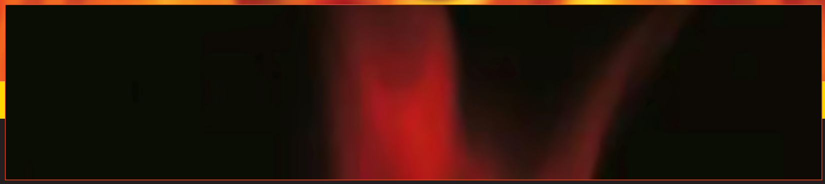

Fire Dynamics Tools (FDT[s])

Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program

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

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NUREG-1805

Fire Dynamics Tools (FDT^{s}):

Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program

Final Report

Manuscript Completed: October 2004
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Prepared for
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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Reactor Regulation (NRR), Division of Systems Safety and Analysis (DSSA), Plant Systems Branch (SPLB), Fire Protection Engineering and Special Projects Section, has developed quantitative methods, known as "Fire Dynamics Tools" (FDT^s), to assist regional fire protection inspectors in performing fire hazard analysis (FHA). These methods have been implemented in spreadsheets and taught at the NRC's quarterly regional inspector workshops. FDT^s were developed using state-of-the-art fire dynamics equations and correlations that were preprogrammed and locked into Microsoft Excel® spreadsheets. These FDT^s will enable the inspector to perform quick, easy, first-order calculations for the potential fire scenarios using today's state-of-the-art principles of fire dynamics. Each FDT^s spreadsheet also contains a list of the physical and thermal properties of the materials commonly encountered in nuclear power plants. This NUREG-series report addresses the technical bases for FDT^s, which were derived from the principles developed primarily in the Society of Fire Protection Engineers (SFPE) *Handbook of Fire Protection Engineering,* National Fire Protection Association (NFPA) *Fire Protection Handbook*, and other fire science literature. The subject matter of this report covers many aspects of fire dynamics and contains descriptions of the most important fire processes. A significant number of examples, reference tables, illustrations, and conceptual drawings are presented in this report to expand the inspector's appreciation in visualizing and retaining the material and understanding calculation methods.

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Tables (continued)

Tables (continued)

LIST OF FIRE DYNAMICS TOOLS

The NRC's Office of Nuclear Reactor Regulation (NRR) developed the fire dynamics tools (FDT[s]) using commercially available software (Microsoft Excel® 2000).

FDT[s]	Chapter and Related Calculation Method(s)
02.1_Temperature_NV.xls	**Chapter 2.** Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire with Natural Ventilation Method of McCaffrey, Quintiere, and Harkleroad (MQH) • Compartment with Thermally Thick/Thin Boundaries
02.2_Temperature_FV.xls	**Chapter 2.** Predicting Hot Gas Layer Temperature in a Room Fire with Forced Ventilation Method of Foote, Pagni, and Alvares (FPA) • Compartment with Thermally Thick/Thin Boundaries Method of Deal and Beyler • Compartment with Thermally Thick/Thin Boundaries
02.3_Temperature_CC.xls	**Chapter 2.** Predicting Hot Gas Layer Temperature in a Room Fire with Door Closed Compartment has Sufficient Leaks to Prevent Pressure Buildup; Leakage is Ignored Method of Beyler
03_HRR_Flame_Height_Burning_ Duration_Calculation.xls	**Chapter 3.** Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration and Flame Height
04_Flame_Height_Calculations.xls	**Chapter 4.** Estimating Wall Fire Flame Height, Line Fire Flame Height Against the Wall, and Corner Fire Flame Height

LIST OF FIRE DYNAMICS TOOLS (continued)

FDT^s	Chapter and Related Calculation Method
	Chapter 5. Estimating Radiant Heat Flux from Fire to a Target Fuel
05.1_Heat_Flux_Calculations_Wind_Free.xls	*Wind-Free Condition* • Point Source Radiation Model (Target at Ground Level) • Solid Flame Radiation Model (Target at Ground Level) • Solid Flame Radiation Model (Target Above Ground Level)
05.2_Heat_Flux_Calculations_Wind.xls	*Presence of Wind* • Solid Flame Radiation Model (Target at Ground Level) • Solid Flame Radiation Model (Target Above Ground Level)
05.3_Thermal_Radiation_From_Hydrocarbon_Fireballs.xls	Estimating Thermal Radiation from Hydrocarbon Fireballs
06_Ignition_Time_Calculations.xls	**Chapter 6.** Estimating the Ignition Time of a Target Fuel Exposed to a Constant Radiative Heat Flux • Method of Estimating Piloted Ignition Time of Solid Materials Under Radiant Exposures Method of (1) Mikkola and Wichman, (2) Quintiere and Harkleroad, and (3) Janssens • Method of Estimating Piloted Ignition Time of Solid Materials Under Radiant Exposures Method of Toal, Silcock and Shields • Method of Estimating Piloted Ignition Time of Solid Materials Under Radiant Exposures Method of Tewarson
07_Cable_HRR_Calculations.xls	**Chapter 7.** Estimating Full-Scale Heat Release Rate of a Cable Tray Fire
08_Burning_Duration_Soild.xls	**Chapter 8.** Estimating Burning Duration of Solid Combustibles
09_Plume_Temperature_Calculations.xls	**Chapter 9.** Estimating Centerline Temperature of a Buoyant Fire Plume

LIST OF FIRE DYNAMICS TOOLS (continued)

FDT[s]	Chapter and Related Calculation Method
10_Detector_Activation_Time.xls	Estimating Detector Response Time **Chapter 10.** Estimating Sprinkler Response Time **Chapter 11.** Estimating Smoke Detector Response Time **Chapter 12.** Estimating Heat Detector Response Time
13_Compartment_ Flashover_ Calculations.xls	**Chapter 13.** Predicting Compartment Flashover • Compartment Post-Flashover Temperature: Method of Law • Minimum Heat Release Rate Required to Compartment Flashover: Method of (1) McCaffrey, Quintiere, and Harkleroad (MQH); (2) Babrauskas; and (3) Thomas
14_Compartment_Over_Pressure_ Calculations.xls	**Chapter 14.** Estimating Pressure Rise Attributable to a Fire in a Closed Compartment
15_Explosion_Claculations.xls	**Chapter 15.** Estimating the Pressure Increase and Explosive Energy Release Associated with Explosions
16_Battery_Room_Flammable_Gas_ Conc.xls	**Chapter 16.** Calculating the Rate of Hydrogen Gas Generation in Battery Rooms • Method of Estimating Hydrogen Gas Generation Rate in Battery Rooms • Method of Estimating Flammable Gas and Vapor Concentration Buildup in Enclosed Spaces • Method of Estimating Flammable Gas and Vapor Concentration Buildup Time in Enclosed Spaces

LIST OF FIRE DYNAMICS TOOLS (continued)

FDT[s]	Chapter and Related Calculation Method
	Chapter 17. Calculating the Fire Resistance of Structural Steel Members
17.1_FR_Beams_Columns_ Substitution_Correlation.xls	• Empirical Correlations
17.2_FR_Beams_Columns_Quasi_ Steady_State_Spray_Insulated.xls	• Beam Substitution Correlation (Spray-Applied Materials) • Column Substitution Correlation (Spray-Applied Materials) • Heat Transfer Analysis using Numerical Methods Protected Steel Beams and Columns (Spray-Applied)
17.3_FR_Beams_Columns_Quasi_ Steady_State_Board_Insulated.xls	• Heat Transfer Analysis using Numerical Methods Protected Steel Beams and Columns (Board Materials)
17.4_FR_Beams_Columns_Quasi_ Steady_State_Uninsulated.xls	• Heat Transfer Analysis using Numerical Methods Unprotected Steel Beams and Columns
18_Visibility_Through_Smoke.xls	**Chapter 18.** Estimating Visibility Through Smoke

DISCLAIMER

The calculation methods presented in this NUREG-series report and programmed in the Fire Dynamics Tools (FDT^s) spreadsheets include scientific calculations, as well as material physical and thermal properties relevant to fire hazard analyses. Each spreadsheet on the CD-ROM has been protected and secured to avoid calculation errors attributable to invalid entries in the cell(s). Although each calculation in each spreadsheet has been verified with the results of hand calculations, there is no absolute guarantee of the accuracy of these calculations.

The first-time analyst should read the text in this report in its entirety before making an analysis. Most of the equations and correlations in the spreadsheets are simple mathematical expressions commonly used in fire protection engineering. The mathematical expressions are not limited, however, and they sometimes give physically impossible values. Where we have encountered this problem, or where a value exceeds known limits, we have added red warning flags to the spreadsheets. For example a red flag appears when an equation increases the hot gas layer temperature as a result of a fire that goes well beyond those that are physically possible.

Finally, with respect to any errors, omissions, or oversights that may still exist in the text, we are of one mind. Any shortcomings are the results of something the other one of us did or did not do. No one else can share them.

The publication of this NUREG-series report completes the initial effort by the NRC's Office of Nuclear Reactor Regulation to produce an Introduction to Fire Dynamics for NRC Inspectors. Future updates or corrections, or new FDT^s spreadsheets will be posted on the NRC's public Web site in the Fire Protection section of the Reactor Operating Experience page at http://www.nrc.gov/reactors/operating/ops-experience/fire-protection.html.

To offer any questions, comments, or suggestions, or to report an error in the NUREG or FDT^s, please send an email message to NXI@nrc.gov or MXS3@nrc.gov, or write to:

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Mr. Iqbal has been actively involved in fire hazard analysis, computer and mathematical fire modeling, smoke spread and fire growth, fire code review and compliance, and fire risk assessment projects for U.S. commercial nuclear power plants. He also reviews and prepares safety evaluation reports for power reactors. Mr. Iqbal is currently involved in preparing safety evaluation reports to support renewal of licenses for extended operation of the Nation's operating nuclear power plants under Title 10, Part 54, of the *Code of Federal Regulations* (10 CFR Part 54). He has also been involved in research and development projects in fire protection engineering, with a particular focus on fundamental and applied aspects of fire safety science, engineering, and technology. In addition, Mr. Iqbal has authored several publications and technical reports on flame spread, burning rate, fire growth on materials, and fire hazard analysis.

Prior to joining the NRC, Mr. Iqbal worked for Hughes Associates, Inc., a leading engineering consulting firm specializing in engineering design, research and development, and advanced technology related to fire protection engineering. There, he was responsible for performing technical studies of a wide range of fire protection problems, as well as fire hazard and risk analysis of unusual and unique situations in commercial and industrial facilities and Department of Energy (DOE) nuclear processing facilities problems involving model building codes and fire codes that fail to adequately address a particular situation.

Mark Henry Salley, P.E.

Mark Henry Salley currently serves as Fire Research Team Leader in the NRC's Office of Nuclear Regulatory Research (RES); however, he prepared much of this publication as a Fire Protection Engineer in NRR. Mr. Salley holds Master and Bachelor of Science degrees in fire protection engineering, both from the University of Maryland at College Park. He is a registered professional engineer in fire protection engineering and a member of the NFPA, SFPE, and American Nuclear Society (ANS).

Prior to joining the NRC, Mr. Salley was the Corporate Fire Protection Engineer for the Tennessee Valley Authority Nuclear (TVAN) program. There, he was responsible for the overall TVAN Fire Protection and Fire Safe-Shutdown Program (under 10 CFR Appendix R). Mr. Salley worked on the restart of Sequoyah Nuclear Plant, Units 1 and 2, as well as Browns Ferry Nuclear Plant, Units 2 and 3. He also played an integral role in the completion of construction, licensing, and startup of Watts Bar Nuclear Plant, Unit 1.

Mr. Salley has also served as a Principle Project Engineer for Parsons-Main Inc. in Charlotte, North Carolina. There, he supported the restart of the K-reactor at the DOE Savannah River Site and the site-wide fire protection upgrade.

Mr. Salley has an extensive background in fire protection engineering, including firefighting, design engineering, fire testing, and analytical analysis. He has also authored papers in the area of fire protection engineering.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Dr. Frederick Mowrer and the University of Maryland, Department of Fire Protection Engineering. Both authors have attended Dr. Mowrer's Advanced Fire Modeling course (ENFP 625) as a part of their postgraduate studies, and the general concepts used in creating and developing the FDT^s spreadsheets are similar to those taught by Dr. Mowrer.

The authors also thank Mr. Sunil Weerakkody, the NRC Project Manager and Fire Protection Section Chief who spearheaded this project. We also gratefully acknowledge the contributions of our colleagues and managers at NRC Headquarters who supported us throughout this project, as well as the NRC's regional managers and fire protection inspectors who offered valuable contributions, support, and suggestions. The regional inspectors also contributed valuable advice during quarterly fire protection seminars to improve the quality of the FDT^s spreadsheets. We developed the final product with them in mind as the end users.

The authors also extend our thanks to Tanya Mensah and James Downs, Fire Protection Engineers with NRR/DSSA/SPLB, as well as the NRR Nuclear Safety Interns (Matthew Yoder, Jason Dreisbach, Joel Rivera-Oritz, and Alexander Velazquez-Lozada) who assisted us in preparing this report and the FDT^s spreadsheets. We deeply appreciate their invaluable assistance. We also gratefully acknowledge George Hausman, a Reactor Inspector in Region III, for assisting in making the FDT^s spreadsheets more user-friendly. We also extend special thanks to Ms. Paula Garrity, a Technical Editor with the Program Management, Policy Development and Analysis Staff of the NRC's Office of Nuclear Regulatory Research (RES), for providing editorial support, navigating us through the formal requirements, and assisting us in setting the style and appearance of the text. We are also indebted to Mr. Lionel Watkins and Ms. Monique King, two talented Visual Information Specialists in the Information and Records Services Division, Publishing and Distribution Services Branch, of the NRC's Office of Chief Information Officer (OCIO), who designed the cover and many of the graphics for this report. In addition, we greatly appreciate the support of Gary Lauffer (Chief of the Publishing Services Branch), Guy Beltz, (the agency's Printing Specialist), and Linda Stevenson (the agency's publications specialist), whose invaluable support and expertise were critical to ensuring the quality of the published manuscript.

Our sincere thanks also go to Mr. Gerald Haynes, a Fire Protection Engineer, with the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF&E) in Washington, DC, who identified the concept of spreadsheets used in the ATF&E fire and arson investigation program. The ATF&E's spreadsheets served as a conceptual model for the NRC's effort. Mr. Haynes, Mr. Stephen Hill, and numerous Certified Fire Inspectors (CFIs) at the ATF&E also provided valuable comments on the development of the NRC's spreadsheets.

Finally, the authors thank the NRC inspectors and external stakeholders who took the time to provide comments, suggestions, and words of encouragement on the first draft of this document when it was published in the *Federal Register* (Vol. 68, No. 140, Page 43400). The following pages acknowledge these contributors.

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Reactor Regulation (NRR), Division of Systems Safety and Analysis (DSSA), Plant Systems Branch (SPLB), Fire Protection Engineering and Special Projects Section, has developed quantitative methods, known as "Fire Dynamics Tools" (FDT^s), to assist regional fire protection inspectors in performing fire hazard analysis (FHA). These methods have been implemented in spreadsheets and taught at the NRC's quarterly regional inspector workshops conducted in 2001–2003. The goal of the training is to assist inspectors in calculating the quantitative aspects of a postulated fire and its effects on safe nuclear power plant (NPP) operation. FDT^s were developed using state-of-the-art fire dynamics equations and correlations that were preprogramed and locked into Microsoft Excel® spreadsheets. These FDT^s will enable the inspector to perform quick, easy, first-order calculations for the potential fire scenarios using today's state-of-the-art principles of fire dynamics. Each FDT^s spreadsheet also contains a list of the physical and thermal properties of the materials commonly encountered in NPPs.

The FDT^s are intended to assist fire protection inspectors in performing risk-informed evaluations of credible fires that may cause critical damage to essential safe-shutdown equipment, as required by the new reactor oversight process (ROP) defined in the NRC's inspection manual*. In the new ROP, the NRC is moving toward a more risk-informed, objective, predictable, understandable, and focused regulatory process. Key features of the new program are a risk-informed regulatory framework, risk-informed inspections, a significance determination process (SDP)** to evaluate inspection findings, performance indicators, a streamlined assessment process, and more clearly defined actions that the NRC will take for plants based on their performance.

This NUREG-series report addresses the technical bases for FDT^s, which were derived from the principles developed primarily in the Society of Fire Protection Engineers (SFPE) *Handbook of Fire Protection Engineering,* National Fire Protection Association (NFPA) *Fire Protection Handbook*, and other fire science literature. The subject matter of this report covers many aspects of fire dynamics and contains descriptions of the most important fire processes. A significant number of examples, reference tables, illustrations, and conceptual drawings are presented in this report to expand the inspector's appreciation in visualizing and retaining the material and understanding calculation methods.

The content of the FDT^s encompasses fire as a physical phenomenon. As such, the inspector needs a working knowledge of algebra to effectively use the formulae presented in this report and the FDT^s. Acquired technical knowledge or course background in the sciences will also prove helpful. The information contained in this report is similar to, but includes less theory and detail than, an undergraduate-level university curriculum for fire protection engineering students.

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* NRC Inspection Manual, Chapter 0609F, Appendix F, "Determining Potential Risk Significance of Fire Protection and Post-Fire Safe Shutdown Inspection Findings," February 27, 2001.

** NRC Inspection Manual, Chapter 0609F, Appendix F, Section F.5, "Fire Protection Risk Significance Screening Methodology—Phase 2, Step 4: Integrated Assessment of DID Findings (Excluding SSD) and Fire Ignition Frequency," February 27, 2001.

The goal of this report is to develop a common body of knowledge of fire protection and fire science to enable the inspector to acquire the understanding, skills, and abilities necessary to effectively apply principles of fire dynamics to analyze the potential effects of a fire in a commercial NPP. The FDT^s will advance the FHA process from an approach that is primarily qualitative to one that is more quantitative. The development of this report, the FDT^s, and the quarterly inspector workshops conducted in 2001–2003 is the NRC's first step in achieving that goal.

Toward that end, on November 22 and 23, 2004, the NRC conducted a 2-day public meeting at the agency's headquarters in Rockville, Maryland, with the sole purpose of sharing an "advanced copy" of NUREG-1805 with all interested stakeholders. The meeting was well-received, and the participants identified numerous suggestions to further refine both the advanced copy and the spreadsheets. We thank those stakeholders for their involvement and have made every attempt to include their valued comments in preparing the final files for the publication of this report.

Fire is a complex subject and transfer of its concepts to useful pursuits is a challenge. We hope that this report and the FDT^s can make a difference in the NRC's fire protection inspection program, specifically risk-informed fire protection initiatives such as the SDP and risk-informed inspection of circuits.

HOW TO USE THIS NUREG AND THE FDT^s

This NUREG-series report and the related Fire Dynamics Tools (FDT^s) provide first-order quantitative methods (i.e., traditional approaches, correlations, computations, closed form approximations or exact solutions, and hazard models) to assess the potential fire hazard development in commercial nuclear power plants (NPPs). This report is divided into chapters that correspond to FDT^s. First-time users should read this report in its entirety before performing an analysis. Once the basic principles are understood, the FDT^s can be used to perform fire dynamics calculations. As explained in this report, appropriate care must be exercised to apply the FDT^s within the limits of their validity.

The CD-ROM that accompanies this report provides separate folders containing the FDT^s spreadsheets. This text exclusively uses the spreadsheets in the "English Units" folder. The folder labeled "SI Units" contains the same FDT^s spreadsheets but requires all user inputs to be in SI units.

The chapters and appendices of this report provide basic text on fire protection engineering, to provide inspectors with an overview of the basic characteristics and behavior of fire, fire hazards of materials and buildings, and an overview of the fundamental methods of fire protection. Appendix F to this report contains a glossary of terms used in the field of fire protection engineering. Appendix I, "Mathematics Review and System of Units," is included to refresh the inspector's understanding of mathematical functions, dimensional consistency in equations, and variables used in the FDT^s. Each chapter contains practice problems for the inspector to apply the principles learned with the FDT^s program. Appendix J provides additional problems for added practice.

Each chapter in this report has one or more spreadsheet(s) based on the method discussed in the chapter. Each spreadsheet is designed to make the calculation method understandable, and all of them are in the same format. The input parameter cells in each spreadsheet are identified in yellow. The user needs to enter data by typing (on the keyboard) and making selections through the use of pull-down menus and dialog boxes. The spreadsheets also bundle many material properties to enable the user to select a single input from a table, instead of entering all of the associated parameters. The user simply needs to select the material from the provided list (pull-down menu), and the spreadsheet will automatically place the associated property data in the corresponding green input cells. For example, an inspector can simply click on "concrete" in the property table, and the correct parameters will appear in the input parameter cells. This will also eliminate errors in manually entering the properties in the input parameter cells. Where material properties are not available in the spreadsheet table, the user will have to enter the values manually without selecting any material from the material properties data table.

The spreadsheets explicitly show the calculation methods — in detail and step-by-step — so that the inspector can follow the application of the FHA methods. The example problems at the end of each chapter, and practice problems in Appendix J, have been designed to be solved mainly with the FDT^s; however, in some cases, simple calculations are required before using the FDT^s. The results of the calculations are designated by the word "ANSWER" in the spreadsheets.

The FDT[s] spreadsheets are programmed with mathematical equations that can produce “numerical” accuracy to any number of decimal places. For consistency, the authors generally chose two decimal places; however, the user should focus on the magnitude of the results and ***not*** attempt to solve problems by placing critical emphasis on decimal values. For example if a component is “damaged” at 700°F (371.11°C) and the calculated results indicate 699.99°F (371.10°C), only an inexperienced user would argue that damage is not probable. In many cases, a resultant close to 690°F (365.55°C) is close enough to suggest damage.

Fire dynamics is a constantly evolving science and rarely dictates a single answer as to how a fire burns. The user is encouraged to perform bounding calculations as a part of the FHA. This will form a window of possible, credible solutions. An example of this concept would be to vary ventilation rates (door open vs. door closed, mechanical ventilation system on vs. off, different vent locations, etc.).

A final word of caution is in order for users of this report and the accompanying spreadsheets. An FHA can often be a complex series of calculations and evaluations that are necessary to gain a comprehensive understanding of the fire risk and its potential effects on NPP safety. This report provides one important element of that process, namely assisting the user in understanding fire dynamics; however, this report was never intended to be the “end-all” text for a complete understanding of fire risk. Experience, engineering judgment, peer review, and other sources of information will be necessary for a complete understanding of the risk. For example, this report does not attempt to answer two important questions: “How accurate are the equations in this text? “Are they ±10%, or do they always over-predict the results?

At the time of this writing, the NRC’s Office of Nuclear Regulatory Research, in cooperation with the Electric Power Research Institute (EPRI), is subjecting this report to “verification and validation” (V&V) against another fire dynamics method and three fire models to answer those very questions. Their final product should help reduce calculation uncertainties and provide additional insights to the methods and models. Another program that has been recommended is the development of a fire modeling user’s guide. Such a guide would compile in a usable format the lessons learned from the V&V exercise, as well as field experience from the use of this report, the accompanying spreadsheets, and other methods. As such, a user’s guide would help to further improve the overall quality of fire risk assessments.

ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
ACRS	Advisory Committee on Reactor Safeguards (NRC)
ADAMS	Agencywide Documents Access and Management System (NRC)
ADS	Automatic Depressurization System
AFFF	Aqueous Film Forming Foam
AFT	Adiabatic Flame Temperature
AFW	Auxiliary Feedwater
AGA	American Gas Association
AHJ	Authority Having Jurisdiction
AISI	American Iron and Steel Institute
AL	Administrative Letter
ALC	Approximate Lethal Concentration
ANS	American Nuclear Society
ANSI	American National Standards Institute
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASCOS	Analysis of Smoke Control Systems
ASET	Available Safe Egress Time
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASMET	Atria Smoke Management Engineering Tools
ASTM	American Society for Testing and Materials
AT	Auxiliary Transformer
ATF&E	Alcohol, Tobacco, Firearms, and Explosives
AWG	American Wire Gauge
BFC	Bromochlorodifluoro-methane
BFNP	Browns Ferry Nuclear Power Plant
BFRL	Building and Fire Research Laboratory
BL	Bulletin
BLEVE	Boiling Liquid, Expanding Vapor Explosion
BOCA	Building Officials & Code Administration International
BREAK1	Berkeley Algorithm for Breaking Window Glass in a Compartment Fire
BS	British Standard
BTP	Branch Technical Position
BTU	British Thermal Unit
BWR	Boiling-Water Reactor
CCW	Component Cooling Water
CFAST	Consolidate Model of Fire Growth and Smoke Transport
CFD	Computational Fluid Dynamics
CFI	Certified Fire Inspector
CFO	Chief Financial Officer (NRC)
CFR	*Code of Federal Regulations*
CHF	Critical Heat Flux

CIB	Conseil Internationale du Batiment
CIBSI	Chartered Institution of Building Services Engineers
CIO	Chief Information Officer (NRC)
CL.S.PE	Chlorosulfonated Polyethylene
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CP	Construction Permit
CPCV	Chlorinated Polyvinylchloride
CPE	Chlorinated Polyethylene
CPSC	Consumer Product Safety Commission
CR	Circular or Neoprene or Chloroprene Rubber
CSNI	Committee on the Safety of Nuclear Installations
CSP	Chlorosulfonated Polyethylene Rubber (Kel-F®)
CSR	Cable Spreading Room
CTEF	Chlorotrifluoroethylene
DDT	Deflagration to Detonation Transition
DETACT-QS	Detector Actuation Quasi-Steady
DETACT-T2	Detector Actuation Time Square
DID	Defense-in-Depth
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DSSA	Division of Systems Safety and Analysis (NRC)
ECCS	Emergency Core Cooling System
EDG	Emergency Diesel Generator
EDO	Executive Director for Operations (NRC)
ELVAC	Elevator Evacuation
EMI/RFI	Electromagnetic or Radio-Frequency Interface
EPA	Environmental Protection Agency
EPR	Ethylene-Propylene Rubber
EPRI	Electrical Power Research Institute
EQ	Equipment Qualification
ESFR	Early Suppression Fast Response
ETFE	Ethylenetetrafluoroethylene (Tefzel®)
EVA	Ethylvinyl Acetate
FAA	Federal Aviation Administration
FDI	Fire Detection Institute
FDM	Fire Demand Model
FDS	Fire Dynamics Simulator
FDT^s	Fire Dynamics Tools
FEM	Finite Element Method
FEMA	Federal Emergency Management Agency
FEP	Fluorinated Polyethylene Propylene (Teflon®)

FFFP	Film-Forming Fluoroprotein Foam
FHA	Fire Hazard Analysis
FIGARO II	Fire and Gas Spread in Room (model)
FIPEC	Fire Performance of Electrical Cables
FIRES-T3	Fire Response of Structures-Thermal Three (model)
FIVE	Fire Induced Vulnerability Evaluation
FMRC	Factory Mutual Research Corporation
FPA	Foote, Pagni, and Alvares
FPE	Fire Protection Engineer(ing)
FPETOOL	Fire Protection Engineering Tool
FPP	Fire Protection Program
FPS	Fire Protection System
FR	Fire-Retardant
FRP	Fiberglass Reinforced Polyester (Plastic)
FRXPE	Fire-Retardant Crosslinked Polyethylene
FSSD	Post-Fire Safe-Shutdown
FTA	Federal Transit Authorization
FTMS	Federal Test Method Standard
GDC	General Design Criteria
GL	Generic Letter
GSA	General Service Administration
GSI	Generic Safety Issue
H_2O	Water
HBr	Hydrogen Bromide
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HEPA	High-Efficiency Particulate Air Filter
HF	Hydrogen Fluoride
HPCI	High Pressure Cooling Injection
HRR	Heat Release Rate
HTGR	High-Temperature Gas-Cooled Reactor
HVAC	Heating, Ventilation, and Air Conditioning
IAFSS	International Association of Fire Safety Science
IBC	International Building Code
ICBO	International Conference of Building Officials
ICS	Integrated Control System
ICSDTS	International Committee for the Study and Development of Tubular Structures
IE	Initiative Events
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IN	Information Notice
INEEL	Idaho National Engineering and Environmental Laboratory
IPEEE	Individual Plant Examination of External Events
ISO	International Organization for Standardization

LAVENT	Link Actuation Vents
LC	Lethal Concentration
LCL	Lethal Concentration Low
LD	Lethal Dose
LDL	Lethal Dose Low
LEL	Lower Explosive Limit
LER	Licensee Event Report
LFL	Lower Flammability Limit
LIFT	Lateral Ignition and Flame Spread (ASTM E 1321 Standard Test Method)
LLNL	Lawrence Livermore National Laboratory
LNG	Liquified Natural Gas
LOC	Limiting Oxidant Concentration
LOCA	Loss-of-Coolant Accident
LPG	Liquid Propane Gas
LWR	Light-Water Reactor
MCC	Motor Control Center
MCR	Main Control Room
MESG	Maximum Experimental Safe Gap
MOV	Motor-Operated Valve
MQH	McCaffrey, Quintiere, and Harkleroad
NBC	National Building Code
NBR	Nitrile
NBS	National Bureau of Standards
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NEMA	National Electrical Manufacturers Association
NFC	National Fire Code
NFPA	National Fire Protection Association
NIOSH	National Institute of Occupational Safety ad Health
NIST	National Institute of Standards and Technology
NO_2	Nitrogen Dioxide
NOUN	Notification of Unusual Event
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation (NRC)
NUREG	NUclear REGulatory Guide
OCIO	Office of Chief Information Officer (NRC)
OL	Operating License
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OSU	Ohio State University

PASS	Personal Alert Safety System
PC	Polycarbonate
PDA	Primary Disconnect Assembly
PE	Polyethylene
PEF	Polyethylene Fluoride
PES	Polyethersulphone
PFA	Perfluoroalkoxy Branched Polymers
PMMA	Polymethylmethacrylate
PP	Polypropylene
PPE	Polytetrafluoroethylene
PRA	Probabilistic Risk Assessment
PS	Polystyrene
PTEF	Polytetrafluoroethylene (Teflon®)
PU	Polyurethane
PVC	Polyvinylchloride
PVF	Polyvinylfluoride
RCP	Reactor Coolant Pump
RES	Office of Nuclear Regulatory Research (NRC)
RG	Regulatory Guide
RHR	Residual Heat Removal
RIS	Regulatory Issue Summary
RMV	Respiratory Minute Volume
ROP	Reactor Oversight Process
RTECS	Registry of the Toxic Effects of Chemical Substance
RTI	Response Time Index
RWFD	Red Wing Fire Department
S/G	Steam Generator
SBC	Standard Building Code
SBCCI	Southern Building Code Congress International
SBDG	Standby Diesel Generator
SBR	Styrene Butadiene Rubber
SCBA	Self-Contained Breathing Apparatus
SDP	Significance Determination Process
SER	Significant Event Report
SFPE	Society of Fire Protection Engineers
SI	System International
SNL	Sandia National Laboratories
SOLAS	Safety of Lives at Sea
SONGS	San Onofre Nuclear Generating Station
SPLB	Plant Systems Branch (NRC)
SRP	Standard Review Plan (NUREG-0800)
SSC	Structure, System, and/or Component

TASEF	Temperature Analysis of Structure Exposed to Fire
TCL	Toxic Concentration Low
TDL	Toxic Dose Low
TFE	Tetrafluoroethylene (Teflon®)
TLC	Toxic Concentration Low
TLV	Threshold Limit Value
TNT	Trinitrotoluene
TRP	Thermal Response Parameter
TSC	Technical Support Center
TTC	Time-Temperature Curve
TVA	Tennessee Valley Authority
TVAN	Tennessee Valley Authority Nuclear Program
UBC	Uniform Building Code
UEL	Upper Explosive Limit
UFC	Uniform Fire Code
UFL	Upper Flammability Limit
UL	Underwriters Laboratories
UPS	Uninterruptible Power Supply
USFA	United States Fire Administration
UVCE	Unconfined Vapor Cloud Explosion
V&V	verification and validation
VRLA	Valve-Regulated Lead Acid
W/D	Weight-to-Heated Perimeter Ratio
XLPE	Crosslinked Polyethylene
XLPO	Crosslinked Polyolefin

NOMENCLATURE

A_c	Compartment floor area
A_e	Surface of element
A_f	Horizontal burning area of fuel
A_H	Ampere hours
A_s	Cross sectional area
A_T	Area of compartment enclosing surfaces (excluding vent areas)
A_v	Area of ventilation openings
b	Flame spread parameter
C	Gas concentration by volume
c	Thermal capacity
c_i	Specific heat of insulation
c_p	Specific heat
c_s	Specific heat of steel
c_v	Specific heat at constant volume
CHF	Critical heat flux for ignition
D	Diameter
D	Heated parameter
D_{SC}	Scaled distance
E	Emissive power
E	Explosive energy released
F	Configuration or shape factor
F	Fire resistance time
FTP	Flux time product
F_c	Float Current per 100 AH
g	Acceleration of gravity
G	Gas discharge rate
h	Thickness of insulation
h	Heat flux time product index
h_c	Compartment height
h_{eff}	Effective heat transfer coefficient
h_{ig}	Heat transfer coefficient at ignition
h_k	Convective heat transfer coefficient
h_v	Height of ventilation opening
H	Thermal capacity of steel section at ambient
H	Height
H_g	Hydrogen gas generation
H_f	Flame height
$H_{f(wall)}$	Wall flame height
$H_{f(wall,line)}$	Line fire flame height
$H_{f(corner)}$	Corner fire flame height

k	Thermal conductivity
k_i	Thermal conductivity of insulation
k c	Thermal inertia
K	Mixing efficiency factor
K	Proportionality constant
l_c	Compartment length
L	Length
LFL	Lower flammability limit
m	Mass
m_f	Mass of fuel vapor
m_f	Mass of fuel burned
m_p	Mass concentration of particulate
$\dot{m}$	Mass flow rate
$\dot{m}_e$	Mass entrainment rate
$\dot{m}_f$	Mass flow rate of fuel
$\dot{m}_o$	Mass flow rate out of enclosure
$\dot{m}_p$	Plume mass flow rate
$\dot{m}''$	Mass loss rate per unit area
M_p	Mass of particulates produced
N	Number of cells (batteries)
N	Number of theoretical air changes
P	Pressure
$\dot{q}''$	Heat flux
$\dot{q}''_{crit}$	Critical heat flux
$\dot{q}''_e$	External heat flux
$\dot{q}''_{min}$	Minimum heat flux required for ignition
$\dot{q}''_r$	Radiative heat flux
Q	Volume of air
Q_{total}	Total energy release
$\dot{Q}$	Heat release rate or energy release rate
$\dot{Q}_c$	Convective energy release rate
$\dot{Q}_{FO}$	Energy release rate to cause flashover
$\dot{Q}_{fs}$	Full-scale energy release rate
$\dot{Q}_{bs}$	Bench-scale energy release rate

r	Radius
R	Radial distance
R	Fire Resistance
RTI	Response time index
S	Visibility
t	Time
t_b	Burning duration
t_D	Detection time
t_{ig}	Ignition time
t_p	Thermal penetration time
t_r	Detector response time
t_t	Smoke transit time
$t_{activation}$	Sprinkler activation time
T	Temperature
T_a	Ambient temperature
T_f	Fire temperature
$T_{FO(max)}$	Post-flashover compartment temperature
T_g	Gas temperature
T_s	Steel temperature
T_{jet}	Ceiling jet temperature
$T_{p(centerline)}$	Plume centerline temperature
$T_{activation}$	Activation temperature
u_{jet}	Ceiling jet velocity
u_w	Wind velocity
u_o	Gas velocity
u*	Nondimensional wind velocity
V	Volume
V_{def}	Volume of gas for deflagration
w	Fuel exposed width
w_c	Compartment width
W	Weight of steel column per linear foot
W_{TNT}	Weight of TNT
y_p	Particulate yield
z	Height of smoke layer interface above floor
z_o	Hypothetical virtual origin of fire source
Z_p	Fireball flame height
H_c	Heat of Combustion
$H_{c,eff}$	Effective heat of combustion
t	Time step
T_g	Gas temperature above ambient
T_{ig}	Ignition temperature above ambient
	Heat transfer coefficient for steel

	Yield (fraction of available energy participating in blast wave generation)
m	Specific extinction coefficient
r	Fraction of total energy radiated
	Thickness
	Flame emissivity
	Ventilation factor
	Flame title or angle of deflection
	Density
a	Density of Ambient Air
c	Density of combustion products
c	Density of concrete
F	Density of fuel vapor
g	Density of gas
i	Density of insulation
	Stafan-Boltzmann constant
o	Detector time constant
	Regression rate

Subscripts

a	Ambient
bs	Bench-scale
c	Compartment
c	Combustion
c	Concrete
c	Current
D	Detection
def	Deflagration
e	Convective
e	External
eff	Effective
e	Entrainment
f	Fire
f	Flame
f	Fuel
f(corner)	Corner flame
f(wall)	Wall flame
f(wall,line)	Line fire flame
FO	Flashover
fs	Full-scale
g	Gas
H	Hours
I	Insulation
ig	Ignition
jet	Ceiling jet
m	Extinction
min	Minimum
o	Out

p	Specific
p	Particulate
p	Plume
p	Penetration
r	Radiative
r	Response
SC	Scale
s	Steel
T	Total
total	Total
t	Transient
TNT	Trinitrotoluene
v	Vent
v	Volume
w	Wind

Superscripts

$(\dot{\ })$	Per unit time
$(\ )''$	Per unit area
$(\dot{\ })''$	Per unit are, per unit time
*	Nondimensional

CHAPTER 1. INTRODUCTION

1.1 Purpose

The purpose of this NUREG-series report is to introduce the principles of fire dynamics and illustrate how fire protection inspectors can apply those principles in a risk-informed manner to better determine whether credible fire scenarios are possible. In this context, we broadly define the term "fire dynamics" as the scientific study of hostile fires. The dynamic nature of fire is a quantitative and mathematically complex subject. It combines physics, chemistry, mathematics, and engineering principles and can be difficult to comprehend for those who have a limited background in these areas. With the objective of quantitatively describing fire and related processes (i.e., ignition, flame spread, fire growth, and smoke movement) and their effects in an enclosure, the Fire Dynamics Tools (FDT^s) have been developed to assist fire protection inspectors in solving fire hazard problems in nuclear power plants (NPPs).

The goal of this report is to provide insights into fire dynamics, without using the sophisticated mathematics that are normally associated with the study of fire dynamics. Nonetheless, inspectors will need a working knowledge of algebra, reading graphs, scientific notation, formulas, and use of some simple mathematics functions to understand the quantitative aspect of fire phenomena. A better understanding of these processes will improve the quality of fire protection inspections conducted by the U.S. Nuclear Regulatory Commission (NRC).

1.2 Objective

The primary objective of this report is to provide a basic calculation methodology for use in assessing potential fire hazards in the NRC-licensed NPPs. The methodology uses simplified, quantitative fire hazard analysis (FHA) techniques to evaluate the potential for credible fire scenarios. One purpose of these evaluations is to determine whether a potential fire can cause critical damage to safe-shutdown components, either directly or indirectly by igniting intervening combustibles. The methodology used in this report is founded on material fire property data implemented in scientific calculations. In addition, the associated techniques have been assessed to ensure applicability and accuracy, and were derived primarily from the principles developed in the Society of Fire Protection Engineers (SFPE) *Handbook of Fire Protection Engineering*, and the National Fire Protection Association (NFPA) *Fire Protection Handbook*. The FHA methods have been implemented as Microsoft Excel® spreadsheets, which incorporate simple, empirical correlations and detailed mathematical equations based on fire dynamics principles. They also build on numerous tables of material fire property data, which have been assembled for NPPs. The combination of these spreadsheets and data tables forms the basis for the FDT^s.

1.3 Regulatory Background on Fire Protection for Nuclear Power Plants

The primary objectives of fire protection programs (FPPs) at U.S. NPPs are to minimize both the probability of occurrence and the consequences of fire. To meet these objectives, the FPPs for operating NPPs are designed to provide reasonable assurance, through defense-in-depth (DID), that a fire will not prevent the performance of necessary safe-shutdown functions and that radioactive releases to the environment in the event of a fire will be minimized. Section II, "General Requirements," of Appendix R to Title 10, Part 50, of the *Code of Federal Regulations* (10 CFR

Part 50), states that the fire protection program shall extend the DID concept to fire protection in fires areas that are important to safety, with the following objectives:

(1) Prevent fires from starting.

(2) Rapidly detect, control, and extinguish those fires that do occur.

(3) Protect structures, systems, and components that are important to safety so that a fire that is not promptly extinguished by the fire suppression activities will not prevent the safe shutdown of the plant.

The first element of this DID approach deals with preventing fires from starting. This can be accomplished by limiting fire sources that could initiate a fire at an NPP, and preventing any existing ignition sources from causing self-sustaining fires in combustible materials. Despite the nuclear industry's best efforts to eliminate or at least control ignition sources, accidental (and purposeful) sources of ignition often exist and can result in hostile fires. This is an important aspect of a total fire safety program, which should not be overlooked.

The second element of the prevention element deals with rapidly detecting, controlling, and extinguishing those fires that do occur. This can be achieved by preventing significant fires from occurring, given the inadvertent or purposeful introduction of an ignition source. If all structures and contents comprised totally noncombustible materials, this would not pose a problem. However, this is not the case. Buildings and their contents are composed of a variety of materials of various degrees of combustibility. Materials with higher thresholds of ignition and less hazardous combustion are continually being developed. Regardless, at least in some cases, the higher resistance to ignition can also result in a higher resistance to fire extinction (Hill, 1982). Electrical cables are a good example. While cables qualified to the Institute of Electrical and Electronic Engineers (IEEE) Standard 383 are more fire-resistant, they are also more difficult to extinguish once they ignite. In any case, the prevention of hostile fires will likely never be the total solution to the fire safety problem in NPPs.

The second element of the DID approach involves limiting fire spread through fire detection and fire suppression. There are various approaches to this element. In the event of a significant fire, its spread might be limited in the following ways:

- early human detection and manual suppression
- provision and maintenance of adequate fire detection and automatic fire suppression systems
- a combination of manual and automatic detection and suppression systems

Heat and smoke detectors; fire alarm systems; Halon 1301, carbon dioxide (CO_2), and dry chemical fire suppression systems; automatic sprinkler, foam, and water spray systems; portable fire extinguishers; hose stations, fire hydrants, and water supply systems; and fire brigades are all part of the second element of the DID approach. Each is highly developed in modern fire protection designs, and is constantly being further refined as fire technology advances. Nonetheless, the DID concept recognizes that the first two elements of fire defense are not always entirely successful in meeting the fire challenge.

The third element of the DID approach involves designing NPP structures, systems, and components (SSCs) to prevent significant damage in the event that the first two elements fail, either partially or fully. This goal may be fulfilled in the following ways:

- Isolate combustible elements by spatial separation, such that a fire in one fuel package will not propagate to any other fuel package.
- Isolate combustible elements by fire-resistant barriers to prevent fires from propagating from one area to another. In particular, fire-rated horizontal and vertical barrier systems will limit fire spread from compartment to compartment.

The NRC's regulatory framework for FPPs at U.S. NPPs is described in a number of regulatory and supporting guidelines, including but not limited to General Design Criterion (GDC) 3, as specified in Appendix R to Title 10, Part 50, of the *Code of Federal Regulations* (10 CFR Part 50); 10 CFR 50.48; Appendix R to 10 CFR Part 50; Regulatory Guide (RG) 1.189 and other regulatory guides, generic communications (e.g., generic letters, bulletins, and information notices), NUREG-series reports; the standard review plan (NUREG-0800); and associated branch technical positions (BTPs).

1.4 Fire Hazard Analysis for Nuclear Power Plants

As previously stated, fire protection for NPPs relies on the DID concept to achieve the required degree of reactor safety by using redundant levels of administrative controls, fire protection systems and features, and safe-shutdown capability. An FHA should be performed to assess the fire hazard and demonstrate that the NPP will maintain its ability to perform safe shutdown functions and minimize radioactive material releases to the environment in the event of a fire.

RG 1.189 lists the following objectives for an FHA:

- Consider potential in situ and transient fire hazards.
- Determine the consequences of fire in any location in the plant, paying particular attention to the impact on the ability to safely shut down the reactor or the ability to minimize and control the release of radioactivity to the environment.
- Specify measures for fire prevention, fire detection, fire suppression, and fire containment, as well as alternative shutdown capability for each fire area containing SSCs that are important to safety in accordance with NRC guidelines and regulations.

1.5 Fire Protection Inspection Findings

Fire protection inspection findings are generally classified as weaknesses associated with one or more objectives of the DID elements introduced above. If a given inspection does not yield any DID-related findings against a fire protection feature or system, the fire protection feature and system are considered to be capable of performing their intended functions and operating in their normal (standby) state.

1.6 Fire Scenario Development for Nuclear Power Plants

In the broadest sense, a fire scenario can be thought of as a specific chain of events that begins with the ignition of a fire and ends either with successful plant shutdown or core damage. The fire is postulated to occur at a specific location in a specific fuel package, and to progress through various stages of fire growth, detection, and suppression. In this process, the fire may damage some set of plant equipment (usually electrical cables). For a given fire source, the FHA may postulate damage to various sets of equipment, depending on how long the fire burns and how large the initial fire is presumed to be. The postulated or predicted fire damage may either directly or indirectly cause the initiating event (such as a plant trip, loss of offsite power, etc.).

When inspectors develop a fire scenario, they should postulate the worst-case, realistic fire, provided that the compartment and configuration of the fire area, room, or zone can support such a fire. For example, a large cabinet fire is one in which fire damage initially extends beyond the cabinet in which the fire originated. The fire damage attributed to a large cabinet fire often extends into the overhead cabling, an adjacent cabinet, or both. A large fire for a pump or motor can often be based initially upon the largest (worst-case) oil spill from the equipment. If the configuration of the compartment, combustibles, etc., supports further growth of the large fire, the fire scenario should postulate that growth. Since scenarios that describe large fires are normally expected to dominate the risk-significance of an inspection finding, scenarios with small fires typically are not included unless they spread and grow into large fires.

1.7 Process of Fire Development

Fire hazards to NPP equipment can arise from many sources, including (but not limited to) thermal damage, fouling, and corrosivity. Fire is essentially a chemical reaction involving solids, liquids, and gases that ignite and undergo a rapid, self-sustaining oxidation process, accompanied by the evolution of heat and light of varying intensities. However, the chemical and physical reactions that take place during a fire are extremely complex and often difficult to describe completely. The most common fires start as a result of the ignition of solid or liquid fuels (combustible materials). Solid and liquid fuels typically become volatile and serve as suppliers of gaseous fuel to support combustion. In the physical model (illustrated in Figure 1-1) the process of fire development begins when the fuel surface starts to heat up as a result of heat transfer from the adjacent surroundings. As the temperature of the fuel surface increases in response to this heat input, the fuel surface begins to emit fuel vapors. The fuel vapors mix (by convection and diffusion) with oxygen in the adjacent boundary layer, ignite (through a chemical reaction), and release additional heat. Some of this liberated heat energy may further increase the surface temperature of the fuel and thereby accelerate the fire growth process.

Many materials react with oxygen to some degree; however, various materials differ in their respective rates of reaction. The difference between slow-and rapid-oxidation reactions is that the latter occur so rapidly that heat is generated faster than it is dissipated, causing the material being oxidized (fuel) to reach its ignition temperature. Once a material reaches its ignition temperature, it ignites and continues to burn until either the fuel or the oxygen is consumed. The heat released during combustion is usually accompanied by a visible flame. However, some materials (such as charcoal) smolder, rather than producing a visible flame. A familiar slow-oxidation reaction is the rusting of iron. Such a reaction releases heat so slowly that the temperature hardly increases more than a few degrees above the temperature of the surroundings. These reactions typically do not cause fires and are not considered combustion.

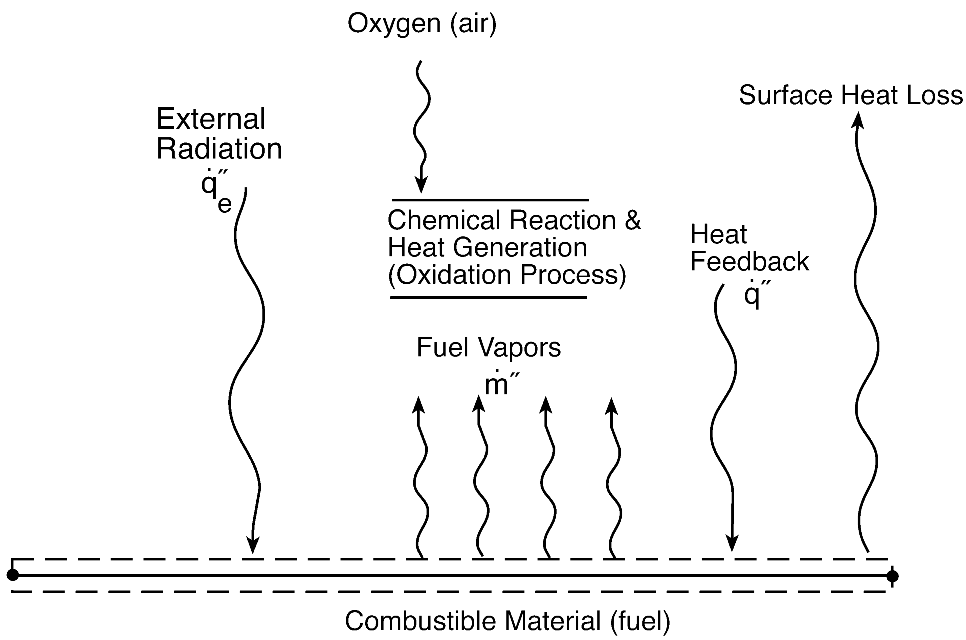

Figure 1-1 Physical Process of Combustion and Fire

Generally, three components are required to support combustion. These three components— fuel, oxygen, and heat source—are depicted in Figure 1-2, which is commonly called the fire triangle. The fire triangle shows that for combustion to occur, fuel, an oxidizing agent, and a heat source must be present in the same place at the same time. If any one of the legs of the triangle is removed, the combustion process will not be sustained. This is the most basic description of the fire phenomenon. It is applicable for most scenarios, with the exception of fire extinguishment involving dry chemicals and Halons.

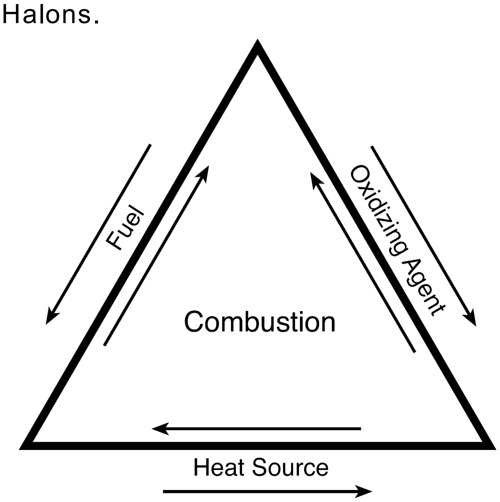

Figure 1-2 The Fire Triangle

1.8 The Fire Hazards

The fire load of NPPs is different than that of fossil-fuel power plants and many other industrial plants. An NPP does not have a constant flow of fuel (e.g., coal or oil) as the hazard. However, an NPP may have similar fire hazards, such as grouped electrical cables and lubricating oils (e.g., turbine, reactor coolant pumps). Table 1-1 lists the combustibles and hazardous materials that are commonly present in NPPs.

Table1-1. Common Combustible and Hazardous Materials in NPPs
Combustible solid fuels Cable insulation and jackets Other thermal and electric insulation materials (e.g., pipe insulation) Building materials Combustible metal deck and roof assemblies Filtering materials including charcoal and high-efficiency particulate air (HEPA) filters Packing materials and waste containers Flexible materials used in connection with a seismic design, including flexible joints Sealing materials (e.g., asphalt, silicone foam, neoprene, etc.) Solidification agents for packing compacted radioactive waste conditioning (e.g., bitumen) Low-level radioactive waste material (e.g., paper, plastic, anti-C-zone clothing, rubber shoes and gloves, overalls, etc.)
Combustible and flammable liquid fuels Lubricants, hydraulic oil, and control fluids Conventional fuels for emergency power units, auxiliary boilers, etc. Paints and solvents
Explosive and flammable gaseous fuels Hydrogen to cool the generators Propane or other fuel gases, such as those used for starting boilers, burning radwaste, etc. Oxygen and hydrogen radiolysis of reactor coolant water within the pressure vessel and addition of hydrogen for improved recombination Hydrogen generated in battery room as a result of overcharging a battery

The quantities and locations of these combustibles vary among NPPs. More importantly, identification of these combustibles and their characteristics only partially identifies the associated fire hazard. The bearing that the fire hazards have on nuclear safety must also be considered in defining the *total* fire hazard. Nuclear safety factors include maintaining the safe-shutdown capability and preventing radiation releases that exceed acceptable limits.

Fire hazards related to NPPs include (but are not limited) to the following examples:

- fire hazard associated with electrical cable insulation
- fire hazard of ordinary combustibles
- oil fire hazards associated with large reactor coolant pump motors
- oil fire hazard involving emergency turbine-driven feedwater pumpsdiesel fuel fire hazard at diesel-driven generators
- fire hazard involving charcoal in filter units
- fire hazard associated with flammable offgases
- fire hazard of protective coatings
- fire hazard of turbine lube oil and hydrogen seal oil

- hydrogen cooling gas fire hazard in turbine generator buildings
- fire hazard associated with electrical switchgear, motor control centers (MCCs), electrical cabinets, load centers, inverter, circuit boards, and transformers

1.8.1 Combustible Materials Found in Nuclear Power Plants

Combustible materials may be found in both large and small concentrations in NPPs. One can assume that outbreaks of fire may occur as a result of a variety of ignition sources. In general, the combustible materials in an NPP can be divided into four broad fuel categories, including (1) transient solid and liquid fuels, (2) in situ combustible consisting both solid and liquid fuels, (3) liquid fuels used in NPP equipment, and (4) explosive and flammable gases, as described in the following sections.

1.8.1.1 Transient Combustibles

Solid transient fuels include general trash, paper waste, wood, plastics, cloth, and construction/modification materials. By contrast, liquid transient fuels commonly include cleaning solvents, paints, and lubricants being transported through the NPP for maintenance of plant equipment. These fuels are generally found in small quantities in most NPP areas at any given time.

1.8.1.2 In Situ Combustibles

The most common category of potential fuels found in NPPs is that of in situ solid fuel elements. Of these, the largest single potential fuel source is cable insulation and jacketing materials. Several factors combine to support the conclusion that cable insulation and jacketing material far and away represent the most important materials to be considered in an NPP FHA, although any other plastic compounds installed in the NPP must also be included in the FHA. Cable insulation and jackets are typically manufactured using organic compounds and, therefore, they will burn under the proper circumstances.

The fire hazard associated with electrical cable insulation and jackets in NPPs is similar to that of other occupancies (e.g., telephone exchange) that use cable trays to support a large number of power, control, and instrument cables. However, an additional factor in NPPs is the added hazard associated with loss of reactor safety system redundancy.

A wide variety of cable insulation and jacketing materials can be commonly found in any given NPP. Cable insulation and jackets commonly encountered in an NPP include materials based on the following compounds:

- acrylonitrile-butadiene-styrene (ABS)
- chlorinated polyvinylchloride (CPVC)
- chlorosulfonated polyethylene rubber (CSP) (Hypalon®)
- chlorotrifluoroethylene (CTEF) (Kel-F®)
- cross-linked polyolefin (XLPO) including the more specific class of cross-linked polyethylene (XLPE)
- ethylenetetrafluoroethylene (ETFE) (Tefzel®)
- ethylene-propylene rubber (EPR)
- fluorinated polyethylene propylene (FEP) (Teflon®)
- neoprene or chloroprene rubber (CR)

- polycarbonate (PC)
- polyethylene (PE)
- polyethylene fluoride (PEF)
- polyethersulphone (PES)
- polypropylene (PP)
- polystyrene (PS)
- polytetrafluoroethylene (PTEF) (Teflon®)
- polyurethane (PU)
- polyvinyl chloride (PVC)
- silicone and silicone/rubber compounds
- styrene-butadiene rubber (SBR)
- tetrafluoroethylene (TFE) (Teflon®)

1.8.1.3 Liquid Fuels

Liquid fuels include lubricating and cooling oils, cleaning solvents, and diesel fuels. These items are commonly used in pumps, motor generators, hydraulic-operated equipment, diesel-driven engines, transformers, and other equipment that require lubrication and cooling with heat transferring oils. Fires involving such types of equipment are relatively common and usually results from leakage or overheating.

1.8.1.4 Explosive and Flammable Gases

Explosive and flammable gases are often present in an NPPs. The most common is hydrogen, which is present as a blanket inside the main generator and a byproduct of reactor operation (through dissociation of water). Battery rooms in NPPs are also a source of hydrogen gas production.

Gases can be categorized as flammable and nonflammable. In addition, some gases are not flammable but support combustion. For example, oxygen does not burn; however, most fires burn more rapidly if the oxygen concentration is increased.

A general word of caution about gaseous fuels: when a compressed gas, like butane, is released, the visible vapor cloud indicates that the gas is colder than the air temperature and, consequently, condensing the moisture in the air. It appears much like a fog; however, this visible cloud is not the extent of the gaseous vapor. This is because the vapor disappears from view as it warms up, but may still linger in the area. Thus, it is possible to stand in an invisible gaseous vapor with a concentration that is within the flammable range. If the vapor were to ignite, the person could be burned severely, if not killed.

1.9 Location of the Fire

Exposure fires involving transient combustibles are assumed to have an equal probability of occurring anywhere in a space or an enclosure, while fires involving fixed combustibles are assumed to occur at the site of the fixed combustible. Since the hazard is greater when a fire is located directly beneath a target (e.g., cable tray or electrical cabinet), this placement is normally evaluated for scenarios involving transient combustibles. For fixed combustibles, the actual geometry between the source and the target is evaluated to determine whether the target is located in the fire plume or ceiling jet region.

1.10 Risk-Informed, Performance-Based Fire Protection

Risk-informed, performance-based fire protection is an integration of decision-based and quantitative risk assessment with a defined approach for quantifying the performance success of fire protection systems (FPSs) (Barry, 2002).

Performance-based fire safety engineering is defined as "An engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and growth effluents; and (4) a quantitative assessment of the effectiveness of design alternatives against objectives," (Custer and Meacham, 1997).

One primary difference between prescriptive and performance-based designs is that a fire safety goal, life safety, property protection, mission continuity, and environmental impact are explicitly stated in the performance-based design, while prescriptive requirements may inhibit fire safety components from the design. Performance-based fire protection design is widely gaining acceptance by various countries around the world including United States. The application of performance-based approach to fire safety analysis will certainly continue to gain widespread acceptance in the future as an alternative to prescriptive building and fire codes.

Risk is a quantitative measure of fire incident loss potential in terms of both the event likelihood and aggregate consequences. In the risk-informed approach, the analyst considers the likelihood that a fire will occur, as well as its potential severity of a fire and consequences. For example, based on the knowledge and experience of the equipment operator, a fire in a given turbine generator is likely to occur 80 percent of the time. Similarly based on the knowledge and experience of the fire protection engineer, the sprinkler system protecting that generator is 90-percent likely to contain and control that fire. Because the risk-informed, performance-based methodology quantifies the likelihood of a fire hazard and the likelihood that the fire protection system will contain or control the fire, it provides a more realistic prediction of the actual risk.

The risk-informed, performance-based approach presents a more realistic predication of potential fire hazards for a given system or process or for an entire operation. The performance-based approach provides solutions based on performance to established goals, rather than on prescriptive requirements with implied goals. Solutions are supported by operator and management about processes, equipment, and components; the buildings or structural housing them; operation data and maintenance personnel; and the fire protection systems in place. Published performance data pertaining to these aspects are also incorporated into the analysis.

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CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL AND FORCED VENTILATION

2.1 Objectives

This chapter has the following objectives:

- Explain the different stages of a compartment fire.
- Identify the types of forced and natural ventilation systems.
- Explain how the various types of forced ventilation systems work.
- Describe how to calculate the hot gas layer temperature and smoke layer height for a fire in a compartment with both natural and forced ventilation systems.

2.2 Introduction

In evaluating the environmental conditions resulting from a fire in an enclosure, it is essential to estimate the temperature of the hot fire gases. These elevated temperatures can often have a direct impact on nuclear power plant (NPP) safety. A temperature estimate is also necessary in order to predict mass flow rates in and out through openings, thermal feedback to the fuel and other combustible objects, and thermal influence (initiating stimulus) on detection and suppression systems. Heat from a fire poses a significant threat to the operation of NPPs, both when the component and equipment come in contact with heated fire gases and when heat is radiated from a distance.

2.3 Compartment Fire Growth

A compartment or enclosure fire is usually a fire that is confined to a single compartment within a structure. Ventilation is achieved through open doors and windows, as well as heating, ventilation, and air conditioning (HVAC) systems. Such a fire typically progresses through several stages (or phases) as a function of time, as discussed in the next section.

2.3.1 Stages of Compartment Fires

Initially, fire in a compartment can be treated as a freely burning, unconfined fire. This treatment is a valid approximation until thermal feedback or oxygen depletion in the compartment becomes significant. In many ventilated spaces, the ventilation is stopped automatically under fire conditions, either through the shutdown of fan units or the closing of fire doors and dampers. In other spaces, however, ventilation systems may continue to operate or unprotected openings may remain open. The course of compartment fires, and the conditions that result, depend on the following variables (among others):

- fire heat release rate (HRR) of the combustible
- enclosure size
- enclosure construction
- enclosure ventilation

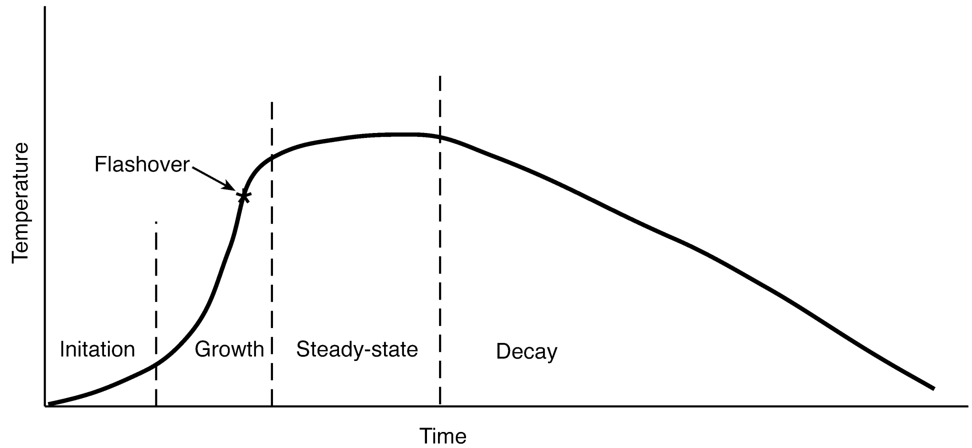


Figure 2-1 Typical Stages of Fire Development

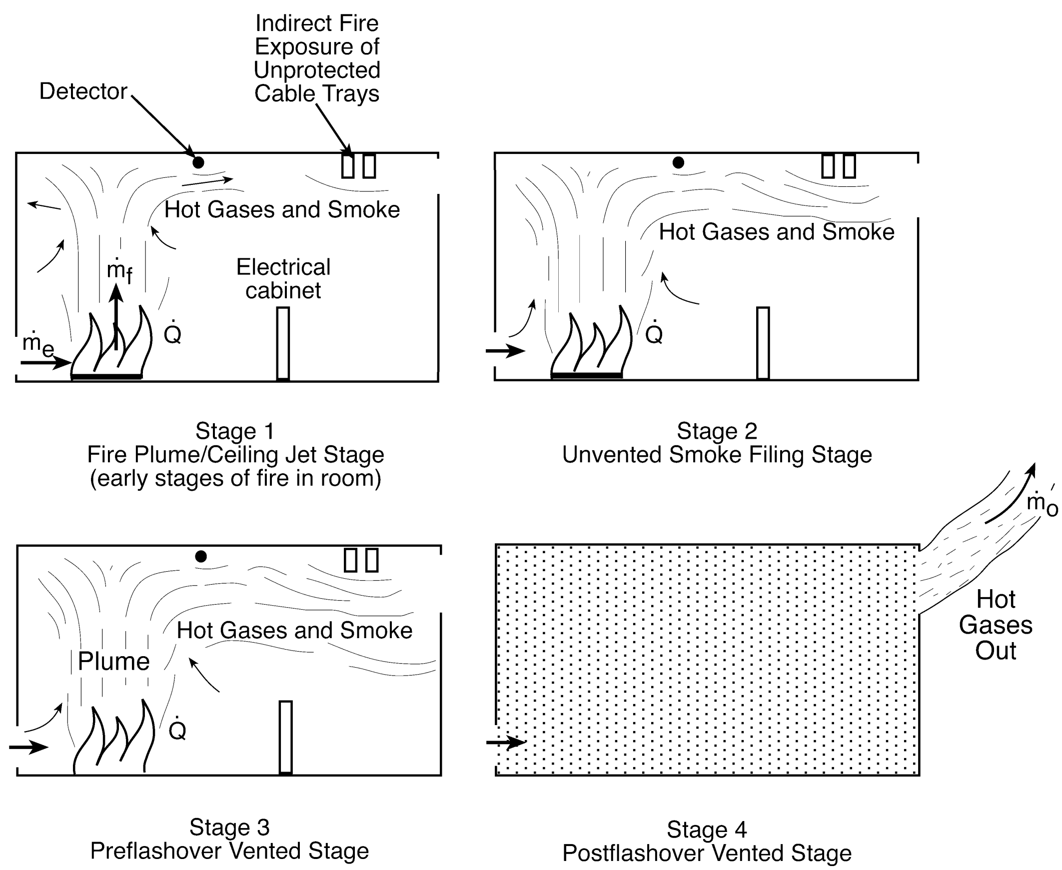


Figure 2-2 Stages of Compartment Fire

Conceptually, compartment fires can be considered in terms of the four stages illustrated in Figures 2-1 and 2-2. The initial stage of compartment fires is the fire plume/ceiling jet phase. During this stage, buoyant hot gases rise to the ceiling in a plume above the fire and spread radially beneath the ceiling as a relatively thin jet. As the plume gases rise to the ceiling, they entrain cool, fresh air. This entrainment decreases the plume temperature and combustion product concentrations, but increases the volume of smoke. The plume gases impinge upon the ceiling and turn to form a ceiling jet, which can continue to extend radially until it is confined by enclosure boundaries or other obstructions (such as deep solid beams at the ceiling level).

Once the ceiling jet spreads to the full extent of the compartment, the second stage of compartment fires ensues. During this stage, a layer of smoke descends from the ceiling as a result of air entrainment into the smoke layer and gas expansion attributable to heat addition to the smoke layer. The gas expansion, in turn increases the average temperature of the smoke layer. However, the continuing entrainment of cool, fresh air into the smoke layer tends to slow this temperature increase.

The duration of this second stage (an unventilated compartment smoke filling phase) depends on the HRR of the fuel, the size and configuration of the compartment, the heat loss histories, and the types and locations of ventilation openings in the compartment. In closed compartments, the smoke layer continues to descend until the room is filled with smoke or until the fire source burns out, as a result of either fuel consumption or oxygen depletion. In ventilated compartments, the smoke layer descends to the elevation where the rate of mass flow into the smoke layer is balanced by the rate of flow from the smoke layer through natural or mechanical ventilation.

The preflashover vented fire stage begins when smoke starts to flow from the compartment. Ventilation may occur naturally through openings in compartment boundaries (such as doorways), or it may be forced by mechanical air handling systems. The smoke layer may continue to expand and descend during the preflashover vented fire stage.

The final stage of compartment fires, known as the postflashover vented phase, represents the most significant hazard, both within the fire compartment and as it affects remote areas of a building. This stage occurs when thermal conditions within the compartment reach a point at which all exposed combustibles ignite, virtually simultaneously in many cases, and air flow to the compartment is sufficient to sustain intense burning. During this stage, the rate of air flow into the compartment and, consequently, the peak rate of burning within the compartment, become limited. The ventilation is limited by the sizes, shapes, and locations of boundary openings for naturally ventilated spaces, or by the ventilation rate from mechanically ventilated spaces. With adequate ventilation, flames may fill the enclosure volume and result in a rapid change from a developing compartment fire to full compartment involvement. This point is commonly referred to as "flashover." Flashover is the point in compartment fire development which can evolve as a rapid transition from a slowly growing to fully developed fire. The underlying mechanism in this phenomenon is essentially a positive feedback from the fire environment to the burning fuel. The formation of a hot ceiling layer at the early stages of a fire leads to radiative feedback to the fuel, which, in turn, increases the burning rate and the temperature of the smoke layer. If heat losses from the compartment are insufficient, a sharp increase in the fire's power (i.e., flashover) will eventually occur.

The International Organization for Standardization (ISO) formally defines flashover as “the rapid transition to a state of total surface involvement in a fire of combustion material within an enclosure.” In fire protection engineering, the term is used as the demarcation point between the preflashover and postflashover stages of a compartment fire. Flashover is not a precise term, and several variations in its definition can be found in the literature. The criteria given usually require that the temperature in the compartment reaches 500 to 600 °C (932 to 1,112 °F), the radiation heat transfer to the floor of the compartment is 15 to 20 kW/m^2 (1.32 to 1.76 Btu/ft^2-sec), or flames appear from the compartment openings. In a compartment with one opening, flashover is principally described by four stages. Specifically, the hot buoyant plume develops at the first stage following ignition, and then reaches the ceiling and spreads as a ceiling jet during the second stage. During the third and fourth stages, the hot layer expands and deepens, while flow through the opening is established.

Flashover usually causes the fire to reach its fully developed state, in which all of the fuel within the room becomes involved. However, all of the fuel gases may not be able to combust within the room because the air supply is limited. Such an air-limited fire is commonly termed “ventilation-limited” or “ventilation-controlled”, as opposed to a “fuel-limited” fire, which is a fire that has an ample supply of oxygen and is limited by the amount of materials (fuel) burning.

2.3.2 Ventilation-Limited or Ventilation-Controlled Fires

A ventilation-limited or ventilation-controlled fire is one that experiences low oxygen concentration as a result of insufficient air supply. The hot fire gases typically have nearly zero oxygen.

2.3.3 Fuel-Limited Fires

In contrast to a ventilation-limited fire, a fuel limited fire is a compartment fire in which the air supply is sufficient to maintain combustion, but the amount of fuel that is burning limits the fire size.

2.4 Compartment Ventilation

General ventilation system design controls heat, odors, and hazardous chemical contaminants. General ventilation can be provided by mechanical systems, by natural draft, or by a combination of the two. Examples of combination systems include (1) mechanical supply with air relief through louvers and/or other types of vents and (2) mechanical exhaust with air replacement inlet louvers and/or doors. Natural ventilation is a controlled flow of air caused by thermal and wind pressure.

Mechanical or forced ventilation is accomplished with fans to create the pressure differentials to produce the desired flows of air. Exhaust in the ventilation process that draws noxious air entrained particulate and vapors from a compartment, collect them into ducts for transport to the outside or to equipment that cleans the air before discharging it to the outside or returning it to the area of origin. In a closed area, exhaust cannot operate at the flows required without having an equal supply of makeup air available. “Makeup air” and “replacement air” are the terms commonly used to refer to the air that has to be brought into a space to limit pressure gradients so that the exhaust process can operate as designed. This air may be brought directly into a space via ducts or indirectly via openings from adjacent areas. The quantity of makeup air must be of a sufficient flow rate to allow the exhaust system to operate within its pressure differential design parameters, yet not be so great as to create a positive pressure within the compartment.

Mechanically ventilated compartments are a common environment for fire growth in NPP structures. A fire in a forced-ventilation compartment is markedly different than in a compartment with natural ventilation. An important factor is that the stratified thermal hot gas layer induced by the fire in a naturally ventilated compartment may be unstable in a forced ventilation compartment. Normally, a ventilating system recirculates most of the exhaust air. If normal operation were to continue during a fire, this recirculation could result in smoke and combustion products being mixed with supply air, and the contaminated mixture being delivered throughout the ventilation zone. To prevent this, dampers are often placed in the system. Upon fire detection in an engineered smoke control system, the damper positions are changed so that all exhaust from the fire zone is dumped, and 100-percent makeup air is drawn from outside the building.

The following four general types of mechanical ventilation systems are commonly encountered, as illustrated in Figure 2-3.

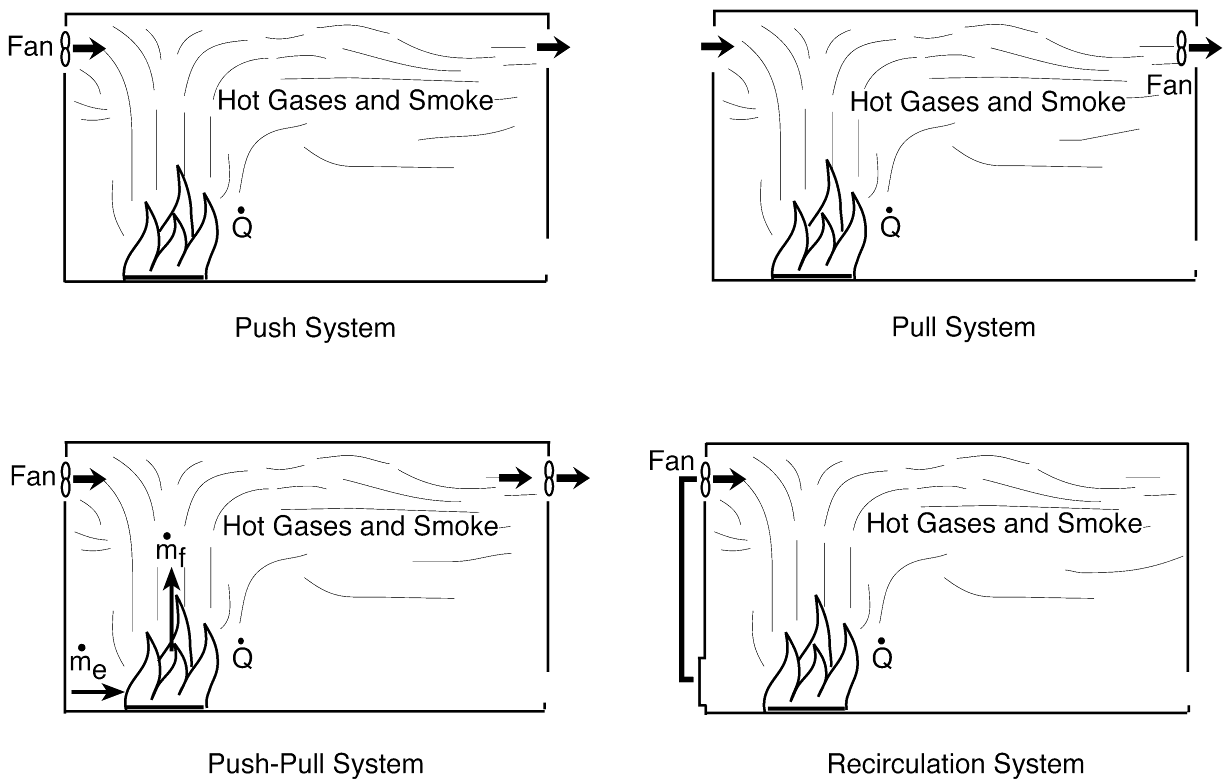


Figure 2-3 Types of Mechanical Ventilation Systems

2.4.1 Definitions

- *Push Systems* - Push systems mechanically supply fresh (outside) air into a compartment at the design volumetric flow rate of the system, while air expulsion occurs freely through transfer grills, registers, or diffusers in the compartment.
- *Pull Systems* - Pull systems mechanically extract hot gases (smoke) from a compartment. Pull systems are designed to extract smoke from a compartment based on the volumetric flow rate of the system. The density of smoke is normally less than that of ambient air because the smoke is at an elevated temperature.
- *Push-Pull Systems* - Push-pull systems both inject and extract air mechanically, with the supply and exhaust fan units typically sized and configured to produce balance supply and exhaust rates under normal operation. Push-pull systems cannot continue to operate at their balanced design flow rate under fire conditions. If the supply and exhaust fan units continue to inject and extract air at the same balanced design volumetric flow rates, the rate of mass injection will exceed the rate of mass extraction because of the difference in the densities of the supply and exhaust streams.
- *Recirculation Systems* - Recirculation systems typically use a single fan unit to mechanically extract air from a space, condition it, and return it to the same space.
- *Volume Flow Rate* handled by the fan is the number of cubic feet of air per minute (cfm) expressed at fan inlet conditions.
- *Fan Total Pressure Rise* is the fan total pressure at the outlet minus the fan total pressure at all inlet (in. of water).
- *Fan Velocity Pressure* is the pressure corresponding to the average velocity determined from the volume flow rate and fan outlet area (in. of water).
- *Fan Static Pressure Rise* is the fan total pressure rise diminished by the fan velocity pressure. The fan inlet velocity head is assumed to be equal to zero for fan rating purposes (in. of water).

2.5 Temperature

When discussing gases, temperature is a measure of the mean kinetic energy of the molecules in a gas. Temperature defines the conditions under which heat transfer occurs. A gas temperature, T_g, describes precisely the state of the average molecular energy in that gas. However that description is not particularly useful for the purposes of describing the physical phenomena that are relevant to fire science. In a broad sense, temperature can be thought of as a measure of the state of a system. Materials behave differently at different temperatures. Water, for example, at atmospheric pressure, is solid below 0 °C (32 °F), liquid between 0 °C (32 °F) and 100 °C (212 °F), and gaseous above 100 °C (212 °F). Similarly, plastic materials begin to gasify at a certain temperature. At a slightly higher temperature, they gasify enough to ignite, and at still higher temperatures, they may self-ignite. For our purpose, then, temperature can be viewed as an indicator of the state of an object system.

There are standard ways to define temperature. The most common are the Fahrenheit and Celsius scales of temperature. Related to these scales is the Kelvin absolute temperature scale[1]. The correspondence between the scales is illustrated in Table 2-1.

Table 2-1. Temperature Conversions

Original Unit	**Conversions**		
	Celsius, T_C	**Fahrenheit, T_F**	**Kelvin, T_K**
Celsius, T_C	-	9/5 (T_C) + 32	T_C + 273.15
Fahrenheit, T_F	5/9 (T_F - 32)	-	5/9 (T_F + 459.7)
Kelvin, T_K	T_K - 273.15	9/5 (T_K - 255.37)	-

The difference between the relative temperature scale and its absolute counterpart is the starting point of the scale. That is, 0 °C is equal to 273 Kelvin and each degree on the Celsius scale is equal to 1 degree on the Kelvin scale. By contrast, the English unit temperature scale and SI (metric) unit temperature scale differ in two main ways. Specifically, zero is defined differently in Celsius than in Fahrenheit, and one degree Fahrenheit represents a different quantity of heat than one degree Celsius for a given heat capacity and mass. It is important to remember that these temperature scales are arbitrary, but they relate to important physical processes and the effect of temperature on an object is what we are really interested in.

Table 2-2 lists the critical temperatures for different exposure conditions and the resultant effects on humans.

Table 2-2. Critical Temperatures for Different Exposure Conditions and Effects on Humans
[Chartered Institution of Building Services Engineers (CIBSE) Guide E. With permission.]

Type and Period of Heat Exposure	**Temperature °C (°F)**	**Effect**
Radiation	185 (365)	Severe skin pain
Conduction (metal) (1 second)	60 (140)	Skin burns
Convection (30 minutes)	100 (212)	Hyperthermia
Convection (< 5 minutes)	120 (248)	Skin and lungs are burned by hot gases
Convection (<1 minute)	190 (374)	Skin and lungs are burned by hot gases

[1] The Rankine scale is used for absolute zero in the English units. Since most fire dynamics equations will be solved in SI units, it will not be discussed here.

In order to calculate or predict the temperatures in a compartment, a description or analytical approximation of the fire phenomena must be created in quantitative terms. This approximation is described in terms of physical equations for chemistry, physics, mathematics, fluid mechanics, and heat and mass transfer, which can be solved to predict the temperature in the compartment. Such an approximation, therefore, is an idealization of the compartment fire phenomena (i.e., ignition, flame spread, and burning rate).

2.6 Estimating Hot Gas Layer Temperature

This section presents methods predicting the temperature achieved by the hot gas layer in an enclosure fire; these methods are currently the most widely accepted in the fire protection engineering literature. Nonetheless, the methods employ assumptions and limitations, which must be understood before using any of the methods presented.

2.6.1 Natural Ventilation: Method of McCaffrey, Quintiere, and Harkleroad (MQH)

The temperatures throughout a compartment in which a fire is burning are affected by the amount of air supplied to the fire and the location at which the air enters the compartment. Ventilation-limited fires produce different temperature profiles in a compartment than well-ventilated fires.

A compartment with a single rectangular wall opening (such as a door or window) is commonly used for room fire experiments. They also are commonly involved in real fire scenarios, where a single door or vent opening serves as the only path for fire-induced natural ventilation to the compartment. The hot gas layer that forms in compartment fires descends within the opening until a quasi-steady balance is struck between the rate of mass inflow to the layer and the rate of mass outflow from the layer.

A complete solution of the mass flow rate in this scenario requires equating and solving two non-linear equations describing the vent flow rate and the plume entrainment rate as a function of the layer interface height (the layer in a compartment that separates the smoke layer from the clear layer). If it is nonvented, the smoke layer gradually descends as the fire increases, thereby lowering the smoke interface and (possibly) eventually filling the compartment. McCaffrey, Quintiere, and Harkleroad (MQH) (1981) (also reported by Walton and Thomas, 1995 and 2002) have developed a simple statistical dimensionless correlation for evaluating fire growth in a compartment (hot gas layer temperature) with natural ventilation. This MQH correlation is based on 100 experimental fires (from 8 series of tests involving several types of fuel) in conventional-sized rooms with openings. The temperature differences varied from T = 20 °C (68 °F) to 600 °C (1,112 °F). The fire source was away from walls (i.e., data was obtained from fires set in the center of the compartment). The larger the HRR $(\dot{Q})$, and the smaller the vent, the higher we expect the upper-layer gas temperature to increase.

The approximate formula for the hot gas layer temperature increase, T_g, above ambient (T_g - T_a) is as follows:

$$\Delta T_g = 6.85\left[\frac{\dot{Q}^2}{\left(A_v\sqrt{h_v}\right)\left(A_T h_k\right)}\right]^{\frac{1}{3}} \qquad (2\text{-}1)$$

Where:

T_g = upper layer gas temperature rise above ambient (T_g - T_a) (K)
$\dot{Q}$ = heat release rate of the fire (kW)
A_v = total area of ventilation opening(s) (m^2)
h_v = height of ventilation opening (m)
h_k = heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surfaces (m^2), excluding area of vent opening(s).

The above equation can be used for multiple vents by summing the values, as follows:

$$\left(\sum_{i=1}^{n}\left(A_v\sqrt{h_v}\right)\right)_i$$

where n is the number of vents, and can be used for different construction materials by summing the A_T values for the various wall, ceiling, and floor elements.

The compartment interior surface area can be calculated as follows:

A_T = ceiling + floor 2 (w_c x l_c)
+ 2 large walls 2 (h_c x w_c)
+ 2 small walls 2 (h_c x l_c)
- total area of vent opening(s) (A_v)

$$A_T = [2\ (w_c \times l_c) + 2\ (h_c \times w_c) + 2\ (h_c \times l_c)] - A_v \qquad (2\text{-}2)$$

Where:

A_T = total compartment interior surface area (m^2), excluding area of vent opening(s)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = total area of ventilation opening(s) (m^2)

For very thin solids, or for conduction through a solid that continues for a long time, the process of conduction becomes stationary (steady-state). The heat transfer coefficient, h_k, after long heating times, can be written as follows:

$$h_k = \frac{k}{\delta} \qquad (2\text{-}3)$$

Where:

k = thermal conductivity (kW/m-K) of the interior lining
  = thickness of the interior lining (m)

This equation is useful for steady-state applications in which the fire burns longer than the time required for the heat to be transferred through the material until it begins to be lost out the back (cold) side. This time is referred to as the thermal penetration time, t_p, which can be calculated as:

$$t_p = \left(\frac{\rho\ c_p}{k}\right)\left(\frac{\delta}{2}\right)^2 \qquad (2\text{-}4)$$

Where:

  = density of the interior lining (kg/m^3)
c_p = thermal capacity of the interior lining (kJ/kg-K)
k = thermal conductivity of the interior lining (kW/m-K)
  = thickness of the interior lining (m)

However, if the burning time is less than the thermal penetration time, t_p, the boundary material retains most of the energy transferred to it and little will be lost out the non-fire (cold) side. The heat transfer coefficient, h_k, in this case, can then be estimated using the following equation for $t < t_p$:

$$h_k = \sqrt{\frac{k\rho c}{t}} \qquad (2\text{-}5)$$

Where:

k c = interior construction thermal inertia [(kW/m^2-K)^2-sec]
(thermal property of the material responsible for the rate of temperature increase)
t = time after ignition in seconds (characteristic burning time)

By contrast, for $t \geq t_p$, the heat transfer coefficient is estimated from Equation 2-3.

As indicated above, the k c parameter is a thermal property of the material responsible for the rate of temperature increase. This is the product of the material thermal conductivity (k), the material density ( ), and the heat capacity (c). Collectively, k c is known as the material thermal inertia. For most materials, c does not vary significantly, and the thermal conductivity is largely a function of the material density. This means that density tends to be the most important material property. Low-density materials are excellent thermal insulators. Since heat does not pass through such materials, the surface of the material actually heats more rapidly and, as a result, can ignite more quickly. Good insulators (low-density materials), therefore, typically ignite more quickly than poor insulators (high-density materials). This is the primary reason that foamed plastics are so dangerous in fires; they heat rapidly and ignite in situations in which a poor insulator would be slower to ignite because of its slower response to the incident heat flux. The thermal response properties (k c), for a variety of generic materials have been reported in the literature. These values have been derived from measurements in the small-scale lateral ignition and flame spread test (LIFT) apparatus (ASTM E1321). Table 2-3 lists typical thermal properties of variety of materials.

Table 2-3. Thermal Properties of Compartment Enclosing Surface Materials
(Klote and Milke, 2002, © ASHRAE. With permission.)

Materials	**Thermal Inertia** **k c** **$(kW/m^2\text{-}K)^2$-sec**	**Thermal Conductivity** **k** **(kW/m-K)**	**Thermal Capacity** **c** **(kJ/kg-K)**	**Density** **(kg/m^3)**
Aluminum (pure)	500	0.206	0.0895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1.0	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20

2.6.2 Natural Ventilation (Compartment Closed): Method of Beyler

Beyler (1991) (also reported by Walton and Thomas, 2002) developed a correlation based on a nonsteady energy balance to the closed compartment, by assuming that the compartment has sufficient leaks to prevent pressure buildup. For constant HRR, the compartment hot gas layer temperature increase, T_g, above ambient (T_g - T_a) is given by the following equation:

$$\Delta T_g = T_g - T_a = \frac{2K_2}{K_1^2}\left(K_1\sqrt{t} - 1 + e^{-K_1\sqrt{t}}\right) \qquad (2\text{-}6)$$

Where:

$$K_1 = \frac{2\left(0.4\sqrt{k\rho c}\right)}{m c_p} \qquad\qquad K_2 = \frac{\dot{Q}}{m c_p}$$

And:

T_g = upper layer gas temperature rise above ambient (T_g - T_a) (K)
k = thermal conductivity of the interior lining (kW/m-K)
= density of the interior lining (kg/m^3)
c = thermal capacity of the interior lining (kJ/kg-K)
$\dot{Q}$ = heat release rate of the fire (kW)
m = mass of the gas in the compartment (kg)
c_p = specific heat of air (kJ/kg-k)
t = exposure time (sec)

2.6.3 Forced Ventilation: Method of Foote, Pagni, and Alvares (FPA)

Foote, Pagni, and Alvares (FPA) (1985) (also reported by Walton and Thomas, 1995 and 2002) developed another method, which follows the basic correlations of the MQH method, but adds components for forced-ventilation fires. This method is based on temperature data that were obtained from a series of tests conducted at the Lawrence Livermore National Laboratory (LLNL). Fresh air was introduced at the floor and pulled out the ceiling by an axial fan. Test fires from 150 to 490 kW were used, producing ceiling jet temperatures from 100 to 300 °C (212 to 572 °F). The approximate constant HRR and ventilation rates were chosen to be representative of possible fires in ventilation-controlled rooms with seven room air changes per hour, which was roughly between 200 and 575 cfm.

The upper-layer gas temperature increase above ambient is given as a function of the fire HRR, the compartment ventilation flow rate, the gas-specific heat capacity, the compartment surface area, and an effective heat transfer coefficient. The nondimensional form of the resulting temperature correlation is as follows:

$$\frac{\Delta T_g}{T_a} = 0.63 \left(\frac{\dot{Q}}{\dot{m} c_p T_a}\right)^{0.72} \left(\frac{h_k A_T}{\dot{m} c_p}\right)^{-0.36} \qquad (2\text{-}7)$$

Where:

T_g = hot gas layer temperature rise above ambient (T_g - T_a) (K)
T_a = ambient air temperature (K)
$\dot{Q}$ = HRR of the fire (kW)
$\dot{m}$ = compartment mass ventilation flow rate (kg/sec)
c_p = specific heat of air (kJ/kg-K)
h_k = heat transfer coefficient (kW/m^2-K)
A_T = total area of compartment enclosing surfaces (m^2)

The above correlation for forced-ventilation fires can be used for different construction materials by summing the A_T values for the various wall, ceiling, and floor elements.

