Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions

- HRR of fire reaches peak immediately upon ignition, as shown in Figure C-3
  - Lower oxygen level assumed to be 10%
  - Spill depth calculated to be 0.069 m based on volume and area
  - Fire duration calculated from pool depth, density and burning rate

$$\Delta t = \frac{\delta\,\rho}{\dot{m}''} = \frac{0.069\text{ m} \times 760\text{ kg/m}^3}{0.039\text{ kg/m}^2/\text{s}} \cong 1345\text{ s}\quad(22.4\text{ min}) \qquad \text{(C-7)}$$

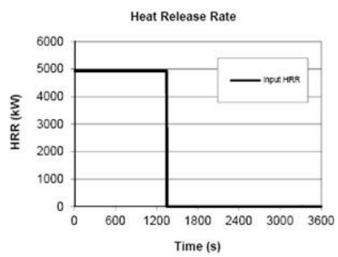


Figure C-3. Heat release rate curve for lubricating oil fire.

Step 4. Calculate Fire-Generated Conditions

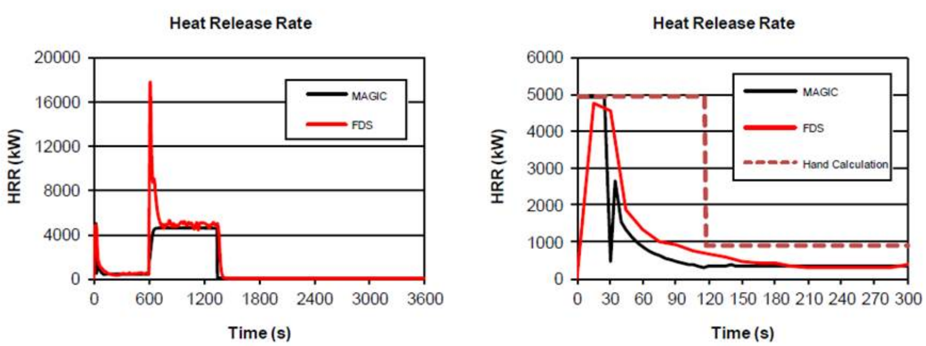
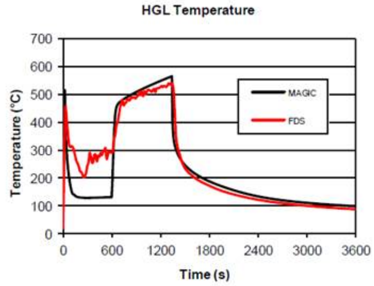
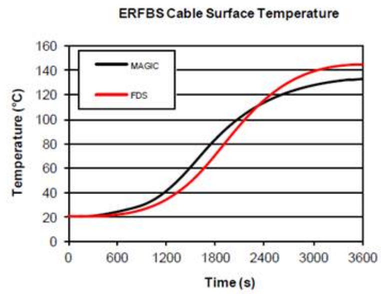
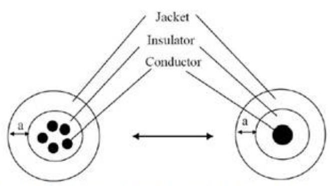


Figure C-9. Heat Release Rate Predicted by Hand Calculations, MAGIC, and FDS for the Pump Room Fire Scenario.

Step 4. Calculate Fire-Generated Conditions

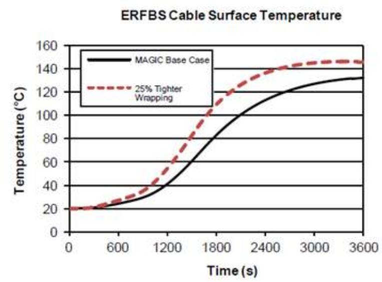






Source: NUREG-1824 (EPRI 1011999), Volume 6, Figure 3-3

Figure C-5. Modeling Multi-Conductor Cables in MAGIC



Step 4. Calculate Fire-Generated Conditions

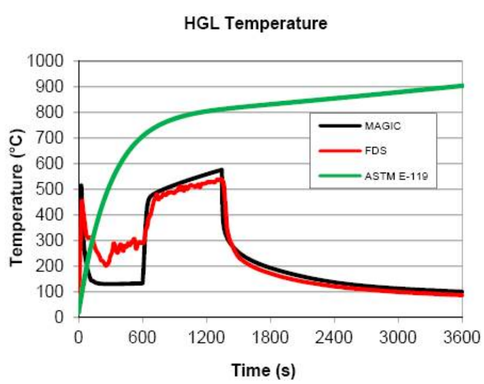


Figure C-11. HGL Temperature Predicted by MAGIC and FDS for the pump room fire scenario.

Step 4. Calculate Fire-Generated Conditions

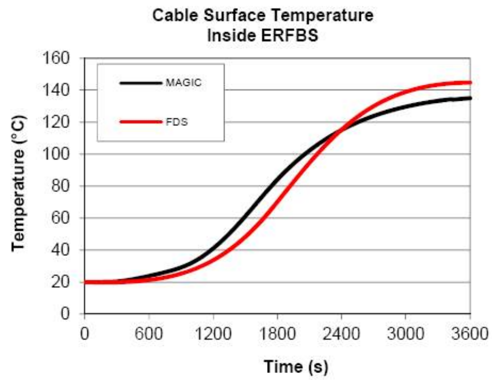


Figure C-12. Cable surface temperature predicted by MAGIC and FDS for the pump room fire scenario.

Step 4. Calculate Fire-Generated Conditions

Comparison to the Standard Fire Endurance Temperature Curve

Figure C-11 includes the standard ASTM E119 temperature curve to which the ERFBS was subjected during its qualification test. The predicted HGL temperatures of both MAGIC and FDS fall below this curve during most of the hour-long simulation, but there is a period near the beginning of the fire where the models' predicted temperatures exceed the standard curve. In order to compare the relative exposure of the ERFBS, it is necessary to consider the integrated incident heat flux corresponding to the model HGL predictions and the ASTM E 119 temperature curve. The integrated heat flux is given by the following formula:

$$q'' = \int_{t_0}^{t_1} \dot{q}''(t)\, dt = \int_{0}^{3600} \sigma(T^4 - T_0^4) + h(T - T_0)\ dt \qquad \text{(C-11)}$$

Applying Eq. (C-11) to each of the HGL temperature curves in Figure C-11 yields values of 346 MJ/m^2 for the ASTM E119 curve and approximately 40 MJ/m^2 for both FDS and MAGIC. This 40 MJ/m^2 exposure corresponds to an approximately 14 min exposure within the standard test furnace. Table C-6 lists the thermal exposure as a function of time in the standard test furnace. It is also significant to note that the maximum predicted exposure temperature remains lower than the maximum exposure temperature that the ERFBS protected raceway was exposed to during the ASTM E119 fire test.

Step 4. Calculate Fire-Generated Conditions

Table C-6. Integrated thermal exposure of an object subjected to the ASTM E119 temperature curve.

Time (min)	Thermal Exposure (MJ/m^2)
5	6
10	23
15	47
20	75
25	104
30	135
35	167
40	200
45	235
50	270
55	307
60	346

Step 5. Sensitivity and Uncertainty Analysis

Table C-5. Summary of the model predictions of the pump room scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Predicted Value	Critical Value	Probability of Exceeding
Cable Temperature (°C)					
MAGIC	1.19	0.27	135	205	0.000
FDS	1.02	0.13	145	205	0.000

Step 5. Sensitivity and Uncertainty Analysis

- Sensitivity of ERFBS construction
  - Comparing Figure C-11 and C-12 shows that ERFBS has large impact on temperature of target cable
  - Additional MAGIC cases run for:
    - Reduced ERFBS thickness by 25% to 0.0375 m
    - Reduced thickness (25%) with increased density to 171 kg/m3 to maintain constant mass per unit area
    - Results plotted in Figure C-13 show that both cases lead to higher cable temperatures

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Example C: Lube Oil Fire in Pump Room

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Step 5. Sensitivity and Uncertainty Analysis

- Sensitivity of ERFBS construction

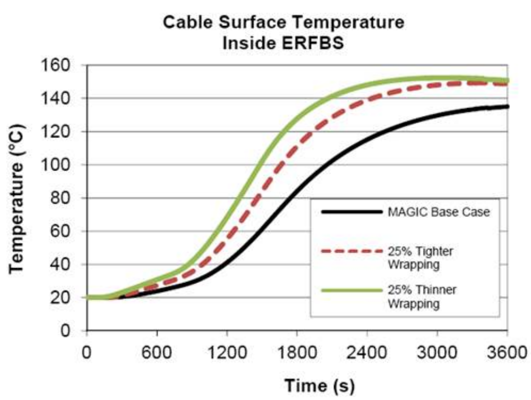

Figure C-13. Cable surface temperature predicted by MAGIC for changes to insulation wrapping.

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Example C: Lube Oil Fire in Pump Room

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Step 5. Sensitivity and Uncertainty Analysis

- Sensitivity of door size
  - Equivalence ratio falls outside of validation range
  - As sensitivity study, MAGIC run with door area doubled
    - This brings equivalence ratio within validation range when doors open

$$\dot{m}_{O_2} = 0.23 \cdot 0.5 A_o \sqrt{h_o} = 0.23 \times 0.5 \times 4.62\ \mathrm{m}^2\ \sqrt{2.1\ \mathrm{m}} \cong 0.77\ \mathrm{kg/s} \qquad \text{(C-12)}$$

$$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\ \dot{m}_{O_2}} = \frac{4934\ \mathrm{kW}}{13{,}100\ \mathrm{kJ/kg} \times 0.77\ \mathrm{kg/s}} \cong 0.5 \qquad \text{(C-13)}$$

  - Figure C-14 shows temperature comparisons for base case and case with double-wide doors
    - Plots show results are very similar, indicating that door size does not significantly affect results
    - Consistent with experimental data that scenario with equivalence ratio near unity produces highest enclosure temperatures

Step 5. Sensitivity and Uncertainty Analysis

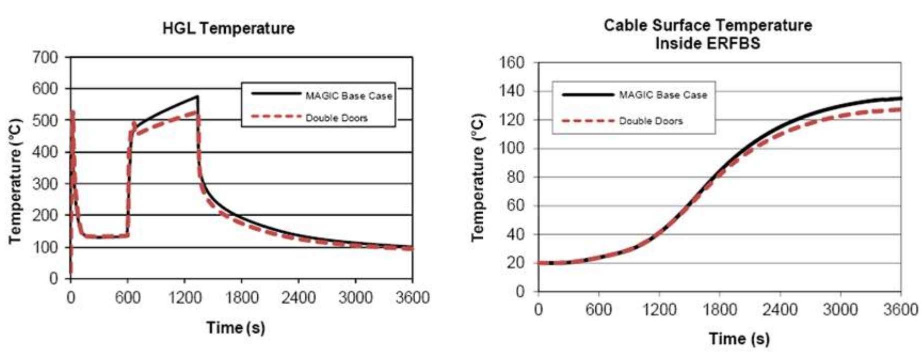

Figure C-14. Temperature predicted by MAGIC for increased door size.

Step 5. Sensitivity and Uncertainty Analysis

- Sensitivity of HRR profile
  - Ventilation-limited HRR may also cause reduction in fuel mass loss rate, such that fuel remains until door is opened
  - This concept is illustrated in Figure C-15

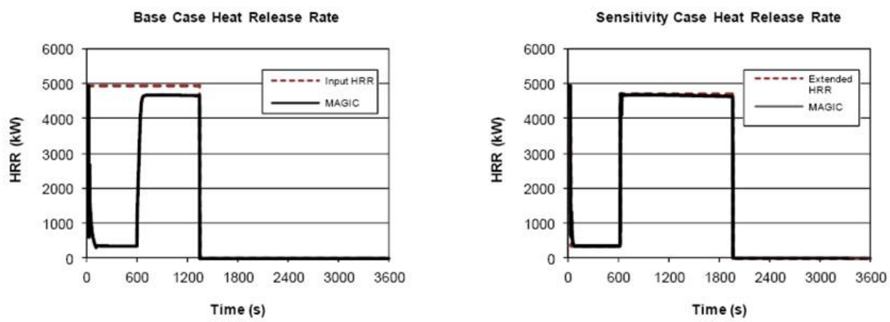

Figure C-15. HRR for base case and HRR sensitivity case.

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Example C: Lube Oil Fire in Pump Room

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Step 5. Sensitivity and Uncertainty Analysis

- With extended HRR shown in Figure C-15, gas and cable temperatures increase as shown in Figure C-16
  - Cable temperature now close to failure temperature of 205C so sensitivity of thermal properties becomes more important

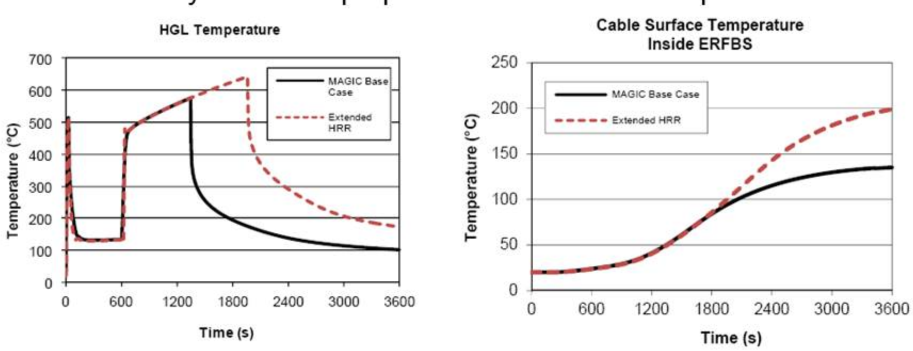

Figure C-16. Temperature for base case and HRR sensitivity case.