2.6.4 Forced Ventilation: Method of Deal and Beyler

Deal and Beyler (1990) (also reported by Walton and Thomas, 2002) developed a simple model of forced ventilated compartment fires. The model is based on a quasi-steady simplified energy equation with a simple wall heat loss model. The model is only valid for times up to 2000 seconds. The approximate compartment hot gas layer temperature increase, T_g, above ambient (T_g - T_a) is given by the following equation:

$$\Delta T_g = T_g - T_a = \frac{\dot{Q}}{\dot{m} c_p + h_k A_T} \qquad (2\text{-}8)$$

Where:

T_g = hot gas layer temperature rise above ambient (T_g - T_a) (K)
T_a = ambient air temperature (K)
$\dot{Q}$ = HRR of the fire (kW)
$\dot{m}$ = compartment mass ventilation flow rate (kg/sec)
c_p = specific heat of air (kJ/kg-K)
h_k = convective heat transfer coefficient (kW/m^2-K)
A_T = total area of compartment enclosing surfaces (m^2)

The convective heat transfer coefficient is given by the following expression:

$$h_k = 0.4 \max \left(\sqrt{\frac{k\rho c}{t}},\ \frac{k}{\delta} \right) \qquad (2\text{-}9)$$

Where:

k = thermal conductivity of the interior lining (kW/m-K)
= density of the interior lining (kg/m^3)
c = thermal capacity of the interior lining (kJ/kg-K)
t = exposure time (sec)
= thickness of the interior lining (m)

2.7 Estimating Smoke Layer Height

When a fire occurs in a compartment, within few seconds of ignition, early flame spread can quickly lead to a flaming, free-burning fire. If left unchecked, the fire continues to grow. Besides releasing energy, the combustion process also yields a variety of other products, including toxic and nontoxic gases and solids. Together, all of these products are generally referred to as the "smoke" produced by the fire.

As the flame spreads across the fuel surface, the fire size, which can be described as the HRR, increases. As the size increases, the radiation heat transfer from the flame to the fuel surface increases, and this increases the burning rate. If the flame has not involved the entire surface area, this increased fire size accelerates the flame spread. Above the flame zone, a buoyant plume is formed. The plume entrains ambient air, which both cools the gas and increases the flow rate. In a typical compartment, the plume strikes the ceiling and forms a ceiling jet, which in turn strikes a wall, and the compartment begins to fill with hot smoke from the ceiling downward. The plume continues to entrain ambient air, adding mass to the layer until it reaches the upper gas layer. Here, as the gas layer descends, less mass is entrained into it. Thus, the amount of gas flow from the plume is a function of the fire size and the height over which entrainment occurs.

As previously stated, the temperature and composition of gas entering the hot gas layer are driven by the fire source and the plume. Once the hot gas enters this hot layer, it cools by losing energy to surrounding surfaces (i.e., ceiling, walls) by conduction, and cools by radiating heat energy to the floor and the cool gas layer near the floor. The rate of descent of the hot gas layer is driven by the size of the compartment and the amount of mass flow from the plume. Since the plume mass flow is a function of the height beneath the gas layer, the layer descends at a progressively slower rate as it gets closer to the fire source.

The plume essentially mixes cool air with the combustion products, thereby increasing the total flow into the hot gas layer, while reducing its temperature and the concentration of gases flowing into it. The plume can only add mass to the upper layer by entrainment along the plume axis below the hot gas layer position. Once it penetrates the hot gas layer, it entrains hot gas, helping to mix the layer, but not increasing its depth.

One of the most important processes that occurs during the early stages of a compartment fire is the filling of the compartment with smoke. Although the hot layer gas temperatures are relatively low [< 200 °C (392 °F)], the composition of the smoke relative to visibility and toxicity and the vertical position of the layer are of interest. Figure 2-4 shows this process schematically.

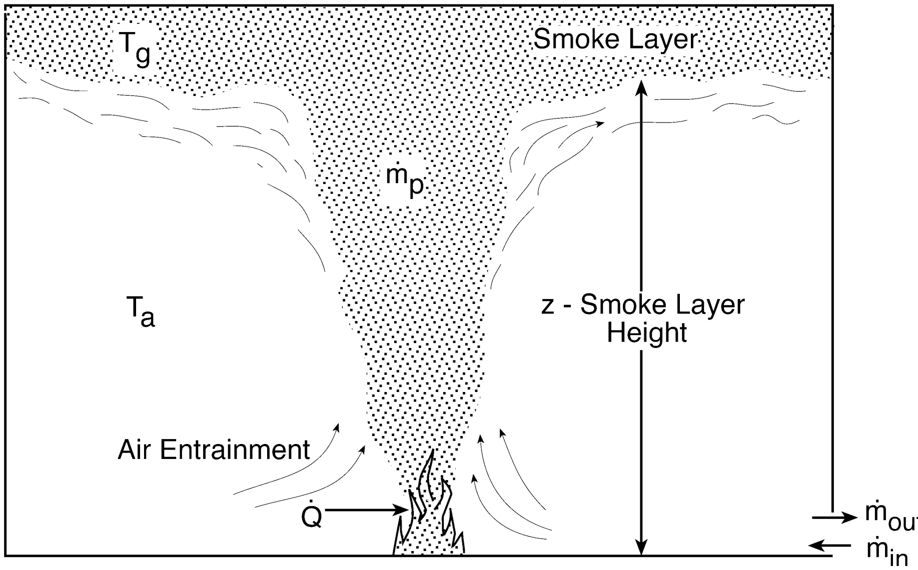


Figure 2-4 Smoke Filling in a Compartment Fire

2.7.1 Smoke Layer

The smoke layer can be described as the accumulated thickness of smoke below a physical or thermal barrier (e.g., ceiling). The smoke layer is typically not a homogeneous mixture, and it does not typically have a uniform temperature. However, for first-order approximations, the calculation methods presented below assume homogeneous conditions. The smoke layer includes a transition zone that is nonhomogeneous and separates the hot upper layer from the smoke-free air (i.e., two zones).

2.7.2 Smoke Layer Interface Position

Figure 2-5 depicts the theoretical boundary (or interface) between a smoke layer and the smoke-free air. In practice, the smoke layer interface is an effective boundary within a transition buffer zone, which can be several feet thick. Below this effective boundary, the smoke density in the transition zone decreases to zero.

2.7.3 Natural Ventilation (Smoke Filling): The Non-Steady-State Yamana and Tanaka Method

In a compartment with larger openings (windows or doors), there will be little or no buildup of pressure attributed to the volumetric expansion of hot gases, with the exception of rapid accumulation of mass or energy. Thus, for the first-order approximations, pressure is assumed to remain at the ambient pressure. The opening flows are thus determined by the hydrostatic pressure differences across the openings, and mass flows out of and into the compartment. We also assume that the upper layer density ($_g$), is some average constant value at all times throughout the smoke-filling process.

Assuming a constant average density in the upper hot gas layer has the advantage that we can form an analytical solution of the smoke-filling rate, where the HRR does not need to be constant (that is, it can be allowed to change with time), and we can use the conservation of mass to arrive at the expression for the smoke-filling rate. When this is done, the height of the smoke layer as a function of time is known, and we can use the conservation of energy to check the stipulated value of $_g$.

Yamana and Tanaka (1985) (also reported by Karlsson and Quintiere, 1999b) developed the expression for the height of the smoke layer interface, z, in terms of time, as follows:

$$z = \left(\frac{2\ k\ \dot{Q}^{\frac{1}{3}}\ t}{3\ A_c} + \frac{1}{h_c^{\frac{2}{3}}} \right)^{-\frac{3}{2}} \qquad (2\text{-}10)$$

Where:

z = height (m) of the smoke layer interface above the floor

$\dot{Q}$ = heat release rate of the fire (kW)

t = time after ignition (sec)

A_c = compartment floor area (m^2)

h_c = compartment height (m)

And:

k = a constant given by the following equation:

$$k = \frac{0.21}{\rho_g} \left(\frac{\rho_a^2 g}{c_p T_a} \right)^{\frac{1}{3}} \qquad (2\text{-}11)$$

Where:

$_g$ = hot gas density kg/m^3

$_a$ = ambient density = 1.20 kg/m^3

g = acceleration of gravity = 9.81 m/sec^2

c_p = specific heat of air = 1.0 kJ/kg-K

T_a = ambient air temperature = 298 K.

Substituting the above numerical values in Equation 2-11, we get the following expression:

$$k = \frac{0.076}{\rho_g} \qquad (2\text{-}12)$$

Where density of the hot gas ($_g$), layer is given by:

$$\rho_g = \frac{353}{T_g} \qquad (2\text{-}13)$$

Where:

T_g = hot gas layer temperature (K) calculated from Equation 2-1

Calculation Procedure

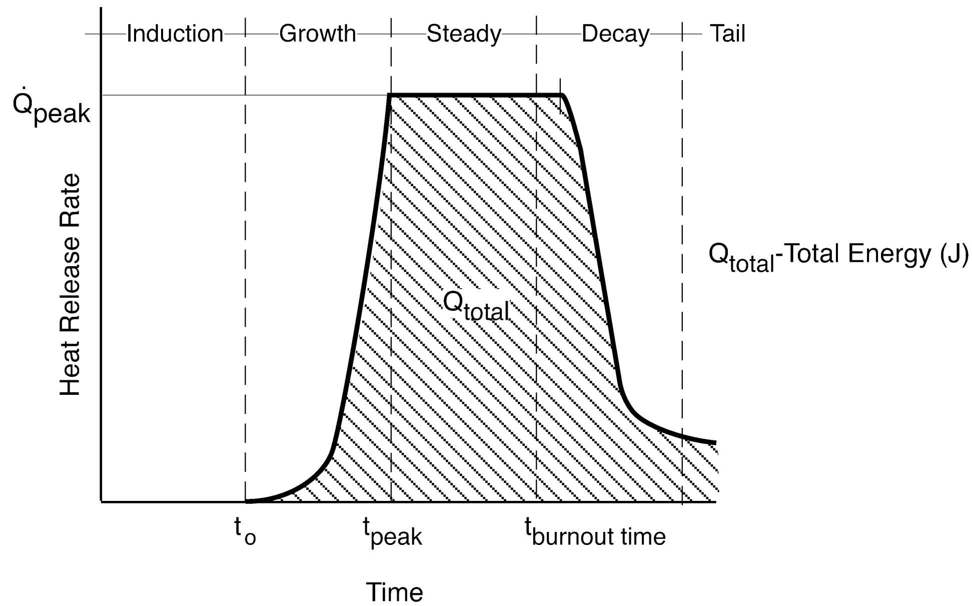
(1) Calculate $_{g}$ from Equation 2-13.
(2) Calculate the constant k from Equation 2-12.
(3) Calculate the smoke layer height (z) at the some time (t) from Equation 2-10 given HRR.

2.8 Data Sources for Heat Release Rate

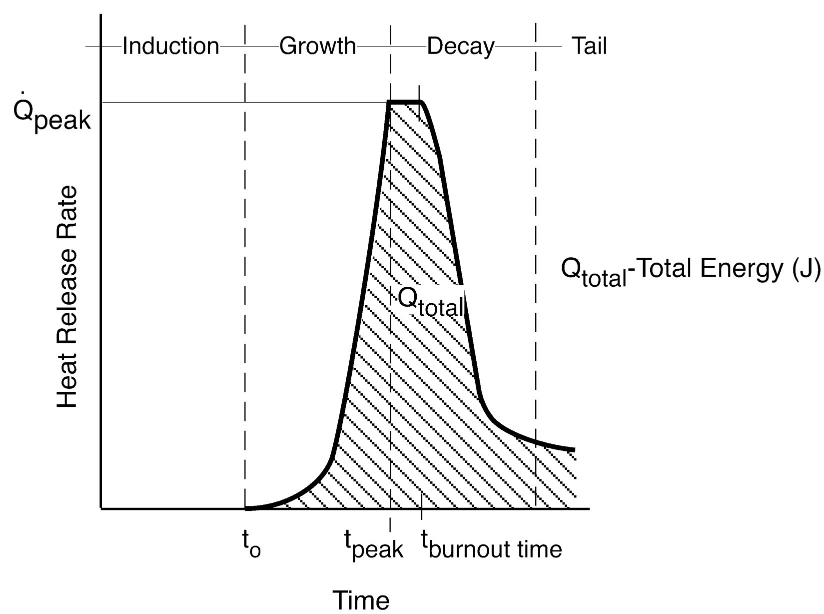
When an object burns, it releases a certain amount of energy per unit of time. For most materials, the HRR of a fuel changes with time, in relation to its chemistry, physical form, and availability of oxidant (air), and is ordinarily expressed as kW (kJ/sec) or Btu/sec and denoted by $\dot{Q}$ (1,000 kW = 1 MW) (1 BTU/sec = 1.055 kW).

Figure 2-5 illustrates the general features of typical HRR histories. HRR commonly demonstrates an acceleratory growth stage, which may follow an induction stage of negligible growth. Objects may or may not exhibit the period of fairly steady burning illustrated in Figure 2-5 (a); this depends on whether fuel burnout begins after the fuel surface is fully involved. Materials that do not begin to burn out before the fuel surface is fully involved (peak HRR) demonstrate the fairly steady burning period exhibited in Figure 2-5 (a) until burnout begins; materials that begin to burn out before the peak HRR is achieved are characterized by heat release curves with distinct peaks, as illustrated in Figure 2-5 (b). In either case, at some time following attainment of peak HRR, a decay stage associated with fuel burnout usually occurs. This decay stage frequently gives way to a tail stage of relatively low HRR. This tail stage, which may persist for an extended time, is normally attributable to the glowing combustion that follows flaming combustion for char-forming products.

The total energy released by a material is equal to the area under the time-HRR curve. This area is influenced by the energy released during the tail stage, which may contribute a considerable portion of the total energy released, but at such a slow rate that it does not constitute the significant hazard.



(a) Burnout Time > Time to Peak HRR



(b) Burnout Time < Time to Peak HRR

Figure 2-5 General Representation of Heat Release Rate Histories for a Fuel Package

2.9 Identification of Fire Scenario

The first step in an FHA is to identify which target(s) to evaluate within an enclosure or compartment. Normally, the target is a safety-related component that is being evaluated for a particular scenario. However, if exposed, intervening combustibles exist between the fire source and the safety-related component, they can become the targets for further evaluation.

Electrical cables typically serve as the primary target for most NPP analyses. The nuclear industry has defined two general types of electrical cables, referred to as IEEE-383 qualified and unqualified. These terms refer to cables that either pass or fail the IEEE-383 fire test standard, respectively. A damage threshold temperature of 370 °C (700 °F) and a critical heat flux of 10 kW/m^2 (1 Btu/ft^2-sec) have been selected for IEEE-383 qualified cable. A damage threshold temperature of 218 °C (425 °F) and a critical heat flux of 5 kW/m^2 (0.5 Btu/ft^2-sec) have been selected for IEEE-383 unqualified cable. These values are reported in several studies, including NUREG/CR-4679, Electrical Power Research Institute (EPRI), "Fire-Induced Vulnerability Evaluation (FIVE) Methodology," and the U.S. Department of Transportation (DOT) study reported in "Combustibility of Electrical Wire and Cable for Rail Rapid Transient Systems," DOT-TSC-UMAT-83-4-1, May 1983.

The second step in an FHA is to identify the location of credible exposure fire sources relative to the target being evaluated. Exposure fires involving transient combustibles are assumed to have an equal probability of occurring anywhere in a space, while exposure fires involving fixed combustibles are assumed to occur at the site of the fixed combustible. Since the hazard is greater when a fire is located directly beneath a target, this placement is evaluated for scenarios involving exposure fires with transient combustibles. For fixed combustibles, the actual geometry between the source and the target is evaluated to determine whether the target is located in the fire plume region.

Representative unit HRR values for a number of fuels present in the NPP (e.g., electrical cables, electrical cabinets, flammable/combustible liquids, and transient combustibles) have been measured and reported in various reports by Lee (1985), Nowlen (1986 and 1987), Chavez (1987), and Babrauskas (1991). Flammable/combustible liquid spill fires and trash fires are the most commonly postulated transient fuel exposure fires in NPPs. Electrical cable fires and electrical cabinet fires are the most commonly postulated fixed fuel fires. Tables 2-4 through 2-10 show the HRR and other data for common fixed and transient combustible materials found in NPPs.

Table 2-4. Measured Heat Release Rate Data for Cable Jacketing Material (Lee, 1981)

Fuel	**HRR per Unit Area** $\dot{Q}''$ **(kW/m²)**	**Heat of Combustion** H_c **(kJ/kg)**
PE/PVC (Polyethylene/Polyvinylchloride)	590	24,000
XPE/FRXPE (Crosslinked Polyethylene/Fire Retardant Crosslinked Polyethylene)	475	28,300
XPE/Neoprene	300	10,300
PE, Nylon/PVC, Nylon	230	9,200
Tefzel™ - ETFE (Ethylenetetrafluoroethylene)	100	3,200

Table 2-5. Measured Heat Release Rate Data for Electrical Cabinets (Nowlen, 1986 and 1987)

Fuel	**Peak HRR*** $\dot{Q}$ **(kW)**
Electrical Cabinet Filled with IEEE-383 Qualified Cables (Vertical doors open)	55
Electrical Cabinet Filled with IEEE-383 Qualified Cables (Vertical doors closed)	No data
Electrical Cabinet Filled with IEEE-383 Unqualified Cables (Vertical doors open)	1,000
Electrical Cabinet Filled with IEEE-383 Unqualified Cables (Vertical doors closed, vent grills only)	185
*Note: HRR contributions in the electrical cabinet are based solely on the cable insulation material, and neglect the energy release based on the current (amperes squared multiplied by time.)	

Table 2-6. Measured Heat Release Rate Data for Transient Combustible Materials (Flammable/Combustible Liquids)

Fuel	**HRR per Unit Area** $\dot{Q}''$ **(kW/m²)**
Diesel oil	1,985
Gasoline	3,290
Kerosene	2,200
Transformer oil	1,795
Lube oil lubrication (used in reactor coolant pump (RCP) motors and turbine)	For lubricating oil, use HRR of transformer oil. Lubricating oil has burning characteristics similar to transformer oil.

Table 2-7. Measured Heat Release Rate Data for Transient Combustible Materials (Trash) (Lee, 1985)

Fuel	**Peak HRR** $\dot{Q}$ **(kW)**
9.1 kg computer paper crumpled up in two plastic trash bags	110
11.4 kg rags, 7.7 paper towels. 5.9 kg plastic gloves and taps, and 5.9 kg methyl alcohol, mixed in two 50-gallon trash bags	120
13.6 kg computer paper crumpled up and divided in two 7.5 kg (50 gallon) plastic trash cans	110
4.6 kg crumpled up computer paper and 31.8 kg folded computer paper, evenly divided into two bags	40

Table 2-8. Measured Heat Release Rate Data
for Transient Combustible Materials (Plywood and Wood Pallet)
(Karlsson and Quintiere, 1999a, © CRC Press, LLC. With permission.)

Fuel	**HRR per Unit Area $\dot{Q}''$ (kW/m^2)**
Douglas fir plywood	124
Fire-retardant treated plywood	81
Wood pallets, stacked 1½ ft high	1,420
Wood pallets, stacked 5 ft high	3,970
Wood pallets, stacked 10 ft high	6,800
Wood pallets, stacked 16 ft high	10,200

Table 2-9. Ignition Thresholds (Pilotless within 30 seconds)
(Naval Ship's Technical Manual, S9086-S3-STM-010/CH-555, 1993)

Material	**Hot Air (Oven Effect) °C (°F)**	**Hot Metal Contact (Frying Pan Effect) (kW/m^2)**	**Radiant Heat Flux (kW/m^2)**
Paper	230 (450)	250 (480)	20
Cloth	250 (480)	300 (570)	35
Wood	300 (570)	350 (660)	40
Cables	375 (700)	450 (840)	60

Table 2-10. Thermal Effects on Electronics
(Naval Ship's Technical Manual, S9086-S3-STM-010/CH-555, 1993)

Temperature °C (°F)	**Effects**
50 (120)	Computer develop faults
150 (300)	Permanent computer damage
250 (480)	Data transmission cable fail

2.10 Assumptions and Limitations

The methods discussed in this chapter have several assumptions and limitations.

*The following assumptions and limitations apply to **all** forced and natural convection situations:*

(1) These methods best apply to conventional-size compartments. They should be used with caution for large compartments.

(2) These methods apply to both transient and steady-state fire growth.

(3) The HRR must be known; it does not need to be constant, and can be allowed to change with time.

(4) Compartment geometry assumes that a given space can be analyzed as a rectangular space with no beam pockets. This assumption affects the smoke filling rate within a space if the space has beam pockets. For irregularly shaped compartments, equivalent compartment dimensions (length, width, and height) must be calculated and should yield slightly higher layer temperatures than would actually be expected from a fire in the given compartment.

(5) These methods predict average temperatures and do not apply to cases in which predication of local temperature is desired. For example, this method should not be used to predict detector or sprinkler actuation or the material temperatures resulting from direct flame impingement.

(6) Caution should be exercised when the compartment overhead are highly congested with obstructions such as cable trays, conduits, ducts, etc.

(7) A single heat transfer coefficient may be used for the entire inner surface of the compartment.

(8) The heat flow to and through the compartment boundaries is unidimensional (i.e., corners and edges are ignored, and the boundaries are assumed to be infinite slabs).

(9) These methods assume that heat loss occurs as a result of mass flowing out through openings. Consequently, these methods do not apply to situations in which significant time passes before hot gases begin leaving the compartment through openings. This may occur in large enclosures (e.g., turbine building), where it may take considerable time for the smoke layer to reach the height of the opening.

*The following assumptions and limitations apply only to **natural convection** situations:*

(10) The correlations hold for compartment upper layer gas temperatures up to approximately 600 °C (1,112 °F) only for naturally ventilated spaces in which a quasi-steady balance develops between the rates of mass inflow and outflow from the hot gas layer.

(11) These correlations assume that the fire is located in the center of the compartment or away from the walls. If the fire is flush with a wall or in a corner of the compartment, the MQH correlation is not valid with coefficient 6.85.

(12) The smoke layer height correlation assumes an average constant value of upper layer density throughout the smoke-filling process.

(13) The correlation does not allow the vent to be placed in the ceiling.

(14) At the EPRI Fire Modeling Workshop, August 26, 2002 in Seattle, Washington, Mark Salley asked Professor James G. Quintiere (one of the authors of the MQH method) what limits apply to compartment size when using the MQH equation. Professor Quintiere replied that the correlation will work for ***any*** size compartment since it is a dimensionless equation. Professor Quintiere also stated that $\dot{Q}$ should be limited by the following expressions:

$$\dot{m}_f \Delta H_c \leq \ 3000 \frac{kJ}{kg} \quad \text{or} \quad 0.5 A_v \sqrt{h_v} \leq \ 3000 \frac{kJ}{kg}$$

Where:

$\dot{m}_f$ = mass loss rate of fuel (kg/sec)

H_c = heat of combustion (kJ/kg)
A_v = area of ventilation opening (m^2)
h_v = Height of ventilation opening (m)

*The following assumptions and limitations apply only to **forced convection** situations:*

(15) These correlations assume that the test compartment is open to the outside at the inlet, and its pressure is fixed near 1 atmosphere.

(16) These correlations do not explicitly account for evaluation of the fire source.

(17) These correlations assume that the fire is located in the center of the compartment or away from the walls. If the fire is flush with a wall or in a corner of the compartment, the Foot, Pagni, and Alvares (FPA) correlation is not valid with coefficient 0.63.

2.11 Required Input for Spreadsheet Calculations

The user must obtain the following values before attempting a calculation using the natural or forced ventilation spreadsheets:

(1) Compartment width (ft)
(2) Compartment length (ft)
(3) Compartment height (ft)
(4) Interior lining material thickness (in)
(6) Fire heat release rate, HRR (kW)

The user must obtain the following values before attempting a calculation using the natural ventilation spreadsheets:

(7) Vent width (ft)
(8) Vent height (ft)
(9) Top of vent from floor (ft)

The user must obtain the following values before attempting a calculation using the forced ventilation spreadsheets:

(10) Forced ventilation rate (cfm)

2.12 Cautions

(1) Use the appropriate spreadsheet (02.1_Temperature_NV.xls, 02.2_Temperature_FV.xls, or 02.3_Temperature_CC.xls) in the CD ROM for calculation.

(2) Make sure to input values using correct units.

(3) The smoke layer height is a conservative estimate and is only intended to provide an indication of where the hot gas layer is located. Calculated smoke layer heights below the vent height are not creditable since the calculation does not account for smoke exiting the vent!

2.13 Summary

Determination of hot gas layer temperatures and smoke layer height associated with compartment fires provides a means of assessing an important aspect of fire hazard, namely the likelihood of hazardous conditions when structural elements are in danger of collapsing, and the thermal feedback to fuel sources or other objects.

When doors and/or windows provide the air for the fire, natural ventilation occurs, and the MQH correlation applies to the prediction of hot gas temperature. The correlation is relatively straightforward, and it yields reasonable results when applied to most situations. Specifically, the correlation gives the temperature increase of the hot gas layer as a function of three primary variables:

(1) fire size ($\dot{Q}$, HRR)
(2) energy losses to the walls (h_k, A_T)
(3) energy loss through vents ($A_v \sqrt{h_v}$)

Forced ventilation can have a significant effect on fire growth, the temperature profile in the compartment, the spread of toxic fire gases, and the descent of the hot gas layer in a multi-room building. The magnitude of this effect, of course, depends on the HRR of the combustibles and the amount and configuration of the forced ventilation. Depending on the arrangement of the supply and exhaust vents, forced ventilation affects the compartment's thermal environment and sensitive equipment, as it relates to the descent of the hot gas layer. For situations involving forced ventilation, the FPA correlation is applied to the prediction of hot gas temperature. Specifically the FPA correlation gives the temperature increase of the hot gas layer as a function of three primary variables:

(1) fire size ($\dot{Q}$, HRR)
(2) energy losses to the walls (h_k, A_T)
(3) energy loss through vents ($\dot{m}_f$ $c_p T_a$)

The depth (or height) of the growing smoke layer increases with time, but it does not change once the smoke layer has reached equilibrium. Unsteady fires do not have a plateau or upper limit for the rate of heat release. In addition, unsteady fires may have a less rapid buildup of pressure. One approach is to relate the interface of a growing smoke layer for an unsteady fire to a t^2 fire profile.

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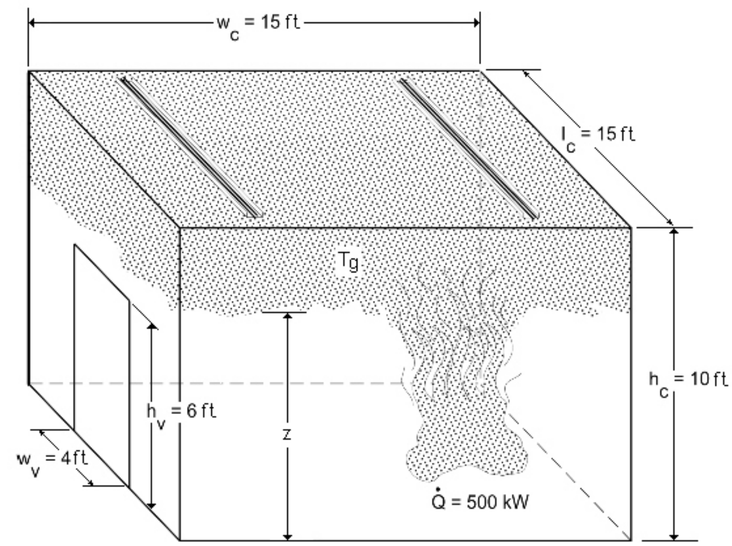
2.16 Problems

2.16.1 Natural Ventilation

Example Problem 2.16.1-1

Problem Statement

Consider a compartment that is 15 ft wide x 15 ft long x 10 ft high (w_c x l_c x h_c), with a simple vent that is 4 ft wide x 6 ft tall (w_v x h_v). The fire is constant with an HRR of 500 kW. Compute the hot gas layer temperature in the compartment and smoke layer height at 2 minutes assuming that the compartment interior boundary material is (a) 1 ft thick concrete and (b) 1.0 inch thick gypsum board. Assume that the top of the vent is 6 ft.



Example Problem 2-1: Compartment with Natural Ventilation

Solution

Purpose:

For two different interior boundary materials determine following:

(1) The hot gas layer temperature in the compartment (T_g) at t = 2 min after ignition

(2) The smoke layer height (z) at t = 2 min after ignition

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)

(2) Simple rectangular geometry (no beam pockets)

(3) One-dimensional heat flow through the compartment boundaries

(4) Constant heat release rate (HRR)

(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) For concrete: 02.1_Temperature_NV.xls (click on *Temperature_ NV Thermally Thick*)

(b) For gypsum board: 02.1_Temperature_NV.xls (click on *Temperature_ NV Thermally Thin*)

Note: Since concrete thickness is greater than one inch, it is necessary to use the correlations for thermally thick material. However, since the gypsum board thickness is equal to 1 inch, it is necessary to use correlations for thermally thin material.

FDT^s Input Parameters: (for both spreadsheets)

- Compartment Width (w_c) = 15 ft
- Compartment Length (l_c) = 15 ft
- Compartment Height (h_c) = 10 ft
- Vent Width (w_v) = 4 ft
- Vent Height (h_v) = 6 ft
- Top of Vent from Floor (V_T) = 6 ft
- Interior Lining Thickness (δ) = 12 in.(concrete) and 1 in. (gypsum board)
- Ambient Air Temperature (T_a) = 77 $^{\circ}$F
- Specific Heat of Air (c_p)= 1 kJ/kg-K
- Material: Select **Concrete** and **Gypsum Board** on the respective FDT^s
- Fire Heat Release Rate $(\dot{Q})$ = 500 kW
- Time after ignition (t) = 2 min

Results*

Interior Boundary Material	Hot Gas Layer Temperature (T_g) °C (°F) (Method of MQH)	Smoke Layer Height (z) z m (ft) (Method of Yamana and Tanaka)
Concrete	147 (296)	1.83 (6.00) (smoke exiting vent, z < V_T)
Gypsum Board	218 (425)	1.83 (6.00) (compartment filled with smoke

*see spreadsheet on next page at t = 2 min

Spreadsheet Calculations

(a) Boundary Material: Concrete

FDT[s]: 02.1_Temperature_NV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Parameter	Value	Unit	Converted
Compartment Width (w_c)	15.00	ft	4.572 m
Compartment Length (l_c)	15.00	ft	4.572 m
Compartment Height (h_c)	10.00	ft	3.048 m
Vent Width (w_v)	4.00	ft	1.219 m
Vent Height (h_v)	6.00	ft	1.829 m
Top of Vent from Floor (V_T)	6.00	ft	1.829 m
Interior Lining Thickness (δ)	12.00	in	0.3048 m

AMBIENT CONDITIONS

Parameter	Value	Unit	Converted
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m³	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

Parameter	Value	Unit
Interior Lining Thermal Inertia ($k\rho c$)	2.9	$(kW/m^2\text{-}K)^2$-sec
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K
Interior Lining Specific Heat (c)	0.75	kJ/kg-K
Interior Lining Density (ρ)	2400	kg/m³

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ $(kW/m^2\text{-}K)^2$-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m³)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Material: Concrete

Scroll to desired material then Click the selection

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270.

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) | 500.00 kW

Calculate

METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2}) (A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

Q = heat release rate of the fire (kW)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

Where A_v = area of ventilation opening (m^2)

w_v = vent width (m)

h_v = vent height (m)

$A_v =$ 2.23 m^2

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

$t_p =$ 26128.98 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

$A_T =$ 95.32 m^2

Compartment Hot Gas Layer Temperature With Natural Ventilation

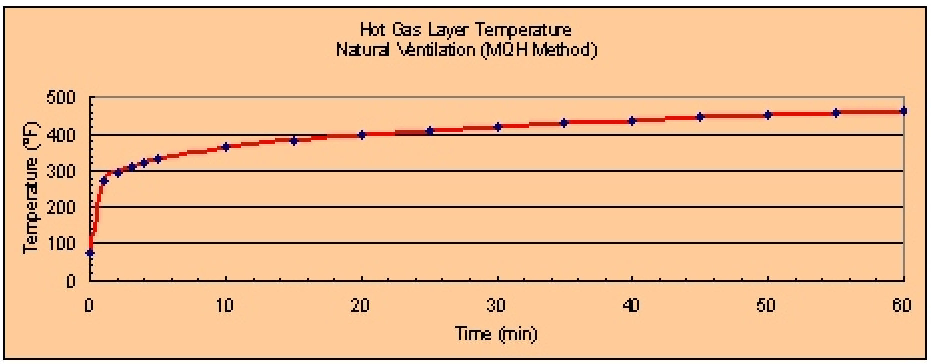
$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2}) (A_T h_k)]^{1/3}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0.00	-	-	298.00	25.00	77.00
1	60	0.22	108.34	406.34	133.34	272.02
2	120	0.16	121.61	419.61	146.61	295.90
3	180	0.13	130.11	428.11	155.11	311.20
4	240	0.11	136.50	434.50	161.50	322.70
5	300	0.10	141.67	439.67	166.67	332.01
10	600	0.07	159.02	457.02	184.02	363.24
15	900	0.06	170.14	468.14	195.14	383.26
20	1200	0.05	178.50	476.50	203.50	398.30
25	1500	0.04	185.26	483.26	210.26	410.47
30	1800	0.04	190.98	488.98	215.98	420.76
35	2100	0.04	195.95	493.95	220.95	429.71
40	2400	0.03	200.36	498.36	225.36	437.64
45	2700	0.03	204.33	502.33	229.33	444.79
50	3000	0.03	207.95	505.95	232.95	451.31
55	3300	0.03	211.28	509.28	236.28	457.30
60	3600	0.03	214.37	512.37	239.37	462.86



ESTIMATING SMOKE LAYER HEIGHT
METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where
- z = smoke layer height (m)
- Q = heat release rate of the fire (kW)
- t = time after ignition (sec)
- h_c = compartment height (m)
- A_c = compartment floor area (m^2)
- k = a constant given by $k = 0.076/\rho_g$
- ρ_g = hot gas layer density (kg/m^3)
- ρ_g is given by $\rho_g = 353/T_g$
- T_g = hot gas layer temperature (K)

Compartment Area Calculation

$A_c = (w_c)(l_c)$

Where
- A_c = compartment floor area (m^2)
- w_c = compartment width (m)
- l_c = compartment length (m)

A_c = 20.90 m^2

Hot Gas Layer Density Calculation

$\rho_g = 353/T_g$

Calculation for Constant K

$k = 0.076/\rho_g$

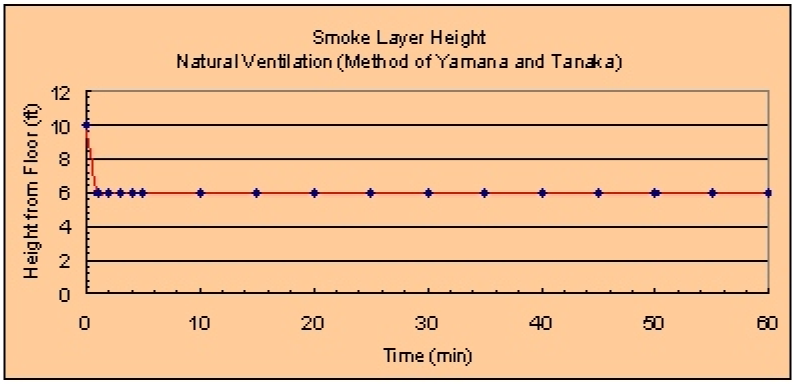
Smoke Gas Layer Height With Natural Ventilation

$z = [(2kQ^{1/3}t/3A_c] + (1/h_c^{2/3}))^{-3/2}$

Results

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

Time (min)	ρ_g (kg/m^3)	Constant (k) (kW/m-K)	Smoke Layer height z (m)	Smoke Layer height z (ft)	
0	1.18	0.064	3.05	10.00	
1	0.87	0.087	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
2	0.84	0.090	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
3	0.82	0.092	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
4	0.81	0.094	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
5	0.80	0.095	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
10	0.77	0.098	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
15	0.75	0.101	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
20	0.74	0.103	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
25	0.73	0.104	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
30	0.72	0.105	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
35	0.71	0.106	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
40	0.71	0.107	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
45	0.70	0.108	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
50	0.70	0.109	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
55	0.69	0.110	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
60	0.69	0.110	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT



NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

(b) Boundary Material: Gypsum Board

FDT[s]: 02.1_Temperature_NV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

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Compartment Length (l_c)	15.00	ft	4.572 m
Compartment Height (h_c)	10.00	ft	3.048 m
Vent Width (w_v)	4.00	ft	1.219 m
Vent Height (h_v)	6.00	ft	1.829 m
Top of Vent from Floor (V_T)	6.00	ft	1.829 m
Interior Lining Thickness (δ)	1.00	in	0.0254 m

AMBIENT CONDITIONS

Parameter	Value	Unit	Converted
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

Parameter	Value	Unit
Interior Lining Thermal Inertia ($k\rho c$)	0.18	(kW/m^2-K)^2-sec
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
Interior Lining Specific Heat (c)	1.1	kJ/kg-K
Interior Lining Density (ρ)	960	kg/m^3

Note : Air density will automatically correct with Ambient Air Temperature (T_a) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m^2-K)^2-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270

Select Material

Gypsum Board

Scroll to desired material then Click the selection

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) | 500.00 | kW

Calculate

METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})\,(A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

Q = heat release rate of the fire (kW)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

Where A_v = area of ventilation opening (m^2)

w_v = vent width (m)

h_v = vent height (m)

$A_v =$ 2.23 m^2

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

$t_p =$ 1001.90 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

$A_T =$ 95.32 m^2

Compartment Hot Gas Layer Temperature With Natural Ventilation

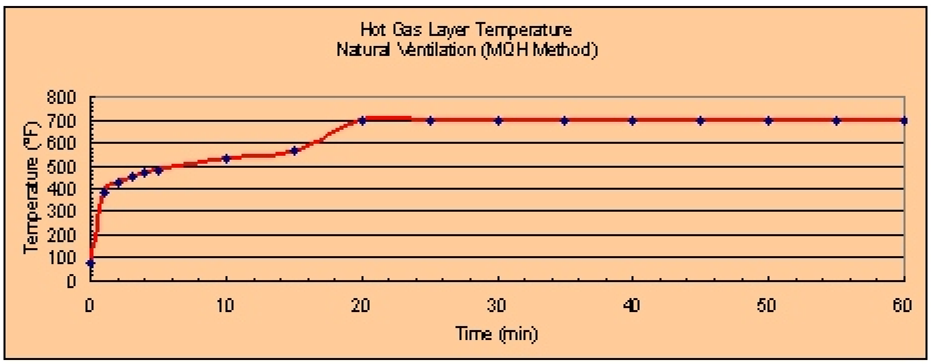
$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})\,(A_T h_k)]^{1/3}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	$(kW/m^2\text{-}K)$	(K)	(K)	(°C)	(°F)
0	0.00	-	-	298.00	25.00	77.00
1	60	0.05	172.18	470.18	197.18	386.92
2	120	0.04	193.27	491.27	218.27	424.88
3	180	0.03	206.78	504.78	231.78	449.20
4	240	0.03	216.93	514.93	241.93	467.48
5	300	0.02	225.15	523.15	250.15	482.28
10	600	0.02	252.73	550.73	277.73	531.91
15	900	0.01	270.39	568.39	295.39	563.71
20	1200	0.01	346.98	644.98	371.98	701.56
25	1500	0.01	346.98	644.98	371.98	701.56
30	1800	0.01	346.98	644.98	371.98	701.56
35	2100	0.01	346.98	644.98	371.98	701.56
40	2400	0.01	346.98	644.98	371.98	701.56
45	2700	0.01	346.98	644.98	371.98	701.56
50	3000	0.01	346.98	644.98	371.98	701.56
55	3300	0.01	346.98	644.98	371.98	701.56
60	3600	0.01	346.98	644.98	371.98	701.56



ESTIMATING SMOKE LAYER HEIGHT
METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where z = smoke layer height (m)
Q = heat release rate of the fire (kW)
t = time after ignition (sec)
h_c = compartment height (m)
A_c = compartment floor area (m^2)
k = a constant given by $k = 0.076/\rho_g$
ρ_g = hot gas layer density (kg/m^3)
ρ_g is given by $\rho_g = 353/T_g$
T_g = hot gas layer temperature (K)

Compartment Area Calculation

$A_c = (w_c)(l_c)$

Where A_c = compartment floor area (m^2)
w_c = compartment width (m)
l_c = compartment length (m)

A_c = 20.90 m^2

Hot Gas Layer Density Calculation

$\rho_g = 353/T_g$

Calculation for Constant K

$k = 0.076/\rho_g$

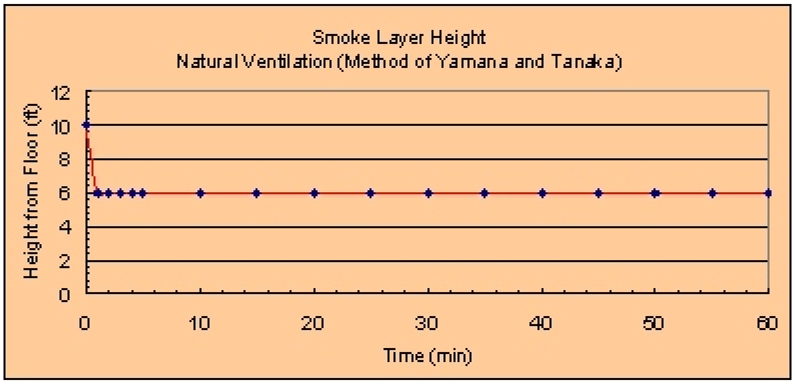
Smoke Gas Layer Height With Natural Ventilation

$z = [(2kQ^{1/3}t/3A_c) + (1/h_c^{2/3})]^{-3/2}$

Results

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

Time (min)	ρ_g (kg/m^3)	Constant (k) (kW/m-K)	Smoke Layer height z (m)	Smoke Layer height z (ft)	
0	1.18	0.064	3.05	10.00	
1	0.75	0.101	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
2	0.72	0.106	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
3	0.70	0.109	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
4	0.69	0.111	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
5	0.67	0.113	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
10	0.64	0.119	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
15	0.62	0.122	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
20	0.55	0.139	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
25	0.55	0.139	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
30	0.55	0.139	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
35	0.55	0.139	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
40	0.55	0.139	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
45	0.55	0.139	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
50	0.55	0.139	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
55	0.55	0.139	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
60	0.55	0.139	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT



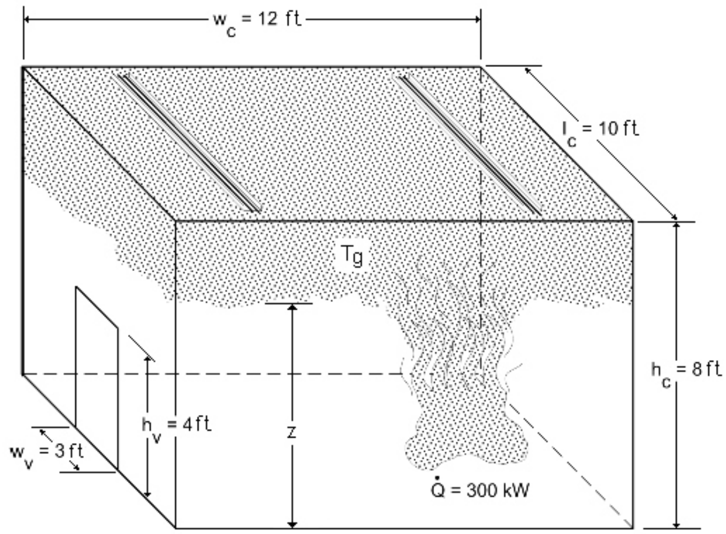
NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

Example Problem 2.16.1-2

Problem Statement

Consider a compartment that is 12 ft wide x 10 ft long x 8 ft high (w_c x l_c x h_c) with a simple vent 3 ft wide x 4 ft tall (w_v x h_v). The construction is essentially 0.5 ft thick gypsum board. The fire is constant with an HRR of 300 kW. Assume that the top of the vent is 4 ft. Compute the hot gas temperature in the compartment, as well as the smoke layer height at 2 minutes.



Example Problem 2-2: Compartment with Natural Ventilation

Solution

Purpose:

(1) The hot gas layer temperature in the compartment (T_g) at t = 2 min after ignition

(2) The smoke layer height (z) at t = 2 min after ignition

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)

(2) Simple rectangular geometry (no beam pockets)

(3) One-dimensional heat flow through the compartment boundaries

(4) Constant Heat Release Rate (HRR)

(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 02.1_Temperature_NV.xls

Note: Since the gypsum board is greater than 1 inch, it is necessary to use the correlations for thermally thick material.

FDT^s Input Parameters:

- Compartment Width (w_c) = 12 ft
- Compartment Length (l_c) = 10 ft
- Compartment Height (h_c) = 8 ft
- Vent Width (w_v) = 3 ft
- Vent Height (h_v) = 4 ft
- Top of Vent from Floor (V_T) = 4 ft
- Interior Lining Thickness (δ) = 6 in
- Ambient Air Temperature (T_a) = 77 °F
- Specific Heat of Air (c_p)= 1 kJ/kg-K
- Material: Select **Gypsum Board** on the FDT^s
- Fire Heat Release Rate $(\dot{Q})$ = 300 kW

Results*

Hot Gas Layer Temperature (T_g) °C (°F) (Method of MQH)	Smoke Layer Height (z) m (ft) (Method of Yamana and Tanaka)
249 (480)	1.22 (4.00) (smoke exiting vent, $z < V_T$)

*see attached spreadsheet on next page at t = 2 min

Spreadsheet Calculations

FDT[s]: 02.1_Temperature_NV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	12.00	ft	3.6576 m
Compartment Length (l_c)	10.00	ft	3.048 m
Compartment Height (h_c)	8.00	ft	2.4384 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	4.00	ft	1.219 m
Top of Vent from Floor (V_T)	4.00	ft	1.219 m
Interior Lining Thickness (δ)	6.00	in	0.1524 m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

Interior Lining Thermal Inertia ($k\rho c$)	0.18	(kW/m^2-K)^2-sec
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
Interior Lining Specific Heat (c)	1.1	kJ/kg-K
Interior Lining Density (ρ)	960	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m^2-K)^2-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Material
Gypsum Board
Scroll to desired material then Click the selection

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) | 300.00 kW

Calculate

METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2}) (A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

Q = heat release rate of the fire (kW)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

Where A_v = area of ventilation opening (m^2)

w_v = vent width (m)

h_v = vent height (m)

A_v = 1.11 m^2

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 36068.24 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 53.88 m^2

Compartment Hot Gas Layer Temperature With Natural Ventilation

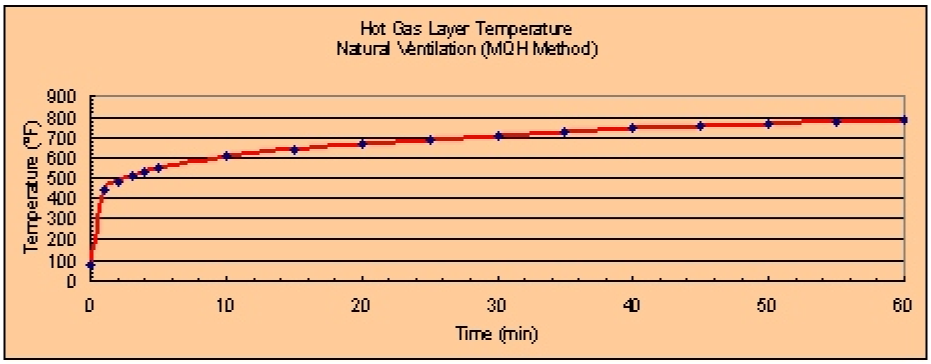
$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2}) (A_T h_k)]^{1/3}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m²-K)	(K)	(K)	(°C)	(°F)
0	0.00	-	-	298.00	25.00	77.00
1	60	0.05	199.69	497.69	224.69	436.44
2	120	0.04	224.14	522.14	249.14	480.45
3	180	0.03	239.81	537.81	264.81	508.66
4	240	0.03	251.59	549.59	276.59	529.86
5	300	0.02	261.12	559.12	286.12	547.02
10	600	0.02	293.10	591.10	318.10	604.58
15	900	0.01	313.59	611.59	338.59	641.46
20	1200	0.01	328.99	626.99	353.99	669.19
25	1500	0.01	341.46	639.46	366.46	691.63
30	1800	0.01	351.99	649.99	376.99	710.59
35	2100	0.01	361.16	659.16	386.16	727.08
40	2400	0.01	369.28	667.28	394.28	741.71
45	2700	0.01	376.60	674.60	401.60	754.89
50	3000	0.01	383.28	681.28	408.28	766.90
55	3300	0.01	389.41	687.41	414.41	777.94
60	3600	0.01	395.10	693.10	420.10	788.18



ESTIMATING SMOKE LAYER HEIGHT
METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where z = smoke layer height (m)
Q = heat release rate of the fire (kW)
t = time after ignition (sec)
h_c = compartment height (m)
A_c = compartment floor area (m^2)
k = a constant given by $k = 0.076/\rho_g$
ρ_g = hot gas layer density (kg/m^3)
ρ_g is given by $\rho_g = 353/T_g$
T_g = hot gas layer temperature (K)

Compartment Area Calculation
$A_c = (w_c)(l_c)$
Where A_c = compartment floor area (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
A_c = 11.15 m^2

Hot Gas Layer Density Calculation
$\rho_g = 353/T_g$

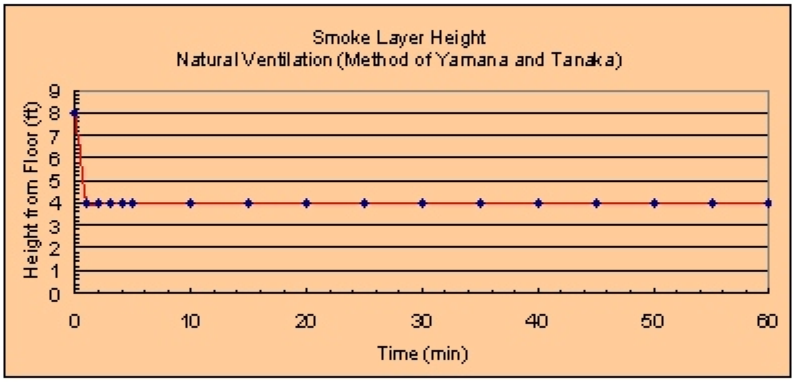
Calculation for Constant K
$k = 0.076/\rho_g$

Smoke Gas Layer Height With Natural Ventilation
$z = [2kQ^{1/3}t/3A_c] + (1/h_c^{2/3})^{-3/2}$

Results

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

Time (min)	ρ_g (kg/m^3)	Constant (k) (kW/m-K)	Smoke Layer height z (m)	Smoke Layer height z (ft)	
0	1.18	0.064	2.44	8.00	
1	0.71	0.107	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
2	0.68	0.112	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
3	0.66	0.116	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
4	0.64	0.118	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
5	0.63	0.120	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
10	0.60	0.127	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
15	0.58	0.132	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
20	0.56	0.135	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
25	0.55	0.138	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
30	0.54	0.140	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
35	0.54	0.142	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
40	0.53	0.144	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
45	0.52	0.145	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
50	0.52	0.147	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
55	0.51	0.148	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT
60	0.51	0.149	1.22	4.00	CAUTION: SMOKE IS EXITING OUT VENT



NOTE

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Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
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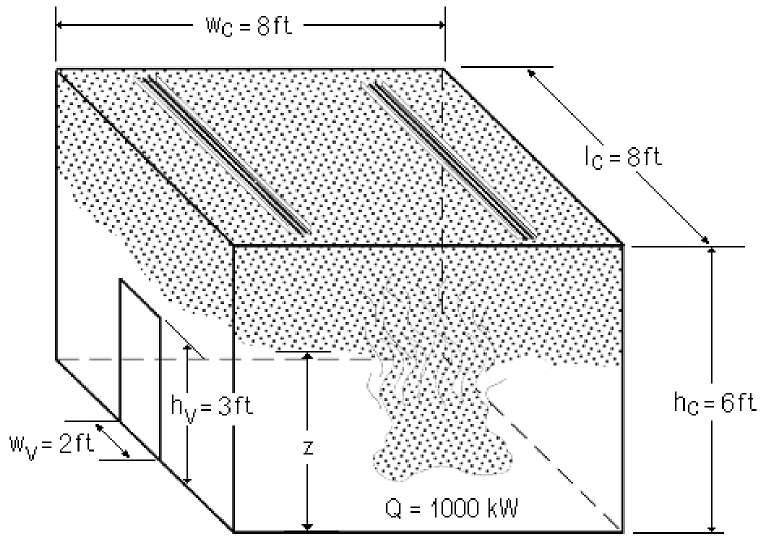
Example Problem 2.16.1-3

Problem Statement

Consider a compartment that is 8 ft wide x 8 ft long x 6 ft high (w_c x l_c x h_c) with a simple vent that is 2 ft wide x 3 ft tall (w_v x h_v). The construction is essentially 0.75 ft thick concrete. The fire is constant with an HRR of 1,000 kW. Assume that the top of the vent is 3 ft. Compute the hot gas temperature in the compartment, as well as the smoke layer height at 3 minutes.



Example Problem 2-3: Compartment with Natural Ventilation

Solution

Purpose:

(1) Determine the hot gas layer temperature in the compartment (T_g) at t = 3 min after ignition

(2) Determine the smoke layer height (z) at t = 3 min after ignition

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)

(2) Simple rectangular geometry (no beam pockets)

(3) One-dimensional heat flow through the compartment boundaries

(4) Constant Heat Release Rate (HRR)

(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 02.1_Temperature_NV.xls

Note: Since concrete thickness is greater than 1 inch, it is necessary to use the correlations for thermally thick material.

FDT^s Input Parameters:

- Compartment Width (w_c) = 8 ft
- Compartment Length (l_c) = 8 ft
- Compartment Height (h_c) = 6 ft
- Vent Width (w_v) = 2 ft
- Vent Height (h_v) = 3 ft
- Top of Vent from Floor (V_T) = 3 ft
- Interior Lining Thickness (δ) = 9 in
- Ambient Air Temperature (T_a) = 77 °F
- Specific Heat of Air (c_p)= 1 kJ/kg-K
- Material: Select **Concrete** on the FDT^s
- Fire Heat Release Rate $(\dot{Q})$ = 1,000 kW

Results*:

Hot Gas Layer Temperature (T_g) °C (°F) (Method of MQH)	Smoke Layer Height (z) m (ft) (Method of Yamana and Tanaka)
571 (1,060)	0.91 (3.00) compartment filled with smoke)

*see spreadsheet on next page at t = 3 min

Spreadsheet Calculations

FDT[s]: 02.1_Temperature_NV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Parameter	Value	Unit	Converted
Compartment Width (w_c)	8.00	ft	2.4384 m
Compartment Length (l_c)	8.00	ft	2.4384 m
Compartment Height (h_c)	6.00	ft	1.8288 m
Vent Width (w_v)	2.00	ft	0.610 m
Vent Height (h_v)	3.00	ft	0.914 m
Top of Vent from Floor (V_T)	3.00	ft	0.914 m
Interior Lining Thickness (δ)	9.00	in	0.2286 m

AMBIENT CONDITIONS

Parameter	Value	Unit	Converted
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m³	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

Parameter	Value	Unit
Interior Lining Thermal Inertia ($k\rho c$)	2.9	$(kW/m^2\text{-}K)^2$-sec
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K
Interior Lining Specific Heat (c)	0.75	kJ/kg-K
Interior Lining Density (ρ)	2400	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ $(kW/m^2\text{-}K)^2$-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Material: Concrete

Scroll to desired material then Click the selection

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) | 1000.00 kW

Calculate

METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2})\,(A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

Q = heat release rate of the fire (kW)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

Area of Ventilation Opening Calculation

$A_v = (w_v)\,(h_v)$

Where A_v = area of ventilation opening (m^2)

w_v = vent width (m)

h_v = vent height (m)

A_v = 0.56 m^2

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)\,(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 14697.55 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 29.17 m^2

Compartment Hot Gas Layer Temperature With Natural Ventilation

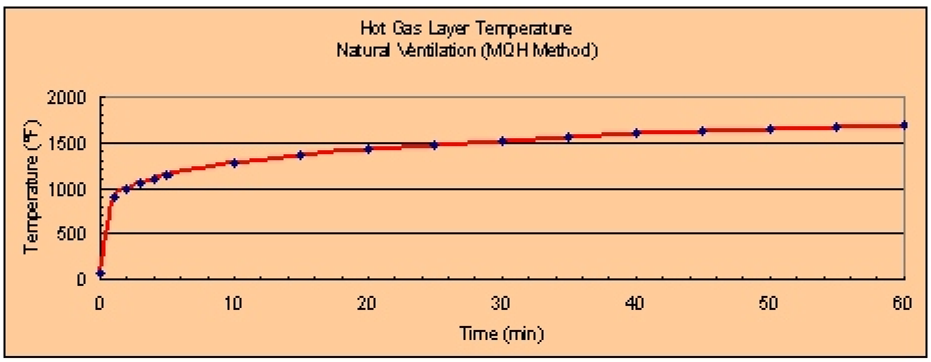
$\Delta T_g = 6.85\,[Q^2/(A_v (h_v)^{1/2})\,(A_T h_k)]^{1/3}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t) (min)	(sec)	h_k (kW/m^2-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	454.72	752.72	479.72	895.50
2	120	0.16	510.41	808.41	535.41	995.74
3	180	0.13	546.09	844.09	571.09	1059.97
4	240	0.11	572.91	870.91	597.91	1108.25
5	300	0.10	594.62	892.62	619.62	1147.32
10	600	0.07	667.44	965.44	692.44	1278.39
15	900	0.06	714.10	1012.10	739.10	1362.39
20	1200	0.05	749.18	1047.18	774.18	1425.52
25	1500	0.04	777.56	1075.56	802.56	1476.62
30	1800	0.04	801.56	1099.56	826.56	1519.80
35	2100	0.04	822.42	1120.42	847.42	1557.35
40	2400	0.03	840.92	1138.92	865.92	1590.66
45	2700	0.03	857.59	1155.59	882.59	1620.67
50	3000	0.03	872.79	1170.79	897.79	1648.02
55	3300	0.03	886.76	1184.76	911.76	1673.17
60	3600	0.03	899.72	1197.72	924.72	1696.49



ESTIMATING SMOKE LAYER HEIGHT
METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where
- z = smoke layer height (m)
- Q = heat release rate of the fire (kW)
- t = time after ignition (sec)
- h_c = compartment height (m)
- A_c = compartment floor area (m^2)
- k = a constant given by $k = 0.076/\rho_g$
- ρ_g = hot gas layer density (kg/m^3)
- ρ_g is given by $\rho_g = 353/T_g$
- T_g = hot gas layer temperature (K)

Compartment Area Calculation

$A_c = (w_c)(l_c)$

Where
- A_c = compartment floor area (m^2)
- w_c = compartment width (m)
- l_c = compartment length (m)

$A_c =$ 5.95 m^2

Hot Gas Layer Density Calculation

$\rho_g = 353/T_g$

Calculation for Constant K

$k = 0.076/\rho_g$

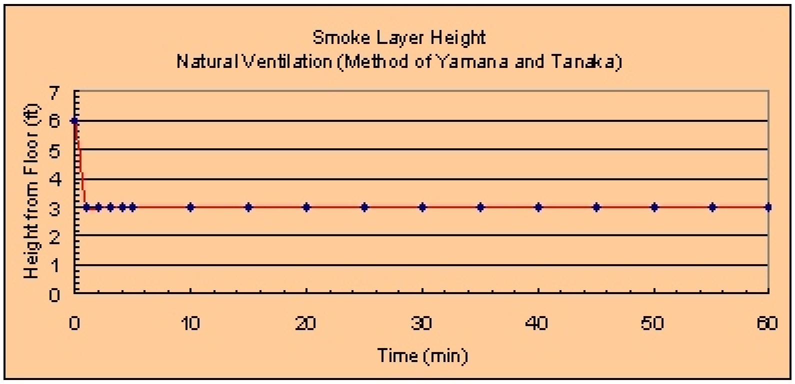
Smoke Gas Layer Height With Natural Ventilation

$z = [(2kQ^{1/3}t/3A_c] + (1/h_c^{2/3}))^{-3/2}$

Results

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

Time (min)	ρ_g (kg/m^3)	Constant (k) (kW/m-K)	Smoke Layer height z (m)	Smoke Layer height z (ft)	
0	1.18	0.064	1.83	6.00	
1	0.47	0.162	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
2	0.44	0.174	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
3	0.42	0.182	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
4	0.41	0.188	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
5	0.40	0.192	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
10	0.37	0.208	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
15	0.35	0.218	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
20	0.34	0.225	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
25	0.33	0.232	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
30	0.32	0.237	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
35	0.32	0.241	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
40	0.31	0.245	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
45	0.31	0.249	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
50	0.30	0.252	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
55	0.30	0.255	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT
60	0.29	0.258	0.91	3.00	CAUTION: SMOKE IS EXITING OUT VENT



NOTE

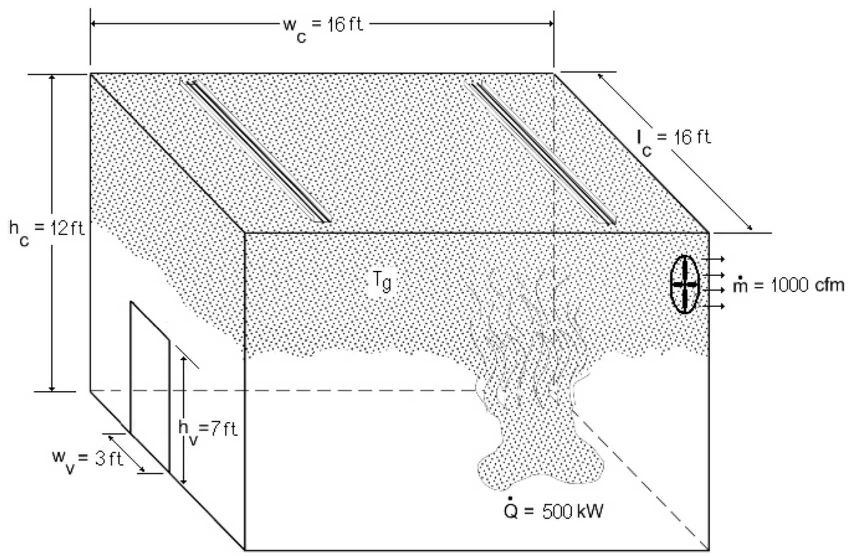
The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

2.16.2 Forced Ventilation

Example Problem 2.16.2-1

Problem Statement

Consider a compartment that is 16 ft wide x 16 ft long x 12 ft high (w_c x l_c x h_c), with a vent opening that is 3 ft wide x 7 ft tall (w_v x h_v). The forced ventilation rate is 1,000 cfm (exhaust). Calculate the hot gas layer temperature for a fire size of 500 kW at 2 minutes after ignition. The compartment boundaries are made of (a) 1 ft thick concrete and (b) 0.7 inch thick gypsum board.



Example Problem 2-4: Compartment with Forced Ventilation

Solution

Purpose:

For two different interior lining materials determine the hot gas layer temperature in the compartment (T_g) at t = 2 min after ignition.

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)
(2) Simple rectangular geometry (no beam pockets)
(3) One-dimensional heat flow through the compartment boundaries
(4) Constant Heat Release Rate (HRR)
(5) The fire is located at the center of the compartment or away from the walls
(6) The bottom of the vent is at the floor level
(7) The compartment is open to the outside at the inlet (pressure = 1 atm)

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) For Concrete:

02.2_Temperature_FV.xls

(b) For Gypsum Board:

02.2_Temperature_FV.xls

Note: Since concrete thickness is greater than one inch, it is necessary to use the correlations for thermally thick material. However, since gypsum board thickness is less than 1 inch, it is necessary to use correlations for thermally thin material. Also, each spreadsheet has a different method to calculate the hot gas layer temperature (T_g). We are going to use both methods to compare the results.

FDT^s Input Parameters: (for both spreadsheets)

- Compartment Width (w_c) = 16 ft
- Compartment Length (l_c) = 16 ft
- Compartment Height (h_c) = 12 ft
- Interior Lining Thickness (δ) = 12 in (concrete) and .7in (gypsum board)
- Ambient Air Temperature (T_a) = 77 °F
- Specific Heat of Air (c_p)= 1 kJ/kg-K
- Material: Select **Concrete** and **Gypsum Board** on the respective FDT^s
- Compartment Mass Ventilation Rate (m) = 1,000 cfm
- Fire Heat Release Rate $(\dot{Q})$ = 500 kW
- Time after ignition (t) = 2 min.

Results*

Boundary Material	Hot Layer Gas Temperature (T_g) °C (°F)	
	Method of Foote, Pagni & Alvares (FPA)	Method of Deal & Beyler
Concrete	142 (288)	87 (190)
Gypsum Board	218 (426)	223 (452)

*see spreadsheets on next page at t = 2 min.

Spreadsheet Calculations
(a) Boundary Material: Concrete
FDT^s: 02.2_Temperature_FV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION
COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	16.00	ft	4.88 m
Compartment Length (l_c)	16.00	ft	4.88 m
Compartment Height (h_c)	12.00	ft	3.66 m
Interior Lining Thickness (δ)	12.00	in	0.3048 m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

Interior Lining Thermal Inertia ($k\rho c$)	2.9	(kW/m^2-K)^2-sec
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K
Interior Lining Specific Heat (c)	0.75	kJ/kg-K
Interior Lining Density (ρ)	2400	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m^2-K)^2-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

Select Material
Concrete
Scroll to desired material then
Click on selection

COMPARTMENT MASS VENTILATION FLOW RATE

Forced Ventilation Flow Rate (m)	1000.00	cfm	0.472 m^3/sec 0.559 kg/sec

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q)	500.00	kW

Calculate

METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/m c_p T_a)^{0.72}(h_k A_T/m c_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

c_p = specific heat of air (kJ/kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries (m^2)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 26128.98 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where A_T = total area of the compartment enclosing surface boundaries (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 118.92 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

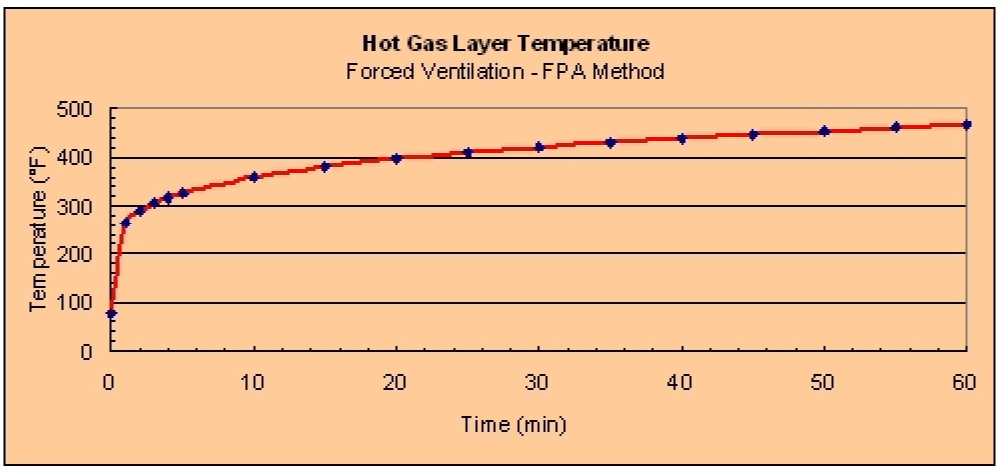
$\Delta T_g/T_a = 0.63(Q/m c_p T_o)^{0.72}(h_k A_T/m c_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	$\Delta T_g/T_0$	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)		(K)	(K)	(°C)	(°F)
0	0	-	-	-	298.00	25.00	77.00
1	60	0.22	0.35	103.76	401.76	128.76	263.77
2	120	0.16	0.39	117.55	415.55	142.55	288.59
3	180	0.13	0.42	126.45	424.45	151.45	304.61
4	240	0.11	0.45	133.17	431.17	158.17	316.71
5	300	0.10	0.47	138.63	436.63	163.63	326.54
10	600	0.07	0.53	157.05	455.05	182.05	359.70
15	900	0.06	0.57	168.94	466.94	193.94	381.10
20	1200	0.05	0.60	177.92	475.92	202.92	397.26
25	1500	0.04	0.62	185.21	483.21	210.21	410.39
30	1800	0.04	0.64	191.39	489.39	216.39	421.51
35	2100	0.04	0.66	196.78	494.78	221.78	431.20
40	2400	0.03	0.68	201.57	499.57	226.57	439.82
45	2700	0.03	0.69	205.88	503.88	230.88	447.59
50	3000	0.03	0.70	209.83	507.83	234.83	454.69
55	3300	0.03	0.72	213.46	511.46	238.46	461.22
60	3600	0.03	0.73	216.83	514.83	241.83	467.29



METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k = 0.4\,\sqrt{(k\rho c / t)}$ for $t < t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia (kW/m^2-K)^2-sec

(a thermal property of material responsible for the rate of temperature rise)

δ = thickness of interior lining (m)

h_k = 0.088 kW/m^2-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

A_T = 118.92 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\, c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

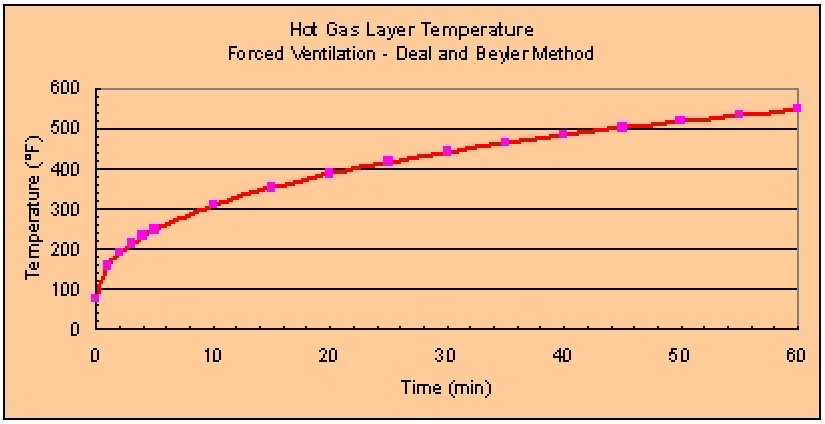
c_p = specific heat of air (kJ/Kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

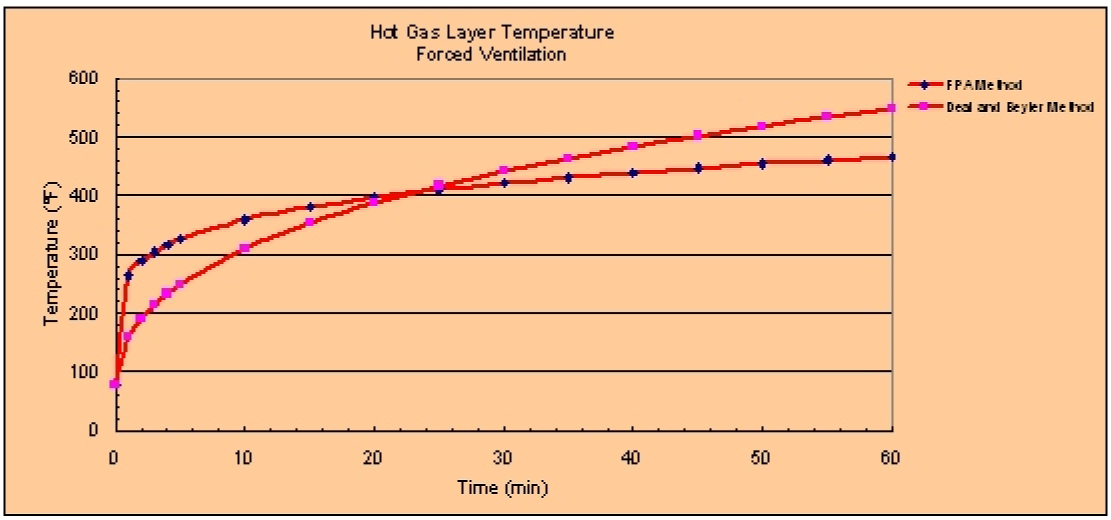
A_T = total area of the compartment enclosing surface boundaries (m^2)

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0	-	-	298.00	25.00	77.00
1	60	0.09	45.39	343.39	70.39	158.70
2	120	0.06	62.87	360.87	87.87	190.16
3	180	0.05	75.80	373.80	100.80	213.43
4	240	0.04	86.39	384.39	111.39	232.50
5	300	0.04	95.50	393.50	120.50	248.90
10	600	0.03	129.33	427.33	154.33	309.80
15	900	0.02	153.41	451.41	178.41	353.15
20	1200	0.02	172.57	470.57	197.57	387.62
25	1500	0.02	188.64	486.64	213.64	416.55
30	1800	0.02	202.57	500.57	227.57	441.62
35	2100	0.01	214.90	512.90	239.90	463.82
40	2400	0.01	225.99	523.99	250.99	483.78
45	2700	0.01	236.08	534.08	261.08	501.94
50	3000	0.01	245.34	543.34	270.34	518.62
55	3300	0.01	253.92	551.92	278.92	534.06
60	3600	0.01	261.90	559.90	286.90	548.43



Summary of Result:



NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) Boundary Material: Gypsum Board
FDT[s]: 02.2_Temperature_FV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION
COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	16.00	ft	4.88 m
Compartment Length (l_c)	16.00	ft	4.88 m
Compartment Height (h_c)	12.00	ft	3.66 m
Interior Lining Thickness (δ)	0.70	in	0.01778 m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m³	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

Interior Lining Thermal Inertia (kρc)	0.18	(kW/m²-K)²-sec
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
Interior Lining Specific Heat (c)	1.1	kJ/kg-K
Interior Lining Density (ρ)	960	kg/m³

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	kρc (kW/m²-K)²-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m³)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Material: Gypsum Board
Scroll to desired material then Click on selection

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

COMPARTMENT MASS VENTILATION FLOW RATE

Forced Ventilation Flow Rate (m)	1000.00	cfm	0.472 m^3/sec
			0.559 kg/sec

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q)	500.00	kW

Calculate

METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/m c_p T_a)^{0.72}(h_k A_T/m c_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

c_p = specific heat of air (kJ/kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries (m^2)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 490.93 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where A_T = total area of the compartment enclosing surface boundaries (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 118.92 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

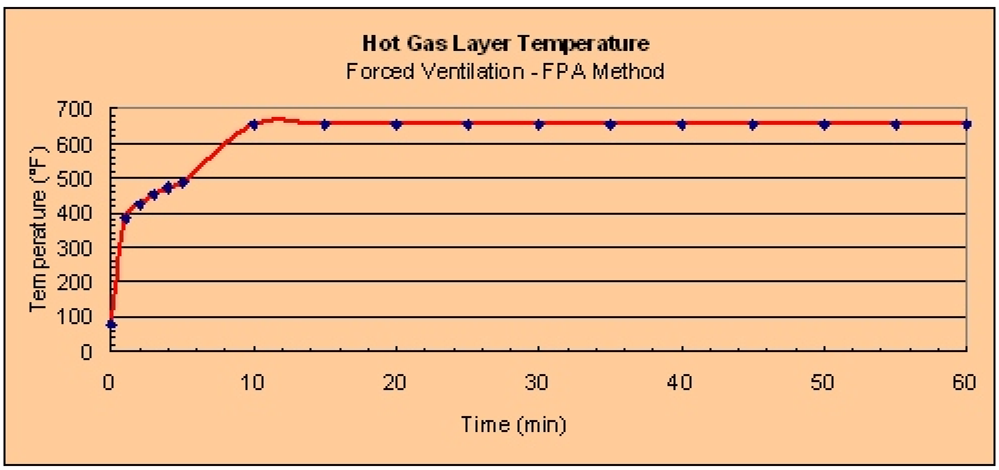
$\Delta T_g/T_a = 0.63(Q/m c_p T_o)^{0.72}(h_k A_T/m c_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	$\Delta T_g/T_0$	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)		(K)	(K)	(°C)	(°F)
0	0	-	-	-	298.00	25.00	77.00
1	60	0.05	0.57	171.13	469.13	196.13	385.04
2	120	0.04	0.65	193.87	491.87	218.87	425.97
3	180	0.03	0.70	208.55	506.55	233.55	452.39
4	240	0.03	0.74	219.63	517.63	244.63	472.34
5	300	0.02	0.77	228.64	526.64	253.64	488.54
10	600	0.01	1.08	320.79	618.79	345.79	654.43
15	900	0.01	1.08	320.79	618.79	345.79	654.43
20	1200	0.01	1.08	320.79	618.79	345.79	654.43
25	1500	0.01	1.08	320.79	618.79	345.79	654.43
30	1800	0.01	1.08	320.79	618.79	345.79	654.43
35	2100	0.01	1.08	320.79	618.79	345.79	654.43
40	2400	0.01	1.08	320.79	618.79	345.79	654.43
45	2700	0.01	1.08	320.79	618.79	345.79	654.43
50	3000	0.01	1.08	320.79	618.79	345.79	654.43
55	3300	0.01	1.08	320.79	618.79	345.79	654.43
60	3600	0.01	1.08	320.79	618.79	345.79	654.43



METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k = 0.4 \sqrt{(k\rho c / t)}$ for $t < t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

δ = thickness of interior lining (m)

h_k = 0.022 kW/m^2-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

A_T = 118.92 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\, c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

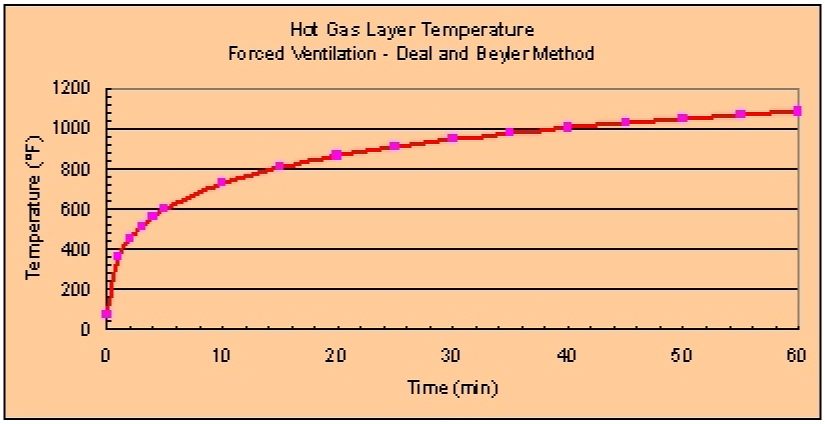
c_p = specific heat of air (kJ/Kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

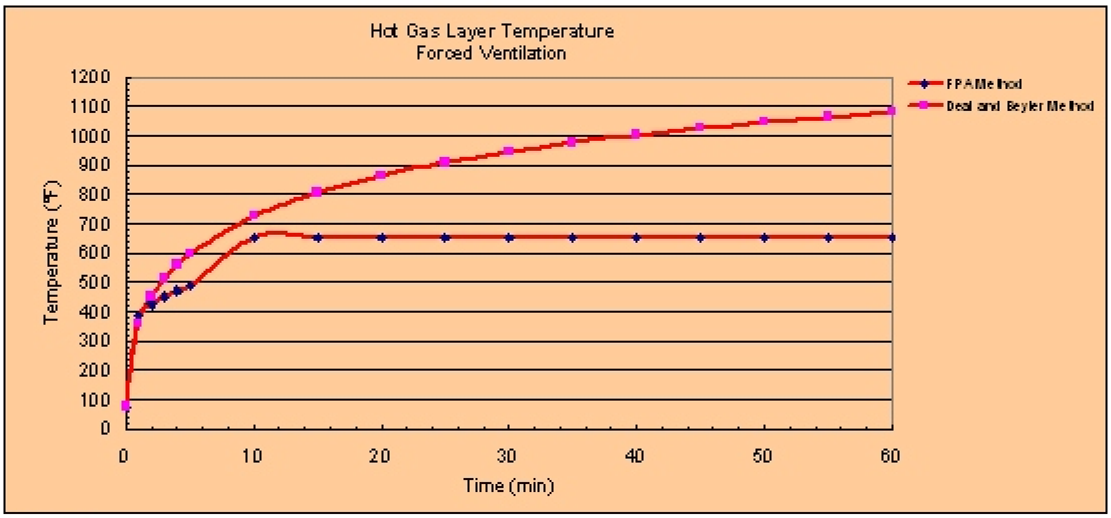
A_T = total area of the compartment enclosing surface boundaries (m^2)

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0	-	-	298.00	25.00	77.00
1	60	0.02	158.01	456.01	183.01	361.42
2	120	0.02	208.22	506.22	233.22	451.80
3	180	0.01	242.34	540.34	267.34	513.21
4	240	0.01	268.57	566.57	293.57	560.43
5	300	0.01	289.99	587.99	314.99	598.99
10	600	0.01	361.55	659.55	386.55	727.79
15	900	0.01	405.93	703.93	430.93	807.67
20	1200	0.00	437.97	735.97	462.97	865.35
25	1500	0.00	462.91	760.91	487.91	910.24
30	1800	0.00	483.22	781.22	508.22	946.80
35	2100	0.00	500.28	798.28	525.28	977.51
40	2400	0.00	514.94	812.94	539.94	1003.89
45	2700	0.00	527.74	825.74	552.74	1026.94
50	3000	0.00	539.08	837.08	564.08	1047.35
55	3300	0.00	549.24	847.24	574.24	1065.63
60	3600	0.00	558.41	856.41	583.41	1082.14



Summary of Result:



NOTE

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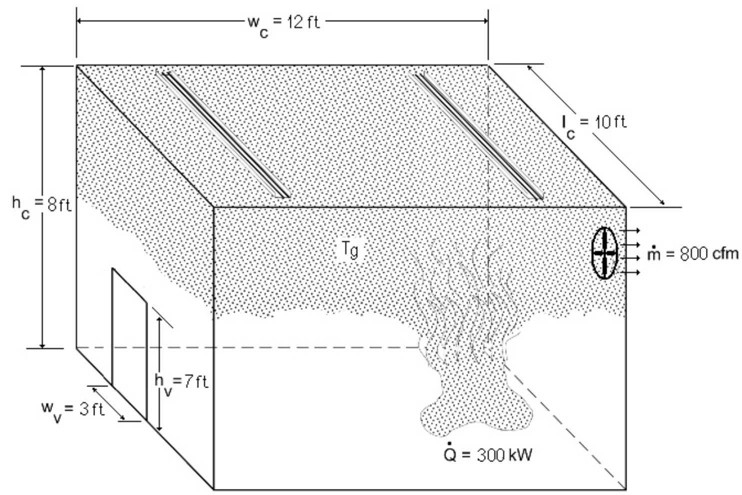
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 2.16.2-2

Problem Statement

Consider a compartment that is 12 ft wide x 10 ft long x 8 ft high (w_c x l_c x h_c) with a vent opening that is 3 ft wide x 7 ft tall (w_v x h_v). The compartment boundaries are made of 0.5 ft thick gypsum board. The forced ventilation rate is 800 cfm (exhaust). Calculate the hot gas layer temperature in the compartment for a fire size of 300 kW at 2 minutes.



Example Problem 2-5: Compartment with Forced Ventilation

Solution

Purpose:

(1) Determine the hot gas layer temperature in the compartment (T_g) at t = 2 min after ignition.

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)
(2) Simple rectangular geometry: no beam pockets
(3) One-dimensional heat flow through the compartment boundaries
(4) Constant Heat Release Rate (HRR)
(5) The fire is located at the center of the compartment or away from the walls
(6) The bottom of the vent is at the floor level
(7) The compartment is open to the outside at the inlet (pressure = 1 atm)

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 02.2_Temperature_FV.xls

Note: Since gypsum board thickness is more than 1 inch, it is required to use correlations for thermally thick materials. Also, the spreadsheet has two different methods to calculate the hot gas layer temperature. Both methods are presented for comparison.

FDT^s Input Parameters:

- Compartment Width (w_c) = 12 ft
- Compartment Length (l_c) = 10 ft
- Compartment Height (h_c) = 8 ft
- Interior Lining Thickness (δ) = 6 in
- Ambient Air Temperature (T_a) = 77 °F
- Specific Heat of Air (c_p)= 1 kJ/kg-K
- Material: Select **Gypsum Board** on the FDT^s
- Compartment Mass Ventilation Rate $(\dot{m})$ = 800 cfm
- Fire Heat Release Rate $(\dot{Q})$ = 300 kW

Results*

Boundary Material	Hot Layer Gas Temperature (T_g) °C (°F)	
	Method of Foote, Pagni & Alvares (FPA)	Method of Deal & Beyler
Gypsum Board	216 (423)	256 (493)

*see spreadsheet on next page at t = 2 min

Spreadsheet Calculations
FDT[s]: 02.2_Temperature_FV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	12.00	ft	3.66 m
Compartment Length (l_c)	10.00	ft	3.05 m
Compartment Height (h_c)	8.00	ft	2.44 m
Interior Lining Thickness (δ)	6.00	in	0.1524 m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

Interior Lining Thermal Inertia ($k\rho c$)	0.18	(kW/m^2-K)^2-sec
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
Interior Lining Specific Heat (c)	1.1	kJ/kg-K
Interior Lining Density (ρ)	960	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m^2-K)^2-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

Select Material
Gypsum Board
Scroll to desired material then
Click on selection

COMPARTMENT MASS VENTILATION FLOW RATE

Forced Ventilation Flow Rate (m) | 800.00 cfm | 0.378 m^3/sec
0.447 kg/sec

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) | 300.00 kW

Calculate

METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/mc_pT_a)^{0.72}(h_kA_T/mc_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

c_p = specific heat of air (kJ/kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries (m^2)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 36068.24 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where A_T = total area of the compartment enclosing surface boundaries (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 55.00 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

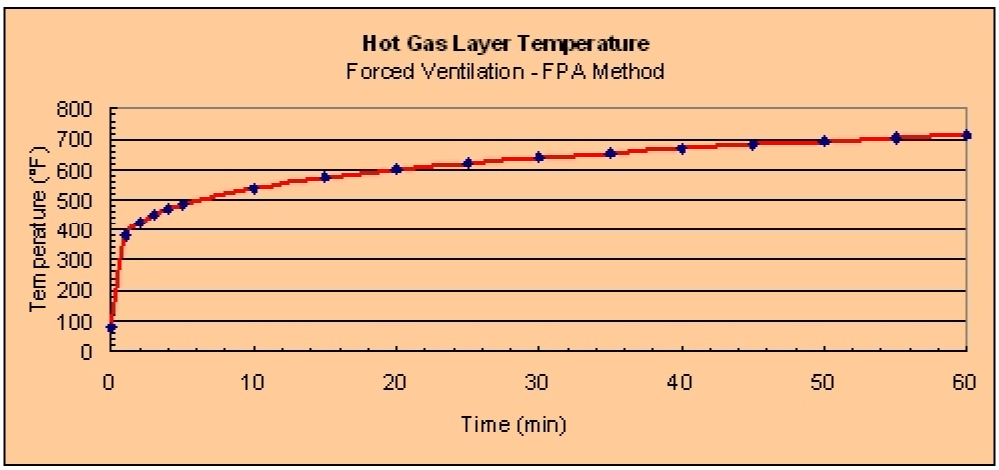
$\Delta T_g/T_a = 0.63(Q/mc_pT_o)^{0.72}(h_kA_T/mc_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	$\Delta T_g/T_0$	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m²-K)		(K)	(K)	(°C)	(°F)
0	0	-	-	-	298.00	25.00	77.00
1	60	0.05	0.57	169.45	467.45	194.45	382.01
2	120	0.04	0.64	191.97	489.97	216.97	422.54
3	180	0.03	0.69	206.50	504.50	231.50	448.71
4	240	0.03	0.73	217.48	515.48	242.48	468.46
5	300	0.02	0.76	226.39	524.39	251.39	484.50
10	600	0.02	0.86	256.47	554.47	281.47	538.65
15	900	0.01	0.93	275.89	573.89	300.89	573.61
20	1200	0.01	0.98	290.56	588.56	315.56	600.00
25	1500	0.01	1.01	302.46	600.46	327.46	621.44
30	1800	0.01	1.05	312.56	610.56	337.56	639.60
35	2100	0.01	1.08	321.35	619.35	346.35	655.43
40	2400	0.01	1.10	329.17	627.17	354.17	669.50
45	2700	0.01	1.13	336.22	634.22	361.22	682.20
50	3000	0.01	1.15	342.66	640.66	367.66	693.78
55	3300	0.01	1.17	348.59	646.59	373.59	704.46
60	3600	0.01	1.19	354.09	652.09	379.09	714.36



METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

h_k = 0.4 √(kρc / t) for t < t_p

Where h_k = heat transfer coefficient (kW/m^2-K)

kρc = interior construction thermal inertia (kW/m^2-K)^2-sec

(a thermal property of material responsible for the rate of temperature rise)

δ = thickness of interior lining (m)

h_k = 0.022 kW/m^2-K

Area of Compartment Enclosing Surface Boundaries

A_T = 2(w_c × l_c) + 2(h_c × w_c) + 2(h_c × l_c)

A_T = 55.00 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\, c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

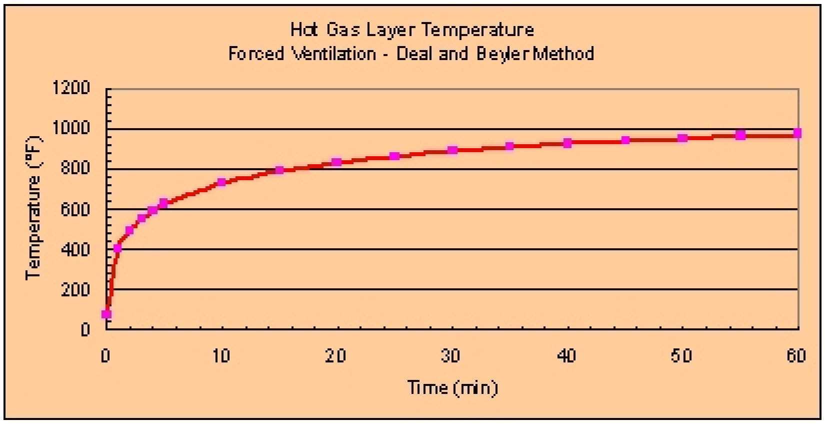
c_p = specific heat of air (kJ/Kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

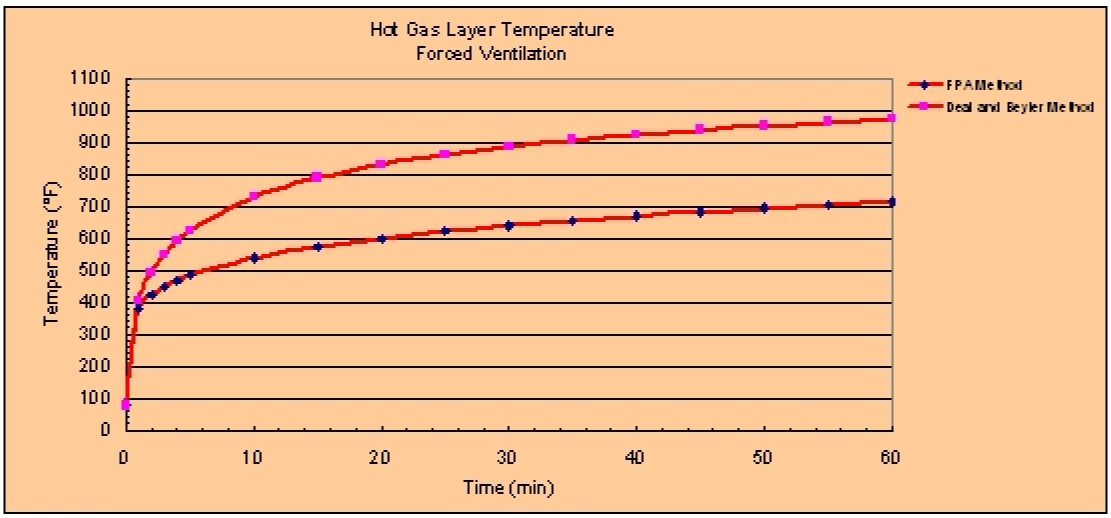
A_T = total area of the compartment enclosing surface boundaries (m^2)

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0	-	-	298.00	25.00	77.00
1	60	0.02	181.58	479.58	206.58	403.84
2	120	0.02	230.90	528.90	255.90	492.62
3	180	0.01	262.48	560.48	287.48	549.47
4	240	0.01	285.79	583.79	310.79	591.42
5	300	0.01	304.22	602.22	329.22	624.60
10	600	0.01	362.20	660.20	387.20	728.95
15	900	0.01	395.59	693.59	420.59	789.06
20	1200	0.00	418.60	716.60	443.60	830.48
25	1500	0.00	435.90	733.90	460.90	861.62
30	1800	0.00	449.62	747.62	474.62	886.31
35	2100	0.00	460.89	758.89	485.89	906.60
40	2400	0.00	470.39	768.39	495.39	923.71
45	2700	0.00	478.57	776.57	503.57	938.43
50	3000	0.00	485.71	783.71	510.71	951.28
55	3300	0.00	492.03	790.03	517.03	962.66
60	3600	0.00	497.68	795.68	522.68	972.82



Summary of Result:



NOTE

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Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
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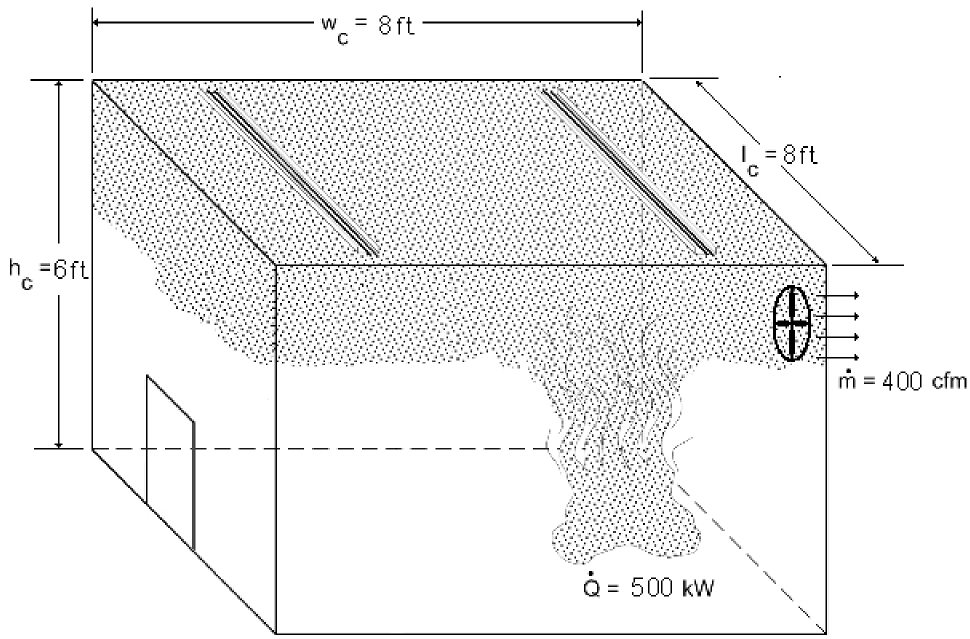
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Problem 2.16.2-3

Problem Statement

Consider a compartment that is 8 ft wide x 8 ft long x 6 ft high (w_c x l_c x h_c). The compartment boundaries are made of 0.75 ft thick brick. The forced ventilation rate is 400 cfm (exhaust). Calculate the hot gas layer temperature in the compartment for a fire size of 500 kW at 2 minutes.



Example Problem 2-6: Compartment with Forced Ventilation

Solution

Purpose:

(1) Determine the hot gas layer temperature in the compartment (T_g) at t = 2 min after ignition.

Assumptions:

(1) Air properties (ambient) at 77 °F (25 °C)
(2) Simple rectangular geometry (no beam pockets)
(3) One-dimensional heat flow through the compartment boundaries
(4) Constant Heat Release Rate (HRR)
(5) The fire is located at the center of the compartment or away from the walls
(6) The bottom of the vent is at the floor level
(7) The compartment is open to the outside at the inlet (pressure = 1 atm)

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 02.2_Temperature_FV.xls

Note: Since the interior lining material thickness is more than 1 inch, it is required to use correlations for thermally thick materials. Also, the spreadsheet has two different methods to calculate the hot gas layer temperature. We are going to use both methods to compare values.

FDT^s Input Parameters:

- Compartment Width (w_c) = 8 ft
- Compartment Length (l_c) = 8 ft
- Compartment Height (h_c) = 6 ft
- Interior Lining Thickness (δ) = 9 in
- Ambient Air Temperature (T_a) = 77 °F
- Specific Heat of Air (c_p)= 1 kJ/kg-K
- Material: Select **Brick** on the FDT^s
- Compartment Mass Ventilation Rate $(\dot{m})$ = 400 cfm
- Fire Heat Release Rate $(\dot{Q})$ = 500 kW

Results*

Boundary Material	Hot Layer Gas Temperature (T_g) °C (°F)	
	Method of Foote, Pagni & Alvares (FPA)	Method of Deal & Beyler
Brick	321 (611)	330 (626)

*see spreadsheet on next page at t = 2 min.

Spreadsheet Calculations
FDT^s: 02.2_Temperature_FV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION
COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	8.00	ft	2.44 m
Compartment Length (l_c)	8.00	ft	2.44 m
Compartment Height (h_c)	6.00	ft	1.83 m
Interior Lining Thickness (δ)	9.00	in	0.2286 m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

Interior Lining Thermal Inertia ($k\rho c$)	1.7	(kW/m^2-K)^2-sec
Interior Lining Thermal Conductivity (k)	0.0008	kW/m-K
Interior Lining Specific Heat (c)	0.8	kJ/kg-K
Interior Lining Density (ρ)	2600	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m^2-K)^2-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Material
Brick
Scroll to desired material then Click on selection

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

COMPARTMENT MASS VENTILATION FLOW RATE

Forced Ventilation Flow Rate (m) | 400.00 cfm | 0.189 m^3/sec
0.224 kg/sec

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) | 500.00 kW

Calculate

METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/m c_p T_a)^{0.72}(h_k A_T/m c_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

c_p = specific heat of air (kJ/kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries (m^2)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 33967.67 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where A_T = total area of the compartment enclosing surface boundaries (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 29.73 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

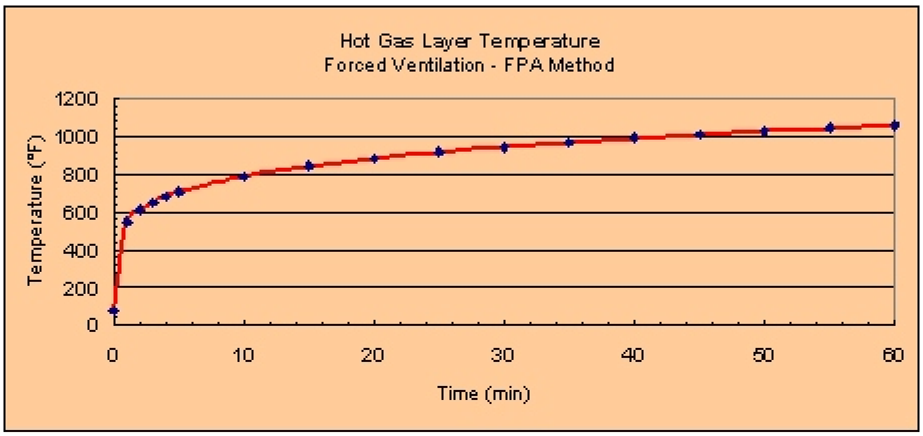
$\Delta T_g/T_a = 0.63(Q/m c_p T_o)^{0.72}(h_k A_T/m c_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	$\Delta T_g/T_a$	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)		(K)	(K)	(°C)	(°F)
0	0	-	-	-	298.00	25.00	77.00
1	60	0.17	0.88	261.70	559.70	286.70	548.05
2	120	0.12	0.99	296.47	594.47	321.47	610.65
3	180	0.10	1.07	318.92	616.92	343.92	651.05
4	240	0.08	1.13	335.87	633.87	360.87	681.56
5	300	0.08	1.17	349.63	647.63	374.63	706.34
10	600	0.05	1.33	396.09	694.09	421.09	789.97
15	900	0.04	1.43	426.08	724.08	451.08	843.95
20	1200	0.04	1.51	448.73	746.73	473.73	884.71
25	1600	0.03	1.57	467.12	765.12	492.12	917.81
30	1800	0.03	1.62	482.70	780.70	507.70	945.86
35	2100	0.03	1.67	496.28	794.28	521.28	970.31
40	2400	0.03	1.71	508.36	806.36	533.36	992.04
45	2700	0.03	1.74	519.25	817.25	544.25	1011.65
50	3000	0.02	1.78	529.19	827.19	554.19	1029.54
55	3300	0.02	1.81	538.35	836.35	563.35	1046.02
60	3600	0.02	1.84	546.84	844.84	571.84	1061.32



METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k = 0.4\sqrt{(k\rho c / t)}$ for $t < t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

δ = thickness of interior lining (m)

h_k = 0.067 kW/m^2-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

A_T = 29.73 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\, c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

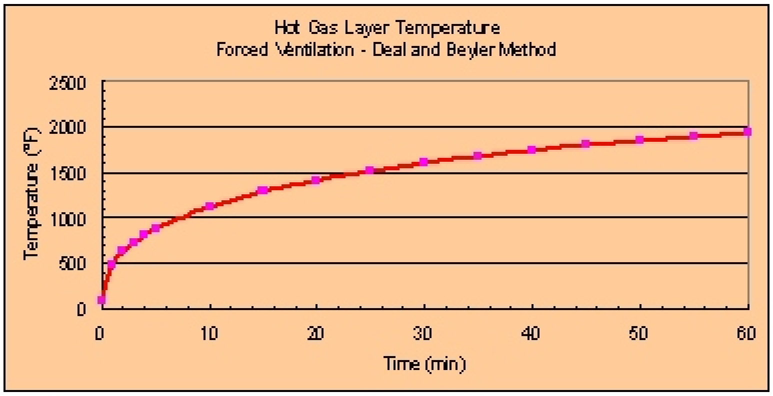
c_p = specific heat of air (kJ/Kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

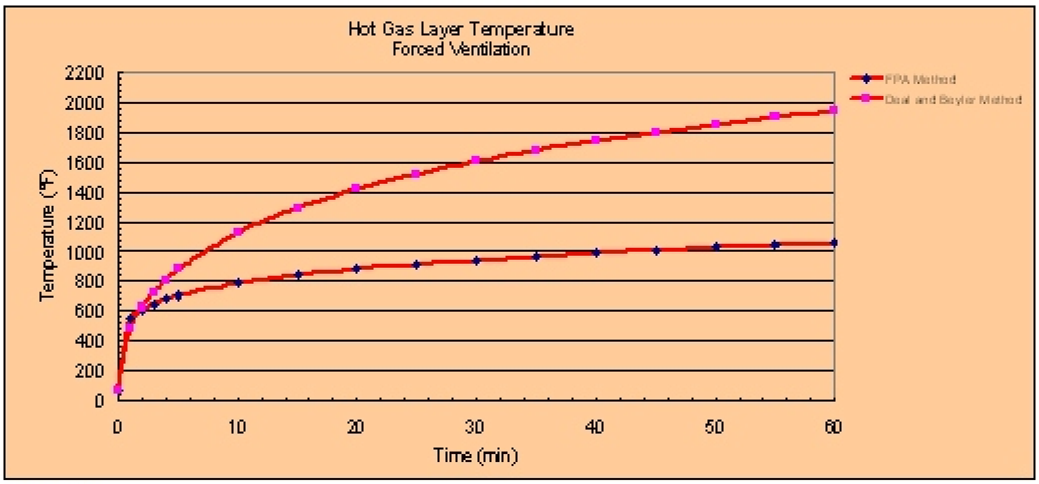
A_T = total area of the compartment enclosing surface boundaries (m^2)

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0	-	-	298.00	25.00	77.00
1	60	0.07	224.69	522.69	249.69	481.44
2	120	0.05	305.06	603.06	330.06	626.11
3	180	0.04	362.51	660.51	387.51	729.52
4	240	0.03	408.35	706.35	433.35	812.03
5	300	0.03	446.91	744.91	471.91	881.44
10	600	0.02	583.70	881.70	608.70	1127.67
15	900	0.02	675.27	973.27	700.27	1292.48
20	1200	0.02	744.93	1042.93	769.93	1417.87
25	1500	0.01	801.34	1099.34	826.34	1519.42
30	1800	0.01	848.79	1146.79	873.79	1604.83
35	2100	0.01	889.74	1187.74	914.74	1678.53
40	2400	0.01	925.74	1223.74	950.74	1743.33
45	2700	0.01	957.84	1255.84	982.84	1801.11
50	3000	0.01	986.78	1284.78	1011.78	1853.21
55	3300	0.01	1013.12	1311.12	1038.12	1900.62
60	3600	0.01	1037.27	1335.27	1062.27	1944.09



Summary of Result



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CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE, HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

3.1 Objectives

This chapter has the following objectives:

- Identify the predominant flammable material in a nuclear power plant (NPP).
- Introduce the methods that are used to estimate the heat release rate.
- Identify the factors that influence the heat release rate and burning rate.
- Explain how to analyze pool fires in NPPs.
- Explain how to analyze the burning duration of pool fires.
- Identify the zones of a candle and the categories of a flame.
- Describe the importance of ceiling configurations.
- Explain turbulent diffusion flames.
- Introduce the factors that determine how fast an object will heat.
- Define relevant terms, including heat release rate, heat of combustion, burning duration, flame height, adiabatic flame, laminar, and turbulent flames.

3.2 Heat Release Rate

Fire development is generally characterized in terms of heat release rate (HRR) vs. time. Thus, determining the HRR (or burning rate)[1] is an essential aspect of a fire hazard analysis (FHA). The relationship between HRR (or $\dot{Q}$) and time for a certain scenario is termed the design fire curve for that scenario, as illustrated in Figure 3-1.

For a routine FHA, it is acceptable to broadly approximate the burning rates (HRRs). For instance, post-flashover structure analyses are often based on the fire duration or severity associated with an aggregate fuel loading (combustible load per unit floor area). However, if it is essential to estimate specific fire effects within an enclosure, it is essential to more accurately determine the burning rate characteristics (i.e., HRR history).

The HRR is not a fundamental property of a fuel and, therefore, cannot be calculated from the basic material properties. It is usually determined from testing. Table 3-1 lists some HRR characteristic values obtained by burning various fuel packages and recording the heat output from various sources. Estimates of fire source intensities (i.e., HRR) can be based either on direct measurements of the burning rates of similar large fuel configurations or the extrapolation of small-scale test data obtained under simulated thermal conditions. In the absence of measured HRR data, the fire protection engineer (FPE) must estimate the HRR history for a particular fuel. While not as accurate as laboratory testing, sufficient information exists in the literature to permit estimates of initial fire growth, peak burning rates, and fire duration for various fuels and fuel geometries.

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1 The heat release rate may be thought of as the "power" of the fire and is some times referred to as fire "power."

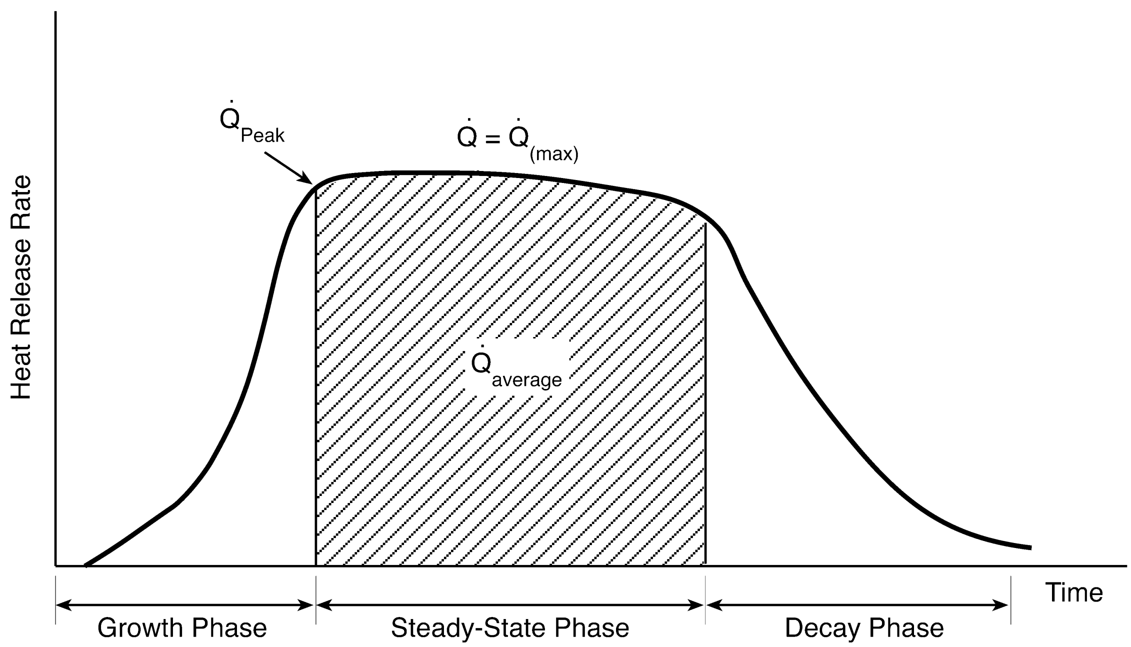


Figure 3-1 A Simple Design Fire Curve

Table 3-1. Rough Measure of Heat Generated from Various Sources
(Karlsson and Quintiere, 1999, © CRC Press, LLC. With permission.)

Fuel	**Heat Release Rate** $(\dot{Q})$
A burning cigarette	5 W
A typical light bulb	60 W
A burning candle	80 W
A human being at normal exertion	100 W
A burning wastepaper basket	100 kW
A burning 1 m^2 pool of gasoline	2.5 MW
Burning wood pallets, stacked to a height of 3 m	7 MW
Burning polystyrene jars, in 2 m^2 cartons 4.9 m high	30–40 MW
Output from a typical reactor at an NPP	3,250–3,411 MW
Note: 1 kW = 1,000 W and 1 MW = 1,000 kW	

Various studies (Lee, 1985, Nowlen, 1986, and 1987, Chavez, 1987, and Babrauskas, 1991) have measured and reported representative unit HRR values for a number of fuels present in an NPP, such as electrical cables, electrical cabinets, and transient combustibles (e.g., flammable/combustible liquids and trash). Flammable/combustible liquid spill fires and trash fires are the most commonly postulated transient fuel exposure fires, while electrical cable and cabinet fires are the most commonly postulated fixed fuel fires in NPPs. In fact, the plastic insulation and jackets on electrical cables are usually the predominant flammable material in an NPP.

The most common method to measure HRR is known as "oxygen consumption calorimetry" (ASTM E1354). The basis of this method is that most gases, liquids, and solids release a constant amount of energy for each unit mass of oxygen consumed. This constant has been found to be 13,100 kJ/kg oxygen consumed and is considered to be accurate within ±5 percent for most hydrocarbon fuels. After ignition, all of the combustion products are collected in a hood and removed through an exhaust duct in which the flow rate and composition of the gases is measured to determine how much oxygen has been used for combustion. The HRR then can be computed using the constant relationship between oxygen consumed and energy released.

Another common method of assessing HRR is to measure the burning rate, which is also known as the mass loss rate. This is done by weighing the fuel package as it burns, using weighing devices or a load cell. Estimating the HRR based on the mass loss rate requires knowledge of the effective heat of combustion. The HRR is then calculated using the following equation:

$$\dot{Q} = \dot{m}\Delta H_{c,eff} \qquad (3\text{-}1)$$

Where:

$\dot{Q}$ = heat release rate (kW)
$\dot{m}$ = burning or mass loss rate (kg/sec)
$H_{c,eff}$ = effective heat of combustion (kJ/kg)

The average burning rates for many products and materials have been experimentally determined in free-burning tests. For many materials, the burning rate is reported per horizontal burning area in units of kg/m^2-sec. If the area of the fuel and the effective heat of combustion are known, the above equation becomes:

$$\dot{Q} = \dot{m}''\Delta H_{c,eff} A_f (1 - e^{-k\beta D}) \qquad (3\text{-}2)$$

Where:

$\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)
A_f = horizontal burning area of the fuel (m^2)
$k\beta$= empirical constant (m^{-1})
D = diameter of burning area (m)

The average burning rate per unit area per unit time, heat of combustion, and fuel-specific properties have been tabulated for a number of different fuels. (See Table 3-2 for free-burning fire characteristics of various fuels.)

Table 3-2. Large-Pool Fire Burning Rate Data
(Babrauskas, 2002, © SFPE. With permission.)

Material	Mass Loss Rate $\dot{m}''$ (kg/m^2-sec)	Heat of Combustion $H_{c,\ eff}$ (kJ/kg)	Density (kg/m^3)	Empirical Constant $k\beta$ (m^{-1})
Cryogenics				
Liquid H_2	0.017	12,000	70	6.1
LNG (mostly CH_4)	0.078	50,000	415	1.1
LPG (mostly C_3H_8)	0.099	46,000	585	1.4
Alcohols				
Methanol (CH_3OH)	0.017	20,000	796	100 **
Ethanol (C_2H_5OH)	0.015	26,800	794	100 **
Simple Organic Fuels				
Butane (C_4H_{10})	0.078	45,700	573	2.7
Benzene (C_6H_6)	0.085	40,100	874	2.7
Hexane (C_6H_{14})	0.074	44,700	650	1.9
Heptane (C_7H_{16})	0.101	44,600	675	1.1
Xylene (C_8H_{10})	0.090	40,800	870	1.4
Acetone (C_3H_6O)	0.041	25,800	791	1.9
Dioxane ($C_4H_8O_2$)	0.018	26,200	1,035	5.4
Diethyl ether ($C_4H_{10}O$)	0.085	34,200	714	0.7
Petroleum Products				
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosene	0.039	43,200	820	3.5
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, hydrocarbon	0.039	46,400	760	0.7
Fuel Oil, heavy	0.035	39,700	940–1,000	1.7
Crude Oil	0.022–0.045	42,500–42,700	830–880	2.8
Solids				
Polymethylmethacrylate $(C_5H_8O_2)_n$	0.020	24,900	1,184	3.3
Polypropylene $(C_3H_6)_n$	0.018	43,200	905	100 **
Polystyrene $(C_8H_8)_n$	0.034	39,700	1,050	100 **
Miscellaneous				
561® Silicon Transformer Fluid	0.005	28,100	960	100 **

** these values are to be used only for computation purposes; the true values are unknown.

The effective heat of combustion (sometimes called the chemical heat of combustion) is a measure of how much energy is released when a unit mass of material is oxidized. This value is typically given in kJ/kg. It is important to distinguish between the complete heat of combustion and the effective heat of combustion. The complete heat of combustion is the measure of energy released when combustion is complete, leaving no residual fuel and releasing all of the chemical energy of the material. The effective heat of combustion is more appropriate for a fire in which combustion is not necessarily complete and some residue remains. This is also sometimes termed the chemical heat of combustion.

For example, Babrauskas (1983 and 1986) distinguishes four burning modes of pool fires as defined by size in Table 3-3.

Table 3-3. Pool Fire Burning Modes

Pool Fire Diameter (m)	**Burning Mode**
<0.05 (2 in)	Convective, laminar
<0.2 (8 in)	Convective, turbulent
0.2 to 1.0 (8 in to 3.3 ft)	Radiative, optically thin
>1.0 (3.3 ft)	Radiative, optically thick

3.2.1 Enclosure Effects on Mass Loss Rate

When an object (fuel) burns inside a compartment, the two main factors that influence the fire growth are energy released and burning or mass loss rate of the fuel. The smoke and hot gases will accumulate at the compartment ceiling level and heat the compartment boundaries (ceiling and walls). These compartment boundary surfaces and the hot gases radiate heat toward the fuel surface, thereby increasing the fuel burning rate. Second, the compartment openings (doors, windows, and other leakage areas) may restrict the availability of oxygen needed for combustion, thereby decreasing the amount of fuel consumed and increasing in the concentration of unburned gases. If the ventilation opening is small, the limited availability of oxygen causes incomplete combustion, thereby decreasing the HRR, which in turn reduces the gas temperature and heat transfer to the fuel surface, while the fuel continues to release volatile gases at a similar or somewhat lower rate. When partial combustion of the gases occurs within the compartment, the gas leaving the compartment mixes with oxygen and flames appear at the ventilation opening. In summary, compartment heat transfer can increase the burning or mass loss rate of the fuel, while compartment ventilation of the available air near the floor decreases the mass loss rate.

3.2.2 Pool Fires

A pool fire involves a horizontal, upward-facing, combustible fuel. The term implies the fuel in the liquid phase (pool), but it can also apply to flat slabs of solids fuels which decompose in a manner similar to liquids [e.g., Polymethylmethacrylate (PMMA or Plexiglass) and Polyethylene (PE)]. Liquid fuel may burn in an open storage container or on the ground in the form of a spill. For a given amount of fuel, spills with a large surface area burn with a high HRR for a short duration, and spills with a smaller surface area burn with a lower HRR for a longer duration. When spilled, the flammable/combustible liquid may form a pool of any shape and thickness, and may be controlled by the confinement of the area geometry such as a dike or curbing. Once ignited, a pool fire spreads rapidly over the surface of the liquid spill area. The burning rate of a given fuel can also be affected by its substrate (i.e., gravel and sand) in a spill. For flammable/combustible liquids, flame spread rates range from approximately 10 cm/sec (4 in/sec) to 2 m/sec (6.6 ft/sec). Pool fires in NPPs can result from leakage of the reactor coolant pump (RCP) at the gland or the seal, oil spill from electrical transformers, and pumps or fuel spray from pipe flanges on equipment such as standby diesel generator (SBDGs). Transient fuels such as liquids used for cleaning and painting are sources of pool fire in an NPP. Figure 3-2 depicts the dynamic feature of a pool fire. Table 3-4 summarizes the burning rate of combustible liquids and solids found in typical NPPs.

Table 3-4. Burning Rates of Some Common Combustible Materials Found in Nuclear Power Plants*

Fuel	**Mass Burning Rate** $\dot{m}''$ **(kg/m²-sec)**	**Heat of Combustion** $H_{c,eff}$ **(kJ/kg)**	**Density (kg/m³)**
Cable Materials			
PE/PVC	0.0044	25,100	-
XPE/FRXPE	0.0037	28,300	-
XPE/Neoprene	0.0043	10,300	-
PE, PP/Cl.S.PE	0.0026	26,800	-
FRXPE/Cl.S.PE	0.0033	17,300	-
PE, Nylon/PVC, Nylon	0.0034	10,200	-
Silicone, glass braid, asbestos	0.0045	24,000	-
XPE/XPE	0.0044	12,500	-
FEP - Teflon™	0.007	3,200	-
ETFE - Tefzel™	0.014	12,600	-
Flammable/Combustible Liquid			
Diesel Oil	0.044	44,400	918
Gasoline	0.055	43,700	740
Kerosene	0.039	43,200	820
Transformer Oil	0.039	46,000	760
Lube Oil (used in RCP motors and turbine lubrication)**	-	-	-
Cellulose Material			
Wood	0.055	13,000–15,000	420–640

*Empirical constants (kβ) are unknown. Use kβ = 100m^{-1} as a conservative estimate.

**For lubricating oil, use properties of transformer oil (has similar burning characteristics).

CL.S.PE-Chlorosulfonated Polyethylene; FR-Fire Retardant; PE-Polyethylene; PP-Polypropylene; PVC-Polyvinylchloride; Teflon™ - FEP-Fluorinated Polyethylene- Propylene; Tefzel™- ETFE-Ethylenetetrafluoroethylene; XLPE-Crosslinked Polyethylene.

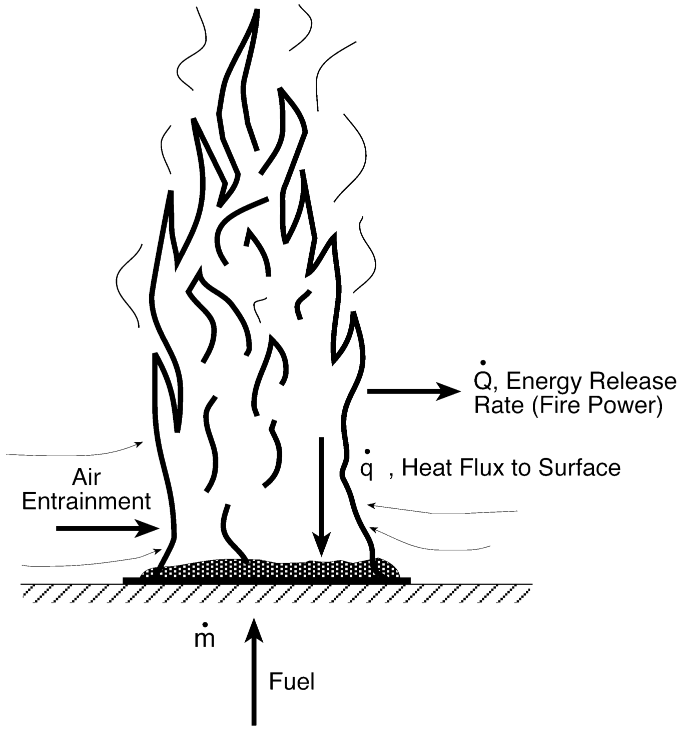


Figure 3-2 Dynamic Features of a Pool Fire

3.3 Burning Duration

The burning rate of a given fuel is controlled by both its chemistry and its form. Fuel chemistry refers to its composition (e.g., cellulosic *vs.* petrochemical). Common cellulosic materials include wood, paper, cotton, and fabric. Petrochemical materials include liquids or plastics that are largely petroleum based. The form (or shape) of the fuel material also has an effect on its burning rate. A particularly important form factor is the surface area to mass ratio of the fuel, which is defined as the surface area available to combust as compared to the total mass of the material.

The concept of burning duration is a way of characterizing the hazard of a compartment fire in terms of the length of time the fuel in the compartment could be expected to burn, which depends on the total amount of fuel available. Fuel loading is the concept that describes the expected burning duration, provided that the necessary amount of air is available (i.e., fuel-controlled fire). A fire burning at a constant HRR consumes fuel mass at a constant rate. Thus, the mass of material being burned per second and the amount of material available to be consumed, it is possible to estimate the total burning duration of a fuel.

3.3.1 Burning Duration of a Pool Fire

When a spilled liquid is ignited, a pool fire develops. Provided that an ample supply of oxygen is available, the amount of surface area of the given liquid becomes the defining parameter. The diameter of the pool fire depends upon the release mode, release quantity (or rate), and burning rate. In some instances, the spill is unrestricted by curbs or dikes, allowing it to spread across the ground and establish a large exposed surface area. Liquid pool fires with a given amount of fuel can burn for long periods of time if they have a small surface area, or for short periods of time over a large spill area. For a fixed mass or volume of flammable/combustible liquid, the burning duration (t_b) for the pool fire is estimated using the following expression:

$$t_b = \frac{4V}{\pi D^2 \nu} \qquad (3\text{-}3)$$

Where:

V = volume of liquid (gallons or m^3)
D = pool diameter (m)
  = regression rate (m/sec)

As a pool of liquid combusts and the fuel is consumed, its depth decreases. The rate of burning, also called the regression rate ( ), is defined as a volumetric loss of liquid per unit surface area of the pool per unit time, as illustrated by the following expression:

$$\nu = \frac{\dot{m}''}{\rho} \qquad (3\text{-}4)$$

Where:

$\dot{m}''$ = mass burning rate of fuel per unit area (kg/m^2-sec)
  = liquid fuel density (kg/m^3)

3.4 Flame Height

A flame is a body or stream of gaseous material involved in the combustion process, which emits radiant energy at specific wavelength bands depending on the combustion chemistry of the fuel involved. In most cases, some portion of the emitted radiant energy is visible to the human eye as the glowing, gaseous portion of a fire, which is typically referred to as its flame.

The flame generally consists of a mixture of oxygen (air) and another gas, typically a combustible substance such as hydrogen, carbon monoxide, or a hydrocarbon. The brightest flames are not always the hottest. For example, hydrogen exhibits a high flame temperature. However it combines with oxygen when burning to form water, hydrogen has an almost invisible flame under ordinary circumstances. When hydrogen is absolutely pure and the air around it is completely free of dust, the hydrogen flame cannot be seen, even in a dark room.

In order to gain a better understanding of flames, a burning candle can be used as an example. When the candle is lit, the heat of the match melts the wax, which is carried up the wick and vaporized by the heat. As it is broken down by the heat, the vaporized wax combines with the oxygen of the surrounding air and produces heat and light in the form of a flame. The candle flame consists of three zones, which are easily distinguished. The innermost, nonluminous zone is composed of a gas/air mixture at a comparatively low temperature. In the second luminous zone, hydrogen (H_2) and carbon monoxide (CO) (two of many products from the decomposition of the wax) react with oxygen to form combustion products, which include water (H_2O) and carbon dioxide (CO_2). In this zone, the temperature of the flame is 590–680 °C (1,094–1,256 °F), which is sufficiently intense to dissociate the gases in the flame and produce free carbon particles. These particles are heated to incandescence and then consumed. Outside the luminous zone is a third, invisible zone in which the remaining CO and H_2 are finally consumed. This zone is not visible to the human eye. Figure 3-3 shows the temperature distribution through the flame of a burning candle.

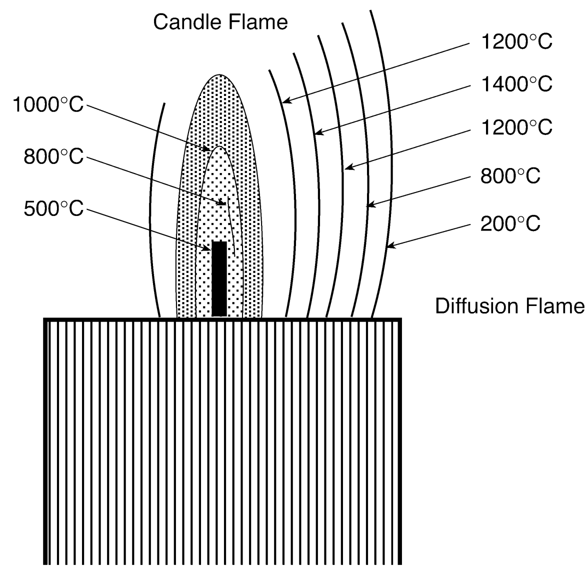


Figure 3-3 Temperature Distribution in the Flame of a Burning Candle

All combustible substances require a finite amount of oxygen for complete burning. (A flame can be sustained in an atmosphere of pure chlorine, but combustion cannot complete.) In the burning of a candle or solids such as wood or coal, the surrounding atmosphere supplies this oxygen. In gas burners, air or pure oxygen is mixed with the gas at the base of the burner so that the carbon is consumed almost instantaneously at the mouth of the burner. This is an example of a premixed flame. The hottest portion of the flame of a Bunsen burner has a temperature of approximately 1,600 °C (2,912 °F). By contrast, the hottest portion of the oxygen-acetylene flames (torch) used for cutting and welding metals reaches approximately 3,500 °C (6,330 °F) because the increased oxygen in the case of the torch yields a significantly higher flame temperature. Any time the oxygen rate is increased (e.g., wind- or airflow-aided combustion or an oxygen-enriched atmosphere), the temperatures obtained will be higher than for the fuel combusting in a normal atmosphere.

A flame can be thought of in two distinct categories, including diffusion flame (Figure 3-4) and premixed flame (Figure 3-5). A diffusion flame is one in which the fuel and oxygen are transported (diffused) from opposite sides of the reaction zone (flame). A premixed flame is one in which the oxygen is mixed with the combustible gas by some mechanical device prior to combustion. Figure 3-6 illustrates a laminar diffusion flame produced by a burning candle. (Laminar means that the flow streamlines are smooth and do not bounce around significantly.) Figure 3-7 illustrates practical examples of premixed flames.

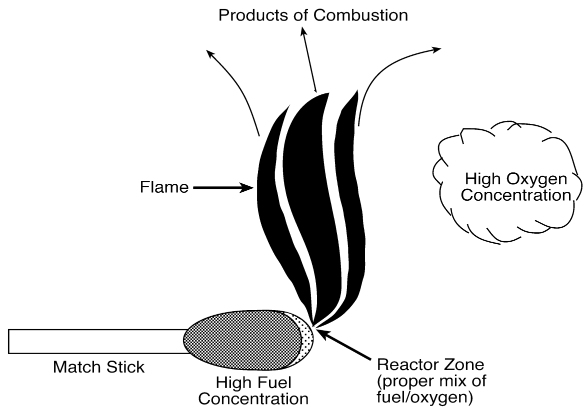


Figure 3-4 Diffusion Flame

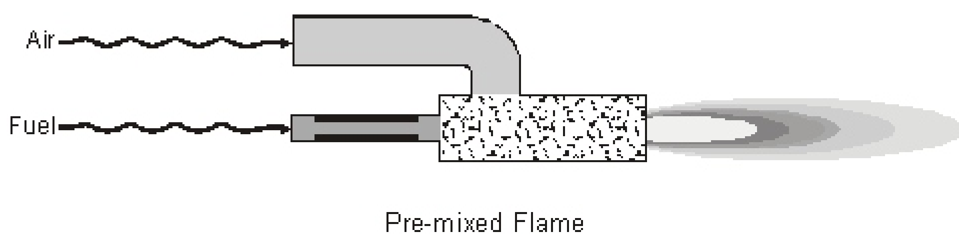


Figure 3-5 Premixed Flame

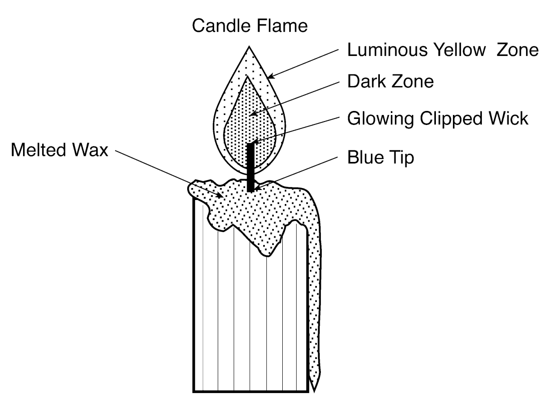
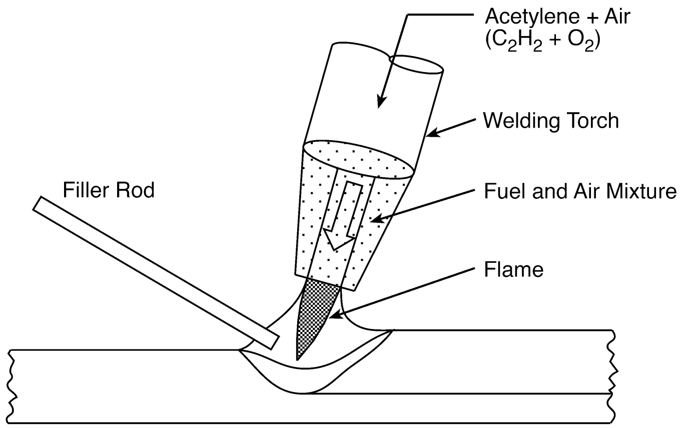
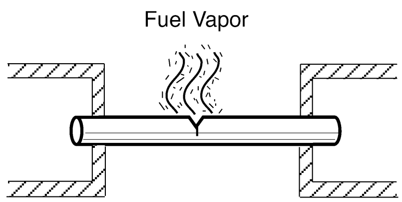


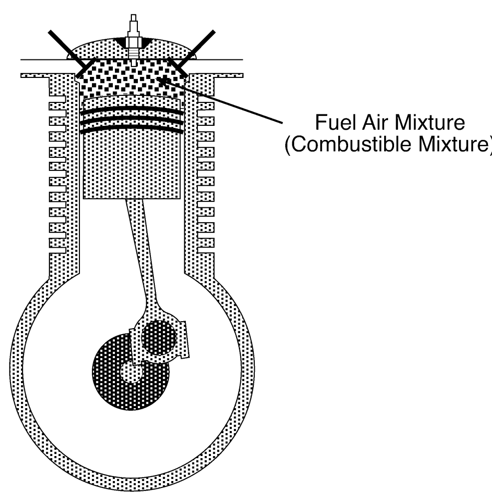
Figure 3-6 Laminar Diffusion Flame



Oxy-Acetylene Flame



Gas Leaking Pipe Break



Internal Combustion (IC) Engine

Figure 3-7 Turbulent Premixed Flames

Most turbulent premixed flames occur in engineered combustion systems, such as a boiler, furnace, process heater, gas burner, oxyacetylene torch, gasoline engine, or home gas cooking range. Most natural flaming processes produce diffusion flames, since no burner or other mechanical device exists to mix fuel and air. Common examples include a candle flame, a trash can fire, a hydrocarbon pool fire, or a forest fire.

3.4.1 Flame Extensions Under Ceiling

Most fire protection engineering (FPE) applications are concerned with the buoyant axisymmetric plume, which is caused by a turbulent diffusion flame above the burning fuel. When a flame impinges on an unconfined ceiling, the unburnt gases spread out radially and entrain air for combustion. A circular flame is then established under the ceiling, forming what is known as a ceiling jet. The ceiling configuration is very important for at least two reasons:

(1) Fire detection devices and automatic sprinklers are generally mounted just under the ceiling, and knowledge of the time of arrival and properties of a potential ceiling jet are crucial for predicting when the devices will be actuated.

(2) The downward thermal radiation from a ceiling jet, and from the hot ceiling itself, is a major factor in preheating and igniting combustible items that are not yet involved in the fire. This radiation heat transfer is very important in affecting the rate of fire spread. Figure 3-8 shows flame extensions under a smooth ceiling.

3.4.2 Flame Impingement

Flame that directly impacts a surface is called flame impingement. Direct flame impingement generally transfers large quantities of heat to the surface. Flame impingement occurs when gases from a buoyant stream rise above a localized area. The buoyant gas stream is generally turbulent except when the fire source is very small.

3.4.3 Flame Temperature

The pulsing behavior of a flame affects its temperature. The temperature varies across the width and height of the flame and the temperature at a fixed position will fluctuate widely, particularly around the edges and near the top of the flame. Therefore, any discussion of flame temperature usually involves reporting the centerline temperature or average flame temperature, which is determined by measuring the temperature at different times and different locations within the flame.

Table 3-5 summarizes the average flame temperature for a range of common fuel types. Notice that the flame temperature for flames involving gasoline is approximately the same as for flames involving wood. While these values may seem odd, they are explained by the different radiation properties of the flames produced by the respective materials.

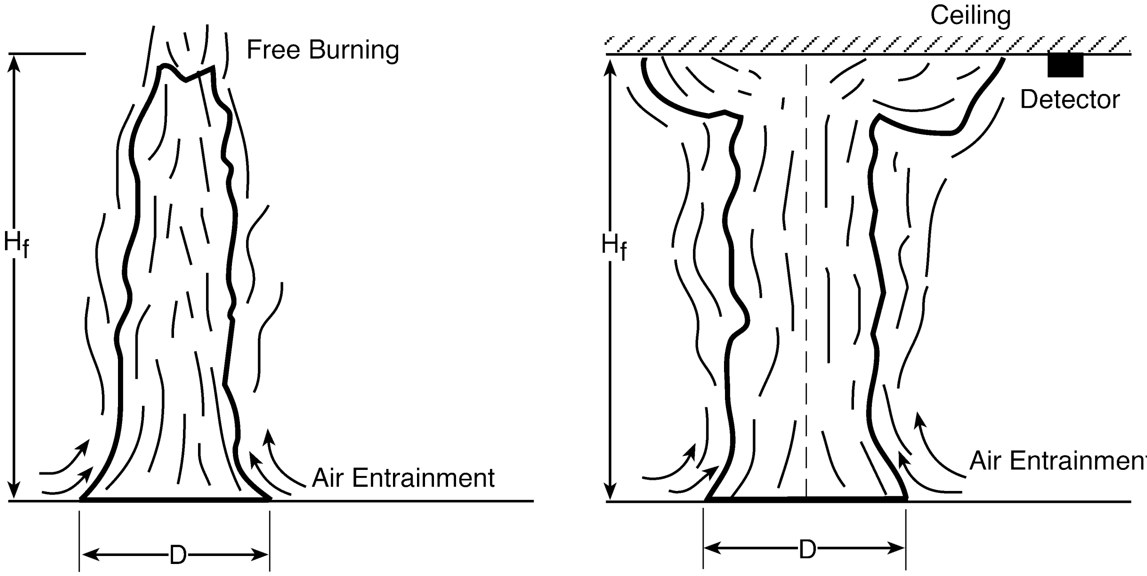


Figure 3-8 Flame Extensions with a Free-Burning Flame
and Under a Smooth Ceiling

Table 3-5. Flame Temperatures of Selected Fuels

Fuel Source (Flames)	**Flame Temperature °C (°F)**
Benzene	921 (1,690)
Gasoline	1,026 (1,879)
JP-4	927 (1,701)
Kerosene	990 (1,814)
Methanol	1,200 (2,192)
Wood	1,027 (1,881)

For convenience, we can subdivide the turbulent diffusion flames from potentially hazardous fires into flames in the open, and room fires as described in the following sections.

3.4.4 Flames Temperatures of Open Fires

The starting point for discussing the flame temperatures of open fires can be the work of the McCaffrey (1979), who extensively studied temperatures in turbulent diffusion flames. McCaffrey used gas burners in a "pool fire" mode (i.e., non-premixed) and studied various characteristics of such fire plumes. He described three different regimes in such a fire plume:

(1) The continuous flame region begins slightly above the base of the fire, where the temperatures are constant and slightly below 900 °C (1,652 °F).

(2) The intermittent flame region is above the continuous flame region. Here the temperatures drop as a function of distance up the plume. The visible flame tips have a temperature of about 320 °C (608 °F).

(3) The thermal plume region is beyond the flame tips, where no more flames are visible and the temperature continues to drop as height increases away from the flame.

French researchers at the University of Poitiers recently made the same types of measurements (Audoin et al., 1995) and reported numerical values indistinguishable from McCaffrey's (Cox and Chitty, 1980). The French researchers measured similar plumes and obtained very similar results of a temperature of 900 °C (1,652 °F) in the continuous flame region, and a temperature of around 340 °C (644 °F) at the flame tips.

Taking all of the above information into account, it appears that flame tip temperatures for turbulent diffusion flames should be estimated as being around 320 to 400 °C (608 to 752 °F). For small flames (less than about 1 m base diameter), continuous flame region temperatures of around 900 °C (1,652 °F) should be expected. For large pools, the latter value can rise to 1,100 to 1,200 °C (2,012 to 2,192 °F).

3.4.5 Flame Temperatures in Room Fires

The fire science community generally agrees that flashover is reached when the average upper gas temperature in the room exceeds 600 °C (1,112 °F). There will be zones with flame temperature of 900 °C (1,652 °F), but wide spatial variations will be seen. Of interest, however, is the peak fire temperature normally associated with room fires. This peak value is governed by ventilation and fuel supply characteristics. As a result of these variables, peak fire temperature values will form a wide frequency distribution (Babrauskas and Williamson, 1979). The maximum value is around 1,200 °C (2,192 °F), although a typical post-flashover room fire will more commonly have a peak temperature of 900 to 1,000 °C (1,652 to 1,832 °F). The time-temperature curve (TTC) for the standard fire endurance test (ASTM E119) extends to 1,260 °C (2,300 °F), as is reached in 8 hours. Note that no jurisdiction demands fire endurance periods of more than 4 hours, at which time, the curve only reaches 1,093 °C (1,999 °F).

The peak temperatures expected in room fires are slightly greater than those found in free-burning open flames. Heat losses from the flame determine how far below the adiabatic flame temperature the actual temperature will be[2]. When a flame is far away from any walls and does not heat the enclosure, it radiates to surroundings which are typically at a starting temperature of 20 °C (68 °F). If the flame is large enough, or the room small enough, for the walls to heat up substantially, the flame exchanges radiation with a body that is several hundred degrees Celsius; the consequence is smaller heat losses leading to a higher flame temperature.

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[2] Adiabatic flame temperature is defined as the flame temperature with no heat loss.

3.4.6 Adiabatic Flame Temperature

Adiabatic means without losing heat. Thus, adiabatic flame temperatures would be achieved in a (theoretical) combustion system in which there are no heat losses and, hence, no radiation losses from the flame. Because this cannot be achieved in practice (given the inefficiencies of combustion) and is never achieved in a fire situation, adiabatic flame temperatures are calculated values.

The amount of energy or heat released from the combustion reaction of fuel and air (or oxygen) is the heat of combustion. If all of the energy released by this chemical reaction were used to raise the temperature of the products (CO_2, H_2O, and N_2) with no heat losses, the resultant temperature would be the adiabatic flame temperature, which represents the maximum possible theoretical temperature for a particular fuel/oxidant combustion. Table 3-6 gives adiabatic flame temperatures for a variety of fuels. Remember from the earlier discussion, a given fuel will always have a higher adiabatic flame temperature when burned in pure oxygen than it will when burned in normal air (21-percent oxygen). This is because the heat of combustion must be used to raise the temperature of the nitrogen in air and, therefore, does not contribute to the energy release.

Table 3-6. Adiabatic Flame Temperatures of Selected Fuels

Fuel Source	**Adiabatic Flame Temperature K (°C) (°F)**
Hydrogen (H_2)	2,525 (2,252) (4,085)
Carbon Monoxide (CO)	2,660 (2,387) (4,329)
Methane (CH_4)	1,446 (1,173) (2,143)
Ethane (C_2H_6)	1,502 (1,129) (2,064)
Ethylene (C_2H_4)	2,565 (2,289) (4,152)
Acetylene (C_2H_2)	2,910 (1,281) (2,338)
Propane (C_3H_8)	1,554 (2,117) (3,843)
Propylene (C_3H_6)	2,505 (2,232) (4,050)
n-Butane (n-C_4H_{10})	1,612 (1,339) (2,442)
n-Octane (n-C_8H_8)	1,632 (1,359) (2,478)
n-Heptane	1,692 (1,419) (2,586)
n-Pentane	1,564 (1,291) (2,356)

The energy required to raise the temperature of the combustion products is determined by the mass of the products, their heat capacities, and the difference between the initial and final temperatures. Specific heat is defined as the amount of energy required to raise the temperature of a given amount of product 1 °C (or K).

3.4.7 Temperatures of Objects

It is common practice for investigators to assume that an object next to a flame of a certain temperature will also be of that same temperature. This assumption is not entirely accurate. If a flame is exchanging heat with an object that was initially at room temperature, it will take a finite amount of time for the temperature of that object to increase to a value similar to that of the flame. Exactly how long this will take is a question for the study of heat transfer, which is usually presented to engineering students over several semesters of university classes. It should be clear that simple rules-of-thumb for first order approximations would not be expected. Here, we will merely point out that the rate at which target objects gain heat is largely governed by their size, density, and thermal conductivity. Small, low-density, low-conductivity objects will heat much faster than massive, dense, highly conductive objects.

3.4.8 Flame Height Calculations

The height of a flame is a significant indicator of the hazard posed by the flame. Flame height directly relates to flame heat transfer and the propensity of the flame to impact surrounding objects. As a plume of hot gases rises above a flame, the temperature, velocity, and width of the plume changes as the plume mixes with its surroundings. The size (height) and temperature of the flame are important in estimating the ignition of adjacent combustibles. Figure 3-9 shows a characteristic sketch of the flame height fluctuations associated with the highly intermittent pulsing structure of a flame, particularly along its perimeter and near its top. This intermittence is driven largely by the turbulent mixing of air and subsequent combustion, and the pulsing behavior, in turns affects the temperature of the flame. Thus the temperature at a fixed position fluctuates widely, particularly around the edges and near the top of the flame. This is why flame temperature is usually reported in terms of the centerline temperature or average flame temperature.

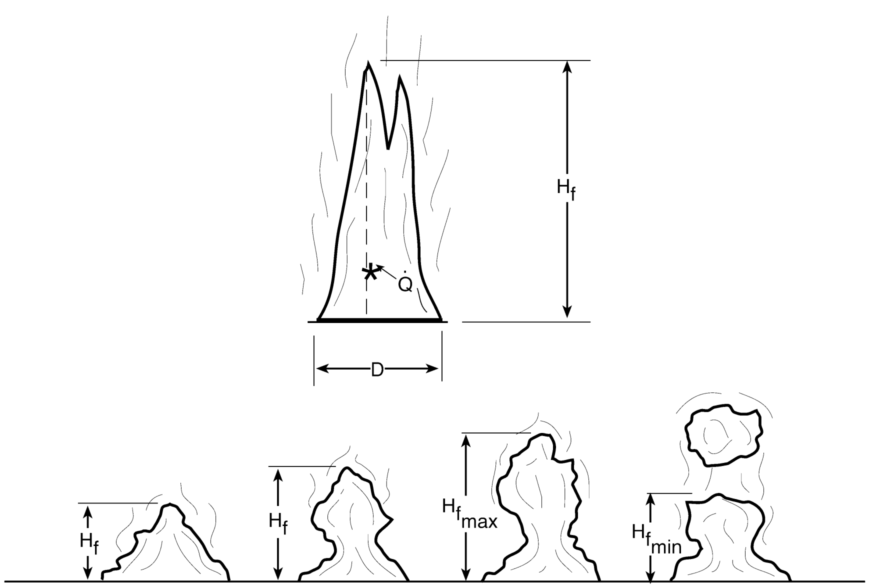

Figure 3-9 Characteristics of Flame Height Fluctuations

Researchers define flame height as the height at which the flame is observed at least 50-percent of the time. Above the fuel source, the flaming region is characterized by high temperature and is generally luminous. Flames from pool fires fluctuate periodically so that the tip of the flame is significantly different from the length of the continuous combustion (or luminous) region. Consequently, flame height has been defined by various criteria in order to correlate data.

The flame height is an important quantitative characteristic of a fire and may affect fire detection and suppression system design, fire heating of building structures, smoke filling rates, and fire ventilation. Flame height typically depends on whether the flame is laminar or turbulent. In general laminar flames are short, while turbulent flames are tall. The following two correlations are widely used to determine the flame height of pool fires (Heskestad, 1995 and Thomas, 1962) respectively:

$$H_f = 0.235\dot{Q}^{\frac{2}{5}} - 1.02D \qquad (3\text{-}6)$$

Where:

H_f = flame height (m)

$\dot{Q}$ = heat release rate of the fire (kW)

D = diameter of the fire (m)

$$H_f = 42\,D\left(\frac{\dot{m}''}{\rho_a\sqrt{gD}}\right)^{0.61} \qquad (3\text{-}7)$$

Where:

H_f = flame height (m)

D = diameter of the fire (m)

$\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)

ρ_a = ambient air density (kg/m^3)

g = gravitational acceleration (m/sec^2)

The above correlations can also be used to determine the length of the flame extension along the ceiling and to estimate radiative heat transfer to objects in the enclosure.

The HRR of the fire can be determined by laboratory or field testing. In the absence of experimental data, the maximum HRR for the fire is given by the following equation:

$$\dot{Q} = \dot{m}''\,DH_{c,eff}A_f\,(1 - e^{-k\beta D}) \qquad (3\text{-}8)$$

Where:

$\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)

$H_{c,eff}$ = effective heat of combustion (kJ/kg)

A_f = horizontal burning area of the fuel (m^2)

$k\beta$= empirical constant (m^{-1})

D = diameter of burning area (m)

For non-circular pools, the effective diameter is defined as the diameter of a circular pool with an area equal to the actual pool area given by the following equation:

$$D = \sqrt{\frac{4A_f}{\pi}} \qquad (3\text{-}9)$$

Where:

A_f is the surface area of the non-circular pool

3.5 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations that apply to HRR:

(1) The pool fire is burning in the open and is characterized by instantaneous, complete involvement of the flammable/combustible liquid.

(2) There is no fire growth period. (Real liquid pool fires grow very quickly, and it is realistic to assume that the pool fire instantaneously reaches its maximum HRR.)

In addition, the following assumptions and limitations apply to burning duration:

(1) The pool is circular or nearly circular and contains a fixed mass or volume of flammable/combustible liquid. The mass or volume of any spill with a non-circular circumference must be approximated as a circular measurement. For example an accidental fuel is ignited in a pump room and causes cable trays to be exposed to a pool fire. The spill area is a rectangular dike with dimensions of 4-ft x 5-ft. The equivalent diameter of the pool fire is given by Equation 3-9:

$$D = \sqrt{\frac{4A_f}{\pi}}$$

Where:

A_f = the surface area of noncircular pool

Therefore, the equivalent diameter of the non-circular pool is as follows:

$$D = \sqrt{\frac{4x20}{\pi}} = 5ft$$

(2) There is no fire growth period. (As stated above, real liquid pool fires grow very quickly, and it is realistic to assume that the pool fire instantaneously reaches its maximum HRR.)

In addition, the following assumptions and limitations apply to flame height:

(1) The flame height correlation described in this chapter was developed for horizontal pool fire sources in the center or away from the center of the compartment. The turbulent diffusion flames produced by fires burning near or close to a wall or in a corner configuration of a compartment effect the spread of the fire. The flame height correlations of fires burning near walls and corners is presented in Chapter 4.

(2) The size of the fire (flame height) depends on the diameter of the fuel and the HRR attributable to the combustion.

(3) This correlation is developed for two-dimensional sources (primarily pool fires) and this method assumes that the pool is circular or nearly circular.

(4) There is no fire growth period. (As stated above, real liquid pool fires grow very quickly, and it is realistic to assume that the pool fire instantaneously reaches its maximum HRR.)

3.6 Required Input for Spreadsheet Calculations

The user must obtain the following values before attempting a calculation using the characteristics of liquid pool fire spreadsheet:

(1) fuel spill volume (gallons)

(2) fuel spill area or dike area (ft^2)

(3) fuel type

3.7 Cautions

(1) Use (03_HRR_Flame_Height_Burning_Duration_Calculation.xls) spreadsheet on the CD-ROM.

(2) Make sure to enter the input parameters in the correct units.

3.8 Summary

An engineering approach to pool fire burning characterization requires a classification according to the dominant heat transfer mechanism, which can be expressed as being dependent on pool diameter. The pool shall include fires resulting from spilled liquids, fires in diked or curbed areas, and fires in open areas. These fires will be typically considered to be circular.

Estimating the burning duration of a pool fire involves the following steps:

(1) Determine the regression rate of the pool fire.
(2) Calculate the equivalent diameter of the pool fire.
(3) Calculate the burning duration of the pool fire.

The flame height is generally defined as the height at which (or above which) the flame is observed at least 50-percent of the time. Visual observations tend to yield slight overestimations of flame height.

Estimating the flame height from a pool fire involves the following steps:

(1) Determine the HRR of the pool fire.
(2) Calculate the equivalent diameter of the pool fire.
(3) Determine the height of the pool fire flame.

3.9 References

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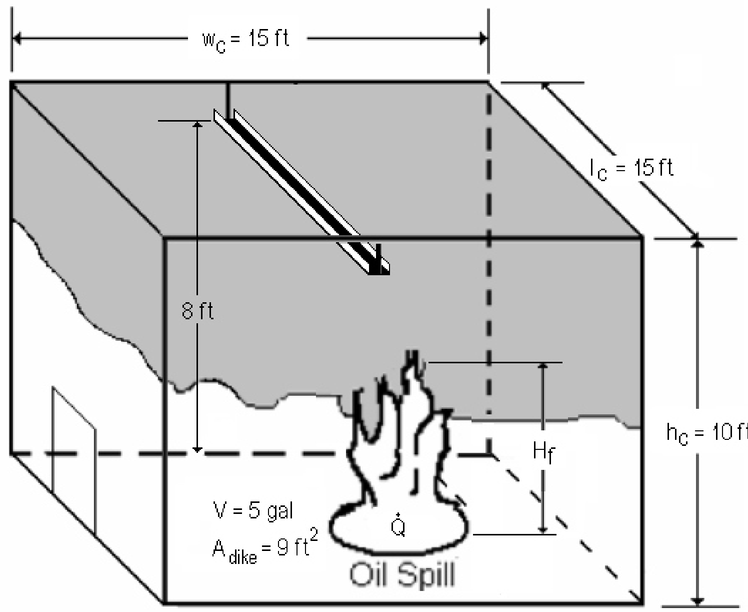
3.11 Problems

Example Problem 3.10-1

Problem Statement

A pool fire scenario arises from a breach (leak or rupture) in an auxiliary cooling water pump oil tank. This event allows the fuel contents of the pump to spill and spread over the compartment floor. A 5-gallon, 9.0-ft^2 surface area spill of flammable liquid (lubricating oil) leads to consideration of a pool fire in a compartment with a concrete floor. The fuel is ignited and spreads rapidly over the surface, reaching steady burning almost instantly. Compute the HRR, burning duration, and flame height of the pool fire. The dimensions of the compartment are 15 ft wide x 15 ft deep x 10 ft heigh. The cable tray is located 8 ft above the pool fire. Determine whether the flame will impinge upon the cable tray. Assume instantaneous and complete involvement of the liquid pool with no fire growth and no intervention by the plant fire department or automatic suppression systems.



Example Problem 3-1: Compartment with Pool Fire

Solution

Purpose:

(1) Determine the Heat Release Rate (HRR) of the fire source.
(2) Determine the burning duration of the pool fire.
(3) Determine the flame height of the pool fire.
(4) Determine whether the flame will impinge upon the cable tray.

Assumptions:

(1) Instantaneous and complete involvement of the liquid in the pool fire
(2) The pool fire is burning in the open
(3) No fire growth period (instantaneous HRR_{max})
(4) The pool is circular or nearly circular and contains a fixed mass of liquid volume
(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

FDT^s Input Parameter:

-Fuel Spill Volume (V) = 5 gallons

-Fuel Spill Area or Dike Area (A_{dike}) = 9.0 ft^2

-Select Fuel Type: **Lube Oil**

Results*

Heat Release Rate (HRR) $\dot{Q}$ kW (Btu/sec)	Burning Duration (t_b) (min.)	Pool Fire Flame Height (H_f) m (ft)	
		Method of Heskestad	Method of Thomas
772 (731)	7.35	2.31 (7.6)	2.67 (8.75)

*see spreadsheet on next page

Both methods for pool fire flame height estimation show that pool fire flame will impinge upon the cable tray.

Spreadsheet Calculations

FDT[s]: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls (HRR-Calculations)

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE, HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Parameter	Value	Unit	Converted
Fuel Spill Volume (V)	5.00	gallons	0.0189 m^3
Fuel Spill Area or Dike Area (A_{dike})	9.00	ft^2	0.836 m^2
Mass Burning Rate of Fuel (m″)	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Density (ρ)	760	kg/m^3	
Empirical Constant (kβ)	0.7	m^{-1}	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec^2	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Calculate

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m″ (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type: Lube Oil

Scroll to desired fuel type

Click on selection

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-25.

$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_{dike}$

Where
- Q = pool fire heat release rate (kW)
- $\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- $\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)
- $A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

Where
- A_{dike} = surface area of pool fire (m^2)
- D = pool fire diamter (m)

$D = \sqrt{(4A_{dike}/\pi)}$

D = 1.032 m

Heat Release Rate Calculation

$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_{dike}$

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	771.52 kW	731.26 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where
- t_b = burning duration of pool fire (sec)
- V = volume of liquid (m^3)
- D = pool diameter (m)
- v = regression rate (m/sec)

Calculation for Regression Rate

$v = \dot{m}''/\rho$

Where
- v = regression rate (m/sec)
- $\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)
- ρ = liquid fuel density (kg/m^3)

v = 0.000051 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b =	441.12 sec	7.35 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 2-10.

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where
- H_f = pool fire flame height (m)
- Q = pool fire heat release rate (kW)
- D = pool fire diameter (m)

Pool Fire Flame Height Calculation

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

H_f =	2.31 m	7.56 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-204.

$H_f = 42\ D\ (m''/\rho_a \sqrt{g D})^{0.61}$

Where H_f = pool fire flame height (m)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

ρ_a = ambient air density (kg/m^3)

D = pool fire diameter (m)

g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation

$H_f = 42\ D\ (m''/\rho_a \sqrt{g D})^{0.61}$

H_f =	2.67 m	8.75 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	7.56
METHOD OF THOMAS	8.75

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft^2)	Area (m^2)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	85.72	3970.11	3.42	4.08
2	0.19	0.49	171.45	1985.05	4.41	5.19
3	0.28	0.60	257.17	1323.37	5.10	5.97
4	0.37	0.69	342.90	992.53	5.66	6.60
5	0.46	0.77	428.62	794.02	6.13	7.13
6	0.56	0.84	514.35	661.68	6.55	7.60
7	0.65	0.91	600.07	567.16	6.92	8.02
8	0.74	0.97	685.80	496.26	7.25	8.40
9	0.84	1.03	771.52	441.12	7.56	8.75
10	0.93	1.09	857.25	397.01	7.85	9.07
11	1.02	1.14	942.97	360.92	8.12	9.38
12	1.11	1.19	1028.69	330.84	8.37	9.67
13	1.21	1.24	1114.42	305.39	8.61	9.94
14	1.30	1.29	1200.14	283.58	8.84	10.20
15	1.39	1.33	1285.87	264.67	9.05	10.45
20	1.86	1.54	1714.49	198.51	10.01	11.55
25	2.32	1.72	2143.11	158.80	10.82	12.48
50	4.65	2.43	4286.23	79.40	13.73	15.87
75	6.97	2.98	6429.34	52.93	15.76	18.28
100	9.29	3.44	8572.46	39.70	17.35	20.20

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation does not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

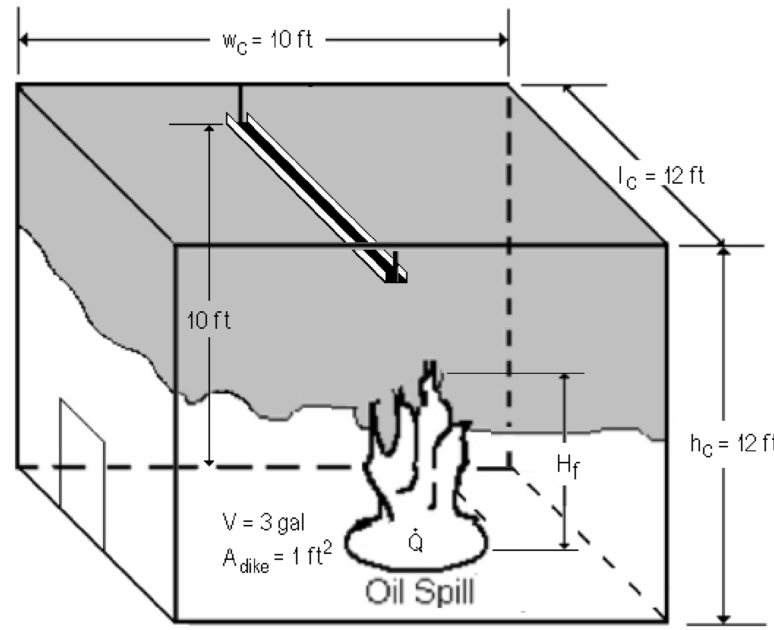
NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 3.10-2

Problem Statement

A standby diesel generator (SBDG) room in a power plant has a 3-gallon spill of diesel fuel over a 1-ft^2 diked area. This event allows the diesel fuel to form a pool. The diesel is ignited and fire spreads rapidly over the surface, reaching steady burning almost instantly. Compute the HRR, burning duration, and flame height of the pool fire. The dimensions of the compartment are 10 ft wide x 12 ft deep x 12 ft high. The cable tray is located 10 ft above the pool fire. Determine whether flame will impinge upon the cable tray. Also, determine the minimum area required of the pool fire for the flame to impinge upon the cable tray. Assume instantaneous, complete involvement of the liquid pool with no fire growth and no intervention by plant fire department or automatic suppression.



Example Problem 3-2: Compartment with Pool Fire

Solution

Purpose:

(1) Determine the Heat Release Rate (HRR) of the fire source.
(2) Determine the burning duration of the pool fire.
(3) Determine the flame height of the pool fire.
(4) Determine whether the flame will impinge upon the cable tray.
(5) Determine the minimum dike area required for the flame to impinge upon the cable tray.

Assumptions:

(1) Instantaneous and complete involvement of the liquid in the pool fire
(2) The pool fire is burning in the open
(3) No fire growth period (instantaneous HRR_{max})
(4) The pool is circular or nearly circular and contains a fixed mass of liquid volume
(5) The fire is located at the center of the compartment or away from the walls

Spreadsheet (FDT[s]) Information:

Use the following FDT[s]:

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

FDTs Input Parameter:

-Fuel Spill Volume (V) = 3 gallons

-Fuel Spill Area or Dike Area (A_{dike}) = 1.0 ft^2

-Select Fuel Type: **Diesel**

Results*

Heat Release Rate (HRR) $\dot{Q}$ kW (Btu/sec)	Burning Duration (t_b) (min.)	Pool Fire Flame Height (H_f) m (ft)	
		Method of Heskestad	Method of Thomas
95 (90)	42	1.1 (3.6)	1.4 (4.5)

*see spreadsheet on next page

Both methods for pool fire flame height estimation show that pool fire flame will not impinge the cable tray.

To determine the minimum dike area required for the flame to impinge upon the cable tray, the user must substitute different values for the area in the spreadsheet until we obtain a flame height value of 10 ft (cable tray height). The user must keep the input values used for the previous results, and change only the area value. This trial and error procedure is shown in the following table.

Trial	A_{dike} (ft^2)	Pool Fire Flame Height (H_f) m (ft)	
		Method of Heskestad	Method of Thomas
1	9	2.4 (8.0)	2.9 (9.6)
2	10	2.6 (8.4)	3.0 (9.9)
3	11	2.6 (8.6)	3.1 (10.2)

To be conservative, we are going to consider the method that gets first the 10-ft flame height. The method of Heskestad tells that the pool fire flame will impinge upon the cable tray if the dike area is 6.1 ft^2. For practical purposes, we could say that a spill pool area around 5–6 ft^2 would be a risk for the cable tray integrity.

Spreadsheet Calculations

FDT[s]: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls (HRR-Calculations)

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE,
HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	3.00	gallons	0.0114 m^3
Fuel Spill Area or Dike Area (A_{dike})	1.00	ft^2	0.093 m^2
Mass Burning Rate of Fuel (m")	0.045	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	44400	kJ/kg	
Fuel Density (ρ)	918	kg/m^3	
Empirical Constant ($k\beta$)	2.1	m^{-1}	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec^2	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Calculate

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25

Select Fuel Type

Diesel

Scroll to desired fuel type
Click on selection

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-25.

$Q = m''\Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

Where
Q = pool fire heat release rate (kW)
m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)
$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)
$k\beta$ = empirical constant (m^{-1})
D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

Where
A_{dike} = surface area of pool fire (m^2)
D = pool fire diamter (m)

$D = \sqrt{(4A_{dike}/\pi)}$

$D =$ 0.344 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	95.47 kW	90.49 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where
t_b = burning duration of pool fire (sec)
V = volume of liquid (m^3)
D = pool diameter (m)
v = regression rate (m/sec)

Calculation for Regression Rate

$v = m''/\rho$

Where
v = regression rate (m/sec)
m'' = mass burning rate of fuel (kg/m^2-sec)
ρ = liquid fuel density (kg/m^3)

$v =$ 0.000049 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b =	2493.65 sec	41.56 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for longer periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 2-10.

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where
H_f = pool fire flame height (m)
Q = pool fire heat release rate (kW)
D = pool fire diameter (m)

Pool Fire Flame Height Calculation

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

H_f =	1.10 m	3.62 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-204.

$H_f = 42\ D\ (\dot{m}'' / \rho_a \sqrt{g\ D})^{0.61}$

Where
- H_f = pool fire flame height (m)
- $\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ρ_a = ambient air density (kg/m^3)
- D = pool fire diameter (m)
- g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation

$H_f = 42\ D\ (\dot{m}'' / \rho_a \sqrt{g\ D})^{0.61}$

H_f =	1.36 m	4.45 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	3.62
METHOD OF THOMAS	4.45

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft^2)	Area (m^2)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	95.47	2493.65	3.62	4.45
2	0.19	0.49	190.95	1246.82	4.67	5.66
3	0.28	0.60	286.42	831.22	5.42	6.52
4	0.37	0.69	381.89	623.41	6.01	7.20
5	0.46	0.77	477.36	498.73	6.52	7.78
6	0.56	0.84	572.84	415.61	6.96	8.29
7	0.65	0.91	668.31	356.24	7.36	8.75
8	0.74	0.97	763.78	311.71	7.72	9.16
9	0.84	1.03	859.25	277.07	8.05	9.55
10	0.93	1.09	954.73	249.36	8.36	9.90
11	1.02	1.14	1050.20	226.70	8.64	10.24
12	1.11	1.19	1145.67	207.80	8.92	10.55
13	1.21	1.24	1241.14	191.82	9.17	10.85
14	1.30	1.29	1336.62	178.12	9.42	11.13
15	1.39	1.33	1432.09	166.24	9.65	11.40
20	1.86	1.54	1909.45	124.68	10.68	12.60
25	2.32	1.72	2386.81	99.75	11.55	13.61
50	4.65	2.43	4773.63	49.87	14.70	17.32
75	6.97	2.98	7160.44	33.25	16.89	19.94
100	9.29	3.44	9547.25	24.94	18.62	22.04

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation doe not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

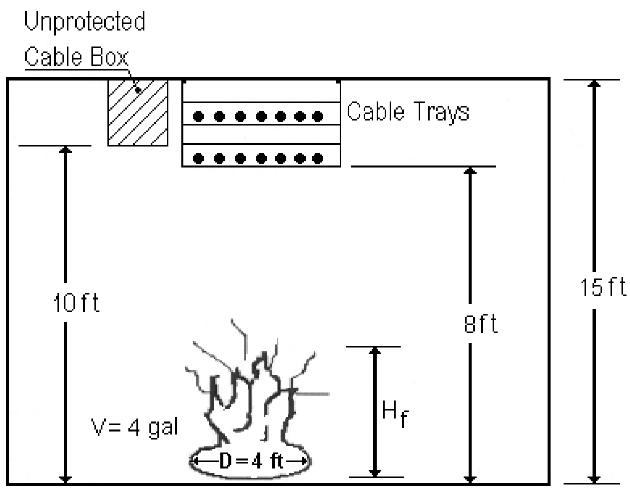
NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 3.10-3

Problem Statement

In one NPP, it was important to determine whether a fire involving a 4-gallon spill of lubricating oil from an auxiliary feedwater (AFW) pump could cause damage to an unprotected electrical cable pull box and cable trays. The unprotected pull box and cable trays were located 10 ft and 8 ft above the AFW pump, respectively. The pump room had a floor area of 20 ft x 20 ft and a ceiling height of 15 ft with a vent opening of 5 ft x 15 ft. Compute the HRR, burning duration, and flame height of the pool fire with a diameter of 4 ft. The lowest cable tray is located 8 ft above the pool. Determine whether flame will impinge upon the cable tray or cable pull box. Assume instantaneous, complete involvement of the liquid pool with no fire growth and no intervention by the plant fire department or automatic suppression systems.



Example 3-3: Compartment with Pool Fire

Solution

Purpose:

(1) Determine the Heat Release Rate (HRR) of the fire source.
(2) Determine the burning duration of the pool fire.
(3) Determine the flame height of the pool fire.
(4) Determine whether the flame will impinge upon the cable tray or cable pull box.

Assumptions:

(1) Instantaneous and complete involvement of the liquid in the pool fire
(2) The pool fire is burning in the open
(3) No fire growth period (instantaneous HRR_{max})
(4) The pool is circular or nearly circular and contains a fixed mass of liquid volume
(5) The fire is located at the center of the compartment or away from the walls

Pre FDT^s Calculations:
The input parameters of the FDT^s assigned for this problem are the fuel spill volume, dike area and fuel material. As we can see, the problem statement does not give the dike area but the pool diameter is given. The dike area can be obtained from the formula of the area of a circle, since we assume that the pool has circular shape.

$$A_{dike} = \frac{\pi}{4}D^2 = \frac{\pi}{4}(4 \quad ft)^2 = 12.56 \quad ft^2$$

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

FDT^s Inputs: (for both spreadsheets)

-Fuel Spill Volume (V) = 4 gallons
-Fuel Spill Area or Dike Area (A_{dike}) = 12.56 ft^2
-Select Fuel Type: **Lube Oil**

Results*

Heat Release Rate (HRR) $\dot{Q}$ kW (Btu/sec)	Burning Duration (t_b) (min.)	Pool Fire Flame Height (H_f) m (ft)	
		Method of Heskestad	Method of Thomas
1,202 (1,139)	4.2	2.8 (9.1)	3.0 (9.8)

*see spreadsheet on next page

Both methods for pool fire flame height estimation show that pool fire flame will impinge upon the cable tray and cable pull box.

Spreadsheet Calculations

FDT^s^: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls (HRR-Calculations)

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE, HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	4.00	gallons	0.0151	m^3
Fuel Spill Area or Dike Area (A_{dike})	12.56	ft^2	1.167	m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec		
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg		
Fuel Density (ρ)	760	kg/m^3		
Empirical Constant (kβ)	0.7	m^{-1}		
Ambient Air Temperature (T_a)	77.00	°F	25.00	°C
			298.00	K
Gravitational Acceleration (g)	9.81	m/sec^2		
Ambient Air Density (ρ_a)	1.18	kg/m^3		

Calculate

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Fuel Type

Lube Oil

Scroll to desired fuel type
Click on selection

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25.

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference : *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-25.

$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_{dike}$

Where
- Q = pool fire heat release rate (kW)
- $\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- $\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)
- $A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

Where
- A_{dike} = surface area of pool fire (m^2)
- D = pool fire diamter (m)

$D = \sqrt{(4A_{dike}/\pi)}$

D = 1.219 m

Heat Release Rate Calculation

$Q = \dot{m}''\Delta H_{c,eff}(1-e^{-k\beta D}) A_{dike}$

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	1201.50 kW	1138.81 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference : *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where
- t_b = burning duration of pool fire (sec)
- V = volume of liquid (m^3)
- D = pool diameter (m)
- v = regression rate (m/sec)

Calculation for Regression Rate

$v = \dot{m}''/\rho$

Where
- v = regression rate (m/sec)
- $\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)
- ρ = liquid fuel density (kg/m^3)

v = 0.000051 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b =	252.87 sec	4.21 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference : *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 2-10.

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where
- H_f = pool fire flame height (m)
- Q = pool fire heat release rate (kW)
- D = pool fire diameter (m)

Pool Fire Flame Height Calculation

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

H_f =	2.77 m	9.07 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-204.

$H_f = 42\ D\ (m''/\rho_a \sqrt{(g\ D)})^{0.61}$

Where H_f = pool fire flame height (m)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

ρ_a = ambient air density (kg/m^3)

D = pool fire diameter (m)

g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation

$H_f = 42\ D\ (m''/\rho_a \sqrt{(g\ D)})^{0.61}$

H_f =	2.99 m	9.82 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	9.07
METHOD OF THOMAS	9.82

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft^2)	Area (m^2)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	95.66	3176.09	3.63	4.08
2	0.19	0.49	191.32	1588.04	4.68	5.19
3	0.28	0.60	286.98	1058.70	5.42	5.97
4	0.37	0.69	382.64	794.02	6.02	6.60
5	0.46	0.77	478.30	635.22	6.52	7.13
6	0.56	0.84	573.97	529.35	6.97	7.60
7	0.65	0.91	669.63	453.73	7.36	8.02
8	0.74	0.97	765.29	397.01	7.72	8.40
9	0.84	1.03	860.95	352.90	8.06	8.75
10	0.93	1.09	956.61	317.61	8.36	9.07
11	1.02	1.14	1052.27	288.74	8.65	9.38
12	1.11	1.19	1147.93	264.67	8.93	9.67
13	1.21	1.24	1243.59	244.31	9.18	9.94
14	1.30	1.29	1339.25	226.86	9.43	10.20
15	1.39	1.33	1434.91	211.74	9.66	10.45
20	1.86	1.54	1913.22	158.80	10.69	11.55
25	2.32	1.72	2391.52	127.04	11.56	12.48
50	4.65	2.43	4783.05	63.52	14.71	15.87
75	6.97	2.98	7174.57	42.35	16.91	18.28
100	9.29	3.44	9566.09	31.76	18.64	20.20

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation does not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 4. ESTIMATING WALL FIRE FLAME HEIGHT, LINE FIRE FLAME HEIGHT AGAINST THE WALL, AND CORNER FIRE FLAME HEIGHT

4.1 Objectives

This chapter has the following objectives:

- Identify the three regions of a diffusion flame.
- Explain how corners and walls affect flames.
- Define relevant terms, including persistent flame region, intermittent flame region, flame height, and flame extension.

4.2 Introduction

If a fire is located close to a wall or a corner (i.e., formed by the intersection of two walls), the resulting restriction on free air entrainment will have a significant effect on fire growth and spread. The primary impact of walls and corners is to reduce the amount of entrained air available to the flame or plume. This lengthens flames and causes the temperature in a plume to be higher at a given elevation than it would be in the open. Remember that the expression for estimating flame height given in Chapter 3 assumes that the fire source is located away from the walls and corners.

When a diffusion flame develops and is in contact with the wall, its structure can be subdivided into three regions, which are commonly identified as the persistent flame region, the intermittent flame region, and the buoyant plume region. As the plume rises to the ceiling, its direction changes from vertical (upward) to horizontal. Until the point where the flow changes direction, the plume is primarily driven by buoyancy. Thereafter, the plume is driven by its residual momentum and becomes a jet, which is referred to as the "ceiling jet."

The flame heats the wall material with which it comes in contact. The heat flux to the wall is a function of location and is highest in the persistent flame region. The flame height depends on the amount of air entrained which, in turn, is proportional to the fuel heat release rate. On occasions, it may also be necessary to calculate the flame projections against a wall from the spill of flammable liquid in a trench or flames emerging from a burning electrical cabinet.

4.3 Flame Height Correlations for Walls Fires, Line Fires, and Corner Fires

In a wall flame, the wall-side heat flux appears to be governed by the flame radiation, while the heat flux in the far field is primarily attributable to convection. This implies that flame height can be a scaling factor representing the distribution of wall heat transfer. Using the analogy of unconfined fires, the flame height is expected to depend only on the gross heat release rate of the fuel. The terms "flame height" and "flame extension" designate the lengths of flame in the vertical and horizontal directions, respectively. A wall flame generated from a fire located against a wall can only entrain air from half of its perimeter. Thus, wall flame can be considered to be geometrically half of an axisymmetric flame and its mass flow rate, in turn, is half of that from an axisymmetric flame.

A flame generated from a fire located in a corner of a compartment (typically where the intersecting walls form a 90° angle) is referred to as corner flame. Corner fires are more severe than wall fires because of the radiative heat exchange between the two burning walls. However, the physical phenomena controlling fire growth in corner and wall scenarios are very similar, if not identical.

4.3.1 Wall Fire Flame Height Correlation

Delichatsios (1984) reported by Budnick, Evans, and Nelson (1997) developed a simple correlation of flame height for elongated fire based on experimental data. Figure 4-1 depicts the configuration used in developing the correlation for wall flame height. In the following correlation, the flame height is based on the rate of HRR per unit length of the fire:

$$H_{f(Wall)} = 0.034\dot{Q}'^{\frac{2}{3}} \qquad (4\text{-}1)$$

Where:

$H_{f(Wall)}$ = wall flame height (m)
0.034 = entrainment coefficient
$\dot{Q}'$ = HRR per unit length of the fire (kW/m)

The above correlation can be used to determine the length of the flame against the wall and to estimate radiative heat transfer to objects in the enclosure.

4.3.2 Line Fire Flame Height Correlation

Delichatsios (1984) reported by Budnick et. al., (1997) also developed a flame height correlation for line fires against a wall. Like the wall fire flame height correlation, this correlation is based on experimental data. The geometry for this case is shown in Figure 4-2. Delichatsios' correlation is expressed by the following equation based on the rate of HRR per unit length of the fire:

$$H_{f(Wall,Line)} = 0.017\dot{Q}'^{\frac{2}{3}} \qquad (4\text{-}2)$$

Where:

$H_{f(Wall, Line)}$ = line fire flame height (m)
0.017 = entrainment coefficient
$\dot{Q}'$ = HRR per unit length of the fire (kW/m)

The above correlation can be used to determine the length of the flame against the wall from a line fire source and can be used to estimate radiative heat transfer to objects in the enclosure.

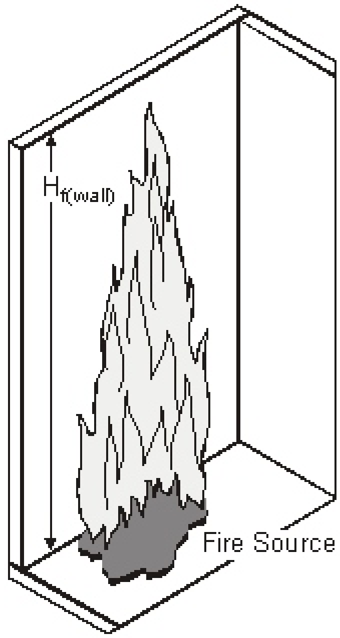


Figure 4-1 Wall Fire Flame Configuration

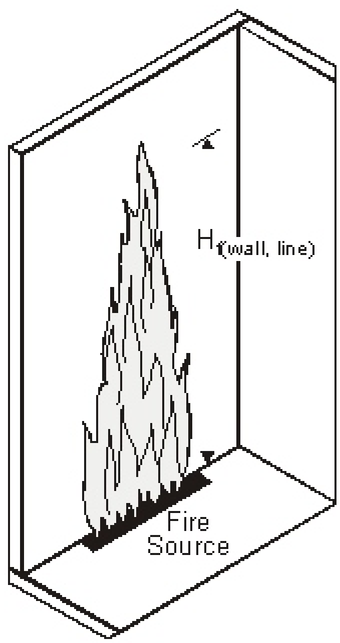


Figure 4-2 Line Fire Flame Against a Wall

4.3.3 Corner Fire Flame Height Correlation

A corner fire may be modeled using a pool fire and specifying the center coordinates as the apex of the corner. At the start of the fire, a diffusion flame develops and makes contact with the walls. As flames spread along the intersection of wall and ceiling, they eventually reach another corner. With a noncombustible ceiling, flames also spread downward. By contrast, with a combustible wall, the heat transfer between two walls in contact with the fire source results in a much more rapid fire spread. Figure 4-3 depicts the configuration used in developing the corner flame height correlation from experimental data. Hasemi and Tokunaga (1983 and 1984) suggest the following expression, based on the correlation of an extensive number of fire tests:

$$H_{f(Corner)} = 0.075\dot{Q}^{\frac{3}{5}} \qquad (4\text{-}3)$$

Where:

$H_{f(Corner)}$ = corner fire flame height (m)
0.075 = entrainment coefficient
$\dot{Q}$ = HRR of the fire (kW)

The above correlation can be used to determine the length of the flame against the intersection of two walls and to estimate radiative heat transfer to objects in the enclosure.

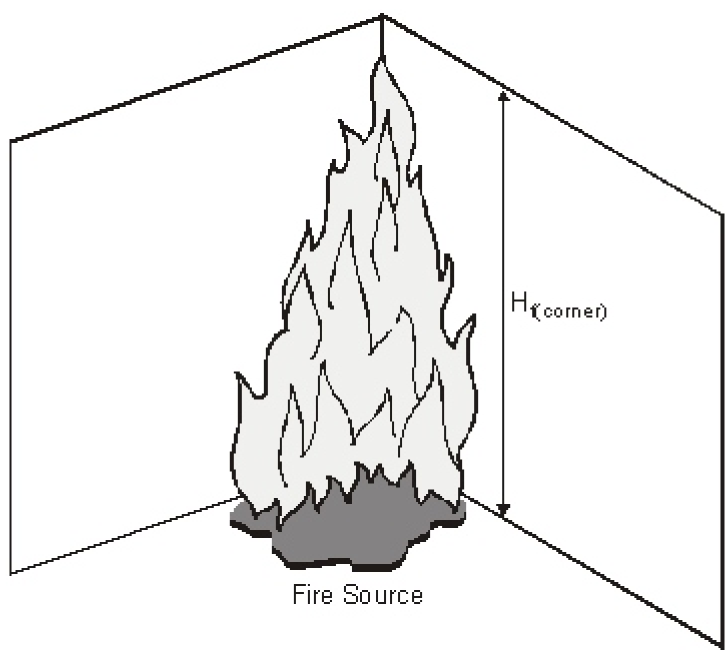


Figure 4-3 Corner Fire Flame Configuration

4.4 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations:

(1) This method includes correlations for flame height for liquid fire.