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Example C: Lube Oil Fire in Pump Room

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Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

Step 6. Document the Analysis

- Conclusions (C.6)
  - Analysis considers potential for relatively large lubricating oil spill fire in small enclosure to damage cable tray with ERFBS
  - Algebraic calculations, MAGIC and FDS all used to evaluate fire conditions within the enclosure
  - MAGIC and FDS also used to calculate thermal response of cables to calculated fire conditions
  - Based on assumed spill area and lube oil burning characteristics, a 5 MW fire is calculated
    - However, ventilation limited burning rate of about 1 MW calculated based on mechanical ventilation rate until door opened at 10 minutes
    - Doors to such rooms should not be opened until firefighters are prepared to suppress fire that will increase with added ventilation

Step 6. Document the Analysis

- Two strategies used to assess integrity of ERFBS
  - Integrated heat flux calculation performed to demonstrate that thermal exposure to ERFBS is approximately 10 times greater in standard fire endurance test than is predicted by MAGIC or FDS
  - Direct calculation of heat penetration through insulating blankets using blanket and cable thermal properties
    - Both models predict cable temperatures below critical values
- Base case for both approaches show ERFBS is expected to prevent cables from reaching critical temperature as a result of a fire involving spilled lubricating oil
  - However, sensitivity study of extended HRR for underventilated conditions shows results could change
- Further analysis of ERFBS thermal properties warranted

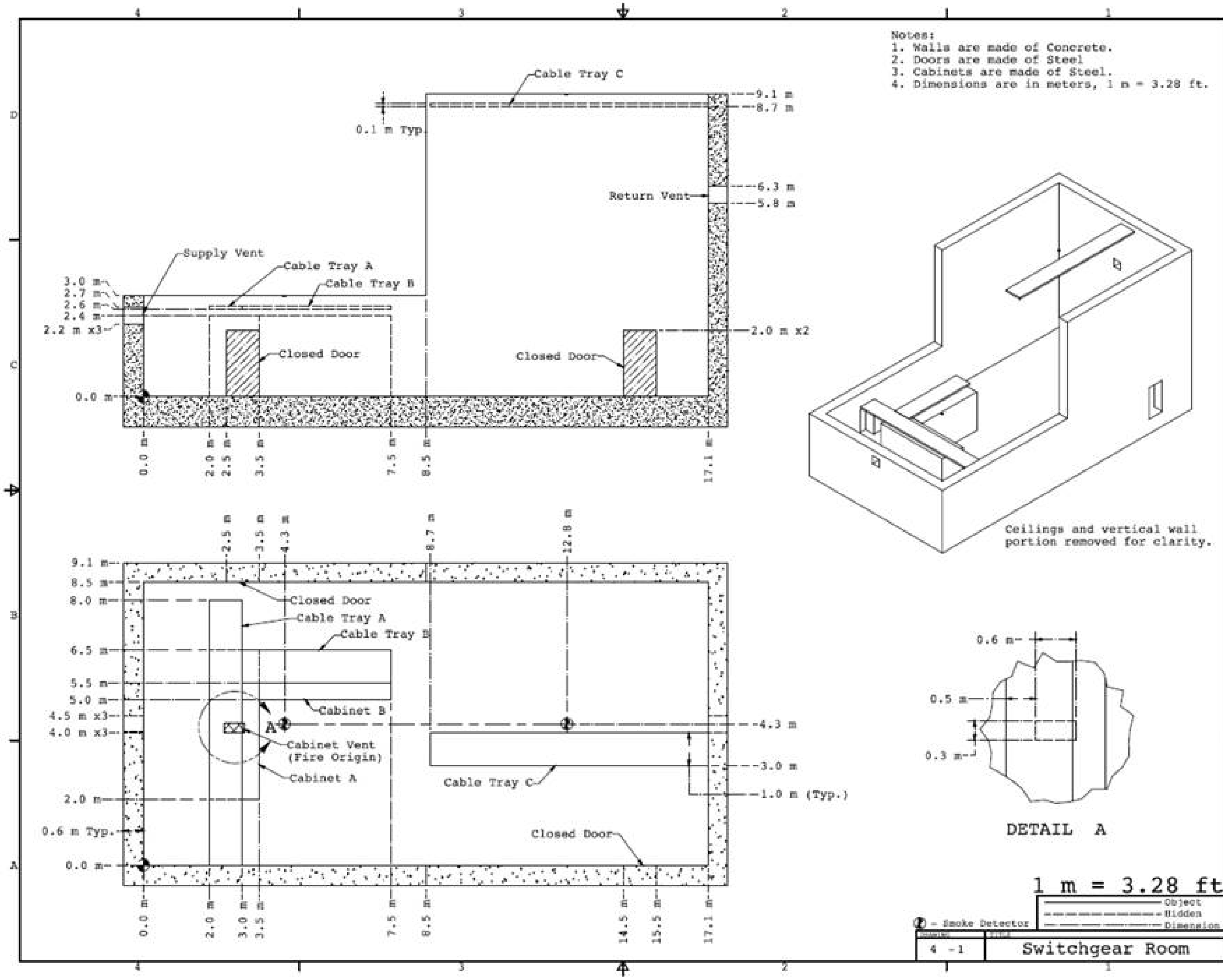
3.4 Example D: MCC Fire in Switchgear Room

Step 1. Define Fire Modeling Goals

- Determine if a fire in the Motor Control Center damages nearby cables and cabinets in a switchgear room
- Define damage to both cables and cabinets as a surface temperature of 400 ºC

Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire


Notes:
1. Walls are made of Concrete.
2. Doors are made of Steel
3. Cabinets are made of Steel.
4. Dimensions are in meters, 1 m = 3.28 ft.
Cable Tray C
9.1 m
8.7 m
0.1 m Typ.
Return Vent
6.3 m
5.8 m
Supply Vent
Cable Tray A
Cable Tray B
3.0 m
2.7 m
2.6 m
2.4 m
2.2 m x3
Closed Door
2.0 m x2
0.0 m
2.0 m
2.5 m
3.5 m
7.5 m
8.5 m
17.1 m
4.3 m
12.8 m
8.0 m
6.5 m
5.5 m
5.0 m
4.5 m x3
4.0 m x3
Cabinet B
Cabinet Vent
(Fire Origin)
Cabinet A
Cable Tray C
3.0 m
1.0 m (Typ.)
0.6 m Typ.
14.5 m
15.5 m
Ceilings and vertical wall
portion removed for clarity.
0.6 m
0.5 m
0.3 m
DETAIL A
1 m = 3.28 ft
Object
Hidden
Dimension
= Smoke Detector
4 -1
Switchgear Room

Material Properties

Table 3-1. Material Properties

Material	Thermal Conductivity (W/m/K)	Density (kg/m^3)	Specific Heat (kJ/kg/K)	Source
Brick	0.8	2600	0.8	NUREG-1805, Table 2-3
Concrete	1.6	2400	0.75	NUREG-1805, Table 2-3
Copper	386	8954	0.38	SFPE Handbook, Table B.6
Gypsum	0.17	960	1.1	NUREG-1805, Table 2-3
Plywood	0.12	540	2.5	NUREG-1805, Table 2-3
PVC	0.192	1380	1.289	NUREG/CR-6850, Appendix R
Steel	54	7850	0.465	NUREG-1805, Table 2-3
XLP	0.235	1375	1.390	NUREG/CR-6850, Appendix R

Material Properties

Cables: The cable trays are filled with cross-linked polyethylene (XPE or XLPE) insulated cables with a neoprene jacket. These are considered thermoset (TS) materials. These cables have a diameter of approximately 1.5 cm (0.6 in), a jacket thickness of approximately 2 mm (0.79 in), 3 conductors, and a mass per unit length of 0.4 kg/m. Tray locations are shown in the compartment drawing. These particular cables have been shown to fail when the temperature just underneath the jacket reaches approximately 400 °C (750 °F) (NUREG/CR-6931, Vol. 2, Table 5.10[18]). A second criterion for damage is exposure to a heat flux that exceeds 11 kW/m^2 (NUREG-1805, Appendix A, Section A.5.4). Damage criteria for the adjacent cabinet are the same as for the cable trays because the cables within the cabinet are subjected to similar thermal exposure conditions as the steel cabinet housing.

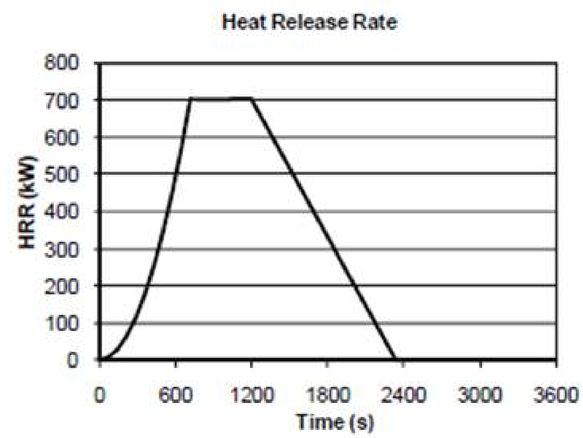
Ventilation

- 3 Air Changes Per Hour (ACH)
- Doors closed
- Compartment volume is 882 m^3
- Volume flow rate is 0.735 m^3/s

Fire

Table G-1
Recommended HRR Values for Electrical Fires

Ignition Source	HRR kW (Btu/s)		Gamma Distribution	
	75th	98th	α	β
Vertical cabinets with qualified cable, fire limited to one cable bundle	69 [1] (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Vertical cabinets with qualified cable, fire in more than one cable bundle	211 [2] (200)	702 [3] (665)	0.7 (0.7)	216 (204)
Vertical cabinets with unqualified cable, fire limited to one cable bundle	90 [4] (85)	211 [2] (200)	1.6 (1.6)	41.5 (39.5)
Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	232 [5] (220)	464 [6] (440)	2.6 (2.6)	67.8 (64.3)
Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	232 [5] (220)	1002 [7] (950)	0.46 (0.45)	386 (366)
Pumps (electrical fires) [8]	69 (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Motors [8]	32 (30)	69 (65)	2.0 (2.0)	11.7 (11.1)
Transient Combustibles [9]	142 (135)	317 (300)	1.8 (1.9)	57.4 (53.7)



HRR taken from Appendix G, NUREG/CR 6850 (EPRI 10111989)

Fire

What is burning?

Cables made of polyethylene (C_2H_4) and neoprene (C_4H_5Cl)

Assume effective fuel: $C_3H_{4.5}Cl_{0.5}$

Table D-1. Products of combustion for the MCC fire.

Parameter	Value	Source
Effective Fuel Formula	$C_3H_{4.5}Cl_{0.5}$	Combination of polyethylene and neoprene
Peak HRR	702 kW	NUREG/CR-6850 (EPRI 1011989), App. G
Time to reach peak HRR	720 s	NUREG/CR-6850 (EPRI 1011989), App. G
Heat of Combustion	10,300 kJ/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
CO_2 Yield	0.63 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
Soot Yield	0.175 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
CO Yield	0.082 kg/kg	*SFPE Handbook*, 4th Ed., Table 3-4.16
Radiative Fraction	0.53	*SFPE Handbook*, 4th Ed., Table 3-4.16

Step 3. Select Fire Models

- Algebraic Models: FDTs can be used for the heat flux calculation. Non-uniform ceiling height a problem for HGL calculations in both FDTs and FIVE-rev1.
- Zone Models: Non-uniform ceiling is a problem. However, CFAST can model the ceiling in terms of a non-uniform cross-section or as adjacent compartments
- CFD: No particular issues for FDS. Two level ceiling is not a problem. May want to use multiple grids.

Table D-2. Normalized parameter calculations for the MCC fire scenario.

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}}$ $= \frac{702\ \mathrm{kW}}{(1.2\ \mathrm{kg/m^3})(1.0\ \mathrm{kJ/kg/K})(293\ \mathrm{K})(0.5^{2.5}\ \mathrm{m^{2.5}})\sqrt{9.8\ \mathrm{m/s^2}}} \cong 3.6$	0.4 – 2.4	No
Flame Length, $H_f + L_f$, relative to the Ceiling Height, H_c	$\frac{H_f + L_f}{H_c} = \frac{2.4\ \mathrm{m} + 2.5\ \mathrm{m}}{3.0\ \mathrm{m}} \cong 1.6$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 0.48\ \mathrm{m}\,(3.7 \times 3.6^{0.4} - 1.02) \cong 2.5\ \mathrm{m}$	0.2 – 1.0	No
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H_c	N/A – There are no targets like sprinklers or smoke detectors under consideration in this example.	1.2 – 1.7	N/A
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\,\dot{m}_{O_2}} = \frac{702\ \mathrm{kW}}{13{,}100\ \mathrm{kJ/kg} \times 0.2\ \mathrm{kg/s}} \cong 0.3$ $\dot{m}_{O_2} = 0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2\ \mathrm{kg/m^3} \times 0.735\ \mathrm{m^3/s} \cong 0.2\ \mathrm{kg/s}$	0.04 – 0.6	Yes
Compartment Aspect Ratio (Lower | Upper)	$\frac{L}{H_c} = \frac{8.5\ \mathrm{m}}{3.0\ \mathrm{m}} \cong 2.8$; $\frac{W}{H_c} = \frac{8.5\ \mathrm{m}}{3.0\ \mathrm{m}} \cong 2.8$ | $\frac{L}{H_c} = \frac{8.6\ \mathrm{m}}{9.1\ \mathrm{m}} \cong 0.9$; $\frac{W}{H_c} = \frac{8.5\ \mathrm{m}}{9.1\ \mathrm{m}} \cong 0.9$	0.6 – 5.7	Yes
Target Distance, r, relative to the Fire Diameter, D	$\frac{r}{D} = \frac{1.1\ \mathrm{m}}{0.5\ \mathrm{m}} \cong 2.2$	2.2 – 5.7	Yes

Step 4. Calculate Fire-Generated Conditions

Heat flux to adjacent cabinet using point source method

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi r^2} = \frac{0.53 \times 702\ \text{kW}}{4\pi \times (1.1\ m)^2} \cong 24.5\ \text{kW/m}^2$$

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Example D: MCR Fire in Switchgear Room

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CFAST – Smokeview rendering of SWGR fire

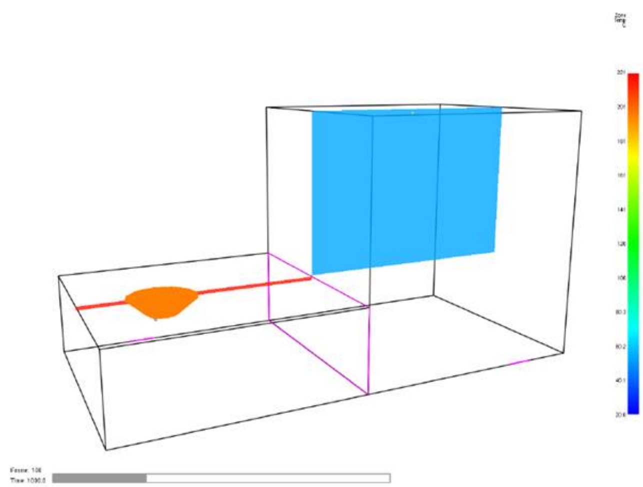

Figure D-4. Geometry of two-height ceiling Switchgear Room as modeled in CFAST.

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Example D: MCR Fire in Switchgear Room

Slide 15

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FDS – Smokeview rendering of SWGR fire

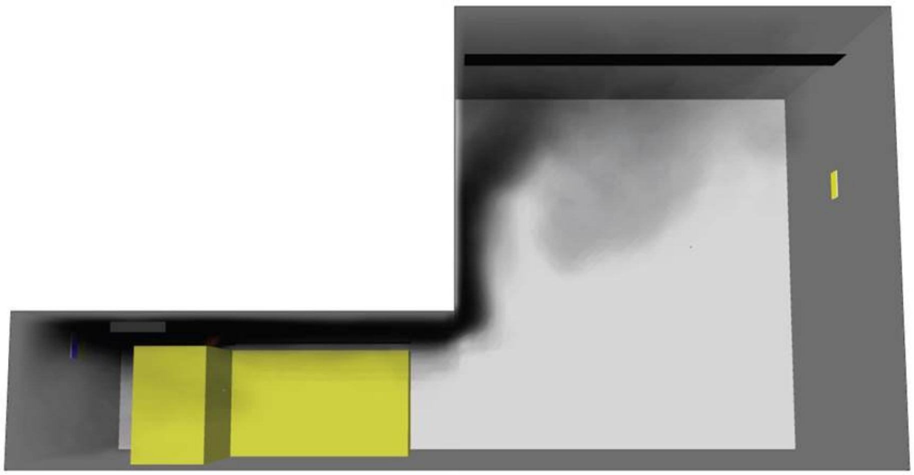


Figure D-5. FDS/Smokeview representation of the MCC/Switchgear Room scenario.