(2) The size of the fire (flame height) depends on the length of the fire.

(3) This correlation is developed for two-dimensional sources.The turbulent diffusion flames produced by fires burning at or near a wall configuration of a compartment affect the spread of the fire.

(4) Air is entrained only from one side during the combustion process.

4.5 Required Input for Spreadsheet Calculations

The user must obtain the following information to use the spreadsheet:

(1) fuel type (material)
(2) fuel spill volume (gallons)
(3) fuel spill area (ft^2)

4.6 Cautions

(1) Use the appropriate spreadsheet (04_Flame_Height_Calculations.xls) on the CD-ROM for wall fire flame height, line fire flame height, and corner fire flame height calculations.

(2) Use the page that best represents the fire configuration.

(3) Make sure to enter the input parameters in the correct units.

4.7 Summary

This chapter describes methods of calculating the height of a flame and its buoyant gases when the fire source is near a wall or a corner. These fire scenarios are often used as idealized representatives of situations of much greater complexity. The correlations presented were obtained from laboratory scale fires providing local measurements of gas temperature and velocity both below and above the flame tips, as well as measurements of visual flame length.

4.8 References

Budnick, E.K., D.D. Evans, and H.E. Nelson, "Simple Fire Growth Calculations," Section 11 Chapter 10, *NFPA Fire Protection Handbook*, 18th Edition, National Fire Protection Association, Quincy, Massachusetts, 1997.

Delichatsios, M.A., "Flame Heights of Turbulent Wall Fire with Significant Flame Radiation," *Combustion Science and Technology*, Volume 39, pp. 195–214, 1984.

Hasemi Y., and T.Tokunaga, "Modeling of Turbulent Diffusion Flames and Fire Plumes for the Analysis of Fire Growth," Proceedings of the 21st National Heat Transfer Conference, American Society of Mechanical Engineers (ASME), 1983.

Hasemi Y., and T.Tokunaga, "Some Experimental Aspects of Turbulent Diffusion Flames and Buoyant Plumes from Fire Sources Against a Wall and in Corner of Walls," *Combustion Science and Technology*, Volume 40, pp. 1–17, 1984.

4.9 Problems

Example Problem 4.9-1

Problem Statement

A pool fire scenario arises from a breach (leak or rupture) in an oil-filled transformer. This event allows the fuel contents of the transformer to spill 2 gallons along a wall with an area of 9 ft^2. A cable tray is located 8 ft above the fire. Calculate the wall flame height of the fire and determine whether the flame will impinge upon the cable tray.

Solution

Purpose:
(1) Calculate the wall flame height.
(2) Determine whether the flame will impinge upon the cable tray.

Assumptions:
(1) Air is entrained only from one side during the combustion process.
(2) The fire is located at or near a wall configuration of a compartment that affects the spread of the fire.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 04_Flame_Height_Calculations.xls (click on *Wall_Flame _Height*)

FDTs Input Parameters:

-Fuel spill volume (V) = 2 gallons
-Fuel Spill Area or Dike Area (A_{dike}) = 9.0 ft^2
-Select Fuel Type: **Transformer Oil, Hydrocarbon**

Results*

Fuel	Wall Fire Flame Height ($H_{f(Wall)}$) m (ft)	Cable Tray Impingement
Transformer Oil, Hydrocarbon	3.0 (10.0)	Yes

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 04_Flame_Height_Calculations.xls (click on Wall_Flame _Height)

CHAPTER 4. ESTIMATING WALL FIRE FLAME HEIGHT

Version 1805.0

The following calculations estimate the wall fire flame height.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	2.00	gallons	0.0076 m^3
Fuel Spill Area or Dike Area (A_{dike})	9.00	ft^2	0.836 m^2
Mass Burning Rate of Fuel (m'')	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Empirical Constant ($k\beta$)	0.7	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m'' (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

Select Fuel Type

Transformer Oil, Hydrocarbon

Scroll to desired fuel type then Click on selection

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, Page 3-26.*

Heat Release Rate Calculation

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-26.

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D})\, A_{dike}$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diamter (m)

D = 1.032 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1-e^{-k\beta D})\, A_{dike}$

Q = 771.52 kW 731.26 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where Q' = heat release rate per unit length (kW/m)

Q = fire heat release rate of the fire (kW)

L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 0.836 m^2

L = 0.914 m

$Q' = Q/L$

Q' = 843.75 kW/m

ESTIMATING WALL FIRE FLAME HEIGHT

Reference: NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-134.

$H_{(wall)} = 0.034\, Q'^{2/3}$

Where $H_{(wall)}$ = wall fire flame height (m)

Q' = rate of heat release per unit length of the fire (kW/m)

$H_{(wall)} = 0.034\, Q'^{2/3}$

$H_{(wall)}$ =	3.04 m	9.96 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, and NFPA Fire Protection Handbook, 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 4.9-2

Problem Statement

A pool fire scenario arises from a transient combustible liquid spill. This event allows the fuel contents of a 15 gallon can to form along a wall with an area of 30 ft^2. A cable tray is located 12 ft above the fire. Determine the line wall fire flame height and whether the flame will impinge upon the cable tray if the spilled liquids are (a) diesel, (b) acetone, and (c) methanol.

Solution

Purpose:

(1) Calculate the line wall fire flame height using three transient combustibles.
(2) Determine whether the flame will impinge upon the cable tray in each case.

Assumptions:

(1) Air is entrained only from one side during the combustion process.
(2) The fire is located at or near a wall configuration of a compartment that affects the spread of the fire.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 04_Flame_Height_Calculations.xls (click on *Wall_Line_Flame _Height*)

FDT^s Input Parameters:

-Fuel spill volume (V) = 15 gallons
-Fuel Spill Area or Dike Area (A_{dike}) = 30.0 ft^2
-Select Fuel Type: Diesel, Acetone, and Methanol

Results*

Fuel	Wall Line Fire Height ($H_{f(Wall\ Line)}$) m (ft)	Cable Tray Impingement
Diesel	3.8 (12.3)	Yes
Acetone	2.44(8.0)	No
Methanol	1.2 (3.8)	No

*See spreadsheets on next page

Spreadsheet Calculations

FDT[s]: 04_Flame_Height_Calculations.xls (click on Wall_Line_Flame _Height)

(a) Diesel

CHAPTER 4. ESTIMATING LINE FIRE FLAME HEIGHT AGAINST THE WALL

Version 1805.0

The following calculations estimate the line fire flame height against the wall.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	15.00	gallons	0.0568 m^3
Fuel Spill Area or Dike Area (A_{dike})	30.00	ft^2	2.787 m^2
Mass Burning Rate of Fuel (m")	0.045	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	44400	kJ/kg	
Empirical Constant (kβ)	2.1	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, Page 3-26.

Select Fuel Type: Diesel

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

Reference: SFPE Handbook of Fire Protection Engineering, 3[rd] Edition, 2002, Page 3-26.

$Q = m''\Delta H_{c,eff} (1 - e^{-k\beta D}) A_f$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m²-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m²)

$k\beta$ = empirical constant (m⁻¹)

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m²)

D = pool fire diameter (m)

D = 1.884 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff} (1-e^{-k\beta D}) A_{dike}$

Q = 5462.02 kW 5177.01 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where Q' = heat release rate per unit length (kW/m)

Q = fire heat release rate of the fire (kW)

L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 2.787 m²

L = 1.669 m

$Q' = Q/L$

Q' = 3271.73 kW/m

ESTIMATING LINE WALL FIRE FLAME HEIGHT

Reference: NFPA Fire Protection Handbook, 19[th] Edition, 2003, Page 3-134.

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

Where $H_{f(wall\ line)}$ = wall fire flame height (m)

Q' = rate of heat release per unit length of the fire (kW/m)

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

$H_{f(wall\ line)}$ =	3.75 m	12.29 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3[rd] Edition, 2002, and NFPA Fire Protection Handbook, 19[th] Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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FDT[s]: 04_Flame_Height_Calculations.xls (click on Wall_Line_Flame _Height)

(b) Acetone

CHAPTER 4. ESTIMATING LINE FIRE FLAME HEIGHT AGAINST THE WALL

Version 1805.0

The following calculations estimate the line fire flame height against the wall.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	15.00	gallons	0.0568 m^3
Fuel Spill Area or Dike Area (A_{dike})	30.00	ft^2	2.787 m^2
Mass Burning Rate of Fuel (m")	0.041	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	25800	kJ/kg	
Empirical Constant (kβ)	1.9	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, Page 3-26.*

Select Fuel Type

Acetone

Scroll to desired fuel typ

Click on selection

Heat Release Rate Calculation

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25.*

$Q = m''\Delta H_{c,eff}\,(1 - e^{-k\beta D})\,A_f$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diameter (m)

D = 1.884 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}\,(1-e^{-k\beta D})\,A_{dike}$

Q = 2865.94 kW 2716.39 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where Q' = heat release rate per unit length (kW/m)

Q = fire heat release rate of the fire (kW)

L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 2.787 m^2

L = 1.669 m

$Q' = Q/L$

Q' = 1716.69 kW/m

ESTIMATING LINE WALL FIRE FLAME HEIGHT

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-134.*

$H_{f(wall\ line)} = 0.017\,Q'^{2/3}$

Where $H_{f(wall\ line)}$ = wall fire flame height (m)

Q' = rate of heat release per unit length of the fire (kW/m)

$H_{f(wall\ line)} = 0.017\,Q'^{2/3}$

$H_{f(wall\ line)}$ =	2.44 m	8.00 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, and NFPA Fire Protection Handbook, 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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FDT[s]: 04_Flame_Height_Calculations.xls (click on Wall_Line_Flame _Height)

(c) Methanol

CHAPTER 4. ESTIMATING LINE FIRE FLAME HEIGHT AGAINST THE WALL

Version 1805.0

The following calculations estimate the line fire flame height against the wall.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	15.00	gallons	0.0568 m^3
Fuel Spill Area or Dike Area (A_{dike})	30.00	ft^2	2.787 m^2
Mass Burning Rate of Fuel (m")	0.017	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	20000	kJ/kg	
Empirical Constant (kβ)	100	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, Page 3-26.*

Select Fuel Type

Methanol

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25.*

$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D})A_f$

Where Q = pool fire heat release rate (kW)

$\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diameter (m)

D = 1.884 m

Heat Release Rate Calculation

$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D})A_{dike}$

Q = 947.61 kW 898.16 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where Q' = heat release rate per unit length (kW/m)

Q = fire heat release rate of the fire (kW)

L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 2.787 m^2

L = 1.669 m

$Q' = Q/L$

Q' = 567.62 kW/m

ESTIMATING LINE WALL FIRE FLAME HEIGHT

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-134.*

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

Where $H_{f(wall\ line)}$ = wall fire flame height (m)

Q' = rate of heat release per unit length of the fire (kW/m)

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

$H_{f(wall\ line)}$ =	1.17 m	3.82 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, and NFPA Fire Protection Handbook, 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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Example Problem 4.9-3

Problem Statement

A pool fire scenario arises from a rupture in a diesel generator fuel line. This event allows diesel fuel to spill 1.5 gallons along the corner of walls with an area of 10 ft^2. An unprotected junction box is located 12 ft above the fire. Determine whether the flame will impinge upon the junction box.

Solution

Purpose:
(1) Calculate the line wall fire flame height.
(2) Determine whether the flame will impinge upon the junction box.

Assumptions:
(1) Air is entrained only from one side during the combustion process.
(2) The fire is located at or near a wall configuration of a compartment that affects the spread of the fire.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 04_Flame_Height_Calculations.xls (click on *Corner_Flame _Height*)

FDTs Input Parameters:

-Fuel spill volume (V) = 1.5 gallons
-Fuel Spill Area or Dike Area (A_{dike}) = 10 ft^2
-Select Fuel Type: **Diesel**

Results*

Fuel	Corner Fire Flame Height ($H_{f(Corner)}$) m (ft)	Junction Box Impingement
Diesel	6.4 (21.1)	Yes

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 04_Flame_Height_Calculations.xls (click on Corner_Flame _Height)

CHAPTER 4. ESTIMATING CORNER FIRE FLAME HEIGHT

Version 1805.0

The following calculations estimate the corner fire flame height.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Parameter	Value	Unit	
Fuel Spill Volume (V)	1.50	gallons	0.0057 m^3
Fuel Spill Area or Dike Area (A_{dike})	10.00	ft^2	0.929 m^2
Mass Burning Rate of Fuel (m'')	0.045	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	44400	kJ/kg	
Empirical Constant ($k\beta$)	2.1	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m'' (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, Page 3-26.*

Select Fuel Type

Diesel

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] *Edition, 2002, Page 3-25.*

$Q = m'' \Delta H_{c,eff} (1 - e^{-k\beta D}) A_f$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diamter (m)

D = **1.088** m

Heat Release Rate Calculation

$Q = m'' \Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

Q = **1667.09** kW **1580.10** Btu/sec

ESTIMATING CORNER FIRE FLAME HEIGHT

Reference: *Hesemi and Tokunaga, "Modeling of Turbulent Diffusion Flames and Fire Plumes for the Analysis of Fire Growth," Growth," Proceeding of the 21*[st] *National Heat Transfer Conference, American Society of Mechanical Engineers (ASME), 1983.*

$H_{f(corner)} = 0.075\ Q^{3/5}$

Where Q = heat release rate of the fire (kW)

$H_{f(corner)} = 0.075\ Q^{3/5}$

$H_{f(corner)}$ =	**6.43 m**	**21.10 ft**	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3[rd] Edition, 2002 and Hesemi and Tokunage, 1983.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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UNITED STATES NUCLEAR REGULATORY COMMISSION

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL

5.1 Objectives

This chapter has the following objectives:

- Introduce the three modes of heat transfer.
- Explain how to calculate the heat flux from a flame to a target outside the flame.
- Discuss point source radiation models and solid flame radiation models.
- Identify the difference between solid flame radiation models at ground level and solid flame radiation models above ground level with and without wind.
- Define relevant terms, including, conduction, convection, radiation, heat flux, emissive power, and configuration factor.

5.2 Introduction

Fire normally grows and spreads by direct burning, which results from impingement of the flame on combustible materials, or from heat transfer to other combustibles by means of conduction, convection, or radiation. All three of these modes of heat transfer may be significant, depending on the specifics of a given fire scenario. Conduction is particularly important in allowing heat to pass through a solid barrier (e.g., fire wall) to ignite material on the other side. Nevertheless, most of the heat transfer in fires typically occurs by means of convection and/or radiation. In fact, it is estimated that in most fires, approximate 70-percent of the heat emanates by convection (heat transfer through a moving gas or liquid). Consider, for example, a scenario in which a fire produces hot gas which is less dense than the surrounding air. This hot gas then rises, carrying heat. The hot products of combustion rising from a fire typically have a temperature in the range of 800–1,200 °C (1,472–2,192 °F) and a density that is one-quarter that of ambient air. In the third mode of heat transfer, known as radiation, radiated heat is transferred directly to nearby objects. One type of radiation, known as thermal radiation, is the significant mode of heat transfer for situations in which a target is located laterally to the exposure fire source. This would be the case, for example, for a floor-based fire adjacent to an electrical cabinet or a vertical cable tray in a large compartment. Thermal radiation is electromagnetic energy occurring in wavelengths from 2 to 16 m (infrared). It is the net result of radiation emitted by the radiating substances such as water (H_2O), carbon dioxide (CO_2), and soot in the flame.

Chapter 2 discussed various methods of predicting the temperature of the hot gas layer and the height of the smoke layer in a room fire with natural or forced ventilation. However, those methods are not applicable when analyzing a fire scenario in a very large open space or compartment. In large spaces, such as the reactor building in a boiling water reactor (BWR) or an open space in a turbine building, the volume of the space is too large for a uniform hot gas layer to accumulate. For such scenarios, fire protection engineers must analyze other forms of heat transfer, such as radiation. A floor-mounted electrical cabinet is an example of a ground-level target. A typical target above ground level is an overhead cable tray.

5.3 Critical Heat Flux to a Target

Radiation from a flame, or any hot gas, is driven by its temperature and emissivity. The emissivity is a measure of how well the hot gas emits thermal radiation (emissivity is defined as the ratio of radiant energy emitted by a surface to that emitted by a black body of the same temperature). Emmisivity is reported as a value between 0 and 1, with 1 being a perfect radiator. The radiation that an observer feels is affected by the flame temperature and size (height) of the flame.

The incident heat flux (the rate of heat transfer per unit area that is normal to the direction of heat flow. It is a total of heat transmitted by radiation, conduction, and convection) required to raise the surface of a target to a critical temperature is termed the critical heat flux. Measured critical heat flux levels for representative cable samples typically range from 15 to 25 kW/m^2 (1.32 to 2.2 Btu/ft^2-sec). For screening purposes, it is appropriate to use value of 10 kW/m^2 (0.88 Btu/ft^2-sec) for IEEE-383 qualified cable and 5 kW/m^2 (0.44 Btu/ft^2-sec) for IEEE-383 unqualified cable. These values are consistent with selected damage temperatures for both types of cables based on the Electrical Power Research Institute (EPRI), "Fire-Induced Vulnerability Evaluation (FIVE)," methodology.

Researchers have developed numerous methods to calculate the heat flux from a flame to a target located outside the flame. Flames have been represented by cylinders, cones, planes, and point sources in an attempt to evaluate the effective configuration factors[1] between the flame and the target. Available predictive methods range from those that are very simple to others that are very complex and involve correlations, detailed solutions to the equations of radiative heat transfer, and computational fluid mechanics. Routine FHAs are most often performed using correlationally based approaches, because of the limited goals of the analyses and the limited resources available for routine evaluation. As a result of their widespread use, a great deal of effort has gone into the development of these methods. Burning rates, flame heights, and radiative heat fluxes are routinely predicted using these approaches.

Fire involving flammable and combustible liquids typically have higher heat release rates (for the same area of fuel involved) than ordinary combustibles fires. The flame from a liquid fire is typically taller, making it a better radiator. Hydrocarbon liquid fires are also quite luminous because of the quantity of soot in the flames. Sooty fires are better emitters of thermal radiation. Thus, an observer approaching a flammable/combustible liquid fire feels more heat than an observer approaching an ordinary combustibles fire of comparable size.

The methods presented in this chapter are drawn from the *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, which examines the accuracy of these methods by comparisons with available experimental data (these methods also presented in the SFPE Engineering Guide, "Assessing Flame Radiation to External Targets from Pool Fires," June 1999).

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1 The configuration factor is a purely geometric quantity, which gives the fraction of the radiation leaving one surface that strikes another surface directly.

5.3.1 Point Source Radiation Model

A point source estimate of radiant flux is conceptually the simplest representation configurational model of a radiant source used in calculating the heat flux from a flame to target located outside the flame. To predict the thermal radiation field of flames, it is customary to model the flame based on the point source located at the center of a flame[2]. The point source model provides a simple relationship that varies as the inverse square of the distance, R. For an actual point source of radiation or a spherical source of radiation, the distance R is simply the distance from the point or from the center of the sphere to the target.

The thermal radiation hazard from a fire depends on a number of parameters, including the composition of the fuel, the size and the shape of the fire, its duration, proximity to the object at risk, and thermal characteristics of the object exposed to the fire. The point source method may be used for either fixed or transient combustibles. They may involve an electrical cabinet, pump, liquid spill, or intervening combustible at some elevation above the floor. For example, the top of a switchgear or motor control center (MCC) cabinet is a potential location for the point source of a postulated fire in this type of equipment. By contrast, the point source of a transient combustible liquid spill or pump fire is at the floor.

The point source model assumes that radiant energy is released at a point located at the center of the fire. The radiant heat flux at any distance from the source fire is inversely related to the horizontal separation distance (R), by the following equation (Drysdale, 1998):

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4 \pi R^2} \qquad (5\text{-}1)$$

Where:

$\dot{q}''$ = radiant heat flux (kW/m^2)

$\dot{Q}$ = heat release rate of the fire (kW)

R = radial distance from the center of the flame to the edge of the target (m)

$_r$ = fraction of total energy radiated

In general, $_r$ depends on the fuel, flame size, and flame configuration, and can vary from approximately 0.15 for low-sooting fuels (e.g., alcohol) to 0.60 for high sooting fuels (e.g., hydrocarbons). For large fires (several meters in diameter), cold soot enveloping the luminous flames can reduce $_r$ considerably. See Figure 5-1 for a graphic representation of the relevant nomenclature.

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2 More realistic radiator shapes give rise to very complex configuration factor equations.

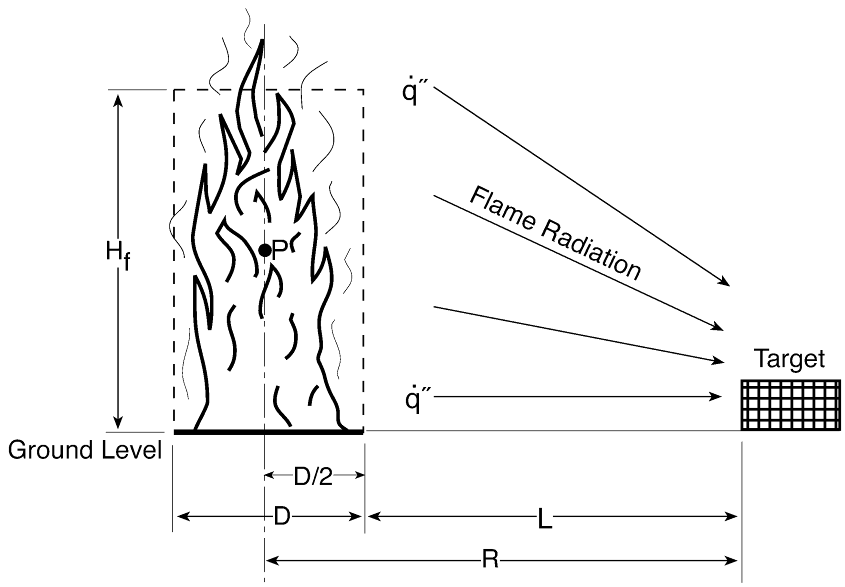

Figure 5-1 Radiant Heat Flux from a Pool Fire
to a Floor-Based Target Fuel (Point Source Model)

The HRR of a fire can be determined by laboratory or field testing. In the absence of experimental data, the maximum HRR for the fire $(\dot{Q})$, is given by the following equation (Babrauskas, 1995):

$$\dot{Q} = \dot{m}'' \Delta H_{c,eff} A_f \left(1 - e^{-k\beta D}\right) \qquad (5\text{-}2)$$

Where:

$\dot{Q}$ = heat release rate of the fire (kW)
$\dot{m}''$ = burning or mass loss rate per unit area per unit time (kg/m^2-sec)
$H_{c,eff}$ = effective heat of combustion (kJ/kg)
A_f = horizontal burning area of the fuel (m^2)
$k\beta$= empirical constant (m^{-1})
D = diameter of burning area (m)

For non-circular pools, the effective diameter is defined as the diameter of a circular pool with an area equal to the actual pool area, given by the following equation:

$$D = \sqrt{\frac{4A_f}{\pi}} \qquad (5\text{-}3)$$

Where:

A_f = surface area of the non-circular pool (m^2)
D = diameter of the fire (m)

5.3.2 Solid Flame Radiation Model with Target At and Above Ground Level

The solid flame spreadsheet associated with this chapter provides a detailed method for assessing the impact of radiation from pool fires to potential targets using configuration factor algebra. This method covers a range of detailed calculations, some of which are most appropriate for first order initial hazard assessments, while others are capable of more accurate predictions.

The solid flame model assumes that, (1) the fire can be represented by a solid body of a simple geometrical shape, (2) thermal radiation is emitted from its surface, and, (3) non-visible gases do not emit much radiation. (See Figures 5-2 and 5-3 for general nomenclature.) To ensure that the fire volume is not neglected, the model must account for the volume because a portion of the fire may be obscured as seen from the target. The intensity of thermal radiation from the pool fire to an element outside the flame envelope for no-wind conditions and for windblown flames is given by the following equation (Beyler, 2002):

$$\dot{q}'' = E F_{1\rightarrow 2} \qquad (5\text{-}4)$$

Where:

$\dot{q}''$ = incident radiative heat flux (kW/m^2)
E = average emissive power at flame surface (kW/m^2)
$F_{1\rightarrow 2}$ = configuration factor

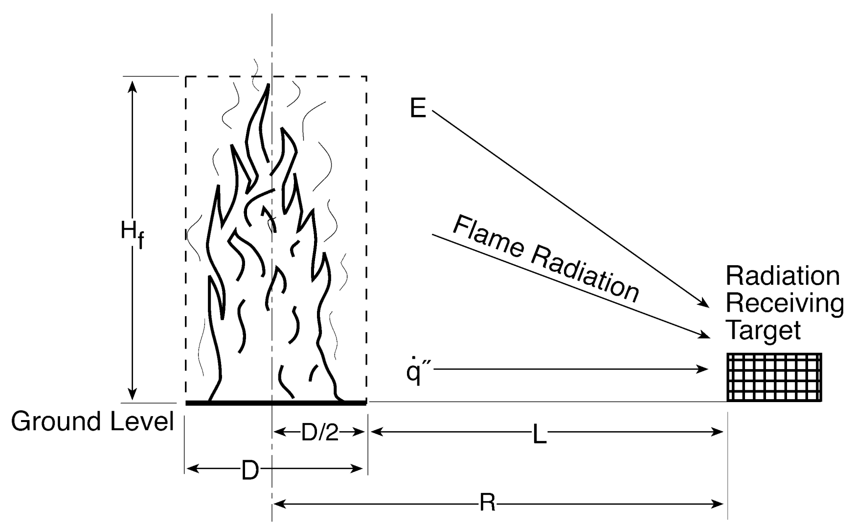

Figure 5-2 Solid Flame Radiation Model with No Wind and Target at Ground Level

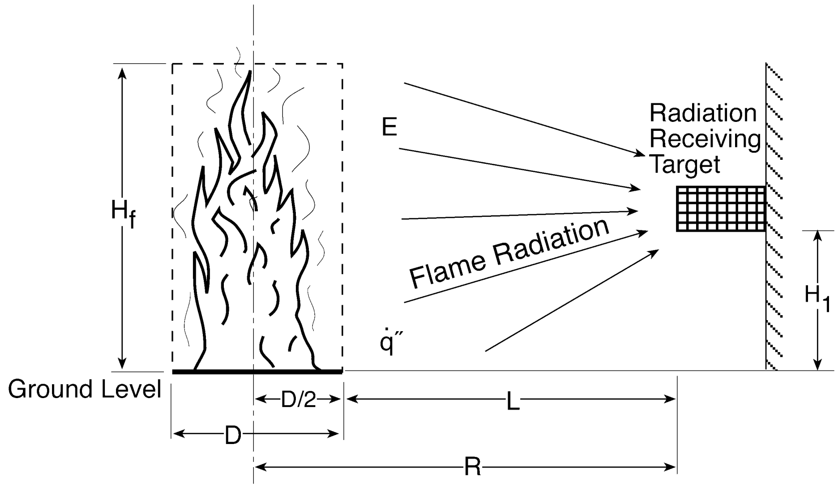

Figure 5-3 Solid Flame Radiation Model with No Wind
and Target Above Ground

5.3.2.1 Emissive Power

Emissive power is the total radiative power leaving the surface of the fire per unit area per unit time. Emissive power can be calculated using of Stefan's law, which gives the radiation of a black body in relation to its temperature. Because a fire is not a perfect black body (black body is defined as a perfect radiator; a surface with an emissivity of unity and, therefore, a reflectivity of zero), the emissive power is a fraction ( ) of the black body radiation (Beyler, 2002):

$$E = \varepsilon \ \sigma \ T^4 \qquad (5\text{-}5)$$

Where:

E = flame emissive power (kW/m^2)
 = flame emissivity
 = Stefan-Boltzmann constant = 5.67×10^{-11} (kW/m^2-K^4)
T = temperature of the fire (K)

The use of the Stefan-Boltzmann constant to calculate radiation heat transfer requires knowledge of the temperature and emissivity of the fire; however, turbulent mixing causes the fire temperature to vary. Consequently, Shokri and Beyler (1989) correlated experimental data of flame radiation to external targets in terms of an average emissive power of the flame. For that correlation, the flame is assumed to be a cylindrical, black body, homogeneous radiator with an average emissive power. Thus, effective power of the pool fire in terms of effective diameter is given by:

$$E = 58 \left(10^{-0.00823D}\right) \quad (5\text{-}6)$$

Where:

E = flame emissive power (kW/m^2)
D = diameter of pool fire (m)

This represents the average emissive power over the whole of the flame and is significantly less than the emissive power that can be attained locally. The emissive power is further reduced with increasing pool diameter as a result of the increasing prominence of black smoke outside the flame, which obscures the radiation from the luminous flame.

For non-circular pools, the effective diameter is defined as the diameter of a circular pool with an area equal to the actual pool area given by Equation 5-3.

5.3.2.2 Configuration Factor $F_{1\rightarrow2}$ under Wind-Free Conditions

The configuration factor[3] is a purely geometric quantity, which provides the fraction of the radiation leaving one surface that strikes another surface directly. In other words the configuration factor gives the fraction of hemispherical surface area seen by one differential element when looking at another differential element on the hemisphere.

The configuration factor is a function of target location, flame size (height), and fire diameter, and is a value between 0 and 1. When the target is very close to the flame, the configuration factor approaches 1, since everything viewed by the target is the flame. The flame is idealized with a diameter equal to the pool diameter, D, and a height equal to the flame height, H_f. If the pool has a length-to-width ratio near 1, an equivalent area circular source can be used in determining the flame length, H_f, for non-circular pools. (See Figure 5-4 and 5-5 for general definitions applicable to the cylindrical flame model under wind-free conditions.)

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3 The configuration factor is also commonly referred to as the “view factor”.

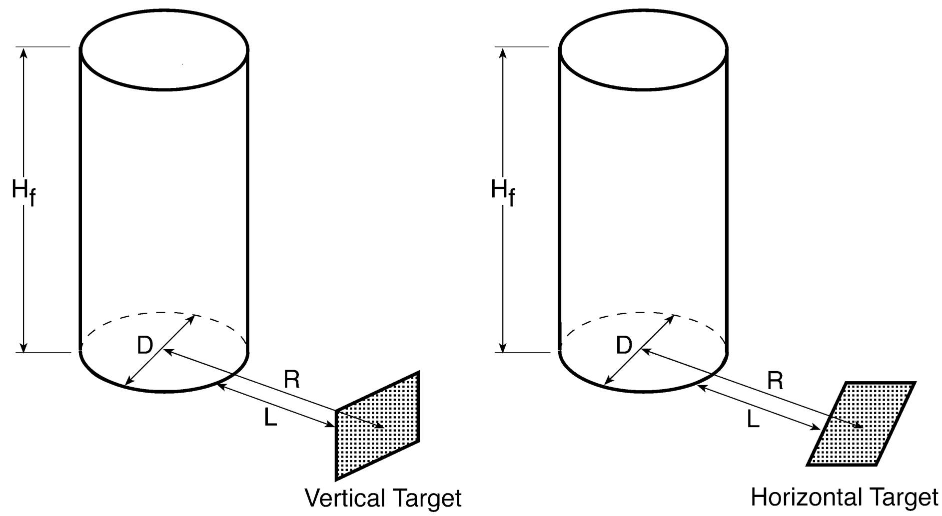

Figure 5-4 Cylindrical Flame Shape Configuration Factor Geometry for Vertical and Horizontal Targets at Ground Level with No Wind

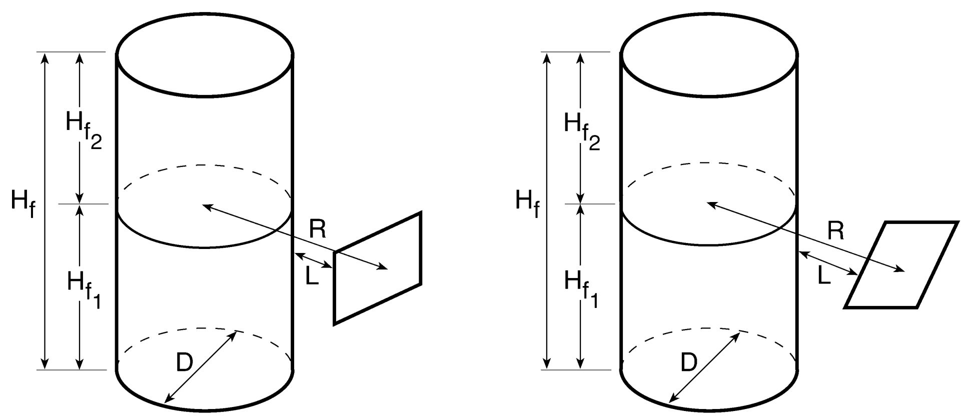

Figure 5-5 Cylindrical Flame Shape Configuration Factor Geometry for Vertical and Horizontal Targets Above Ground with No Wind

Flame height of the pool fire is then determined using the following correlation (Heskestad, 1995):

$$H_f = 0.235 \ \dot{Q}^{\frac{2}{5}} - \ 1.02 \ \ D \qquad (5\text{-}8)$$

Where:

H_f = flame height (m)

$\dot{Q}$ = heat release rate of the fire (kW)

D = diameter of the burning area (m)

The HRR of the fire can be determined by laboratory or field testing. In the absence of experimental data, the maximum HRR for the fire $(\dot{Q})$, is given by Equation 5-2.

The radiation exchange factor between a fire and an element outside the fire depends on the shape of the flame, the relative distance between the fire and the receiving element, and the relative orientation of the element. The turbulent diffusion flame can be approximated by a cylinder. Under wind-free conditions, the cylinder is vertical (Figure 5-4). If the target is either at ground level or at the flame height, a single cylinder can represent the flame. However, if the target is above the ground, two cylinders should be used to represent the flame.

For horizontal and vertical target orientations at ground level with no-wind conditions, given the diameter and height of the flame, the configuration (or view factor) $F_{1\rightarrow2}$ under wind-free conditions is determined using the following equations related to cylindrical radiation sources (Beyler, 2002):

$$F_{1\rightarrow2,H} = \left(\frac{\left(B - \frac{1}{S}\right)}{\pi\sqrt{B^2 - 1}} \tan^{-1}\sqrt{\frac{(B+1)(S-1)}{(B-1)(S+1)}} - \frac{\left(A - \frac{1}{S}\right)}{\pi\sqrt{A^2 - 1}} \tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}} \right) \qquad (5\text{-}9)$$

$$F_{1\rightarrow2,V} = \left(\frac{1}{\pi S}\tan^{-1}\left(\frac{h}{\sqrt{S^2-1}}\right) - \frac{h}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \frac{Ah}{\pi S\sqrt{A^2-1}}\tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}} \right) \qquad (5\text{-}10)$$

Where:

$$A = \frac{h^2 + S^2 + 1}{2S}, \quad B = \frac{1 + S^2}{2S}$$

$$S = \frac{2L}{D}, \quad h = \frac{2H_f}{D}$$

And:

L = the distance between the center of the cylinder (flame) to the target (m)

H_f = the height of the cylinder (flame) (m)

D = the cylinder (flame) diameter (m)

The maximum configuration factor (or view factor) at a point is given by the vectorial sum of the horizontal and vertical configuration factors:

$$F_{1\to 2,max(no-wind)} = \sqrt{F^2_{1\to 2,H} + F^2_{1\to 2,V}} \qquad (5\text{-}11)$$

As previously stated, for targets above the ground, two cylinders should be used to represent the flame. In such instances, one cylinder represents the flame below the height of the target, while the other represents the flame above the height of the target (See Figure 5-5). Thus, the following expressions are used to estimate the configuration factor (or view factor) under wind-free conditions for targets above ground level:

$$F_{1\to 2,V_1} = \left(\begin{array}{l} \frac{1}{\pi S}.\tan^{-1}\left(\frac{h_1}{\sqrt{S^2-1}}\right) - \frac{h_1}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \\ \frac{A_1 h_1}{\pi S\sqrt{A_1^{\,2}-1}}\tan^{-1}\sqrt{\frac{(A_1+1)(S-1)}{(A_1-1)(S+1)}} \end{array} \right) \qquad (5\text{-}12)$$

Where:

$$S = \frac{2L}{D}$$

$$h_1 = \frac{2H_{f_1}}{D}$$

$$A_1 = \frac{h_1^2 + S^2 + 1}{2S}$$

$$F_{1\to 2,V_2} = \left(\begin{array}{l} \frac{1}{\pi S}.\tan^{-1}\left(\frac{h_2}{\sqrt{S^2-1}}\right) - \frac{h_2}{\pi S}\tan^{-1}\sqrt{\frac{(S-1)}{(S+1)}} + \\ \frac{A_2 h_2}{\pi S\sqrt{A_2^{\,2}-1}}\tan^{-1}\sqrt{\frac{(A_2+1)(S-1)}{(A_2-1)(S+1)}} \end{array} \right) \qquad (5\text{-}13)$$

Where:

$$S = \frac{2L}{D}$$

$$h_2 = \frac{2H_{f_2}}{D}$$

$$A_2 = \frac{h_2^2 + S^2 + 1}{2S}$$

And:

L = the distance between the center of the cylinder (flame) to the target (m)
H_f = the height of the cylinder (flame) (m)
D = the cylinder (flame) diameter (m)

The total configuration factor or (view factor) at a point is given by the sum of two configuration factor as follows:

$$F_{1\to 2,V(no-wind)} = F_{1\to 2,V1} + F_{1\to 2,V2} \qquad (5\text{-}14)$$

5.3.2.3 Configuration Factor $F_{1\to 2}$ in Presence of Wind

As discussed in pervious section, in the solid flame radiation model the turbulent flame is approximated by a cylinder. Under wind-free conditions, the cylinder is vertical, in the presence of wind, the flame may not remain vertical and thermal radiation to the surrounding objects will change in the presence of a significant wind. The flame actually follows a curved path and makes an angle of tilt or an angle of deflection approximate to its curved path. Figures 5-6 and 5-7 describe the flame configuration in presence of wind velocity (u_w) for target at and above ground level.

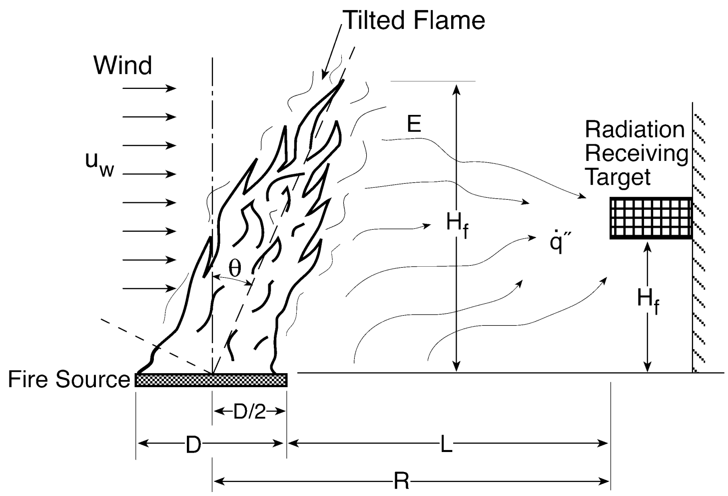

Figure 5-6 Solid Flame Radiation Model in Presence of Wind and Target Above Ground Level

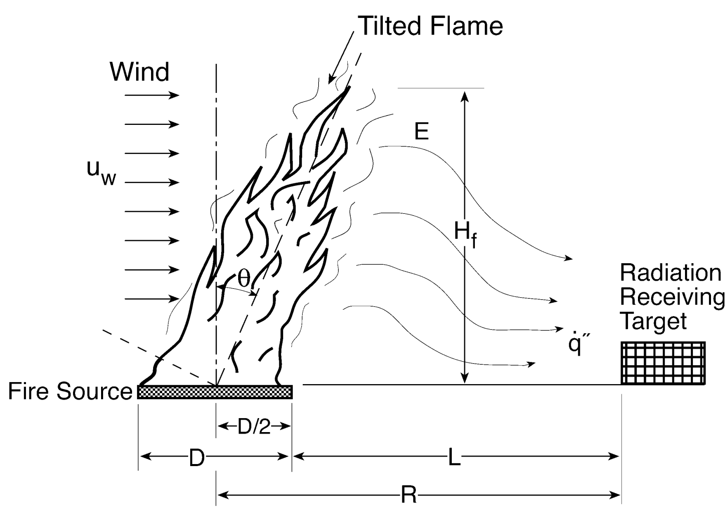

Figure 5-7 Solid Flame Radiation Model in Presence of Wind and Target at Ground Level

For horizontal and vertical target orientations at ground level in presence of wind, the expression for estimating the configuration factors is expressed by the following equations (Beyler, 2002):

$$\pi F_{1\rightarrow 2,H} = \begin{pmatrix} \tan^{-1}\dfrac{\sqrt{\dfrac{b+1}{b-1}}}{\pi\sqrt{B^2-1}} - \dfrac{a^2+(b+1)^2-2(b+1+ab\sin\theta)}{\sqrt{AB}}\tan^{-1}\sqrt{\dfrac{A}{B}}\sqrt{\dfrac{(b-1)}{(b+1)}} + \\ \dfrac{\sin\theta}{\sqrt{C}}\left(\tan^{-1}\dfrac{ab-(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\dfrac{(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}}\right) \end{pmatrix} \qquad (5\text{-}15)$$

$$\pi F_{1\rightarrow 2,V} = \begin{pmatrix} \dfrac{a\cos\theta}{b-a\sin\theta}\dfrac{a^2+(b+1)^2-2b(1+a\sin\theta)}{\sqrt{AB}}\tan^{-1}\sqrt{\dfrac{A}{B}}\sqrt{\dfrac{(b-1)}{(b+1)}} + \\ \dfrac{\cos\theta}{\sqrt{C}}\left(\tan^{-1}\dfrac{ab-(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}} + \tan^{-1}\dfrac{(b^2-1)\sin\theta}{\sqrt{b^2-1}\sqrt{C}}\right) - \\ \dfrac{a\cos\theta}{(b-a\sin\theta)}\tan^{-1}\sqrt{\dfrac{b-1}{b+1}} \end{pmatrix} \qquad (5\text{-}16)$$

Where:

$$a = \frac{H_f}{r}$$

$$b = \frac{R}{r}$$

$$A = a^2 + (b+1)^2 - 2a(b+1)\sin\theta$$

$$B = a^2 + (b-1)^2 - 2a(b-1)\sin\theta$$

$$C = 1 + (b^2-1)\cos^2\theta$$

And:

H_f = the height of the tilted cylinder (flame) (m)
r = the cylinder (flame) radius (m)
R = distance from center of the pool fire to edge of the target (m)
= flame title or angle of deflection (radians)

The maximum configuration factor for a target at ground level in the presence of wind at a point is given by the vectorial sum of the horizontal and vertical configuration factors:

$$F_{1\rightarrow 2,max(wind)} = \sqrt{F^2_{1\rightarrow 2,H} + F^2_{1\rightarrow 2,V}} \qquad (5\text{-}17)$$

For targets above the ground in presence of wind, two cylinders must be used to represent the flame. In such instances, one cylinder represents the flame below the height of the target, while the other represents the flame above the height of the target. The following expressions are used to estimate the configuration or view factor in presence of wind for targets above ground level:

$$\pi F_{1\to 2,V1} = \left(\begin{array}{l} \frac{a_1 \cos\Theta}{b - a_1 \sin\Theta} \frac{a_1^2 + (b+1)^2 - 2b(1 + a_1 \sin\Theta)}{\sqrt{AB}} \tan^{-1} \sqrt{\frac{A_1}{B_1}} \sqrt{\frac{(b-1)}{(b+1)}} + \\ \frac{\cos\Theta}{\sqrt{C}} \left(\tan^{-1} \frac{a_1 b - (b^2 - 1)\sin\Theta}{\sqrt{b^2 - 1}\sqrt{C}} + \tan^{-1} \frac{(b^2 - 1)\sin\Theta}{\sqrt{b^2 - 1}\sqrt{C}} \right) - \\ \frac{a_1 \cos\Theta}{(b - a_1 \sin\Theta)} \tan^{-1} \sqrt{\frac{b-1}{b+1}} \end{array} \right) \qquad (5\text{-}18)$$

$$\pi F_{1\to 2,V} = \left(\begin{array}{l} \frac{a_2 \cos\Theta}{b - a\sin\Theta} \frac{a_2^2 + (b+1)^2 - 2b(1 + a_2 \sin\Theta)}{\sqrt{AB}} \tan^{-1} \sqrt{\frac{A_2}{B_2}} \sqrt{\frac{(b-1)}{(b+1)}} + \\ \frac{\cos\Theta}{\sqrt{C}} \left(\tan^{-1} \frac{a_2 b - (b^2 - 1)\sin\Theta}{\sqrt{b^2 - 1}\sqrt{C}} + \tan^{-1} \frac{(b^2 - 1)\sin\Theta}{\sqrt{b^2 - 1}\sqrt{C}} \right) - \\ \frac{a_2 \cos\Theta}{(b - a_2 \sin\Theta)} \tan^{-1} \sqrt{\frac{b-1}{b+1}} \end{array} \right) \qquad (5\text{-}19)$$

Where:

$$a_1 = \frac{2H_{f1}}{r} = \frac{2H_1}{r}$$

$$a_2 = \frac{2H_{f2}}{r} = \frac{2(H_f - H_{f1})}{r}$$

$$b = \frac{R}{r}$$

$$A_1 = a_1^2 + (b+1)^2 - 2a_1(b+1)\sin\Theta$$

$$A_2 = a_2^2 + (b+1)^2 - 2a_2(b+1)\sin\Theta$$

$$B_1 = a_1^2 + (b-1)^2 - 2a_1(b-1)\sin\Theta$$

$$B_2 = a_2^2 + (b-1)^2 - 2a_2(b-1)\sin\Theta$$

$$C = 1 + (b^2 - 1)\cos^2\Theta$$

And:

H_1 = H_{f1} = vertical distance of target from ground level (m)
H_f = the height of the tilted cylinder (flame) (m)
r = the cylinder (flame) radius (m)
R = distance from center of the pool fire to edge of the target (m)
= flame title or angle of deflection (radians)

The total configuration or view factor at a point is given by the sum of two configuration factors, as follows:

$$F_{1\rightarrow 2,V(wind)} = F_{1\rightarrow 2,V1} + F_{1\rightarrow 2,V2} \qquad (5\text{-}20)$$

In presence of wind, the expression for estimating flame height is expressed by the following correlation, based on the experimental data (Thomas, 1962):

$$H_f = 55D \left(\frac{\dot{m}''}{\rho_a \sqrt{gD}}\right)^{0.67} \left(u^*\right)^{-0.21} \qquad (5\text{-}21)$$

Where:

D = diameter of pool fire (m)
$\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)
$_a$ = ambient air density (kg/m^3)
g = gravitational acceleration (m/sec^2)
u* = nondimensional wind velocity

The nondimensional wind velocity is given by:

$$u^* = \frac{u_w}{\left(\frac{g\dot{m}''D}{\rho}\right)^{\frac{1}{3}}} \qquad (5\text{-}22)$$

Where:

u* = nondimensional wind velocity
u_w = wind speed or wind velocity (m/sec)
g = gravitational acceleration (m/sec^2)
$\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)
D = diameter of pool fire (m)
= density of ambient air (kg/m^3)

The correlation relating to angle of tilt or angle of deflection ( ), of the flame from the vertical are expressed by the following equations based on the American Gas Association (AGA) data:

$$\begin{aligned} \cos\theta &= \{1 \quad \text{for } u^* \leq 1 \\ \cos\theta &= \left\{\frac{1}{\sqrt{u^*}} \quad \text{for } u^* \geq 1\right. \end{aligned} \qquad (5\text{-}23)$$

Where:

= angle of tilt or angle of deflection (radians)
u* = nondimensional wind velocity

5.4 Method of Estimating Thermal Radiation from Hydrocarbon Fireball

For industrial processes, many substances that are gases at ambient conditions are stored in container or vessel under pressure in a saturated liquid/vapor form. A rupture of a such vessel will result in a violent incident as the liquid expands into its gaseous form. This phase change forms blast waves with energy equivalent to the change in internal energy of the liquid/vapor; this phenomenon is called the BLEVE. BLEVE is an acronym of Boiling Liquid, Expanding Vapor Explosion. National Fire Protection Association (NFPA), defined a BLEVE as the failure of a major container into two or more pieces, occurring at a moment when the contained liquid is at temperature above its boiling point at normal atmospheric pressure. Typically, a BLEVE occurs in a metal container that has been overheated above 538 °C (1,000 °F) (Nolan 1996). The metal may not be able to withstand the internal stress and therefore failure occurs. The contained liquid space of the vessel normally acts as a heat absorber, so the wetted portion of the container is usually not at risk, only the surfaces of the internal vapor space. Most BLEVEs occur when containers are less than ½ to ⅓ full of liquid.

A container can fail for a number of reasons. It can be damaged by impact from an object, thus causing a crack to develop and grow, either as a result of internal pressure, vessel material brittleness, or both. Thus, the container may rupture completely after impact. Weakening the container's metal beyond the point at which it can withstand internal pressure can also cause large cracks, or even cause the container to separate into two or more pieces. Weakening can result from corrosion, internal overheating, or manufacturing defects, etc.

5.4.1 Radiation Due to BLEVEs with Accompanying Fireball

In additional to the container becoming a projectile, the hazard posed by a BLEVE is the fireball and the resulting radiation. The rapid failure of the container is followed by a fireball or major fire, which produces a powerful radiant heat flux.

Four parameters often used to determine a fireball's thermal radiation hazard are the mass of fuel involved and the fireball's diameter, duration, and thermal emissive power. Radiation hazards can then be calculated from empirical relation.

Radiation received by an object relatively distant from the fireball can be calculated by the following expression (Hasegawa and Sato, 1977 and Roberts, 1982):

$$\dot{q}_r'' = \frac{828\ m_F^{0.771}}{R^2} \qquad (5\text{-}24)$$

Where:

$\dot{q}_r''$ = thermal radiation from fireball (kW/m^2)
m_F = mass of fuel vapor (kg)
R = distance from the center of the fireball to the target (m)

The distance from the center of the fireball to the target is given by the following relation:

$$R = \sqrt{Z_p^2 + L^2} \qquad (5\text{-}25)$$

Where:

R = distance from the center of the fireball to the target (m)
Z_p = fireball flame height (m)
L = distance at ground level from the origin (m)

The fireball flame height is given by the following expression (Fay and Lewis 1976):

$$Z_p = 12.73 \ (V_F)^{\frac{1}{3}} \qquad (5\text{-}26)$$

Where:

Z_p = fireball flame height (m)
V_F = volume of fuel vapor (m^3)

The volume of fireball can be calculated from the following relation:

$$V_F = \frac{m_F}{\rho_F} \qquad (5\text{-}27)$$

Where:

V_F = volume of fuel vapor (m^3)
m_F = mass of fuel vapor (kg)
$_F$ = fuel vapor density (kg/m^3)

5.5 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations.

The following assumption applies to **all** radiation models:

(1) The pool is circular or nearly circular.

The following assumptions and limitations apply to point source radiation models:

(1) Except near the base of pool fires, radiation to the surroundings can be approximated as being isotropic or emanating from a point source.

(2) The point source model overestimates the intensity of thermal radiation at the observer's (target) locations close to the fire. This is primarily because the near-field radiation is greatly influenced by the flame size, shape, and tilt, as well as the relative orientation of the observer (target).

(3) A theoretical analysis of radiation from small pool fire by Modak (1977) indicated that the point source model is within 5-percent the correct incident heat flux when L/D >2.5.

(4) The energy radiated from the flame is a specified fraction of the energy released during combustion.

(5) The model can be used to determine thermal radiation hazards in scenarios for which a conservative estimate of the hazard is generally acceptable.

The following limitation applies to solid flame radiation models at and above ground level:

(1) The correlation of emissive power was developed on the basis of data from experiments that included kerosene, fuel oil, gasoline, JP-4, JP-5[4], and liquified natural gas (LNG). With the exception of the LNG, these are quite luminous flames, so the correlation should be suitable for most fuels. The pool diameters ranged from 1 to 50 m.

5.6 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) fuel type (material)
(2) fuel spill area or curbed area (ft^2)
(3) distance between fire and target (ft)
(4) vertical distance of target from ground level (ft)
(5) wind speed (ft/min)

5.7 Cautions

(1) Use the appropriate spreadsheet (05.1_Heat_Flux_Calculations_Wind_Free.xls or 05.2_Heat_Flux_Calculations_Wind) on the CD-ROM for the calculation.

(2) Make sure units are correct on input parameters.

---

[4] Common jet fuel.

5.8 Summary

Estimating the thermal radiation field surrounding a fire involves the following steps:

(1) Characterize the geometry of the pool fire; that is, determine its HRR and physical dimensions. In calculating thermal radiation, the size of the fire implies the time-averaged size of the visible envelope.

(2) Characterize the radiative properties of the fire; that is, determine the average irradiance of the flames (emissive power).

(3) Calculate the radiant intensity at a given location. This can be accomplished after determining the geometry of the fire; its radiation characteristics; and the location, geometry, and orientation of the target.Determine the HRR from Equation 5-2 or from experimental data available in the literature.

(4) Determine the height of the pool fire.

(5) Calculate the view or configuration factor.

(6) Determine the effective emissive power of the flame.

(7) Calculate the radiative heat flux to the target.

5.9 References

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5.10 Additional Readings

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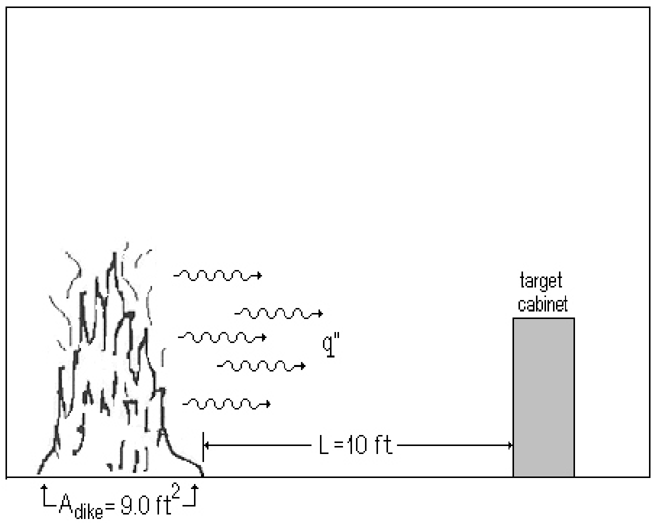
5.11 Problems

Example Problem 5.11-1

Problem Statement

A pool fire scenario arises from a breach (leak or rupture) in a transformer. This event allows the fuel contents of the transformer to spill and spread over the compartment floor. The compartment is very large and has a high ceiling (e.g., typical reactor building elevation of a BWR, turbine building open area). A pool fire ensues with a spill area of 9.0 ft^2 on the concrete floor. Calculate the flame radiant heat flux to a target (cabinet) at ground level with no wind using: a) point source radiation model and b) solid flame radiation model. The distance between the fire source and the target edge is assumed to be 10 ft.



Example Problem 5-1: Radiant Heat Flux from a Pool Fire to a Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the pool fire to the target cabinet using the point source and solid flame radiation models.

Assumptions:

(1) The pool is circular or nearly circular.

(2) Radiation to the surroundings can be approximated as being isotropic or emanating from a point source (valid for point source radiation model only).

(3) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_ Heat_Flux_Calculations_Wind_Free.xls

(click on *Point Source* and *Solid Flame 1* for point source and solid flame analysis respectively).

FDT^s Input Parameters: (For both spreadsheets)
-Fuel Spill Area or Curb Area (A_{curb}) = 9.0 ft^2
-Distance between Fire Source and Target (L) = 10 ft
-Select Fuel Type: **Transformer Oil, Hydrocarbon**

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)
Point Source	1.45 (0.13)
Solid Flame	3.05 (0.27)

* see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 05.1_ Heat_Flux_Calculations_Wind_Free.xls (Point Source)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION POINT SOURCE RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel (m")		0.039	kg/m²-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	46000	kJ/kg	
Empirical Constant (kβ)		0.7	m⁻¹	
Heat Release Rate (Q)		771.52	kW	
Fuel Area or Dike Area (A_{dike})		9.00	ft²	0.84 m²
Distance between Fire and Target (L)		10.00	ft	3.048 m
Radiative Fraction (χ_r)		0.30		

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? ______ kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m²-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m⁻¹)
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type: Transformer Oil, Hydrocarbon

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-272.*

POINT SOURCE RADIATION MODEL

$q'' = Q\,\chi_r / 4\pi R^2$

Where
- q'' = incident radiative heat flux on the target (kW/m²)
- Q = pool fire heat release rate (kW)
- χ_r = radiative fraction
- R = distance from center of the pool fire to edge of the target (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where
- A_{dike} = surface area of pool fire (m²)
- D = pool fire diamter (m)

D = 1.03 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D})\,A_f$

Where
- Q = pool fire heat release rate (kW)
- m'' = mass burning rate of fuel per unit surface area (kg/m²-sec)
- ΔH_c = effective heat of combustion of fuel (kJ/kg)
- A_f = surface area of pool fire (area involved in vaporization) (m²)
- $k\beta$ = empirical constant (m⁻¹)
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 771.52 kW

Distance from Center of the Fire to Edge of the Target Calculation

$R = L + D/2$

Where
- R = distance from center of the pool fire to edge of the target (m)
- L = distance between pool fire and target (m)
- D = pool fire diameter (m)

R = 3.56 m

Radiative Heat Flux Calculation

$q'' = Q\,\chi_r / 4\pi R^2$

q'' =	1.45 kW/m²	0.13 Btu/ft²-sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel (m")		0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	46000	kJ/kg	
Empirical Constant (kβ)		0.7	m^{-1}	
Heat Release Rate (Q)		771.52	kW	
Fuel Area or Dike Area (A_{dike})		9.00	ft^2	0.84 m^2
Distance between Fire and Target (L)		10.00	ft	3.048 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

Transformer Oil, Hydrocarbon

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276*.

SOLID FLAME RADIATION MODEL

$q" = EF_{1\rightarrow 2}$

Where: $q"$ = incident radiative heat flux on the target (kW/m^2)
E = emissive power of the pool fire flame (kW/m^2)
$F_{1\rightarrow 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where: A_{dike} = surface area of pool fire (m^2)
D = pool fire diameter (m)

$D =$ 1.03 m

Emissive Power Calculation

$E = 58\,(10^{-0.00823\,D})$

Where: E = emissive power of the pool fire flame (kW/m^2)
D = diameter of the pool fire (m)

$E =$ 56.88 kW/m^2

View Factor Calculation

$F_{1\rightarrow 2,H} = (B-1/S)/\pi(B^2-1)^{1/2}\tan^{-1}((B+1)(S-1)/(B-1)(S+1))^{1/2} - (A-1/S)/(\pi(A^2-1)^{1/2})\tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$

$F_{1\rightarrow 2,V} = 1/(\pi S)\tan^{-1}(h/(S^2-1)^{1/2}) - (h/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + Ah/\pi S(A^2-1)^{1/2}\tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$

$A = (h^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h = 2H_f/D$

$F_{1\rightarrow 2,max} = \sqrt{(F^2_{1\rightarrow 2,H} + F^2_{1\rightarrow 2,V})}$

Where: $F_{1\rightarrow 2,H}$ = horizontal view factor
$F_{1\rightarrow 2,V}$ = vertical view factor
$F_{1\rightarrow 2,max}$ = maximum view factor
R = distance from center of the pool fire to edge of the target (m)
H_f = height of the pool fire flame (m)
D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where: R = distance from center of the pool fire to edge of the target (m)
L = distance between pool fire and target (m)
D = pool fire diameter (m)

$R = L + D/2 =$ 3.564 m

Heat Release Rate Calculation

$Q = m"\Delta H_{c,eff}\,(1 - e^{-k\beta D})\,A_{dike}$

Where: Q = pool fire heat release rate (kW)
$m"$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
ΔH_c = effective heat of combustion of fuel (kJ/kg)
A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
$k\beta$ = empirical constant (m^{-1})
D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

$Q =$ 771.52 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\,Q^{2/5} - 1.02\,D$

Where: H_f = flame height (m)
Q = heat release rate of fire (kW)
D = fire diameter (m)

$H_f =$ 2.305 m

$S = 2R/D =$ 6.908

$h = 2H_f/D =$ 4.468

$A = (h^2+S^2+1)/2S =$ 4.971

$B = (1+S^2)/2S =$ 3.526

Radiative Heat Flux Calculation

$q'' = EF_{1\rightarrow 2}$

q'' =	3.05	kW/m^2	0.27	Btu/ft^2-sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

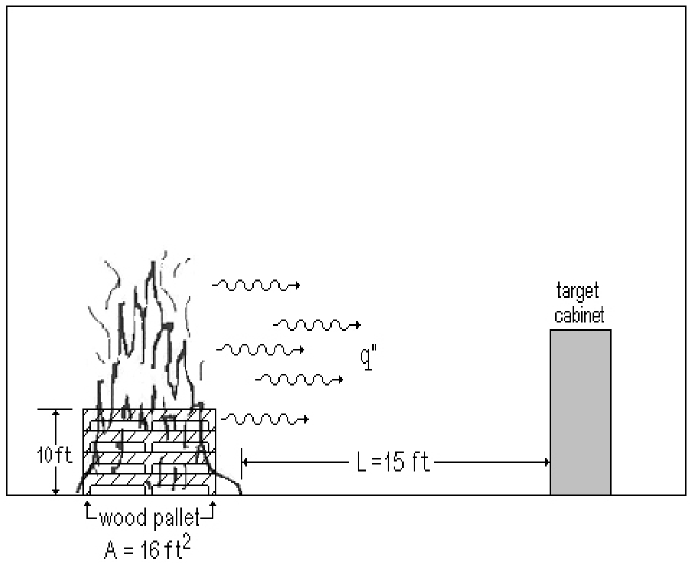
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 5.11-2

Problem Statement

A transient combustible fire scenario may arise from burning wood pallets (4 ft x 4 ft = 16 ft^2), stacked 10 ft high on the floor of a compartment with a very high ceiling. Calculate the flame radiant heat flux to a target (safety-related cabinet) at ground level with no wind, using the point source radiation model and the solid flame radiation model. The distance between the fire source and the target edge (L) is assumed to be 15 ft.



Example Problem 5-2: Radiant Heat Flux from a Burning Pallet to a Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the fire source to the target cabinet using the point source and solid flame radiation models.

Assumptions:

(1) The fire source will be nearly circular.

(2) Radiation to the surroundings can be approximated as being isotropic or emanating from a point source (valid for point source radiation model only).

(3) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls

(click on *Point Source* and *Solid Flame 1* for point source and solid flame analysis respectively)

FDT^s Inputs: (For both spreadsheets)

-Fuel Spill Area or Curb Area (A_{curb}) = 16 ft^2

-Distance between Fire Source and Target (L) = 15 ft

-Select Fuel Type: **Douglas Fir Plywood**

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)
Point Source	0.15 (0.01)
Solid Flame	0.45 (0.04)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Point Source)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION POINT SOURCE RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel (m")		0.01082	kg/m²-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	10900	kJ/kg	
Empirical Constant (kβ)		100	m⁻¹	
Heat Release Rate (Q)		175.31	kW	
Fuel Area or Dike Area (A_{dike})		16.00	ft²	1.49 m²
Distance between Fire and Target (L)		15.00	ft	4.572 m
Radiative Fraction (χ_r)		0.30		

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? ______ kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m²-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m⁻¹)
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

Douglas Fir Plywood

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-272*.

POINT SOURCE RADIATION MODEL

$q'' = Q \chi_r / 4 \pi R^2$

Where q'' = incident radiative heat flux on the target (kW/m^2)
Q = pool fire heat release rate (kW)
χ_r = radiative fraction
R = distance from center of the pool fire to edge of the target (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)
D = pool fire diamter (m)

D = 1.38 m

Heat Release Rate Calculation

$Q = m'' \Delta H_{c,eff} (1 - e^{-k\beta D}) A_f$

Where Q = pool fire heat release rate (kW)
m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
ΔH_c = effective heat of combustion of fuel (kJ/kg)
A_f = surface area of pool fire (area involved in vaporization) (m^2)
$k\beta$ = empirical constant (m^{-1})
D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 175.31 kW

Distance from Center of the Fire to Edge of the Target Calculation

$R = L + D/2$

Where R = distance from center of the pool fire to edge of the target (m)
L = distance between pool fire and target (m)
D = pool fire diameter (m)

R = 5.26 m

Radiative Heat Flux Calculation

$q'' = Q \chi_r / 4 \pi R^2$

q'' =	0.15	kW/m^2	0.01	Btu/ft^2-sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION
SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel (m")		0.01082	kg/m^2-sec		
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	10900	kJ/kg		
Empirical Constant (kβ)		100	m^{-1}		
Heat Release Rate (Q)		175.31	kW		
Fuel Area or Dike Area (A_{dike})		16.00	ft^2	1.49	m^2
Distance between Fire and Target (L)		15.00	ft	4.572	m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-26*.

Select Fuel Type

Douglas Fir Plywood

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276*.

SOLID FLAME RADIATION MODEL

$\dot{q}'' = E F_{1\rightarrow 2}$

Where	$\dot{q}''$ = incident radiative heat flux on the target (kW/m^2)
	E = emissive power of the pool fire flame (kW/m^2)
	$F_{1\rightarrow 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where	A_{dike} = surface area of pool fire (m^2)
	D = pool fire diameter (m)
D =	1.38 m

Emissive Power Calculation

E =	$58\,(10^{-0.00823\,D})$
Where	E = emissive power of the pool fire flame (kW/m^2)
	D = diameter of the pool fire (m)
E =	56.51 kW/m^2

View Factor Calculation

$F_{1\rightarrow 2,H}$ =	$(B-1/S)/\pi(B^2-1)^{1/2}\tan^{-1}((B+1)(S-1)/(B-1)(S+1))^{1/2} - (A-1/S)/(\pi(A^2-1)^{1/2})\tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$
$F_{1\rightarrow 2,V}$ =	$1/(\pi S)\tan^{-1}(h/(S^2-1)^{1/2}) - (h/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + Ah/\pi S(A^2-1)^{1/2}\tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$
A =	$(h^2+S^2+1)/2S$
B =	$(1+S^2)/2S$
S =	$2R/D$
h =	$2H_f/D$
$F_{1\rightarrow 2,max}$ =	$\sqrt{(F^2_{1\rightarrow 2,H} + F^2_{1\rightarrow 2,V})}$

Where	$F_{1\rightarrow 2,H}$ = horizontal view factor
	$F_{1\rightarrow 2,V}$ = vertical view factor
	$F_{1\rightarrow 2,max}$ = maximum view factor
	R = distance from center of the pool fire to edge of the target (m)
	H_f = height of the pool fire flame (m)
	D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where	R = distance from center of the pool fire to edge of the target (m)
	L = distance between pool fire and target (m)
	D = pool fire diameter (m)
R = L + D/2 =	5.260 m

Heat Release Rate Calculation

$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D})A_{dike}$

Where	Q = pool fire heat release rate (kW)
	$\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
	ΔH_c = effective heat of combustion of fuel (kJ/kg)
	A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
	$k\beta$ = empirical constant (m^{-1})
	D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)
Q =	175.31 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\,Q^{2/5} - 1.02\,D$

Where	H_f = flame height (m)
	Q = heat release rate of fire (kW)
	D = fire diameter (m)
H_f =	0.453 m

$S = 2R/D$ =	7.647
$h = 2H_f/D$ =	0.658
$A = (h^2+S^2+1)/2S$ =	3.917
$B = (1+S^2)/2S$ =	3.889

Radiative Heat Flux Calculation

$q'' = EF_{1\rightarrow 2}$

q" =	**0.45**	**kW/m^2**	**0.04**	**Btu/ft^2-sec**	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

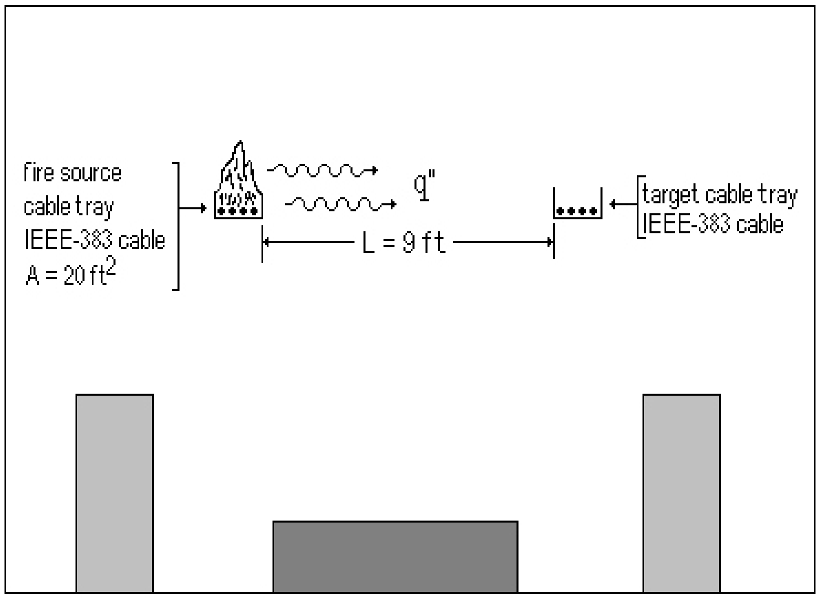
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

Example Problem 5.11-3

Problem Statement

A fire scenario may arise from a horizontal cable tray burning in a very large compartment. The cables in the tray are IEEE-383 unqualified and made of PE/PVC insulation material (assume that the exposed area of the cable is 20 ft^2). Another safety-related cable tray also filled with IEEE-383 unqualified made of PE/PVC insulation material is located at a radial distance (L) of 9 ft from the fire source. Calculate the flame radiant heat flux to a target (safety-related cable tray) using the point source radiation model and solid flame radiation model. Is this heat flux sufficient to ignite the cable tray?



Example Problem 5-3: Radiant Heat Flux from a Burning Cable Tray to a Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the burning cable tray to the target cable tray using the point source and solid flame radiation models.

(2) Determine if the heat flux is sufficient to ignite the cable tray.

Assumptions:

(1) The fire source will be nearly circular.

(2) Radiation to the surroundings can be approximated as being isotropic or emanating from a point source (point source radiation model only).

(3) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls

(click on *Point Source* and *Solid Flame 1* for point source and solid flame analysis, respectively).

FDT^s Inputs: (For both spreadsheets)

-Mass Burning Rate of Fuel $(\dot{m}'')$ = 0.0044 kg/m^2-sec

-Effective Heat of Combustion of Fuel ($H_{c,eff}$) = 25,100 kJ/kg

-Empirical Constant (kβ) = 100 m^{-1} (use this if actual value is unknown)

-Fuel Spill Area or Curb Area (A_{curb}) = 20 ft^2

-Distance between Fire Source and Target (L) = 9 ft

Note: Since the insulation material (PE/PVC) is not available in the thermal properties data of the spreadsheet, we have to input the mass burning rate and effective heat of combustion in the spreadsheet. Values of cable materials properties are available in Table 3-4. Select **User-Specified Value**, and enter the respective values.

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)
Point Source	0.4 (0.03)
Solid Flame	1.1 (0.10)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Point Source)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION POINT SOURCE RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel (m'')		0.0044	kg/m²-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	25100	kJ/kg	
Empirical Constant ($k\beta$)		100	m⁻¹	
Heat Release Rate ($\dot{Q}$)		205.20	kW	
Fuel Area or Dike Area (A_{dike})		20.00	ft²	1.86 m²
Distance between Fire and Target (L)		9.00	ft	2.7432 m
Radiative Fraction (χ_r)		0.30		

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m²-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m⁻¹)
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

User Specified Value

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-272*.

POINT SOURCE RADIATION MODEL

$q'' = Q \chi_r / 4 \pi R^2$

Where
- q'' = incident radiative heat flux on the target (kW/m^2)
- Q = pool fire heat release rate (kW)
- χ_r = radiative fraction
- R = distance from center of the pool fire to edge of the target (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where
- A_{dike} = surface area of pool fire (m^2)
- D = pool fire diamter (m)

D = 1.54 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_f$

Where
- Q = pool fire heat release rate (kW)
- m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ΔH_c = effective heat of combustion of fuel (kJ/kg)
- A_f = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 205.20 kW

Distance from Center of the Fire to Edge of the Target Calculation

$R = L+D/2$

Where
- R = distance from center of the pool fire to edge of the target (m)
- L = distance between pool fire and target (m)
- D = pool fire diameter (m)

R = 3.51 m

Radiative Heat Flux Calculation

$q'' = Q \chi_r / 4 \pi R^2$

q'' =	0.40 kW/m^2	0.03 Btu/ft^2-sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
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CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Parameter		Value	Unit	
Mass Burning Rate of Fuel (m")		0.0044	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	25100	kJ/kg	
Empirical Constant (kβ)		100	m^{-1}	
Heat Release Rate (Q)		1026.02	kW	
Fuel Area or Dike Area (A_{dike})		100.00	ft^2	9.29 m^2
Distance between Fire and Target (L)		9.00	ft	2.7432 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-26*.

Select Fuel Type
User Specified Value
Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276.*

SOLID FLAME RADIATION MODEL

$q" = EF_{1\to 2}$

Where	$q"$ = incident radiative heat flux on the target (kW/m^2)
	E = emissive power of the pool fire flame (kW/m^2)
	$F_{1\to 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where	A_{dike} = surface area of pool fire (m^2)
	D = pool fire diameter (m)
D =	3.44 m

Emissive Power Calculation

E =	$58\ (10^{-0.00823D})$
Where	E = emissive power of the pool fire flame (kW/m^2)
	D = diameter of the pool fire (m)
E =	54.34 kW/m^2

View Factor Calculation

$F_{1\to 2,H}$ =	$(B-1/S)/\pi(B^2-1)^{1/2}\tan^{-1}((B+1)(S-1)/(B-1)(S+1))^{1/2}-(A-1/S)/(\pi(A^2-1)^{1/2})\tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$
$F_{1\to 2,V}$ =	$1/(\pi S)\tan^{-1}(h/(S^2-1)^{1/2})-(h/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+Ah/\pi S(A^2-1)^{1/2}\tan^{-1}((A+1)(S-1)/(A-1)(S+1))^{1/2}$
A =	$(h^2+S^2+1)/2S$
B =	$(1+S^2)/2S$
S =	$2R/D$
h =	$2H_f/D$
$F_{1\to 2,max}$ =	$\sqrt{(F^2_{1\to 2,H} + F^2_{1\to 2,V})}$

Where	$F_{1\to 2,H}$ = horizontal view factor
	$F_{1\to 2,V}$ = vertical view factor
	$F_{1\to 2,max}$ = maximum view factor
	R = distance from center of the pool fire to edge of the target (m)
	H_f = height of the pool fire flame (m)
	D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where	R = distance from center of the pool fire to edge of the target (m)
	L = distance between pool fire and target (m)
	D = pool fire diameter (m)
$R = L + D/2$ =	4.463 m

Heat Release Rate Calculation

$Q = m"\Delta H_{c,eff}\ (1 - e^{-k\beta D})\ A_{dike}$

Where	Q = pool fire heat release rate (kW)
	$m"$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
	ΔH_c = effective heat of combustion of fuel (kJ/kg)
	A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
	$k\beta$ = empirical constant (m^{-1})
	D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)
Q =	1026.02 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\ Q^{2/5} - 1.02\ D$

Where	H_f = flame height (m)
	Q = heat release rate of fire (kW)
	D = fire diameter (m)
H_f =	0.255 m

$S = 2R/D$ =	2.595
$h = 2H_f/D$ =	0.148
$A = (h^2+S^2+1)/2S$ =	1.494
$B = (1+S^2)/2S$ =	1.490

Radiative Heat Flux Calculation

$q'' = EF_{1\rightarrow 2}$

q'' =	**1.14** kW/m^2	**0.10** Btu/ft^2-sec	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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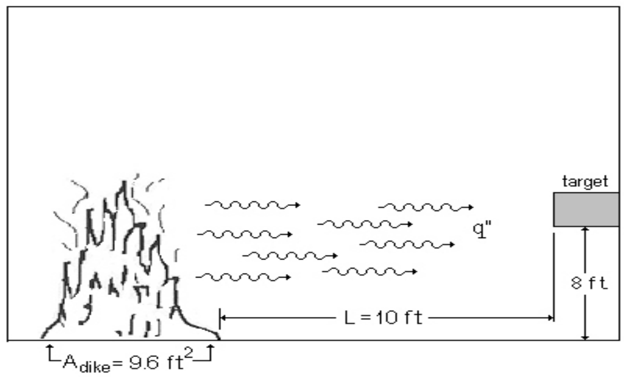
UNITED STATES NUCLEAR REGULATORY COMMISSION

Example Problem 5.11-4

Problem Statement

A pool fire scenario may arise from a leak in a pump. This event allows the lubricating oil to spill and spread over the compartment floor. A pool fire ensues with a spill of 9.6 ft^2 is considered in a compartment with a concrete floor. The distance (L) between the pool fire and the target edge is assumed to be 10 ft. Calculate the flame radiant heat flux to a vertical target (safety-related) 8 ft high above the floor with no wind, using the solid flame radiation model. If the vertical target contains IEEE-383 unqualified cables, could there be cable failure in this fire scenario?



Example Problem 5-4: Radiant Heat Flux from a Pool Fire to a Vertical Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the pool fire to the vertical target using the solid flame radiation model.

(2) Determine if the IEEE-383 unqualified cables are damaged.

Assumptions:

(1) The fire source will be nearly circular.

(2) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls (click on *Solid Flame* 2)

FDT^s Inputs:

-Fuel Spill Area or Curb Area (A_{curb}) = 9.6 ft^2

-Distance between Fire Source and Target (L) = 10 ft

-Vertical Distance of Target from Ground (H_1 = H_{f1}) = 8 ft

-Select Fuel Type: **Lube Oil**

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)	Cable Failure
Solid Flame	3.0 (0.26)	No $\dot{q}_r'' < \dot{q}_{critical}''$

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Solid Flame 2)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL ABOVE GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire above ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel (m'')		0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	46000	kJ/kg	
Empirical Constant ($k\beta$)		0.7	m^{-1}	
Heat Release Rate (Q)		841.15	kW	
Fuel Area or Dike Area (A_{dike})		9.60	m^2	0.89 m^2
Distance between Fire and Target (L)		10.00	ft	3.048 m
Vertical Distance of Target from Ground ($H_T - H_F$)		8.00	ft	2.4384 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? | | kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

Lube Oil

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276.*

SOLID FLAME RADIATION MODEL

$q" = EF_{1\rightarrow 2}$

Where
- $q"$ = incident radiative heat flux on the target (kW/m^2)
- E = emissive power of the pool fire flame (kW/m^2)
- $F_{1\rightarrow 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where
- A_{dike} = surface area of pool fire (m^2)
- D = pool fire diameter (m)

$D =$ 1.07 m

Emissive Power Calculation

$E = 58\ (10^{-0.00823\ D})$

Where
- E = emissive power of the pool fire flame (kW/m^2)
- D = diameter of the pool fire (m)

$E =$ 56.84 (kW/m^2)

View Factor Calculation

$F_{1\rightarrow 2,V1} = 1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2}) - (h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_1h_1/\pi S(A_1^2-1)^{1/2}\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$

$F_{1\rightarrow 2,V2} = 1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2}) - (h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_2h_2/\pi S(A_2^2-1)^{1/2}\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$

$A_1 = (h_1^2+S^2+1)/2S$

$A_2 = (h_2^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h_1 = 2H_{f1}/D$

$h_2 = 2H_{f2}/D$

$F_{1\rightarrow 2,V} = F_{1\rightarrow 2,V1} + F_{1\rightarrow 2,V2}$

Where
- $F_{1\rightarrow 2,V}$ = total vertical view factor
- R = distance from center of the pool fire to edge of the target (m)
- H_f = height of the pool fire flame (m)
- D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where
- R = distance from center of the pool fire to edge of the target (m)
- L = distance between pool fire and target (m)
- D = pool fire diameter (m)

$R = L+D/2 =$ 3.581 m

Heat Release Rate Calculation

$Q = m"\Delta H_{c,eff}\ (1 - e^{-k\beta D})\ A_{dike}$

Where
- Q = pool fire heat release rate (kW)
- $m"$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ΔH_c = effective heat of combustion of fuel (kJ/kg)
- A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

$Q =$ 841.15 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\ Q^{2/5} - 1.02\ D$

Where
- H_f = flame height (m)
- Q = heat release rate of fire (kW)
- D = fire diameter (m)

$H_f =$ 2.389 m

$S = 2R/D =$ 6.721

$h_1 = 2H_{f1}/D =$ 4.576

$h_2 = 2H_{f2}/D =$ $2(H_f - H_{f1})/D =$ -0.094

$A_1 = (h_1^2+S^2+1)/2S =$ 4.993

Radiative Heat Flux Calculation

$q'' = E F_{1\rightarrow 2}$

q" =	2.99	kW/m^2	0.26	Btu/ft^2-sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

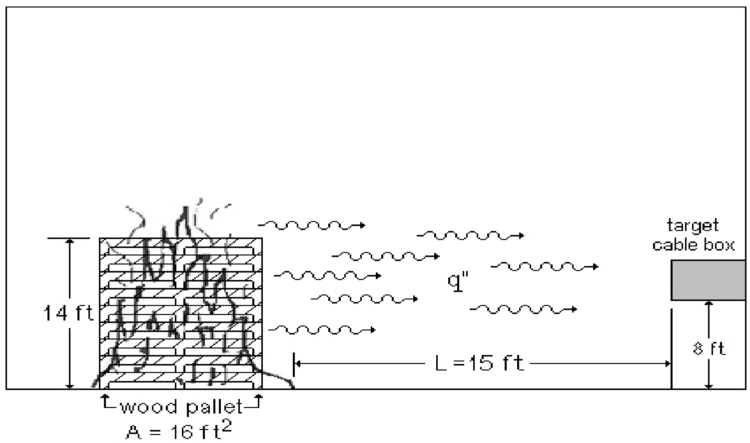
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 5.11-5

Problem Statement

A transient combustible fire scenario may arise from burning wood pallets (4 ft x 4 ft = 16 ft^2), stacked 14 ft high on the floor of a compartment. Calculate the flame radiant heat flux from exposure fire to a vertical target (safety-related electrical junction box) located 8 ft high above the floor, with no wind, using the solid flame radiation model. The distance (L) between the transient fire and the target edge is assumed to be 15 ft.



Example Problem 5-5: Radiant Heat Flux from a Burning Pallet to a Vertical Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the burning pallet to the vertical target fuel using the solid flame radiation model.

Assumptions:

(1) The fire source will be nearly circular.

(2) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls (click on *Solid Flame 2*)

FDT^s Inputs:

-Fuel Spill Area or Curb Area (A_{curb}) = 16 ft^2

-Distance between Fire Source and Target (L) = 15 ft

-Vertical Distance of Target from Ground (H_1 = H_{f1}) = 8 ft

-Select Fuel Type: **Douglas Fir Plywood**

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)
Solid Flame	0.30 (0.03)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Solid Flame 2)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL ABOVE GROUND LEVEL UNDER WIND-FREE CONDITION SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire above ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel ($\dot{m}''$)		0.01082	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	10900	kJ/kg	
Empirical Constant ($k\beta$)		100	m^{-1}	
Heat Release Rate ($\dot{Q}$)		175.31	kW	
Fuel Area or Dike Area (A_{dike})		16.00	ft^2	1.49 m^2
Distance between Fire and Target (L)		15.00	ft	4.572 m
Vertical Distance of Target from Ground ($H_t = H_f$)		8.00	ft	2.4384 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate $\dot{m}''$ (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

Douglas Fir Plywood

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276*.

SOLID FLAME RADIATION MODEL

$q'' = EF_{1\to2}$

Where q'' = incident radiative heat flux on the target (kW/m^2)

E = emissive power of the pool fire flame (kW/m^2)

$F_{1\to2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diamter (m)

D = 1.38 m

Emissive Power Calculation

$E = 58\ (10^{-0.00823\ D})$

Where E = emissive power of the pool fire flame (kW/m^2)

D = diameter of the pool fire (m)

E = 56.51 (kW/m^2)

View Factor Calculation

$F_{1\to2,V1} = 1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2}) - (h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_1 h_1/\pi S(A_1^2-1)^{1/2}\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$

$F_{1\to2,V2} = 1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2}) - (h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_2 h_2/\pi S(A_2^2-1)^{1/2}\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$

$A_1 = (h_1^2+S^2+1)/2S$

$A_2 = (h_2^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h_1 = 2H_1/D$

$h_2 = 2H_2/D$

$F_{1\to2,V} = F_{1\to2,V1} + F_{1\to2,V2}$

Where $F_{1\to2,V}$ = total vertical view factor

R = distance from center of the pool fire to edge of the target (m)

H = height of the pool fire flame (m)

D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where R = distance from center of the pool fire to edge of the target (m)

L = distance between pool fire and target (m)

D = pool fire diameter (m)

R = L+D/2 = 5.260 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D})A_{dike}$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

ΔH_c = effective heat of combustion of fuel (kJ/kg)

A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 175.31 kW

Pool Fire Flame Height Calculation

$H = 0.235\ Q^{2/5} - 1.02\ D$

Where H = flame height (m)

Q = heat release rate of fire (kW)

D = fire diameter (m)

H = 0.453 m

$S = 2R/D =$ 7.647

$h_1 = 2H_1/D =$ 3.545

$h_2 = 2H_2/D =$ $2(H-H_1)/D =$ -2.887

$A_1 = (h_1^2+S^2+1)/2S =$ 4.710

Radiative Heat Flux Calculation

$q" = EF_{1\rightarrow 2}$

q" =	0.30	kW/m^2	0.03	Btu/ft^2-sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

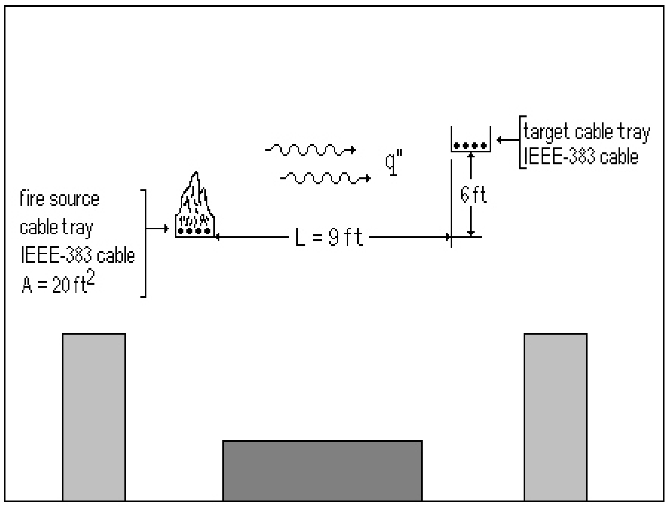
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 5.11-6

Problem Statement

A fire scenario may arise from a horizontal cable tray burning in a very large compartment. The cables in the tray are IEEE-383 unqualified and made of XPE/FRXPE insulation material (assume that the exposed area of the cable is 20 ft^2). A safety-related cable tray is also filled with IEEE-383 qualified made of XLPE insulation material located at a radial distance (L) of 9 ft from the fire source and 6 ft above the fire source. Calculate the flame radiant heat flux to a target (safety-related cable tray) using the solid flame radiation model. Is the IEEE-383 qualified cable tray damaged?



Example Problem 5-6: Radiant Heat Flux from a Burning Cable Tray to a Vertical Target Fuel

Solution

Purpose:

(1) Calculate the radiant heat flux from the burning cable tray to the vertical target cable tray using the solid flame radiation model.

(2) Determine if the IEEE-383 cable tray (target) is damaged.

Assumptions:

(1) The fire source will be nearly circular.

(2) The correlation for solid flame radiation model is suitable for most fuels.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 05.1_Heat_Flux_Calculations_Wind_Free.xls (click on *Solid Flame 2*)

FDT^s Inputs:

-Mass Burning Rate of Fuel $(\dot{m}'')$ = 0.0037 kg/m^2-sec

-Effective Heat of Combustion of Fuel ($H_{c,eff}$) = 28,300 kJ/kg

-Fuel Spill Area or Curb Area (A_{curb}) = 20 ft^2

-Distance between Fire Source and Target (L) = 9 ft

-Vertical Distance of Target from Ground (H_1 = H_{f1}) = 6 ft

Note: Since the insulation material (XPE/FRXPE) is not available in the thermal properties data of the spreadsheet, we have to input the mass burning rate and effective heat of combustion in the spreadsheet. Values of cable materials properties are available in Table 3-4. Select **User-Specified Value**, and enter the $\dot{m}''$ and $H_{c,eff}$ values from Table 3-4.