Step 4. Calculate Fire-Generated Conditions

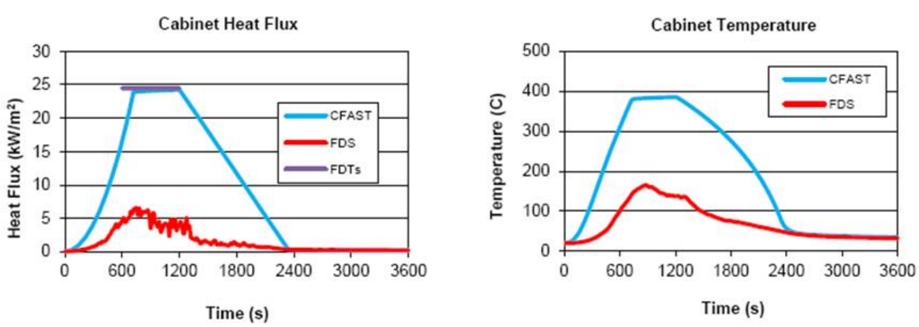
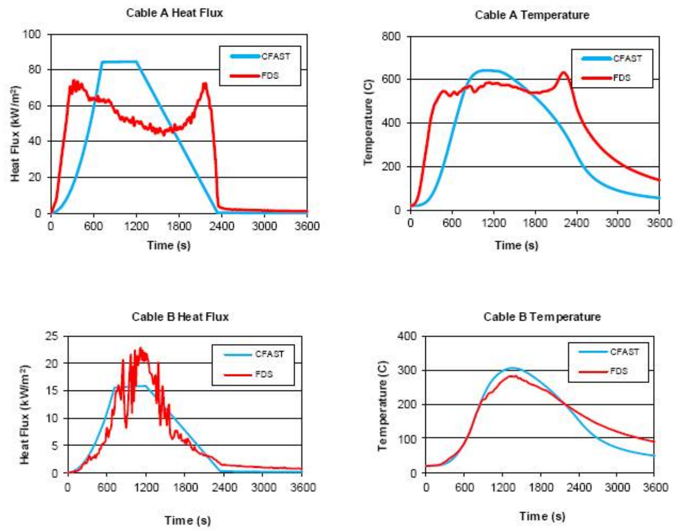


Figure D-10. Heat flux and temperature predictions for the adjacent cabinet.

Step 4. Calculate Fire-Generated Conditions



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Example D: MCR Fire in Switchgear Room

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Step 4. Calculate Fire-Generated Conditions

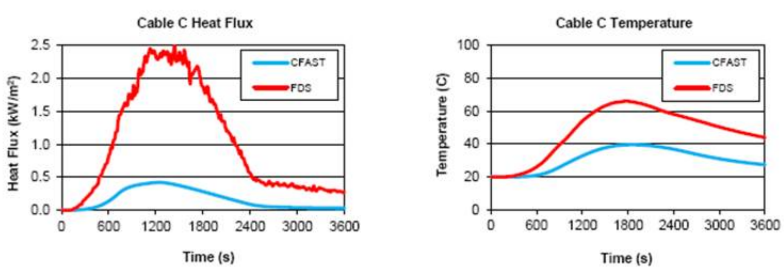

Figure D-11. Summary of the cable predictions for the MCC/Switchgear Room.

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Example D: MCR Fire in Switchgear Room

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Step 5. Sensitivity and Uncertainty Analysis

Table D-3. Summary of the model predictions of the MCC fire scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Target	Predicted Value	Critical Value	Probability of Exceeding
Surface Temperature (°C), Initial Value = 20 °C						
CFAST	1	0.27	Cabinet	390	400	0.460
FDS	1.02	0.13		170	400	0.000*
CFAST	1	0.27	Cable A	705	400	0.950
FDS	1.02	0.13		620	400	0.997
CFAST	1	0.27	Cable B	305	400	0.112
FDS	1.02	0.13		280	400	0.000
CFAST	1	0.27	Cable C	40	400	0.000
FDS	1.02	0.13		65	400	0.000
Heat Flux (kW/m^2)						
CFAST	0.81	0.47	Cabinet	24.3	11	0.911
FDS	0.85	0.22		6.0	11	0.006*
CFAST	0.81	0.47	Cable A	104	11	0.974
FDS	0.85	0.22		75.0	11	1.000
CFAST	0.81	0.47	Cable B	15.8	11	0.823
FDS	0.85	0.22		23.0	11	0.997
CFAST	0.81	0.47	Cable C	0.2	11	0.000
FDS	0.85	0.22		2.5	11	0.000

* These results require closer scrutiny. See discussion below.

Step 5. Sensitivity and Uncertainty Analysis

D.5.2 Cable Damage Based on Temperature Alone

The predicted cable temperatures for the three trays are shown in Figure D-11. CFAST and FDS estimate cable temperatures using the THIEF methodology (NUREG/CR-6931, Vol. 3). Both models predict that the cables in Tray A are likely to fail.

Neither model predicts that the cables in Tray B will reach the failure temperature of 400 °C (750 °F), but the CFAST prediction of 300 °C (572 °F) suggests that there is a 9% probability that the cable temperature could be as high as the critical value. Note that these predictions are sensitive to the exact location of the target cable within the tray, its view of the fire, and the HGL temperature. In this case, the cables in Tray B are heated primarily by convection and radiation from the HGL. Given that the HRR is the most important parameter controlling the temperature of the HGL, how much would the HRR have to increase to increase the CFAST prediction from 300 °C (572 °F) to 400 °C (752 °F)? Table 4-3 indicates that the rise in the HGL temperature is proportional to the HRR to the 2/3 power. Following the methodology in Section 4.4.1, in order to increase the predicted HGL temperature by 100 °C (212 °F), the peak HRR, $\dot{Q}$, must increase by approximately:

$$\Delta\dot{Q} = \frac{3}{2}\dot{Q}\frac{\Delta T}{T - T_0} = \frac{3}{2}\,702\ \text{kW} \times \frac{100\ ^\circ\text{C}}{300\ ^\circ\text{C} - 20\ ^\circ\text{C}} \cong 376\ \text{kW} \qquad \text{(D-3)}$$

Step 6. Document the Analysis

D.6 Conclusion

The purpose of the calculations in this example is to predict if and when various components within a compartment will become damaged due to a fire in the MCC. The fire model analyses performed for this scenario indicate that the fire would damage the cables in Tray A because all the models (FDT^s, CFAST, FDS) predict that the flames would directly impinge on the cables themselves.

- CFAST and FDS predict that the cables in Tray B are likely to be damaged based on the heat flux criterion. However, neither model predicts that the interior cable temperatures are likely to be high enough to cause failure.
- Neither FDS nor CFAST predicts that the cables in Tray C would be damaged.
- A point source heat flux analysis indicates that the adjacent cabinet housing would be exposed to a heat flux that would cause damage. Even though FDS does not predict damage, its predictions of heat flux to surfaces very near the adjacent cabinet are sufficiently high to cast doubt on the conclusion that the cabinet would not be damaged. Small changes in the positions of various obstructions could easily change the predicted heat flux by an order of magnitude. Even though the point source method tends to over-predict the heat flux to targets close to the fire, there is too much uncertainty in the geometric configuration to accept the validity of the more detailed calculation.

3.5 Example E: Transient Fire in Cable Spreading Room

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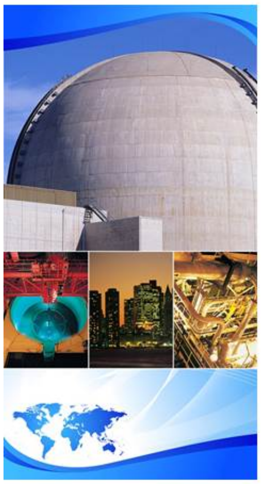

EPRI/NRC-RES Fire PRA Methodology

Module 5: Advanced Fire Modeling
Example E: Transient Fire in Cable Spreading Room

Joint RES/EPRI Fire PRA Workshop
2012
Washington, D.C.

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Step 1. Define Fire Modeling Goals

- Estimate the impact on safe-shutdown cables due to a fire in a trash bin inside a Cable Spreading Room.
- Transient combustibles have been identified as a possible source of fire that may impact the cables. The purpose of the calculation is to analyze this condition and determine whether the cable targets will fail, and, if so, at what time failure occurs.
- Follow guidance provided in Chapter 11 of NUREG/CR-6850 (EPRI 1011989), Volume 2, “Detailed Fire Modeling (Task 11).”

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Example E: Cable Spreading Room Fires

Slide 2

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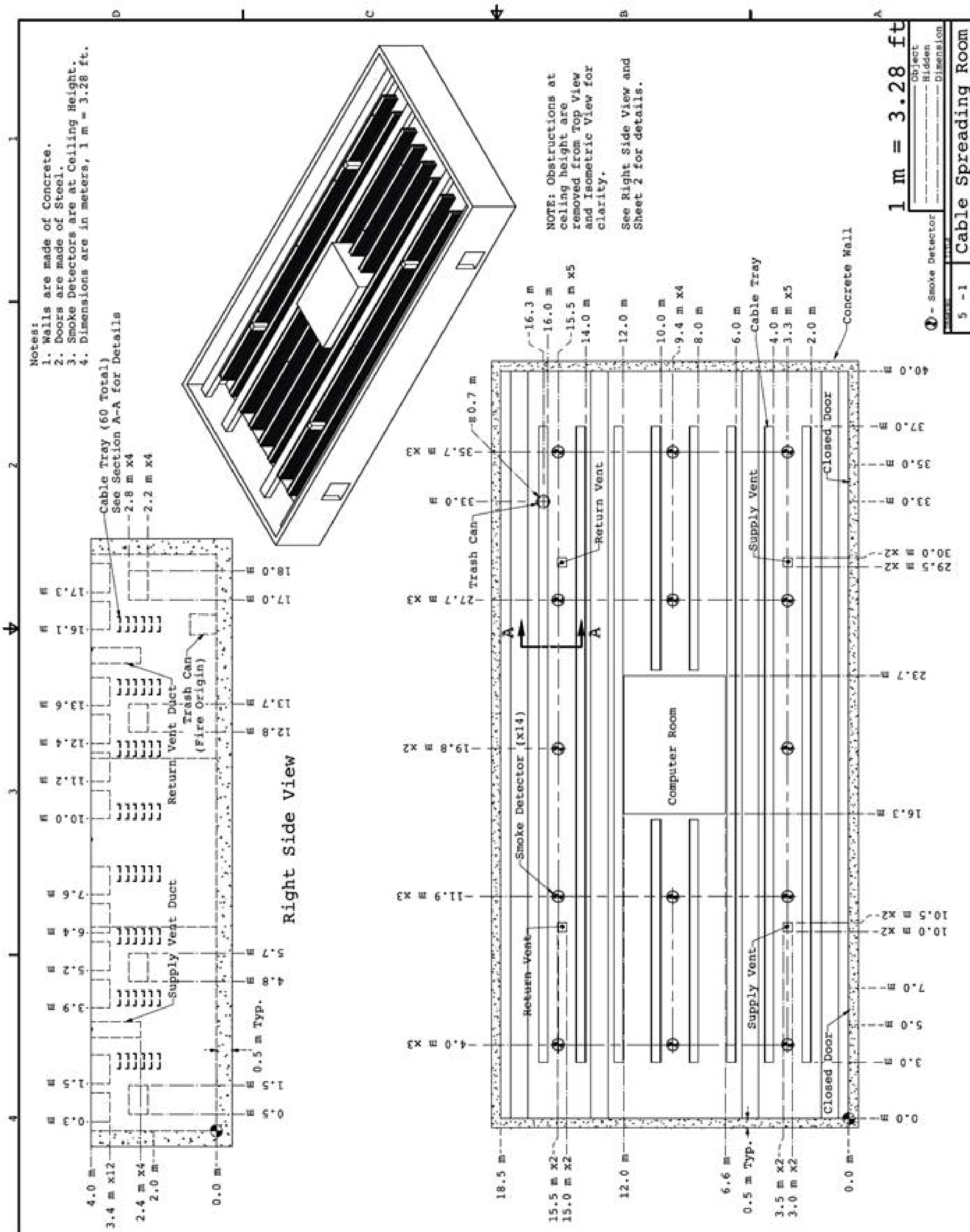
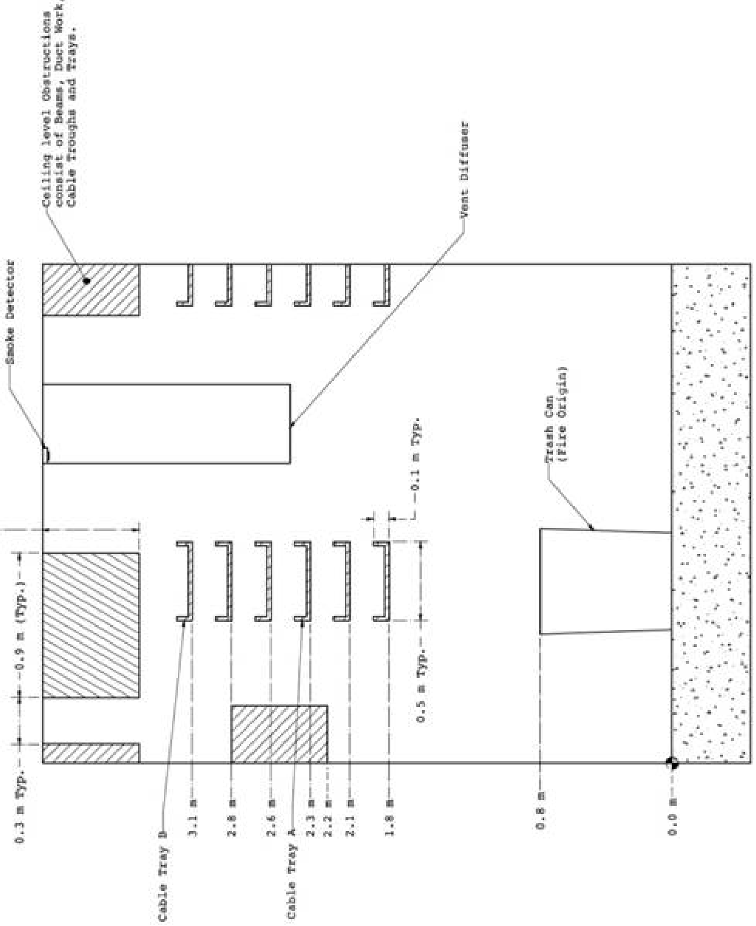
Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire



Notes:
1. Walls are made of Concrete.
2. Doors are made of Steel.
3. Smoke Detectors are at Ceiling Height.
4. Dimensions are in meters, 1 m = 3.28 ft.
Cable Tray (60 Total)
See Section A-A for Details
Right Side View
Return Vent Duct
Supply Vent Duct
Trash Can
(Fire Origin)
0.5 m Typ.
NOTE: Obstructions at ceiling height are removed from Top View and Isometric View for clarity.
See Right Side View and Sheet 2 for details.
Smoke Detector (x14)
Return Vent
Supply Vent
Computer Room
Closed Door
Cable Tray
Concrete Wall
Trash Can
1 m = 3.28 ft
Smoke Detector
Object
Hidden
Dimension
Cable Spreading Room
5 -1


Ceiling level Obstructions consist of Beams, Duct Work, Cable Troughs and Trays.
Smoke Detector
Vent Diffuser
0.6 m (Typ.)
0.9 m (Typ.)
0.3 m Typ.
0.1 m Typ.
0.5 m Typ.
Trash Can (Fire Origin)
Cable Tray B
Cable Tray A
3.1 m
2.8 m
2.6 m
2.3 m
2.2 m
2.1 m
1.8 m
0.8 m
0.0 m

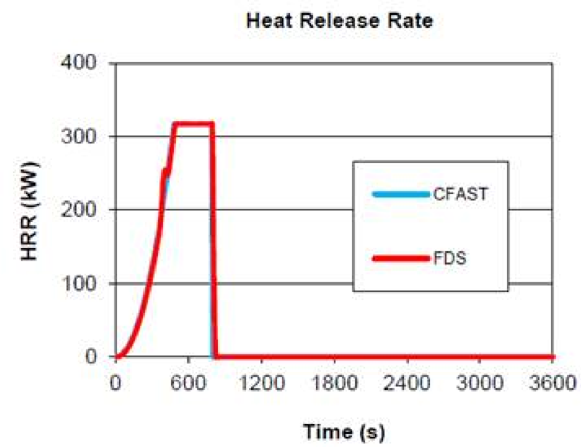
Ventilation

- The CSR has two doors on the east wall that are normally closed.
- Standard procedure calls for an operator to investigate the fire within 600 s (10 min) of an alarm condition.
- Two supply vents and two return vents. 1.4 m^3/s for each.
- Leakage – often the “leakage area” is the area of the crack under the door.
- Exact supply and exhaust location only important for CFD.
- Zone models usually only consider height of ducts off floor and orientation of the vent.