Results*

Radiation Model	Radiant Heat Flux $\dot{q}''$ kW (Btu/ft^2-sec)	Cable Failure
Solid Flame	0.60 (0.05)	No, $\dot{q}''_r < \dot{q}''_{critical}$

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Solid Flame 2)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL ABOVE GROUND LEVEL UNDER WIND-FREE CONDITION
SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire above ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel (m'')		0.0037	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	FALSE	28300	kJ/kg	
Empirical Constant ($k\beta$)		20	m^{-1}	
Heat Release Rate (Q)		194.56	kW	
Fuel Area or Dike Area (A_{dike})		20.00	ft^2	1.86 m^2
Distance between Fire and Target (L)		9.00	ft	2.7432 m
Vertical Distance of Target from Ground ($H_1 = H_f$)		6.00	ft	1.8288 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-26.*

Select Fuel Type

User Specified Value

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276.*

SOLID FLAME RADIATION MODEL

$q'' = E F_{1\rightarrow 2}$

Where q'' = incident radiative heat flux on the target (kW/m^2)

E = emissive power of the pool fire flame (kW/m^2)

$F_{1\rightarrow 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diameter (m)

D = 1.54 m

Emissive Power Calculation

$E = 58\ (10^{-0.00823\ D})$

Where E = emissive power of the pool fire flame (kW/m^2)

D = diameter of the pool fire (m)

E = 56.33 (kW/m^2)

View Factor Calculation

$F_{1\rightarrow 2,V1} = 1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2}) - (h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_1 h_1/\pi S(A_1^2-1)^{1/2}\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$

$F_{1\rightarrow 2,V2} = 1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2}) - (h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2} + A_2 h_2/\pi S(A_2^2-1)^{1/2}\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$

$A_1 = (h_1^2+S^2+1)/2S$

$A_2 = (h_2^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h_1 = 2H_{f1}/D$

$h_2 = 2H_{f2}/D$

$F_{1\rightarrow 2,V} = F_{1\rightarrow 2,V1} + F_{1\rightarrow 2,V2}$

Where $F_{1\rightarrow 2,V}$ = total vertical view factor

R = distance from center of the pool fire to edge of the target (m)

H_f = height of the pool fire flame (m)

D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where R = distance from center of the pool fire to edge of the target (m)

L = distance between pool fire and target (m)

D = pool fire diameter (m)

$R = L+D/2$ = 3.512 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}\ (1 - e^{-k\beta D})\ A_{dike}$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

ΔH_c = effective heat of combustion of fuel (kJ/kg)

A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 194.56 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\ Q^{2/5} - 1.02\ D$

Where H_f = flame height (m)

Q = heat release rate of fire (kW)

D = fire diameter (m)

H_f = 0.366 m

$S = 2R/D$ = 4.567

$h_1 = 2H_{f1}/D$ = 2.378

$h_2 = 2H_{f2}/D$ = $2(H_f-H_{f1})/D$ = -1.902

$A_1 = (h_1^2+S^2+1)/2S$ = 3.012

Radiative Heat Flux Calculation

$q'' = EF_{1\rightarrow 2}$

q" =	0.57	kW/m^2	0.05	Btu/ft^2-sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

CHAPTER 6. ESTIMATING THE IGNITION TIME OF A TARGET FUEL EXPOSED TO A CONSTANT RADIATIVE HEAT FLUX

6.1 Objectives

This chapter has the following objectives:

- Explain the importance of the location of the ignition source.
- Explain the importance of the position, spacing, and orientation of the fuel(s).
- Describe ignition parameters.
- Discuss how to calculate ignition time.
- Define relevant terms, including ignition temperature, flash point, piloted ignition, and non-piloted ignition.

6.2 Introduction

When performing a fire hazard analysis (FHA), it is essential to understand ignition of materials since the ignition of a combustible material is typically the first step in any fire scenario. Moreover, once a fire starts, the ignition delay times of other materials, coupled with flame spread, will affect the rate at which the fire spreads and develops. Thus, secondary ignition of other materials is another important step in fire development.

Theories regarding ignition and flame spread on solids are based on the concept of a critical surface temperature called the ignition temperature, T_{ig}. This critical surface temperature is related to the flash point (the lowest temperature at which a flammable vapor/air mixture exists at the surface) in the ignition of liquids for the case of piloted ignition, or the auto-ignition temperature if no pilot is present. The flash point phenomenon can be observed with solids under conditions of surface heating, but cannot be defined in terms of a bulk temperature. Because solid fuel must decompose to create fuel vapors (rather than simply evaporating), there is not a unique flash point temperature for a solid fuel. Both piloted and automatic ignition occur in an identical fashion for the evaporated or decomposed fuel gases of liquid and solid fuels, respectively, as illustrated in Figure 6-1.

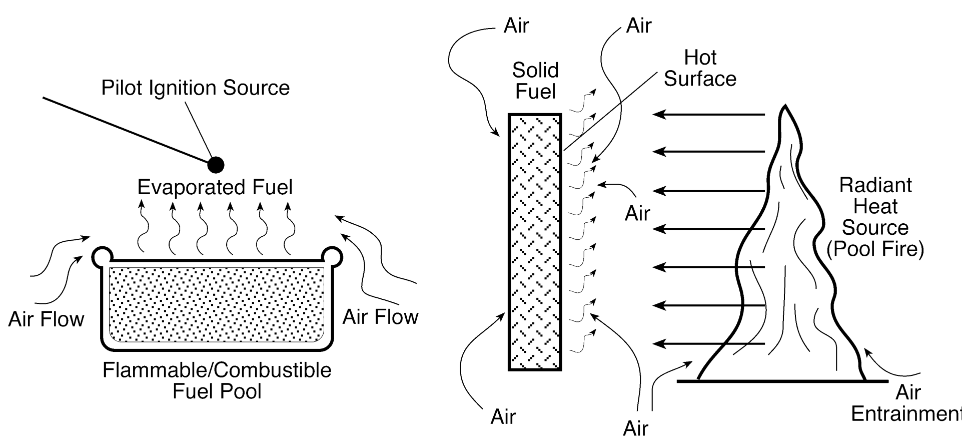


Figure 6-1 Ignition Processes for Liquid and Solid Fuels

For ignition to occur, the solid fuel must be heated sufficiently to vaporize and form a flammable pre-mixed system (see Figure 6-2). An ignition source, such as a spark or small flame must also be present, for piloted ignition or the gas mixture must be heated sufficiently to cause auto-ignition. The critical surface temperature at which these ignitions occur is called the ignition temperature, T_{ig}. Piloted ignition requires a much lower temperature than automatic (or spontaneous) ignition. For example, wood has a typical piloted ignition temperature of 350 °C (662 °F) and 600 °C (1,112 °F) for auto-ignition. Ignition temperature can be considered to be a property of the solid, but it is not truly constant and can vary with the rate of heating.

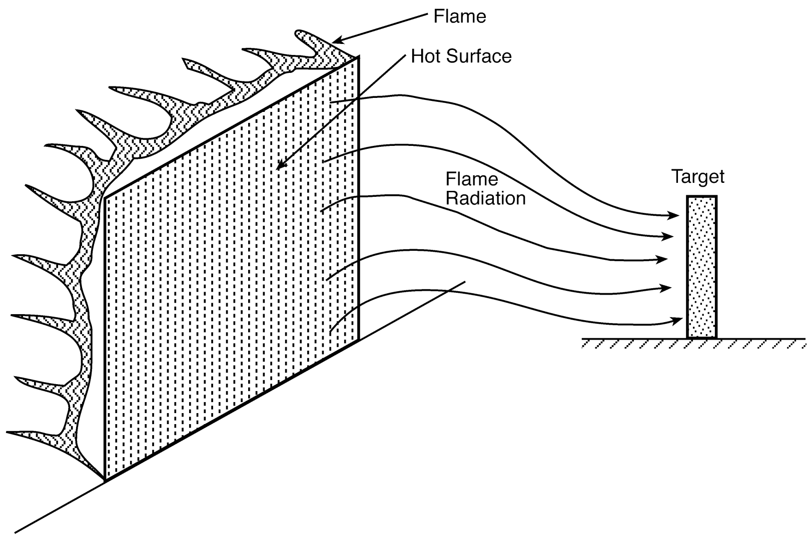


Figure 6-2 External Radiation to a Solid Target Object
from a Flame or Hot Surface at Elevated Temperature

Heating of solids to ignition can be accomplished by radiation from flames or hot gases, by flame contact, or by contact with hot gases. In any of these cases, the measure of the severity of the heating sources is the heat flux, usually measured in kW/m^2 (Btu/ft^2-sec). Table 6-1 lists typical heat fluxes from various sources, which clearly show the significance of radiation in fires.

Table 6-1. Typical Heat Fluxes from Various Sources

Source	**Heat Flux (kW/m^2)**	**Comment**
Flame radiation	0–200	Depends on size of flame and distance from the flame
Flame convection	10–20	Direct flame contact
Hot gas convection	0–10	Direct gas contact
Hot gas radiation	1–150	Depends on gas temperature, soot concentration, and distance from hot gases

6.3 Ignition Sources and Fire Development

An ignition source can consist of a spark with a low energy content, a heated surface, or a large pilot flame. The source of energy can be chemical, electrical, or mechanical. The greater the energy of the ignition source, the faster the fire will subsequently grow on the fuel source surface. A spark or a glowing cigarette may initiate smoldering combustion, which may continue to smolder for a long time before flaming combustion begins. The smoldering often producing low heat but considerable amounts of toxic gases. A pilot flame usually produces flaming combustion and results in quicker flame spread and fire growth.

The location of the ignition source is also very important. For example, a pilot flame positioned at the lower end of a window curtain may cause rapid upward flame spread and fire growth. By contrast, the same pilot flame placed at the top of the curtain would cause much slower fire growth with a slow, downward flame spread.

The position of the fuel can also have a marked effect on fire development. If the fuel is burning away from walls, the cool air is entrained into the plume from all directions. When the fuel is close to a wall, however, the entrainment of cold air is limited; this causes higher temperatures and higher flames since combustion must take place over a greater distance.

The spacing and orientation of the fuels are also important. The spacing in the compartment determines, to a considerable extent, how quickly the fire spreads between the fuel packages. Upward flame spread on a vertically oriented fuel surface will occur more rapidly than lateral spread along a horizontally oriented fuel surface. Similarly, a fuel package with a large surface area will burn more rapidly than an otherwise equivalent fuel package with a small surface area. A pile of wooden sticks, for example, will burn more rapidly than a single log of wood of the same mass.

6.4 Ignition Time for Thermally Thick Materials

Ignition time can be computed by calculating the time to achieve sufficient vaporization to result in a flammable mixture plus the time for the mixture to ignite. Except for cases of low ambient oxygen, the gas phase process is much faster than the heating time of a solid. Typical values of sufficient mass loss rates (burning rates) to enable ignition are on the order of 2 to 6 g/m^2. These values are associated with the initiation of pyrolysis (combustion). Hence, ignition time for a solid can be effectively computed by simple heat conduction theory. The surface of the solid must be heated to its ignition temperature, T_{ig}. Table 6-2 lists measured ignition times for typical thick solid fuels.

Table 6-2. Typical Ignition Times of Thick Solid Fuels (Quintiere, 1997)

Materials	**Heat Flux** $\dot{q}''_e$ **(kW/m^2)**	**Time to Ignition** t_{ig} **(sec)**
Plexiglas, Polyurethane foam, Acrylate carpet	10	300
Wool carpet	20	70
Paper of gypsum board	20	150
Wood particle board	20	250
Polyisocyanurate foam	30	5
Wool/nylon carpet	30	70
Hardboard	30	150

The steady-state surface temperature of a thermally thick fuel is independent of the material's physical properties. The rate of heating and the time required to reach steady-state are material dependent. At steady-state, the incident heat is entirely lost to the surrounding surface by convection and re-radiation, but the temperature of the fuel remains constant. The heat flux required to adjust the surface temperature to the ignition temperature, T_{ig}, is known as the critical heat flux (CHF). Ignition or flame spread is not possible below the threshold level of heating represented by the CHF.

6.4.1 Method of Tewarson

As a fuel surface is exposed to heat flux, most of the heat is transferred to the interior of the material. The ignition principle suggests that the rate with which heat is transferred depends on the ignition temperature (T_{ig}), ambient temperature, (T_a), material thermal conductivity (k), material specific heat (c), and the material density ( ). The combined effects are expressed by a parameter defined as the thermal response parameter (TRP), of the material as follows (Tewarson, 1995):

$$\mathrm{TRP} = \Delta T_{ig}\sqrt{k\rho c} \qquad (6\text{-}1)$$

Where:

TRP = thermal response parameter (kW-sec$^{1/2}$/m^2)
T_{ig} = (T_{ig} - T_a) = ignition temperature above ambient (K)
k = material thermal conductivity (kW/m-K)
c = material specific heat (kJ/kg-K)
= material density (kg/m^3)

TRP is a useful parameter for engineering calculations to assess resistance to ignition and flame spread. The important material variables in the above equation are k c. These variables combine to form a material's thermal inertia. (See Chapter 2, Section 2.6.1 for a more detailed discussion of thermal inertia.) For most materials, c does not vary significantly, and the thermal conductivity is largely a function of the material density. This means that density is the most important material property. Low-density materials are excellent thermal insulators because heat does not readily pass the material, the surface of the material actually heats more rapidly and, as a result, can be ignited more quickly. For thin materials, the weight or thickness plays an important role.

The ignition principle suggests that, for thermally thick materials, the inverse of the square root of ignition time is expected to be a linear function of the external heat flux away from the CHF value (Tewarson, 1995):

$$\sqrt{\frac{1}{t_{ig}}} = \frac{\left(\dot{q}_e'' - CHF\right)\sqrt{\frac{4}{\pi}}}{TRP} \qquad (6\text{-}2)$$

$$t_{ig} = \frac{\pi}{4}\left(\frac{TRP}{\dot{q}_e'' - CHF}\right)^2 \qquad (6\text{-}3)$$

Where:

t_{ig} = ignition time (sec)
$\dot{q}_e''$ = external heat flux (kW/m^2)
CHF = critical heat flux for ignition (kW/m^2)
TRP = thermal response parameter ($kW\text{-}sec^{1/2}/m^2$)

The above equation applies to the transient period (before steady-state). Most common materials behave as thermally thick materials and satisfy Equation 6-3. The CHF and TRP values for materials are derived from the ignition data measured in the Flammability Apparatus, a commercial instrument designed by the Factory Mutual Research Corporation (FMRC) for measuring bench-scale HRR based on the oxygen consumption calorimetry. The CHF and TRP values for various materials are listed in Table 6-3. The CHF are extrapolated from the experimental correlation when the time to ignition goes to infinity, thus making CHF dependent on the model used for correlating the data. The minimum heat flux for ignition should not be confused with the CHF for ignition. Jenssens (1991) defined minimum heat flux for ignition and CHF for ignition as follows:

- Minimum heat flux for ignition is the heat flux below which ignition under practical condition (in bench-scale test or real-scale test cannot occur).
- CHF for ignition is an estimate of minimum heat flux derived from a correlation of experimental data.

Table 6-3. Critical Heat Flux and Thermal Response Parameters of Selected Materials (Tewarson, 1995, © SFPE. With permission.)

Material	Critical Heat Flux (CHF) (kW/m^2)	Thermal Response Parameter (TRP) ($kW\text{-}sec^{1/2}/m^2$)
Electrical Cables: Power		
PVC/PVC	13–25	156–341
PE/PVC	15	221–244
PVC/PE	15	263
Silicone/PVC	19	212
Silicone/crosslinked polyolefine	25–30	435–457
EPR (ethylene-propylene rubber/EPR)	20–23	467–567
XLPE/XLPE	20–25	273–386
XLPE/EVA (ethyl-vinyl acetate)	12–22	442–503
XLPE/Neoprene	15	291
XLPO/XLPO	16–25	461–535
XLPO, PVF, (polyvinylidine fluoride)/XLPO	14–17	413–639
EPR/Chlorosulfonated PE	14–19	283–416
EPR, FR	14–28	289–448
Electrical Cables: Communications		
PVC/PVC	15	131
PE/PVC	20	183
XLPE/XLOP	20	461–535
Si/XLOP	20	457
EPR-FR	19	295
Chlorinated PE	12	217
ETFE/EVA	22	454
PVC/PVF	30	264
FEP/FEP	36	638–652
Synthetic Materials		
Polypropylene	15	193
Nylon	15	270
Polymethylmethacrylate (PMMA)	11	274
Polycarbonate	15	331
Polycarbonate panel	16	420
Natural Materials		
Wood (red oak)	10	134
Wood (Douglas fir)	10	138
Wood (Douglas fir/fire retardant, FR)	10	251
Corrugated paper (light)	10	152

For first order approximation of ignition of solids, this discussion is highly simplified and ignores several secondary aspects of the process. Nonetheless, the discussion shows that two properties of a thick solid fuel significantly affect its ignition behavior. The ignition temperature of the solid is clearly important and reflects the thermal stability of the material. Ignition temperature can be thought of as a chemical property. Materials that are thermally stable are difficult to ignite and exhibit higher ignition temperatures. The primary physical property of the material is its density. The surface of low density material heats more rapidly, causing more rapid ignition of the material. Table 6-4 summarizes typical ignition data for various materials.

Table 6-4. Ignition Temperature and Thermal Properties of Materials
(Quintiere, 1997)

Materials	**Ignition Temperature** T_{ig} (°C)	**Density** (kg/m^3)	**Thermal Conductivity** k (kW/m-K)	**Specific Heat** c (kJ/kg-K)	**Thermal Inertia** k c (kW/m^2-K)^2-sec
Polymethylmethacrylate (PMMA)	278	1200	0.00026	2.1	0.66
Polyurethane foam	280	20	0.000034	1.4	0.00095
Douglas fir particle board (1.23 cm)	382	650	0.00011	2.0	0.14
Plywood plain (1.23 cm)	390	540	0.00012	2.5	0.16
Polystyrene foam (5.08 cm)	630	20	0.000034	1.5	0.0010

To obtain ignition time, several correlations are available in the literature. Although each correlation uses the CHF and critical surface temperature criterion, each technique correlates the data differently resulting in method-specific values for pseudo material properties required in the analysis. Four more techniques are presented for calculating the time to ignition for thermally thick materials under constant radiative heat flux. These methods are based on the principles from SFPE Engineering Guide, “Piloted Ignition of Solid Materials Under Radiant Exposure.”

6.4.2 **Method of Mikkola and Wichman** (SFPE Engineering Guide, 2002)

The time to ignition can be calculated using following correlation:

$$t_{ig} = \frac{\pi}{4} \quad k\rho c \frac{\left(T_{ig} - T_a\right)^2}{\left(\dot{q}_r'' - \dot{q}_{crit}''\right)^2} \qquad (6\text{-}4)$$

Where:

t_{ig} = ignition time (sec)
$k \;\; c$ = material thermal inertia $(kW/m^2\ K)^2$-sec
T_{ig} = ignition temperature (°C)
T_a = ambient air temperature (°C)
$\dot{q}_r''$ = external heat flux (kW/m^2)
$\dot{q}_{crit}''$ = critical heat flux for ignition (kW/m^2)

6.4.3 **Method of Quintiere and Harkleroad** (SFPE Engineering Guide, 2002)

The time to ignition can be calculated using following correlation:

$$t_{ig} = \left(\frac{\dot{q}_{min}''}{b \quad \dot{q}_r''} \right)^2 \qquad (6\text{-}5)$$

Where:

t_{ig} = ignition time (sec)
$\dot{q}_{min}''$ = minimum heat flux (kW/m^2)
$\dot{q}_r''$ = critical heat flux for ignition (kW/m^2)
b = flame spread parameter $(1/\sqrt{sec})$

6.4.4 **Method of Janssens** (SFPE Engineering Guide, 2002)

The time to ignition can be calculated using following correlation:

$$t_{ig} = 0.563 \left(\frac{k \rho c}{h_{ig}^2} \right) \left(\frac{\dot{q}_e''}{\dot{q}_{crit}''} - 1 \right)^{-1.83} \qquad (6\text{-}6)$$

Where:

t_{ig} = ignition time (sec)
k c = material thermal inertia $(kW/m^2\ K)^2$-sec
h_{ig} = heat transfer coefficient at ignition (kW/m^2-K)
$\dot{q}_e''$ = external heat flux (kW/m^2)
$\dot{q}_{crit}''$ = critical heat flux for ignition (kW/m^2)

The above three correlations used the material properties listed in Table 6-5.

Table 6-5. Ignition and Flame Spread Properties of Materials
(SFPE Engineering Guide, 2002. With permission.)

Materials	**Ignition Temperature** T_{ig} (°C)	**Thermal Inertia** k c (kW/m^2 K)^2-sec	**Minimum Heat Flux for Ignition** $\dot{q}''_{min}$ (kW/m^2)	**Flame Spread Parameter** b (1/ $\sqrt{sec}$)
PMMA Polycast (1.59mm)	278	0.73	9	0.04
Hardboard (6.35 mm)	298	1.87	10	0.03
Carpet (Arcylic)	300	0.42	10	0.06
Fiber Insulation Board	355	0.46	14	0.07
Hardboard (3.175mm)	365	0.88	14	0.05
PMMA Type G (1.27 cm)	378	1.02	15	0.05
Asphalt Shingle	378	0.7	15	0.06
Douglas Fir Particle Board (1.27 cm)	382	0.94	16	0.05
Plywood Plain (1.27 cm)	390	0.54	16	0.07
Plywood Plain (0.635 cm)	390	0.46	16	0.07
Foam Flexible (2.54 cm)	390	0.32	16	0.09
GRP (2.24 mm)	390	0.32	16	0.09
Hardboard (Gloss Paint) (3.4 mm)	400	1.22	17	0.05
Hardboard (Nitrocellulose Paint)	400	0.79	17	0.06
GRP (1.14 mm)	400	0.72	17	0.06
Particle Board (1.27 cm Stock)	412	0.93	18	0.05
Carpet (Nylon/Wool Blend)	412	0.68	18	0.06

Table 6-5. Ignition and Flame Spread Properties of Materials (continued)
(SFPE Engineering Guide, 2002. With permission.)

Materials	**Ignition Temperature** T_{ig} (°C)	**Thermal Inertia** $k\rho c$ $(kW/m^2 K)^2$-sec	**Minimum Heat Flux for Ignition** $\dot{q}''_{min}$ (kW/m^2)	**Flame Spread Parameter** b $(1/\sqrt{sec})$
Gypsum Board, Wallboard (S142M)	412	0.57	18	0.07
Carpet # 2 (Wool Untreated)	435	0.25	20	0.11
Foam, Rigid (2.54 cm)	435	0.03	20	0.32
Fiberglass Shingle	445	0.5	21	0.08
Polyisocyanurate (5.08 cm)	445	0.02	21	0.36
Carpet # 2 (Wool Treated)	455	0.24	22	0.12
Carpet # 1 (Wool, Stock)	465	0.11	23	0.18
Aircraft Panel Epoxy Fiberite	505	0.24	28	0.13
Gypsum Board FR (1.27 cm)	510	0.4	28	0.1
Polycarbonate (1.52 mm)	528	1.16	30	0.06
Gypsum Board (Common) (1.52 mm)	565	0.45	35	0.11
Plywood FR (1.27 cm)	620	0.76	44	0.1
Polystyrene (5.08 cm)	630	0.38	46	0.14

6.4.5 **Method of Toal, Silcock, and Shields** (SFPE Engineering Guide, 2002)

The time to ignition can be calculated using following correlation:

$$t_{ig} = \frac{FTP_n}{\left(\dot{q}_r'' - \dot{q}_{crit}''\right)^n} \qquad (6\text{-}7)$$

Where:

t_{ig} = ignition time (sec)
FTP = flux time product $(kW\text{-}sec/m^2)^n$
$\dot{q}_r''$ = exposure or external heat flux (kW/m^2)
$\dot{q}_{crit}''$ = critical heat flux for ignition (kW/m^2)
n = flux time product index ($n \geq 1$)

Equation 6-7 uses the material properties listed in Table 6-6.

Table 6-6. Ignition and Flame Spread Properties of Materials
(SFPE Engineering Guide, 2002. With permission.)

Materials	**Flux Time Product FTP $(kW\text{-}sec/m^2)^n$**	**Critical Heat Flux $\dot{q}_{crit}''$ (kW/m^2)**	**Flux Time Product Index n**
Chipboard	5,370	6.4	1.49
Chipboard (Horizontal) (15 mm)	9,921	9	1.7
Chipboard (Vertical) (15 mm)	11,071	10	1.7
Fiberboard	3,981	8.3	1.66
Hardboard	8,127	8.1	1.49
Hardboard (Painted Gloss)	9,332	8.1	1.51
Hardwood	2,818	8.1	1.5
Plywood	6,164	10.6	1.51
Plywood (Horizontal) (12 mm)	5,409	8.5	1.5
Plywood (Vertical) (12 mm)	42,025	10	2

Table 6-6. Ignition and Flame Spread Properties of Materials (continued)
(SFPE Engineering Guide, 2002. With permission.)

Materials	**Flux Time Product FTP $(kW\text{-}sec/m^2)^n$**	**Critical Heat Flux $\dot{q}''_{crit}$ (kW/m^2)**	**Flux Time Product Index n**
Plywood (Painted Gloss)	6,761	11.4	1.5
PMMA (Cast) (3mm)	3,100	5	1.25
PMMA (Extruded) (2 mm)	1,290	9	1
Polyethylene (2mm)	2,220	12.5	1
Polypropylene (3.3 mm)	8,110	6.5	1.5
PVC (Extruded Gray) (3 mm)	5,130	15	1.5
PVC (Pressed White) (3 mm)	95,000	8	2
Softwood	5,130	13.7	1.53
Softwood (Horizontal) (20 mm)	44,079	10	2.2
Softwood (Vertical) (20 mm)	16,502	12	1.9
Softwood Intumescent Paint	4,569	13	1.5

6.5 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations.

(1) For ignition to occur, a solid material must be heated sufficiently to vaporize and form a flammable mixture.

(2) Ignition occurs when the surface reaches a critical temperature defined as the ignition temperature.

(3) A heat source must be present to ignite the solid.

(4) The solid is assumed to be infinitely thick.

(5) The methods are all derived through the solid with radiant heating on the surface.

6.6 Required Input for Spreadsheet Calculations

(1) Target fuel type (material)

(2) Exposed radiative heat flux to target (kW/m^2)

6.7 Cautions

(1) Use (06_Ignition_Time_Calculations.xls) spreadsheet on the CD-ROM for calculations.

(2) Make sure to enter to use correct parameters in the correct units.

6.8 Summary

This chapter discusses ignition phenomena associated with thermally thick materials, as well as material properties that have major effects on ignition and flame spread. For thin materials, the weight or thickness of the material plays a very important role. For thick materials, the density of the material has a major impact on ignition and flame spread rates.

6.9 References

Quintiere, J.G., *Principles of Fire Behavior*, Delmar Publishers, Albany, New York, 1997.

SFPE Engineering Guide, "Piloted Ignition of Solid Materials Under Radiant Exposure," Society of Fire Protection Engineers, Bethesda, Maryland, January 2002.

Tewarson, A., "Generation of Heat and Chemical Compounds in Fires," Section 3, Chapter 4, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

6.10 Additional Readings

Fire Dynamics, Course Guide, Federal Emergency Management Agency (FEMA), United States Fire Administration (USFA), National Emergency Training Center, Emmitsburg, Maryland, 1995.

Janssens, M.L., "Fundamental Thermophysical Characteristics of Wood and their Role in Enclosure Fire Growth," Doctor of Philosophy Dissertation, University of Gent, Belgium, September 1991.

Karlsson, B., and J.G. Quintiere, *Enclosure Fire Dynamics*, Chapter 2, "A Qualitative Description of Enclosure Fires," CRC Press LLC, New York, pp. 11–24, 1999.

6.11 Problems

Example Problem 6.11-1

Problem Statement

Calculate the ignition time for a PVC/PE power cable, assuming that a 6.5-ft (2-m) diameter pool fire produces a 25-kW/m^2 heat flux.

Solution

Purpose:
(1) Calculate the ignition time for a PVC/PE power cable.

Assumptions:
(1) The material is infinitely thick.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 06_Ignition_Time_Calculations.xls (click on *Ignition_Time _Calculations3*)

FDT^s Input Parameters:
-Exposure or External Radiative Heat Flux to Target Fuel $(\dot{q}''_e)$ = 25 kW/m^2
-Click on the option button (⊙) for Electrical Cables - Power
-Select Material: PVC/PE

Results*

Material	**Ignition Time** (t_{ig}) (min.) Method of Tewarson
PVC/PE	9.0

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 06_Ignition_Time_Calculations.xls (Ignition_Time _Calculations3)

CHAPTER 6. ESTIMATING THE IGNITION TIME OF A TARGET FUEL EXPOSED TO A CONSTANT RADIATIVE HEAT FLUX

Version 1805.0

The following calculations estimate time to ignition for flame spread of solid fuels exposed to a constant external radiative heat flux.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

Exposure or External Radiative Heat Flux to Target Fuel ($\dot{q}''_e$)	25.00	kW/m²
Target Critical Heat Flux for Ignition (CHF)	15.00	kW/m²
Target Thermal Response Parameter (TRP)	263	kW-sec$^{1/2}$/m²
	Calculate	

CRITICAL HEAT FLUX AND THERMAL RESPONSE PARAMETER FOR MATERIALS

Materials	Critical Heat Flux for Ignition CHF (kW/m²)	Thermal Response Parameter (TRP) (kW-sec$^{1/2}$/m²)	
Electrical Cables - Power			
PVC/PVC	19.00	248.5	Select Material
PE/PVC	15.00	232.5	PVC/PE
PVC/PE	15.00	263	Scroll to desired material then
Silicone/PVC	19.00	212	Click on selection
Silicone/cross linked polyolefin (XLPO)	27.50	446	
EPR (ethylene-propylene rubber/EPR)	21.50	517	
XLPE/XLPE	22.50	329.5	
XLPE/EVA (ethyl vinyl acetate)	17.00	472.5	
XLPE/Neoprene	15.00	291	
XLPO/XLPO	20.50	498	
XLPO, PVF (polyvinylidine fluoride)/XLPO	15.50	526	
EPR/Chlorosulfonated PE	16.50	349.5	
EPR, FR	21.00	368.5	
User Specified Value	Enter Value	Enter Value	
Electrical Cables - Communications			Select Material
PVC/PVC	15.00	131	
PE/PVC	20.00	183	Scroll to desired material then
XLPE/XLOP	20.00	498	Click on selection
SIX/XLOP	20.00	457	
EPR-FR	19.00	295	
Chlorinated PE	12.00	217	
ETFE/EVA	22.00	454	
PVC/PVF	30.00	264	
FEP/FEP	36.00	645	
User Specified Value	Enter Value	Enter Value	
Synthetic Materials			Select Material
Polypropylene	15.00	193	
Nylon	15.00	270	Scroll to desired material then
Polymethylmethacrylate (PMMA)	11.00	274	Click on selection
Polycarbonate	15.00	331	
Polycarbonate panel	16.00	420	
User Specified Value	Enter Value	Enter Value	
Natural Materials			Select Material
Wood (red oak)	10.00	134	
Wood (douglas fir)	10.00	138	Scroll to desired material then
Wood (douglas fir/fire retardant, FR)	10.00	251	Click on selection
Corrugated paper (light)	10.00	152	
User Specified Value	Enter Value	Enter Value	

Reference: SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-58.

ESTIMATING IGNITION TIME FOR COMBUSTIBLES
METHOD OF TEWARSON
THERMALLY THICK MATERIALS

Reference: SFPE Handbook of Fire Protection Engineering, 3[rd] Edition, 2002, Page 3-53.

$\sqrt{1/t_{ig}} = (\sqrt{4/\pi})(q''_e - CHF)/TRP$

$t_{ig} = (\pi/4)(TRP)^2/(q''_e - CHF)^2$

Where

t_{ig} = target ignition time (sec)

q''_e = external radiative heat flux to target (kW/m^2)

CHF = target critical heat flux for ignition (kW/m^2)

TRP = thermal response parameter of target material (kW-sec$^{1/2}$/m^2)

t_{ig} = $(\pi/4)(TRP)^2/(q''_e - CHF)^2$

t_{ig} =	543.26 sec	9.05 minutes	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3[rd] Edition 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 6.11-2

Problem Statement
Determine the time for 2-inch-thick Douglas fir plywood to ignite when it is subjected to a flame heat flux of 25 kW/m^2, assuming the surface of the plywood is initially at 68 °F (20 °C).

Solution

Purpose:
(1) Calculate the ignition time of Douglas fir plywood.

Assumptions:
(1) The material is infinitely thick.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:
(a) 06_Ignition_Time_Calculations.xls (click on *Ignition_Time _Calculations3*)

FDT^s Input Parameters:

-Exposure or External Radiative Heat Flux to Target Fuel $(\dot{q}_e'')$ = 25 kW/m^2

-Click on the option button (⊙) for Natural Materials
-Select Material: **Wood (Douglas fir)**

Note: The ignition time calculation method (Tewarson) provided in the spreadsheet *Ignition_Time _Calculations3* does not require the material thickness or initial surface temperature; therefore, material thickness and temperature are additional information only. However, if the initial temperature of the material is relatively high (compare with ambient temperature range), the ignition time value definitely will not be realistic based on this method. Also, we are assuming the material as infinitely thick to use the method; thus, we do not have to consider the thickness for this problem.

Results*

Material	Ignition Time (t_{ig}) (min.) Method of Tewarson
Wood (Douglas fir)	1.11

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 06_Ignition_Time_Calculations.xls (Ignition_Time _Calculations3)

CHAPTER 6. ESTIMATING THE IGNITION TIME OF A TARGET FUEL EXPOSED TO A CONSTANT RADIATIVE HEAT FLUX

Version 1805.0

The following calculations estimate time to ignition for flame spread of solid fuels exposed to a constant external radiative heat flux.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

Exposure or External Radiative Heat Flux to Target Fuel ($\dot{q}''_e$)	25.00	kW/m^2
Target Critical Heat Flux for Ignition (CHF)	10.00	kW/m^2
Target Thermal Response Parameter (TRP)	138	$kW\text{-}sec^{1/2}/m^2$
	Calculate	

CRITICAL HEAT FLUX AND THERMAL RESPONSE PARAMETER FOR MATERIALS

Materials	Critical Heat Flux for Ignition CHF (kW/m^2)	Thermal Response Parameter (TRP) ($kW\text{-}sec^{1/2}/m^2$)	
Electrical Cables - Power			
PVC/PVC	19.00	248.5	Select Material
PE/PVC	15.00	232.5	
PVC/PE	15.00	263	Scroll to desired material then
Silicone/PVC	19.00	212	Click on selection
Silicone/cross linked polyolefin (XLPO)	27.50	446	
EPR (ethylene-propylene rubber/EPR)	21.50	517	
XLPE/XLPE	22.50	329.5	
XLPE/EVA (ethyl-vinyl acetate)	17.00	472.5	
XLPE/Neoprene	15.00	291	
XLPO/XLPO	20.50	498	
XLPO, PVF (polyvinylidine fluoride)/XLPO	15.50	526	
EPR/Chlorosulfonated PE	16.50	349.5	
EPR, FR	21.00	368.5	
User Specified Value	Enter Value	Enter Value	
Electrical Cables - Communications			Select Material
PVC/PVC	15.00	131	
PE/PVC	20.00	183	Scroll to desired material then
XLPE/XLOP	20.00	498	Click on selection
Si/XLOP	20.00	457	
EPR-FR	19.00	295	
Chlorinated PE	12.00	217	
ETFE/EVA	22.00	454	
PVC/PVF	30.00	264	
FEP/FEP	36.00	645	
User Specified Value	Enter Value	Enter Value	
Synthetic Materials			Select Material
Polypropylene	15.00	193	
Nylon	15.00	270	Scroll to desired material then
Polymethylmethacrylate (PMMA)	11.00	274	Click on selection
Polycarbonate	15.00	331	
Polycarbonate panel	16.00	420	
User Specified Value	Enter Value	Enter Value	
Natural Materials			Select Material
Wood (red oak)	10.00	134	Wood (douglas fir)
Wood (douglas fir)	10.00	138	Scroll to desired material then
Wood (douglas fir/fire retardant, FR)	10.00	251	Click on selection
Corrugated paper (light)	10.00	152	
User Specified Value	Enter Value	Enter Value	

Reference: SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-56.

ESTIMATING IGNITION TIME FOR COMBUSTIBLES
METHOD OF TEWARSON
THERMALLY THICK MATERIALS

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-53

$\sqrt{1/t_{ig}} = (\sqrt{4/\pi})(q''_e - CHF)/TRP$

$t_{ig} = (\pi/4)(TRP)^2/(q''_e - CHF)^2$

Where

t_{ig} = target ignition time (sec)

q''_e = external radiative heat flux to target (kW/m²)

CHF = target critical heat flux for ignition (kW/m²)

TRP = thermal response parameter of target material (kW-sec$^{1/2}$/m²)

t_{ig} = $(\pi/4)(TRP)^2/(q''_e - CHF)^2$

t_{ig} =	66.48 sec	1.11 minutes	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 7. ESTIMATING THE FULL-SCALE HEAT RELEASE RATE OF A CABLE TRAY FIRE

7.1 Objectives

This chapter has the following objectives:

- Describe the numerous functions that electrical cables perform in a nuclear power plant (NPP).
- Explain the factors that determine how a cable will behave in a fire.
- Describe the ways that fires can occur in cable tray installations.
- Discuss the various types of combustion reactions.
- Explain the processes that electrical failures can initiate in a cable tray.

7.2 Introduction

Fires in grouped electrical cable trays pose distinct fire hazards in power generating facilities. In the past, cable tray installations have caused fires that resulted in serious damage to NPPs. In fact, during the 1950s and early 1960s, NPPs in the United States experienced several fires with serious losses propagated by electrical cables. A 1966 NFPA fire hazard study (Hedland, 1966) described 24 such fires, the most serious of which occurred at the Peach Bottom Atomic Power Station operated by Philadelphia Electric Company. The most important aspect of the NAPA study, however, is that it pointed out (probably for the first time) that *grouped cables can spread flame much faster than individual cables*.

The 1975 fire at the Browns Ferry Nuclear Power Plant (BFNP) operated by the Tennessee Valley Authority (TVA) demonstrated the vulnerability of electric cables installed in an NPP when exposed to elevated temperatures as a result of a fire. In response to the Browns Ferry incident, the NRC's Executive Director for Operations (EDO) established a special review group to identify lessons that can be learned from the event and to make recommendations for the future treatment of cable trays and cable fires (NUREG-0050). After the BFNP fire, the NRC conducted a series of operating plant inspections and thorough reviews of NPP fire protection programs. On the basis of this information, the NRC issued new fire protection requirements in 10 CFR 50.48 and Appendix R to 10 CFR Part 50. The new regulations imposed a minimum set of fire protection program and post-fire safe-shutdown (FSSD) requirements. (See Appendix A for more on electrical cables.)

Electrical cables perform numerous functions in an NPP:

- power cables that supply electricity to motors, transformers, and heaters
- lighting cables that supply electricity to normal lighting fixtures and fluorescent lighting ballasts
- control cables that connect plant equipment such as motor-operated valves (MOVs) and motor starters to remote initiating devices (e.g., switches, relays, and contacts)
- instrumentation cables that transmit low-voltage signals between input devices (e.g., readout panels)
- communication cables (telephone lines)
- heat tracing cables.

The primary cables of concern for FSSD of the reactor are typically power, control, and instrumentation cables. The function of a given cable dictates its acceptable operating parameters. These parameters are important because what constitutes acceptable performance of one type of cable at elevated fire temperatures may not be acceptable performance for another (e.g., a cable that demonstrates acceptable performance for power applications at a certain elevated fire temperature may not be acceptable for instrumentation applications at the same temperature).

Power cables are the least susceptible to fire-induced failure. Control cables are more susceptible to such failure than power cables but typically less susceptible than instrument cables, which are often the most easily affected by elevated temperatures and the first to suffer fire-induced failures.

7.3 Cable Tray Fire Burning Mode Classification

Electrical cables constitute a serious fire hazard for NPPs because the combustible polymeric insulation and jacket material are present in large quantities. This large fuel load can cause NPP fires to burn for extended periods. To compound the problem, the combustion of a fully developed cable fire may be incomplete because of the presence of smoke; whereas general building fires on ground level usually burn in the presence of clear air, because smoke escapes through windows and doors before descending to the fuel.

The behavior of cables in a fire depends on a number of factors, including their constituent materials and construction, as well as their location and installation geometry. The component material and the construction of the cable are very important, as is the nature of the given fire. For example, polymer-insulated cables are regarded as fire hazards because all organic materials will burn under most fire conditions and will liberate heat and toxic gases (such as carbon monoxide.) Depending on their location and means of installation, cables can contribute to a fire in a number of ways. For example, burning cables can propagate flames from one area to another or they can add to the amount of fuel available for combustion and can liberate smoke containing toxic and corrosive gases. Similarly, the grouped cables could pose a more serious threat in situations where they run through open spaces connecting different parts of an NPP. In these situations, the cables could propagate and spread the fire between compartments. Thus, the hazards associated with burning cables must be considered in the context of the surroundings. Sometimes, cables comprise a very small proportion of the combustible material; in other situations, they can be the major contribution.

Cable tray fires can occur from various sources. The scenarios of concern include (1) a fire within a cable tray (regardless of how it is initiated) and (2) as exposure fire (i.e., a fire that originates outside of the cable tray and subsequently ignites the cable tray). It is common practice to consider only self-ignited cable fires to occur in power cable trays since they carry enough electrical energy for ignition. Control and instrumentation cables typically do not carry enough electrical energy for self ignition.

To determine the behavior of a given type of cable, they are subject to a variety of standard small- and large scale tests. As stated in NUREG/CR-2431, "Burn Mode Analysis of Horizontal Cable Tray Fires," February 1982, the cable fire growth tests performed to date have demonstrated different burn modes in horizontal and vertical configurations. The results of horizontal and vertical cable tray tests showed that jacket or insulation material may melt (thermoplastic) or form a considerable char (thermoset). The insight gained from the various cable tray fire tests indicate different types of combustion reactions.

- In pyrolysis, flaming was uniform over the outer surface of the cable bundle and throughout the cable bundle. The cable region involved in the fire grew steadily for the duration of the test.
- With smoldering and/or melting, the jacket and/or insulation material melted and coalesced into a large mass, and flaming occurred principally on the outer surface of the fused mass. Fire involvement depended upon the shape and position of the fused mass within the cable tray.
- With deep-seated combustion, the jacket and/or insulation material formed considerable char, and flaming occurred principally on the outer surface of the cable bundle. Flaming was neither continuous nor uniform, but rather occurred as sporadic bursts of fire. After the surface flaming subsided, a glowing cable region slowly progressed along the cables with sporadic flaming issuing from the region. The deep-seated fire, as a subclass of smoldering combustion, is defined as having a fuel interior temperature between the fuel vapor and surface auto-ignition temperatures of the fuel and a fuel surface temperature below the upper or surface auto-ignition temperature.
- Interior combustion resulted in uniform flaming over the outer surface and throughout the cable bundle. The cable region involved in the fire grew steadily and continuously, and the surface fire slowly progressed along the cable with sporadic flaming.

7.4 Cable Tray Heat Release Rate

As stated above, cable insulation and jacket material dominates the combustible fuel loading in most NPP areas. Most of this material is found on cables that are routed in extensive cable tray arrays. Review of the literature on cable tray fires indicates that there are no reliable correlations for the rate of heat release from a full-scale fire. The most systematic studies available are those from Tewarson, et al. (1979), and Sumitra (1982). A useful engineering analysis and basic correlation of their data has been prepared by Lee, 1985, who showed that the peak full-scale HRR can be predicted according to the bench-scale HRR measurements. Lee's correlation for the HRR from measured data is based on the following equation:

$$\dot{Q}_{fs} = 0.45 \quad \dot{Q}''_{bs} \quad A_f \qquad (7\text{-}1)$$

Where:

$\dot{Q}_{fs}$ = full-scale HRR (kW)

$\dot{Q}''_{bs}$ = bench-scale HRR (kW/m^2)

A_f = exposed cable tray area actively pyrolyzing (m^2)

The bench-scale HRR $(\dot{Q}''_{bs})$, is the peak value measured under the heat flux condition of 60 kW/m^2. The pyrolysis or burning area, A_f, can vary with time as a cable fire spreads. For screening purposes, this area can be estimated assuming area of the fuel involved in fire.

The bench-scale HRR data for a number of cable types measured by Tewarson, et al., and Sumitra, are tabulated in Table 7-1. Note that polyethylene/polyvinylchloride (PE/PVC) cables were the most flammable of all cables tested.

Table 7-1. Bench-Scale HRR of a Cable Tray Fire

Cable Sample	**Bench-Scale HRR per Unit Area $\dot{Q}''_{bs}$ (kW/m^2)**
Id PE	1,071
PE/PVC	589
XPE/FRXPE	475
XPE/Neoprene	354
PE, PP/Cl.S.PE	345
XPE/Neoprene	302
FRXPE/Cl.S.PE	258
PE, Nylon/PVC, Nylon	231
XPE/Cl.S.PE	204
Silicone, glass braid, asbestos	182
XPE/XPE	178
PE, PP/Cl.S.PE	177
Silicone, glass braid	128
Teflon	98
Cl.S. - Chlorosulfonated; FRXPE - Fire Retardant Crosslinked Polyethylene; PE - Polyethylene; PP - Polypropylene; PVC - Polyvinylchloride; XPE - Crosslinked Polyethylene	

Typically, the IEEE-383-qualified cables are thermoset material, while the unqualified cables are constructed of thermoplastic material. Table 7-2 lists commonly found cables.

Table 7-2. Thermoplastic vs. Thermoset Cables

Thermoplastic Cable Construction Allied Chemical's Halar (ethylene copolymer with chlorotrifluoroethylene) DuPont's PFA (perflouroalkoxy branched polymers) Dynamit Nobel's Dyflor (polyvinylidene fluoride) Ethylenetetrafluoroethylene (ETFE) (known as Tefzel®) Fluorinated polyethylene-polypropylene (FEP) (known as Teflon®) Low and high polyethylene (PE) Nylon, chlorinated polyethylene (CPE) Polyvinyl chloride (PVC) Polyvinyl fluoride (PVF) (known as Tedlar®) Polyurethane, polypropylene (PPE) Polytetrafluoroethylene (PTFE) (known as Teflon®) Teflon, and fluorinated polymers such as DuPont's TFE copolymers with ethylene (known as Tefzel®)
Thermoset Cable Construction Crosslinked polyethylene (XLPE) Crosslinked polyolefin (XLPO) Chloroprene rubber (CR) DuPont's Hypalon (Chlorosulphonated polyethylene) Ethylvinyl acetate (EVA) Ethylene propylene rubber (EPR) Nitrile or rubber butadiene nitrite (NBR) Styrene butadiene rubber (SBR) Polybutadiene, neoprene, and silicone rubber

7.5 Cable Failure Criteria (Critical Temperature and Critical Heat Flux)

Electrical failure can initiate several fire-related processes, such as melting, pyrolysis, gasification, ignition, and combustion of cable. The lower the heat flux requirement to ignite the electrical cables, the greater the fire hazard is in terms of ignition and flame spread.

A quantitative FHA requires a damage threshold for cables exposed to fires. Electrical cables are typically the primary target for most analyses. The two general types of electrical cables that are anticipated in an NPP are qualified and unqualified. These terms respectively refer to cables that pass or fail the fire test defined in the IEEE-383 standard promulgated by the Institute of Electrical and Electronic Engineers (IEEE). See Appendix A, Section A.5.8, for a discussion of cable damage threshold exposure heat-flux.

7.6 Assumptions and Limitations

The method discussed in this chapter is subject to several assumptions and limitations:

(1) This correlation is based on the data obtained from flaming fire of cable samples.

(2) A complex cable tray configuration may be present in many NPPs. For very complex cable tray arrays, the above correlation would give a less accurate approximation for the HRR.

(3) The equation should be used to calculate the HRR for any type of cable.

7.7 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) cable type (material)

(2) exposed cable tray burning area (ft^2)

7.8 Cautions

(1) Use (07_Cable_HRR_Calculations.xls) spreadsheet on the CD-ROM for calculation.

(2) Make sure to enter the input parameters in the correct units.

7.9 Summary

There is currently no direct HRR data available on the burning of full-scale or intermediate-scale cable tray arrays. Available mass loss data, measured in a series of intermediate-scale fires, was used to estimate HRR. The resulting HRR, in turn, was used to develop a predicted method for full-scale fire behavior based on the bench-scale HRR data for cables.

Estimating the HRR, $\dot{Q}_{fs}$, of cables involves the following steps:

(1) Determine the bench-scale HRR, $\dot{Q}''_{bs}$.

(2) Calculate the exposed cable tray area, A_f.

7.10 References

"Fire-Induced Vulnerability Evaluation (FIVE) Methodology," EPRI TR-100370, Electric Power Research Institute, Palo Alto, California, 1992.

Hedlund, C.F., "Grouped Combustible Wire and Cables," *Fire Journal*, Volume 60, pp. 5–8, March 1966.

Lee, B.T., "Heat Release Rate Characteristics of Some Combustibles Fuel Sources in Nuclear Power Plants," NBSIR 85-3195, U.S. Department of Commerce, National Bureau of Standards (NBS), Washington, DC, July 1985.

NUREG-0050, "Recommendations Related to Browns Ferry Fire," Report by Special Review Group, U.S. Nuclear Regulatory Commission, Washington, DC, February 1976.

NUREG/CR-2431, "Burn Mode Analysis of Horizontal Cable Tray Fires," U.S. Nuclear Regulatory Commission, Washington, DC, February 1982.

Sumitra, P.S., "Categorization of Cable Flammability. Part I, Intermediate-Scale Fire Tests of Cable Tray Installations," Interim Report NP-1881, EPRI Research Project 1165-1, Factory Mutual Research Corporation, Norwood Massachusetts, 1982.

Tewarson, A., J.L. Lee, and R.F. Pion, "Categorization of Cable Flammability, Part I, Experimental Evaluation of Flammability Parameters of Cables Using Laboratory-Scale Apparatus," EPRI Project RP1165-1, Factory Mutual Research Corporation, Norwood, Massachusetts, 1979.

7.11 Additional Readings

Babrauskas, V., "Burning Rates," Section 3, Chapter 3-1, *SFPE Handbook of Fire Protection Engineering,* 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

Babrauskas, V., "Free-Burning Fires," *Fire Safety Journal*, Volume 11, page 33–51, 1986.

7.12 Problems

Example Problem 7.12-1

Problem Statement
A 32-gallon trash can exposure fire source is located 2 m (6.5 ft) beneath a horizontal cable tray. It is assumed that the trash fire ignites an area of approximately 2 m^2 (21 ft^2) of the cable tray. The cables in the tray are IEEE-383 unqualified and made of PE/PVC insulation material. Compute the full-scale HRR of the PE/PVC cable insulation. The bench-scale HRR of PE/PVC is 589 kW/m^2.

Solution

Purpose:
(1) Calculate the full-scale HRR of the PE/PVC insulation material.

Assumptions:
(1) Lee's correlation is valid for this fire scenario.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:
(a) 07_Cable_HRR Calculations.xls

FDT^s Input Parameters:
-Exposure Cable Tray Burning Area (A_f) = 21 ft^2
-Select Material: **PE/PVC** (the one with a bench-scale HRR of 589 kW/m^2)

Results*

Cable Insulation	Full Scale HRR ($\dot{Q}_{fs}$) kW (Btu/sec)
PE/PVC	517 (490)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 07_Cable_HRR Calculations.xls

CHAPTER 7. ESTIMATING THE FULL-SCALE HEAT RELEASE RATE OF A CABLE TRAY FIRE

Version 1805.0

The following calculations estimate the full-scale cable tray heat release rate.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Cable Selected.
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 Bench-Scale HRR (Q_{bs})	589	kW/m^2	
Exposed Floor Area (Length x Width) of Burning Cable Tray (A)	21.00	ft^2	1.951 m^2

Calculate

HEAT RELEASE RATE DATA FOR CABLE TRAY FIRE

BENCH-SCALE HRR OF CABLE TRAY FIRE

Cable Type	Bench-Scale HRR per Unit Floor Area (L x W) Q''_{bs} (kW/m^2)
XLPE	1071
PE/PVC	589
XPE/FRXPE	475
PE/PVC	395
PE/PVC	359
XPE/Neoprene	354
PE, PP/Cl.S.PE	345
PE/PVC	312
XPE/Neoprene	302
PE, PP/Cl.S.PE	299
PE, PP/Cl.S.PE	271
FRXPE/Cl.S.PE	258
PE, Nylon/PVC, Nylon	231
PE, Nylon/PVC, Nylon	218
XPE/Cl.S.PE	204
Silicone, glass braid, asbestos	182
XPE/XPE	178
PE, PP/Cl.S.PE	177
Silicone, glass braid	128
Teflon	98
User Specified Value	Enter Value

Reference: *"Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.*

Select Cable Type

PE/PVC

Scroll to desired cable type then Click on selection

ESTIMATING FULL-SCALE CABLE TRAY HEAT RELEASE RATE

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition 2002, Page 3-18.

$Q_{fs} = 0.45\ Q_{bs}\ A$

Where Q_{fs} = cable tray full-scale HRR (kW)

Q_{bs} = cable tray bench-scale HRR (kW)

A = exposed floor area (length x width) of burning cable tray (m^2)

Heat Release Rate Calculation

$Q_{fs} = 0.45\ Q_{bs}\ A$

Q_{fs} =	517.10 kW	490.12 Btu/sec

Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and has inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 7.12-2

Problem Statement

A 1.5-ft-high stack of untreated wood pallets (exposure fire source) from a recent plant modification ignites and is located 1.5 m (5 ft) beneath a horizontal cable tray. It is assumed that the wood pallets ignite an area of approximately 4 m^2 (43 ft^2) of the cable tray. The cables in the tray are IEEE-383 qualified and made of PE insulation material. Compute the full-scale HRR of PE cable insulation. The bench-scale HRR of PE material is 1,071 kW/m^2.

Solution

Purpose:

(1) Calculate the full-scale HRR of the PE insulation material.

Assumptions:

(1) Lee's correlation is valid for this fire scenario.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 07_Cable_HRR Calculations.xls

FDT^s Input Parameters:

-Exposure Cable Tray Burning Area (A_f) = 43 ft^2

-Select Material: **Id PE**

Results*

Cable Insulation	Full Scale HRR ($\dot{Q}_c$) kW (Btu/sec)
Id PE	1,925 (1,825)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 07_Cable_HRR Calculations.xls

CHAPTER 7. ESTIMATING THE FULL-SCALE HEAT RELEASE RATE OF A CABLE TRAY FIRE

Version 1805.0

The following calculations estimate the full-scale cable tray heat release rate.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Cable Selected.
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 Bench-Scale HRR ($\dot{Q}''_{bs}$)	1071	kW/m²	
Exposed Floor Area (Length x Width) of Burning Cable Tray (A)	43.00	ft²	3.995 m²

Calculate

HEAT RELEASE RATE DATA FOR CABLE TRAY FIRE

BENCH-SCALE HRR OF CABLE TRAY FIRE

Cable Type	Bench-Scale HRR per Unit Floor Area (L x W) $\dot{Q}''_{bs}$ (kW/m²)
Id PE	1071
PE/PVC	589
XPE/FRXPE	475
PE/PVC	395
PE/PVC	359
XPE/Neoprene	354
PE, PP/Cl.S.PE	345
PE/PVC	312
XPE/Neoprene	302
PE, PP/Cl.S.PE	299
PE, PP/Cl.S.PE	271
FRXPE/Cl.S.PE	258
PE, Nylon/PVC, Nylon	231
PE, Nylon/PVC, Nylon	218
XPE/Cl.S.PE	204
Silicone, glass braid, asbestos	182
XPE/XPE	178
PE, PP/Cl.S.PE	177
Silicone, glass braid	128
Teflon	98
User Specified Value	Enter Value

Select Cable Type

Id PE

Scroll to desired cable type then Click on selection

Reference: "Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.

ESTIMATING FULL-SCALE CABLE TRAY HEAT RELEASE RATE

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition 2002, Page 3-16.

$Q_{fs} = 0.45\ Q_{bs}\ A$

Where Q_{fs} = cable tray full-scale HRR (kW)

Q_{bs} = cable tray bench-scale HRR (kW)

A = exposed floor area (length x width) of burning cable tray (m^2)

Heat Release Rate Calculation

$Q_{fs} = 0.45\ Q_{bs}\ A$

Q_{fs} =	1925.31 kW	1824.85 Btu/sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and has inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 7.12-3

Problem Statement

A 3.5 ft diameter flammable liquid (lubricating oil) pool fire arises from a breach in an auxiliary cooling water pump oil tank. The pool fire is located on the floor, 3 m (10 ft) beneath a horizontal cable tray. It is assumed that the pool fire ignites an area of approximately 1 m^2 (10.8 ft^2) of the cable tray. The cables in the tray are IEEE-383 unqualified and made of XPE/FRXPE insulation material. Compute the full scale HRR of XPE/FRXPE cable insulation. The bench-scale HRR of XPE/FRXPE is 475 kW/m^2.

Solution

Purpose:

(1) Calculate the full-scale HRR of the XPE/FRXPE insulation material.

Assumptions:

(1) Lee's correlation is valid for this fire scenario.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 07_Cable_HRR Calculations.xls

FDT^s Input Parameters:

-Exposure Cable Tray Burning Area (A_f) = 10.8 ft^2

-Select Material: **XPE/FRXPE**

Results*

Cable Insulation	Full Scale HRR $(\dot{Q}_{fs})$ kW (Btu/sec)
XPE/FRXPE	214 (203)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 07_Cable_HRR Calculations.xls

CHAPTER 7. ESTIMATING THE FULL-SCALE HEAT RELEASE RATE OF A CABLE TRAY FIRE

Version 1805.0

The following calculations estimate the full-scale cable tray heat release rate.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Cable Selected.
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 Bench-Scale HRR ($\dot{Q}_{bs}$) — 475 kW/m²

Exposed Floor Area (Length x Width) of Burning Cable Tray (A) — 10.80 ft² — 1.003 m²

Calculate

HEAT RELEASE RATE DATA FOR CABLE TRAY FIRE

BENCH-SCALE HRR OF CABLE TRAY FIRE

Cable Type	Bench-Scale HRR per Unit Floor Area (L x W) $\dot{Q}''_{bs}$ (kW/m²)
XPE	1071
PE/PVC	589
XPE/FRXPE	475
PE/PVC	395
PE/PVC	359
XPE/Neoprene	354
PE, PP/Cl.S.PE	345
PE/PVC	312
XPE/Neoprene	302
PE, PP/Cl.S.PE	299
PE, PP/Cl.S.PE	271
FRXPE/Cl.S.PE	258
PE, Nylon/PVC, Nylon	231
PE, Nylon/PVC, Nylon	218
XPE/Cl.S.PE	204
Silicone, glass braid, asbestos	182
XPE/XPE	178
PE, PP/Cl.S.PE	177
Silicone, glass braid	128
Teflon	98
User Specified Value	Enter Value

Select Cable Type: XPE/FRXPE

Scroll to desired cable type then Click on selection

Reference: *"Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.*

ESTIMATING FULL-SCALE CABLE TRAY HEAT RELEASE RATE

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition 2002, Page 3-16.

$Q_{fs} = 0.45\ Q_{bs}\ A$

Where Q_{fs} = cable tray full-scale HRR (kW)

Q_{bs} = cable tray bench-scale HRR (kW)

A = exposed floor area (length x width) of burning cable tray (m^2)

Heat Release Rate Calculation

$Q_{fs} = 0.45\ Q_{bs}\ A$

Q_{fs} =	214.47 kW	203.28 Btu/sec

Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and has inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 8. ESTIMATING BURNING DURATION OF SOLID COMBUSTIBLES

8.1 Objectives

This chapter has the following objectives:

- Introduce factors that influence the fire duration of solid combustibles.
- Explain how to estimate fire durations for various solid combustibles.
- Approximate first order estimates of burning durations.

8.2 Introduction

The burning duration can be thought of as the time between ignition and the decay phase of a fire. The burning duration (fire) for a given compartment size and ventilation condition is driven by the fuel load. Fuel loading, given in terms of kg (fuel)/m^2 or lb (fuel)/ft^2 is based on the amount of combustibles per unit floor area has been traditionally used to approximate the fire duration. Higher fuel loads typically mean longer durations assuming a fire burning at a constant HRR consumes fuel mass at a constant rate. Given the mass of material being burned per second and the amount of material available to be consumed, it is possible to calculate a first order estimate for the total burning duration of a fuel. Note that for ventilation-controlled fires, higher fuel loads have no effect on compartment temperature, with the exception that the fire duration increases the gas temperature.

8.3 Burning Duration of Solid Combustibles

Fire duration of solid combustibles is an approximation of the potential destructive impact of the burnout[1] of all of the available fuel in a compartment or enclosure with at least one ventilation opening. The intensity and duration of a fully developed fire depend upon the amount of combustibles available, their burning rates, and the air available to support their combustion. Fire intensity is lower when the walls and ceiling absorb significant amounts of energy, rather than acting primarily as insulation or radiation barriers. The possibility that the fire barriers can fail is important to keep in mind. Long after the fully developed fire begins to decay, the fire barriers are still being challenged. However, as in many real fire situations, this threat is usually mitigated by automatic and/or manual fire suppression activities.

---

[1] Burnout as used in this discussion, is when all the available combustibles are consumed. It should be remembered that in most fires, the combustion will be incomplete.

The burning duration of solid combustibles can be estimated if the HRR and total energy contained in the fuel are known. The burning duration can be estimated from the following equation (Buchanan, 2001):

$$\dot{Q} = \frac{E}{t_{solid}} \qquad (8\text{-}1)$$

Where:

$\dot{Q}$ = heat release rate of the fire (kW)
E = total energy contained in the fuel (kJ)
t_{solid} = burning duration of solid fuel (sec)

The maximum possible energy that can be released when fuel burns is the energy contained in the fuel, E, given by the following equation:

$$E = m_{fuel}\,\Delta H_c \qquad (8\text{-}2)$$

Where:

m_{fuel} = mass of fuel (kW)
H_c = heat of combustion (kJ/kg)

Therefore, Equation (8-1) can be expressed as follows:

$$t_{Solid} = \frac{m_{Fuel}\Delta H_c}{\dot{Q}'' A_{Fuel}} \qquad (8\text{-}3)$$

Where:

t_{Soild} = burning duration (sec)
m_{Fuel} = mass of solid fuel (kg)
H_c = effective heat of combustion (kJ/kg)
$\dot{Q}''$ = heat release rate per unit floor area (kW/m^2)
A_{Fuel} = exposed floor area (length x width) of fuel (m^2)

The exposed fuel surface area (length x width) of fuel (m^2) can be calculated as follows:

$$A_{Fuel} = L \times W \qquad (8\text{-}4)$$

Where:

A_{Fuel} = fuel surface area (m^2)
W = fuel exposed width (m)
L = fuel exposed length (m)

Table 8-1 lists the thermal properties of solid combustible materials.

Table 8-1. Thermal Properties of Common Solid Combustible Materials
(Tewarson, 1995, © SFPE. With permission.)

Materials	**HRR per Unit Floor Area** $\dot{Q}''$ **(kW/m²)**	**Heat of Combustion** H_c **(kJkg)**
PE/PVC	589	24,000
XPE/FRXPE	475	28,300
XPE/Neoprene	354	10,300
PE, Nylon/PVC, Nylon	231	9,200
Teflon	98	3,200
Douglas fir plywood	124	13,000–15,000
Fire-retardant treated plywood	81	13,500
Particle board, 19 mm thick	1,900	17,500
Nylon 6/6	1,313	32,000
Polymethlmethacrylate (PMMA)	665	26,000
Polypropylene (PP)	1,509	43,200
Polystyrene (PS)	1,101	42,000
Polyethylene (PE)	1,408	46,500
Polycarbonate	420	24,400
Polyurethene	710	45,000
Polyvinyl Chloride (PVC) Flexible	237	15,700
Strene-butadiene Copolymers (SBR)	163	44,000
Ethylene Propylene Dien Rubber	956	28,800
Empty Cartons 15 ft high	1700	12,700
Wood pallets, stacked 1.5 ft high	1,420	13,000–15,000
Wood pallets, stacked 5 ft high	3,970	13,000–15,000
Wood pallets, stacked 10 ft high	6,800	13,000–15,000

8.4 Assumptions and Limitations

The method discussed in this chapter is subject to several assumptions and limitations:

(1) Combustion is incomplete (leaving some residual fuel) and takes place entirely within the confines of the compartment.

(2) Virtually all of the potential energy in the fuel is released in the involved compartment.

8.5 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) fuel type (material)

(2) mass of solid fuel (lb)

(3) exposed fuel surface area (ft^2)

8.6 Cautions

(1) Use (08_Burning_Duration_Soild.xls) spreadsheet on the CD-ROM for calculation.

(2) Make sure to enter the input parameters in the correct units.

8.7 Summary

Estimating the burning duration of solid combustibles involves the following steps:

(1) Determine the mass of fuel.

(2) Calculate the surface area of combustible solid.

(3) Calculate the burning duration using HRR per unit floor area and fuel heat of combustion.

8.8 References

Buchanan, A.H., "Structural Design for Fire Safety," John Wiley & Sons, Limited, 2001, p. 38.

Karlsson, B., and J.G. Quintiere, *Enclosure Fire Dynamics*, Chapter 3, "Energy Release Rates," CRC Press LLC, New York, pp. 25–46, 1999.

Tewarson, A., "Generation of Heat and Chemical Compounds in Fires," Section 3, Chapter 5, *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 2002.

8.9 Problems

Example Problem 8.9-1

Problem Statement

A horizontal power cable fails as a result of self-initiated fire and burn in a compartment. Compute the burning duration of a cable tray with an exposed surface area of 1 ft^2 filled with 10 lb of non-IEEE-383-qualified PE/PVC cables. The heat release per unit floor area of PE/PVC is 589 kW/m^2, and the heat of combustion is 24,000 kJ/kg.

Solution

Purpose:

(1) Calculate the burning duration of the cable material (PE/PVC).

Assumptions:

(1) Combustion is incomplete and takes place entirely within the confines of the compartment.

(2) Virtually all of the potential energy in the fuel is released in the involved compartment.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 08_Burning_Duration Solid.xls

FDT^s Input Parameters:

-Mass of Solid Fuel (m_{solid}) = 10 lb

-Exposure Fuel Surface Area (A_{fuel}) = 1 ft^2

-Select Material: **PE/ PVC**

Results*

Material	Burning Duration (t_{solid}) (min.)
PE/PVC	33

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 08_Burning_Duration Solid.xls

CHAPTER 8. ESTIMATING BURNING DURATION OF SOLID COMBUSTIBLES

Version 1805.0

The following calculations provides an approximation of the burning duration of solid combustibles based on free burning rate with a given surface area.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Mass of Solid Fuel (m_{solid})	10.00	lb	4.54 kg
Exposed Floor Area (Length x Width) of Fuel (A_{fuel})	1.00	ft^2	0.09 m^2
Heat Release Rate per Unit Floor Area (Q'')	589	kW/m^2	
Effective Heat of Combustion ($\Delta H_{c,eff}$)	24000	kJ/kg	
	Calculate		

THERMAL PROPERTIES OF SOLID COMBUSTIBLE MATERIALS

Materials	HRR per Unit Floor Area (L x W) Q'' (kW/m^2)	Heat of Combustion ΔH_c (kJ/kg)
PE/PVC	589	24000
XPE/FRXPE	475	28300
XPE/Neoprene	354	10300
PE, Nylon/PVC, Nylon	231	9200
Teflon	98	3200
Douglas fir plywood	221	17600
Fire retardant treated plywood	81	13500
Particle Board, 19 mm thick	1900	17500
Nylon 6/6	1313	32000
Polymethylmethacrylate (PMMA)	665	26000
Polypropylene (PP)	1509	43200
Polystyrene (PS)	1101	42000
Polyethylene (PE)	1408	46500
Polycarbonate	420	24400
Polyurethane	710	45000
Polyvinyl Chloride (PVC) Flexible	237	15700
Styrene-butadiene Copolymers (SBR)	163	44000
Ethylene Propylene Dien Rubber (EPDM)	956	28800
Empty Cartons 15 ft high	1700	12700
Wood pallets, stacked 1.5 ft high	1420	14000
Wood pallets, stacked 5 ft high	3970	14000
Wood pallets, stacked 10 ft high	6800	14000
User Specified Value	Enter Value	Enter Value

Select Material

PE/PVC

Scroll to desired material then Click on selection

References: "Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.
Karlsson and Quintiere, Enclosure Fire Dynamics, Chapter 3,: Energy Release Rate," CRC Press, 1999.
Johnson, D. G., "Combustion Properties of Plastics," Journal of Applied Fire Science, Volume 4, No. 3, 1994-95, pp. 185-201.
Hirschler, M. M., "Heat Release from Plastic Materials," Heat Release in Fires, Babrauskas and Grayson, Editors, Elsevier Applied Science, 1992.

BURNING DURATION OF SOLID COMBUSTIBLES

Reference: *Buchanan, A.H., "Structural Design for Fire Safety," 2001, Page 38.*

The burning duration of a solid fuel can be calculated if the total energy contained in the fuel and HRR are known.

The burning duration is given by:

$Q = E / t_{solid}$

or

$t_{solid} = (E) / (Q'' A_{Fuel})$

Where t_{solid} = burning duration of solid combustible (sec)
$E = m_{Fuel} \Delta H_c$ = total energy contained in the fuel (kJ)
Q = heat releare rate of fire (kW)
Q'' = heat release rate per unit floor area of fuel (kW/m^2)
A_{Fuel} = exposed floor area (length x width) of fuel (m^2)

$t_{solid} = (m_{Fuel} \Delta H_c) / (Q'' A_{Fuel})$

Where m_{Fuel} = mass of solid fuel (kg)
ΔH_c = fuel effective heat of combustion (kJ/kg)

$t_{solid} = (m_{solid} \Delta H_c) / (Q'' A_{solid})$

t_{solid} =	1989.44 sec	33.16 minutes	Answer

NOTE

The above calculations are based on principles developed in the Structural Design for Fire Safety, 2001.
Calculations are based on certain assumptions and have inherent limitations.
The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 8.9-2

Problem Statement

A horizontal cable tray filled with non-IEEE-383 qualified XPE/FRXPE cables are ignited as a result of overhead welding and burn in a compartment 20 ft wide x 20 ft deep x 10 ft high. The cable tray has a nominal width of 2 ft and a linear length of 24 ft (i.e., exposed surface area of 48 ft^2). Compute the burning duration of XPE/FRXPE cables assuming the mass of cables is 50 lb. The heat release per unit area of XPE/FRXPE is 475 kW/m^2 and heat of combustion is 28,300 kJ/kg.

Solution

Purpose:

(1) Calculate the burning duration of the cable material (XPE/FRXPE).

Assumptions:

(1) Combustion is incomplete and takes place entirely within the confines of the compartment.
(2) Virtually all of the heat energy in the fuel is released in the involved compartment.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:

(a) 08_Burning_Duration Solid.xls

FDT^s Input Parameters:

-Mass of Solid Fuel (m_{solid}) = 50 lb
-Exposure Fuel Surface Area (A_{fuel}) = 48 ft^2
-Select Material: **XPE/FRXPE**

Results*

Material	Burning Duration (t_{solid}) (min.)
XPE/FRXPE	5

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 08_Burning_Duration Solid.xls

CHAPTER 8. ESTIMATING BURNING DURATION OF SOLID COMBUSTIBLES

Version 1805.0

The following calculations provides an approximation of the burning duration of solid combustibles based on free burning rate with a given surface area.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Mass of Solid Fuel (m_{solid})	50.00	lb	22.68 kg
Exposed Floor Area (Length x Width) of Fuel (A_{fuel})	48.00	ft^2	4.46 m^2
Heat Release Rate per Unit Floor Area ($\dot{Q}''$)	475	kW/m^2	
Effective Heat of Combustion ($\Delta H_{c,eff}$)	28300	kJ/kg	

Calculate

THERMAL PROPERTIES OF SOLID COMBUSTIBLE MATERIALS

Materials	HRR per Unit Floor Area (L x W) $\dot{Q}''$ (kW/m^2)	Heat of Combustion ΔH_c (kJ/kg)
PE/PVC	589	24000
XPE/FRXPE	475	28300
XPE/Neoprene	354	10300
PE, Nylon/PVC, Nylon	231	9200
Teflon	98	3200
Douglas fir plywood	221	17600
Fire retardant treated plywood	81	13500
Particle Board, 19 mm thick	1900	17500
Nylon 6/6	1313	32000
Polymethylmethacrylate (PMMA)	665	26000
Polypropylene (PP)	1509	43200
Polystyrene (PS)	1101	42000
Polyethylene (PE)	1408	46500
Polycarbonate	420	24400
Polyurethane	710	45000
Polyvinyl Chloride (PVC) Flexible	237	15700
Styrene-butadiene Copolymers (SBR)	163	44000
Ethylene Propylene Dien Rubber (EPDM)	956	28800
Empty Cartons 15 ft high	1700	12700
Wood pallets, stacked 1.5 ft high	1420	14000
Wood pallets, stacked 5 ft high	3970	14000
Wood pallets, stacked 10 ft high	6800	14000
User Specified Value	Enter Value	Enter Value

Select Material

XPE/FRXPE

Scroll to desired material then Click on selection

References: "Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.
Karlsson and Quintiere, Enclosure Fire Dynamics, Chapter 3, Energy Release Rate," CRC Press, 1999.
Johnson, D. G., "Combustion Properties of Plastics," Journal of Applied Fire Science, Volume 4, No. 3, 1994-95, pp. 185-201.
Hirschler, M. M., "Heat Release from Plastic Materials," Heat Release in Fires, Babrauskas and Grayson, Editors, Elsevier Applied Science, 1992.

BURNING DURATION OF SOLID COMBUSTIBLES

Reference: *Buchanan, A.H., "Structural Design for Fire Safety," 2001, Page 38.*

The burning duration of a solid fuel can be calculated if the total energy contained in the fuel and HRR are known.

The burning duration is given by:

$Q = E / t_{solid}$

or

$t_{solid} = (E) / (Q'' A_{Fuel})$

Where t_{solid} = burning duration of solid combustible (sec)

$E = m_{Fuel}\,\Delta H_C$ = total energy contained in the fuel (kJ)

Q = heat releare rate of fire (kW)

Q" = heat release rate per unit floor area of fuel (kW/m^2)

A_{Fuel} = exposed floor area (length x width) of fuel (m^2)

$t_{solid} = (m_{Fuel}\,\Delta H_C) / (Q'' A_{Fuel})$

Where m_{Fuel} = mass of solid fuel (kg)

ΔH_C = fuel effective heat of combustion (kJ/kg)

$t_{solid} = (m_{solid}\,\Delta H_C) / (Q'' A_{solid})$

t_{solid} =	303.01 sec	5.05 minutes	Answer

NOTE

The above calculations are based on principles developed in the Structural Design for Fire Safety, 2001.
Calculations are based on certain assumptions and have inherent limitations.
The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 8.9-3

Problem Statement

A fire involving a 1.5-ft-high stack of wood pallets is located in a compartment 40 ft wide x 40 ft deep x 10 ft high. The mass of the wood pallets is 30 lb. Compute the burning duration of the wood pallet fire in the compartment. The exposed surface area of the wood pallets is 4 ft x 4 ft or 16 ft^2.

Solution

Purpose:

(1) Calculate the burning duration of the stack of wood pallets.

Assumptions:

(1) Combustion is incomplete and takes place entirely within the confines of the compartment.

(2) Virtually all of the heat energy in the fuel is released in the involved compartment.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 08_Burning_Duration Solid.xls

FDT^s Input Parameters:

-Mass of Solid Fuel (m_{solid}) = 30 lb

-Exposure Fuel Surface Area (A_{fuel}) = 16 ft^2

-Select Material: **Wood pallet, stacked 1.5 ft high**

Results*

Material	Burning Duration (t_{solid}) (min.)
Wood pallet, stacked 1.5 ft high	1.5

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 08_Burning_Duration Solid.xls

CHAPTER 8. ESTIMATING BURNING DURATION OF SOLID COMBUSTIBLES

Version 1805.0

The following calculations provides an approximation of the burning duration of solid combustibles based on free burning rate with a given surface area.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Mass of Solid Fuel (m_{solid})	30.00	lb	13.61 kg
Exposed Floor Area (Length x Width) of Fuel (A_{fuel})	16.00	ft^2	1.49 m^2
Heat Release Rate per Unit Floor Area ($\dot{Q}''$)	1420	kW/m^2	
Effective Heat of Combustion ($\Delta H_{c,eff}$)	14000	kJ/kg	
	Calculate		

THERMAL PROPERTIES OF SOLID COMBUSTIBLE MATERIALS

Materials	HRR per Unit Floor Area (L x W) $\dot{Q}''$ (kW/m^2)	Heat of Combustion ΔH_c (kJ/kg)
PE/PVC	589	24000
XPE/FRXPE	475	28300
XPE/Neoprene	354	10300
PE, Nylon/PVC, Nylon	231	9200
Teflon	98	3200
Douglas fir plywood	221	17600
Fire retardant treated plywood	81	13500
Particle Board, 19 mm thick	1900	17500
Nylon 6/6	1313	32000
Polymethylmethacrylate (PMMA)	665	26000
Polypropylene (PP)	1509	43200
Polystyrene (PS)	1101	42000
Polyethylene (PE)	1408	46500
Polycarbonate	420	24400
Polyurethane	710	45000
Polyvinyl Chloride (PVC) Flexible	237	15700
Styrene-butadiene Copolymers (SBR)	163	44000
Ethylene Propylene Dien Rubber (EPDM)	956	28800
Empty Cartons 15 ft high	1700	12700
Wood pallets, stacked 1.5 ft high	1420	14000
Wood pallets, stacked 5 ft high	3970	14000
Wood pallets, stacked 10 ft high	6800	14000
User Specified Value	Enter Value	Enter Value

Select Material

Wood pallets, stacked 1.5 ft high

Scroll to desired material then Click on selection

References: "Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.
Karlsson and Quintiere, Enclosure Fire Dynamics, Chapter 3,: Energy Release Rate," CRC Press, 1999.
Johnson, D. G., "Combustion Properties of Plastics," Journal of Applied Fire Science, Volume 4, No. 3, 1994-95, pp. 185-201.
Hirschler, M. M., "Heat Release from Plastic Materials," Heat Release in Fires, Babrauskas and Grayson, Editors, Elsevier Applied Science, 1992.

BURNING DURATION OF SOLID COMBUSTIBLES

Reference: *Buchanan, A.H., "Structural Design for Fire Safety," 2001, Page 38.*

The burning duration of a solid fuel can be calculated if the total energy contained in the fuel and HRR are known.

The burning duration is given by:

$Q = E / t_{solid}$

or

$t_{solid} = (E) / (Q'' A_{Fuel})$

Where t_{solid} = burning duration of solid combustible (sec)
$E = m_{Fuel} \Delta H_c$ = total energy contained in the fuel (kJ)
Q = heat releare rate of fire (kW)
Q'' = heat release rate per unit floor area of fuel (kW/m^2)
A_{Fuel} = exposed floor area (length x width) of fuel (m^2)

$t_{solid} = (m_{Fuel} \Delta H_c) / (Q'' A_{Fuel})$

Where m_{Fuel} = mass of solid fuel (kg)
ΔH_c = fuel effective heat of combustion (kJ/kg)

$t_{solid} = (m_{solid} \Delta H_c) / (Q'' A_{solid})$

t_{solid} =	90.26 sec	1.50 minutes	Answer

NOTE

The above calculations are based on principles developed in the Structural Design for Fire Safety, 2001.
Calculations are based on certain assumptions and have inherent limitations.
The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

CHAPTER 9. ESTIMATING THE CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

9.1 Objectives

This chapter has the following objectives:

- Discuss various types of fire plumes.
- Discuss the fire plume that is most common encountered.
- Identify the temperature and flow characteristics of the fire plume.
- Define relevant terms including fire plume, air entrainment, plume temperature, ceiling jet, and virtual origin.

9.2 Introduction

A fire plume is a buoyantly rising column of hot combustion products, along with unburned fuel vapor and admixed air. When fire in a building continues to grow, the plume typically impinges on the ceiling, unless the fire remains very small or the ceiling is very high. The interaction of a plume with a ceiling is discussed in subsequent sections.

Figure 9-1 shows a turbulent column of hot gases rising because of buoyancy differences. The effect of the turbulence will cause rapid mixing of the hot gases with the cooler surrounding air. The addition of cold mass to the rising column decreases its velocity, widens the column, and reduces its temperature. When plume height is large in comparison to the width of the base of the plume, the average midline temperature (relative to ambient temperature) is found to decrease at a rate that is inversely proportional to the height of the plume raised to the $^5/_3$ power. Similarly, the average velocity of the midline is inversely proportional to the height of the plume raised to the ⅓ power. Correlations have been developed to predict the temperature and velocity distribution across a plume at any given height. These correlations are related in terms of the HRR driving the plume.

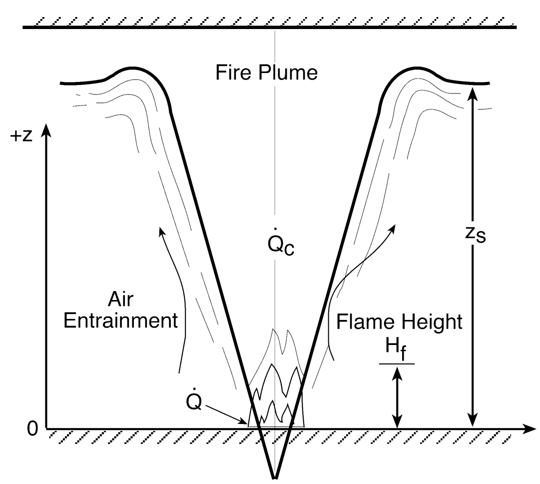


Figure 9-1 A Buoyant Turbulent Plume Showing Air Entrainment

The foregoing discussion refers to a rising column of hot gases, with no combustion taking place. This is applicable to a fire in which the combustion occurs close to the base of the fire plume. However, if combustion continues within the fire plume, the release of heat increases the plume temperature and velocity. The turbulence intensity in a fire plume is high; the velocity fluctuations at the centerline can be up to 30 percent of the average velocity, and the temperature fluctuations can be even greater.

In general, a fire plume contains smoke particles. As surrounding air mixes into the plume, it dilutes the smoke and reduces the temperature. This mixing is called entrainment. In order to predict which environment a given fire will produce, it is necessary to know the rate of entrainment into the plume. Researchers have proposed various correlations to calculate the rate of entrainment in a fire plume, however, the results are not entirely reliable. Small ambient distribution in the air near the plume can also have substantial effects on the entrainment rate. When combustion occurs only in the lower portion of a plume, there is roughly an order of magnitude more entrained air present than the stoichiometric requirement at the plume height above when there is no combustion occurring.

A fire plume can be subdivided into flaming (reacting) and non-flaming (non-reacting) zones. The flaming zone lies just above the fire source and the fuel vapors released by the combustibles burn in this zone. The air required by the reaction is supplied by the entrainment attributable to the upward movement of the reactants. Above the flaming zone where no reaction is taking place in the column of hot products of combustion is defined as the non-flaming zone.

9.3 Fire Plume Characteristics

Fire plumes can be characterized into various groups, depending on the scenario under investigation. This chapter focuses on the point source thermal plume, which is the plume most commonly encountered in fire dynamics applications. The point source thermal plume (or axisymmetric buoyant plume), as described by George, Alpert, and Tamanini (1977) and Alpert and Ward (1984), results when a diffusion flame is formed above the burning fuel. An axis of symmetry is assumed to exist along the vertical centerline of the plume. Another fire plume category, known as the line plume, is caused by a diffusion flame formed above a long and narrow burner that allows air to be entrained from two sides as the hot gases rise. Examples of line fires including flame spread over flammable wall linings, a balcony spill plume, a long sofa, a row of townhouses, and the advancing front of forest fire.

The unconfined axisymmetric plume has no physical barriers to limit vertical movement or restrict air entrainment across the plume boundary. In a confined space the fire plume can be influenced by surrounding surfaces. For example, the area through which air may be entrained is reduced if an item is burning against a wall. Similarly, if the fire plume impinges on a ceiling, it will be deflected horizontally to form a ceiling jet. Impingement on a ceiling also reduces the amount of air entrained by the plume. The most important consequence of plumes interacting with their surroundings is heat transfer to the surfaces involved and the speed at which these surfaces (if combustible) will ignite and contribute to the fire growth process.

The axisymmetric fire plume is conventionally divided into three zones, as shown in Figure 9-2. In the continuous flame zone, the upward velocity is near zero at the base and increases with height. In the intermittent flame zone the velocity is relatively constant, while in the far field zone the velocity decreases with height.

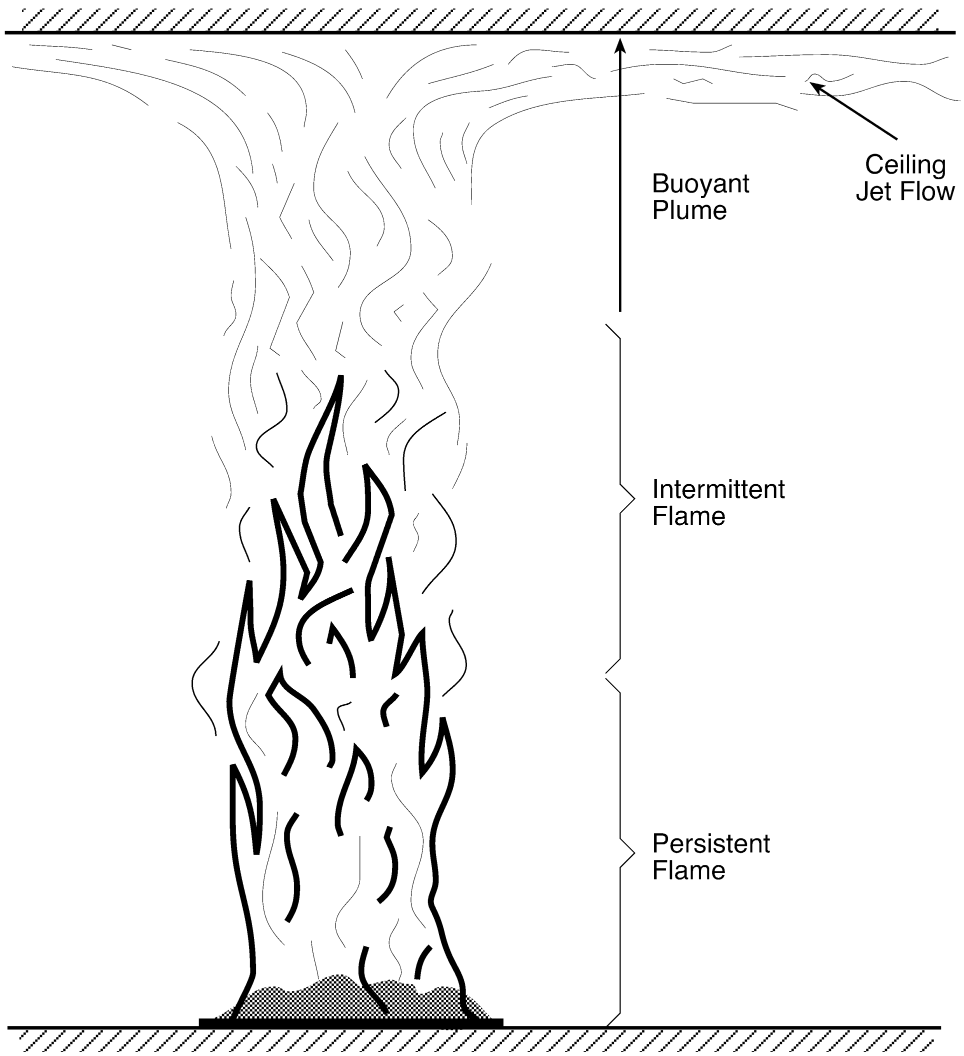


Figure 9-2 Three Zones of the Axisymmetric Buoyant Fire Plume

The quantity of air entrained, along with a resultant decrease in plume temperature and increase in the total mass transported in the plume, are governed by the plume velocity and entrainment coefficient. The entrained flow is proportional to the plume velocity at a particular elevation. This proportional constant is the entrainment coefficient. Hence, the amount of air entrained is related to the plume velocity multiplied by the entrainment coefficient.

Temperature, velocity, and mass flow rates of the fire plume above the flame are critical to the many technical aspects of fire growth in a compartment, including the following examples:

- the rate of formation and descent of the smoke layer
- the temperature and concentration of the hot smoke layer
- the required size of the smoke and heat venting systems
- the actuation time of sprinklers and detectors

9.3.1 Plume Temperature

The peak temperature is found in the plume centerline, and decreases toward the edge of the plume where more ambient air is entrained to cool the plume. The centerline temperature, denoted $T_{p(centerline)}$, varies with height. In the continuous flame region, for example, the centerline temperature is roughly constant and represents the mean flame temperature. By contrast, the temperature decreases sharply above the flames as an increasing amount of ambient air is entrained into the plume. The symbol $T_{p(centerline)}$ describes the increase in centerline plume temperature above the ambient temperature, T_a, as shown in the following equation:

$$\Delta T_{p(centerline)} = T_{p(centerline)} - T_a \quad (9\text{-}1)$$

Numerous correlations are available to estimate the plume centerline temperature. These correlations relate the temperature as a function of HRR and of height above the source. For example, consider a region of a ceiling jet at radial distance from the fire axis equal to the vertical distance from the fire source to the ceiling. In this region, the maximum velocity in the jet drops to half the value near the fire axis, and the temperature (relative to ambient) drops to about 40 percent of the value near the fire axis. The maximum velocity and temperature exist at a distance below the ceiling equal to about 1-percent of the distance from the fire source to the ceiling. If the walls are much farther away than this, the temperature and velocity of the ceiling jet decay to negligibly low values before the jet encounters the nearest wall. However, if the nearest wall is not far away, a reflection occurs when the jet reaches the wall, and the reflected jet moves back toward the fire axis just under the original jet. Thus, the hot layer under the ceiling becomes thicker.

If the compartment has an opening and fire continues, the hot layer ultimately becomes thick enough to extend below the top of the opening, after which the hot, smoke-laden gases begin to exit from the compartment.

Heskestad (1995) provided a simple correlation for estimating the maximum centerline temperature of a fire plume as a function of ceiling height and HRR:

$$T_{p(centerline)} - T_a = \frac{9.1\left(\frac{T_a}{g c_p^2 \rho_a^2}\right)^{\frac{1}{3}} \dot{Q}_c^{\frac{2}{3}}}{\left(z - z_0\right)^{\frac{5}{3}}} \qquad (9\text{-}2)$$

Where:

$T_{p(centerline)}$ = plume centerline temperature (K)
T_a = ambient air temperature (K)
$\dot{Q}_c$ = convective HRR (kW)
g = acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/Kg-K)
$_a$ = ambient air density (kg/m^3)
z = elevation above the fire source (m)
z_0 = hypothetical virtual origin of the fire (m)

The virtual origin is the equivalent point source height of a finite area fire (Figure 9-3). The location of the virtual origin is needed to calculate the thermal plume temperature for fires that originate in an area heat source. The thermal plume calculations are based on the assumption that the plume originates in a point heat source. Area heat sources include pool fires and burning three-dimensional objects such as cabinets and cable trays. The use of a point heat source model for area sources is accomplished by calculating the thermal plume parameters at the virtual point source elevation, rather than the actual area source elevation.

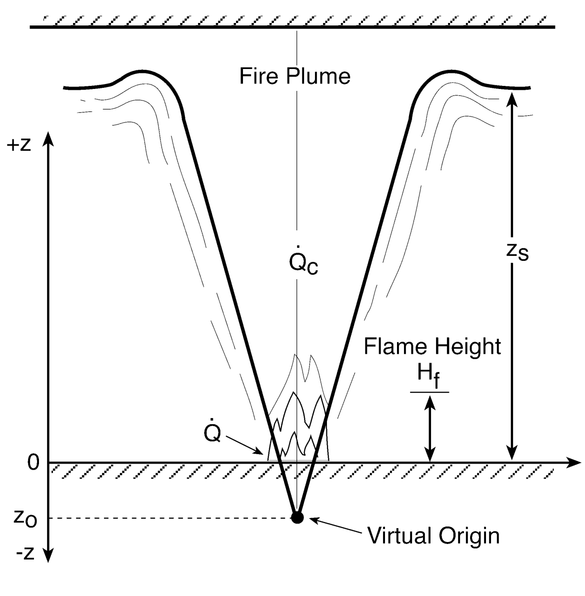


Figure 9-3 Fire Plume with Virtual Origin

The virtual origin, z_0, depends on the diameter of the fire source and the total energy released, as follows:

$$\frac{z_0}{D} = -1.02 + 0.083\frac{\dot{Q}^{\frac{2}{5}}}{D} \qquad (9\text{-}3)$$

Where:

z_0 = virtual origin (m)
D = diameter of fire source (m)
$\dot{Q}$ = total HRR (kW)

For non-circular pools, the effective diameter is defined as the diameter of a circular pool with an area equal to the actual area given by the following equation:

$$D = \sqrt{\frac{4A_f}{\pi}} \qquad (9\text{-}4)$$

Where:

D = diameter of the fire (m)
A_f = fuel spill area or curb area (m^2)

Total HRR $\dot{Q}$ is used when calculating the mean flame height and position of the virtual origin. However, the convective HRR $\dot{Q}_c$ is used when estimating other plume properties, since this is the part of the energy release rate that causes buoyancy. The energy losses attributable to radiation from the flame are typically on the order of 20 to 40 percent of the total HRR $\dot{Q}$. The higher of these values is valid for the sootier and more luminous flames, often from fuels that burn with a low combustion efficiency. The convective HRR is, therefore, often in the range 0.6 $\dot{Q}$ to 0.8 $\dot{Q}$ where $\dot{Q}$ is the total HRR.

9.4 Application for Centerline Fire Plume Correlation

The centerline temperature correlation can be used to predict the temperature increase of the structural elements and subsequent failure of the compartment structure. Also, thermal plume temperature may be used to estimate the temperature of a target located above the plume.

As previously discussed, it is common for a fire plume impinging on a ceiling to make a 90-degree turn and spread out readily under the ceiling, thereby forming a ceiling jet. This ceiling jet is important for two reasons:

(1) Devices to detect the fire, as well as automatic sprinklers, are generally mounted right under the ceiling. Knowledge of the time of arrival and properties of the ceiling jet are crucial to predict when a device will actuate. The actuation of devices, (e.g., sprinklers smoke and thermal detectors) are discussed in Chapters 10, 11, and 12.

(2) The downward thermal radiation from the ceiling jet (including a small fraction from the hot ceiling itself) is a major factor in preheating and igniting combustible items that are not yet involved in the fire. This radiation is very important in determining the rate of fire spread.

9.5 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations.

(1) All heat energy is released at a point.

(2) The correlation was developed for two-dimensional area sources.

(3) If the surrounding air is at an elevated temperature, the temperature difference between the plume and the surrounding environment is small. In this situation, the thermal plume cools less effectively, so Equation 9-2 will underestimate the temperature.

(4) The thermal plume equation is not valid when the momentum forces in a plume are more significant than the buoyant forces, as in a jet fire. If this type of situation is encountered, specialized calculation approaches should be used.

9.6 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) heat release rate of the fire (kW)

(2) distance from the top of the fuel to the ceiling (ft)

(3) surface area of the combustible fuel (ft^2)

9.7 Cautions

(1) Use (09_Plume_Temperature_Calculations.xls) spreadsheet in the CD-ROM for calculation.

(2) Make sure to use correct units when entering the input parameters.

9.8 Summary

This chapter discusses fire plume and ceiling jet flow concepts and related fire hazard calculations. The region of hot gas that flows above the flame is called a plume. The plume changes in temperature, velocity, and diameter primarily because surrounding air is entrained (or mixed) into the upward plume flow. This entrained air reduces the plume temperature and increases the width of the plume. The total flow of the gases increases rapidly high above the flame. The plume temperature and combustion product concentrations are highest just above the flame. Moving upward, the temperature decreases because the cooler entrained air from the surrounding environment is mixed with the hot plume gas flow. The concentration of combustion products is also reduced.

Estimating the centerline temperature of a fire plume involves the following steps:

(1) Calculate the diameter of the fire.

(2) Calculate the virtual origin of the fire.

(3) Calculate the convective HRR.

(4) Calculate the plume centerline temperature $T_{p(centerline)}$.

9.9 References

Alpert, R.L., and E.J. Ward, "Evaluation of Unsprinklered Fire Hazard," *Fire Safety Journal*, Volume 7, No. 177, 1984.

Heskestad, G., "Fire Plumes," Section 2, Chapter 2, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

George, W.K., R.L. Alpert and F. Tamanini, "Turbulence Measurements in an Axisymmetric Buoyant Plume," *International Journal of Heat Mass Transfer,* Volume 20*,* pp.1145–1154, 1977.

9.10 Additional Readings

Drysdale, D.D., *An Introduction to Fire Dynamics*, Chapter 4, "Diffusion Flames and Fire Plumes," 2nd Edition, John Wiley and Sons, New York, 1998.

Fire Dynamics, Course Guide, Federal Emergency Management Agency (FEMA), United States Fire Administration (USFA), National Emergency Training Center, Emmitsburg, Maryland, 1995.

Friedman, R., *Principle of Fire Protection Chemistry and Physics*, 3rd Edition, National Fire Protection Association, Quincy, Massachusetts, 1998.

Karlsson, B., and J.G. Quintiere, *Enclosure Fire Dynamics*, Chapter 4, "Fire Plumes and Flame Heights," CRC Press LLC, New York, pp. 181–225, 1999.

Quintiere, J.G., *Principles of Fire Behavior*, Delmar Publishers, Albany, New York, 1997.

9.11 Problems

Example Problem 9.11-1

Problem Statement
A steel beam is located 25 ft above the floor. Calculate the temperature of the beam exposed from a 34.5 ft^2 lube oil pool fire. Assume the HRR of the fire is 5,000 kW.

Solution

Purpose:
(1) Determine the plume centerline temperature for the pool fire scenario.

Assumptions:
(1) All heat is released at a point.
(2) Buoyant forces are more significant than momentum forces.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 09_Plume_Temperature_Calculations.xls

FDT^s Input Parameters:
-Heat Release Rate $(\dot{Q})$ = 5,000 kW
-Distance from the Top of the Fuel to the Ceiling (z) = 25 ft
-Area of Combustible Fuel (A_c) = 34.5 ft^2

Results*

Heat Release Rate $\dot{Q}$ (kW)	Plume Centerline Temperature ($T_{p(centerline)}$) °C (°F)
5,000	244 (471)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 09_Plume_Temperature_Calculations.xls

CHAPTER 9. ESTIMATING CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

Version 1805.0

The following calculations estimate the centerline plume temperature in a compartment fire.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
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

Heat Release Rate of the Fire (Q)	5000.00	kW		
Elevation Above the Fire Source (z)	25.00	ft	7.62	m
Area of Combustible Fuel (A_c)	34.50	ft^2	3.21	m^2
Ambient Air Temperature (T_a)	77.00	°F	25.00	°C
	Calculate		298.00	K

AMBIENT CONDITIONS

Specific Heat of Air (c_p)	1.00	kJ/kg-K
Ambient Air Density (ρ_a)	1.18	kg/m^3
Acceleration of Gravity (g)	9.81	m/sec^2
Convective Heat Release Fraction (χ_c)	0.70	

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

ESTIMATING PLUME CENTERLINE TEMPERATURE

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 2-6.*

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

Where $T_{p(centerline)}$ = plume centerline temperature (°C)
Q_c = convective portion of the heat release rate (kW)
T_a = ambient air temperature (K)
g = acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/kg-K)
ρ_a = ambient air density (kg/m^3)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fire (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\, Q$

Where Q_c = convective portion of the heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release fraction

Q_c = 3500 kW

Fire Diameter Calculation

$A_c = \pi D^2/4$

Where A_c = area of combustible fuel (m^2)
D = fire diameter (m)

$D = \sqrt{(4\,A_c/\pi)}$

D = 2.02 m

Hypothetical Virtual Origin Calculation

$z_0/D = -1.02 + 0.083\,(Q^{2/5})/D$

Where z_0 = virtual origin of the fire (m)
Q = heat release rate of fire (kW)
D = fire diameter (m)

z_0/D = 0.22

z_0 = 0.44 m

Centerline Plume Temperature Calculation

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

$T_{p(centerline)} - T_a =$	**218.97**	
$T_{p(centerline)} =$	**516.97**	K

$T_{p(centerline)} =$	**243.97** °C	**471.15** °F		**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 9.11-2

Problem Statement

Estimate the maximum plume temperature at the ceiling of an 8-ft-high room above a 1,000-kW trash fire with an area of 10 ft^2. Assume that the ambient air temperature is 77 °F.

Solution

Purpose:

(1) Determine the maximum plume centerline temperature for the transient combustible fire scenario.

Assumptions:

(1) All heat is released at a point.

(2) Buoyant forces are more significant than momentum forces.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 09_Plume_Temperature_Calculations.xls

FDT^s Input Parameters:

-Heat Release Rate $(\dot{Q})$ = 1000 kW

-Distance from the Top of the Fuel to the Ceiling (z) = 8 ft

-Area of Combustible Fuel (A_c) = 10 ft^2

Results*

Heat Release Rate $\dot{Q}$ (kW)	Plume Centerline Temperature ($T_{p(centerline)}$) °C (°F)
1,000	549 (1021)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 09_Plume_Temperature_Calculations.xls

CHAPTER 9. ESTIMATING CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

Version 1805.0

The following calculations estimate the centerline plume temperature in a compartment fire.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
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

Heat Release Rate of the Fire (Q)	1000.00	kW	
Elevation Above the Fire Source (z)	8.00	ft	2.44 m
Area of Combustible Fuel (A_c)	10.00	ft^2	0.93 m^2
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
	Calculate		298.00 K

AMBIENT CONDITIONS

Specific Heat of Air (c_p)	1.00	kJ/kg-K
Ambient Air Density (ρ_a)	1.18	kg/m^3
Acceleration of Gravity (g)	9.81	m/sec^2
Convective Heat Release Fraction (χ_c)	0.70	

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

ESTIMATING PLUME CENTERLINE TEMPERATURE

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 2-6.*

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

Where $T_{p(centerline)}$ = plume centerline temperature (°C)
Q_c = convective portion of the heat release rate (kW)
T_a = ambient air temperature (K)
g = acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/kg-K)
ρ_a = ambient air density (kg/m^3)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fire (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\,Q$

Where Q_c = convective portion of the heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release fraction

Q_c = 700 kW

Fire Diameter Calculation

$A_c = \pi D^2/4$

Where A_c = area of combustible fuel (m^2)
D = fire diameter (m)

$D = \sqrt{(4\,A_c/\pi)}$

D = 1.09 m

Hypothetical Virtual Origin Calculation

$z_0/D = -1.02 + 0.083\,(Q^{2/5})/D$

Where z_0 = virtual origin of the fire (m)
Q = heat release rate of fire (kW)
D = fire diameter (m)

z_0/D = 0.19

z_0 = 0.21 m

Centerline Plume Temperature Calculation

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

$T_{p(centerline)} - T_a =$	**524.40**
$T_{p(centerline)} =$	**822.40** K

$T_{p(centerline)} =$	**549.40 °C**	**1020.92 °F**	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
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CHAPTER 10. ESTIMATING SPRINKLER RESPONSE TIME

10.1 Objectives

This chapter has the following objectives:

- Explain the advantages and disadvantages of sprinklers.
- Identify the four basic types of sprinkler systems.
- Describe the purpose of sprinklers.
- Explain how sprinklers function.

10.2 Introduction

Sprinklers are manufactured in a variety of temperature ratings and orifice sizes. In selecting sprinkler systems, one must carefully consider the potential fire hazard, ceiling configuration, corrosiveness of the environment, susceptibility to damage, etc. Every situation must be thoroughly analyzed to choose the best type of sprinkler system for a given hazard.

Sprinklers produce a cooling effect on the fire when the water from a sprinkler vaporizes to cool the burning materials below their ignition temperature. Sprinklers are designed to control a fire. However, many times the sprinkler system extinguishes the fire because the surrounding materials can no longer heat to their ignition temperature. If the first sprinkler cannot control the fire, a second sprinkler is activated which provides additional cooling. This process continues until the fire is controlled. Sprinklers are reliable thermosensitive devices, they rarely fail, are cost effective, and typically use less water than fire hoses. This helps reduce the amount of equipment damage by applying water directly over the fire. Human response time (i.e., discovery of the fire, travel time by the fire brigade) usually takes much longer than the time required for automatic sprinklers to control a fire while it is still in the early stages. This also reduces the amount of time available for smoke to be produced and damage equipment.

There are four basic types of automatic sprinkler systems. Within these four basic categories, sprinkler systems can be further classified according to the hazard they protect (such as ordinary hazard or in-rack exposure protection), additives to the system (such as antifreeze or foam), or special connection to the system (such as multipurpose piping). Despite these various classifications, sprinkler systems can still be categorized as one of the following four basic types:

- The *automatic wet pipe sprinkler system* is the most prevalent type because it is permanently charged with water, meaning that it is always ready for a fire. When the fusible element of the sprinkler reaches its predetermined temperature, it activates and water flows out of the orifice toward the deflector, causing the water to finely spray on the burning combustibles. An alarm check valve is installed where the water initially enters from the supply source. That valve has fittings to permit the connection of both local and remote location alarms. It also acts as a "check valve," permitting water to flow only toward the sprinkler. The disadvantage of the wet pipe sprinkler system is that they are not suitable for automatic fire protection in unheated buildings, and should a sprinkler be broken from the piping or a pipe or fitting fail, water will be discharged on to building contents that may be susceptible to water damage.

- The *automatic dry pipe sprinkler system* is similar to the automatic wet pipe system, with the exception that the water in wet pipe system is replaced by compressed air (or nitrogen) and the alarm check valve is replaced by a dry pipe valve. Compressed air holds the dry pipe valve shut, thereby preventing water from entering the system. When a sprinkler activates the air is released, and the water pressure from the supply system opens the dry pipe valve. Water then enters the system, fills the piping, and is discharge by the open sprinkler. The use of a dry pipe sprinkler is subject to many limitations. They should only be used in low-temperature areas because of (1) delay time from releasing the compressed air to water availability and (2) internal pipe corrosion and tuberculation from alternating wet and dry periods.
- The *deluge system* simultaneously discharges water from every open sprinkler on the system. There are no fusible elements in the sprinklers or spray nozzles to hold back the water. The system turns on when a “deluge” valve at the water supply side automatically opens. The system is typically actuated by heat detectors mounted above the open sprinklers. Most deluge systems can also be manually actuated. One disadvantage to this system is water damage can be extensive because of the amount of water that is used with all of the open sprinklers.
- The *pre-action system* is similar to a deluge system with closed heads. Before the water can be released, two conditions must be satisfied. First, the fusible element of the sprinkler must be activated and, second the detector must open the deluge valve. The advantage to this system is that it reduces the amount of accidental discharge to water-sensitive equipment. The disadvantage is that the system is more expensive and complicated than an automatic wet pipe system.

The effectiveness of a sprinkler installation depends on many factors. Some factors are characteristics of the system itself, such as the thermal rating and spacing of the sprinklers, the depth at which the individual sprinklers are mounted below the ceiling, and their pressure and flow characteristics. Other factors are characteristics of the building or compartment in which the system is installed. Compartment characteristics include the height of the ceiling; the area of the compartment; and the presence of openings, joists, or ventilation currents at the ceiling level, which can affect the flow of hot gases. Still other factors depend upon the type of fire load in the compartment, such as the type of combustible and the closeness and height of its stacking, which can affect both the rate of fire development and the ability of the sprinkler system to control the fire.

As previously stated, sprinklers are the most reliable thermosensitive devices, but many factors can cause them to fail, including a lack of available water caused by a closed water supply valve; a broken water supply header; or an empty water tank. A fire pump could also fail to start automatically. If the pump is driven by an electric motor, such pump failures could result from a power failure. If the pump is driven by a diesel engine, pump failures could result from poor maintenance, dead batteries, or a lack of fuel. Other causes of failure could include shutting down for maintenance or repairs, allowing unusual items to enter water mains, corrosion or tuberculation in the sprinkler piping, corroded or painted sprinkler heads, partial sprinklers, combustible overloading, or an inadequate water supply.

Sprinkler technology is changing fast. The installation requirements for the common types of sprinklers are discussed in NFPA 13. Newer sprinklers that are not covered in NFPA 13 must be installed in accordance with their specific listing requirements.

There are three basic installation configurations of sprinklers (upright, pendant, and sidewall) and a number of different variations of the three. Within these three basic types of sprinklers, there are a number of different kinds of sprinklers:

- Spray sprinkler
- Conventional sprinkler
- Fast-response sprinkler
- Residential sprinkler
- Extended coverage sprinkler
- Quick-response sprinkler
- Quick-response extended coverage sprinkler
- Large-drop sprinkler
- Early suppression fast response (ESFR) sprinkler
- Open sprinkler
- Special sprinkler
- Specific application sprinkler
- Flush sprinkler
- Concealed sprinkler
- Recessed sprinkler
- Corrosion-resistant sprinkler
- In-rack sprinkler
- Dry sprinkler

The ESFR sprinkler is one of the newer sprinklers being widely used for high challenge fires. Unlike other sprinklers that are designed only to control fires, the ESFR is designed with a fast response, large water droplet size, and the velocity to extinguish a high-challenge fire. As a result, very strict design and installation requirements must be followed when using an ESFR sprinkler.

The extended coverage sprinkler is another relatively new sprinkler technology. This usually reduces the number of required branch lines, thereby decreasing the cost of the system.

10.3 Operating Principles of Automatic Sprinklers

The two main functions of an automatic sprinkler system are to (1) detect a fire and (2) control it or prevent its growth. Automatic sprinklers are installed to protect property and occupants, give warning of fire existence and control only in burning areas.

The most common sprinklers have either a soldered metallic element or a liquid-filled bulb. The NFPA Handbook, 18th Edition, defines fusible sprinklers as common fusible-style automatic sprinklers that operate when a metal alloy of a predetermined melting point fuses. Various combinations of levers, struts, and links or other soldered members are used to reduce the force acting upon the solder so that the sprinkler is held closed with the smallest practical amount of metal and solder. This minimizes the time of operation by reducing the mass of fusible metal to be heated. The solders used with the automatic sprinklers are alloys of optimum fusibility composed primarily of tin, lead cadmium, and bismuth, which all have sharply defined melting points. Although an individual metal may have a low melting point, an alloy that includes that metal may have a lower melting point. The mixture of two or more metals that gives the lowest possible melting point is called a *eutectic alloy*.

Bulb sprinklers are a second style of operating element. Such sprinklers use a process in which heat causes the liquid in the bulb to expand and shatter the bulb at a predetermined temperature. This releases a seal valve and allows water to be sprayed onto the burning materials by the deflector. The predetermined temperature can be changed by adjusting the type and amount of liquid in the bulb. Bulb sprinklers are the most stable against atmospheric corrosion.

Other styles of thermosensitive operating elements that may be employed to provide automatic discharge include bimetallic discs, fusible alloy pellets, and chemical pellets.

10.3.1 Heat Transfer Characteristics for Heat-Sensitive Elements

Figure 10-1 schematically illustrates the fundamental heat transfer characteristics for the heat-sensitive element of the sprinkler. Conduction from the heated gas, convection from the heated gas, and radiation from the fire combine to transfer heat to the fusible element. Heat is always transferred away from the element by conduction to its supporting structure. Heat-sensitive elements are generally not perfectly insulated from other components of the sprinkler. The link mechanism holds the sprinkler closed and finite thermal resistance permits heat flow from the element. The quantity versus time history for the difference between the in-flow and out-flow of heat determines the time for the element to reach its operating temperature.

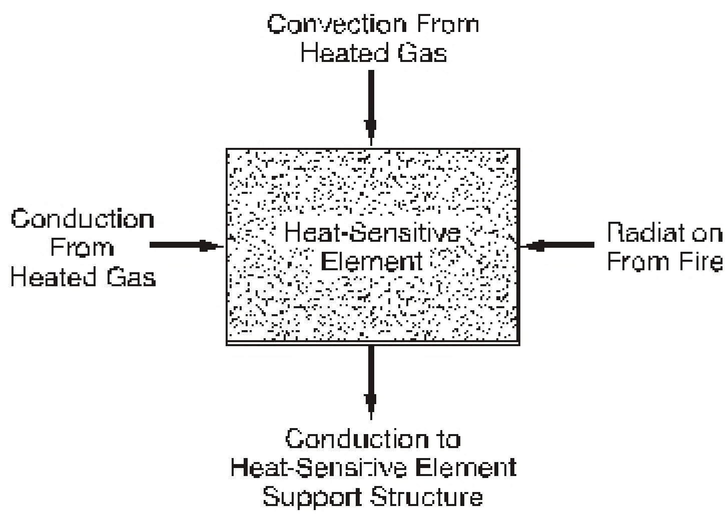

Figure 10-1 Heat Transfer Characteristics of the Heat-Sensitive Element of a Sprinkler

10.3.2 Sprinkler Dynamics

Figure 10-2 shows how the mechanical force exists in a solder-type link-and-lever-style automatic sprinkler. The construction shown is diagrammatic and does not represent any particular sprinkler. This figure is reproduced from the NFPA Handbook, 18th Edition (Isman, 1997).

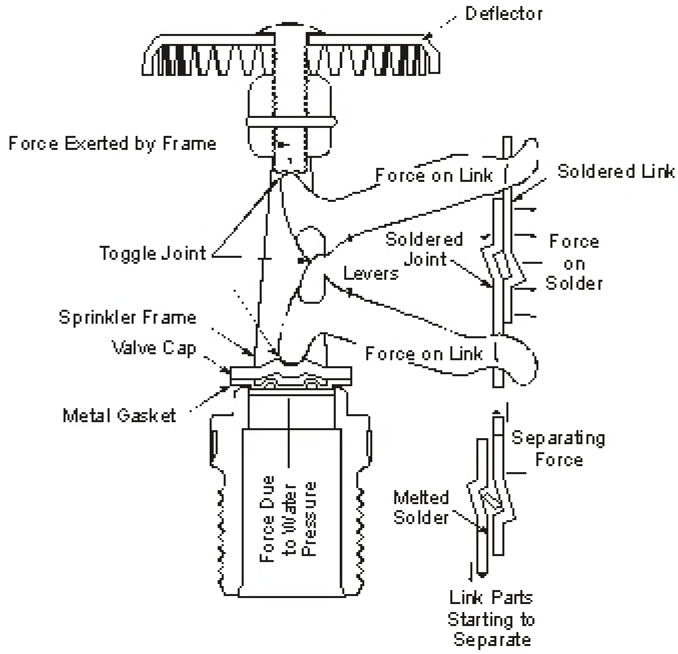

Figure 10-2 Representative Arrangement
of a Solder-Type Link-and-Lever Automatic Sprinkler
(Adapted from NFPA Handbook 18th Edition, 1997 with permission)

The mechanical force normally exerted on the top of the cap or valve is many times that developed by the water pressure below, so that the possibility of leakage, even from water hammer or exceptionally high pressure, is practically eliminated. The mechanical force in a link-and-lever sprinkler is produced by tension in the sprinkler frame, usually created by tightening the screw that holds the deflector down against the toggle joint formed by the levers. This pressure is applied against the valve or cap, but the line of force is not direct. The eccentricity of the loading permits a leveraged reduction of the force, first by the toggle effect of the two levers, and second by the mechanism of the link parts. The force resisted by the solder is made relatively low because solder of the composition needed to give the desired operating temperatures is subject to cold flow under high stress. The sprinkler frame or other parts usually posses a degree of elasticity to provide the energy that produces a positive, sharp release of the operating parts.

To ensure that cold flow will not be a problem, the laboratories that test and list sprinklers use statistical methods to simulate long-term loading of heat-responsive elements. Statistical methods are also employed to ensure that the crush strength of glass bulbs is sufficiently higher than the frame loads that will be applied to the bulbs.

10.3.3 Temperature Ratings of Automatic Sprinklers

Automatic sprinklers have various temperature ratings that are based on the UL standardized test (Operating temperature (bath) test) in which a sprinkler is immersed in a liquid and temperature of the liquid is raised very slowly until the sprinkler operates. In the bath test, an automatic sprinkler operates within a range having a maximum temperature not to excess of either 5 °C (10 °F) or 107 percent of the minimum temperature of the range, whichever is greater. For the purpose of this determination, the marked temperature rating is to be included as one of the values within the range, making a total of eleven values in the range. Water is to be used in bath tests of sprinklers that have operating temperature ratings of 79 °C (175 °F) or lower. Samples having operating temperature ratings of 80–302 °C (176–575 °F) are to be bath-tested in an oil having a flash point exceeding the test temperature (Bryan, 1990).

General sprinkler ratings are given in Table 10-1, based on the NFPA 13, "Standard for Installation of Sprinkler Systems."

Table 10-1. Temperature Ratings, Classification, and Color Coding of Automatic Sprinklers

Maximum Ceiling Temperature °C (°F)	**Temperature Rating °C (°F)**	**Temperature Classification**	**Color Code**	**Glass Bulb Color**
38 (100)	57–77 (135–170)	Ordinary	Uncolored or black	Orange or red
66 (150)	79–107 (175–225)	Intermediate	White	Yellow or green
107 (225)	121–149 (250–300)	High	Blue	Blue
149 (300)	163–191 (325–375)	Extra high	Red	Purple
191 (375)	204–246 (400–475)	Very extra high	Green	Black
246 (475)	260–302 (500–575)	Ultra high	Orange	Black
329 (625)	343 (650)	Ultra high	Orange	Black

The temperature rating of each fusible-element-style automatic sprinkler is typically stamped on the soldered link. For bulb sprinklers, the temperature rating must be stamped or cast on some visible part of the sprinkler such as the deflector. Color codes are also used for glass bulbs and frame arms of fusible-element sprinklers. In addition, the recommended maximum room temperature is restricted for both bulbs and fusible-element sprinklers because fusible-element begins to lose its strength somewhat below its actual melting point. Premature operation of a solder sprinkler usually depends on the extent to which the normal room temperature is exceeded, the duration of the excessive temperature, and the load on the operating parts of the sprinkler. While glass bulb sprinklers do not lose strength at temperatures close to their operating temperatures, using them at such temperatures can result in continuous loss and reforming of the air bubble, which creates stresses on the bulb (NFPA Handbook, 18th Edition, 1997). Table 10-2 provides temperature ratings for sprinklers.

Table 10-2. Generic Sprinkler Temperature Rating ($T_{activation}$)

Temperature Classification	**Range of Temperature Ratings °C (°F)**	**Generic Temperature Ratings °C (°F)**
Ordinary	57–77 (135–170)	74 (165)
Intermediate	79–107 (175–225)	100 (212)
High	121–149 (250–300)	135 (275)
Extra high	163–191 (325–375)	177 (350)
Very extra high	204–246 (400–475)	232 (450)
Ultra high	260–302 (500–575)	288 (550)
Ultra high	343 (650)	288 (550)

The concept of a response time index (RTI) was developed by Factory Mutual Research Corporation (FMRC) to be a fundamental measure of thermal sprinkler sensitivity. A sprinkler's RTI is determined in plunge tests with a uniform gas flow of constant temperature and velocity and can be used to predict the sprinkler's activation time in a fire environment. The RTI was developed under the assumption that conductive heat exchange between the sensing element and supportive parts is negligible. The RTI is a function of the time constant, , of the sprinkler which is related to the mass and surface area of the sprinkler thermal element. Faster sprinklers have low RTIs and smaller time constants. Sprinkler thermal elements with low time constants have low ratios of mass to surface area. This is the basis of quick-response sprinklers.

The RTI is defined by the following equation:

$$RTI = \frac{m_e c_{p(e)}}{h_e A_e} \sqrt{u_{jet}} \qquad (10\text{-}1)$$

Where:

m_e = mass of element (kg)
$c_{p(e)}$ = specific heat of element (kJ/kg-K)
h_e = convective heat transfer coefficient (kW/m^2-K)
A_e = surface area of element (m^2)
u_{jet} = velocity of gas moving past the sprinkler (m/sec)

Table 10-3 provides generic RTIs for sprinklers.

Table 10-3. Generic Sprinkler Response Time Index (RTI)

Common Sprinkler Type	**Generic Response Time Index RTI (m-sec)$^{1/2}$**
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34

NFPA 13 states that "ordinary-temperature-rated sprinklers shall be used throughout the buildings" unless the temperature of the building is other than normal. NFPA 13 goes onto define three cases that would follow in the event of an "abnormal" temperature: These cases are as follows:

(1) "When the maximum ceiling temperatures exceed 38 °C (100 °F), sprinklers with temperatures in accordance with the maximum ceiling temperatures of Table 10-1 shall be used."

(2) "Intermediate- and high-temperature sprinklers shall be permitted to be used throughout ordinary and extra hazard occupancies."

(3) Sprinkler should be installed with intermediate-temperature classification if they are "located within 12 in. (305 mm) to one side or 30 in. (762 mm) above an uncovered steam main, heating coil, or radiator; sprinklers under glass or plastic skylights exposed to direct rays of the sun; sprinklers in an unventilated, concealed space, under an uninsulated roof, or in an unventilated attic; or sprinklers in unventilated show windows having high-powered electric lights near the ceiling. Sprinklers within 2.1 m (7 ft) of a low-pressure blow-off valve that discharges free in a large room" should be classified with high-temperature classification. Sprinklers protecting commercial-type cooking equipment and ventilation systems shall be of the high-or extra-high-temperature classification as determined by use of a temperature measuring device."

10.3.4 Sprinkler Activation

As part of a fire hazard analysis, it is often desirable to estimate both the burning characteristics of selected fuels and their effects in enclosures, as well as when fire protection devices (such as automatic sprinklers or heat and smoke detectors) will activate for specific fire conditions. Equations are available to permit the user to estimate these effects, principally on the basis of experimental correlations.

It has been determined experimentally that convective heat transfer is the most important element in activating sprinklers. Convective heat transfer involves heat transfer through a circulating medium, which, in the case of fire sprinklers, is the room air. The air heated by the fire rises in a plume, entraining other room air as it rises. When the plume hits the ceiling, it generally splits to produce a ceiling gas jet (ceiling jet refers to the relatively rapid gas flow in a shallow layer beneath the ceiling surface, which is driven by the buoyancy of the hot combustion products). The thickness of the ceiling jet flow is approximately 5 to 12-percent of the height of the ceiling above the fire source, with the maximum temperature and velocity occurring 1-percent of the distance from the ceiling to the fire source. The heat sensing elements of the sprinklers within this ceiling jet are then heated by conduction of the heat from the air.

Researchers have developed computer programs to calculate the response time of sprinklers installed below the unconfined ceilings. These programs can determine the time to operation for a user specified fire HRR history. They are convenient to use because they enable the analyst to avoid the tedious repetitive calculations needed to analyze a growing fire. However, an analyst can easily perform these calculations with a scientific hand calculator for steady fires that have a constant HRR. In cases requiring a more detailed analysis of a fire that has important changes in HRR over time, the fire may be represented as a series of steady fires occurring immediately after one another.

For steady-state fires, the time ($t_{activation}$) required to heat the sensing element of a suppression device from room temperature to operation temperature is given by the following equation (Budnick, Evans, and Nelson, 1997):

$$t_{activation} = \frac{RTI}{\sqrt{u_{jet}}} \ln\left(\frac{T_{jet} - T_a}{T_{jet} - T_{activation}}\right) \qquad (10\text{-}2)$$

Where:

$t_{activation}$ = sprinkler head activation time (sec)
RTI = response time index $(m\text{-}sec)^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$T_{activation}$ = activation temperature of sprinkler head (°C)

The expressions for estimating the maximum ceiling jet temperature and velocity as a function of ceiling height, radial position, and HRR were developed from analysis of experiments with large-scale fires having HRR from 668 kW to 98,000 kW. The expressions are given for two regions—one where the plume directly strikes the ceiling and the other outside the plume region where a true horizontal flow exists.

The ceiling jet temperature and velocity correlations of a fire plume are given by the following expressions:

$$T_{jet} - T_a = \frac{16.9 \ \dot{Q}^{\frac{2}{3}}}{H^{\frac{5}{3}}} \qquad \text{for } \frac{r}{H} \leq 0.18 \qquad (10\text{-}3)$$

$$T_{jet} - T_a = \frac{5.38 \left(\frac{\dot{Q}}{r}\right)^{\frac{2}{3}}}{H} \qquad \text{for } \frac{r}{H} > 0.18 \qquad (10\text{-}4)$$

$$u_{jet} = 0.96 \left(\frac{\dot{Q}}{H}\right)^{\frac{1}{3}} \qquad \text{for } \frac{r}{H} \leq 0.15 \qquad (10\text{-}5)$$

$$u_{jet} = \frac{0.195 \ \dot{Q}^{\frac{1}{3}} \ H^{\frac{1}{2}}}{r^{\frac{5}{6}}} \qquad \text{for } \frac{r}{H} > 0.15 \qquad (10\text{-}6)$$

Where:

T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$\dot{Q}$ = heat release rate of the fire (kW)
r = radial distance from the plume centerline to the sprinkler head (m)
H = distance from the top of the fuel package to the ceiling level (m)
u_{jet} = ceiling jet velocity (m/sec)

The above correlations are used extensively to calculate the maximum temperature and velocity in the ceiling jet at any distance, r, from the fire axis. Note that the regions for which each expression is valid are given as a function of the ratio of the radial position, r, to the ceiling height, H. Moving away from the centerline of the plume jet, r/H increases. For regions where r/H>0.18, Equation 10-4 is used. Based on the cases where the hot gases have begun to spread under a ceiling located above the fire, Equation 10-3 applies for a small radial distance, r, from the impingement point. (See Figure 10-3.)

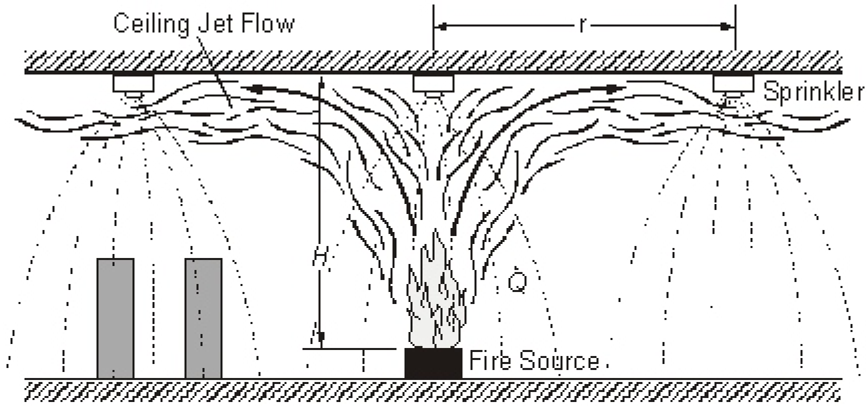

Figure 10-3 Ceiling Jet Flow Beneath an Unconfined Ceiling and Sprinkler Activation

As with the velocities in the ceiling jet flow, u_{jet}, there are two regions, under a ceiling including (1) one close to the impingement point where velocities are nearly constant and (2) another farther away where velocities vary with radial position.

The ceiling jet temperature is important in fire safety because it is generally the region where sprinklers are located; therefore, knowledge of the temperature and velocity of the ceiling jet as a function of position enables us to estimate the sprinklers response time.

The temperature and velocity of a ceiling jet also vary with the depth of the jet. Moving away from the ceiling, the temperature increases to a maximum, then decreases closer to the edge of the jet. This profile is not symmetric as it is with a plume, the maximum occurs along the plume centerline.

With knowledge of plume ceiling jet temperature and velocity, we can estimate the actuation time of a sprinkler, if we also know the spacing and the speed or thermal inertia of the sprinkler. The response of a sprinkler head is given by its RTI.

10.3.5 Sprinkler Spray Interaction with Plume

Once a sprinkler head actuates, water must penetrate the plume to reach the burning fuel surfaces. For this reason, the droplets must have sufficient velocity and size to penetrate through the hot gases flowing in the opposite direction. If a droplet is too small, it will evaporate and/or be moved upward by the plume. For very high-energy release rate fires that grow quickly, it is sometimes necessary to use large drop sprinklers designed to yield droplet sizes and velocities that carry the drops through the plume and flame onto the burning surface.

10.4 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations:

(1) The method assumes the ceiling is unconfined, unobstructed, smooth, flat, and horizontal. The method does not account for effects due to walls or overhead obstructions.

(2) The plume ceiling jet correlations of temperature and velocity assume that the fire source is located away from walls and corners. The primary impact of walls and corners is to reduce the amount of entrained air into the plume. This has the effect of lengthening flames and causing the temperature in a plume to be higher at a given elevation than it would be in the open.

(3) The correlations for estimating the maximum ceiling jet temperature and velocity were developed for steady-state fires and plumes under unconfined ceilings (where the smoke layer does not develop below the ceiling jet during the time of interest).

(4) The plume ceiling jet correlations are valid for unconfined ceilings, as the environment for the outside ceiling jet is uniform in temperature and atmospheric ambient.

(5) All calculations for determining time to operation only consider the convective heating of sensing elements by the hot fire gases. They do not explicitly account for any direct heating by radiation from the flames. The sprinkler is treated as a lumped mass model. The lumped model assumes that thermal gradients are neglected within the thermal element.

(6) This method does not apply to predict response time of sprinklers installed on heat collectors[1] far below the ceiling (in mid air). When sprinklers are too far below the ceiling, most of the heat energy rises past the sprinklers and heat collectors and the sprinklers are not activated. Locating the sprinkler close to the ceiling ensures that the sprinkler will be in the hot gas layer, minimizing activation time and enabling the sprinkler to provide a fully developed water supply pattern to control the fire[2].

10.5 Required Input for Spreadsheet Calculations

The user must obtain the following parameters before using the spreadsheet:

(1) heat release rate of the fire (kW)
(2) activation temperature of the sprinkler (°F)
(3) distance from top of fuel package to the ceiling (ft)
(4) radial distance from the plume centerline to the sprinkler (ft)
(5) ambient air temperature (°F)
(6) sprinkler type

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[1] A flat shield installed above sprinklers.

[2] NRC Information Notice 2002-24, "Potential Problems with Heat Collectors on Fire Protection Sprinklers," July 19, 2002.

10.6 Cautions

(1) Use (10_Detector_Activation_Time.xls) and select the "Sprinkler" spreadsheet on the CD-ROM for estimating sprinkler response time.
(2) Make sure to input parameters using the correct units.

10.7 Summary

This chapter discusses a method of calculating the response time of sprinkler under an unconfined smooth ceiling in response to steady-state fires. Parameters H and r both relate to the calculation of sprinkler actuation time.

10.8 References

Bryan, J.L., *Automatic Sprinkler and Standpipe Systems*, 2nd Edition, Appendix C, "Operating Temperature (Bath) Test," p. 505, National Fire Protection Association, Quincy, Massachusetts, 1990.

Budnick, E.K., D.D. Evans, and H.E. Nelson, "Simplified Fire Growth Calculations" Section 11, Chapter 10, *NFPA Fire Protection Handbook*, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1997.

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NFPA 13, "Standard for Installation of Sprinkler Systems," 2002 Edition, National Fire Protection Association, Quincy, Massachusetts.

10. 9 Additional Readings

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Alpert, R.L., and E.J. Ward, "Evaluation of Unsprinklered Fire Hazard," *Fire Safety Journal*, Volume 7, No. 177, 1984.

Bryan, J.L., *Fire Suppression and Detection Systems*, Macmillan Publishing Company, New York, 1993.

Fire Dynamics Course Guide, Federal Emergency Management Agency (FEMA), United States Fire Administration (USFA), National Emergency Training Center, Emmitsburg, Maryland, 1995.

Heskestad, G., "Fire Plumes," Section 2, Chapter 2, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

Schifiliti, R.P., B.J. Meacham, and R.P. Custer, "Design of Detection Systems," Section 4, Chapter 1, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

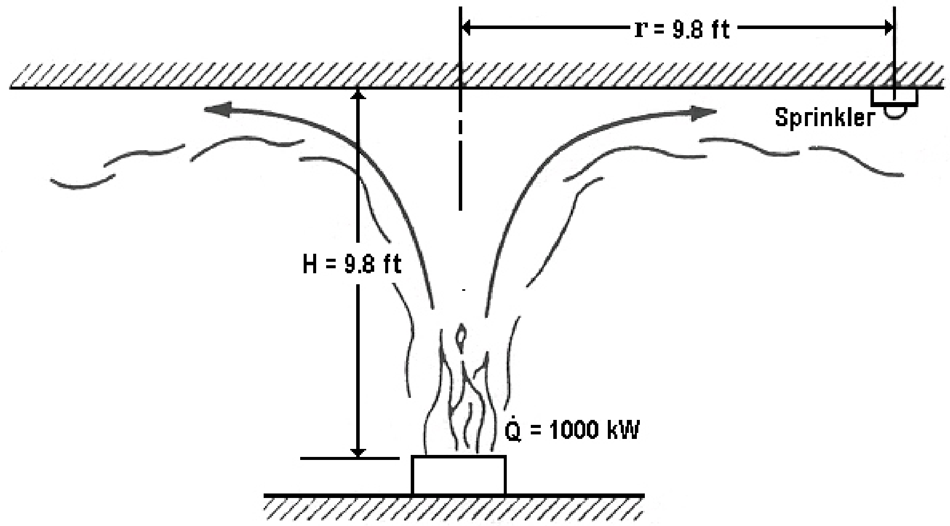
Zalosh, R.G., *Industrial Fire Protection*, John Wiley & Sons Ltd., West Sussex, England, 2003.

10.10 Problems

Example Problem 10.10-1

Problem Statement

A fire with $\dot{Q}$ = 1,000 kW occurs in a space that is protected with sprinklers. Sprinklers are rated at 165 °F (74 °C) [standard response link with RTI = 130 $(m\text{-}sec)^{1/2}$] and located 9.8 ft (3 m) on center. The ceiling is 9.8 ft (3.0 m) above the fire. The ambient temperature is 77 °F. Would the sprinklers activate, and if so how long would it take for them to activate?



Solution

Purpose:
- (1) Determine if the sprinklers will be activated for the fire scenario.
- (2) If the sprinkles are activated, how long would it take for them to activate?

Assumptions:
- (1) The fire is located away from walls and corners.
- (2) The fire is steady state.
- (3) The ceiling is unconfined.
- (4) Only convective heat transfer from the hot fire gases is considered.
- (5) There is no heavily obstructed overhead.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (click on *Sprinkler*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 1,000 kW

-Distance from the Top of the Fuel Package to the Ceiling (H) = 9.8 ft

-Radial Distance from the Plume Centerline to the Sprinkler (r) = 9.8 ft

-Ambient Air Temperature (T_a) = 77 °F

-Select Type of Sprinkler = Standard response link

-Select Sprinkler Classification = Ordinary

Note: Ordinary classification has been selected because the rated value for the sprinklers in this problem (165 °F) is within the range of temperature ratings for ordinary sprinklers (135 °F – 170 °F).

Results*

Sprinkler Type	Sprinkler Activation Time ($t_{activation}$) (min.)
Standard response link	2.9

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 10_Detector_Activation_Time.xls (Sprinkler)

CHAPTER 10. ESTIMATING SPRINKLER RESPONSE TIME

Version 1805.0

The following calculations estimate sprinkler activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Sprinkler Selected.
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

Heat Release Rate of the Fire (Q) (Steady State)	1000.00	kW	
Sprinkler Response Time Index (RTI)	130	(m-sec)$^{1/2}$	
Activation Temperature of the Sprinkler ($T_{activation}$)	165	°F	73.89 °C
Height of Ceiling above Top of Fuel (H)	9.80	ft	2.99 m
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	9.80	ft	2.99 m
Ambient Air Temperature (T_a)	68.00	°F	20.00 °C
			293.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		

r/H = 1.00

Calculate

GENERIC SPRINKLER RESPONSE TIME INDEX (RTI)*

Common Sprinkler Type	Generic Response Time Index (RTI) (m-sec)$^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34
User Specified Value	Enter Value

Select Type of Sprinkler
Standard response link
Scroll to desired sprinkler type then Click on selection

Reference: *Madrzykowski, D., "Evaluation of Sprinkler Activation Prediction Methods" ASIAFLAM'95, International Conference on Fire Science and Engineering, 1st Proceeding, March 15-16, 1995, Kowloon, Hong Kong, pp. 211-218.*

*Note: The actual RTI should be used when the value is available.

GENERIC SPRINKLER TEMPERATURE RATING ($T_{activation}$)*

Temperature Classification	Range of Temperature Ratings (°F)	Generic Temperature Ratings (°F)
Ordinary	135 to 170	165
Intermediate	175 to 225	212
High	250 to 300	275
Extra high	325 to 375	350
Very extra high	400 to 475	450
Ultra high	500 to 575	550
Ultra high	650	550
User Specified Value	–	Enter Value

Select Sprinkler Classification
Ordinary
Scroll to desired sprinkler class then Click on selection

Reference: *Automatic Sprinkler Systems Handbook, 6th Edition, National Fire Protection Association, Quincy, Massachusetts, 1994, Page 67.*

*Note: The actual temperature rating should be used when the value is available.

ESTIMATING SPRINKLER RESPONSE TIME

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\ (\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = sprinkler activation response time (sec)

RTI = sprinkler response time index (m-sec)$^{1/2}$

u_{jet} = ceiling jet velocity (m/sec)

T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

$T_{activation}$ = activation temperature of sprinkler (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\ (Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38\ (Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

Q_c = convective portion of the heat release rate (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the sprinkler (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c Q$

Where Q_c = convective portion of the heat release rate (kW)

Q = heat release rate of the fire (kW)

χ_c = convective heat release rate fraction

Q_c = 700 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.00 r/H > 0.15

$T_{jet} - T_a$ = {5.38 (Qc/r)^2/3}/H

$T_{jet} - T_a$ = 68.46

T_{jet} = 88.46 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\ (Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\ Q^{1/3}\ H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)

Q = heat release rate of the fire (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the sprinkler (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.00 r/H > 0.15

u_{jet} = (0.195 Q^1/3 H^1/2)/r^5/6

u_{jet} = 1.354 m/sec

Sprinkler Activation Time Calculation

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\,(\ln\,(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation} =$ 172.85 sec

The sprinkler will respond in approximately	2.88 minutes	**Answer**

NOTE: If $t_{activation}$ = "NUM" Sprinkler does not activate

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

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Example Problem 10.10-2

Problem Statement
If the sprinklers in Problem 10-1 are replaced by sprinklers with a response time index (RTI) of 235 (m-sec)$^{1/2}$, how long would it take for them to activate?

Solution

Purpose:
(1) Determine the activation time for the specified sprinkles under the fire scenario of Problem 10-1.

Assumptions:
(1) The fire is located away from walls and corners.
(2) The fire is steady state.
(3) The ceiling is unconfined.
(4) Only convective heat transfer from the hot fire gases is considered.
(5) There is no heavily obstructed overhead.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 10_Detector_Activation_Time.xls (click on *Sprinkler*)
FDT^s Input Parameters:
-Heat Release Rate of the Fire $(\dot{Q})$ = 1000 kW
-Distance from the Top of the Fuel Package to the Ceiling (H) = 9.8 ft
-Radial Distance from the Plume Centerline to the Sprinkler (r) = 9.8 ft
-Ambient Air Temperature (T_a) = 77 °F
-Select Type of Sprinkler = Standard response bulb
-Select Sprinkler Classification = Ordinary
Note: The RTI value of 235 (m-sec)$^{1/2}$ corresponds to standard response bulb sprinkler. Ordinary classification has been selected because the rated value for the sprinklers in this problem (165 °F, same as Problem 10-1) is within the range of temperature ratings for ordinary sprinklers (135 °F – 170 °F).

Results*

Sprinkler Type	Sprinkler Activation Time ($t_{activation}$) (min.)
Standard response bulb	5.2

*see spreadsheet on next page

Spreadsheet Calculations

FDTs: 10_Detector_Activation_Time.xls (Sprinkler)

CHAPTER 10. ESTIMATING SPRINKLER RESPONSE TIME

Version 1805.0

The following calculations estimate sprinkler activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Sprinkler Selected.
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

Heat Release Rate of the Fire (Q) (Steady State)	1000.00	kW	
Sprinkler Response Time Index (RTI)	235	(m-sec)$^{1/2}$	
Activation Temperature of the Sprinkler ($T_{activation}$)	165	°F	73.89 °C
Height of Ceiling above Top of Fuel (H)	9.80	ft	2.99 m
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	9.80	ft	2.99 m
Ambient Air Temperature (T_a)	68.00	°F	20.00 °C
			293.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		

r/H = 1.00

Calculate

GENERIC SPRINKLER RESPONSE TIME INDEX (RTI)*

Common Sprinkler Type	Generic Response Time Index (RTI) (m-sec)$^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34
User Specified Value	Enter Value

Select Type of Sprinkler
Standard response bulb
Scroll to desired sprinkler type then Click on selection

Reference: *Madrzykowski, D., "Evaluation of Sprinkler Activation Prediction Methods" ASIAFLAM'95, International Conference on Fire Science and Engineering, 1st Proceeding, March 15-16, 1995, Kowloon, Hong Kong, pp. 211-218.*

*Note: The actual RTI should be used when the value is available.

GENERIC SPRINKLER TEMPERATURE RATING ($T_{activation}$)*

Temperature Classification	Range of Temperature Ratings (°F)	Generic Temperature Ratings (°F)
Ordinary	135 to 170	165
Intermediate	175 to 225	212
High	250 to 300	275
Extra high	325 to 375	350
Very extra high	400 to 475	450
Ultra high	500 to 575	550
Ultra high	650	550
User Specified Value	–	Enter Value

Select Sprinkler Classification
Ordinary
Scroll to desired sprinkler class then Click on selection

Reference: *Automatic Sprinkler Systems Handbook, 6th Edition, National Fire Protection Association, Quincy, Massachusetts, 1994, Page 67.*

*Note: The actual temperature rating should be used when the value is available.

ESTIMATING SPRINKLER RESPONSE TIME

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\,(\ln(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = sprinkler activation response time (sec)

RTI = sprinkler response time index (m-sec)$^{1/2}$

u_{jet} = ceiling jet velocity (m/sec)

T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

$T_{activation}$ = activation temperature of sprinkler (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\,(Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38\,(Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

Q_c = convective portion of the heat release rate (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the sprinkler (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\,Q$

Where Q_c = convective portion of the heat release rate (kW)

Q = heat release rate of the fire (kW)

χ_c = convective heat release rate fraction

Q_c = 700 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.00 r/H > 0.15

$T_{jet} - T_a$ = {5.38 (Qc/r)^2/3}/H

$T_{jet} - T_a$ = 68.46

T_{jet} = 88.46 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\,(Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\,Q^{1/3}\,H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)

Q = heat release rate of the fire (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the sprinkler (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.00 r/H > 0.15

u_{jet} = (0.195 Q^1/3 H^1/2)/r^5/6

u_{jet} = 1.354 m/sec

Sprinkler Activation Time Calculation

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\ (\ln\ (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation} =$ 312.45 sec

The sprinkler will respond in approximately	5.21 minutes	**Answer**

NOTE: If $t_{activation}$ = "NUM" Sprinkler does not activate

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
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CHAPTER 11. ESTIMATING SMOKE DETECTOR RESPONSE TIME

11.1 Objectives

This chapter has the following objectives:

- Introduce the critical factors that influence smoke detector performance.
- Identify the various types of smoke detectors.
- Describe how to estimate the response time of a smoke detector.

11.2 Introduction

Reliable fire detection is an essential part of the fire protection program in nuclear power plants (NPPs), it relates to both fire control or extinguishment and safe evacuation of occupants. Most of the devices associated with fire detection and suppression are typically located near the ceiling surfaces. In the event of a fire, hot gases in the fire plume rise directly above the burning fuel and impinge upon the ceiling. The ceiling surface causes the flow to turn and move horizontally beneath the ceiling to other areas of the building located at some distance from the fire. The response of detection devices (heat/smoke detectors) and sprinklers installed below the ceiling submerged in this hot flow of combustion products provides the basis for the building's active fire protection features.

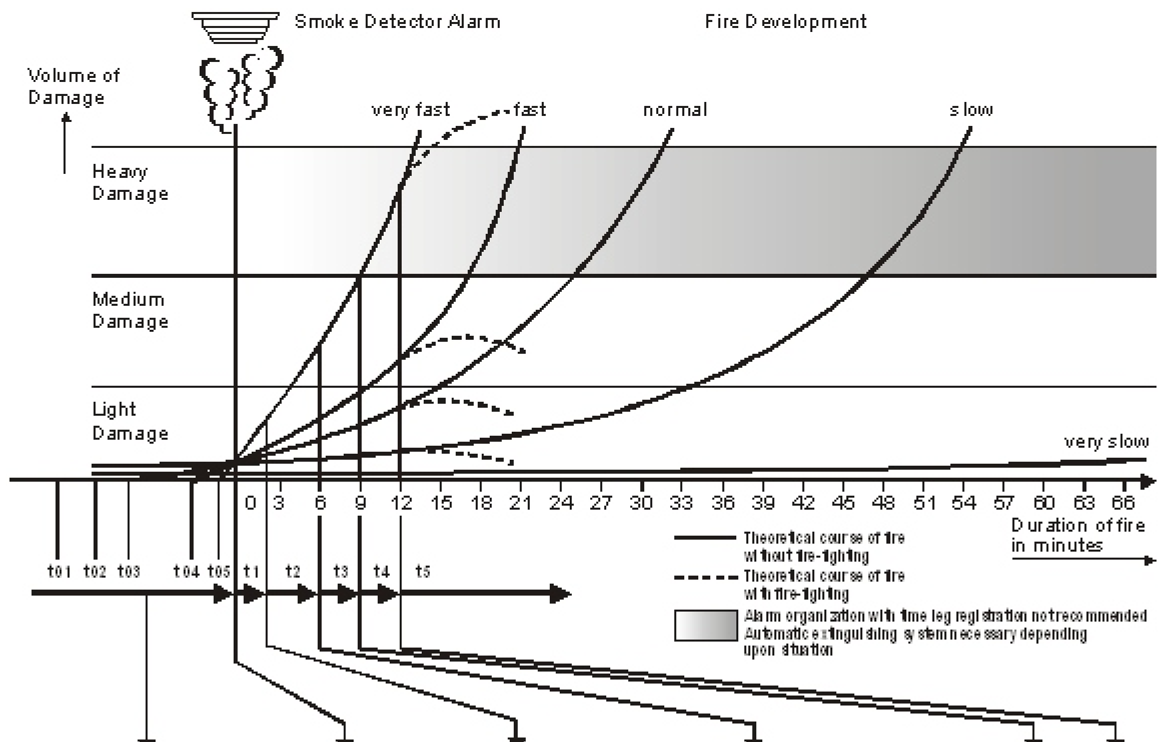
Smoke and heat detectors are best suited for fire detection in confined spaces, where rapid heat generation can be expected in the event of a fire. Smoke and heat detectors have been installed extensively in most NPPs. Generally, such detectors are installed as part of a building-wide alarm system, which typically alarms in the main control room (MCR). The purpose of such systems is to provide early warning to building occupants, and rapid notification of the fire brigade. Some detection devices will also perform the function of automatically actuating suppression systems and interfacing with other building systems such as heating, ventilation, and air-conditioning (HVAC).

Detection is critical to fire safety in NPPs since a potential fire hazard may jeopardize safe plant shutdown. Consequently, safety-related systems must be protected before redundant safety-related systems become damaged by a fire.

Throughout the nuclear industry there has been considerable responsive action relative to the nuclear safety-related fire protection and incorporating sound fire protection principles in nuclear facility design. New standards, regulatory guides, and criteria have been publicized since the fire at the 1975 Browns Ferry Nuclear Power Plant (BFNP). Recognizing the unique characteristics of fires in NPPs, requirements have been established for locating smoke detectors. Particular emphasis has been given to establishing criteria for early warning detection of electrical cable fires. Figure 11-1 shows a qualitative relationship between time and damage for different rates of fire development and average detection reaction and fire fighting.

11.3 Characteristics of Smoke Production

Two essential factors influencing the performance of smoke detectors are the particle size of the smoke and the fire-induced air velocities. The velocities created by the thermal column tend to diffuse the smoke through the upper wall and ceiling regions of the enclosure where the particles enter the detector and activate the unit. For example, residential detectors respond effectively to air flow velocities above 0.25 m/sec (50 ft/min) generated by flaming combustion. The same detectors may fail to respond when the fire-induced thermal column velocities created by the smoldering fire are below 0.15 (30 ft/min).



Inident	Start of fire	Incipient phase before fire detection by fire alarm	Early warning detector detects fire	Start of RS check 1*	Reaction of operating personnel	Cancelling of RS check 1*	Start of RS check 2*	Investigate source of signal	Decision: –Emergency: Press alarm push-button, alerting fire department	Start of initial rescue and fire-fighting operations	Assembly time of fire department	Turn-out time of fire department	Start co-ordinating fire-fighting
Time point	t01 – t05	t01 – t05/t1	t1	t1	t1 – t2	t2	t2	t2 – t3	t3	t3	t3 – t4	t4 – t5	t5
Time requirement ϕ	—	unknown	—	—	ca. 2 min.	—	—	ca. 4 min.	—	—	ca. 3 min.	ca. 3 min.	—
ϕ Time requirement total	—	—	—	—	—	ca. 2 min.	—	—	ca. 6 min.	—	—	ca. 12 min.	—
Detection phase				Reaction, assembly and fire-fighting phase									

* RS check = Reconnaissance squad check

Figure 11-1 Qualitative Relationship Between Time and Damage
for Different Speeds of Fire Development and Average Detection, Reaction, and Fire Fighting
(NUREG/CR-2409, "Requirements for Establishing Detector Siting Criteria in Fires Involving Electrical Materials")

Smoke production of a given fuel material varies with the sample size, arrangement, and configuration of the fuel; material moisture content; and ignition energy. Custer and Bright (1974) report that the earliest indication of a fire occurrence usually involves the heating of materials during the pre-ignition stage, which produces submicron particles ranging in size from $5x10^{-4}$–$1x10^{-3}$ micrometer. Custer and Bright also reported that the size of the particle produced by the diffusion flame combustion varies with the heating of the atmosphere and the development of the fire progressing from smoldering to flaming combustion. Larger particles are formed by coagulation, with the particle size distribution varying between 0.1 micrometer and 4.0 micrometers. The smaller particles, below 0.1 micrometer, tend to disappear as a result of the formation of larger particles by coagulation, while the larger particles tend to settle out through the process of sedimentation. The particle size appears to be one of the most critical variables relative to the operation and performance of the specific smoke detector unit, considering that the detector is suitably located to be exposed to the smoke concentrations, and it is designed to enhance the entry of smoke into the detector unit.

Budnick (1984) states that the critical variables affecting the activation of a smoke detector are as follows:

> *A smoke detector responds to an accumulation of smoke particulate within the device's sensing chamber. In a developing fire, the response will depend on a complex interrelationship of environmental factors such as fire size and growth rate, fuel type and smoke generation rate, room geometry and ventilation, and detector characteristics such as location, smoke entry characteristics and predetermined detector sensitivity thresholds*.

Relative to the rate of fire development, diffusion flame combustion appears to vary with the velocity of the flame spread (which is influenced by fuel arrangement and configuration), ventilation velocity, oxygen concentrations, and energy input at ignition.

11.4 Operating Principles of Smoke Detectors

Typically, a smoke detector will detect most fires more rapidly than a heat detector. Visible products of combustion consist primarily of unconsumed carbon and carbon-rich particles, while invisible products of combustion consist of solid particles smaller than 5 microns, as well as various gases and ions. NFPA 72, "National Fire Alarm Code®," defines the types of listed smoke detectors in the following manner:

- **Photoelectric light obscuration smoke detection** is the principle of using a light source and a photosensitive sensor onto which the principal portion of the source emission is focused. When smoke particles enter the light path, some of the light is scattered and some is absorbed, thereby reducing the light reaching the receiving sensor. The light reduction signal is processed and used to convey an alarm condition when it meets preset criteria (see Figure 11-2).
- **Photoelectric light scattering smoke detection** is the principle of using a light source and a photosensitive sensor arranged so that the rays from the light source do not normally fall onto the photosensitive sensor. When smoke particles enter the light path, some of the light is scattered bu reflection and refraction onto the sensor. The light signal is processed and used to convey an alarm condition when it meets preset criteria (see Figure 11-2).

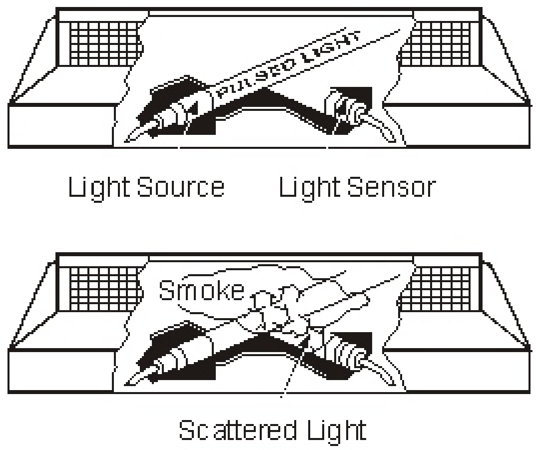


Figure 11-2 Illustration of the Photoelectric Principle

- **Ionization smoke detection** is the principle of using a small amount of radioactive material to ionize the air between two differentially charged electrodes to sense the presence of smoke particles. Smoke particles entering the ionization volume decrease the conductance of the air by reducing ion mobility. The reduced conductance signal is processed and used to convey an alarm condition when it meets preset criteria (see Figure 11-3).

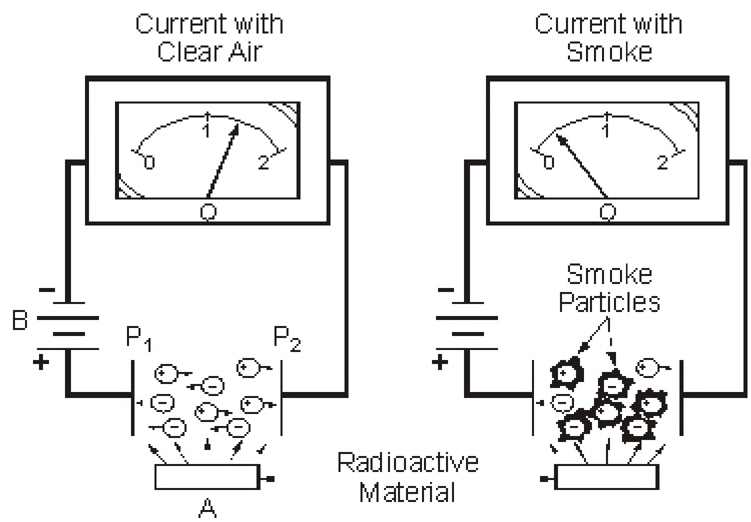


Figure 11-3 Illustration of the Ionization Principle

- **Combination detection** either responds to more than one of the fire phenomena or employs more than one operating principle to sense these phenomena. Typical examples are a combination of heat and smoke detectors or a combination of rate-of-rise and fixed-temperature heat detectors.

- **Projected beam detection** uses the principle of photoelectric light obscuration smoke detection, but the beam spans the protected area.
- **Air sampling detection** uses a piping or tubing distribution network that runs from the detector to the area(s) to be protected. An aspiration fan in the detector housing draws air from the protected area back to the detector through air sampling ports, piping, or tubing. At the detector, the air is analyzed for fire products.

As a class, smoke detectors using the ionization principle provide a somewhat faster response to high-energy (open flaming) fires, since such fires produce large numbers of the smaller smoke particles. Smoke detectors operating on the photoelectric principle tend to respond faster to the smoke generated by low-energy (smoldering) fires, which generally produce more of the larger smoke particles. However, each type of smoke detector is subjected to, and must pass, the same fires at testing laboratories in order to be listed by Underwriters Laboratories (UL).

Combustion product detectors of the ionization type are called spot detectors (meaning that the element is concentrated at a particular location), and those of the photoelectric type are available as both spot detectors and line detectors. A line detector means that detection is continuous along a path. Ionization detectors are usually found as spot detectors for area protection, and may be modified with air shields or sampling tubes for installation as air duct detectors. Projected beam photoelectric detectors are most often applied as line detectors for large open area protection. Line detectors are also beneficial in areas with high ceilings. They give the earliest warnings of abnormal conditions in these applications by responding to the smoke particles produced by fires. By contrast spot detectors are typically located in various areas of the building. They typically protect areas up to 84 m^2 (900 ft^2) depending on ceiling surface conditions and room height. Ionization and photoelectric detectors offer the greatest potential in residential safety. Some ionization and photoelectric detectors are also manufactured with dual modes of operation. Specifically, a fixed-temperature, thermal-activation device is also located in the detector.

Most conventional smoke detectors provide a binary go/no-go form of detection. This means that other than *alarm* or *no-alarm* condition, no other information is transmitted to the fire alarm control unit. In order to provide a stable smoke detector, the system design must ensure that the sensitivity level of the detector matches the environment in the facility to be protected. Newer types of spot smoke detectors are now capable of providing information on the level of smoke at the device.

Current standards (such as NFPA 72, National Fire Alarm Code®) stipulate the spacing of smoke detectors based upon tests performed by nationally recognized testing laboratories such as Underwriters Laboratories (UL 268). An alternative performance design method can be found in Appendix B to NFPA 72 and is limited to flaming fires no ceilings higher than 8.5 m (30 ft). This method was developed from an experimental study conducted in the late 1970s for the Fire Detection Institute (FDI), however, it suffers from certain limitations related to the scope of the experiments conducted. Nevertheless, this design method introduced some important concepts, including design of a detection system to activate for a critical fire size (HRR) representing an acceptable threat level for the protected space. This is a departure from the earlier concept of detection “as quickly as possible,” which often led to oversensitivity.

Technology improvements in microprocessor use in fire alarm systems have led to development of new smoke detector concepts. These new sensors use analog technology to measure the conditions in the protected area, or space, and transmit that information to the computer-based fire alarm control unit. Thus, the new sensors can report when components are too dirty to function properly or too sensitive as result of any number of conditions in the protected space. Analog sensors provide an essentially false-alarm-free system with regard to the conditions that are normally found in a building. This sensor technology also allows the system designer to adjust the sensor's sensitivity to accommodate the ambient environment or use an extra-sensitive setting to protect a high-value or mission-sensitive area. These sensors are available as photoelectric; ionization; or combination thermal, photoelectric, and ionization units. As fire alarm system technology continues to advance and existing NPPs are upgraded, the analog sensors will be the sensors of choice for any system application, regardless of system size.

11.5 Smoke Detector Response

The response characteristics of smoke detectors are not as well understood as those of sprinklers and thermal detectors. Smoke detector alarm conditions depend on more than smoke concentration. Smoke particle sizes and optical or particle scattering properties can affect the smoke concentration value necessary to reach the alarm condition. For sprinklers and thermal detectors, measured values of response time index (RTI) characterize the lag time between gas temperature and sensing element temperature. For smoke detectors, there is no analogous method to characterize the lag time between gas flow smoke concentration and the smoke concentration within the sensing chamber. In the absence of understanding the many processes affecting smoke detector response, smoke detectors can be approximated as low-temperature heat detectors with no thermal lag (i.e., low-RTI devices).

The time required for automatic actuation of a smoke detector is dependent on fire size, geometry, type of detector, and environment conditions within the compartment. In many installations, ceiling-mounted spot smoke detectors have been suggested as one means of fire detection. In some cases, the actuation time for ceiling-mounted spot smoke detectors may be unacceptably long. Projected beam smoke detectors may be the preferable means of fire detection. The actuation time of ceiling-mounted smoke detectors can be estimated by considering the temperature of the smoke layer (Heskestad and Delichatsios, 1977).

11.5.1 Method of Alpert

Smoke detector activation is identical to that for a heat detector, with the exception of the response of smoke detectors to a modest rise in the ceiling jet temperature. Heskestad and Delichatsios (1977) correlated a smoke temperature change of 10 °C (18 °F) from typical fuels.

For steady-state fire, the method for estimating the response of a smoke detector is based on the correlations developed by Alpert (1972) for activation of a sprinkler and is given by the following equation (Budnick, Evans, and Nelson, 1997):

$$t_{activation} = \frac{RTI}{\sqrt{u_{jet}}} \ln\left(\frac{T_{jet} - T_a}{T_{jet} - T_{activation}}\right) \qquad (11\text{-}1)$$

Where:

$t_{activation}$ = sprinkler head activation time (sec)
RTI = Response Time Index (m-sec)$^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$T_{activation}$= activation temperature of detector (°C)

Factory Mutual Research Corporation (FMRC) developed the RTI concept to be a fundamental measure of thermal detector sensitivity. A detector’s RTI is determined in plunge tests with a uniform gas flow of constant temperature and velocity and can be used to predict the detector’s activation time in any fire environment. For the purpose of calculating smoke detector response time, it is assumed that the smoke detectors are low-RTI devices.

The ceiling jet temperature and velocity correlations of a fire plume in Equation 11-1 are given by the following expression:

$$T_{jet} - T_a = \frac{16.9\ \dot{Q}^{\frac{2}{3}}}{H^{\frac{5}{3}}} \quad \text{for} \frac{r}{H} \leq 0.18 \qquad (11\text{-}2)$$

$$T_{jet} - T_a = \frac{5.38\ \left(\frac{\dot{Q}}{r}\right)^{\frac{2}{3}}}{H} \quad \text{for} \frac{r}{H} > 0.18 \qquad (11\text{-}3)$$

$$u_{jet} = 0.96\ \left(\frac{\dot{Q}}{H}\right)^{\frac{1}{3}} \quad \text{for} \frac{r}{H} \leq 0.15 \qquad (11\text{-}4)$$

$$u_{jet} = \frac{0.195\ \dot{Q}^{\frac{1}{3}}\ H^{\frac{1}{2}}}{r^{\frac{5}{6}}} \quad \text{for} \frac{r}{H} > 0.15 \qquad (11\text{-}5)$$

Where:

T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$\dot{Q}$ = heat release rate of the fire (kW)
H = distance from the top of the fuel package to the ceiling level (m)
r = radial distance from the plume centerline to the detector (m)
u_{jet} = ceiling jet velocity (m/sec)

11.5.2 Method of Mowrer

Mowrer (1990) developed a smoke detector response time correlation based on the concept of smoke transport lag time for quasi-steady fires. The response time of a smoke detector comprises two separate times, including the transport lag time of the plume and the transport lag time of the ceiling jet, as illustrated by the following equation:

$$t_{activation} = t_{pl} + t_{cj} \qquad (11\text{-}6)$$

Where:

$t_{activation}$ = detector activation time (sec)
t_{pl} = transport lag time of plume (sec)
t_{cj} = transport lag time of ceiling jet (sec)

The transport lag time of the plume, t_{pl}, is the time for the fire gases to reach the ceiling at the plume centerline and can be represented by the following correlation:

$$t_{pl} = C_{pl} \frac{H^{\frac{4}{3}}}{\dot{Q}^{\frac{1}{3}}} \qquad (11\text{-}7)$$

Where:

t_{pl} = transport lag time of plume (sec)
C_{pl} = plume lag time constant = 0.67 (experimentally determined)
H = height of ceiling above top of fuel (m)
$\dot{Q}$ = heat release rate of the fire (kW)

The transport lag time of the ceiling jet, t_{cj}, is the time for the fire gases to reach the detector at the plume centerline and can be represented by the following correlation:

$$t_{cj} = \frac{1}{C_{cj}} \frac{r^{\frac{11}{6}}}{\dot{Q}^{\frac{1}{3}} H^{\frac{1}{2}}} \qquad (11\text{-}8)$$

Where:

t_{cj} = transport lag time of plume (sec)
r = radial distance to the detector (m)
C_{cj} = ceiling jet lag time constant = 1.2 (experimentally determined)
H = height of ceiling above top of fuel (m)
$\dot{Q}$ = heat release rate of the fire (kW)

11.5.3 Method of Milke

Milke (1990) presented a method for estimating smoke detector response time based on the enclosure fire testing described in NUREG/CR-4681. The operation of detectors for smoke from typical fuels has been correlated to a temperature change from the following correlation:

$$t_{activation} = \frac{XH^{\frac{4}{3}}}{\dot{Q}^{\frac{1}{3}}} \qquad (11\text{-}9)$$

Where:

$t_{activation}$ = detector activation time (sec)
H = height of ceiling above top of fuel (m)
$\dot{Q}$ = heat release rate of the fire (kW)

$$X = 4.6 x 10^{-4} Y^2 + 2.7 x 10^{-15} Y^6 \qquad (11\text{-}10)$$

$$Y = \frac{\Delta T_c H^{\frac{5}{3}}}{\dot{Q}^{\frac{2}{3}}} \qquad (11\text{-}11)$$

Where:

H = height of ceiling above top of fuel (m)
$\dot{Q}$ = heat release rate of the fire (kW)
T_c = temperature rise of gases under the ceiling for smoke detector to activate

Before estimating smoke detector response time, stratification effects can be calculated. The potential for stratification relates to the difference in temperature between the smoke and surrounding air at any elevation and is given by the following correlation (NFPA 92B, Section A.3.4).

$$H_{max} = \frac{74 \dot{Q}_c^{\frac{2}{5}}}{\Delta T_{f \rightarrow c}} \qquad (11\text{-}12)$$

Where:

H_{max} = the maximum ceiling clearance to which a plume can rise (ft)
$\dot{Q}_c$ = convective heat release rate of the fire (Btu/sec)
$T_{f->c}$ = difference in ambient gas temperature between the fuel location and ceiling level (°F)

The convective portion of the heat release rate, $\dot{Q}_c$, can be estimated as 70 percent of the total heat release rate. Thus, $\dot{Q}_c$ is given by the following equation:

$$\dot{Q}_c = \chi_c \dot{Q}$$

Where:

χ_c = convective heat release fraction (0.70)

$\dot{Q}$ = heat release rate of the fire (Btu/sec)

Difference in ambient gas temperature between the fuel location and ceiling level can be estimated from the following equation:

$$\Delta T_{f \to c} = \frac{1300 \dot{Q}_c^{\frac{2}{3}}}{H^{\frac{5}{3}}}$$

Where:

$\Delta T_{f->c}$ = difference in ambient gas temperature between the fuel location and ceiling level (°F)

$\dot{Q}_c$ = convective heat release rate of the fire (Btu/sec)

H = height of ceiling above top of fuel (ft)

If the H_{max} is greater than H, the smoke would be expected to reach the ceiling-mounted smoke detector and result in activation.

11.6 Assumptions and Limitations

The method discussed in this chapter is subject to several assumptions and limitations.

(1) The fire is steady state.

(2) The forced ventilation system is off. As ventilation is increased, detector response times increase.

(3) Both flaming and non-flaming fire sources can be used.

(4) Caution should be exercised with this method when the overhead area is highly obstructed.

(5) The detectors are located at or very near to ceiling. Very near to ceiling would include code compliant detectors mounted on the bottom flange of structural steel beams. This method is not applicable to detectors mounted well below ceiling in free air.

11.7 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet.

(1) heat release rate of the fire (kW)

(2) ceiling height of the compartment (ft)

(3) radial distance from the centerline of the plume (ft)

11.8 Cautions

(1) Use (10_Detector_Activation_Time.xls) and select "Smoke" spreadsheet in the CD-ROM for calculations.

(2) Make sure to use correct units when entering the input parameters.

(3) Remember that there are broad assumptions within each calculation method because of the statistical makeup of the test methods. Although a specific method may be a good estimate, use the results with caution.

11.9 Summary

This chapter discusses three methods of calculating the activation time of smoke detectors under unobstructed ceilings in response to steady-state fires. In the first method, smoke detector activation is identical to that for a heat detector, with the exception that the response of the smoke detector to a modest rise in the ceiling jet temperature has been assumed. In the second method, the response time of a smoke detector was estimated using the transport lag time of the plume and the transport lag time of the ceiling jet. In the third method, the operation of smoke detectors was estimated using the stratification of smoke.

11.10 References

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UL 268, "Smoke Detectors for Fire Protective Signaling Systems," 4th Edition, Underwriters Laboratory, Northbrook, Illinois, 1996.

11.11 Additional Readings

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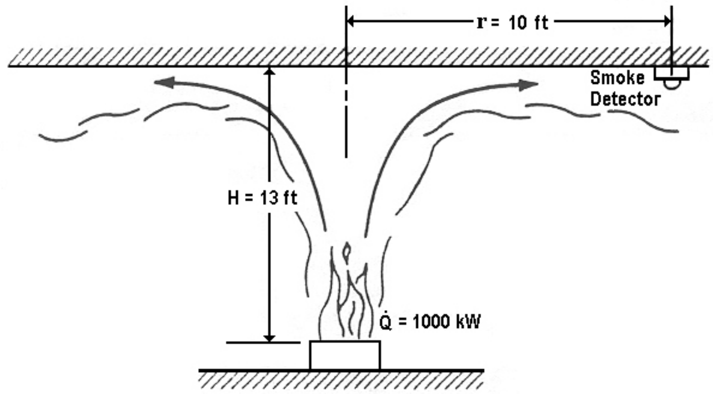
11.12 Problems

Example Problem 11.12-1

Problem Statement
Estimate the response time of a smoke detector that is located 10 ft radially from the centerline of a 1,000-kW pool fire in a 13-ft-tall compartment.



Example Problem 11-1: Fire Scenario with Smoke Detector

Solution

Purpose:

(1) Determine the response time of the smoke detector for the fire scenario.

Assumptions:

(1) The fire is steady state
(2) The forced ventilation system is off
(3) There is no heavily obstructed overhead

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (click on *Smoke_Detector*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 1,000 kW

-Ceiling Height (H) = 13 ft

-Radial Distance from the Plume Centerline to the Smoke Detector (r) = 10 ft

Results*

Heat Release Rate $\dot{Q}$ (kW)	Smoke Detector Activation Time (t_R) (sec)		
1,000	Method of Alpert	Method of Mowrer	Method of Milke
	0.42	0.74	0.26

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 10_Detector_Activation_Time.xls (Smoke_Detector)

CHAPTER 11. ESTIMATING SMOKE DETECTOR RESPONSE TIME

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The following calculations estimate smoke detector response time.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
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

Heat Release Rate of the Fire (Q) (Steady State)	1000.00 kW	947.82 Btu/sec
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	10.00 ft	3.05 m
Height of Ceiling above Top of Fuel (H)	13.00 ft	3.96 m
Activation Temperature of the Smoke Detector ($T_{activation}$)	86.00 °F	30.00 °C
Smoke Detector Response Time Index (RTI)	5.00 (m-sec)$^{1/2}$	
Ambient Air Temperature (T_a)	77.00 °F	25.00 °C 298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70	
Plume Lag Time Constant (C_{p}) (Experimentally Determined)	0.67	
Ceiling Jet Lag Time Constant (C_{cj}) (Experimentally Determined)	1.2	
Temperature Rise of Gases Under the Ceiling (ΔT_c) for Smoke Detector to Activate	18.00 °F	10 °C
r/H =	0.77	

Calculate

ESTIMATING SMOKE DETECTOR RESPONSE TIME
METHOD OF ALPERT

Reference: *NFPA Fire Protection Handbook, 19[th] Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(u_{jet})^{1/2}) (\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

This method assume smoke detector is a low RTI device with a fixed activation temperature

Where
- $t_{activation}$ = detector activation time (sec)
- RTI = detector response time index (m-sec)$^{1/2}$
- u_{jet} = ceiling jet velocity (m/sec)
- T_{jet} = ceiling jet temperature (°C)
- T_a = ambient air temperature (°C)
- $T_{activation}$ = activation temperature of detector (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\, (Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38\, (Q_c/r)^{2/3}/H$ for r/H > 0.18

Where
- T_{jet} = ceiling jet temperature (°C)
- T_a = ambient air temperature (°C)
- Q_c = convective portion of the heat release rate (kW)
- H = height of ceiling above top of fuel (m)
- r = radial distance from the plume centerline to the detector (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\, Q$

Where
- Q_c = convective portion of the heat release rate (kW)
- Q = heat release rate of the fire (kW)
- χ_c = convective heat release rate fraction

Q_c = 700 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.77 r/H > 0.15

>0.15	50.92	<0.15	134.28

$T_{jet} - T_a =$ 5.38 ((Qc/r)^2/3)/H

$T_{jet} - T_a =$ 50.92

$T_{jet} =$ 75.92 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\ (Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\ Q^{1/3}\ H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)

Q = heat release rate of the fire (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the detector (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.77 r/H > 0.15

>0.15	1.53	<0.15	6.07

$u_{jet} =$ (0.195 Q^1/3 H^1/2)/r^(5/6)

$u_{jet} =$ 1.533 m/sec

Smoke Detector Response Time Calculation

$t_{activation} = (RTI/(\sqrt{u_{jet}}))(\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation} =$ 0.42 sec **Answer**

NOTE: If $t_{activation}$ = "NUM" Detector does not activate

METHOD OF MOWRER

References: *Mowrer, F., "Lag Times Associated With Fire Detection and Suppression," Fire Technology, August 1990, p. 244.*

$t_{activation} = t_{pl} + t_{cj}$

Where $t_{activation}$ = detector activation time (sec)

t_{pl} = transport lag time of plume (sec)

t_{cj} = transport lag time of ceiling jet (sec)

Transport Lag Time of Plume Calculation

$t_{pl} = C_{pl}\ (H)^{4/3}/(Q)^{1/3}$

Where t_{pl} = transport lag time of plume (sec)

C_{pl} = plume lag time constant

H = height of ceiling above top of fuel (m)

Q = heat release rate of the fire (kW)

$t_{pl} =$ 0.42 sec

Transport Lag Time of Ceiling Jet Calculation

$t_{cj} = (r)^{11/6}/(C_{cj})\ (Q)^{1/3}\ (H)^{1/2}$

Where t_{cj} = transport lag time of ceiling jet (sec)

C_{cj} = ceiling jet lag time constant

r = radial distance from the plume centerline to the detector (m)

H = height of ceiling above top of fuel (m)

Q = heat release rate of the fire (kW)

$t_{cj} =$ 0.32 sec

Smoke Detector Response Time Calculation

$t_{activation} = t_{pl} + t_{cj}$

$t_{activation} =$ 0.74 sec **Answer**

METHOD OF MILKE

References: Milke, J., "Smoke Management for Covered Malls and Atria," Fire Technology, August 1990, p. 223.
NFPA 92B, "Guide for Smoke Management Systems in Mall, Atria, and Large Areas," 2000 Edition, Section A.3.4.

$t_{activation} = X\ H^{4/3}/Q^{1/3}$

Where $t_{activation}$ = detector activation time (sec)
$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-15}\ Y^6$
H = height of ceiling above top of fuel (ft)
Q = heat release rate from steady fire (Btu/sec)

Where $Y = \Delta T_c\ H^{5/3} /\ Q^{2/3}$
ΔT_c = temperature rise of gases under the ceiling for smoke detector to activate (°F)

Before estimating smoke detector response time, stratification effects can be calculated. NFPA 92B, 2000 Edition, Section A.3.4 provides following correlation to estimate smoke stratification in a compartment.

$H_{max} = 74\ Q_c^{2/5} /\ \Delta T_{f-c}^{3/5}$

Where H_{max} = the maximum ceiling clearance to which a plume can rise (ft)
Q_c = convective portion of the heat release rate (Btu/sec)
ΔT_{f-c} = difference in temperature due to fire between the fuel location and ceiling level (°F)

Convective Heat Release Rate Calculation

$Q_c = Q\ \chi_c$

Where Q_c = convective portion of the heat release rate (Btu/sec)
Q = heat release rate of the fire (Btu/sec)
χ_c = convective heat releas rate fraction

Q_c = 663.47 Btu/sec

Difference in Temperature Due to Fire Between the Fuel Location and Ceiling Level

$\Delta T_{f-c} = 1300\ Q_c^{2/3} /\ H^{5/3}$

Where ΔT_{f-c} = difference in temperature due to fire between the fuel location and ceiling level (°F)
Q_c = convective portion of the heat release rate (Btu/sec)
H = ceiling height above the fire source (ft)

ΔT_{f-c} = 1375.90 °F

Smoke Stratification Effects

$H_{max} = 74\ Q_c^{2/5} /\ \Delta T_{f-c}^{3/5}$

H_{max} = 13.03 ft

In this case the highest point of smoke rise is estimated to be 13.03 ft
Thus, the smoke would be expected to reach the ceiling mounted smoke detector.

$Y = \Delta T_c\ H^{5/3} /\ Q^{2/3}$

Y = 13.41

$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-16}\ Y^6$

X = 0.08

Smoke Detector Response Time Calculation

$t_{activation} = X\ H^{4/3}/Q^{1/3}$

$t_{activation}$ =	0.26 sec	Answer

Summary of Result:

Calculation Method	Smoke Detector Response Time (sec)
METHOD OF ALPERT	0.42
METHOD OF MOWRER	0.74
METHOD OF MILKE	0.26

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003, method described in Fire Technology, 1990, and NFPA 92B, "Guide for Smoke Management Systems in Malls, Atria, and Large Areas," 2000 Edition, Section A.3.4. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situations and, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 11.12-2

Problem Statement

During a routine inspection, an NRC resident inspector finds a stack of 4-ft-high wooden pallets left in the NPP after a recent MOV modification. When the inspector questions the licensee about this transient combustible, the licensee assures the inspector that if the transient ignited, the smoke detection system would alarm in less than 1 minute.

The SFPE Handbook provides test data for a stack of 4-ft-high wooden pallets, from which the HRR can be estimated at 3.5 MW.

The compartment has a 25-ft ceiling with the smoke detectors spaced 30 ft on center. The pallets are located in the worst position (i.e., in the center of four smoke detectors).

How long does it take the smoke detector to alarm?

Solution

Purpose:

(1) Determine the response time of the smoke detector for the fire scenario.

Assumptions:

(1) The fire is steady-state.
(2) The forced ventilation system is off.
(3) There is no heavily obstructed overhead.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (click on *Smoke_Detector*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 3,500 kW

-Ceiling Height (H) = 25 ft

-Radial Distance from the Plume Centerline to the Smoke Detector (r) = 21.2 ft

Results*

Heat Release Rate $\dot{Q}$ (kW)	Smoke Detector Activation Time (t_R) (sec)		
	Method of Alpert	Method of Mowrer	Method of Milke
3,500	0.55	1.27	0.67

*see spreadsheets on next page

Therefore, it can be assumed that the smoke detectors would alarm within 1 minute.