Fire

Table G-1
Recommended HRR Values for Electrical Fires

Ignition Source	HRR kW (Btu/s)		Gamma Distribution	
	75th	98th	α	β
Vertical cabinets with qualified cable, fire limited to one cable bundle	69 [1] (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Vertical cabinets with qualified cable, fire in more than one cable bundle	211 [2] (200)	702 [3] (665)	0.7 (0.7)	216 (204)
Vertical cabinets with unqualified cable, fire limited to one cable bundle	90 [4] (85)	211 [2] (200)	1.6 (1.6)	41.5 (39.5)
Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	232 [5] (220)	464 [6] (440)	2.6 (2.6)	67.8 (64.3)
Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	232 [5] (220)	1002 [7] (950)	0.46 (0.45)	386 (366)
Pumps (electrical fires) [8]	69 (65)	211 [2] (200)	0.84 (0.83)	59.3 (56.6)
Motors [8]	32 (30)	69 (65)	2.0 (2.0)	11.7 (11.1)
Transient Combustibles [9]	142 (135)	317 (300)	1.8 (1.9)	57.4 (53.7)



HRR taken from Appendix G, NUREG/CR 6850 (EPRI 10111989)

What is burning?

A trash fire ignites within a cylindrical steel waste bin 0.8 m (2.6 ft) high and 0.6 m (2.0 ft) in diameter, containing 5 kg of trash.

Duration of Fire

Total energy released is 5 kg x 30,400 kJ/kg = 152,000 kJ

$$Q = 152{,}000\ \text{kJ} = \int_0^{480} \dot{Q}_p \left(\frac{t}{480}\right)^2 dt + \int_{480}^{t_f} \dot{Q}_p\, dt = 317\ \text{kW} \left(\frac{480\ \text{s}}{3} + (t_f - 480\ \text{s})\right) \qquad \text{(E-1)}$$

Solving for t_f yields a total burning time of 800 s.

Table E-1. Products of combustion for CSR fire.

Parameter	Value	Source
Effective Fuel Formula	$C_4H_7O_{2.5}$	Assumption
Peak HRR	317 kW	NUREG/CR-6850 (EPRI 1011989), App. G
Time to reach peak HRR	480 s	NUREG/CR-6850 (EPRI 1011989), App. G
Heat of Combustion	30,400 kJ/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
CO_2 Yield	2.0 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
Soot Yield	0.038 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
CO Yield	0.014 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
Radiative Fraction	0.40	*SFPE Handbook*, 4th ed., Table 3-4.16

Step 3. Select Fire Models

- Algebraic Models: FPA algorithm in FIVE provides estimate of HGL temperature within a closed, ventilated compartment. FDTs do not allow for time-dependent HRR. Both FIVE and FDTs can estimate smoke detector activation time.
- Zone Models: Both CFAST and MAGIC include algorithms to estimate the temperature of cable targets.
- CFD: Typical application of FDS. The primary advantage of a CFD model for this fire scenario is that the CFD model can predict local conditions at the specific location of the target cables and includes more complete radiation calculations from the fire to the cable targets.

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Example E: Cable Spreading Room Fires

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Applicability of Validation

Table E-2. Key parameters and their ranges of applicability to NUREG-1824.

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{317\ \text{kW}}{(1.2\ \text{kg/m}^3)(1.0\ \text{kJ/kg/K})(293\ \text{K})(0.6^{2.5}\ \text{m}^{2.5})\sqrt{9.8\ \text{m/s}^2}} \cong 1.0$	0.4 – 2.4	Yes
Flame Length, L_f, relative to the Ceiling Height, H	$\frac{H_f + L_f}{H} = \frac{0.8\ \text{m} + 1.6\ \text{m}}{4.0\ \text{m}} = 0.6$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 0.6\ \text{m}\,(3.7 \times 1.0^{0.4} - 1.02) \cong 1.6\ \text{m}$	0.2 – 1.0	Yes
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H	N/A – Ceiling jet targets are not included in simulation.	1.2 – 1.7	N/A
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\,\dot{m}_{O_2}} = \frac{317\ \text{kW}}{13{,}100\ \text{kJ/kg} \times 0.4\ \text{kg/s}} \cong 0.06$ $\dot{m}_{O_2} = 0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2\ \text{kg/m}^3 \times 1.4\ \text{m}^3/\text{s} \cong 0.4\ \text{kg/s}$	0.04 – 0.6	Yes
Compartment Aspect Ratio	$\frac{L}{H} = \frac{40\ \text{m}}{4.0\ \text{m}} = 10 \qquad \frac{W}{H} = \frac{18.5\ \text{m}}{4.0\ \text{m}} \cong 4.6$	0.6 – 5.7	No
Target Distance, r, relative to the Fire Diameter, D	$\frac{r}{D} = \frac{2.3\ \text{m}}{0.6\ \text{m}} \cong 3.8$	2.2 – 5.7	Yes

Notes: (1) The "Fire Height", $H_f + L_f$, is the sum of the height of the fire off the floor plus the fire's flame length.

Step 4. Calculate Fire-Generated Conditions

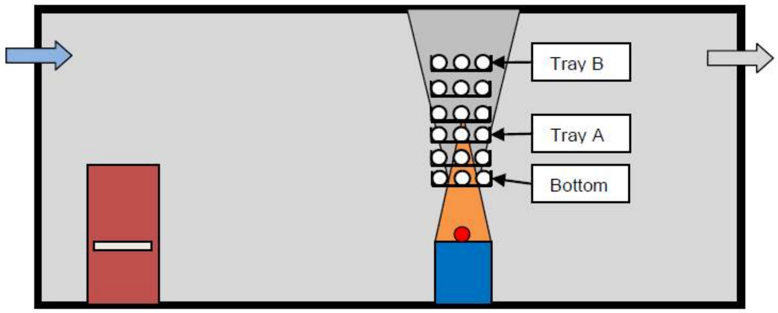


Figure E-4. Schematic diagram of transient trash fire in cable spreading room.

Step 4. Calculate Fire-Generated Conditions

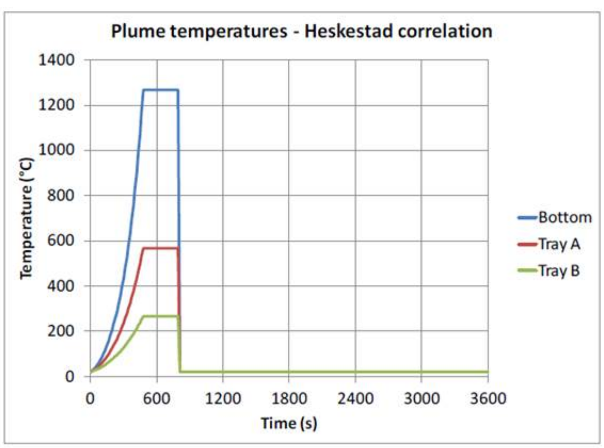


Figure E-5. Plume temperatures at cable trays located above transient trash fire.

Step 4. Calculate Fire-Generated Conditions

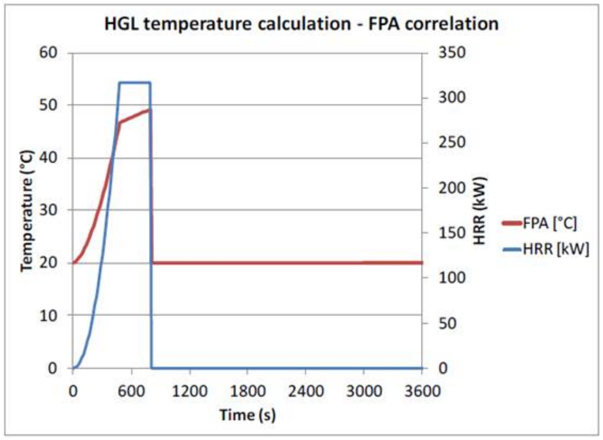


Figure E-6. Average HGL temperature from FPA correlation for CSR trash fire scenario.

Step 4. Calculate Fire-Generated Conditions

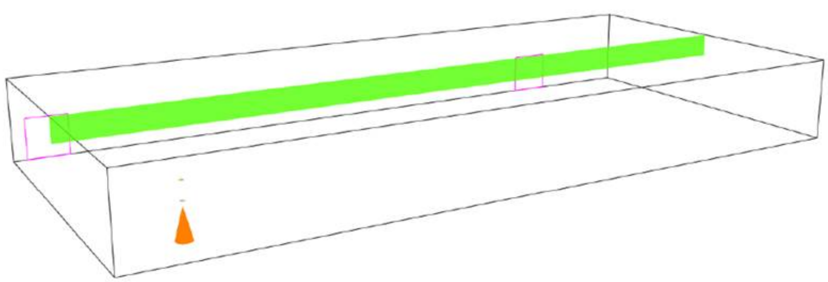


Figure E-7. CFAST rendering of the Cable Spreading Room scenario.

Step 4. Calculate Fire-Generated Conditions

FDS simulation, elevation view.

Step 4. Calculate Fire-Generated Conditions

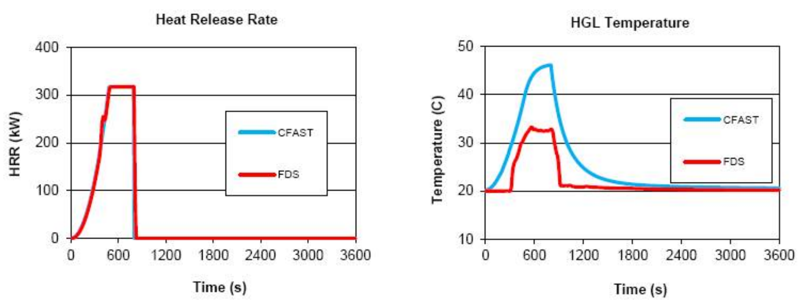


Figure E-14. Heat release rate and estimated HGL temperature for Cable Spreading Room scenario.

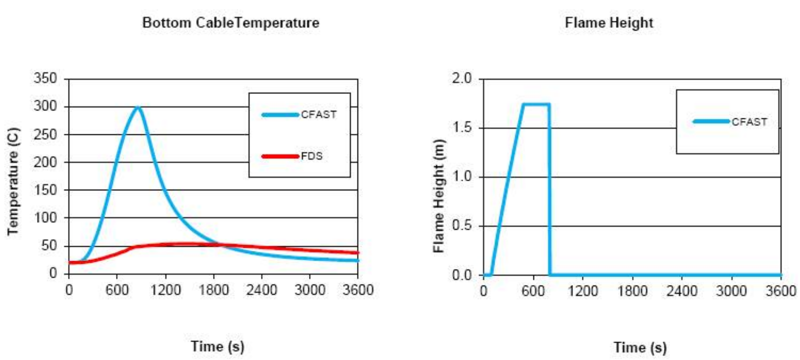
Step 4. Calculate Fire-Generated Conditions

- Smoke detection (E.5.1)
  - Table E-6 shows CFAST/FDS results for detector activation
  - CFAST models smoke detector as heat detector with low RTI and activation temperature
    - No consensus in literature on appropriate RTI / activation temperature
  - FDS uses smoke concentration to predict detector activation
    - Given presence of beam pockets and obstructions, even FDS is subject to significant uncertainty for detector activation prediction

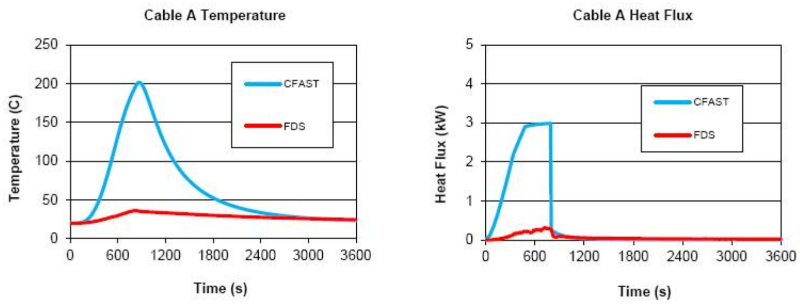
Table E-6. Smoke detector activation times, Cable Spreading Room.

Model	Time (s)
CFAST	170 s
FDS	160 s

Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions



Step 4. Calculate Fire-Generated Conditions

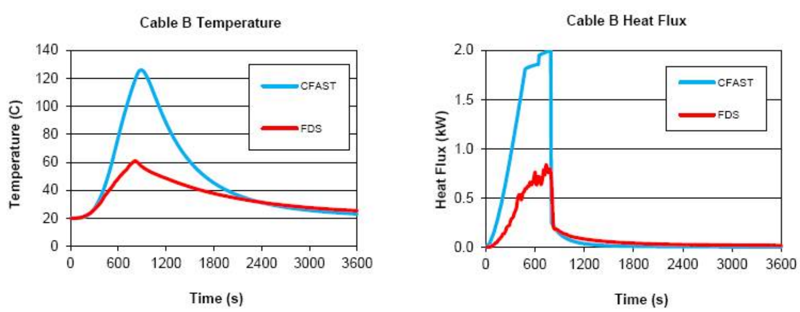


Figure E-15. Estimated cable conditions for the Cable Spreading Room.

Step 5. Sensitivity and Uncertainty Analysis

Table E-5. Summary of the model predictions of the CSR scenario.

Model	Bias Factor, δ	Standard Deviation, σ_M	Location	Predicted Value	Critical Value	Probability of Exceeding
Temperature (°C), Initial Value = 20 °C						
CFAST	1	0.27	Bottom Cable	298	205	0.893
FDS	1.02	0.13		54	205	0.000
CFAST	1	0.27	Cable A	202	205	0.472
FDS	1.02	0.13		36	205	0.000
CFAST	1	0.27	Cable B	126	205	0.003
FDS	1.02	0.13		61	205	0.000
Heat Flux (kW/m^2)						
CFAST	0.81	0.47	Bottom Cable	4.2	6	0.367
FDS						
CFAST	0.81	0.47	Cable A	3.0	6	0.091
FDS	0.85	0.22		0.3	6	0.000
CFAST	0.81	0.47	Cable B	2.0	6	0.000
FDS	0.85	0.22		0.8	6	0.001

Alternative Analysis – Parameter Propagation

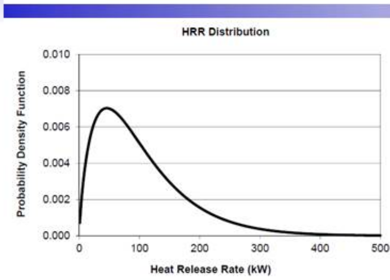


Figure E-16. Distribution of HRR for a trash fire.

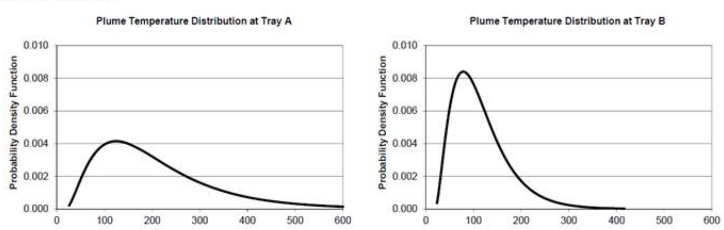


Figure E-17. Distribution of plume temperatures at Trays 3 and 6, respectively.

Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

Step 6. Document the Analysis

- Conclusions:
- Analysis shows that a 317 kW waste bin fire located beneath a vertical array of cable trays is unlikely to damage cables in the trays 3 and 6 levels above the fire
  - Both CFAST and FDS estimate peak temperatures and heat fluxes below the failure criteria for cables in 3^{rd} tray from bottom
- FDS calculates temperatures and heat fluxes well below critical values at the protected lowest cable tray
- CFAST calculations for unprotected cables demonstrate importance of protection provided by solid metal lower surface of lowest cable tray

3.6 Example F: Lube Oil Fire in Turbine Building

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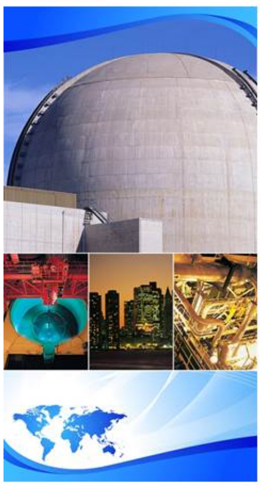

EPRI/NRC-RES Fire PRA Methodology

Module V:
Advanced Fire Modeling
Example F: Lube Oil Fire in Turbine Building

Joint RES/EPRI Fire PRA Workshop
2012
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Step 1. Define Fire Modeling Goals

- Determine the heat flux to and temperature of structural steel columns in a turbine hall due to a lube oil fire.
- Evaluate structural steel response for two potential curb locations.
- This type of analysis may arise when addressing ASME/ANS RA-Sa-2009

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Example F: Lube Oil Fire in Turbine Building
Slide 2
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Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire

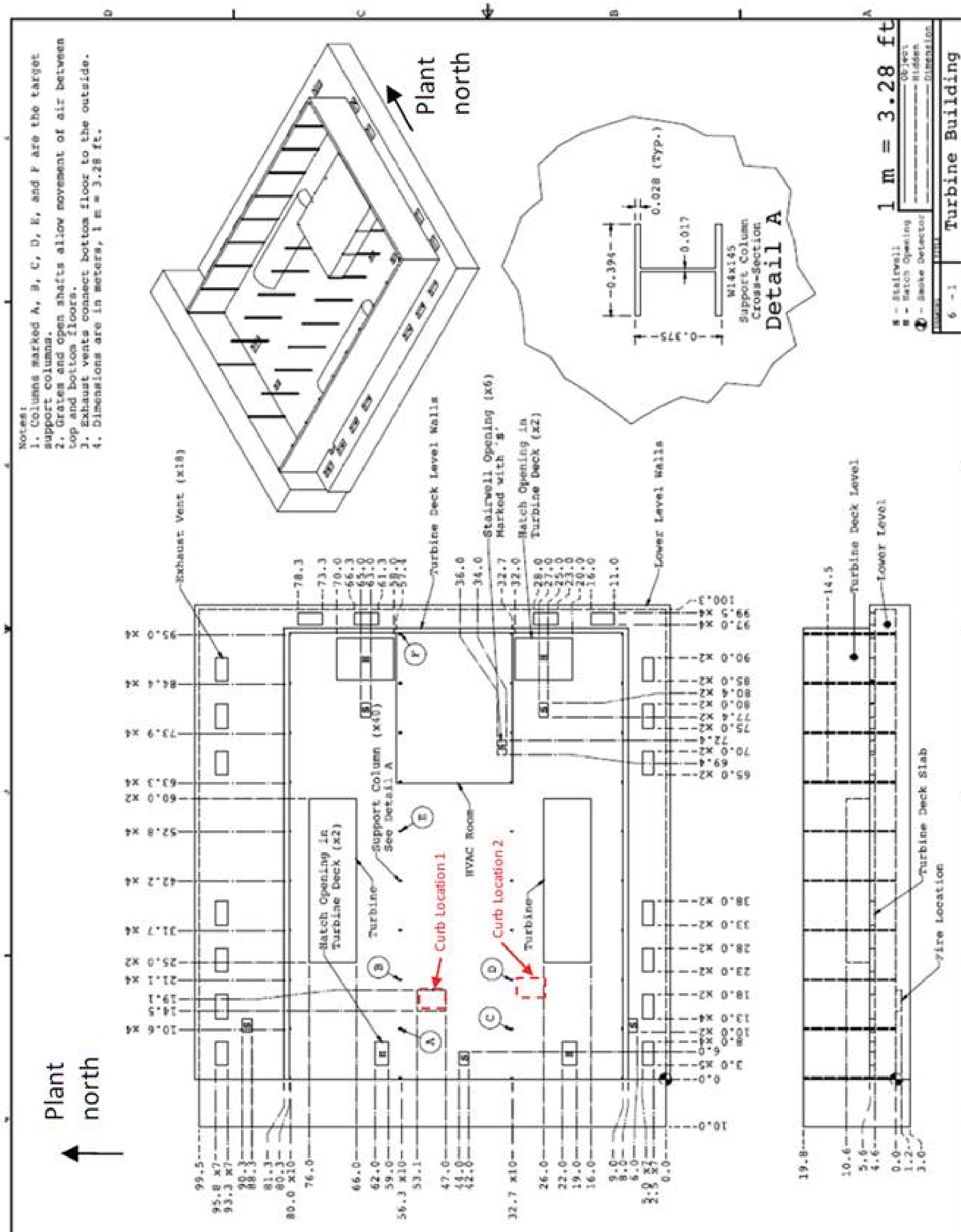
Notes:
1. Columns marked A, B, C, D, E, and F are the target support columns.
2. Grates and open shafts allow movement of air between top and bottom floors.
3. Exhaust vents connect bottom floor to the outside.
4. Dimensions are in meters, 1 m = 3.28 ft.
Plant north
Plant north
Exhaust Vent (x18)
Turbine Deck Level Walls
Stairwell Opening (x6) Marked with 'S'
Hatch Opening in Turbine Deck (x2)
Lower Level Walls
Support Column (x40) See Detail A
Hatch Opening in Turbine Deck (x2)
Turbine
Turbine
HVAC Room
Curb Location 1
Curb Location 2
Turbine Deck Level
Lower Level
Turbine Deck Slab
Turbine Location
Fire Location
W14x145 Support Column Cross-Section
Detail A
0.394
0.375
0.017
0.028 (Typ.)
S - Stairwell
H - Hatch Opening
Smoke Detector
1 m = 3.28 ft
Turbine Building

Figure F-2. Structural Steel Column in the Turbine Building.

Figure F-3. Main Turbine Lubricating Oil Tanks in the Turbine Building.

Material Properties

Table F-1. Structural steel failure criteria (ASTM E119-10a).

Member	Maximum Cross-Section Average Temperature °C (°F)
Beam	593 (1,099)
Column	538 (1,000)

Ventilation

- Large, open area
- Forced ventilation intentionally shut down at start of fire
- 18 exhaust vents to the outside around the perimeter

Fire

Table F-2. Data for lubricating oil fire.

Parameter	Value	Source
Effective Fuel Formula	C_nH_{2n+2}	Developed from fuel chemistry (*n* in range of 12-15)
Mass burning rate	0.039 kg/s.m^2	NUREG-1805 Table 3-4
Fuel volume	3,000 L	Specified
Density	760 kg/m^3	NUREG-1805 Table 3-4
Heat of Combustion	46,000 kJ/kg	NUREG-1805 Table 3-4
CO_2 Yield	2.64 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
Soot Yield	0.059 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
CO Yield	0.019 kg/kg	*SFPE Handbook*, 4th ed., Table 3-4.16
Radiative Fraction	0.34	*SFPE Handbook*, 4th ed., Table 3-4.16
Mass Extinction Coefficient	8,700 m^2/kg	Mulholland and Croarkin (2000)

The peak heat release rate (HRR), $\dot{Q}$, is computed from the fuel mass burning rate, $\dot{m}''$, the heat of combustion, ΔH, and the specified area of the spill, A:

$$\dot{Q} = \dot{m}'' \, \Delta H \, A = 0.039 \text{ kg/m}^2/\text{s} \times 46{,}000 \text{ kJ/kg} \times 28.1 \text{ m}^2 \cong 50{,}400 \text{ kW} \qquad \text{(F-1)}$$

The fire duration, Δt, is determined from the pool depth, δ, density, ρ, and burning rate, $\dot{m}''$:

$$\Delta t = \frac{\delta \, \rho}{\dot{m}''} = \frac{0.11 \text{ m} \times 760 \text{ kg/m}^3}{0.039 \text{ kg/m}^2/\text{s}} \cong 2{,}144 \text{ s} \quad (35.7 \text{ min}) \qquad \text{(F-2)}$$

Step 3. Select Fire Models

- Algebraic Models: Fire resistance calculations typically use a pre-defined time-temperature curve, like ASTM E 119. Not appropriate here. However, heat flux calculations are valid.
- Zone Models: Challenging case – too many assumptions violated, in particular the ratio of flame height to ceiling height. Zone models not used.
- CFD: Near-field or engulfing fire heat flux is a challenge for any model

Table F-3. Normalized Parameter Calculations for the Turbine Building Fire Scenario.

Quantity	Normalized Parameter Calculation						Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{50{,}400\ \mathrm{kW}}{(1.1\ \mathrm{kg/m^3})(1.0\ \mathrm{kJ/kg/K})(309\ \mathrm{K})(6.0^{2.5}\ \mathrm{m^{2.5}})\sqrt{9.8\ \mathrm{m/s^2}}} \cong 0.524$						0.4 – 2.4	Yes
Flame length, L_f, relative to ceiling height, H_c	$\frac{L_f}{H_c} = \frac{11.0\ \mathrm{m}}{4.6\ \mathrm{m}} \cong 2.4$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 6.0\ \mathrm{m}\,(3.7 \times 0.52^{0.4} - 1.02) \cong 11\ \mathrm{m}$						0.2 – 1.0	No
Ceiling jet radius relative to the ceiling height, H_c	N/A						1.2 – 1.7	N/A
Equivalence ratio based on opening area	See Section F.3.2 for discussion of this parameter.						0.04 – 0.6	Yes
Compartment aspect ratios	$\frac{L}{H_c} = \frac{100.3\ \mathrm{m}}{4.6\ \mathrm{m}} \cong 21.8$; $\frac{W}{H_c} = \frac{99.5\ \mathrm{m}}{4.6\ \mathrm{m}} \cong 21.6$						0.6 – 5.7	No
Target distance to fire diameter (Columns A,B,C,D,E,F)	$\frac{8.5\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 1.4$	$\frac{7.2\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 1.2$	$\frac{18.8\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 3.1$	$\frac{18.3\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 3.1$	$\frac{36.5\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 6.1$	$\frac{78.\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 13.1$	2.2 – 5.7	Yes/No
	$\frac{28.0\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 4.7$	$\frac{26.9\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 4.5$	$\frac{8.8\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 1.5$	$\frac{3.9\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 0.7$	$\frac{43.3\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 7.2$	$\frac{80.\ \mathrm{m}}{6.0\ \mathrm{m}} \cong 13.5$		

The calculation of the equivalence ratio is challenging because natural ventilation is provided through the 18 roof vents located around the perimeter of the turbine deck level. To evaluate the potential impact of ventilation on the fire for this scenario, the quantity of oxygen available in the turbine building is compared to the amount of oxygen that would be consumed by the specified lubricating oil fire. Given a total volume of approximately 209,600 m^3, the mass of oxygen within the turbine building is estimated to be:

$$m_{O_2,\mathrm{tot}} = \rho V Y_{O_2} = 1.1\ \mathrm{kg/m^3} \times 209{,}600\ \mathrm{m^3} \times 0.23 \cong 53{,}030\ \mathrm{kg} \qquad \text{(F-3)}$$

The mass of oxygen required to burn all the fuel is estimated to be:

$$m_{O_2,\mathrm{req}} = \frac{\dot{Q}\,\Delta t}{\Delta H_{O_2}} = \frac{50{,}400\ \mathrm{kW} \times 2{,}144\ \mathrm{s}}{13{,}100\ \mathrm{kJ/kg}} \cong= 8{,}249\ \mathrm{kg} \qquad \text{(F-4)}$$

Step 4. Calculate Fire-Generated Conditions

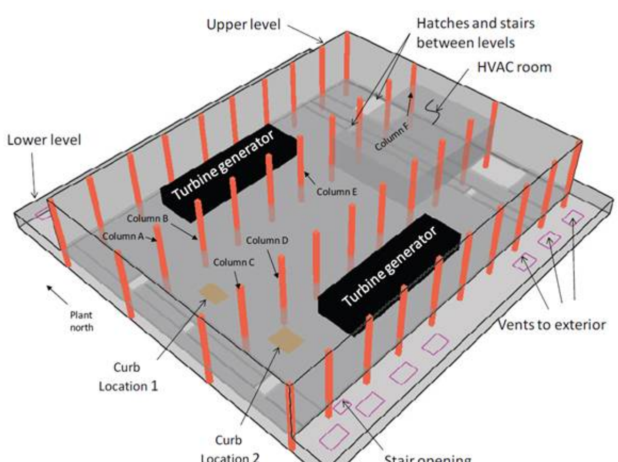

Figure F-5. FDS Geometry for the Turbine Building Fire Scenario.

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Example F: Lube Oil Fire in Turbine Building

Slide 13

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Flame extension beneath turbine deck

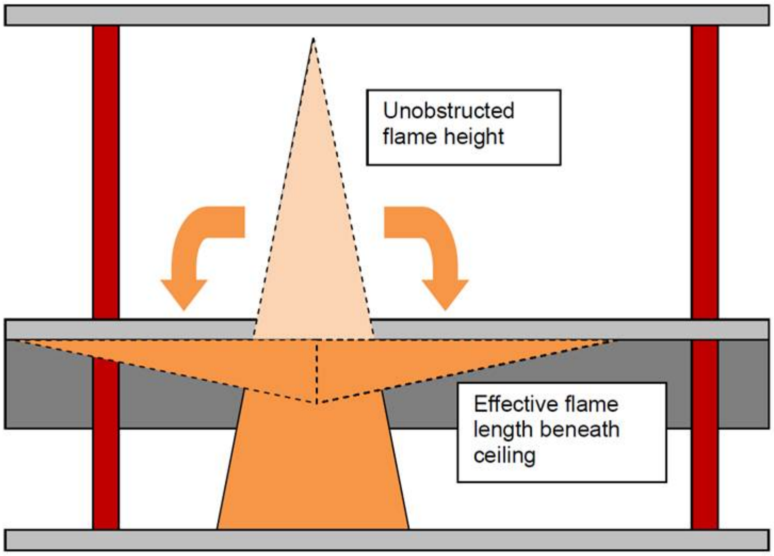


Figure F-4. Schematic diagram of the fire impinging on the ceiling.

Flame extension beneath turbine deck

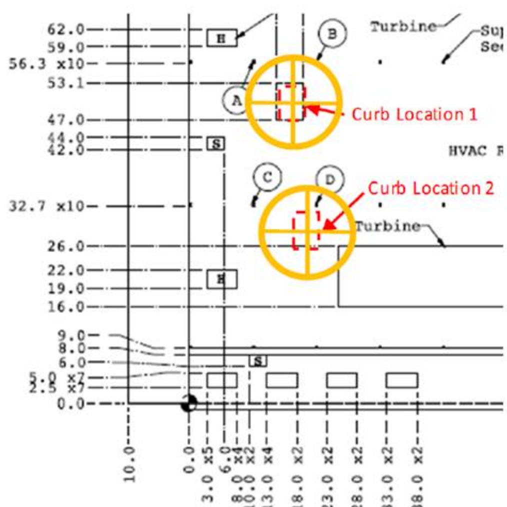


Figure F-5. Detail from Figure F-1 with estimated flame extension beneath ceiling superimposed.