Spreadsheet Calculations
FDT[s]: 10_Detector_Activation_Time.xls (Smoke_Detector)

CHAPTER 11. ESTIMATING SMOKE DETECTOR RESPONSE TIME

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The following calculations estimate smoke detector response time.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
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

Heat Release Rate of the Fire (Q) (Steady State)	3500.00 kW	3317.37 Btu/sec
Radial Distance to the Detector (r) "never more than 0.707 or 1/2√2 of the listed spacing"	21.20 ft	6.46 m
Height of Ceiling above Top of Fuel (H)	25.00 ft	7.62 m
Activation Temperature of the Smoke Detector ($T_{activation}$)	86.00 °F	30.00 °C
Smoke Detector Response Time Index (RTI)	5.00 (m-sec)$^{1/2}$	
Ambient Air Temperature (T_a)	77.00 °F	25.00 °C 298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70	
Plume Lag Time Constant (C_{pl}) (Experimentally Determined)	0.67	
Ceiling Jet Lag Time Constant (C_{cj}) (Experimentally Determined)	1.2	
Temperature Rise of Gases Under the Ceiling (ΔT_c) for Smoke Detector to Activate	18.00 °F	10 °C
r/H =	0.85	

Calculate

ESTIMATING SMOKE DETECTOR RESPONSE TIME
METHOD OF ALPERT

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(u_{jet})^{1/2}) (\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

This method assume smoke detector is a low RTI device with a fixed activation temperature

Where $t_{activation}$ = detector activation time (sec)
RTI = detector response time index (m-sec)$^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$T_{activation}$ = activation temperature of detector (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9 (Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38 (Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
Q_c = convective portion of the heat release rate (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the detector (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c Q$

Where Q_c = convective portion of the heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release rate fraction

Q_c = 2450 kW

Radial Distance to Ceiling Height Ratio Calculation
r/H = 0.85 r/H > 0.15

>0.15	36.99	<0.15	104.09

$T_{jet} - T_a =$ 5.38 ((Q c/r)^2/3)/H
$T_{jet} - T_a =$ 36.99
$T_{jet} =$ 61.99 (°C)

Ceiling Jet Velocity Calculation
$u_{jet} = 0.96\ (Q/H)^{1/3}$ for r/H = 0.15
$u_{jet} = (0.195\ Q^{1/3}\ H^{1/2})/r^{5/6}$ for r/H > 0.15
Where u_{jet} = ceiling jet velocity (m/sec)
Q = heat release rate of the fire (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the detector (m)

Radial Distance to Ceiling Height Ratio Calculation
r/H = 0.85 r/H > 0.15

>0.15	1.73	<0.15	7.41

$u_{jet} =$ (0.195 Q^1/3 H^1/2)/r^(5/6)
$u_{jet} =$ 1.726 m/sec

Smoke Detector Response Time Calculation
$t_{activation} = (RTI/(\sqrt{u_{jet}}))(\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation}$ = 0.55 sec	Answer

NOTE: If $t_{activation}$ = "NUM" Detector does not activate

METHOD OF MOWRER

References: *Mowrer, F., "Lag Times Associated With Fire Detection and Suppression," Fire Technology, August 1990, p. 244.*

$t_{activation} = t_{pl} + t_{cj}$
Where $t_{activation}$ = detector activation time (sec)
t_{pl} = transport lag time of plume (sec)
t_{cj} = transport lag time of ceiling jet (sec)

Transport Lag Time of Plume Calculation
$t_{pl} = C_{pl}\ (H)^{4/3}/(Q)^{1/3}$
Where t_{pl} = transport lag time of plume (sec)
C_{pl} = plume lag time constant
H = height of ceiling above top of fuel (m)
Q = heat release rate of the fire (kW)
t_{pl} = 0.66 sec

Transport Lag Time of Ceiling Jet Calculation

$t_{cj} = (r)^{11/6}/(C_{cj})\ (Q)^{1/3}\ (H)^{1/2}$
Where t_{cj} = transport lag time of ceiling jet (sec)
C_{cj} = ceiling jet lag time constant
r = radial distance from the plume centerline to the detector (m)
H = height of ceiling above top of fuel (m)
Q = heat release rate of the fire (kW)
t_{cj} = 0.61 sec

Smoke Detector Response Time Calculation
$t_{activation} = t_{pl} + t_{cj}$

$t_{activation}$ = 1.27 sec	Answer

METHOD OF MILKE

References: Milke, J., "Smoke Management for Covered Malls and Atria," Fire Technology, August 1990, p. 223.
NFPA 92B, "Guide for Smoke Management Systems in Mall, Atria, and Large Areas," 2000 Edition, Section A.3.4.

$t_{activation} = X\, H^{4/3}/Q^{1/3}$

Where $t_{activation}$ = detector activation time (sec)
$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-15}\ Y^6$
H = height of ceiling above top of fuel (ft)
Q = heat release rate from steady fire (Btu/sec)

Where $Y = \Delta T_c\, H^{5/3} / Q^{2/3}$
ΔT_c = temperature rise of gases under the ceiling for smoke detector to activate (°F)

Before estimating smoke detector response time, stratification effects can be calculated. NFPA 92B, 2000 Edition, Section A.3.4 provides following correlation to estimate smoke stratification in a compartment.

$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f-c}^{3/5}$

Where H_{max} = the maximum ceiling clearance to which a plume can rise (ft)
Q_c = convective portion of the heat release rate (Btu/sec)
ΔT_{f-c} = difference in temperature due to fire between the fuel location and ceiling level (°F)

Convective Heat Release Rate Calculation
$Q_c = Q\ \chi_c$

Where Q_c = convective portion of the heat release rate (Btu/sec)
Q = heat release rate of the fire (Btu/sec)
χ_c = convective heat releas rate fraction

Q_c = 2322.16 Btu/sec

Difference in Temperature Due to Fire Between the Fuel Location and Ceiling Level
$\Delta T_{f-c} = 1300\ Q_c^{2/3} / H^{5/3}$

Where ΔT_{f-c} = difference in temperature due to fire between the fuel location and ceiling level (°F)
Q_c = convective portion of the heat release rate (Btu/sec)
H = ceiling height above the fire source (ft)

ΔT_{f-c} = 1066.53 °F

Smoke Stratification Effects
$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f-c}^{3/5}$

H_{max} = 25.05 ft

In this case the highest point of smoke rise is estimated to be 25.05 ft
Thus, the smoke would be expected to reach the ceiling mounted smoke detector.

$Y = \Delta T_c\ H^{5/3} / Q^{2/3}$

Y = 17.30

$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-16}\ Y^6$

X = 0.14

Smoke Detector Response Time Calculation
$t_{activation} = X\, H^{4/3}/Q^{1/3}$

$t_{activation}$ = 0.67 sec **Answer**

Summary of Result:

Calculation Method	Smoke Detector Response Time (sec)
METHOD OF ALPERT	0.55
METHOD OF MOWRER	1.27
METHOD OF MILKE	0.67

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19^{h} Edition, 2003, method described in Fire Technology, 1990, and NFPA 92B, "Guide for Smoke Management Systems in Malls, Atria, and Large Areas," 2000 Edition, Section A.3.4. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situations and, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 11.12-3

Problem Statement

During a triennial inspection, an NRC inspector discovers that every other smoke detector has inadvertently been painted and is not functional. The detection system in the compartment is single-zoned to arm a pre-action sprinkler system. The detectors are 20 ft on center. The ceiling is 23 ft. The sprinkler system uses 165 °F sprinklers, 10 ft on center, 4 inches from the ceiling. The licensee states that even with half the smoke detectors inoperable, a smoke detector would alarm and charge the pre-action system before a quick-response link-type sprinkler head fuses. The expected fire in the compartment is approximately 750 kW. Is the licensee's statement true?

Solution

Purpose:

(1) Determine the response time of the smoke detector for the fire scenario.

(2) Determine the response time of the sprinkler system.

Assumptions:

(1) The fire is steady-state.

(2) The forced ventilation system is off.

(3) There is no heavily obstructed overhead.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (click on *Smoke-Detector*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 750 kW

-Ceiling Height (H) = 23 ft

-Radial Distance from the Plume Centerline to the Smoke Detector (r) = 20 ft

(b) 10_Detector_Activation_Time.xls (click on *Sprinkler*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 750 kW

-Select Quick Response Link

-Select Ordinary

-Ceiling Height (H) = 23 ft

-Radial Distance from the Plume Centerline to the Sprinkler (r) = 7.1 ft

Results*

Heat Release Rate $\dot{Q}$ (kW)	Smoke Detector Activation Time (t_R) (sec)		
	Method of Alpert	Method of Mowrer	Method of Milke
3,500	2.0	1.94	6.0

The sprinkler heads do not activate.

*see spreadsheet on next page

Therefore, the licensee's statement is true; however, the non-activation of the sprinkler heads should be of great concern.

Spreadsheet Calculations

(a) FDT[s]: 10_Detector_Activation_Time.xls (Smoke_Detector)

CHAPTER 11. ESTIMATING SMOKE DETECTOR RESPONSE TIME

Version 1805.0

The following calculations estimate smoke detector response time.

Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

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

Heat Release Rate of the Fire ($\dot{Q}$) (Steady State)	750.00	kW	710.87 Btu/sec
Radial Distance to the Detector (r) "never more than 0.707 or 1/2√2 of the listed spacing"	20.00	ft	6.10 m
Height of Ceiling above Top of Fuel (H)	23.00	ft	7.01 m
Activation Temperature of the Smoke Detector ($T_{activation}$)	86.00	°F	30.00 °C
Smoke Detector Response Time Index (RTI)	5.00	(m-sec)$^{1/2}$	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		
Plume Lag Time Constant (C_{p}) (Experimentally Determined)	0.67		
Ceiling Jet Lag Time Constant (C_{j}) (Experimentally Determined)	1.2		
Temperature Rise of Gases Under the Ceiling (ΔT_c) for Smoke Detector to Activate	18.00	°F	10 °C
r/H =	0.87		

Calculate

ESTIMATING SMOKE DETECTOR RESPONSE TIME
METHOD OF ALPERT

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\,(\ln\,(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

This method assume smoke detector is a low RTI device with a fixed activation temperature

Where
- $t_{activation}$ = detector activation time (sec)
- RTI = detector response time index (m-sec)$^{1/2}$
- u_{jet} = ceiling jet velocity (m/sec)
- T_{jet} = ceiling jet temperature (°C)
- T_a = ambient air temperature (°C)
- $T_{activation}$ = activation temperature of detector (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\,(\dot{Q}_c)^{2/3}/H^{5/3}$ for r/H ≤ 0.18

$T_{jet} - T_a = 5.38\,(\dot{Q}_c/r)^{2/3}/H$ for r/H > 0.18

Where
- T_{jet} = ceiling jet temperature (°C)
- T_a = ambient air temperature (°C)
- $\dot{Q}_c$ = convective portion of the heat release rate (kW)
- H = height of ceiling above top of fuel (m)
- r = radial distance from the plume centerline to the detector (m)

Convective Heat Release Rate Calculation

$\dot{Q}_c = \chi_c\,\dot{Q}$

Where
- $\dot{Q}_c$ = convective portion of the heat release rate (kW)
- $\dot{Q}$ = heat release rate of the fire (kW)
- χ_c = convective heat release rate fraction

$\dot{Q}_c$ = 525 kW

Radial Distance to Ceiling Height Ratio Calculation
r/H = 0.87 r/H > 0.15

>0.15	14.97	<0.15	42.83

$T_{jet} - T_a =$ 5.38 ((Qc/r)^2/3)/H
$T_{jet} - T_a =$ 14.97
$T_{jet} =$ 39.97 (°C)

Ceiling Jet Velocity Calculation
$u_{jet} = 0.96\ (Q/H)^{1/3}$ for r/H = 0.15
$u_{jet} = (0.195\ Q^{1/3}\ H^{1/2})/r^{5/6}$ for r/H > 0.15
Where u_{jet} = ceiling jet velocity (m/sec)
Q = heat release rate of the fire (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the detector (m)

Radial Distance to Ceiling Height Ratio Calculation
r/H = 0.87 r/H > 0.15

>0.15	1.04	<0.15	4.56

$u_{jet} =$ (0.195 Q^1/3 H^1/2)/r^(5/6)
$u_{jet} =$ 1.040 m/sec

Smoke Detector Response Time Calculation
$t_{activation} = (RTI/(\sqrt{u_{jet}}))(\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$
$t_{activation} =$ 1.99 sec Answer

NOTE: If $t_{activation}$ = "NUM" Detector does not activate

METHOD OF MOWRER

References: *Mowrer, F., "Lag Times Associated With Fire Detection and Suppression," Fire Technology, August 1990, p. 244.*

$t_{activation} = t_{pl} + t_{cj}$
Where $t_{activation}$ = detector activation time (sec)
t_{pl} = transport lag time of plume (sec)
t_{cj} = transport lag time of ceiling jet (sec)

Transport Lag Time of Plume Calculation
$t_{pl} = C_{pl}\ (H)^{4/3}/(Q)^{1/3}$
Where t_{pl} = transport lag time of plume (sec)
C_{pl} = plume lag time constant
H = height of ceiling above top of fuel (m)
Q = heat release rate of the fire (kW)
$t_{pl} =$ 0.99 sec

Transport Lag Time of Ceiling Jet Calculation

$t_{cj} = (r)^{11/6}/(C_{cj})\ (Q)^{1/3}\ (H)^{1/2}$
Where t_{cj} = transport lag time of ceiling jet (sec)
C_{cj} = ceiling jet lag time constant
r = radial distance from the plume centerline to the detector (m)
H = height of ceiling above top of fuel (m)
Q = heat release rate of the fire (kW)
$t_{cj} =$ 0.95 sec

Smoke Detector Response Time Calculation
$t_{activation} = t_{pl} + t_{cj}$
$t_{activation} =$ 1.94 sec Answer

METHOD OF MILKE

References: Milke, J., "Smoke Management for Covered Malls and Atria," Fire Technology, August 1990, p. 223.
NFPA 92B, "Guide for Smoke Management Systems in Mall, Atria, and Large Areas," 2000 Edition, Section A.3.4.

$t_{activation} = X\,H^{4/3}/Q^{1/3}$

Where $t_{activation}$ = detector activation time (sec)
$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-15}\ Y^6$
H = height of ceiling above top of fuel (ft)
Q = heat release rate from steady fire (Btu/sec)

Where $Y = \Delta T_c\ H^{5/3} / Q^{2/3}$
ΔT_c = temperature rise of gases under the ceiling for smoke detector to activate (°F)

Before estimating smoke detector response time, stratification effects can be calculated.
NFPA 92B, 2000 Edition, Section A.3.4 provides following correlation to estimate smoke stratification in a compartment.

$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f-c}^{3/5}$

Where H_{max} = the maximum ceiling clearance to which a plume can rise (ft)
Q_c = convective portion of the heat release rate (Btu/sec)
ΔT_{f-c} = difference in temperature due to fire between the fuel location and ceiling level (°F)

Convective Heat Release Rate Calculation
$Q_c = Q\ \chi_c$

Where Q_c = convective portion of the heat release rate (Btu/sec)
Q = heat release rate of the fire (Btu/sec)
χ_c = convective heat releas rate fraction

Q_c = 497.61 Btu/sec

Difference in Temperature Due to Fire Between the Fuel Location and Ceiling Level
$\Delta T_{f-c} = 1300\ Q_c^{2/3} / H^{5/3}$

Where ΔT_{f-c} = difference in temperature due to fire between the fuel location and ceiling level (°F)
Q_c = convective portion of the heat release rate (Btu/sec)
H = ceiling height above the fire source (ft)

ΔT_{f-c} = 438.85 °F

Smoke Stratification Effects
$H_{max} = 74\ Q_c^{2/5} / \Delta T_{f-c}^{3/5}$

H_{max} = 23.05 ft

In this case the highest point of smoke rise is estimated to be 23.05 ft
Thus, the smoke would be expected to reach the ceiling mounted smoke detector.

$Y = \Delta T_c\ H^{5/3} / Q^{2/3}$

Y = 42.04

$X = 4.6\ 10^{-4}\ Y^2 + 2.7\ 10^{-16}\ Y^6$

X = 0.81

Smoke Detector Response Time Calculation
$t_{activation} = X\,H^{4/3}/Q^{1/3}$

$t_{activation}$ = 5.96 sec Answer

Summary of Result:

Calculation Method	Smoke Detector Response Time (sec)
METHOD OF ALPERT	1.99
METHOD OF MOWRER	1.94
METHOD OF MILKE	5.96

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003, method described in Fire Technology, 1990, and NFPA 92B, "Guide for Smoke Management Systems in Malls, Atria, and Large Areas," 2000 Edition, Section A.3.4. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situations and, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT^s: 10_Detector_Activation_Time.xls (Sprinkler)

CHAPTER 10. ESTIMATING SPRINKLER RESPONSE TIME

Version 1805.0

The following calculations estimate sprinkler activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Sprinkler Selected.
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

Heat Release Rate of the Fire (Q) (Steady State)	750.00	kW	
Sprinkler Response Time Index (RTI)	34	(m-sec)$^{1/2}$	
Activation Temperature of the Sprinkler ($T_{activation}$)	165	°F	73.89 °C
Height of Ceiling above Top of Fuel (H)	23.00	ft	7.01 m
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	7.10	ft	2.16 m
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		

r/H = 0.31

Calculate

GENERIC SPRINKLER RESPONSE TIME INDEX (RTI)*

Common Sprinkler Type	Generic Response Time Index (RTI) (m-sec)$^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34
User Specified Value	Enter Value

Select Type of Sprinkler: Quick response link

Scroll to desired sprinkler type then Click on selection

Reference: *Madrzykowski, D., "Evaluation of Sprinkler Activation Prediction Methods" ASIAFLAM95, International Conference on Fire Science and Engineering, 1st Proceeding, March 15-16, 1995, Kowloon, Hong Kong, pp. 211-218.*

*Note: The actual RTI should be used when the value is available.

GENERIC SPRINKLER TEMPERATURE RATING ($T_{activation}$)*

Temperature Classification	Range of Temperature Ratings (°F)	Generic Temperature Ratings (°F)
Ordinary	135 to 170	165
Intermediate	175 to 225	212
High	250 to 300	275
Extra high	325 to 375	350
Very extra high	400 to 475	450
Ultra high	500 to 575	550
Ultra high	650	550
User Specified Value	–	Enter Value

Select Sprinkler Classification: Ordinary

Scroll to desired sprinkler class then Click on selection

Reference: *Automatic Sprinkler Systems Handbook, 6th Edition, National Fire Protection Association, Quincy, Massachusetts, 1994, Page 67.*

*Note: The actual temperature rating should be used when the value is available.

ESTIMATING SPRINKLER RESPONSE TIME

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(\sqrt{u_{jet}})) (\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = sprinkler activation response time (sec)

RTI = sprinkler response time index $(m\text{-}sec)^{1/2}$

u_{jet} = ceiling jet velocity (m/sec)

T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

$T_{activation}$ = activation temperature of sprinkler (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9 (Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38 (Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

Q_c = convective portion of the heat release rate (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the sprinkler (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c Q$

Where Q_c = convective portion of the heat release rate (kW)

Q = heat release rate of the fire (kW)

χ_c = convective heat release rate fraction

Q_c = 525 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.31 r/H > 0.15

$T_{jet} - T_a$ = {5.38 (Qc/r)^2/3}/H

$T_{jet} - T_a$ = 29.85

T_{jet} = 54.85 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96 (Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\ Q^{1/3}\ H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)

Q = heat release rate of the fire (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the sprinkler (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.31 r/H > 0.15

u_{jet} = (0.195 Q^1/3 H^1/2)/r^5/6

u_{jet} = 2.465 m/sec

Sprinkler Activation Time Calculation

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\,(\ln\,(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation} =$ #NUM! sec

The sprinkler will respond in approximately	#NUM!	minutes	**Answer**

NOTE: If $t_{activation}$ = "NUM" Sprinkler does not activate

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 12. ESTIMATING HEAT DETECTOR RESPONSE TIME

12.1 Objectives

This chapter has the following objectives:

- Explain where heat detectors are located.
- Identify the various types of heat detectors and how they work.
- Describe how to calculate the activation time of a heat detector.

12.2 Introduction

Heat detectors are one of the oldest forms of automatic fire detection devices, and they typically have the lowest false alarm rate of all automatic fire detection devices. Nonetheless, they are generally the slowest to detect fires because they do not detect smoke. Rather, they respond either when the detecting element reaches a predetermined fixed temperature or when the temperature changes at a specified rate. Thus, heat detectors usually do not provide enough early warning in case of a life-threatening situation. As a result, heat detectors are best suited for fire detection in a small confined space where rapidly building high-heat-output fires are expected, in areas where ambient conditions would not allow the use of other fire detection devices, or where speed of detection is not a primary consideration.

Heat detectors are generally located on or near the ceiling, where they can respond to the convected thermal energy of a fire. They may be used in combination with smoke detectors, since smoke detectors usually activate before the flames and heat would are sufficient to alarm the heat detector. In general, heat detectors are designed to operate when heat causes a prescribed change in a physical or electrical property of a material or gas.

The following excerpts are from the procedure specified by Underwriters' Laboratories, Inc., for using thermal detectors in automatic fire detection systems. Notice that to prevent false alarms, detectors should be installed only after considering the limitation on their operational rating and the prevalent ceiling temperatures. For example, ordinary detectors rated from 57–74 °C (135–165 °F) should be installed only where ceiling temperatures do not exceed 37.7 °C (100 °F).

12.3 Underwriters' Laboratories, Inc., Listing Information for Heat-Detecting Automatic Fire Detectors

"A heat-detecting type of automatic fire detector is an integral assembly of heat-responsive elements and non-coded electrical contacts, which function automatically under conditions of increased air temperature." Listing under this heading applies to fire alarm heat detectors only and not to wiring or other appliances of which they form a part. Fire alarm heat detectors are of the fixed-temperature, combination fixed-temperature, and rate-of-rise or rate compensation types. There are basically two types: (1) spot-type is one in which the thermally sensitive element is a compact unit of small area, and (2) line-type is one in which the thermally sensitive element is continuous along the line. These heat detectors have been investigated for indoor use only unless otherwise indicated in the individual listing.

Ordinarily, heat detectors are intended for locations where normal ceiling temperatures prevail below 37.7 °C (100 °F). Locations where ceiling temperatures are likely to be unduly high, from sources of heat other than fire conditions such as boiler rooms, dry kilns, etc., demand special consideration and selection of heat detectors operating normally at higher temperatures, and which are capable of withstanding high temperatures for long periods of time.

Care should be exercised to select heat detectors having the proper temperature rating to guard against false alarms from premature operation. These detectors are intended to be installed in accordance with NFPA 72E-Automatic Fire Detectors. For ceiling temperatures exceeding 37.7 °C (100 °F), install 57.2–73.8 °C (135–165 °F) (ordinary) rating thermostats. For ceiling temperatures exceeding 37.7 °C (100 °F), but not 65.5 °C (150 °F), install 79.4–107.2 °C (175–225 °F) (intermediated) rating thermostats. For ceiling temperatures exceeding 65.5 °C (150 °F), but not 107.2 °C (225 °F), install 121.1 to 148.8 °C (250–300 °F) (high) rating thermostats. For ceiling temperatures exceeding 107.2 °C (225 °F), but not 148.8 °C (300 °F), install 162.7–182.2 °C (325–360 °F) (extra high) rating thermostats.

Low-degree rated heat detectors are intended only for installation in areas having controlled temperature conditions at least -6.6 °C (20 °F) below rating. The spacings specified are for flat, smooth ceiling construction of ordinary height, generally regarded as the most favorable condition for distribution of heated air currents resulting from a fire. Under other forms of ceiling construction, reduced spacings may be required.

The fire tests conducted to determine the suitability of the spacings are conducted in an 18.3 x 18.3 m (60 x 60 ft) room having a 4.8-m (15-ft, 9-in.) high smooth ceiling and minimum air movement. The test fire (denatured alcohol) is located approximately 0.91 m (3 ft) above the floor and is of a magnitude so that sprinkler operation is obtained in approximately 2 minutes. For comparative purposes, automatic sprinklers rated at 71.7 °C (160 °F) are installed on a 3.05 x 3.05 m (10 x 10 ft) spacing schedule in an upright position with the deflectors approximately 17.5 cm (7 in) below the ceiling. At the maximum permissible spacing for the heat detectors, they must operate prior to operation of the sprinklers.

The placement and spacing of heat detecting devices should be based on consideration of the ceiling construction, ceiling height, room or space areas, spaced subdivisions, normal room temperature, possible exposure of the devices to abnormal heat (such as uninsulated steam pipes) or to draft conditions likely to be encountered at the time of a fire.

12.4 Operating Principle of Heat Detectors

Spot type heat detectors respond to temperature changes in the surrounding environment. They are designed to respond to the convected thermal energy of a fire. They detect at either a predetermined fixed temperature or at a specified rate of temperature rise. In general, a heat detector is designed to sense a prescribed change in a physical or electrical property of its material when exposed to heat.

12.4.1 Fixed-Temperature Heat Detectors

Fixed-temperature detectors are intended to alarm when the temperature of their operating elements reaches specific points. The air temperature at the time of operation may be higher than the rated temperature due to the thermal inertia of the operating elements. This condition is called thermal lag. Fixed-temperature heat detectors are available to cover a wide range of operating temperatures from 57 °C (135 °F) and higher. Higher temperature detectors are sometimes necessary so that detection can be provided in areas normally subjected to high ambient (nonfire) temperatures. Fixed-temperature heat detectors are manufactured in seven temperature range groups, and the proper detector is selected based on the highest ambient temperature of the room for which it is designed. Fixed-temperature detectors are available in several types.

12.4.1.1 Fusible-Element Type

One type of fusible-element spot detector is the eutectic (fusible) metal type. Eutectic metal employs a mixture of either bismuth, lead, tin or cadmium which melts at a predetermined temperature. Eutectic metals that melt rapidly at a predetermined temperature are used to actuate the operating elements of the heat detector. When the element fuses (i.e., melts), the spring action closes contacts and initiates an alarm. Devices using eutectic elements cannot be restored. When their element fuses, alarms are signaled by various mechanical or electrical means (typically by a closed set of contacts).

12.4.1.2 Continuous Line Type

One type of line detector uses a pair of wires in a normally open circuit enclosed in a braided sheath to form a single-cable assembly. When the predetermined temperature is reached, the insulation, which holds the conductors apart melts, and the two wires come in contact which initiates the alarm. The fused section of the cable must be replaced to restore the system. Alternatively, this type of detector may use a stainless steel capillary tube containing a coaxial center conductor separated from the tube wall by a temperature-sensitive glass semiconducting material. As the temperature rises, the semiconductor decreases and allows more current to flow, thereby initiating the alarm.

12.4.1.3 Bimetallic Type

These spot detectors are generally of two types, including (1) the bimetal strip and (2) the bimetal snap disc. As it is heated, the bimetal strip deforms in the direction of the contact point. The operating element of a snap disc device is a bimetal disc composed of two metals with different thermal growth rates formed into a concave shape in its unstressed condition. Generally, a heat detector is attached to the detector frame to speed the transfer of heat from the room air to the bimetal. As the disc (not part of the electrical circuit) is heated, the stresses developed in the two different metals cause it to suddenly reverse the curvature and become convex. This provides a rapid positive action that closes the alarm contacts. These devices are typically self-restoring after heat is removed.

12.4.2 Rate Compensation Heat Detectors

These spot type detectors respond when the temperature of the air surrounding the detector reaches a predetermined temperature, regardless of the rate of temperature rise. A typical example is a spot-type detector with a tubular casing of metal that tends to expand lengthwise as it is heated, and an associated contact mechanism that will close at a certain point in the elongation. A second metallic element inside the tube exerts an opposing force on the contacts, tending to hold them open. The forces are balanced so that, with a slow rate of temperature rise, there is more time for heat to penetrate to the inner element. This inhibits contact closure until the total device has been heated to its rated temperature level. However, with a fast rate of temperature rise, there is less time for heat to penetrate to the inner element. The element therefore exerts less of an inhibiting effect, so contact closure is obtained when the total device has been heated to a lower level. This, in effect, compensates for thermal lag.

12.4.3 Rate-of-Rise Heat Detectors

These spot type detectors operate when the room temperature rises at a rate which exceeds a predetermined value. For example, the effect of a flaming fire on the surrounding area is to rapidly increase air temperature in the space. A fixed-temperature detector will not initiate an alarm until the air temperature near the ceiling exceeds the design operating point. The rate-of-rise detector, however, will function when the rate of temperature increase exceeds a predetermined value, typically around 7 to 8 °C (12 to 15 °F) per minute. Rate-of-rise detectors are designed to compensate for the normal changes in ambient temperature [less than 6.7 °C (12 °F) per minute] that are expected under non-fire conditions.

12.4.4 Pneumatic Heat Detectors

In a pneumatic spot type heat detector, air heated in a tube or chamber expands, increasing the pressure in the tube or chamber. This exerts a mechanical force on a diaphragm that close the alarm contacts. If the tube or chamber were hermetically sealed, slow increases in ambient temperature, a drop in the barometric pressure, or both, would cause the detector to initiate an alarm regardless of the rate of temperature change. To overcome this, pneumatic detectors have a small orifice to vent the higher pressure that builds up during slow increases in temperature or during a drop in barometric pressure. The vents are sized so that when the temperature changes rapidly, as in a fire, the rate of expansion exceeds the venting rate and pressure rises. When the temperature rise exceeds 7 to 8 °C (12 to 15 °F) per minute, the pressure is converted to mechanical action by a flexible diaphragm. Pneumatic heat detectors are available for both line- and spot-type detectors.

12.4.4.1 Line-Type Heat Detectors

The line-type consists of metal tubing, in a loop configuration, attached to the ceiling of the area to be protected. Lines of the tubing are normally spaced not more than 9.1 m (30 ft) apart, not more than 4.5 m (15 ft) from a wall, and with no more than 305 m (1,000 ft) of tubing on each circuit. Also, a minimum of at least 5-percent of each tube circuit or 7.6 m (25 ft) of tube, whichever is greater, must be in each protected area. Without this minimum amount of tubing exposed to a fire condition, insufficient pressure would build up to achieve proper response.

In small areas where the line-type tube detector might have insufficient tubing exposed to generate sufficient pressures to close the alarm contacts, air chambers or rosettes of tubing are often used. These units act like a spot-type detector by providing the volume of air required to meet the 5-percent or 7.6 m (25 ft) requirement. Since a line-type rate-of-rise detector is an integrating detector, it will actuate either when a rapid heat rise occurs in one area of exposed tubing, or when a slightly less rapid heat rise takes place in several areas when tubing on the same loop is exposed. The pneumatic principle is also used to close contacts within spot-type detector. The difference between the line-and spot-type detectors is that the spot-type contains all of the air in a single container rather than in a tube that extends from the detectors assembly to the protected area(s).

12.4.5 Combination Heat Detectors

Many spot type heat detectors are available that utilize both the rate-rise and fixed-temperature principles. The advantage of units such as these is that the rate-of-rise elements will respond quickly to rapidly developing fires, while the fixed-temperature elements will respond to slowly developing smoldering fires when design alarm temperature is reached. The most common combination detector uses a vented air chamber and a flexible diaphragm for the rate-of-rise function, while the fixed-temperature element is usually leaf-spring restrained by a eutectic metal. When the fixed-temperature element reaches its design operating temperature, the eutectic metal fuses and releases the spring, which closes the contacts.

12.4.6 Electronic Spot-Type Thermal Detectors

These detectors utilize a sensing element consisting of one or more thermistors, which produce a change in electrical resistance in response to an increase in temperature. This resistance is monitored by associated electronic circuitry, and the detector responds when the resistance changes at an abnormal rate (rate-of-rise type) or when the resistance reaches a specific value (fixed-temperature type).

12.5 Fixed-Temperature Heat Detector Activation

Fixed-temperature heat detectors are generally modeled by calculating the heat transfer from the fire gases to the detector element, and the resultant temperature change. To simplify the calculation, all current detector models treat the detector as a “lumped mass.” A lumped mass model assumes that there are no temperature gradients within the detector element. This assumption is reasonable for solder-type heat detectors, since the operating element has a low mass. With bimetallic-type detectors, the lumped mass assumption may introduce some error, since heat must be transferred to two slightly different parts.

Analytical methods for calculating detector temperature require that equations for temperature and velocity of fire gases as a function of time must be inserted into the basic heat transfer equation. The resulting differential equation must be integrated to arrive at an analytical solution to the heat transfer equation.

For steady-state fires, the time required to heat the sensing element of a suppression device from room temperature to operation temperature is given by (Budnick, Evans, and Nelson, 1997):

$$t_{activation} = \frac{RTI}{\sqrt{u_{jet}}} \ln\left(\frac{T_{jet} - T_a}{T_{jet} - T_{activation}}\right) \qquad (12\text{-}1)$$

Where:

$t_{activation}$ = sprinkler head activation time (sec)
RTI = Response Time Index $(m\text{-}sec)^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$T_{activation}$ = activation temperature of detector (°C)

The RTI concept was developed by Factory Mutual Research Corporation (FMRC) to be a fundamental measure of thermal detector sensitivity. A detector’s RTI is determined in plunge tests with a uniform gas flow of constant temperature and velocity and can be used to predict the detector’s activation time in any fire environment. The RTI was developed under the assumption that conductive heat exchange between the sensing element and supportive parts is negligible. The RTI is a function of the time constant, , of the detector, which is related to the mass and surface area of the detector element. Faster detectors have low response time indices and smaller time constants. Detector elements with low time constants have low ratios of mass to surface area. The RTI is defined by the following equation:

$$RTI = \frac{m_e c_{p(e)}}{h_e A_e} \sqrt{u_{jet}} \qquad (12\text{-}2)$$

Where:

m_e = mass of element (kg)
$c_{p(e)}$ = specific heat of element (kJ/kg-K)
h_e = convective heat transfer coefficient (kW/m^2-K)
A_e = surface area of element (m^2)
u_{jet} = velocity of gas moving past the detector (m/sec)

The flow of heat and ceiling jet into a heat detector sensing element is not instantaneous; it occurs over a period of time. A measure of the speed with which heat transfer occurs (the thermal coefficient) is needed to accurately predict heat detector response. Called the detector time constant ($_0$), this measure should be determined by a validated test (Heskestad, 1976). For a given detector, the convective heat transfer coefficient (h_e) and are approximately proportional to the square root of the velocity (u) of the gases passing the detector. This relationship can be expressed as the characteristic response time index, RTI, for a given detector:

$$RTI \cong \tau u^{\frac{1}{2}} \cong \tau_0 u_0^{\frac{1}{2}} \quad (12\text{-}3)$$

Where:

RTI = response time index (m-sec)$^{1/2}$

$_0$ = detector time constant (sec)

u_0 = gas velocity (m/sec)

The detector time constant, $_0$, is measured in the laboratory at some reference velocity, u_0. This expression can be used to determine the detector's RTI.

UL-listed detector spacing can be used as a measure of detector sensitivity. Heskestad and Delichatsios (1977), analyzed UL test data and calculated the time constant, $_0$, for various combinations of UL-listed spacing and detector-operated temperature. The Subcommittee of NFPA 72 expanded that table to include a larger selection of detectors. The table is reproduced here as Table 12-1.

Table 12-1. Time Constant of Any Listed Detector

Listed Spacing (ft)	**Underwriter's Laboratories, Inc. (UL) Temperature Rating (°F)**						**FMRC (All Temperatures)**
	128	**135**	**145**	**160**	**170**	**196**	
	Detector Time Constant, $_0$ (sec)						
10	400	330	262	195	160	97	196
15	250	190	156	110	89	45	110
20	165	135	105	70	52	17	70
25	124	100	78	48	32	-	48
30	95	80	61	36	22	-	36
40	71	57	41	18	-	-	-
50	59	44	30	-	-	-	-
70	36	24	9	-	-	-	-

Note: These time constants are based on an analysis of the UL and FMRC listing test procedures.
This table is reproduced from NFPA 72, Appendix B, 1999 Edition.

The time constants listed in Table 12-1 are based on a reference velocity of 1.5 m/sec (5 ft/sec). These time constants can be converted to RTI values be using Equation 12-4, as follows:

$$RTI = \tau_0 \sqrt{1.5} \left(\frac{m}{sec}\right)^{\frac{1}{2}} \qquad (12\text{-}4)$$

Table 12-2 provides the calculated values of RTI based on the detector time constant ($_0$) in Table 12-1.

Table 12-2. Detector Response Time Index of Any Listed Detector

Listed Spacing (ft)	**Underwriter's Laboratories, Inc. (UL) Temperature Rating (°F)**						**FMRC (All Temperatures)**
	128	**135**	**145**	**160**	**170**	**196**	
	Detector RTI (m-sec)$^{1/2}$						
10	490	404	321	239	196	119	240
15	306	233	191	135	109	55	135
20	325	165	129	86	64	21	86
25	152	123	96	59	39	-	59
30	116	98	75	44	27	-	44
40	87	70	50	22	-	-	-
50	72	54	37	-	-	-	-
70	44	29	11	-	-	-	-

The expressions for estimating the maximum ceiling jet temperature and velocity as a function of ceiling height, radial position, and HRR were developed from an analysis of experiments with large-scale fires having HRRs from 668 kW to 98,000 kW. The expressions are given for two regions—one where the plume directly strikes the ceiling and the other, outside the plume region where a true horizontal flow exists.

The ceiling jet temperature and velocity correlations of a fire plume are given by the following expression:

$$T_{jet} - T_a = \frac{16.9\ \dot{Q}^{\frac{2}{3}}}{H^{\frac{5}{3}}} \quad \text{for} \frac{r}{H} \leq 0.18 \qquad (12\text{-}5)$$

$$T_{jet} - T_a = \frac{5.38\ \left(\frac{\dot{Q}}{r}\right)^{\frac{2}{3}}}{H} \quad \text{for} \frac{r}{H} > 0.18 \qquad (12\text{-}6)$$

$$u_{jet} = 0.96\ \left(\frac{\dot{Q}}{H}\right)^{\frac{1}{3}} \quad \text{for} \frac{r}{H} \leq 0.15 \qquad (12\text{-}7)$$

$$u_{jet} = \frac{0.195\ \dot{Q}^{\frac{1}{3}}\ H^{\frac{1}{2}}}{r^{\frac{5}{6}}} \quad \text{for} \frac{r}{H} > 0.15 \qquad (12\text{-}8)$$

Where:

T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$\dot{Q}$ = heat release rate of the fire (kW)
H = distance from the top of the fuel package to the ceiling level (m)
r = radial distance from the plume centerline to the detector (m)
u_{jet} = ceiling jet velocity (m/sec)

The above correlations are used extensively to calculate the maximum temperature and velocity in the ceiling jet at any distance, r, from the fire axis. Note that the regions for which each expression is valid are given as a function of the ratio of the radial position, r, to the ceiling height, H. Moving away from the centerline of the plume jet, r/H increases. So, for example, for regions where r/H>0.18, Equation 12-6 should be used. Based on the cases where the hot gases have begun to spread under a ceiling located above the fire, Equation 12-5 applies for a small radial distance, r, from the impingement point (see Figure 12-1).

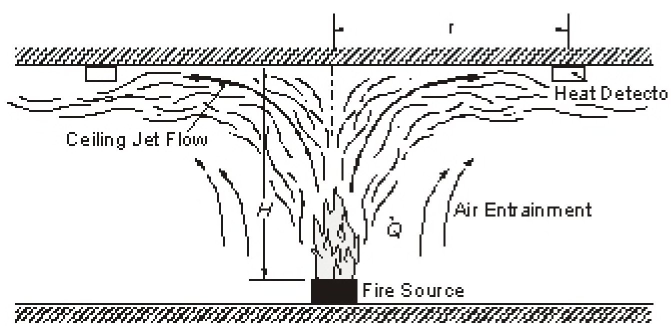


Figure 12-1 Ceiling Jet Flow Beneath and Unconfined Ceiling Showing a Heat Detector

As with the temperatures velocities in the ceiling jet flow, u_{jet}, there are two regions under a ceiling, including (1) one close to the impingement point where velocities are nearly constant and (2) another farther away where velocities vary with radial position.

The ceiling jet temperature is important in fire safety because it is generally the region where sprinklers are located; therefore, knowledge of the temperature and velocity of the ceiling jet as a function of position enables us to estimate the detector response time. The temperature and velocity of a ceiling jet varies with the depth of the jet. Moving away from the ceiling, the temperature increases to a maximum, then decreases closer to the edge of the jet. This profile is not symmetric as it is with a plume, where the maximum occurs along the plume centerline. With the knowledge of plume ceiling jet temperature and velocity, we can estimate the actuation time of a fixed-temperature if we also know the spacing and the speed or thermal inertia of the detector. The response of a fixed-temperature heat detector is given by its RTI.

12.6 Assumptions and Limitations

The method discussed in this chapter is subject to several assumptions and limitations:

(1) The plume ceiling jet correlations of temperature and velocity assume that the fire source is located away from walls and corners. The primary impact of walls and corners is to reduce the amount of entrained air into the plume. This has the effect of lengthening flames and causing the temperature in a plume to be higher at a given elevation than it would be in the open.

(2) The correlations for estimating the maximum ceiling jet temperature and velocity were developed for steady-state fires and plumes under unconfined ceiling (where the smoke layer does not develop below the ceiling jet during the time of interest).

(3) The plume ceiling jet correlations are valid for unconfined flat ceilings, as the environments outside the ceiling jet are uniform in temperature and are atmospheric ambient. Caution should be exercised with this method when the ceiling has an irregular surface such as beam pockets.

(4) The correlations for estimating the maximum ceiling jet temperature and velocity were developed for steady-state fires and plumes under unconfined ceiling (where the smoke layer does not develop below the ceiling jet during the time of interest).

(5) The plume ceiling jet correlations are valid for unconfined ceilings, as the environments outside the ceiling jet are uniform in temperature and are atmospheric ambient.

(6) All calculations for determining time to operation only consider the convective heating of sensing elements by the hot fire gases. They do not explicitly account for any direct heating by radiation from the flames.

(7) Caution should be exercised with this method when the overhead area is highly obstructed.

(8) The detectors are located at or very near to the ceiling. Very near to the ceiling would include code compliant detectors mounted on the bottom flange of structural steel beams. These methods are not applicable to detectors mounted well below the ceiling in free air.

12.7 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) heat release rate of the fire (kW)

(2) listed spacing of detectors (ft)

(3) activation temperature of detectors (°F)

(4) height to ceiling (ft)

(5) ambient room temperature (°F)

12.8 Cautions

(1) Use (10_Detector_Activation_Time.xls) and select “FTHDetector” spreadsheet on the CD-ROM for calculations.

(2) Make sure all inputs are recorded in the correct units.

12.9 Summary

This chapter discusses a method of calculating the response time of heat detectors under unobstructed ceilings in response to steady-state fires without forced ventilation.

12.10 References

Budnick, E.K., D.D. Evans, and H.E. Nelson, "Simplified Fire Growth Calculations" Section 11, Chapter 10, *NFPA Fire Protection Handbook*, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1997.

Heskestad, G., and H.F. Smith, "Investigation of a New Sprinkler Sensitivity Approval Test: The Plunge Test," FMRC Serial No. 22485, Factory Mutual Research Corporation, Norwood, Massachusetts, December 1976.

Heskestad, G., and M.A. Delichatsios, "Environments of Fire Detectors—Phase 1: Effects of Fire Size, Ceiling Height and Material," Measurements Volume I, NBS-GCR-77-86, Analysis Volume II, NBS-GCR-77-95, National Bureau of Standards, Washington, DC, 1977.

NFPA 72, National Fire Alarm Code®, 1999 Edition, Appendix B: Engineering Guide for Automatic Fire Detection Spacing, National Fire Protection Association, Quincy, Massachusetts.

12.11 Additional Readings

Alpert, R.L., "Calculation of Response Time of Ceiling-Mounted Fire Detectors," *Fire Technology*, Volume 8, pp. 181–195, 1972.

Alpert, R.L., and E.J. Ward, "Evaluation of Unsprinklered Fire Hazard," *Fire Safety Journal*, Volume 7, No. 177, 1984.

Bryan, J.L., *Fire Suppression and Detection Systems*, Macmillan Publishing, New York, 1993.

Evans, D.A., "Ceiling," Sec. 2, Ch. 4, *SFPE Handbook of Fire Protection Engineering*, 2nd Ed., P.J. DiNenno, Editor-in-Chief, National Fire Protection Assoc., Quincy, Massachusetts, 1995.

Moore, W.D., "Automatic Fire Detectors" Sec. 5, Ch. 2, *NFPA Fire Protection Handbook*, 18th Ed., A.E. Cote, Editor-in-Chief, National Fire Protection Assoc., Quincy, Massachusetts, 1997.

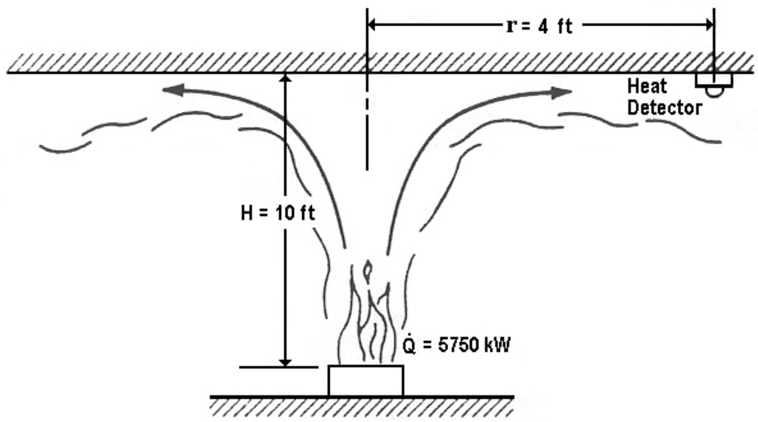
Schifiliti, R.P., B.J. Meacham, and R.P. Custer, Chapter 1, Section 4, "Design of Detection Systems," *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

12.12 Problems

Example Problem 12.12-1

Problem Statement

A 34.5-ft^2 (3.20-m^2) lube oil pool fire with $\dot{Q}$ = 5,750 kW occurs in a space protected with fixed-temperature heat detectors. Calculate the activation time for the fixed-temperature heat detectors, using 10-ft (3.05-m) spacing, in an area with a ceiling height of 10 ft (3.05 m). The detector activation temperature is 128 °F (53 °C), the radial distance to the detector is 4 ft (1.22 m), and the ambient temperature is 77 °F (25 °C).



Example Problem 12-1: Fire Scenario with Heat Detectors

Solution

Purpose:

(1) Determine the response time of the fixed-temperature heat detectors for the fire scenario.

Assumptions:

(1) The fire is located away from walls and corners.
(2) The fire is steady state and plume is under unconfined ceiling.
(3) Only convective heat transfer from the hot fire gases is considered.
(4) There is no heavily obstructed overhead.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (click on *FTHDetector*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 5,750 kW

-Radial Distance to the Detector (r) = 4 ft

-Activation Temperature of the Fixed-Temperature Heat Detector ($T_{activation}$) = 128 °F

-Distance from the Top of the Fuel Package to the Ceiling (H) = 10 ft

-Ambient Air Temperature (T_a) = 77 °F

-Click on the option button (⊙) for FTH detectors with $T_{activation}$ = 128 °F

-Select Detector Spacing: 10

Results*

Detector Type	Heat Detector Activation Time ($t_{activation}$) (min.)
Fixed-Temperature	0.27

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 10_Detector_Activation_Time.xls (FTHDetector)

CHAPTER 12. ESTIMATING HEAT DETECTOR RESPONSE TIME

Version 1805.0

The following calculations estimate fixed temperature heat detector activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Detector Selected.
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

Heat Release Rate of the Fire (Q) (Steady State)	5750.00	kW	
Radial Distance to the Detector (r) "never more than 0.707 or 1/2√2 of the listed spacing"	4.00	ft	122 m
Activation Temperature of the Fixed Temperature Heat Detector ($T_{activation}$)	145	°F	6278 °C
Detector Response Time Index (RTI)	321.00	(m-sec)$^{1/2}$	
Height of Ceiling above Top of Fuel (H)	10.00	ft	305 m
Ambient Air Temperature (T_a)	68.00	°F	2000 °C
			29300 K
Convective Heat Release Fraction (χ_c)	0.70		
r/H = 0.40	Calculate		

INPUT DATA FOR ESTIMATING HEAT DETECTOR RESPONSE TIME

Activation Temperature $T_{activation}$

T= 128 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	490	128
15	306	128
20	325	128
25	152	128
30	116	128
40	87	128
50	72	128
70	44	128
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

10

Scroll to desired spacing then Click on selection

T= 135 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	404	135
15	233	135
20	165	135
25	123	135
30	98	135
40	70	135
50	54	135
70	20	135
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 145 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	321	145
15	191	145
20	129	145
25	96	145
30	75	145
40	50	145
50	37	145
70	11	145
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 160 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	239	160
15	135	160
20	86	160
25	59	160
30	44	160
40	22	160
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 170 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	196	170
15	109	170
20	64	170
25	39	170
30	27	170
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 196 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	119	196
15	55	196
20	21	196
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then

Click on selection

Reference: *NFPA Standard 72, National Fire Alarm Code, Appendix B, Table B-3.2.5.1, 1999, Edition.*

ESTIMATING FIXED TEMPERATURE HEAT DETECTOR RESPONSE TIME

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(\sqrt{u_{jet}}))(\ln(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = detector activation time (sec)

RTI = detector response time index (m-sec)$^{1/2}$

u_{jet} = ceiling jet velocity (m/sec)

T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

$T_{activation}$ = activation temperature of detector (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\,(Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38\,(Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

Q_c = convective portion of the heat release rate (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the detector (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\, Q$

Where Q_c = convective heat release rate (kW)

Q = heat release rate of the fire (kW)

χ_c = convective heat release fraction

Q_c = 4025 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.40 r/H > 0.15

>0.15	391.35	<0.15	667.38

$T_{jet} - T_a =$ 5.38 ((Qc/r)^2/3)/H

$T_{jet} - T_a =$ 391.35

$T_{jet} =$ 411.35 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\ (Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\ Q^{1/3}\ H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)
Q = heat release rate of the fire (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the detector (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.40 r/H > 0.15

$u_{jet} =$ (0.195 Q^1/3 H^1/2)/r^(5/6)

$u_{jet} =$ 5.171 m/sec

Detector Activation Time Calculation

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\ (\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation} =$ 16.34 sec

The detector will respond in approximately	0.27 minutes	Answer

NOTE: If $t_{activation}$ = "NUM" Detector does not activate

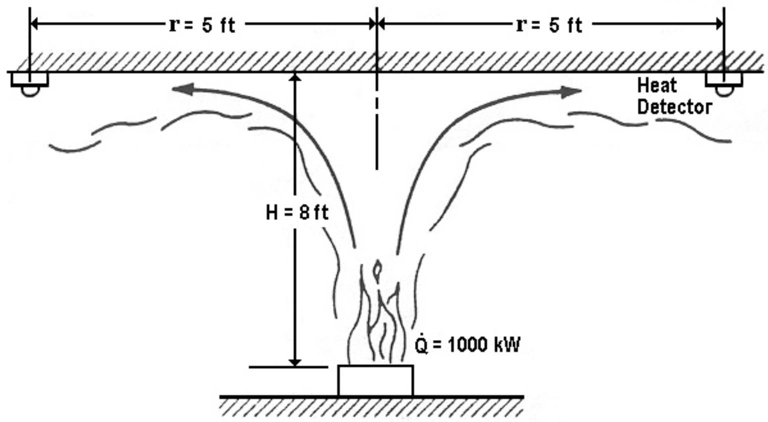
NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations.
The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 12.12-2

Problem Statement

A trash fire with $\dot{Q}$ = 1,000 kW occurs in a space protected with fixed-temperature heat detectors. Calculate the activation time for the fixed-temperature heat detectors, using 10 ft (3.05 m) spacing, in an area with a ceiling height of 8 ft (2.43 m). The fire is located directly between heat detectors. The detector activation temperature is 160 °F (71 °C), and the ambient temperature is 77 °F (25 °C).



Example Problem 12-2: Fire Scenario with heat detectors that are equidistant from the fire source

Solution

Purpose:

(1) Determine the response time of the fixed-temperature heat detectors for the fire scenario.

Assumptions:

(1) The fire is located away from walls and corners.
(2) The fire is steady state and plume is under unconfined ceiling.
(3) Only convective heat transfer from the hot fire gases is considered.
(4) There is no heavily obstructed overhead.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (click on *FTHDetector*)

FDT^s Input Parameters:

-Heat Release Rate of the Fire $(\dot{Q})$ = 1,000 kW

-Radial Distance to the Detector (r) = 5 ft

-Activation Temperature of the Fixed-Temperature Heat Detector ($T_{activation}$) = 160 °F

-Distance from the Top of the Fuel Package to the Ceiling (H) = 8 ft

-Ambient Air Temperature (T_a) = 68 °F

-Click on the option button (⊙) for FTH detectors with $T_{activation}$ = 160 °F

-Select Detector Spacing: 10

Results*

Detector Type	Heat Detector Activation Time ($t_{activation}$) (min.)
Fixed-Temperature	1.34

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 10_Detector_Activation_Time.xls (FTHDetector)

CHAPTER 12. ESTIMATING HEAT DETECTOR RESPONSE TIME

Version 1805.0

The following calculations estimate fixed temperature heat detector activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Detector Selected.
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

Parameter	Value	Unit	Converted
Heat Release Rate of the Fire (Q) (Steady State)	1000.00	kW	
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	5.00	ft	1.52 m
Activation Temperature of the Fixed Temperature Heat Detector ($T_{activation}$)	160	°F	71.11 °C
Detector Response Time Index (RTI)	239.00	(m-sec)$^{1/2}$	
Height of Ceiling above Top of Fuel (H)	8.00	ft	2.44 m
Ambient Air Temperature (T_a)	68.00	°F	20.00 °C
			293.00 K
Convective Heat Release Fraction (χ_c)	0.70		

r/H = 0.63

Calculate

INPUT DATA FOR ESTIMATING HEAT DETECTOR RESPONSE TIME

Activation Temperature $T_{activation}$

○ T= 128 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	490	128
15	306	128
20	325	128
25	152	128
30	116	128
40	87	128
50	72	128
70	44	128
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

○ T= 135 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	404	135
15	233	135
20	165	135
25	123	135
30	98	135
40	70	135
50	54	135
70	20	135
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

○ T= 145 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	321	145
15	191	145
20	129	145
25	96	145
30	75	145
40	50	145
50	37	145
70	11	145
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 160 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	239	160
15	135	160
20	86	160
25	59	160
30	44	160
40	22	160
User Specified Value	Enter Value	Enter Value

Select Detector Spacing
10
Scroll to desired spacing then Click on selection

T= 170 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	196	170
15	109	170
20	64	170
25	39	170
30	27	170
User Specified Value	Enter Value	Enter Value

Select Detector Spacing
Scroll to desired spacing then Click on selection

T= 196 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	119	196
15	55	196
20	21	196
User Specified Value	Enter Value	Enter Value

Select Detector Spacing
Scroll to desired spacing then
Click on selection

Reference: *NFPA Standard 72, National Fire Alarm Code, Appendix B, Table B-3.2.5.1, 1999, Edition.*

ESTIMATING FIXED TEMPERATURE HEAT DETECTOR RESPONSE TIME

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(\sqrt{u_{jet}}))(\ln(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = detector activation time (sec)

RTI = detector response time index (m-sec)$^{1/2}$

u_{jet} = ceiling jet velocity (m/sec)

T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

$T_{activation}$ = activation temperature of detector (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\,(Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38\,(Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)

T_a = ambient air temperature (°C)

Q_c = convective portion of the heat release rate (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the detector (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c Q$

Where Q_c = convective heat release rate (kW)

Q = heat release rate of the fire (kW)

χ_c = convective heat release fraction

Q_c = 700 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.63 r/H > 0.15

>0.15	131.35	<0.15	301.61

$T_{jet} - T_a$ = 5.38 ((Qc/r)^2/3)/H

$T_{jet} - T_a$ = 131.35

T_{jet} = 151.35 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\ (Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\ Q^{1/3}\ H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)

Q = heat release rate of the fire (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the detector (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.63 r/H > 0.15

u_{jet} = (0.195 Q^1/3 H^1/2)/r^(5/6)

u_{jet} = 2.143 m/sec

Detector Activation Time Calculation

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\ (\ln\ (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation}$ = 80.46 sec

The detector will respond in approximately	1.34 minutes	Answer

NOTE: If $t_{activation}$ = "NUM" Detector does not activate

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations.
The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER

13.1 Objectives

This chapter has the following objectives:

- Explain the incipient stage of a fire.
- Characterize flashover and its stages.
- Describe how to predict the HRR required for flashover and post-flashover temperature in a compartment.

13.2 Introduction

Following ignition, a compartment fire experiences a slow growth period, which is often referred to as the "incipient stage." During this stage, all of the measurable fire parameters [heat release rate (HRR), rate of fuel or oxygen consumption, and temperature of the compartment gases] are low and increase at a low rate.

After the incipient stage, the fire begins to grow more rapidly, as in the parabolic fire growth curves described by the t^2 fires. (See Appendix B for details.) The HRR and rate of fuel/oxygen consumption also increase rapidly. This acceleration, in turn, also increases the compartment gas temperature. In an adequately ventilated compartment, the rate of air entering the compartment also increases. At some point in the history of a given fire, the rate of fire growth increases so rapidly that all combustibles in the compartment reach their ignition temperature and become involved in the combustion process and "flashover" is achieved. Flashover is a complex topic and a number of theories and calculation methods will be presented. Figure 13-1 illustrates of the post-flashover compartment fire in which the fire is assumed to be volumetric rather than point source.

At the high temperatures that occur in the gas layer of a post-flashover fire, significant radiative heat transfer occurs from the carbon dioxide gas, water vapor, and soot particles in the smoke. The gas layer and flames radiate to the floor, walls and ceiling, back to the fire and fuel sources, to any other objects that may be present in the compartment, and out through any openings in the enclosure. In addition, the heated walls, ceiling, and other heated objects are re-radiating heat back within the enclosure.

Often, a post-flashover fire may have significant fuel to continue burning, but the air entering the room may be limited. The fire, which might otherwise continue to grow if it were burning in unconfined space, enters a period where it is said to be "ventilation controlled," meaning that the fire ceases to grow because of a lack of oxygen. The rates of fuel consumption and heat release stall, and the compartment temperature ceases to climb as rapidly it did before flashover. These parameters may then begin to decrease slightly as a result of the less-than-stoichiometric air-fuel mixture. The fire may continue to decay until the air supply ratio become stoichiometric or greater, thereby allowing further fire growth. At this point, the fire may become "fuel-controlled," meaning the amount of available fuel (rather than the available air supply) dictates the rate of burning.

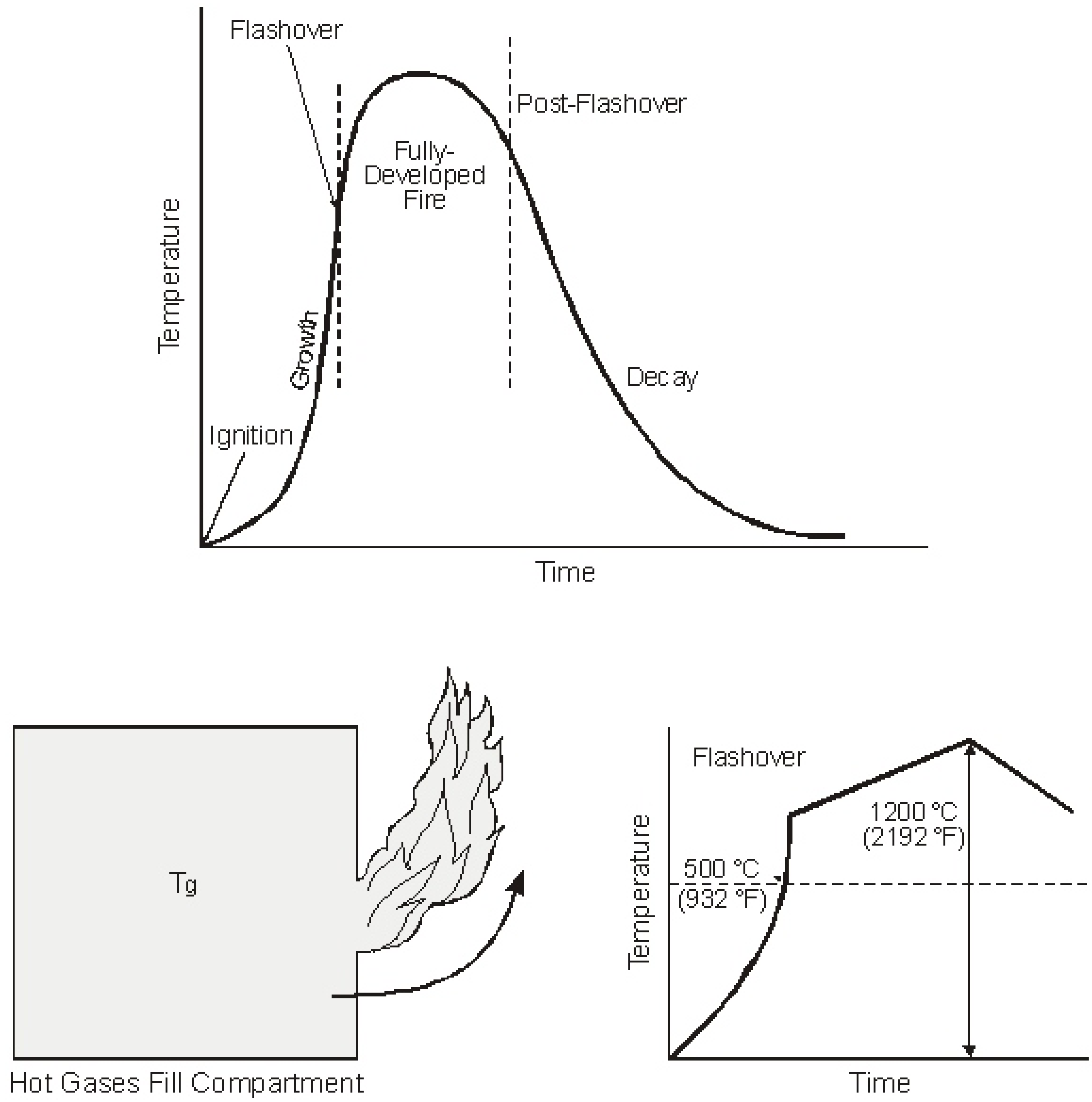


Figure 13-1 Flashover and Postflashover Compartment Fire

The fire may again grow to a ventilation controlled condition and continue in a transient state alternate between ventilation and fuel control throughout the remaining active burning period of the fire. It is during this post-flashover stage that the fire barrier system must function at its highest efficiency to contain the fire. Eventually, the fire will enter its final fuel-controlled state as the fuel is totally consumed and the fire decays to extinction.

Several physical processes may be described in order to characterize the event that is frequently referred to as flashover. Fire fighters generally recognize flashover as the condition characterized by emission of flames through the open doorway of a fire compartment. It is the transition from the fire growth stage to the fully developed stage in the development of a compartment fire that is stages demarcates pre-flashover and post-flashover. Flashover is the phenomenon that defines the point of time at which all combustibles in the compartment are involved in the fire and flames appear to fill the entire volume. Gas temperatures of 300 to 650 °C (572 to 1,202 °F) have been associated with the onset of flashover, although temperatures of 500 to 600 °C (932 to 1,112 °F) are more widely accepted.

The International Standards Organization (ISO), "Glossary of Fire Terms and Definitions" (ISO/CD 13943), defines "flashover" as "the rapid transition to a state of total surface involvement in a fire of combustion material within an enclosure," Flashover is the term given to the relatively abrupt change from a localized fire to the complete involvement of all combustibles within a compartment.

Flashover is described by four fire stages. The hot buoyant plume develops during the first stage following ignition, and then reaches the ceiling and spreads as a ceiling jet (second stage). During the third and fourth stages, the hot layer expands and deepens, and flow through the opening is established.

When a fire in a compartment is allowed to grow without intervention, temperatures in the hot upper layer increase, thereby increasing radiant heat flux to all objects in the room. If a critical level of heat flux is reached, all exposed combustible items in the room will begin to ignite and burn, leading to a rapid increase in both heat release rate and temperatures. This transition is called "flashover". The fire is then referred to as "post-flashover fire," a "fully developed fire," or a fire that has reached "full room involvement."

The above descriptions of flashover are somewhat general. In order to more clearly define the specific point at which flashover occurs, we must use some definite physical characteristics:

(1) Flashover is the time at which the temperature rise in the hot gas reaches 500 °C (932 °F). [600 °C (1112 °F) is sometimes also used to define flashover].

(2) Flashover is the time at which the radiant heat flux density at the floor of the compartment reaches a minimum value of 20 kW/m^2 throughout.

(3) Flashover may be defined in terms of the rate of heat release ($\dot{Q}_{FO}$) from the fire in comparison to the total area of the compartment enclosing surfaces (A_T), the area of any ventilation openings (A_v), and the height of any ventilation openings (H_v), is illustrated by the following expression:

$$\dot{Q}_{FO} \propto \sqrt{A_T A_v \sqrt{H_v}} \qquad (13\text{-}1)$$

The first definition, in terms of temperature of the ceiling layer, is based upon experimental observation. Some compartment fire tests define the flashover point as the time at which flames just begin to emerge through openings in the compartment. Examination of the empirical data from testing has shown that the flame emergence point generally corresponds to a ceiling layer temperature between 500 °C to 600 °F (932 °F to 1,112 °F).

The second definition of flashover is given in terms of heat flux at the floor of the compartment. In essence, this definition describes the heat flux that would be necessary to establish simultaneous ignition of most ordinary combustibles throughout the enclosure. A radiant heat flux density of 20 kW/m^2 is sufficient for piloted ignition of most ordinary combustibles. In most cases, a ceiling layer at 500 °C (932 °F) will radiate to the floor at a minimum rate of 20 kW/m^2 in a typical compartment.

The third definition, which correlates HRR and compartment geometries, is more descriptive and more useful for predicting the physical conditions that might be necessary to establish either of the criteria required by the first two definitions. While researchers use different definitions for the onset of flashover, they reach some level of agreement on the temperature and heat flux necessary for the onset of flashover.

Hägglund, Jannson, and Onnermark (1974) experimentally observed flames exiting the doorway when the gas temperature about 10 mm (0.40 in) below the ceiling reached 600 °C (1,112 °F). Babrauskas (1977) applied this criterion to a series of 10 full-scale mattress fires; however, only 2 exhibited a potential to flashover the test compartment. These two mattress fires led to maximum gas temperatures well in excess of 600 °C (1,112 °F), with flashover observed near that temperature. In experiments conducted in a full-scale compartment at the National Bureau of Standards (NBS), now the National Institute of Standards and Technology (NIST), Fang (1975) reported an average upper room temperature ranging from 450 to 650 °C (842 to 1,202 °F) provided sufficient a level of radiation transfer to result in the ignition of crumpled newspaper indicators at floor level in the compartment. The average upper room gas temperature necessary for spontaneous ignition of newsprint was 540 ± 40 °C (1,004 ± 104 °F). It should be noted that this average included low temperatures at the mid-height of the compartment, and that temperatures measured 25 mm (1 in.) below the ceiling in this test series usually exceeded 600 °C (1,112 °F).

Fang (1975) also found that strips of newspaper placed at floor level in room burn tests ignited by fluxes of 17 to 25 kW/m^2, while 6.4 mm (1/4 in.) thick fir plywood ignited at 21 to 33 kW/m^2. Lee and Breese (1979) reported average heat fluxes at floor level of 17 to 30 kW/m^2 at flashover for full-scale tests of submarine compartments.

The NFPA 555 "Guide on Methods for Evaluating Potential for Room Flashover," (NFPA 555) define as room flashover in terms of temperature rise and heat flux at floor level. According to the NFPA guide, a gas temperature rise at flashover of 600 °C (1,112 °F) is a reasonable expectation, as is heat flux 20 kW/m^2 at floor level at flashover.

13.3 Compartment Flashover

Researchers have extensively studied the minimum HRR needed to cause flashover in a compartment. The studies suggest that minimum rate increases with the size of the compartment and depends, in a complex way, on the ventilation in the compartment. If there is too little ventilation, flashover cannot occur. If there is an excessive amount of ventilation, the excess air flow dilutes and cools the smoke, so a larger HRR is needed to reach the critical temperature condition for flashover. The construction materials and thickness of the ceiling and upper walls are also important factors in determining whether flashover will occur. These factors also determine the time required for flashover in a compartment that does reach the critical temperature.

Researchers have used several approaches to estimate the onset of flashover within a compartment. These approaches are typically based on simplified mass and energy balances in a single-compartment fire along with correlations to fire experiments. Visually, researchers report flashover as a discrete event in full-scale fire tests and actual fire incidents. Numerous variables can affect the transition of a compartment fire to flashover. Thermal influences are clearly important where radiative and convective heat flux are assumed to be driving forces. Ventilation conditions, compartment volume, and chemistry of the hot gas layer can also influence the occurrence of flashover. Rapid transition to flashover adds to the uncertainty of attempts to quantify the onset of flashover with laboratory measurements.

Although the flashover process is not easy to quantify in terms of measurable physical parameters, a working definition can be formulated from the considerable body of flashover-related full-scale fire test data accumulated from a variety of sources.

13.3.1 Method of Predicting Compartment Flashover HRR

The occurrence of flashover within a compartment is the ultimate signal of untenable conditions within the compartment of fire origin as well as a sign of greatly increased risk to other compartments within the structure. A number of experimental studies of full-scale fire have been performed provide simple correlations to predict HRR required for flashover.

13.3.1.1 Method of McCaffrey, Quintiere, and Harkleroad (MQH)

McCaffrey, Quintiere, and Harkleroad (1981) found that their data for predicting compartment hot gas temperature may extend to predict the HRR required to result in flashover in the compartment and obtained the following expression:

$$\dot{Q}_{FO} = 610 \sqrt{h_k A_T A_v \sqrt{h_v}} \qquad (13\text{-}2)$$

Where:

$\dot{Q}_{FO}$ = heat release rate to cause flashover (kW)
h_k = effective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surfaces (m^2), excluding area of vent opening
A_v = area of the ventilation openings (m^2)
h_v = height of the ventilation openings (m)

13.3.1.2 Method of Babrauskas

Babrauskas (1980) developed a simplified relationship that represent values correlated to experiments produce flashover. Based on the 33 compartment fire tests with HRR range from 11 to 3,840 kW with fuels primarily of wood and polyurethane, Babrauskas found that the HRR required to cause flashover is describe by the following relation:

$$\dot{Q}_{FO} = 750 \quad A_v \sqrt{h_v} \qquad (13\text{-}3)$$

Where:

$\dot{Q}_{FO}$ = heat release rate to cause flashover (kW)
A_v = area of the ventilation openings (m^2)
h_v = height of the ventilation openings (m)

Equation 13-3 is an extremely simply and easy to use relation, though it does not take into account the area and thermal properties of compartment enclosing surfaces.

13.3.1.3 Method of Thomas

Thomas (1981) (also reported by Walton and Thomas, 1995) developed a semi-empirical calculation of the HRR required to cause flashover in a compartment. He presented a simple model of flashover in a compartment, which he used to study the influence of wall-lining materials and thermal feedback to the burning items. He predicted a temperature rise of 520 °C (968 °F) and a black body radiation level of 22 kW/m^2 to an ambient surface away from the neighborhood of burning wood fuel at the predicted critical heat release rate necessary to cause flashover. Thomas' flashover is the result of simplifications applied to an energy balance of a compartment fire. The resulting correlation yields the minimum HRR for flashover:

$$\dot{Q}_{FO} = 7.8 A_T + 378 A_v \sqrt{h_v} \qquad (13\text{-}4)$$

Where:

$\dot{Q}_{FO}$ = heat release rate to cause flashover (kW)
A_T = total area of the compartment enclosing surfaces (m^2), excluding area of vent opening
A_v = area of the ventilation openings (m^2)
h_v = height of the ventilation openings (m)

The constants in Equation 13-4 represent values derived from experiments producing flashover. This correlation assumes that conduction has become stationary. The thermal penetration time is long for compartments with thick concrete walls, and it is unlikely that a fire slowly and gradually grows up to Q_{FO} in a number of hours. A reasonable time frame for estimating the likelihood of flashover is in the range of a few minutes up to around 30 minutes. We note that firefighter reaction time is usually also within this range (Karlsson and Quintiere, 1999).

13.3.2 Method of Predicting Compartment Post-Flashover Temperature

After flashover has occurred, the exposed surfaces of all combustibles items in the compartment will be burning and the HRR will developed to a maximum, producing high temperatures (see Figure 13-1). Typically, this may be as high as 1,100 °C (2,012 °F), but much higher temperatures can be obtained under certain conditions[1] (Drysdale, 1998). These will be maintained until the rate of generation of flammable volatile begins to decrease as a result of fuel consumption. It is during the period of the fully developed fire that building elements may reach temperatures at which they may fail.

Thomas (1974) developed an approach to estimate peak compartment temperature based on post-flashover enclosure fire data. Law (1978) extended this approach to include both natural and forced ventilation through the evaluation of extensive pre-flashover compartment fire test data. The results indicate that the predictions reasonably, but not exactly, predict the temperatures reported in the test fires.

Drawing on data gathered in the Conseil Internationale du Batiment (CIB) Research Program of fully developed compartment fires Thomas (1974) and Law (1978) found following correlation to predict post-flashover compartment temperature with natural ventilation:

$$T_{FO(max)} = 6000 \; \frac{\left(1 - e^{-0.1\Omega}\right)}{\sqrt{\Omega}} \qquad (13\text{-}5)$$

$$\Omega = \frac{A_T - A_v}{A_v \sqrt{h_v}} \qquad (13\text{-}6)$$

Where:

$\dot{Q}_{FO}$ = heat release rate to cause flashover (kW)
= ventilation factor
A_T = total area of the compartment enclosing surfaces (m^2), excluding area of vent opening
A_v = area of the ventilation openings (m^2)
h_v = height of the ventilation openings (m)

Note that Equation 13-5 does not consider variations in the thermophysical properties of compartment enclosing surfaces.

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[1]We occasionally encounter temperatures in excess of 1300–1400 °C (2,372–2,552 °F), which is sufficient to cause the surface of bricks to fuse (melt). For example, the Summit Rail Tunnel Fire (Department of Transport, 1984) produced sufficiently high temperatures to cause the faces of brick-lined ventilation shafts to fuse.

13.4 Fire Severity

Fires burn with differing intensities and produce significant spatial variability in terms of severity. The fundamental step in designing structures (fire barriers) for fire safety is to verify that the fire resistance of the structure (or each part of the structure is greater than the severity of the fire to which the structure is exposed. The verification requires that the following condition be satisfied:

$$\text{FireResistance} \geq \text{FireSeverity}$$

Where fire resistance is measure of the ability of the structure to resist collapse, fire spread or other failure during exposure to a fire of specified severity, and fire severity is a measure of the potential destructive impact of the burnout of all the available fuel in a compartment (Buchanan, 2001) most often it defined in terms of a period of exposure to the standard test fire.

Damage to a structure is largely dependent on the amount of heat absorbed by the structural elements. Heat transfer from post-flashover fires is primarily radiative which is proportional to the forth power of the absolute temperature. Hence, the severity of a fire is largely dependent on the temperatures reached and the duration of the high temperatures.

13.4.1 Method of Margaret Law

Law (1974) developed a correlation to predict fire severity (duration) based on data developed through an international research program. The fire severity correlation predicts the potential impact of a pos-flashover fire in terms of equivalent exposure in a fire endurance furnace fired to follow the European equivalent standard similar to ASTM E119 and NFPA 251.

The fire severity of available fuel load in a compartment with at least one opening can be estimated from the following equation:

$$t_f = \frac{KL_{eq}}{\left(A_v A_T\right)^{\frac{1}{2}}} \qquad (13\text{-}7)$$

Where:

t_f = fire severity or duration (sec)
K = correlational constant
L_{eq} = total fire or fuel load in equivalent of wood (kg)
A_v = area of ventilation opening (m^2)
A_T= total area of the compartment enclosing boundaries excluding area of vent opening (m^2)

Total fire or fuel load in compartment equivalent of wood with a given mass if given by:

$$L_{eq} = \frac{LDH_c}{DH_{c,wood}} \qquad (13\text{-}8)$$

Where:

L_{eq} = total fire or fuel load in equivalent of wood (kg)
L = total fire or fuel load in compartment (kg)
H_c = effective heat of combustion (kJ/kg)
$H_{c,\ wood}$ = wood heat of combustion (kJ/kg)

The compartment interior surface area can be calculated as follows:

A_T = ceiling + floor 2 (w_c x l_c)
+ 2 large walls 2 (h_c x w_c)
+ 2 small walls 2 (h_c x l_c)
- total area of vent opening(s) (A_0)

$$A_T = [2\ (w_c \times l_c) + 2\ (h_c \times w_c) + 2\ (h_c \times l_c)] - A_v \qquad (13\text{-}9)$$

Where:

A_T = total compartment interior surface area (m^2), excluding area of vent opening(s)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = total area of ventilation opening(s) (m^2)

The total area of ventilation opening is given by:

$$A_v = w_v \times h_v \qquad (13\text{-}10)$$

Where:

A_v = total area of ventilation opening(s) (m^2)
w_v = vent width (m)
h_v = vent height (m)

13.5 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations:

(1) The correlations were developed from a simplified mass and energy balance on a single compartment with ventilation openings.

(2) The experimental data used to develop the correlation included compartments with thermally thick walls and fires of wood cribs. Typically, heat transfer through compartment surfaces is accounted for with a semi-infinite solid approximation.

(3) The fire severity correlation is not appropriate for compartment that do not have openings for ventilation. While no precise minimum can be stated, it is suggested that this method not be used unless the size of the opening is at least 0.4 m^2 (4 ft^2).

13.6 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) compartment width (ft)

(2) compartment length (ft)

(3) compartment height (ft)

(4) vent width (ft)

(5) vent height (ft)

13.7 Cautions

(1) Use spreadsheet (13_Compartment_ Flashover_Calculations.xls) on the CD-ROM for calculations.

(2) Make sure input parameters are recorded in the correct units.

13.8 Summary

Flashover is a complex topic. Determination of temperatures associated with compartment fires provides a means of assessing the likelihood of the occurrence of flashover. Danger of flashover is assumed to occur if the analysis indicates a smoke layer temperature in excess of 450 °C (842 °F). Typically, flashover occurs when the smoke layer temperature reaches between 500 °C (932 °F) and 600 °F (1,112 °F). Hot smoke layers are considered to be close to black body radiators. At 450 °C (842 °F) the radiation from the smoke would be approximately 15 kW/m^2 (1.32 Btu/ft^2-sec). Temperatures above the 450 °C (842 °F) level generate a higher incident heat flux on the burning fuel in a compartment than if the fire were in the open.

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13.10 Problems

Example Problem 13.10-1

Problem Statement
Consider a compartment 20 ft wide x 25 ft long x 12 ft high (w_c x l_c x h_c), with an opening 3 ft wide and 8 ft high (w_v x h_v). The interior lining material of the compartment is 6 in. concrete. Calculate the HRR necessary for flashover, $\dot{Q}_{FO}$, and the post-flashover compartment temperature, T_{PFO}.

Solution

Purpose:
(1) Determine the heat release rate for flashover for the given compartment.

Assumptions:
(1) Natural Ventilation

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 13_Compartment_Flashover_Calculations.xls
(click on *Post_Flashover_Temperature* to calculate the post-flashover temperature)
(click on *Flashover-HRR* to calculate the HRR for flashover)

FDT^s Input Parameters:
-Compartment Width (w_c) = 20 ft
-Compartment Length (l_c) = 25 ft
-Compartment Height (h_c) = 12 ft
-Vent Width (w_v) = 3 ft
-Vent Height (h_v) = 8 ft
-Interior Lining Thickness (δ) = 6 in. (*Flashover-HRR only*)
-Select Material: **Concrete** (*Flashover-HRR only*)

Results*

Post-Flashover Compartment Temperature (T_{PFO}) °C (°F)	HRR for Flashover ($\dot{Q}_{FO}$) (kW)		
Method of Law	Method of MQH	Method of Brabauskas	Method of Thomas
811 (1,492)	1,612	2,611	2,806

*see spreadsheet on next page

Spreadsheet Calculations

(a) FDT^s: 13_Compartment_Flashover_Calculations.xls (Post_Flashover_Temperature)

CHAPTER 13. PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
Version 1805.0

The following calculations estimate the compartment post-flashover temperature.
Parameters in YELLOW CELLS are Entered by the User.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	8.00	ft	2.438 m

Calculate

PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
METHOD OF MARGARET LAW

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-183.*

$T_{PFO\,(max)} = 6000\,(1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

Where $T_{PFO\,(max)}$ = maximum compartment post-flashover temperature (°C)
Ω = ventilation factor

Where $\Omega = (A_T - A_v) / A_v\,(\sqrt{h_v})$
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Area of Ventilation Opening Calculation

$A_v = (w_v)\,(h_v)$

Where A_v = area of ventilation opening (m^2)
w_v = vent width (m)
h_v = vent height (m)

A_v = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 191.01 m^2

Ventilation Factor Calculation

$\Omega = (A_T - A_v) / A_v (\sqrt{h_v})$

Where Ω = ventilation factor

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

A_v = area of ventilation opening (m^2)

h_v = vent height (m)

Ω = 54.22 $m^{-1/2}$

Compartment Post-Flashover Temperature Calculation

$T_{PFO\,(max)} = 6000 (1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

$T_{PFO\,(max)}$ =	811.24 °C	1492.23 °F	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT^s: 13_Compartment_Flashover_Calculations.xls (Flashover_HRR)

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER HEAT RELEASE RATE

Version 1805.0

The following calculations estimate the minimum heat release rate required to compartment flashover.

Parameters in YELLOW CELLS are Entered by the User.

Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	3.00	ft	0.9144 m
Vent Height (h_v)	8.00	ft	2.44 m
Interior Lining Thickness (δ)	6.00	in	0.1524 m
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

Material	Thermal Conductivity k (kW/m-K)
Aluminum (pure)	0.206
Steel (0.5% Carbon)	0.054
Concrete	0.0016
Brick	0.0008
Glass, Plate	0.00076
Brick/Concrete Block	0.00073
Gypsum Board	0.00017
Plywood	0.00012
Fiber Insulation Board	0.00053
Chipboard	0.00015
Aerated Concrete	0.00026
Plasterboard	0.00016
Calcium Silicate Board	0.00013
Alumina Silicate Block	0.00014
Glass Fiber Insulation	0.000037
Expanded Polystyrene	0.000034
User Specified Value	Enter Value

Reference: *Klote, J., J. Milke, Principles of Smoke Management*, 2002, Page 270.

Select Material

Concrete

Scroll to desired material then Click on selection

PREDICTING FLASHOVER HEAT RELEASE RATE
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_V\ (\sqrt{h_V}))}$

Where Q_{FO} = heat release rate necessary for flashover (kW)
h_k = effective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_V = area of ventilation opening (m^2)
h_V = height of ventilation opening (m)

Heat Transfer Coefficient Calculation

$h_k = k/\delta$ Assuming that compartment has been heated thoroughly before flashover, i.e., $t > t_p$.

Where h_k = effective heat transfer coefficient (kW/m^2-K)
k = interior lining thermal conductivity (kW/m-K)
δ = interior lining thickness (m)

h_k = 0.010 kW/m^2-K

Area of Ventilation Opening Calculation

$A_V = (w_V)(h_V)$

Where A_V = area of ventilation opening (m^2)
w_V = vent width (m)
h_V = vent height (m)

A_V = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_V$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_V = area of ventilation opening (m^2)

A_T = 191.01 m^2

Minimum Heat Release Rate for Flashover

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_V\ (\sqrt{h_V}))}$

Q_{FO} = 1611.84 kW	Answer

METHOD OF BABRAUSKAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 750\ A_V\ (\sqrt{h_V})$

Where Q_{FO} = heat release rate necessary for flashover (kW)
A_V = area of ventilation opening (m^2)
h_V = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 750\ A_V\ (\sqrt{h_V})$

Q_{FO} = 2611.29 kW	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 7.8\, A_T + 378\, A_v (\sqrt{h_v})$

Where Q_{FO} = heat release rate necessary for flashover (kW)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 7.8\, A_T + 378\, A_v (\sqrt{h_v})$

Q_{FO} =	2805.96 kW	Answer

Summary of Result

Calculation Method	Flashover HRR (kW)
METHOD OF MQH	1612
METHOD OF BABRAUSKAS	2611
METHOD OF THOMAS	2806

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
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Example Problem 13.10-2

Problem Statement

Consider a compartment 20 ft wide x 25 ft long x 12 ft high (w_c x l_c x h_c), with an opening 3 ft wide and 8 ft high (w_v x h_v). The interior lining material of the compartment is 5/8 in. gypsum. Calculate the HRR necessary for flashover, $\dot{Q}_{FO}$, and the post-flashover compartment temperature, T_{PFO}.

Solution

Purpose:

(1) Determine the heat release rate for flashover for the given compartment.

Assumptions:

(1) Natural Ventilation

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 13_Compartment_Flashover_Calculations.xls

(click on *Post_Flashover_Temperature* to calculate the post-flashover temperature)

(click on *Flashover-HRR* to calculate the HRR for flashover)

FDT^s Input Parameters:

- -Compartment Width (w_c) = 20 ft
- -Compartment Length (l_c) = 25 ft
- -Compartment Height (h_c) = 12 ft
- -Vent Width (w_v) = 3 ft
- -Vent Height (h_v) = 8 ft
- -Interior Lining Thickness (δ) = .63 in. (*Flashover-HRR only*)
- -Select Material: **Gypsum Board** (*Flashover-HRR only*)

Results*

Post-Flashover Compartment Temperature (T_{PFO}) °C (°F)	HRR for Flashover $(\dot{Q}_{FO})$ (kW)		
Method of Law	Method of MQH	Method of Brabauskas	Method of Thomas
811 (1,492)	1,621	2,611	2,806

*see spreadsheet on next page

Spreadsheet Calculations
(a) FDT^s: 13_Compartment_Flashover_Calculations.xls (Post_Flashover_Temperature)

CHAPTER 13. PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
Version 1805.0

The following calculations estimate the compartment post-flashover temperature.
Parameters in YELLOW CELLS are Entered by the User.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	8.00	ft	2.438 m

Calculate

PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
METHOD OF MARGARET LAW

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-183.*

$T_{PFO\,(max)} = 6000\,(1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

Where $T_{PFO\,(max)}$ = maximum compartment post-flashover temperature (°C)
Ω = ventilation factor

Where $\Omega = (A_T - A_v) / A_v\,(\sqrt{h_v})$
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Area of Ventilation Opening Calculation
$A_v = (w_v)\,(h_v)$
Where A_v = area of ventilation opening (m^2)
w_v = vent width (m)
h_v = vent height (m)

A_v = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries
$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$
Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 191.01 m^2

Ventilation Factor Calculation

$\Omega = (A_T - A_V) / A_V (\sqrt{h_V})$

Where Ω = ventilation factor

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

A_V = area of ventilation opening (m^2)

h_V = vent height (m)

Ω = 54.22 $m^{-1/2}$

Compartment Post-Flashover Temperature Calculation

$T_{PFO\,(max)} = 6000 (1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

$T_{PFO\,(max)}$ =	811.24 °C	1492.23 °F	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDTs: 13_Compartment_Flashover_Calculations.xls (Flashover_HRR)

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER HEAT RELEASE RATE

Version 1805.0

The following calculations estimate the minimum heat release rate required to compartment flashover.

Parameters in YELLOW CELLS are Entered by the User.

Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	8.00	ft	2.44 m
Interior Lining Thickness (δ)	0.63	in	0.016002 m
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

Material	Thermal Conductivity k (kW/m-K)
Aluminum (pure)	0.206
Steel (0.5% Carbon)	0.054
Concrete	0.0016
Brick	0.0008
Glass, Plate	0.00076
Brick/Concrete Block	0.00073
Gypsum Board	0.00017
Plywood	0.00012
Fiber Insulation Board	0.00053
Chipboard	0.00015
Aerated Concrete	0.00026
Plasterboard	0.00016
Calcium Silicate Board	0.00013
Alumina Silicate Block	0.00014
Glass Fiber Insulation	0.000037
Expanded Polystyrene	0.000034
User Specified Value	Enter Value

Select Material

Gypsum Board

Scroll to desired material then Click on selection

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 270.

PREDICTING FLASHOVER HEAT RELEASE RATE
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_v\ (\sqrt{h_v}))}$

Where Q_{FO} = heat release rate necessary for flashover (kW)
h_k = effective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Heat Transfer Coefficient Calculation

$h_k = k/\delta$ Assuming that compartment has been heated thoroughly before flashover, i.e., $t > t_p$.

Where h_k = effective heat transfer coefficient (kW/m^2-K)
k = interior lining thermal conductivity (kW/m-K)
δ = interior lining thickness (m)

h_k = 0.011 kW/m^2-K

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

Where A_v = area of ventilation opening (m^2)
w_v = vent width (m)
h_v = vent height (m)

A_v = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 191.01 m^2

Minimum Heat Release Rate for Flashover

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_v\ (\sqrt{h_v}))}$

Q_{FO} =	1621.40 kW	Answer

METHOD OF BABRAUSKAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 750\ A_v\ (\sqrt{h_v})$

Where Q_{FO} = heat release rate necessary for flashover (kW)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 750\ A_v\ (\sqrt{h_v})$

Q_{FO} =	2611.29 kW	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (\sqrt{h_v})$

Where Q_{FO} = heat release rate necessary for flashover (kW)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (\sqrt{h_v})$

Q_{FO} = 2805.96 kW **Answer**

Summary of Result

Calculation Method	Flashover HRR (kW)
METHOD OF MQH	1621
METHOD OF BABRAUSKAS	2611
METHOD OF THOMAS	2806

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

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Example Problem 13.10-3

Problem Statement

Consider a compartment 20 ft wide x 25 ft long x 12 ft high (w_c x l_c x h_c), with an opening 6 ft wide and 8 ft high (w_v x h_v). The interior lining material of the compartment is 6 in. concrete. Calculate the HRR necessary for flashover, $\dot{Q}_{FO}$, and the post-flashover compartment temperature, T_{PFO}.

Solution

Purpose:

(1) Determine the heat release rate for flashover for the given compartment.

Assumptions:

(1) Natural Ventilation

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 13.1_Compartment_Flashover_Calculations.xls
(click on *Post_Flashover_Temperature* to calculate the post-flashover temperature)
(click on *Flashover-HRR* to calculate the HRR for flashover)

FDT^s Input Parameters:

-Compartment Width (w_c) = 20 ft
-Compartment Length (l_c) = 25 ft
-Compartment Height (h_c) = 12 ft
-Vent Width (w_v) = 6 ft
-Vent Height (h_v) = 8 ft
-Interior Lining Thickness (δ) = 6 in. (*Flashover-HRR only*)
-Select Material: **Concrete** (*Flashover-HRR only*)

Results*

Post-Flashover Compartment Temperature (T_{PFO}) °C (°F)	HRR for Flashover $(\dot{Q}_{FO})$ (kW)		
Method of Law	Method of MQH	Method of Brabauskas	Method of Thomas
1084 (1,982)	2,266	5,223	4,105

*see spreadsheet on next page

Spreadsheet Calculations

(a) FDT[s]: 13_Compartment_Flashover_Calculations.xls (Post_Flashover_Temperature)

CHAPTER 13. PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE

Version 1805.0

The following calculations estimate the compartment post-flashover temperature.
Parameters in YELLOW CELLS are Entered by the User.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	6.00	ft	1.829 m
Vent Height (h_v)	8.00	ft	2.438 m

Calculate

PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
METHOD OF MARGARET LAW

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-183.*

$T_{PFO\,(max)} = 6000\,(1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

Where $T_{PFO\,(max)}$ = maximum compartment post-flashover temperature (°C)
Ω = ventilation factor

Where $\Omega = (A_T - A_v) / A_v\,(\sqrt{h_v})$
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)

Area of Ventilation Opening Calculation

$A_v = (w_v)\,(h_v)$

Where A_v = area of ventilation opening (m^2)
w_v = vent width (m)
h_v = vent height (m)

A_v = 4.46 m^2

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 188.78 m^2

Ventilation Factor Calculation

$\Omega = (A_T - A_V) / A_V (\sqrt{h_V})$

Where Ω = ventilation factor

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

A_V = area of ventilation opening (m^2)

h_V = vent height (m)

Ω = 26.47 $m^{-1/2}$

Compartment Post-Flashover Temperature Calculation

$T_{PFO\,(max)} = 6000\,(1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

$T_{PFO\,(max)}$ =	1083.57 °C	1982.42 °F

Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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(b) FDT[s]: 13_Compartment_Flashover_Calculations.xls (Flashover_HRR)

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER HEAT RELEASE RATE
Version 1805.0

The following calculations estimate the minimum heat release rate required to compartment flashover.