Radiative heat flux – hand calculation

For the point source method, the estimated peak HRR is 50,400 kW, the radiative fraction is 0.33, and the horizontal distance from the center of the lubricating oil pool to the nearest column (Column D) is approximately 4.2 m (13.8 ft):

$$\dot{q}_r'' = \frac{\chi_r \, \dot{Q}}{4\pi \, r^2} = \frac{0.33 \, \times 50{,}400 \text{ kW}}{4\pi \, \times \, 4.2^2 \text{ m}^2} \cong 75.0 \text{ kW/m}^2 \qquad \text{(F-5)}$$

Column heating – hand calculation

In order to estimate an approximate time for a column to reach the specified failure temperature of 538 °C when subjected to different radiant heat fluxes, a simple energy balance is used to calculate the rate of temperature rise of the steel in response to this imposed heat flux:

$$\rho_s c_s V_s \frac{dT_s}{dt} = \dot{q}_r'' \, A_s \qquad \text{(F-6)}$$

The subscript s refers to steel. For a constant heat flux, this differential equation can be readily integrated to yield the steel temperature as a function of time:

$$T_s - T_0 = \frac{\dot{q}_r'' \, t}{\rho_s c_s (V_s/A_s)} \qquad \text{(F-7)}$$

To calculate the time, t_{crit} , when the steel failure temperature is reached, this equation is rearranged, with the critical steel temperature, T_{crit}, inserted for the steel temperature.

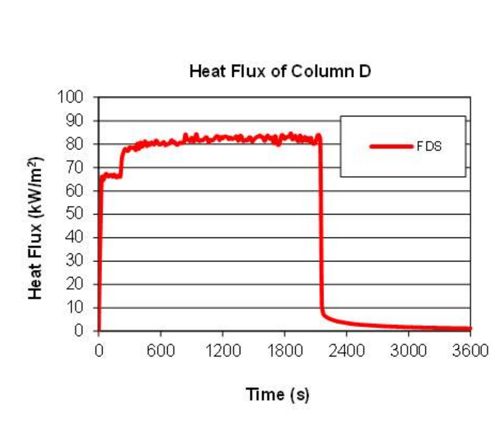
$$t_{\text{crit}} = \frac{\rho_s c_s (V_s/A_s)(T_{\text{crit}} - T_0)}{\dot{q}_r''} = \frac{c_s (W/D)(T_{\text{crit}} - T_0)}{\dot{q}_r''} \qquad \text{(F-8)}$$

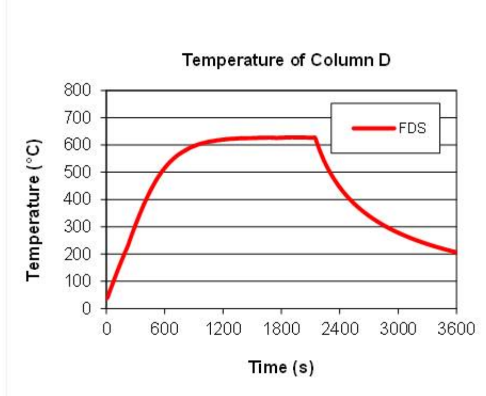
The term V_s/A_s is sometimes called the section factor and is the effective thickness of the steel member; it is calculated as the cross-sectional area of a steel member divided by the heated perimeter of the member. In the US, it is more common to use a parameter referred to as the W/D ratio, which is simply the section factor multiplied by the steel density. For a W14x145 steel column, the W/D ratio has a value of approximately 96.2 kg/m^2 (1.64 lb/ft/in). With this value used for the W/D ratio, the time to reach the critical steel temperature for the column can be estimated, based on the radiant heat flux estimated in equation F-5, as:

$$t_{\text{crit}} = \frac{(0.465 \text{ kJ/kg/°C})(96.2 \text{ kg/m}^2)(538 \text{ °C} - 36 \text{ °C})}{75.0 \text{ kW/m}^2} \cong 300 \text{ s} \qquad \text{(F-9)}$$

Column heating – FDS calculation

FDS Results, Curb Location 2





Step 5. Sensitivity and Uncertainty Analysis

Table F-4. Summary of results for the Turbine Building fire scenarios.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Target	Predicted Value	Critical Value	Probability of Exceeding
Surface Temperature (°C), Initial Value = 36 °C						
Curb Location 1						
FDS	1.02	0.13	Column A	270	538	0.000
FDS	1.02	0.13	Column B	260	538	0.000
FDS	1.02	0.13	Column C	170	538	0.000
FDS	1.02	0.13	Column D	150	538	0.000
FDS	1.02	0.13	Column E	90	538	0.000
FDS	1.02	0.13	Column F	50	538	0.000
Curb Location 2						
FDS	1.02	0.13	Column A	130	538	0.000
FDS	1.02	0.13	Column B	120	538	0.000
FDS	1.02	0.13	Column C	400	538	0.001
FDS	1.02	0.13	Column D	620	538	0.828
FDS	1.02	0.13	Column E	75	538	0.000
FDS	1.02	0.13	Column F	50	538	0.000

F.6 Conclusion

This analysis has addressed the potential for a relatively large lubricating oil fire to damage exposed structural steel in a turbine building. The analysis is complicated by the significant flame impingement on the ceiling caused by an oil fire spread over a relatively large area. This type of fire behavior is beyond the validation range addressed in NUREG-1824 (EPRI 1011999).

Algebraic calculations were performed to estimate the extent of flame extension beneath the ceiling. These algebraic calculations indicate that at least one of the columns (Column D) would be engulfed in the flames extending from the fire at Curb Location 2 These calculations also indicate that other columns would be located near the outer extent of flames from Curb Locations 1 and 2. Algebraic calculations were also performed to estimate the time to reach the critical steel temperature of the nearest column. These calculations indicate that damage could occur within a time frame of approximately five minutes. These calculations indicate that a more detailed analysis is warranted. The CFD model, FDS, was used to perform this more detailed analysis because zone models do not have the necessary physical models to simlulate the postulated fire.

Based on the FDS simulation of this scenario, a 50 MW lubricating oil fire in Curb Location 1 is not predicted to cause the steel columns to exceed a temperature of 538 °C (1,000 °F). This is not the case for the proposed Curb Location 2, which is located closer to Column D. Consequently, the recommendation for the design package is to install the curbed area at Curb Location 1.

3.7 Example G: Transient Fire in a Corridor

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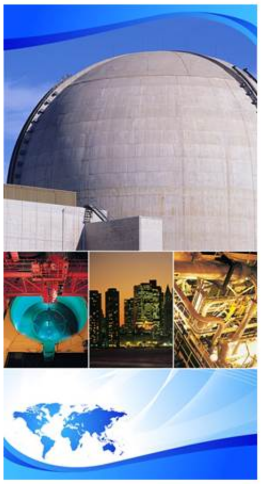


EPRI/NRC-RES Fire PRA Methodology

Module V:
Advanced Fire Modeling
Example G: Transient Fire in a Corridor

Joint RES/EPRI Fire PRA Workshop
2012
Washington, D.C.

A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Step 1. Define Fire Modeling Goals

- Determine if important safe-shutdown equipment will fail due to a fire involving a stack of pallets in a hallway
- Also determine time to smoke detector activation

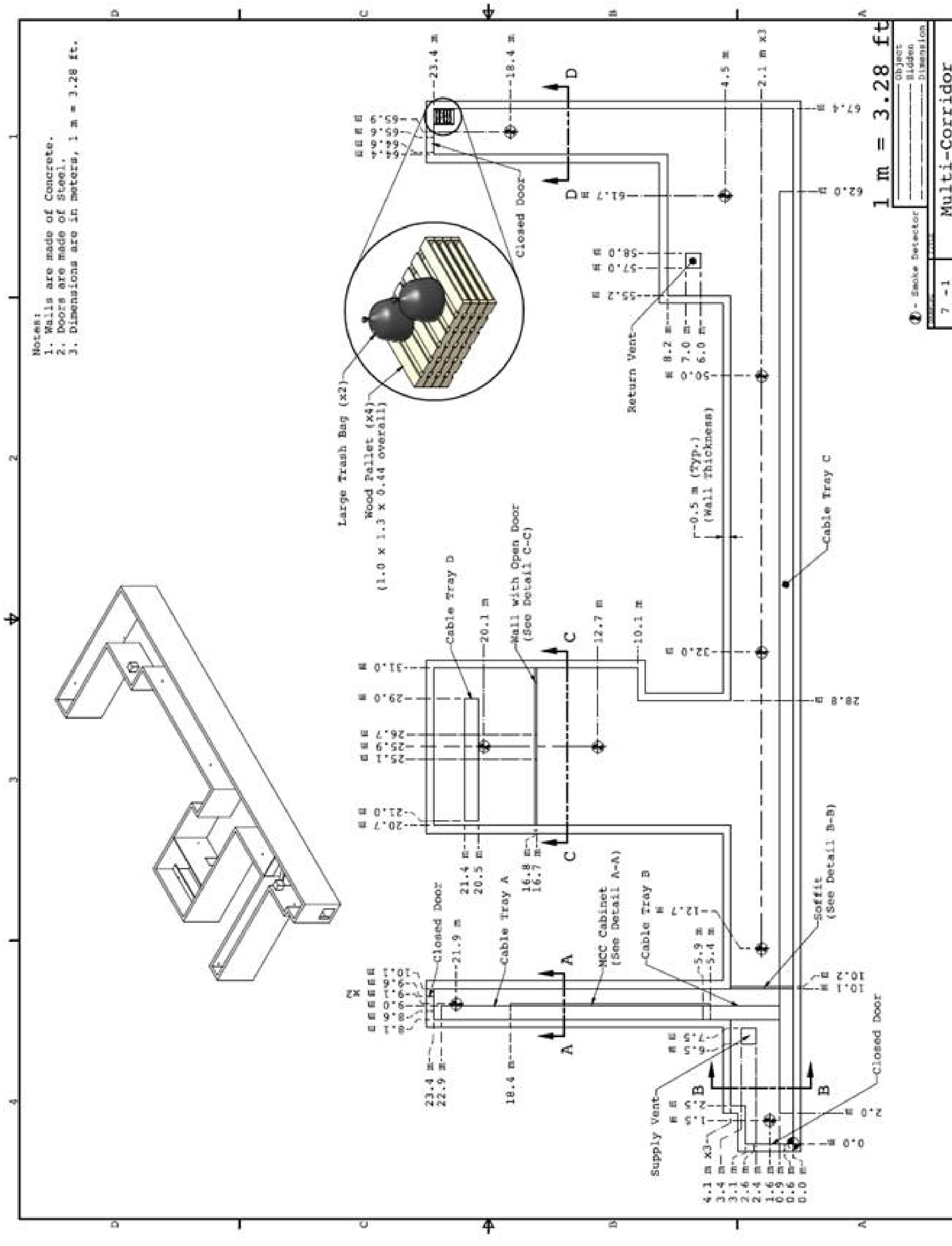
Fire PRA Workshop, 2012, Washington, D.C.
Example G: Transient Fire in a Corridor

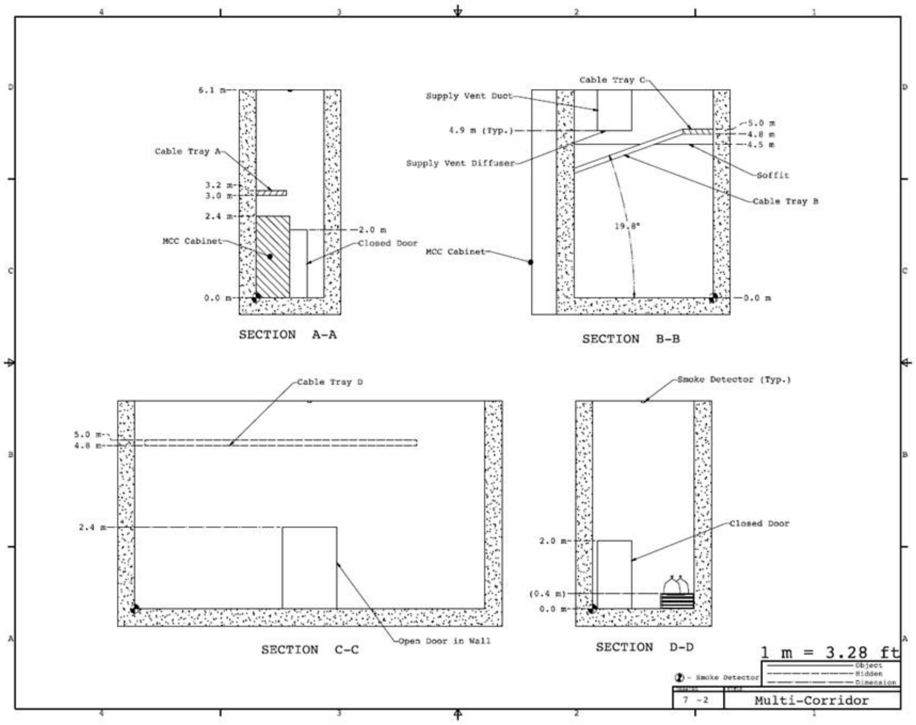
Slide 2

A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire


Notes:
1. Walls are made of Concrete.
2. Doors are made of Steel.
3. Dimensions are in meters, 1 m = 3.28 ft.
Large Trash Bag (x2)
Wood Pallet (x4)
(1.0 x 1.3 x 0.44 overall)
Closed Door
Return Vent
0.5 m (Typ.)
(Wall Thickness)
Cable Tray C
Cable Tray D
Wall with Open Door
(See Detail C-C)
Cable Tray A
MCC Cabinet
(See Detail A-A)
Cable Tray B
Soffit
(See Detail B-B)
Supply Vent
= Smoke Detector
1 m = 3.28 ft
Object
Hidden
Dimension
Multi-Corridor
7 -1



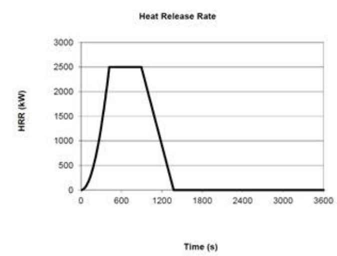
Ventilation and Detection

- 1.67 m^3/s air flow
- All doors closed
- 9 smoke detectors with a sensitivity of 4.9 %/m
- No suppression system

Fire

Table G-1. Products of combustion for a wood pallet fire.

Parameter	Value	Source
Effective Fuel Formula	$C_6H_{10}O_5$	Cellulose
Peak HRR	2500 kW	*SFPE Handbook*, 4^{th} Ed., Figs. 3-1.65, 3-1.100
Time to reach peak HRR	420 s	*SFPE Handbook*, 4^{th} Ed., Figs. 3-1.64
Heat of Combustion	17,100 kJ/kg	*SFPE Handbook*, 4^{th} Ed., Table 3-4.16
Heat of Combustion per unit mass of oxygen consumed	13,100 kJ/kg	Hugget 1980, Average value
CO_2 Yield	1.27 kg/kg	*SFPE Handbook*, 4^{th} Ed., Table 3-4.16
Soot Yield	0.015 kg/kg	*SFPE Handbook*, 4^{th} Ed., Table 3-4.16
CO Yield	0.004 kg/kg	*SFPE Handbook*, 4^{th} Ed., Table 3-4.16
Radiative Fraction	0.37	*SFPE Handbook*, 4^{th} Ed., Table 3-4.16



Step 3. Select Fire Models

- Algebraic Models: Not designed for multiple compartment scenarios, but can be used to assess room of origin or in this case, the corridor containing the pallets
- Zone Models: Scenario consistent with physical assumptions
- CFD: No need in this case. All questions answered satisfactorily with simpler models.

Applicability of Validation

Table G-2. Normalized parameter calculations for the Multi-Compartment Corridor fire scenario.

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	$\dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty D^{2.5}\sqrt{g}} = \frac{2500\text{ kW}}{(1.2\text{ kg/m}^3)(1.0\text{ kJ/kg/K})(293\text{ K})(1.3^{2.5}\text{ m}^{2.5})\sqrt{9.8\text{ m/s}^2}} = 1.2$	0.4 – 2.4	Yes
Flame Length, L_f, relative to the Ceiling Height, H	$\frac{H_f + L_f}{H} = \frac{0.44\text{ m} + 3.8\text{ m}}{6.1\text{ m}} = 0.7$ $L_f = D\left(3.7\,\dot{Q}^{*2/5} - 1.02\right) = 1.3\text{ m}\,(3.7 \times 1.2^{0.4} - 1.02) = 3.8\text{ m}$	0.2 – 1.0	Yes
Ceiling Jet Horizontal Radial Distance, r_{cj}, relative to the Ceiling Height, H	$\frac{r_{cj}}{H - H_f} = \frac{4.46\text{ m}}{6.1\text{ m} - 0.44\text{ m}} = 0.8$	1.2 – 1.7	No
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	$\varphi = \frac{\dot{Q}}{\Delta H_{O_2}\dot{m}_{O_2}} = \frac{2500\text{ kW}}{13{,}100\text{ kJ/kg} \times 0.46\text{ kg/s}} = 0.4$ $\dot{m}_{O_2} = 0.23\,\rho_\infty \dot{V} = 0.23 \times 1.2\text{ kg/m}^3 \times 1.67\text{ m}^3/\text{s} \cong 0.46\text{ kg/s}$	0.04 – 0.6	Yes
Compartment Aspect Ratios	$\frac{L}{H} = \frac{15.2\text{ m}}{6.1\text{ m}} = 2.49\ ;\ \frac{W}{H} = \frac{3.0\text{ m}}{6.1\text{ m}} = 0.49$	0.6 – 5.7	No
Target Distance, r, relative to the Fire Diameter, D	N/A	2.2 – 5.7	N/A

Notes: (1) The effective diameter of the base of the fire, D, is calculated using $D = \sqrt{4A/\pi}$, where A is the area of the pallets.

(2) The "Fire Height", $H_f + L_f$, is the sum of the height of the fire off the floor plus the fire's flame length.

Step 4. Calculate Fire-Generated Conditions

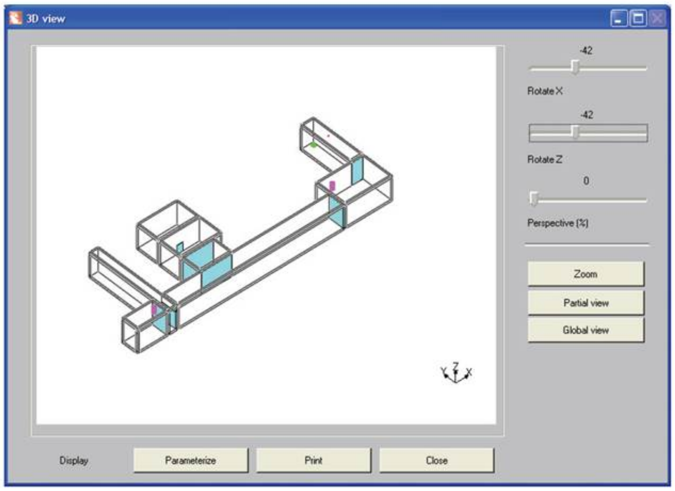


Figure G-4. MAGIC rendering of the Corridor scenario.

Step 4. Calculate Fire-Generated Conditions

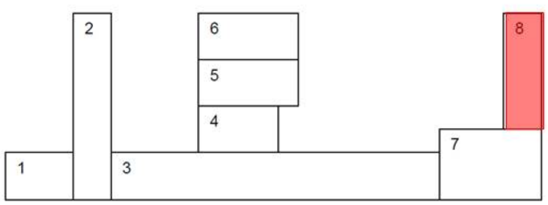


Figure G-3. Effective corridor layout for implementation in zone models (not to scale).

Table G-3. Compartment dimensions for Corridor scenario.

Comp.	Length (m)	Width (m)	Area (m^2)
1	8.1	4.1	33.2
2	2.0	23.4	46.8
3	45.1	4.1	184.9
4	8.1	6.0	48.6
5	10.3	6.6	68.0
6	10.3	6.6	68.0
7	12.2	8.2	100.0
8	3	15.2	45.6

Step 4. Calculate Fire-Generated Conditions

- Algebraic models (G.4.1)
  - HGL temperature in fire compartment calculated with MQH correlation corrected for fire locationin corner
    - Reasonable to assume that if HGL temperature in fire compartment is below cable temperature, then cables will not be damaged in any compartment
  - Alpert ceiling jet correlation used to calculate time when ceiling jet temperature is 30C; detection assumed at this temperature
    - Because of corridor geometry, Delichatsios confined ceiling jet correlation also used

Step 4. Calculate Fire-Generated Conditions

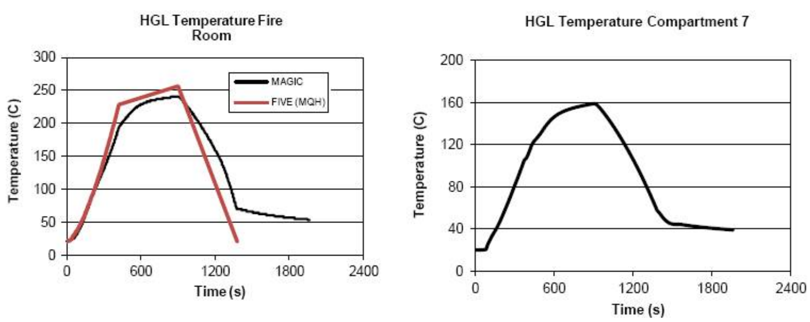


Figure G-9. Hot Gas Layer Temperature Predictions by MAGIC for the Corridor Scenario.

Step 4. Calculate Fire-Generated Conditions

G.5.2 Smoke Detection

The smoke detector activation time in the corridor containing the fire is based on the time for the ceiling jet temperature to reach 30°C at the detector location. The results, plotted in Figure G-11, show that the two correlations from FIVE produce identical results of 50 s. MAGIC predicts 40 s.

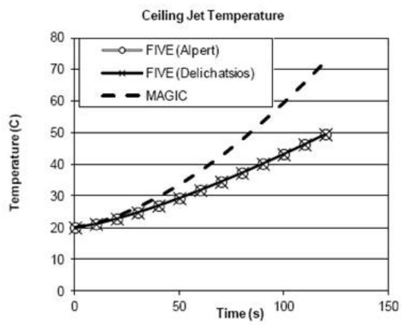


Figure G-11. Detector temperature prediction by MAGIC for fire corridor.

Step 5. Sensitivity and Uncertainty Analysis

Table G-2. Summary of the model predictions of the Corridor scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Ventilation	Predicted Value	Critical Value	Probability of Exceeding
HGL Temperature (°C), Initial Value = 20 °C						
FIVE (MQH)	1.56	0.32	Natural	256	330	0.001
MAGIC	1.01	0.07	Mechanical	240	330	0.000

Step 5. Sensitivity and Uncertainty Analysis

What happens if the room height is reduced?

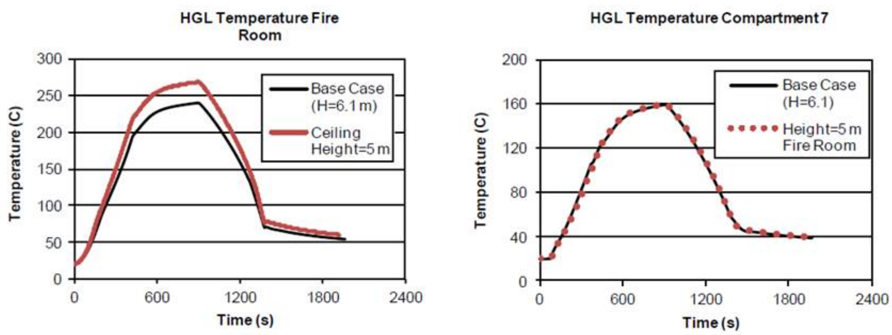


Figure G-10. Hot Gas Layer Temperature for Reduced Ceiling Height by MAGIC.

Step 6. Document the Analysis

- Follow the steps; clearly explain the entire process
- Answer the original question
- Report model predictions with uncertainty and sensitivity included
- Include all references

G.6. Conclusions

- MQH correlation used to estimate conditions within fire corridor
  - HGL in corridor lower than cable damage temperature
  - Temperatures in other compartments will be lower than in corridor, so cable damage not expected in other compartments
- MAGIC used to predict HGL temperatures in all interconnected compartments from pallet / trash fire
  - MAGIC calculations also show HGL temperatures below cable damage temperature
  - Calculations account for model uncertainty and sensitivity to variations in HRR
- Simplified model of smoke detector activation indicates detector activation between 40 – 50 s after ignition

3.8 Example H: Cable Tray Fire in Annulus

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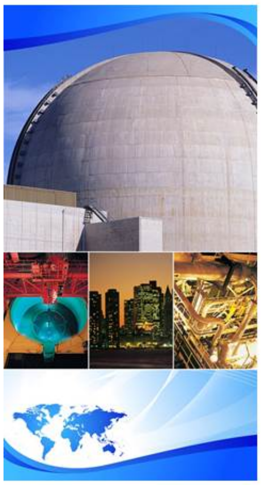

EPRI/NRC-RES Fire PRA Methodology

Module V:
Advanced Fire Modeling
Example H: Cable Tray Fire in Annulus

Joint RES/EPRI Fire PRA Workshop
2012
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Step 1. Define Fire Modeling Goals

- Determine potential for damage to redundant safe-shutdown cables due to a fire in an adjacent tray in annulus region of the containment building.
- Follow guidance provided in Chapter 11 of NUREG/CR-6850 (EPRI 1011989), Volume 2, Appendix R, “Cable Fires”

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Example H: Cable Tray Fire in Annulus

Slide 2

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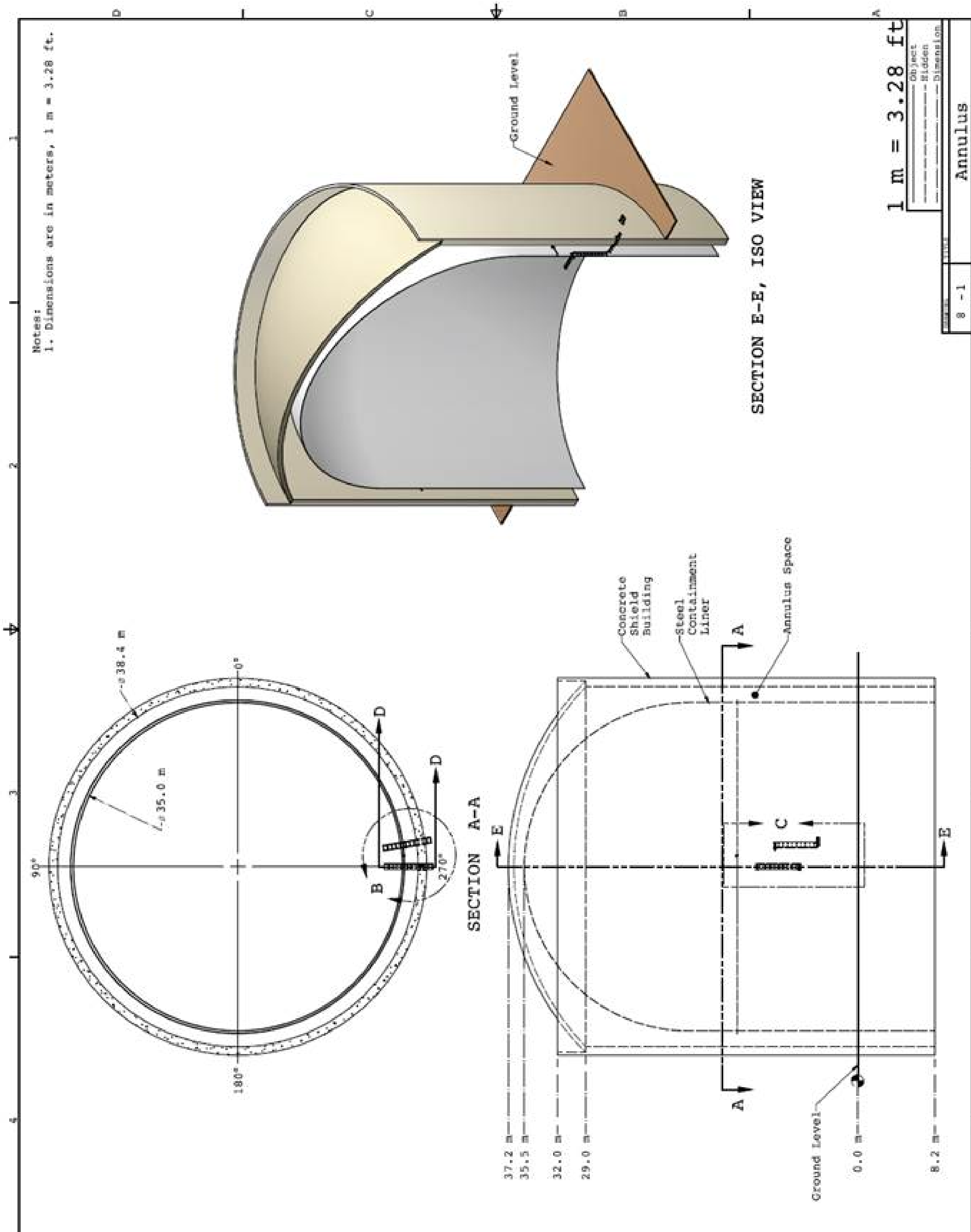
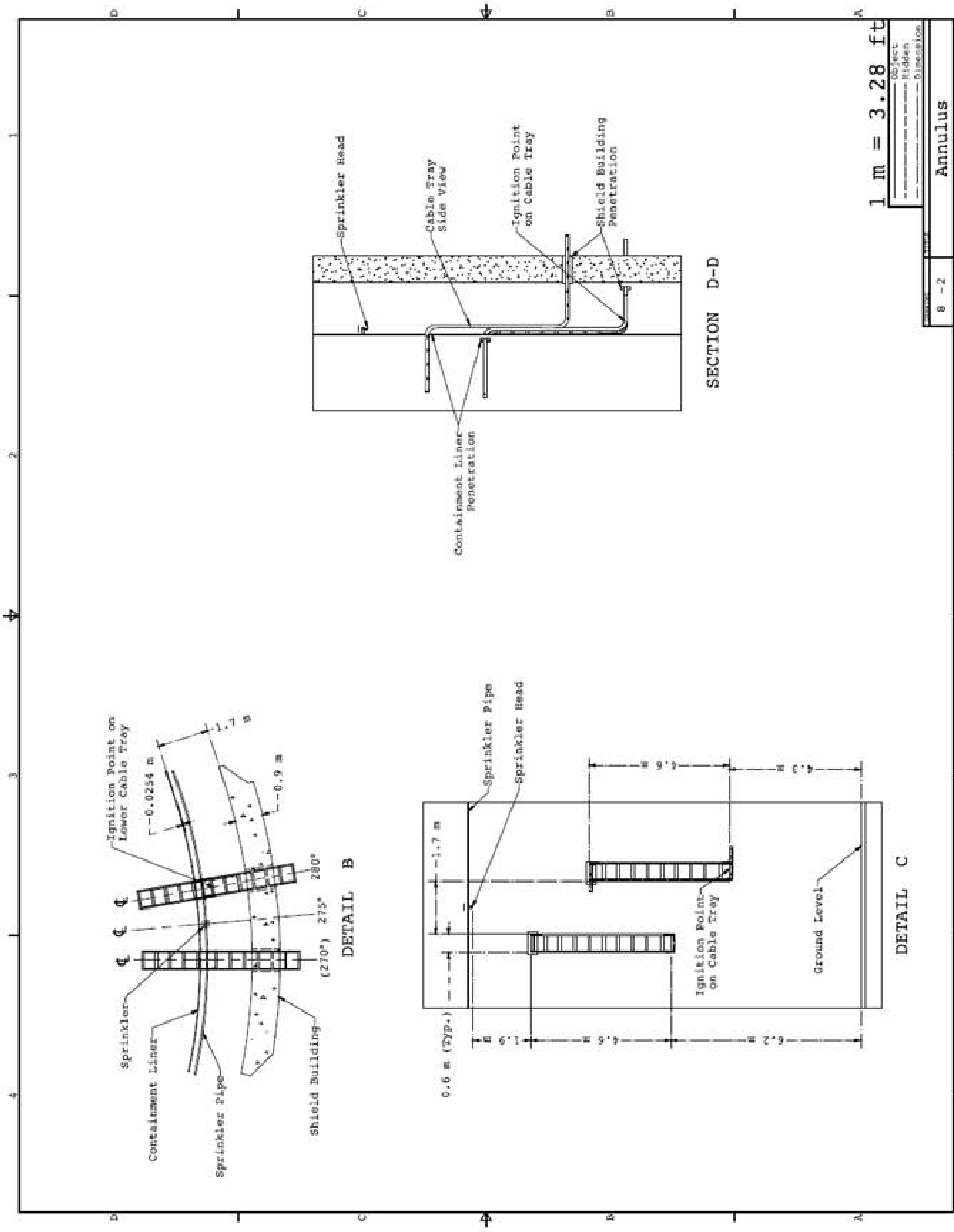

Notes:
1. Dimensions are in meters, 1 m = 3.28 ft.
Ground Level
SECTION E-E, ISO VIEW
1 m = 3.28 ft
Annulus
⌀38.4 m
⌀35.0 m
90°
0°
180°
270°
SECTION A-A
Concrete Shield Building
Steel Containment Liner
Annulus Space
37.2 m
35.5 m
32.0 m
29.0 m
Ground Level
0.0 m
8.2 m


Sprinkler Head
Cable Tray Side View
Ignition Point on Cable Tray
Shield Building Penetration
Containment Liner Penetration
SECTION D-D
Ignition Point on Lower Cable Tray
0.0254 m
1.7 m
0.9 m
280°
275°
(270°)
DETAIL B
Sprinkler
Containment Liner
Sprinkler Pipe
Shield Building
Sprinkler Pipe
Sprinkler Head
1.7 m
4.6 m
4.3 m
0.6 m (Typ.)
1.9 m
4.6 m
6.2 m
Ignition Point on Cable Tray
Ground Level
DETAIL C
1 m = 3.28 ft
Object
Hidden
Dimension
Annulus
8 -2

Fire

HRR taken from Appendix R, NUREG/CR 6850 (EPRI 10111989)

R.4.1.2 Recommended Values for Flame Spread in Horizontal Cable Trays

Consider a single vertical cable tray ignited at the bottom. Assume a heating distance of 2 mm and an incident heat flux of 70 kW/m^2.

- Flame spread for PVC cable = 0.9 mm/sec
- Flame spread for XPLE cable = 0.3 mm/sec

Table R-4
Flame Spread Estimates for PVC Cable

Material	Bench Scale HRR [kW/m^2]	Flame Spread Rate [mm/s]
PE/PVC	395	156
PE/PVC	359	137
PE/PVC	312	112
PE/PVC	589	258

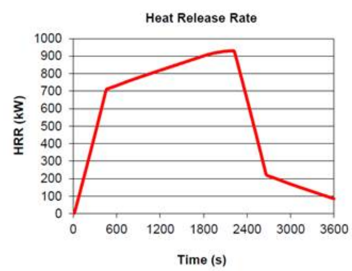


Figure H-1. Heat release rate for a cable fire in the annulus.

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Example H: Cable Tray Fire in Annulus

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<u>What is burning?</u>

Cables made of polyethylene (C_2H_4) and polyvinylchloride (C_2H_3Cl).

Assume effective fuel: $C_2H_{3.5}Cl_{0.5}$

Table H-1. Products of combustion for a PE/PVC cable fire.

Parameter	Value	Source
Heat of Combustion	20,900 kJ/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
CO_2 Yield	1.29 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
Soot Yield	0.136 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
CO Yield	0.147 kg/kg	*SFPE Handbook,* 4th ed., Table 3-4.16
Radiative Fraction	0.49	*SFPE Handbook,* 4th ed., Table 3-4.16

Material Properties

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. There are approximately 120 cables in each tray. The mass of each cable is 0.4 kg/m. The mass fraction of copper is 0.67. These cables fail when the internal temperature just underneath the jacket reaches approximately 205 °C (400 °F) or the exposure heat flux exceeds 6 kW/m² (NUREG-1805, Appendix A).

$$m_c'' = \frac{n\,Y_p\,(1-\nu)m'}{W} = \frac{120 \times 0.33 \times (1-0) \times 0.4\ \text{kg/m}}{0.6\ \text{m}} \cong 26.4\ \text{kg/m}^2 \qquad \text{(H-1)}$$

$$\Delta t = \frac{m_c''\,\Delta H}{5\,\dot{q}_{\text{avg}}''/6} = \frac{26.4\ \text{kg/m}^2 \times 20{,}900\ \text{kJ/kg}}{5/6 \times 250\ \text{kW/m}^2} \cong 2648\ \text{s} \qquad \text{(H-2)}$$

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Example H: Cable Tray Fire in Annulus

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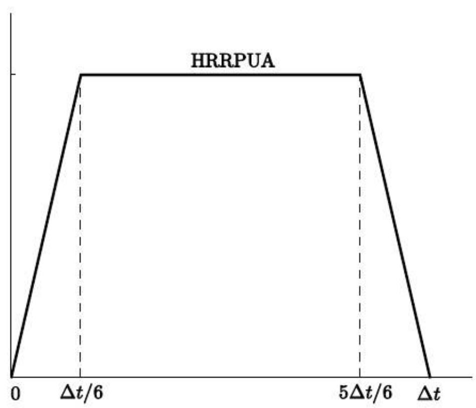

Figure 9-1. Idealized time history of the local heat release rate per unit area.

Step 3. Select Fire Models

- Algebraic Models: Point source heat flux
- Zone Models: Typically not used outside of a compartment.
- CFD: FDS assumes rectangular geometry, but it can approximate the curved wall using a series of "stair steps"

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Example H: Cable Tray Fire in Annulus

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Table H-2. Normalized parameter calculations for the annulus fire scenario.

Quantity	Normalized Parameter Calculation	Validation Range	In Range?
Fire Froude Number	N/A – The fire does not conform to classic fire plume theory.	0.4 – 2.4	No
Fire Height, $H_f + L_f$, relative to the Ceiling Height, H_c	N/A – The fire does not conform to classic fire plume theory.	0.2 – 1.0	No
Ceiling Jet Radial Distance, r_{cj}, relative to the Ceiling Height, H_c	N/A – The ceiling height is essentially infinite.	1.2 – 1.7	N/A
Equivalence Ratio, φ, as an indicator of the Ventilation Rate	N/A – The scenario is outside of a clearly defined compartment.	0.04 – 0.6	N/A
Compartment Aspect Ratio	N/A – The scenario is outside of a clearly defined compartment.	0.6 – 5.7	N/A
Target Distance, r, relative to the Fire Diameter, D	See discussion in Section H.3.3.	2.2 – 5.7	Yes

CHRISTIFIRE 2, Vertical Tests

Two trays of PVC Instrument Cable separated by 6 inches

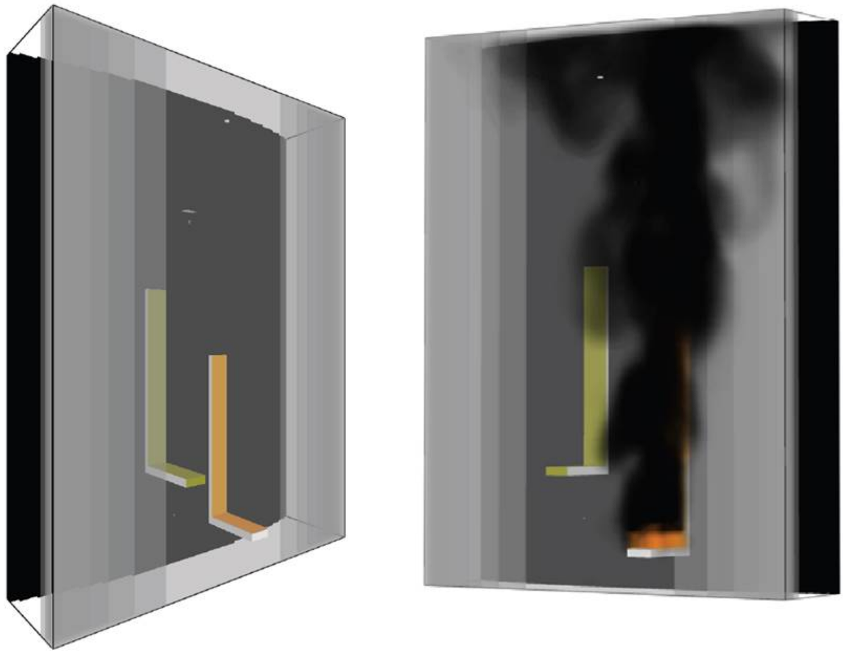
October 2011, NIST Large Fire Lab

Step 4. Calculate Fire-Generated Conditions

Two forms of the point source radiation model

$$\dot{q}''_{\text{ps}} = \frac{\chi_r \, \dot{Q}}{4\pi \, r^2} = \frac{0.49 \; \times 945 \text{ kW}}{4\pi \; \times \; 2.0^2 \text{ m}^2} \cong 9.2 \text{ kW/m}^2 \qquad \text{(H-3)}$$

$$\dot{q}''_{\text{dps}} = \frac{\chi_r}{4\pi} \sum_i \frac{\dot{Q}_i}{{r_i}^2} = \frac{0.49}{4\pi} \left(\frac{255}{2.9^2} + \frac{172.5}{2.4^2} + \frac{172.5}{2.0^2} + \frac{172.5}{2.2^2} + \frac{172.5}{2.9^2} \right) \frac{\text{kW}}{\text{m}^2} \cong 6.2 \text{ kW/m}^2 \qquad \text{(H-4)}$$



FDS simulation.

Step 5. Sensitivity and Uncertainty Analysis

Table H-2. Summary of model predictions for the annulus fire scenario.

Model	Bias Factor, δ	Standard Deviation, $\tilde{\sigma}_M$	Target	Predicted Value	Critical Value	Probability of Exceeding
Heat Flux (kW/m²)						
Point Source	1.42	0.55	Cables	9.2	6.0	0.553
Distributed Point Source	1.42	0.55		6.2	6.0	0.248
FDS	1.10	0.17		2.5	6.0	0.000
Target Temperature (°C)						
FDS	1.02	0.13	Cables	120.0	205.0	0.000
Plume Temperature (°C)						
FDS	1.15	0.11	Sprinkler	90.0	100.0	0.001

Sensitivity Analysis – how do changes in the input parameters affect the outcome?

Output Quantity = Constant × (Input Parameter)$^{\text{Power}}$

(Relative Change in Output) = Power x (Relative Change in Input)

Relative Change in Plume Temperature= 2/3 x Relative Change in HRR

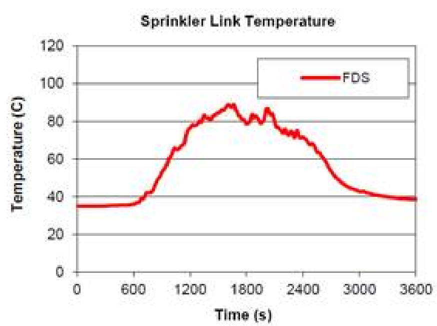


Figure H-6. Predicted sprinkler link temperature for the annulus fire scenario.

$$\Delta \dot{Q} = \frac{3}{2}\dot{Q}\frac{\Delta T}{T - T_0} = \frac{3}{2} 945\ \mathrm{kW} \times \frac{10\ {}^\circ\mathrm{C}}{90\ {}^\circ\mathrm{C} - 35\ {}^\circ\mathrm{C}} \cong 258\ \mathrm{kW}$$

Table 4-3. Sensitivity of model outputs from Volume 2 of NUREG-1824 (EPRI 1011999).

Output Quantity	Important Input Parameters	Power Dependence
HGL Temperature	HRR Surface Area Wall Conductivity Ventilation Rate Door Height	2/3 -1/3 -1/3 -1/3 -1/6
HGL Depth	Door Height	1
Gas Concentration	HRR Production Rate	1/2 1
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

H.6 Conclusion

Simple point source heat flux calculations indicate that a fire in one of the cable trays within the annulus region of the containment building might damage the cables in an adjacent tray. However, an additional analysis using FDS indicates that cable damage is unlikely due to the orientation of the target cables and the blockage of thermal radiation by the cable tray itself. This suggests that the details of the cable tray location, orientation, and configuration can significantly impact potential for damage.

FDS predicts that sprinkler activation above the fire is unlikely. However, its prediction is sensitive to the exact location of the sprinkler relative to a fire plume that may be subject to unpredictable air movements throughout the entire facility. Alternative protection strategies, such as shielding between trays or other thermal barriers, should be considered to ensure the protection of the redundant cables.

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The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) and the Electric Power Research Institute (EPRI) working under a memorandum of understanding (MOU) jointly conducted two sessions of the NRC–RES/EPRI Fire Probabilistic Risk Assessment (PRA) Workshop on July 16–20, 2012, and September 24–28, 2012, at the Bethesda Marriott in Bethesda, MD. The purpose of the workshop was to provide detailed, hands-on training on the fire PRA methodology described in the technical document, NUREG/CR-6850 (EPRI 1011989) entitled "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities." This fire PRA methodology document supports implementation of the risk-informed, performance-based rule in Title 10 of the Code of Federal Regulations (10 CFR) 50.48(c) endorsing National Fire Protection Association (NFPA) Standard 805, as well as other applications such as exemptions or deviations to the agency's current regulations and fire protection significance determination process (SDP) phase 3 applications.

This NUREG/CP documents both of the two sessions of the NRC-RES/EPRI Fire PRA Workshop delivered in 2012 and includes the slides and handout materials delivered in each module of the course as well as video recordings of the training that was delivered. This NUREG/CP can be used as an alternative training method for those who were unable to physically attend the training sessions. This report can also serve as a refresher for those who attended one or more training sessions and could also be useful preparatory material for those planning to attend future sessions.

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