Parameters in YELLOW CELLS are Entered by the User.

Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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
COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	6.00	ft	1.829 m
Vent Height (h_v)	8.00	ft	2.44 m
Interior Lining Thickness (δ)	6.00	in	0.1524 m
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

Material	Thermal Conductivity k (kW/m-K)
Aluminum (pure)	0.206
Steel (0.5% Carbon)	0.054
Concrete	0.0016
Brick	0.0008
Glass Plate	0.00076
Brick/Concrete Block	0.00073
Gypsum Board	0.00017
Plywood	0.00012
Fiber Insulation Board	0.00053
Chipboard	0.00015
Aerated Concrete	0.00026
Plasterboard	0.00016
Calcium Silicate Board	0.00013
Alumina Silicate Block	0.00014
Glass Fiber Insulation	0.000037
Expanded Polystyrene	0.000034
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 270.

Select Material

Concrete

Scroll to desired material then Click on selection

PREDICTING FLASHOVER HEAT RELEASE RATE
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_V\ (\sqrt{h_V}))}$

Where Q_{FO} = heat release rate necessary for flashover (kW)
h_k = effective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
A_V = area of ventilation opening (m^2)
h_V = height of ventilation opening (m)

Heat Transfer Coefficient Calculation

$h_k = k/\delta$ Assuming that compartment has been heated thoroughly before flashover, i.e., $t > t_p$.

Where h_k = effective heat transfer coefficient (kW/m^2-K)
k = interior lining thermal conductivity (kW/m-K)
δ = interior lining thickness (m)

h_k = 0.010 kW/m^2-K

Area of Ventilation Opening Calculation

$A_V = (w_V)(h_V)$

Where A_V = area of ventilation opening (m^2)
w_V = vent width (m)
h_V = vent height (m)

A_V = 4.46 m^2

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_V$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_V = area of ventilation opening (m^2)

A_T = 188.78 m^2

Minimum Heat Release Rate for Flashover

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_V\ (\sqrt{h_V}))}$

Q_{FO} =	2266.14 kW	Answer

METHOD OF BABRAUSKAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 750\ A_V\ (\sqrt{h_V})$

Where Q_{FO} = heat release rate necessary for flashover (kW)
A_V = area of ventilation opening (m^2)
h_V = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 750\ A_V\ (\sqrt{h_V})$

Q_{FO} =	5222.58 kW	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (\sqrt{h_v})$

Where
- Q_{FO} = heat release rate necessary for flashover (kW)
- A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
- A_v = area of ventilation opening (m^2)
- h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (\sqrt{h_v})$

Q_{FO} = 4104.66 kW **Answer**

Summary of Result

Calculation Method	Flashover HRR (kW)
METHOD OF MQH	2266
METHOD OF BABRAUSKAS	5223
METHOD OF THOMAS	4105

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
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UNITED STATES NUCLEAR REGULATORY COMMISSION

CHAPTER 14. ESTIMATING PRESSURE RISE ATTRIBUTABLE TO A FIRE IN A CLOSED COMPARTMENT

14.1 Objectives

This chapter has the following objectives:

- Discuss some systems of pressure measurement.
- Explain how to calculate pressure rise.
- Define relevant terms, including pressure rise.

14.2 Introduction

In a closed compartment or a compartment with small leakages, the release of heat from the combustion process could cause compartment pressure to rise as a result of the volumetric expansion of gases. It is this pressure rise that drives the mass flow out, and prevents mass flow into the compartment. In Chapter 2, we referred to this as the first stage of the fire.

When thermal energy rapidly accumulates in the form of hot gases, and the compartment has small openings to the surroundings, this pressure rise is very rapid and any hydrostatic pressure differences with height are negligible. For example, an addition of 100 kW to a 60-m^3 (2,119-ft^3) enclosure with an opening of 0.01 m^2 (0.10 ft^2) will cause a steady-state pressure rise of ≈1,000 Pa (0.14 psi) in several seconds. The hydrostatic pressure difference decreases at a rate of 10 Pa (0.0014 psi) per meter as the height increases. In this case, we see that the difference is negligible and the vent flow is determined by the pressure rise caused by the volumetric expansion of gases. Figure 14-1 illustrates the overpressure-time profile in an enclosure.

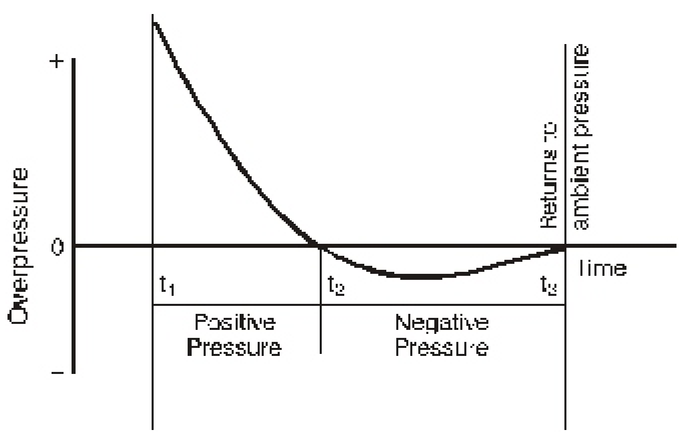

Figure 14-1 Overpressure Generated at a Fixed Location

Failure of a compartment due to pressure rise from a fire would be extremely rare. The vast majority of compartments have some form of leakage. Pressure rise (and buoyancy) are important to recognize in fire dynamic analysis because the increase in pressure can cause smoke and other products of combustion to be transported into adjoining compartments.

14.3 Definition of Pressure

Pressure can be defined as the amount of force brought to bear on some unit area of an object. When we press our thumb down on a table, we are applying force on the table. The harder we press, the greater the force, and the greater the pressure we apply to the table's surface.

Similarly, the air in the sky above us presses down on our bodies and all objects around us with a pressure of approximately 14.7 pounds per square inch (psi) of surface area. This pressure, which is essentially the average air pressure at sea level, is also known as one standard atmosphere. A pressure of two atmospheres *generally* means that a pressure of 29.4 psi is present, or two times the standard atmospheric pressure of 14.7 psi.

We emphasize the word "generally" because pressure also has absolute and relative scales of measurement. The 14.7 psi of atmospheric pressure at sea level is an absolute measurement, which is more properly presented in units of pounds per square inch-absolute, or psia for short. Zero psia refers to a complete absence of pressure, such as one might find in the perfect vacuum of outer space. By contrast, the most common relative scale of measurement, which is primarily used only in the United States, presents numerical values in terms of gauge pressure, where a reading of zero matches an absolute pressure of one standard atmosphere. In this system, an absolute pressure of 15.7 psia would be expressed as 1.0 pound per square inch-gauge, or 1.0 psig for short. Thus, two atmospheres of absolute pressure would be equivalent to one atmosphere gauge pressure (*Handbook of Chemical Hazard Analysis Procedures*).

Among the other systems of pressure measurement that are of an absolute nature, the most common include the following examples:

- Millimeters of mercury (mm Hg): 760 mm Hg equal one standard atmosphere.
- Inches of mercury (in. Hg): 29.9 in. Hg equal one standard atmosphere.
- Pascals (Pa) or Newton per square meter (N/m^2): 101,325 Pa or 101,325 N/m^2 equal one standard atmosphere.
- Bars: 1.01325 bars equal one standard atmosphere.
- Inches of water (in. H_2O): 407.6 in. H_2O equal one standard atmosphere.

Inches of water and inches of mercury are not commonly used in the scientific community, with the exception that meteorologists have traditionally reported current atmospheric pressures in inches of mercury. Nonetheless, it is beneficial to know of their existence.

14.4 Pressure Rise Calculations

As previously discussed, the combustion process raises the temperature of a gaseous system. This increase in temperature, in turn, causes a pressure rise attributable to expansion of the gases. According to the ideal gas law, when heat is added to an ideal gas in a fixed volume, the pressure must rise in response to the temperature. In a building fire situation, the resulting pressure and the rate of pressure rise are often kept very small by gas leaks through openings in the walls of the buildings (such as cracks around windows and doors). However, situations may arise where the enclosure can be considered to be well sealed, such as certain compartments on ships.

According to Karlsson and Quintiere (1999), the maximum pressure difference inside a compartment as a result of expansion of gases is given by the following expression:

$$\frac{P - P_a}{P_a} = \frac{\dot{Q}t}{V \rho_a c_v T_a} \qquad (14\text{-}1)$$

Where:

P = compartment pressure attributable to combustion (atm)
P_a = initial atmospheric pressure (atm)
$\dot{Q}$ = heat release rate of the fire (kW)
t = time (sec)
V = compartment volume (m^3)
$_a$ = ambient air density (kg/m^3)
c_v = specific heat of air at constant volume (kJ/kg-K)
[values of c_v range from 0.71 to 0.85 kJ/kg-K]
T_a = ambient air temperature (K)

14.5 Assumptions and Limitations

The method discussed in this chapter is subject to several assumptions and limitations:

(1) The energy release rate is constant.

(2) The mass loss rate of the fuel is neglected in the conversion of mass.

(3) The specific heat does not change with temperature.

(4) The hydrostatic pressure difference over the height of the compartment is ignored and assumed to be negligible compared to the dynamic pressure.

14.6 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) compartment width (ft)

(2) compartment length (ft)

(3) compartment height (ft)

(4) fire heat release rate (ft)

(5) time after ignition (s)

14.7 Cautions

(1) Use (14_Compartment_Over_Pressure_Calculations.xls) spreadsheet on the CD-ROM for calculations.

(2) Make sure to input values using correct units.

14.8 Summary

According to the ideal gas law, when heat is added to an ideal gas in a fixed volume, the pressure must rise in response to the temperature. In a building fire situation, the resulting pressure and the rate of pressure rise are often kept small by gas leaks through openings in the walls of the buildings (such as through penetrations and cracks around windows/doors). However, situations may arise where the enclosure can be considered to be well sealed. It is important to recognize the increase in pressure within the fire compartment will cause products of combustion to also be transported into adjacent spaces.

The purpose of this chapter is to provide simple analytical method for calculating the dynamic pressure build-up in a closed compartment. We then use the results to show that the rapid pressure rise. This result can be used to justify the so-called "constant pressure assumption," which is typically used when examining a "leaky" compartment fire.

14.9 References

Handbook of Chemical Hazard Analysis Procedures, Federal Emergency Management Agency (FEMA), US Department of Transportation (DOT), and U.S. Environmental Protection Agency (EPA).

Karlsson, B., and J.G. Quintiere, *Enclosure Fire Dynamics*, Chapter 8, "Conservation Equations and Smoke Filling," CRC Press LLC, New York, pp. 181–225, 1999.

14.10 Problems

Example Problem 14-10.1

Problem Statement

A closed compartment in a facility pump room has dimensions 10 ft wide x 12 ft long x 10 ft high (w_c x l_c x h_c). A fire starts with a constant HRR of $\dot{Q}$ = 100 kW. Estimate the pressure rise attributable to the expansion of gases after 10 seconds.

Solution

Purpose:

(1) Estimate the pressure rise in the compartment 10 seconds after ignition.

Assumptions:

(1) The energy release rate is constant.
(2) The mass rate of the fuel is neglected in the conversion of mass.
(3) The specific heat is constant with temperature.
(4) The hydrostatic pressure difference over the height of the compartment is negligible compared to the dynamic pressure.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 14_Compartment_Over_Pressure_Calculations.xls

FDT^s Input Parameters:

-Compartment Width (w_c) = 10 ft
-Compartment Length (l_c) = 12 ft
-Compartment Height (h_c) = 10 ft
-Fire Heat Release Rate ($\dot{Q}$) = 100 kW
-Time After Ignition (t) = 10 sec

Results*

Pressure Rise	11.90 kPa (1.73 psi)

*see spreadsheet on next page

Spreadsheet Calculations
FDT[s]: 14_Compartment_Over_Pressure_Calculations.xls

CHAPTER 14. ESTIMATING PRESSURE RISE DUE TO A FIRE IN A CLOSED COMPARTMENT

Version 1805.0

The following calculations estimate the pressure rise in a compartment due to fire and combustion.
Parameters in YELLOW CELLS are Entered by the User.
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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	10.00	ft	3.05 m
Compartment Length (l_c)	12.00	ft	3.66 m
Compartment Height (h_c)	10.00	ft	3.05 m
Fire Heat Release Rate (Q)	100.00	kW	
Time after Ignition (t)	10.00	sec	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K

Calculate

AMBIENT CONDITIONS

Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa
Specific Heat of Air at Constant Volume (c_v)	0.71	kJ/kg-K	
(Note: Values of c_v ranges from 0.71 to 0.85 kJ/kg-k)			
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

METHOD OF KARLSSON AND QUINTIERE

Reference: *Karlsson and Quintiere, Enclosure Fire Dynamics, 1999, Page 102.*

$(P - P_a) / P_a = Q\,t / (V \rho_a c_v T_a)$

Where P = compartment pressure due to fire and combustion (kPa)
P_a = initial atmospheric pressure (kPa)
Q = heat release rate of the fire (kW)
t = time after ignition (sec)
V = compartment volume (m^3)
ρ_a = ambient density (kg/m^3)
c_v = specific heat of air at constant volume (kJ/kg-K)
T_a = ambient air temperature (K)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where V = volume of the compartment (m^3)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)

V = 33.98 m^3 1200 ft^3

Pressure Rise in Compartment

$(P - P_a) / P_a = Q\,t / (V \rho_a c_v T_a)$

$(P-P_a)/P_a$ = 0.117 atm

Multiplying by the atmospheric pressure (P_a) = 101 kPa

Gives a pressure difference = 11.90 kPa 1.73 psi Answer

This example shows that in a very short time the pressure in a closed compartment rises to quite large value.

Most buildings have leaks of some sort. The above example indicates that even though a fire compartment may be closed, the pressure is very rapid and would presumably lead to sufficient leaks to prevent further pressure rise from occurring. We will use this conclusion when dealing with pressure rises in enclosures with small leaks.

NOTE

The above calculations are based on principles developed in the Enclosure Fire Dynamics. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 14.10-2

Problem Statement

A facility has a sealed compartment (assume zero leakage) with a blowout panel that is designed to fail at two atmospheres. The compartment is 20 ft wide x 25 ft long x 10 ft high. A fire is assumed with a constant heat release rate of 255 kW.

At what time (sec) does the blowout panel fail?

Solution

Purpose:

(1) Estimate the time after ignition the pressure reaches 2 atm (202.5 kPa).

Assumptions:

(1) The energy release rate is constant.
(2) The mass rate of the fuel is neglected in the conversion of mass.
(3) The specific heat is constant with temperature.
(4) The hydrostatic pressure difference over the height of the compartment is negligible compared to the dynamic pressure.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 14_Compartment_Over_Pressure_Calculations.xls

FDT^s Input Parameters:

-Compartment Width (w_c) = 20 ft
-Compartment Length (l_c) = 25 ft
-Compartment Height (h_c) = 10 ft
-Fire Heat Release Rate $(\dot{Q})$ = 255 kW
-Time After Ignition (t) = varies until output is 202.5 kPa

Results*

Time after ignition	278 sec

*see spreadsheet on next page

Spreadsheet Calculations
FDT[s]: 14_Compartment_Over_Pressure_Calculations.xls

CHAPTER 14. ESTIMATING PRESSURE RISE DUE TO A FIRE IN A CLOSED COMPARTMENT

Version 1805.0

The following calculations estimate the pressure rise in a compartment due to fire and combustion.
Parameters in YELLOW CELLS are Entered by the User.
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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.10 m
Compartment Length (l_c)	25.00	ft	7.62 m
Compartment Height (h_c)	10.00	ft	3.05 m
Fire Heat Release Rate (Q)	255.00	kW	
Time after Ignition (t)	278.00	sec	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K

Calculate

AMBIENT CONDITIONS

Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa
Specific Heat of Air at Constant Volume (c_v)	0.71	kJ/kg-K	
(Note: Values of c_v ranges from 0.71 to 0.85 kJ/kg-k)			
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

METHOD OF KARLSSON AND QUINTIERE

Reference: *Karlsson and Quintiere, Enclosure Fire Dynamics, 1999, Page 102.*

$(P - P_a) / P_a = Q\,t / (V\,\rho_a\,c_v\,T_a)$

Where
- P = compartment pressure due to fire and combustion (kPa)
- P_a = initial atmospheric pressure (kPa)
- Q = heat release rate of the fire (kW)
- t = time after ignition (sec)
- V = compartment volume (m^3)
- ρ_a = ambient density (kg/m^3)
- c_v = specific heat of air at constant volume (kJ/kg-K)
- T_a = ambient air temperature (K)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where
- V = volume of the compartment (m^3)
- w_c = compartment width (m)
- l_c = compartment length (m)
- h_c = compartment height (m)

V = 141.58 m^3 5000 ft^3

Pressure Rise in Compartment

$(P - P_a) / P_a = Q\,t / (V\,\rho_a\,c_v\,T_a)$

$(P-P_a)/P_a$ = 1.998 atm

Multiplying by the atmospheric pressure (P_a) = 101 kPa

Gives a pressure difference = 202.48 kPa 29.37 psi **Answer**

This example shows that in a very short time the pressure in a closed compartment rises to quite large value.

Most buildings have leaks of some sort. The above example indicates that even though a fire compartment may be closed, the pressure is very rapid and would presumably lead to sufficient leaks to prevent further pressure rise from occurring. We will use this conclusion when dealing with pressure rises in enclosures with small leaks.

NOTE

The above calculations are based on principles developed in the Enclosure Fire Dynamics. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
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CHAPTER 15. ESTIMATING THE PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

15.1 Objectives

This chapter has the following objectives:

- Define the nature and implications of an explosion.
- Explain the various causes, hazards, and effects of explosions.
- Explain how to calculate the energy released by an explosion.
- Explain how to calculate the pressure increase attributable to an explosion.

15.2 Introduction

In its most widely accepted sense, the term "explosion" means a bursting associated with a loud, sharp noise and an expanding pressure front, varying from a supersonic shock wave to a relatively mild wind. The term has also been extended to encompass chemical or physical/chemical events that produce explosions.

An explosion is defined as a sudden and violent release of high-pressure gages into the environment. The primary keyword in this definition is "rapid." The release must be sufficiently fast so that energy contained in the high-pressure gas dissipates in a shock wave. The second key word is "high pressure," which signifies that, at the instant of release, the gas pressure is above the pressure of the surroundings. Note that the basic definition is independent of the source or mechanism by which the high-pressure gas is produced (Senscal, 1997).

Despite this commonly accepted definition, the literature includes many other interrelations of the concept of an explosion:

- A rapid release of high-pressure gases into the environment (Cruice, 1991).
- A sudden conversion of potential energy (chemical or mechanical) into kinetic energy in the form of rapidly expanding gases (NFPA, 921).
- A physical reaction characterized by four elements: high-pressure gas; confinement or restriction of the pressure; rapid production or release of that pressure; and change or charge to the confining (restricting) structure, container, or vessel caused by the pressure release. The generation and violent escape of gases are the primary criteria of an explosion (NFPA 921).
- The noise or bang attributable to the sudden release of a strong pressure wave or blast wave, which relates to the basic meaning of the word, "sudden outburst" (Bodhurtha, 1980).
- An exothermic chemical process that when occurring at constant volume, gives rise to a sudden and significant pressure rise (Vervalin, 1985).

- In general scientific terms, an explosion is said to have occurred in the atmosphere if energy is released over a sufficiently small time and in a sufficiently small volume so as to generate a pressure wave of finite amplitude traveling away from the source (Baker et al., 1983). This energy may have originally been stored in the system in a variety of forms; these include nuclear, chemical, electrical, or pressure energy, for example. However, the release is not considered to be explosive unless it is rapid enough and concentrated enough to produce a pressure wave that one can hear. Even though many explosions damage their surroundings, it is not necessary that external damage be produced by the explosion. All that is necessary is that the explosion is capable of being heard.

While these definitions differ, they share the following characteristics of an explosion:

- release of high pressure gases
- rapid expansion of gases
- formation of a pressure wave or blast wave of sufficient intensity to be heard

The last of these characteristic is often favored by explosion investigators. The ability to be heard enables investigations to define whether an incident was an explosion, based on what happened and what the results were.

Explosions are often characterized by their primary means of generation (physical or chemical); this categorization includes the following types of explosions:

- Physical explosions are those caused when the high-pressure gas is generated only by mechanical means without any chemical change, as in the following types of explosions:
  - — external heating of a tank resulting in increased internal pressure and resultant failure of the tank
  - — sudden release of super-heated liquid which flash-evaporates, causing a rapid explosion
- Chemical explosions are those when the high-pressure gas is generated only by chemical reactions without any physical or chemical interaction, as in the following:
  - — Combustion explosions are caused by rapid oxidation of combustion material, which results in an explosion of gases that triggers a pressure wave. Combustion explosions include the following types:
    - ‣ dust explosions
    - ‣ gas explosions
    - ‣ natural gas explosions
    - ‣ backdraft explosions
    - ‣ mists
  - — Thermal explosions are a special class of chemical explosions where the heat released by the reaction of two or more chemical compounds results in a more rapid reaction rate that eventually results in an explosion. These types of explosions are a great concern in chemical processes.
  - — Condensed phase explosions are those caused by rapid reactions of chemical components in the solid or liquid phase. This type of chemical explosion includes those resulting from high explosives or propellants (solid and liquid) used for missile fuel.

- — Nuclear explosions are associated with the fission or fusion of matter.
- — Detonations and deflagrations are often distinguished by the speed or rate of propagation of the combustion wave through the material. In a detonation, the flame or combustion wave propagates through the reactants at supersonic speeds on the order of 2,000 m/sec (6,562 ft/sec). By contrast, the rate of propagation in a deflagration is below the speed of sound in air at 20 °C (68 °F), which is approximately 330 m/sec (1,082 ft/sec). The fact that detonations propagate at supersonic speeds implies the existence of a shock wave, which is the reason that the reactions propagate so rapidly. (The shock wave compresses reactants, causing the reaction to occur faster.) The practical distinction between detonations and deflagrations also relates to the amount of damage caused. Specifically, the pressure attained during a detonation can be up to 20 atmospheres (284 psi). By contrast, the overpressure caused by the pressure in a typical deflagration wave is on the order of 1 atmosphere (14.70 psi) for C_2H_2 in air.

15.3 Explosion Hazard

The hazards associated with deflagration include catastrophic equipment failure, ejection of flame and unburned product (possibly hazardous in its own right) into the surroundings, possible secondary explosions leading to catastrophic facility damage, and personal injury. The following elements must exist *simultaneously* in order for a deflagration to occur:

- a flammable mixture consisting of a fuel and oxygen, usually from air, or other oxidant
- a means of ignition
- an enclosure

The term “flammable mixture” denotes that the fuel and oxygen components are intimately mixed and are each present at a concentration that falls within a flammable composition boundary characteristic of each system of fuel, oxygen, and inert material (inert gas or solid). Ignition of a flammable mixture occurs when a point source of sufficient energy achieves a temperature above the ignition temperature of the mixture. All incandescent sparks (e.g., mechanical, electrical, electrostatic) have sufficient temperature to cause ignition, but may lack sufficient energy to heat a minimal propagating mass to its ignition temperature. A hot process surface may have a temperature below that required for prompt ignition, but may have a large energy content. Dust deposits on such surfaces can be subjected to accelerated self-heating and eventual ignition.

Should ignition of a flammable mixture occur within an enclosure, regardless whether of the enclosure has ventilation points, the internal pressure will increase as necessary, to satisfy the non-steady-state material balance equation. The time needed to achieve the maximum deflagration pressure depends on size of the enclosure and the characteristics of the fuel, but generally can extend up to a few hundred milliseconds. Some venting of the expanding combustion gases occurs through normal process openings, but these are usually too small to prevent the development of destructive pressures.

15.4 Explosive Range

A certain quantity—neither too little nor too much—of flammable gas mixed with a certain quantity of air allows a mixture to become explosive and propagate the explosion flame. The lower and upper boundaries of this "explosive range" are known as the lower explosion limit (LEL) and the upper explosion limit (UEL), respectively[1]. When the quantity of flammable gas and/or air is either below or above these boundaries, the mixture is not explosive and will not propagate the explosion flame. At the LEL or UEL, the mixture will burn when ignited, causing an insignificant flame propagation. Between the two boundaries, there is a point at which flame propagation reaches its maximum.

15.5 Backdraft Explosion

Fires in oxygen-starved environments result in unburned fuel, "fuel vapor," which is a complex mixture of combustion gases, vapors, and aerosols suspended in the smoke. If the gas layer is hot enough (i.e., at its ignition temperature) it may immediately ignite when the fuel-rich smoke layer mixes with air (thereby receiving adequate oxygen) when the smoke-filled compartment or building is vented.

By contrast, when the gas layer is relatively cool, particularly in a severely oxygen-restricted fire, the fuel vapor may not immediately ignite when the compartment or building is vented. Rather, in such instances the ignition of the fuel vapor may be delayed until fresh air is introduced, mixes, with the vapor, and makes its way back to the fire source. When this occurs, the flame itself becomes the ignition source, and the ignition delay results from the time required to mix the fuel-rich smoke layer with oxygen-rich fresh air. This phenomenon, known as a "backdraft explosion," has the characteristics of a premixed fuel/air deflagration.

15.6 Smoke Explosion

It is also possible for a smoldering fire to produce sufficient unburned fuel and carbon monoxide to form a premixed combustible atmosphere. If the smoldering fire raises the temperature to the autoignition temperature of the mixture, the smoke/gas cloud will deflagrate causing a "smoke explosion." Such explosions have been observed in smoldering fires involving polyurethane foams.

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[1] The terms "upper flammability limit" (UFL) and "lower flammability limit" (LFL) are also used to describe the flammable range of gases. For our purposes, they are synonymous with UEL and LEL respectively.

15.7 Unconfined and Confined Explosions

Explosions that occur in open air, known as "unconfined explosions," are fundamentally different — and require different countermeasures — than "confined explosions," which occur within some sort of containment. Confined explosions often occur in a process vessel or pipework, but may also occur in buildings. The explosion of a flammable mixture in a process vessel or pipework may be a detonation or a deflagration. The overpressure in a confined explosion is attributable to the expansion of the hot gases and may be exacerbated by the release of gases through an explosion vent (even a door or window) when the resulting turbulence produces a second pressure peak, as illustrated in Figure 15-1 (Harris, 1983).

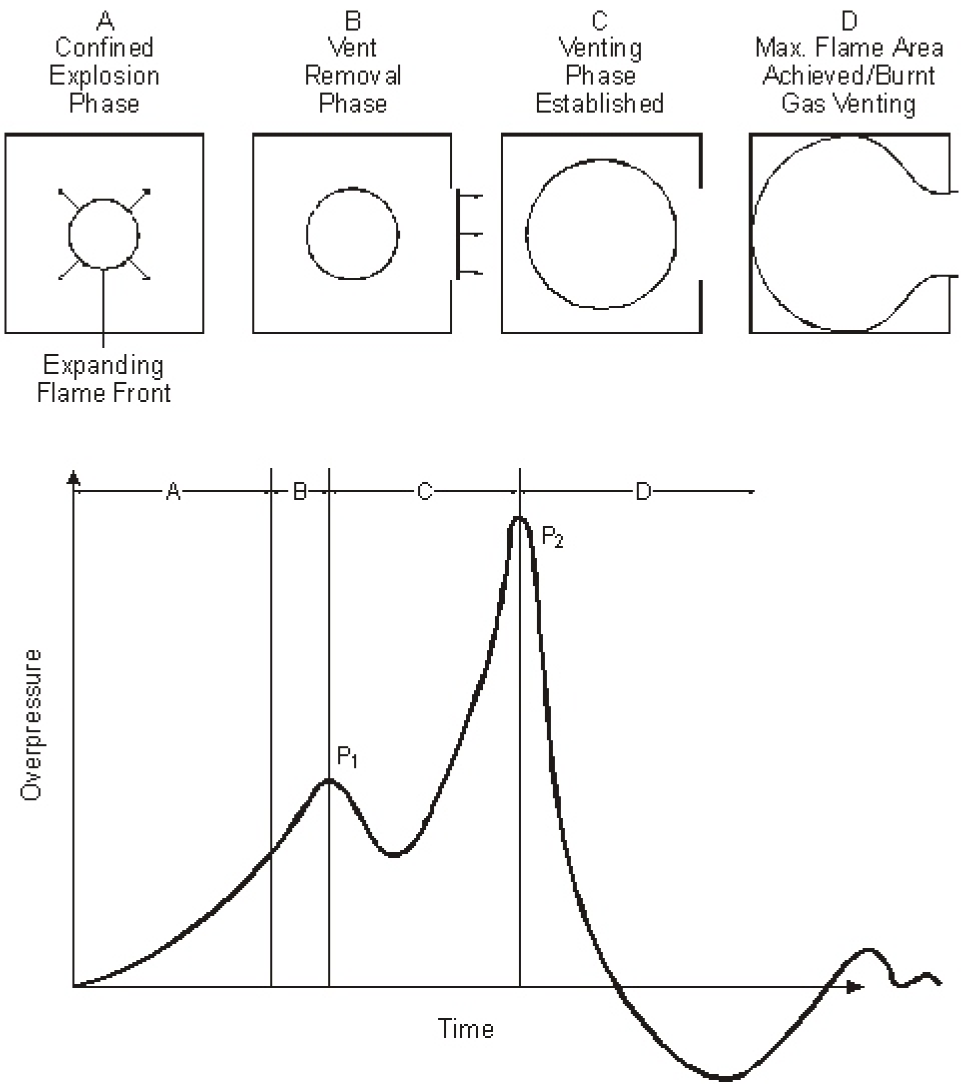

Figure 15-1 Pressure Peaks of an Explosion Inside a Building

Confined explosion usually will not cause an accidental release of gas in any quantity directly into the atmosphere. Rather, such explosions usually release gases within some form of such as compartment or building of an industrial plant. If a flammable mixture forms and is ignited under these contained conditions, a confined gas explosion will occur. Moreover, if a gas is accidentally released into the air, mixes with air and is ignited, the flame front travels through the mixture, propagating in a spherical geometry whenever possible rather than remaining stationary, as illustrated in Figure 15-2.

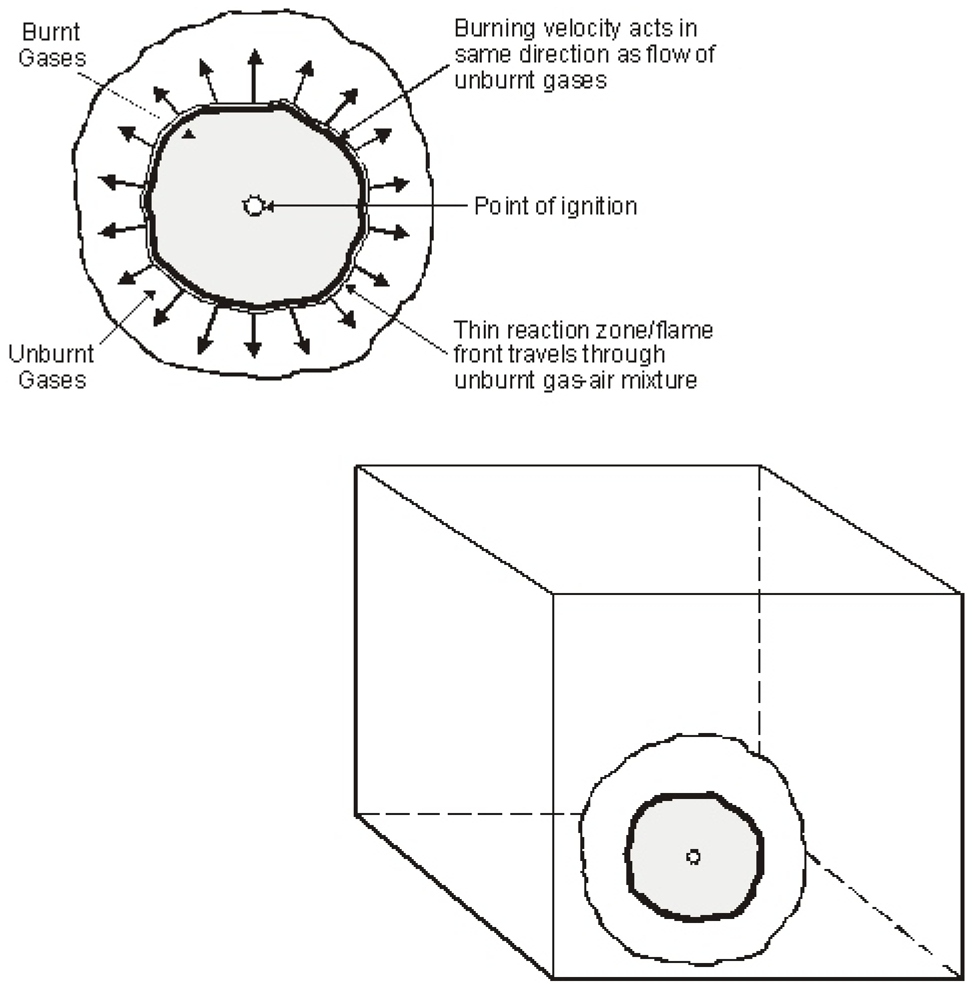

Figure 15-2 Propagation of Explosion Flame

15.8 Estimating the Effects of Explosions

When a firecracker or a stick of dynamite explodes, the violence and speed of the reactions taking place produce what is referred to as either a shock wave or a blast wave. Technically speaking, there is a difference between these two terms, but we will treat them rather interchangeably here. Either type of wave can be thought of as a thin shell of highly compressed air and/or hot gases that expands rapidly in all directions from the point at which the explosion is initiated. Such waves can move at velocities exceeding the speed of sound in air, and, therefore, are capable of producing sonic "booms," much like those associated with supersonic aircraft. This is how significant explosions produce a loud "bang."

The damage caused by a shock or blast wave striking an object or a person is a complex function of many factors, and it is well beyond the scope of this chapter to describe all of the complex interactions involved. Instead, we will simply refer to the wave as a rapidly expanding shell of compressed gases. We can then measure the strength of the wave in units of pressure (psi), and we can relate the effects of peak overpressure within the wave (i.e., the maximum pressure in the wave in excess of normal atmospheric pressure) to the level of property or personal injury that is likely to result.

Table 15-1 lists damage effects on people and property, which might be expected to result from explosions characterized by various peak overpressures (Clancey, 1972). It is important to note that peak overpressures in a shock or blast wave are highest near the source of the explosion and decrease rapidly with distance from the explosion site. Additionally, it must be noted that the extent of damage incurred is heavily influenced by the location of the blast relative to nearby reflecting surfaces.

Table 15-1. Estimated Damage Attributable to Explosive Overpressure (Clancey, 1972)

Overpressure* (psig)	**Expected Damage**
0.03	Occasional breaking of large windows that are already under strain.
0.04	Glass failure caused by loud noises (143 dB) or sonic booms.
0.10	Breaking of small windows under strain.
0.15	Typical glass failure.
0.40	Some damage to house ceilings; 10% window glass breakage.
0.40	Limited minor structural damage.
0.50–1.0	Windows usually shattered; some damage to window frames.
0.7	Minor damage to house structures.
1.0	Houses made uninhabitable by partial demolition.
1.0–2.0	Failure and buckling of corrugated metal panels; housing wood panels are blown in.
1.0–8.0	Slight to serious injuries (e.g., skin lacerations from flying glass and other missiles).

Table 15-1. Estimated Damage Attributable to Explosive Overpressure (Clancey, 1972)

Overpressure* (psig)	**Expected Damage**
1.3	Slight distortion of the steel frames of clad buildings.
2.0	Partial collapse of walls and roofs of houses.
2.0–3.0	Shattering of non-reinforced concrete or cinder block walls.
2.3	Lower limit of serious structural damage.
2.4–12.2	Up to 90% eardrum rupture among exposed populations.
2.5	50% destruction of home brickwork.
3.0	Distortion of steel frame buildings; may pull away from their foundations.
3.0–4.0	Ruin of frameless steel panel buildings.
4.0	Rupture of cladding of light industrial buildings.
5.0	Snappy of wood utility poles.
5.0–7.0	Nearly complete destruction of houses.
7.0	Overturning of loaded train cars.
7.0-8.0	Shearing of flexure causes failure of 8–12-inch thick non-reinforced brick.
9.0	Demolition of loaded train cars.
10.0	Probable total destruction of building.
0.10	Up to 99% fatalities among exposed populations as a result of direct blast effects.

* These are the peak pressures formed (in excess of normal atmospheric pressure) by blast and shock waves. For SI units, 1 psi = 6.894757 kPa.

As shown in Table 15-1, an explosion may give rise to (1) blast damage, (2) thermal effects, (3) missile damage, (4) ground shock, (5) cratering, and (6) personal injury. Not all of these effects arise from every explosion. For example, an aerial blast may not cause a crater.

In addition to the personal injuries and property damage caused by direct exposure to peak overpressures, the blast wave also has the potential to cause indirect, secondary effects:

- Damage may result from missiles, fragments, and environmental debris set in motion by the explosion or by the heat generated.
- Damage may result from forcible movement of exposed people and their subsequent impact with ground surfaces, walls, or other stationary objects.

Many of the data on the effects of explosions come from studies of industrial and military explosives, but an increasing amount of information is becoming available from the investigation of process plant explosions.

15.8.1 Estimating Explosive Energy Release in a Confined Explosion

One typical explosion in an enclosure is caused by flammable gas leaking, which mixes with air in the enclosure and subsequently ignites to cause an explosion.

The energy released by expansion of compressed gas upon rupture of a pressurized enclosure may be estimated using the following equation (Zalosh, 1995):

$$E = \alpha \Delta H_C m_F \quad (15\text{-}1)$$

Where:

E = explosive energy released (kJ)
= yield (i.e., the fraction of available combustion energy participating in blast wave generation)
H_c = theoretical net heat of combustion (kJ/kg)
m_F = mass of flammable vapor release (kg)

The yield, , is typically in the range of 1 percent (0.01) for unconfined mass releases, to 100 percent (1.0) for confined vapor releases (Zalosh, 1995). Table 15-2 presents the theoretical net heat of combustion for flammable gases.

Table 15-2. Heat of Combustion, Ignition Temperature, and Adiabatic Flame Temperature* of Flammable Gases

Flammable Gas	**Heat of Combustion H_c (kJ/kg)**	**Ignition Temperature T_{ig} °C (°F)**	**Adiabatic Flame Temperature T_{ad} °C (°F)**
Acetylene	48,220	755 (1,391)	2,637(4,779)
Carbon monoxide (commercial)	10,100	765 (409)	2,387 (4,329)
Ethane	47,490	945 (1,733)	1,129 (2,064)
Ethylene	47,170	875 (1,607)	2,289 (4,152)
Hydrogen	130,800	670 (1,238)	2,252 (4,085)
Methane	50,030	1190 (2,174)	1,173 (2,143)
n-Butane	45,720	1025 (1,877)	1,339 (2,442)
n-Heptane	44,560	-	1,419 (2,586)
n-Octane	44,440	-	1,359 (2,478)
n-Pentane	44,980	-	1,291 (2,356)
Propane	46,360	1,010 (1,850)	1,281 (2,338)
Propylene	45,790	1,060 (1,940)	2,232 (4,050)
*Adiabatic flame temperature of lower limiting fuel/air mixture.			

15.8.2 TNT Mass Equivalent Calculations

One of the most common methods used to estimate the effects of an explosion is to relate the exploding fuel to trinitrotoluene (TNT). This method converts the energy contained in the flammable cloud into an equivalent mass of TNT, primarily because blast effects of TNT have been extensively studied as a function of TNT weight and distance from the source. Hence, we can infer the blast effects of an explosion by relating an explosion to an "equivalent" explosion of TNT. To do so, we relate a given fuel type and quantity to an equivalent TNT charge weight, as follows (Zalosh, 1995):

$$W_{TNT} = \frac{E}{4500} \qquad (15\text{-}2)$$

Where:

W_{TNT} = weight of TNT (kg)
E = explosive energy released (kJ)

15.8.3 Blast Effects

Blast effects can also be related to the equivalent weight of TNT using by the relationship between the distance from the source, the charge weight, and the overpressure caused by the blast wave, including the reflected shock wave. Figure 15-3 (Zalosh, 1995) gives the relationship between overpressure and "scaled distance" (D_{sc}) (in English and metric units). Scaled distance is the distance at which the overpressure is calculated divided by the cube root of the TNT charge weight.

$$D_{sc} = \frac{D}{W_{TNT}^{\frac{1}{3}}} \qquad (15\text{-}3)$$

Where:

D_{sc} = scaled distance $[m/(kg)^{1/3}]$

D = distance at which the overpressure is calculated (m)

W_{TNT} = weight of TNT (kg)

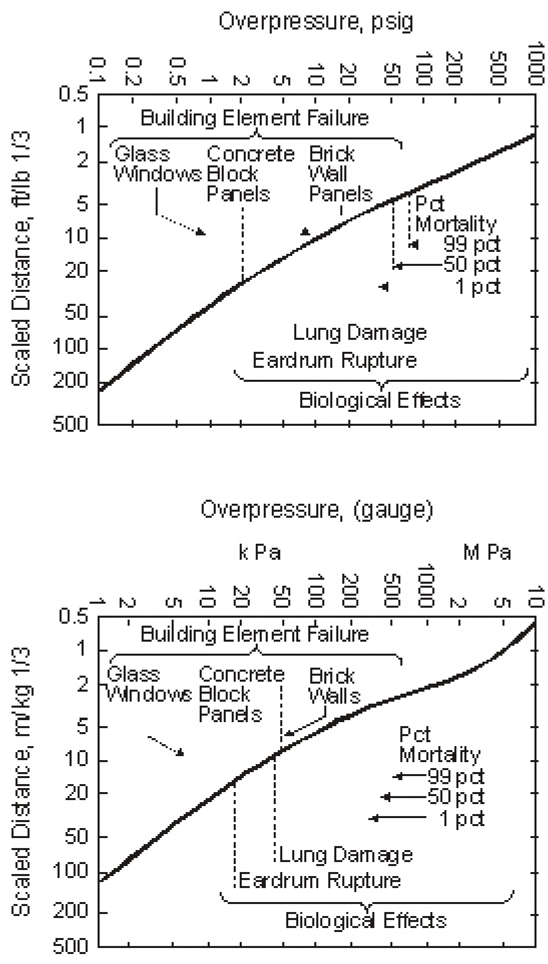

Figure 15-3 Ideal Blast Wave Overpressure vs. Scaled Distance
(Zalosh, 1995, © SFPE. With permission.)

15.9 Effects of Pressure on Humans and the Environments

Human beings are capable of withstanding relatively high dynamic pressures and considerably higher static pressures. When people are fatally injured as a result of blast waves, it is usually because of falling objects, rather than the pressure associated with the blast wave. Table 15-3 summarizes the pressure effects of blast waves on humans (Fischer et al., 1995), which also depend on the impulse of the blast wave. With the exception of smoke gas explosions, fires seldom reach pressures as high as those listed in Table 15-3. A maximum pressure of 8 bar is produced if a premixed gas-air mixture is ignited inside a building. Outside a building, similar explosion produce pressures of the same order of magnitude if the release results in an unconfined vapor cloud explosion (UVCE). Even higher pressures result if the release causes a detonation both inside and outside a building. However, detonations are very rare.

Usually, it is difficult to predict the pressures produced. In addition, the consequences for humans depend to a significant degree on whether something nearby can strike people in the vicinity of the explosion. Consequently, it is generally not worth the effort to find better values for pressure effects on humans. Similarly, pressure effects are usually limited to a small area, and the effect of pressure on the environment is seldom discussed.

Table 15-3. Pressure Effects on Humans

Pressure (kPa)	**Effect**
35 kPa	Limit for eardrum rupture
70 kPa	Limit for lung damage
100 kPa	50-percent eardrum rupture
180 kPa	1-percent mortality
210 kPa	10-percent mortality
260 kPa	50-percent mortality
300 kPa	90-percent mortality
350 kPa	99-percent mortality

15.10 Effects of Pressure on Components

Existing literature provides only limited data on the effects of pressure on components (such as machines); however, it appears that components are usually unaffected by pressure if they are solid and more sensitive to pressure variations if they contain cavities. When it comes to building elements such as windows, walls, and doors, the literature does provide acceptable data. Table 15-4 lists typical failure pressures of such elements (Harris, 1983).

Table 15-4. Typical Failure Pressures of Some Building Elements

Element	**Typical Failure Pressure (kPa)**
Glass windows	2–7
Room doors	2–3
Light partition walls	2–5
50-mm-thick breeze block walls	4–5
Unrestrained brick walls	7–15

15.11 Estimating the Pressure Increase Attributable to a Confined Explosion

The combustion process raises the temperature of a gaseous system and that, in turn, increases the pressure of the system by expanding the gases. The “ideal gas law” quantifies the effects, as follows:

$$P_1T_1 = P_2T_2 \qquad (15\text{-}4)$$

Where P_1T_1 and P_2T_2 represent the pressure and temperature at state 1 and state 2, respectively, in a constant volume system.

The pressure increase caused by the expansion of the gases is determined by the following equation:

$$P_2 = P_1 \frac{T_1}{T_2} \qquad (15\text{-}5)$$

Assuming that the entire confining enclosure is filled with a gas/air mixture, the maximum pressure inside the enclosure at the end of combustion (P_{max}) is given by the following equation:

$$\frac{P_{max}}{P_{amb}} = \frac{T_{ad}}{T_{amb}} \qquad (15\text{-}6)$$

and

$$P_{max} = \left(\frac{T_{ad}}{T_{amb}}\right) P_{amb} \qquad (15\text{-}7)$$

Where:

P_{max} = maximum pressure at end of combustion (kPa)
P_{amb} = initial ambient atmospheric pressure prior to ignition (kPa)
T_{ad} = adiabatic flame temperature of burned gas (K)
T_{amb} = initial ambient temperature gas/air mixture (K)

Remember that absolute temperature (K or R) must be used in these equations. The adiabatic flame temperature of the burned gas should be approximately the values shown for the given flammable gas(es) in Table 15-2.

15.12 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations:

(1) The method assumes point source blast wave energy correlation (i.e., TNT equivalent energy).

(2) The ideal point source blast wave correlations cannot be valid within or near the flammable vapor cloud.

(3) Flammable gases and vapors are mixed with air (or some other oxidant) in proportions between the lower and upper flammable limits.

(4) It is important to recognize that practical applications of flammability/exposibility data for explosion hazard evaluation should account for nonuniform or stratified vapor-air mixtures.

15.13 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) fuel type (material)

(2) mass of flammable vapor (lb)

(3) ambient temperature (°F)

(4) ambient pressure (psi)

15.14 Cautions

(1) Use (15_Explosion_Calculations.xls) spreadsheet on the CD-ROM for pressure increase and explosive energy release calculations associated with explosions.

(2) Make sure to enter the input parameters in the correct units.

15.15 Summary

This chapter discusses methods of calculating the pressure increase and explosive energy release associated with explosions. Within that content, an explosion is defined as a sudden and violent release of high-pressure gases into the environment. The violence of the explosion depends on the rate at which the energy of the high-pressure gases is released. The energy stored in a car tire, for example, is capable of causing an explosive burst, but it can also be dissipated by gradual release. In general, an explosion can release any of the basic types of energy, including (1) physical energy (2) chemical energy.

Physical energy may take such forms as pressure energy in gases, strain energy in metals, or electrical energy. Examples of the violent release of physical energy include the explosion of a vessel as a result of high gas pressure and the sudden rupture of a vessel as a result of brittle fracture. Another physical form is thermal energy, which generally play an important role in creating the conditions for an explosion, rather than as a source of energy for the explosion itself. In particular, superheating a liquid under pressure causes flashing of the liquid if it is let down to atmospheric pressure.

Chemical energy is derived from a chemical reaction. Examples of the violent release of chemical energy are explosions of a vessel as a result of the combustion of flammable gas. Chemical explosions are either (1) uniform explosions or (2) propagating explosions. An explosion in a vessel tends to be a uniform explosion, while an explosion in a long pipe produces a propagating explosion.

15.16 References

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15.17 Additional Readings

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Handbook of Chemical Hazard Analysis Procedures, Federal Emergency Management Agency (FEMA), U.S. Department of Transportation (DOT), and U.S. Environmental Protection Agency (EPA).

Lees, F.P., *Loss Prevention in the Process Industries, Hazard Identification, Assessment and Control*, Volume, 1, Butterworths-Heinnemann, London and Boston, 1980.

15.18 Problems

Example Problem 15.18-1

Problem Statement
In an NPP, a liquid propane gas (LPG)-driven forklift is used to un load materials from an upcoming outage. Mechanical failure could result in the release of LPG in the area. The maximum fuel capacity of the forklift is 10 gallons. Calculate pressure rise, energy released by expanding LPG, and equivalent TNT charge weight. Assume that the mass of the vapor released is 48 lb.

Solution

Purpose:
(1) Estimate pressure rise, energy released, and TNT equivalent.

Assumptions:
(1) The atmospheric pressure is 14.7 psi.
(2) Ambient air temperature is 77 °F.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 15_Explosion_Calculations.xls

FDT^s Input Parameters:
-Select Fuel Type = Propane
-Percent yield = 100%
-Mass of flammable vapor release = 48 lb

Results*

Pressure Rise	528.6 kPa (76.7 psi)
Energy Released	1,011,491 kJ (957,983 Btu)
Equivalent TNT	225 kg (496 lb)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 15_Explosion_Calculations.xls

CHAPTER 15. ESTIMATING PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

Version 1805.0

The following calculations estimate the pressure and energy due to an explosion in a confined space.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

EXPLOSIVE FUEL INFORMATION

Adiabatic Flame Temperature of the Fuel (T_{ad})	2338	°F	1281.11 °C 1554.11 K
Heat of Combustion of the Fuel (ΔH_c)	46360	kJ/kg	
Yield (α), i.e., the fraction of available combustion 1 percent for unconfined mass release and 100 percent for confined vapor release energy participating in blast wave generation	100.00	%	1
Mass of Flammable Vapor Release (m_F)	48.00	lb	21.82 kg
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa

Calculate

THERMAL PROPERTIES FOR FUELS

FLAMMABILITY DATA FOR FUELS

Fuel	Adiabatic Flame Temperature T_{ad} (°F)	Heat of Combustion ΔH_c (kJ/kg)
Acetylene	4779	48,220
Carbon Monoxide	4329	10,100
Ethane	2244	47,490
Ethylene	4152	47,170
Hydrogen	4085	130,800
Methane	2143	50,030
n-Butane	2442	45,720
n-Heptane	2586	44,560
n-Pentane	2356	44,980
n-Octane	2478	44,440
Propane	2338	46,360
Propylene	4050	45,790
User Specified Vlaue	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 2[nd] Edition, 1995, Page 1-86.

Select Fuel Type

Propane

Scroll to desired fuel type then Click on selection

METHOD OF ZALOSH

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-312.*

Pressure Rise from an Confined Explosion

$(P_{max})/P_a = (T_{ad}/T_a)$

Where P_{max} = maximum pressure developed at completion of combustion (kPa)

P_a = initial atmospheric pressure (kPa)

T_{ad} = adiabatic flame temperature (K)

T_a = ambient temperature (K)

$P_{max} = (T_{ad}/T_a)\ P_a$

P_{max} =	528.57 kPa	76.66 psi	Answer

Blast Wave Energy Calculation

$E = \alpha\ \Delta H_c\ m_F$

Where E = blast wave energy (kJ) [E is the Trinitrotoluene (TNT) equivalent energy]

α = yield (α is the fraction of available combustion energy participating in blast wave generation)

ΔH_c = heat of combustion (kJ/kg)

m_F = mass of flammable vapor release (kg)

E =	1011490.91 kJ	957983.04 Btu	Answer

TNT Mass Equivalent Calculation

$W_{TNT} = E/4500$

Where W_{TNT} = weight of TNT (kg)

E = explosive energy release (kJ)

W_{TNT} =	224.78 kg	495.55 lb	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

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Example Problem 15.18-2

Problem Statement
An investigator is performing a review of an accident at a facility. The report states that a pipe fitter accidently left his acetylene "B" tank on which leaked its contents and caused the explosion. Assuming the tank was full (40 ft^3 of gas at atmospheric pressure), how large could the explosion have been?

Solution

Purpose:
(1) Estimate energy released, and TNT equivalent.

Assumptions:
(1) The atmospheric pressure is 14.7 psi.
(2) Ambient air temperature is 77 °F.

Spreadsheet (FDT^s) Information:
Use the following FDT^s:
(a) 15_Explosion_Calculations.xls

FDT^s Input Parameters:
-Select Fuel Type = Acetylene
-Percent yield = 100%
-Mass of vapor release = volume x density (from manufacture's Web site)
$40\ ft^3 \times .0677\ lb/ft^3 = 2.7\ lb$

Results*

Energy Released	59,179 kJ (56,049 Btu)
Equivalent TNT	13.2 kg (29.0 lb)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 15_Explosion_Calculations.xls

CHAPTER 15. ESTIMATING PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

Version 1805.0

The following calculations estimate the pressure and energy due to an explosion in a confined space.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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 cells(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

EXPLOSIVE FUEL INFORMATION

Adiabatic Flame Temperature of the Fuel (T_{ad})	4779	°F	2637.22 °C 2910.22 K
Heat of Combustion of the Fuel (ΔH_c)	48220	kJ/kg	
Yield (α), i.e., the fraction of available combustion 1 percent for unconfined mass release and 100 percent for confined vapor release energy participating in blast wave generation	100.00	%	1
Mass of Flammable Vapor Release (m_F)	2.70	lb	1.23 kg
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa

Calculate

THERMAL PROPERTIES FOR FUELS

FLAMMABILITY DATA FOR FUELS

Fuel	Adiabatic Flame Temperature T_{ad} (°F)	Heat of Combustion ΔH_c (kJ/kg)
Acetylene	4779	48,220
Carbon Monoxide	4329	10,100
Ethane	2244	47,490
Ethylene	4152	47,170
Hydrogen	4085	130,800
Methane	2143	50,030
n-Butane	2442	45,720
n-Heptane	2586	44,560
n-Pentane	2356	44,980
n-Octane	2478	44,440
Propane	2338	46,360
Propylene	4050	45,790
User Specified Viaue	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 1-88.*

Select Fuel Type

Acetylene

Scroll to desired fuel type then Click on selection

METHOD OF ZALOSH

Reference: SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-312.

Pressure Rise from an Confined Explosion

$(P_{max})/P_a = (T_{af}/T_a)$

Where P_{max} = maximum pressure developed at completion of combustion (kPa)

P_a = initial atmospheric pressure (kPa)

T_{af} = adiabatic flame temperature (K)

T_a = ambient temperature (K)

$P_{max} = (T_{af}/T_a)\ P_a$

P_{max} =	989.80 kPa	143.56 psi	**Answer**

Blast Wave Energy Calculation

$E = \alpha\ \Delta H_c\ m_F$

Where E = blast wave energy (kJ) [E is the Trinitrotoluene (TNT) equivalent energy]

α = yield (α is the fraction of available combustion energy participating in blast wave generation)

ΔH_c = heat of combustion (kJ/kg)

m_F = mass of flammable vapor release (kg)

E =	59179.09 kJ	56048.52 Btu	**Answer**

TNT Mass Equivalent Calculation

$W_{TNT} = E/4500$

Where W_{TNT} = weight of TNT (kg)

E = explosive energy release (kJ)

W_{TNT} =	13.15 kg	28.99 lb	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

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Example Problem 15.18-3

Problem Statement

Which has a larger TNT mass equivalent: 10 lb (mass vapor) of acetylene or 5 lb (mass vapor) of hydrogen?

Solution

Purpose:

(1) Estimate TNT equivalent.

Assumptions:

(1) The atmospheric pressure is 14.7 psi.
(2) Ambient air temperature is 77 °F.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 15_Explosion_Calculations.xls

FDT^s Input Parameters:

-Select Fuel Type = Acetylene
-Percent yield = 100%
-Mass of flammable vapor release = 10 lb
-Select Fuel Type = Hydrogen
-Percent yield = 100%
-Mass of flammable vapor release = 5 lb

Results*

	Acetylene	Hydrogen
Equivalent TNT	48.7 kg (107 lb)	66.0 kg (146 lb)

*see spreadsheet on next page

Therefore, 5 lb of hydrogen produces more explosive force than 10 lb of acetylene.

Spreadsheet Calculations

(a) FDT[s]: 15_Explosion_Calculations.xls (Acetylene)

CHAPTER 15. ESTIMATING PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

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Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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 cells(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

EXPLOSIVE FUEL INFORMATION

Parameter	Value	Unit	Converted
Adiabatic Flame Temperature of the Fuel (T_{ad})	4779	°F	2637.22 °C 2910.22 K
Heat of Combustion of the Fuel (ΔH_c)	48220	kJ/kg	
Yield (α), i.e., the fraction of available combustion 1 percent for unconfined mass release and 100 percent for confined vapor release energy participating in blast wave generation	100.00	%	1
Mass of Flammable Vapor Release (m_F)	10.00	lb	4.55 kg
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa

Calculate

THERMAL PROPERTIES FOR FUELS

FLAMMABILITY DATA FOR FUELS

Fuel	Adiabatic Flame Temperature T_{ad} (°F)	Heat of Combustion ΔH_c (kJ/kg)
Acetylene	4779	48,220
Carbon Monoxide	4329	10,100
Ethane	2244	47,490
Ethylene	4152	47,170
Hydrogen	4085	130,800
Methane	2143	50,030
n-Butane	2442	45,720
n-Heptane	2586	44,560
n-Pentane	2356	44,980
n-Octane	2478	44,440
Propane	2338	46,360
Propylene	4050	45,790
User Specified Vaue	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 1-86.*

Select Fuel Type

Acetylene

Scroll to desired fuel type then Click on selection

METHOD OF ZALOSH

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-312.*

Pressure Rise from an Confined Explosion

$(P_{max})/P_a = (T_{ad}/T_a)$

Where
- P_{max} = maximum pressure developed at completion of combustion (kPa)
- P_a = initial atmospheric pressure (kPa)
- T_{ad} = adiabatic flame temperature (K)
- T_a = ambient temperature (K)

$P_{max} = (T_{ad}/T_a)\ P_a$

P_{max} =	989.80 kPa	143.56 psi	**Answer**

Blast Wave Energy Calculation

$E = \alpha\ \Delta H_c\ m_F$

Where
- E = blast wave energy (kJ) [E is the Trinitrotoluene (TNT) equivalent energy]
- α = yield (α is the fraction of available combustion energy participating in blast wave generation)
- ΔH_c = heat of combustion (kJ/kg)
- m_F = mass of flammable vapor release (kg)

E =	219181.82 kJ	207587.10 Btu	**Answer**

TNT Mass Equivalent Calculation

$W_{TNT} = E/4500$

Where
- W_{TNT} = weight of TNT (kg)
- E = explosive energy release (kJ)

W_{TNT} =	48.71 kg	107.38 lb	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(B) FDT[s]: 15_Explosion_Calculations.xls (Hydrogen)

CHAPTER 15. ESTIMATING PRESSURE INCREASE AND EXPLOSIVE ENERGY RELEASE ASSOCIATED WITH EXPLOSIONS

Version 1805.0

The following calculations estimate the pressure and energy due to an explosion in a confined space.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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 cells(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

EXPLOSIVE FUEL INFORMATION

Adiabatic Flame Temperature of the Fuel (T_{ad})	4085	°F	2251.67 °C 2524.67 K
Heat of Combustion of the Fuel (ΔH_c)	130800	kJ/kg	
Yield (α), i.e., the fraction of available combustion 1 percent for unconfined mass release and 100 percent for confined vapor release energy participating in blast wave generation	100.00	%	1
Mass of Flammable Vapor Release (m_F)	5.00	lb	2.27 kg
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa

Calculate

THERMAL PROPERTIES FOR FUELS

FLAMMABILITY DATA FOR FUELS

Fuel	Adiabatic Flame Temperature T_{ad} (°F)	Heat of Combustion ΔH_c (kJ/kg)
Acetylene	4779	48,220
Carbon Monoxide	4329	10,100
Ethane	2244	47,490
Ethylene	4152	47,170
Hydrogen	4085	130,800
Methane	2143	50,030
n-Butane	2442	45,720
n-Heptane	2586	44,560
n-Pentane	2356	44,980
n-Octane	2478	44,440
Propane	2338	46,360
Propylene	4050	45,790
User Specified Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 1-86.*

Select Fuel Type

Hydrogen

Scroll to desired fuel type then Click on selection

METHOD OF ZALOSH

Reference: *SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995, Page 3-312.*

Pressure Rise from an Confined Explosion

$(P_{max})/P_a = (T_{ad}/T_a)$

Where P_{max} = maximum pressure developed at completion of combustion (kPa)

P_a = initial atmospheric pressure (kPa)

T_{ad} = adiabatic flame temperature (K)

T_a = ambient temperature (K)

$P_{max} = (T_{ad}/T_a)\ P_a$

P_{max} =	858.67 kPa	124.54 psi	Answer

Blast Wave Energy Calculation

$E = \alpha\ \Delta H_c\ m_F$

Where E = blast wave energy (kJ) [E is the Trinitrotoluene (TNT) equivalent energy]

α = yield (α is the fraction of available combustion energy participating in blast wave generation)

ΔH_c = heat of combustion (kJ/kg)

m_F = mass of flammable vapor release (kg)

E =	297272.73 kJ	281547.00 Btu	Answer

TNT Mass Equivalent Calculation

$W_{TNT} = E/4500$

Where W_{TNT} = weight of TNT (kg)

E = explosive energy release (kJ)

W_{TNT} =	66.06 kg	145.64 lb	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 16. CALCULATING THE RATE OF HYDROGEN GAS GENERATION IN BATTERY ROOMS

16.1 Objectives

This chapter has the following objectives:

- Explain how hydrogen gas is generated in a battery room.
- Describe the conditions under which hydrogen gas will ignite.
- Describe possible ignition sources in a battery room.
- Explain methods of controlling the combustion of hydrogen gas.
- Describe how to estimate hydrogen gas generation rates.

16.2 Introduction

Battery rooms in nuclear power plants (NPPs) represent a potential problem area because of the generation of hydrogen gas. An NPP is typically equipped with large banks of 250-V dc and 125-V dc battery systems (NUREG/CR-2726). The 250-V dc system consists of two banks of 120 lead-calcium (lead-acid) storage cells, and the 125-V dc system typically contains four banks of 60 cells. Each bank is mounted in two rows of battery racks and located in its own battery room.

During operation, as the batteries change chemical energy to electrical energy, the sulfuric acid content of the electrolyte becomes depleted. Therefore, the batteries must be recharged if they are to be used continuously. This is done by connecting a dc charging source that enables current to flow through the battery in the direction opposite of its normal flow, thereby driving the acid back into the electrolyte. However, the byproducts of this charging process, or electrolysis, can present a safety issue. As a cell becomes nearly charged, the charging current becomes greater than that necessary to force the remaining amount of sulfuric acid back into the electrolyte. This results in ionization of the water in the electrolyte liberates hydrogen gas at the positive plate. The maximum rate of formation is 0.42×10^{-3} m^3 (0.42 liter) of hydrogen and 0.21×10^{-3} m^3 (0.21 liter) of oxygen per ampere-hour overcharge at standard temperature and pressure. The gas mixture is explosive when the hydrogen concentration in air exceeds 4.1-percent by volume.

Although the release of this gas is undesirable, the process is necessary to develop a full charge in the cell. Consequently, NPPs must take precautions to prevent explosions from ignition of the flammable gas mixture of hydrogen and oxygen formed during overcharging of lead-acid cells. NPPs employ several methods to reduce the risk associated with high hydrogen concentrations. Regardless of the method used, proper implementation requires an accurate measurement of the hydrogen concentration. A variety of hydrogen detectors are available for use in NPPs. A standard practice is to set hydrogen detection devices to activate at 2.0–2.5-percent by volume of the lower explosive limit (LEL).

16.3 Combustion of Hydrogen Gas

Hydrogen gas has an extremely wide flammability range and the highest burning velocity of any gas. Its ignition temperature is reasonably high [500 °C (932 °F)], but its ignition energy is very low. Because hydrogen contains no carbon, it burns with a nonluminous flame, which is often invisible in daylight. At ordinary temperatures, hydrogen is very light, weighing only about $^1/_{15}$ as much as air.

Combustion of hydrogen according to the reaction—

$$2H_2 + O_2 \text{ ----------> } 2H_2O + \text{Energy (heat)}$$

results in a release of about 57.8 kcal/g-mole (5.2 x 10^4 Btu/lb-mole) of hydrogen burned (NUREG/CR-6042). For a flammable gas mixture, the flammability limits are defined as the limiting concentrations of fuel, at a given temperature and pressure, in which a flame can propagate indefinitely. Limits for upward propagation of flames are wider than those for downward propagation. Limits for horizontal propagation are between those for upward and downward propagation.

The lower flammability limit (LFL) is the minimum concentration of hydrogen required to propagate a flame, while the upper flammability limit (UFL) is the maximum concentration. At the LFL, the hydrogen is in short supply and the oxygen (air) is present in excess. At the UFL for hydrogen in air, the oxygen (air) is in short supply, about 5-percent oxygen by volume. In air at standard temperature and pressure (25 °C, 1 atm), and 100-percent relative humidity, the LFL for hydrogen combustion is 4.1-percent hydrogen concentration by volume. Table 16-1 indicates the approximate hydrogen concentrations required for combustibility in air (NUREG/CR-6042).

Table 16-1. Hydrogen Flammability Limits in Air at Room Temperature

Possible Reaction	Lower Flammability Limit Volume Percent of Hydrogen	Upper Flammability Limit Volume Percent of Hydrogen
Upward propagation	4.1	74
Horizontal propagation	6.0	74
Downward propagation	9.0	74

Figure 16-1 shows the flammability limits of hydrogen with the addition of excess carbon dioxide and nitrogen (diluents). Note that with 75-percent additional nitrogen, the atmosphere is inert. This corresponds to 5-percent oxygen at the limit of the flammable region, a value very close to that of the UFL for hydrogen air combustion. Similarly, the atmosphere is inert when the carbon dioxide concentration is 60-percent or above, corresponding to 8-percent oxygen or less. The larger specific heat of carbon dioxide reduces the flame temperature and flame velocity; hence, carbon dioxide suppresses flammability more than nitrogen. By contrast, it requires about 60-percent steam to inert a hydrogen-air-steam mixture. Figure 16-2 indicates the regions of flammability of hydrogen-air-steam mixtures (Shapiro and Moffette, 1957).

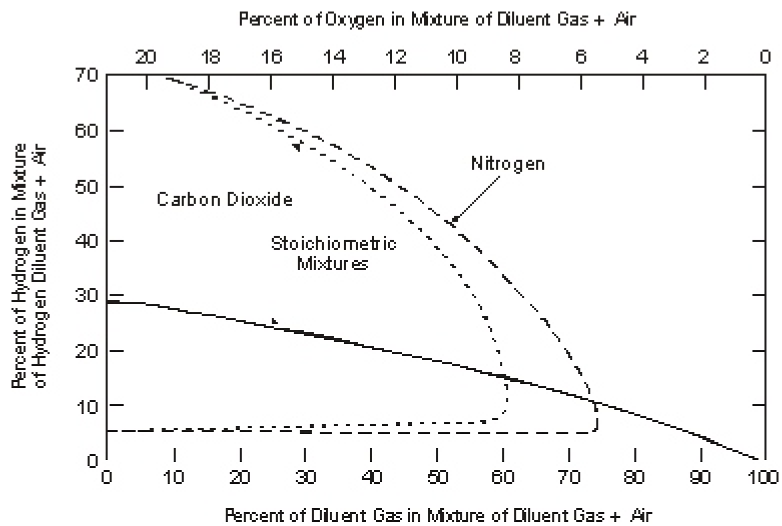

Figure 16-1 Flammability Limits of Hydrogen in Air Diluted with Carbon Dioxide and Nitrogen (Shapiro and Moffette, 1957)

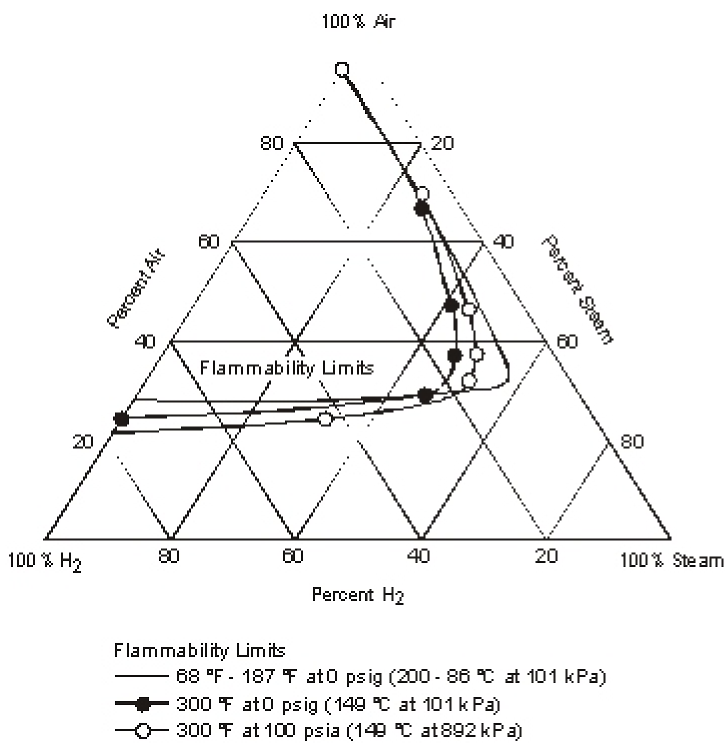

Figure 16-2 Flammability Limits of Hydrogen in Air-Steam Mixtures (Shapiro and Moffette, 1957)

16.4 Ignition of Hydrogen Gas

Accidental ignition of hydrogen could be caused by several sources in a structure if the hydrogen concentration in air were to reach sufficient levels. Ignition of dry hydrogen-air mixtures, particularly when the mixtures are well within the flammability limits, can occur with a very small input of energy (Shapiro and Moffette, 1957). Common sources of ignition are sparks from electrical equipment and the discharge of small static electric charges. In fact, the minimum energy required from a spark for ignition of a quiescent hydrogen air mixture is on the order of 10^{-4} J (10^{-7} Btu)—a very weak spark. Figure 16-3 (Drell and Belles, 1958) shows the ignition energy required as a function of hydrogen concentration. For a flammable mixture, the required ignition energy increases as the hydrogen concentration approaches the flammability limits. The addition of a diluent, such as steam, substantially increases the required ignition energy.

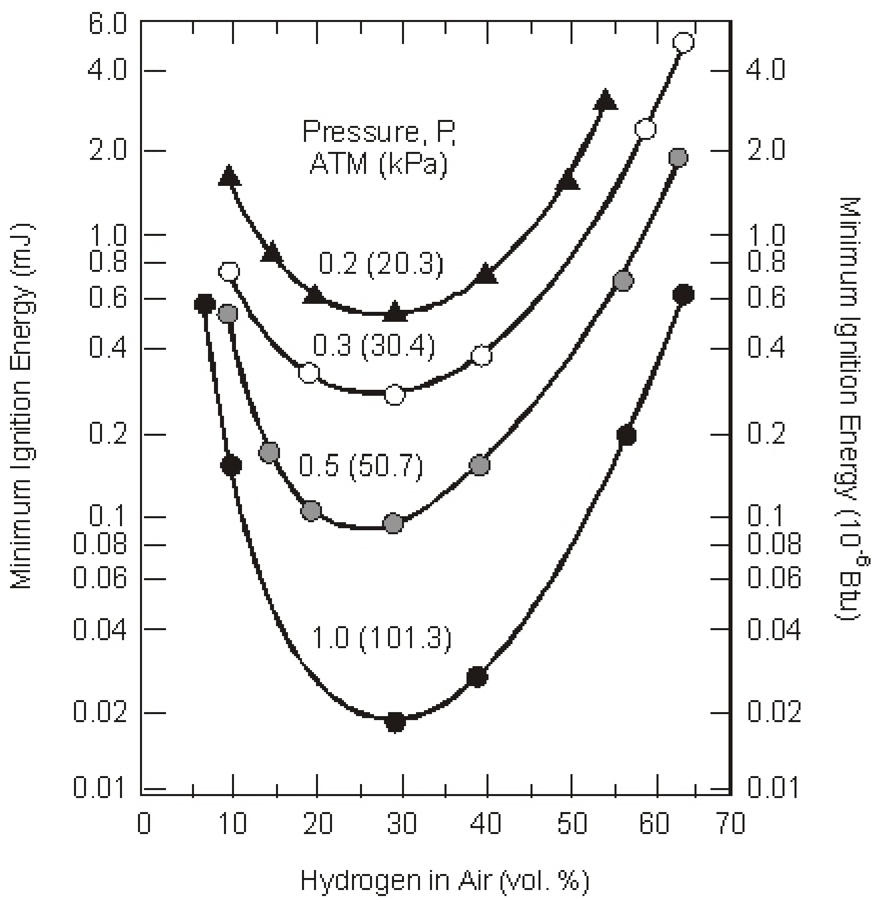

Figure 16-3 Spark Ignition Energies for Dry Hydrogen-Air Mixtures (Drell and Belles, 1958)

16.4.1 Battery as an Ignition Source

Given the discussion in the previous section, it is relatively easy to accept the fact that a battery can act as an ignition source for the hydrogen-air mixture that results from its own charging process. Since all functional vented batteries generate a stoichiometric mixture of hydrogen and oxygen gases during overcharging and expel them normally from the cell into the battery container, a potential always exists that these gases may explode. Normally, the battery case does not contain any ignition sources, but several abnormal possibilities do exist. One is the internal short-circuiting of a relatively dry cell in overcharging, resulting in an explosion inside the cell with a subsequent ejection of flames into the battery case. A second and more likely source of ignition may exist at an improperly maintained cell terminal, as a result of the high temperatures generated during high-rate discharge. A third source of ignition may occur at the site of stray leakage currents.

16.4.2 Control of Hydrogen Gas Combustion

An NPP can effectively control a flammable gas-oxidant mixture by reducing the concentration of oxidant or by adding an inert constituent to the mixture. Both processes can be explained most easily by referring to a flammability diagram. Figure 16-4 (NFPA 69, 1997 Edition) for example, shows a typical flammability diagram representing a mixture of combustible gas, an inert gas, (nitrogen), and an oxidant, (oxygen), at a given temperature and pressure. A mixture of air (79-percent N_2 and 21-percent O_2, by volume) and combustible gas is represented by line DABE. A given mixture of combustible gas and air, whether ignitable or not, is specified by some point on this line. Point A indicates the UFL of this mixture, while point B represents its LFL. Point C represents the limiting oxidant concentration to prevent ignition; any mixture containing less oxygen cannot be ignited. Any point within the area bounded by curve FBCAG is in the flammable range and can be ignited. Any mixture of oxygen and combustible gas alone (i.e., without any nitrogen) is represented by the left-hand side of the triangle. Any mixture of nitrogen and combustible gas alone (i.e., no oxygen present) is represented by the right-hand side of the triangle.

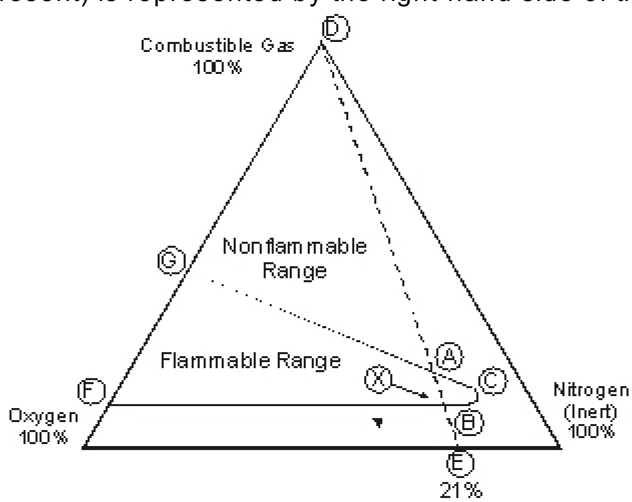

Figure 16-4 Typical Flammability Diagram
(NFPA 69, 1997 Edition, © NFPA. With permission.)

NPPs rely on several simple (but extremely important) methods to prevent hydrogen combustion in battery rooms. First, the rooms are well-ventilated to prevent excessive hydrogen buildup. The battery room ventilation system in NPPs typically limits hydrogen concentration to less than 2 percent of the total volume of the room and maintains a constant temperature of 25 °C (77 °F). The air flow rate is approximately 10 air changes per hour. As an additional precaution, no open flame or smoking is allowed in the proximity of the battery room. Also, any work in the room must be performed with non-sparking tools made of brass, aluminum, or wood (Linden, 1994).

To date, there have been no major accidents involving hydrogen gas in the battery rooms at NPPs (NUREG/CR-2726). However, in other (non-nuclear) industries, there have been instances of hydrogen explosions reported in battery charging areas ranging in size from submarine battery rooms to uninterruptible power supply (UPS) battery rooms where batteries create a real problem during periods of high recharge.

On March 20, 2001, a hydrogen explosion occurred in the UPS/battery room of a large computer data center in Sacramento, California ("Explosion in Rancho Cordova," 2001). The explosion blew a 400+ ft^2 hole in the roof, collapsed numerous walls and ceilings throughout the data center, and significantly damaged a large portion of the 50,000 ft^2 building.

16.5 Fire Protection Code Requirements for Battery Rooms

Regarding battery room fire protection for NPPs, Regulatory Guide (RG) 1.189 states that battery rooms should be separated from each other and other areas of the plant by barriers having a minimum fire rating of 3 hours, inclusive of all penetrations and openings. RG 1.189 also states that ignition sources (such as the DC switchgear room and inverters should not be located in batteries rooms. In addition, RG 1.189 recommends that automatic fire detection should be provided to alarm and annunciate in the control room and alarm locally. Ventilation systems in the battery rooms should also be capable of maintaining the hydrogen gas concentration well below 2 percent. Loss of ventilation should be alarmed in the control room and standpipe, and a hose station and portable fire extinguishers should be readily available outside the room.

Similar to RG 1.189, Section E2.12 of NFPA 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," 2001 Edition recommends that battery rooms should be separated from adjacent areas by fire-rated barriers. It also recommends that battery rooms should be ventilated to limit the concentration of hydrogen gas to 1-percent by volume in accordance with NFPA 69, "Standard on Explosion Prevention Systems." In addition, NFPA 805 requires that direct current switchgear and inverters should not be located in battery rooms. For detailed information, refer to IEEE-484, "Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications."

In similar fashion, Section 8.7 of NFPA 804, "Standard for Fire Protection for Advanced Light Water Reactor Electric Generating Plants," 2001 Edition recommends that battery rooms should be protected against fires and explosion, and that ventilation should be provided to limit the concentration of hydrogen to 2-percent by volume. It also recommends that battery rooms should be separated from other areas of the plant by fire barriers having a 1-hour minimum rating and direct current switchgear and inverters should not be located in battery rooms.

Finally, Section 3-4 of NFPA 801, "Standard for Fire Protection for Facilities Handling Radioactive Materials," 2003 Edition, provides additional guidance for battery rooms, stating that "the facility shall be subdivided into separate fire areas as determined by the fire hazards analysis for the purpose of limiting the spread of fire, protecting personnel, and limiting the consequential damage to the facility. Fire areas shall be separated from each other by barriers with fire resistance commensurate with the potential fire severity. " Specifically, Section A-3-4 of NFPA 801 recommends that battery rooms should be separated by fire barriers having a 3-hour minimum rating. It also recommends that electrical equipment, such as the switchgear and relay rooms should be located in separate fire areas.

NFPA 70E, "Standard for Electrical Safety Requirements for Employee Workshops," 2000 Edition contains additional requirements for vented-type batteries, which require ventilation to limit hydrogen gas concentration exceeding 1-percent by volume. Similar requirements exist for valve-regulated lead-acid (VRLA) storage batteries.

16.6 Method of Calculating the Rate of Hydrogen Generation in Battery Rooms

As previously explained, hydrogen gas is primarily generated in battery rooms as a result of battery overcharge. The generation of hydrogen is particularly important because of its rapid production rate and high flammability. A hydrogen-rich environment could accumulate in a battery room if the ventilation flow through the space is completely stopped or other events allow hydrogen accumulation. The formation of flammable fuel (hydrogen)/oxidant mixtures within a battery room can lead to premixed flame propagation in the form of fire and explosion events, which can cause failure of the structures, ventilation systems, power systems, and monitoring systems. A significant amount of hydrogen gas is liberated only when the battery approaches full charge. The maximum hydrogen evolution rate is 7.56×10^{-6} m^3 (0.000267 ft^3) per minute per charging ampere per cell at 25 °C (77 °F) and 1-atmosphere (Yuasa, Inc., 2000).

The method to calculate the amount of hydrogen produced from batteries in an enclosure is excerpted from the appendix to Section 58.00 of the Yuasa Catalog (2000). This method considers an antimony alloy-type (flat plate, tubular, or Manchex) battery at a point where it is nearing its end of life, or equalizing charge at 2.33 VPC (volts per cell).

The rate of hydrogen generation from a battery can be approximated using the following equation (Yuasa, Inc., 2000):

$$H_{gen} = \frac{F_C}{1000} \; \frac{A_H}{100} \; K \; N \qquad (16\text{-}1)$$

Where:

H_{gen} = hydrogen gas generation, ft^3/min
F_C = float current per 100 A_H (temperature compensated) in milliamperes
A_H = ampere hours (nominal 8 hour)
K = constant - 1 A_H = 0.000267 ft^3
N = number of cells

Table 16-2 summarizes the float current (F_C) demand of fully charged stationary lead-acid cells.

Table 16-2. Float Current Demand for a Stationary Battery

Charge Voltage (VPC)	**Float Current (F_C) milliamperes per 100 AH @ 8-hour rate**		
	Antimony		**Calcium**
	New	**Old**	
2.15	15	60	-
2.17	19	80	4
2.20	26	105	6
2.23	37	150	8
2.25	45	185	11
2.27	60	230	12
2.33	120	450	24
2.37	195	700	38
2.41	300	1,100	58
Note: The above values apply when the electrolyte temperature is 25 °C (77 °F). The values double for every 8 °C (15 °F) of temperature rise. If the temperature drops, the current value is halved for every 8 °C (15 °F) decrease. Antimony ranges indicate current increases attributable to cell aging.			

16.7 Method of Calculating Flammable Gas and Vapor Concentration Buildup in Enclosed Spaces

The minimum and maximum concentration of combustible material in a homogeneous mixture with a gaseous oxidizer that will propagate a flame is called flammable limits. Upper and lower flammability limits represent the range of concentrations of fuel in air in which a premixed flame can propagate.

A deflagration is possible if the concentration of a gas rises above its LFL. A detonation can occur if the velocity of a propagation of a combustion zone is greater than the speed of sound in the unreacted medium. For a detonation pressure rises are estimated as 2 to 4 times that of a deflagration. Deflagrations are characterized by slow subsonic propagation of a flame front, and slow but uniform rise in the pressure and temperature of the gas by the heat released from the combustion.

A detonation produces a shock wave driven and sustained by the chemical energy released from the chemical reaction. The shock wave and the reaction propagate together in the unburned gas at a speed which exceeds that of sound in the unburned medium, i.e., of the order of 1,500 to 2,000 m/sec (Fardis et al., 1983). The shock front is characterized by an abrupt increase in pressure, temperature, and density of the gas, and by the net forward movement of the gas particles. Shock reflection produces a large pressure on the wall (e.g., 2 to 4 times the incident pressures for a deflagration), and generates a purely mechanical wave which propagates inward in the already burnt gas until interacts with another wave produced by the reflection elsewhere.

The volume gas or vapor for deflagration is give by the following expression:

$$V_{def} = \frac{V}{LFL} \qquad (16\text{-}2)$$

Where:

V_{def} = volume of gas vapor for deflagration (ft^3)
V = volume of the enclosure (ft^3)
LFL = lower flammability of gas or vapor (percent-volume)

16.8 Method of Calculating Flammable Gas and Vapor Concentration Buildup Time in Enclosed Spaces

NFPA 69, "Standard on Explosion Prevention Systems," provides a method to calculate the time to buildup of combustible concentration of a flammable gas in enclosed area.

If a constant source of flammable gas is introduced into an enclosed volume, the buildup of flammable gas concentration is given by the following equation:

$$C = \frac{G}{Q}\left(1 - e^{-KN}\right) \qquad (16\text{-}3)$$

Where:

C = gas concentration by volume
G = flammable/combustible gas discharge rate (ft^3/min)
Q = volume of air in enclosure (ft^3/min)
K = mixing efficiency factor (constant)
N = number of theoretical air changes

Equation (16-3) can be rewritten into a more convenient logarithmic form:

$$\ln\left(1 - \frac{CQ}{G}\right) = -KN \qquad (16\text{-}4)$$

In perfect conditions, K = 1.0, Table 16-3 lists mixing efficiency factor (K) for certain conditions.

Table 16-3. Mixing Efficiency for Various Ventilation Arrangements

Method of Supplying	Efficiency K Values	
	Single Exhaust Opening	**Multiple Exhaust Opening**
No Positive Supply		
Infiltration through cracks	0.2	0.3
open doors, or windows	0.2	0.4
Forced Air Supply		
Grills and registers	0.3	0.5
Diffusers	0.5	0.7
Perforated ceiling	0.8	0.9

16.9 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations:

(1) Hydrogen gas is primarily generated in battery rooms as a result of battery overcharge.

(2) The generation of hydrogen environment could occur if the ventilation flow through the vapor space is completely stopped or other events allow hydrogen accumulation.

(3) This method assumes that significant amounts of hydrogen gas are liberated only when the battery approaches full charge.

(4) The calculations will produce a first order approximation.

(5) The battery hydrogen generation equation is based on one specific vendor's recommendations.

16.10 Required Input for Spreadsheet Calculations

The user must obtain the following data before attempting a calculation with the spreadsheet:

(1) charge voltage (vpc)

(2) ampere Hours

(3) number of cells

16.11 Cautions

(1) Make sure to input data in the correct units.

(2) Use spreadsheet (16_Battery_Room_Flammable_Gas_Conc.xls) on the CD-ROM for calculations.

16.12 Summary

(1) Adequate ventilation is the most common form of fire prevention/protection in battery rooms. Ventilation must be adequate to prevent hydrogen gas from exceeding a concentration of 2 percent by volume, and to ensure that pockets of trapped hydrogen gas do not develop (particularly at the ceiling).

(2) The exhaust air outlets from the battery room shall be located separately so that a hazardous concentration of the exhausted air cannot enter or be drawn into the fresh air intakes of environmental air handling systems.

(3) Building and fire codes require spill containment systems for battery installations that contain electrolyte.

(4) NPP should maintain an ambient temperature of 23 to 26 °C (72 to 78 °F) in battery rooms.

(5) To extinguish a fire in a battery room containing lead-acid batteries, use CO_2, fire protection foam, or dry chemical extinguishing media. Do not discharge the extinguisher directly onto the battery. The resulting thermal shock may cause cracking of the battery case and/or cover.

(6) In case of fire, the power should be shut off if batteries are on charge. Use a positive-pressure, self-contained breathing apparatus. Remember that water applied to an electrolyte generates heat and causes it to splatter. Wear acid-resistant clothing.

16.13 References

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16.14 Problems

Example Problem 16.14-1

Problem Statement
Assume a 60-cell GT-41 (3,730 Ampere-hour) battery near the end of its life, on equalize at 2.33 VPC at an electrolyte temperature of 92 °F (33 °C). Estimate the rate of hydrogen generation (in cubic feet per minute).

Solution

Purpose:

(1) Estimate the rate of hydrogen generation.

Assumptions:

(1) Old Antimony-type battery

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 16_Battery_Room_Flammable_Gas_Conc.xls
(click on Battery_Room_Hydrogen)

FDT^s Input Parameters:

-Ampere Hours = 3730 Ah
-Number of Cells = 60
-Click on Old Antimony type and Select 2.33 VPC

Results*

Generation Rate	0.538 ft^3/m (0.0152 m^3/min)

*see spreadsheet on next page

Spreadsheet Calculations

FDT[s]: 16_Battery_Room_Flammable _Gas_Conc.xls (Battery_Room_Hydrogen)

CHAPTER 16. CALCULATING THE RATE OF HYDROGEN GAS GENERATION IN BATTERY ROOMS

Version 1805.0

The following calculations estimate the hydrogen gas generation in battery rooms.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Charge Voltage Selected.
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

BATTERY INFORMATION

Float Current (F_c)	450	mA per 100 A.h @ 8-hr. rate
Ampere Hours (A_h)	3730.00	Ampere hours
Number of Cells (N)	60.00	
Constant (K)	0.000267	ft³

COMPARTMENT INFORMATION

Compartment Width (w_c)	26.00	ft
Compartment Length (l_c)	50.00	ft
Compartment Height (h_c)	12.00	ft

FLAMMABLE GAS INFORMATION

Lower Flammability Limit of Hydrogen	4.00	Percent	0.040

Calculate

Float Current Demand of Fully Charged Stationary Lead-Acid Cells

Reference: *Yuasa, Inc., Safety Storage, Installation, Operation, and Maintenance Manual, Section 58.00, Heritage Series, Flooded Lead-Acid Batteries, 2000.*

New Antimony Charge Voltage (VPC)	F_c* Antimony New
2.15	15
2.17	19
2.20	26
2.23	37
2.25	45
2.27	60
2.33	120
2.37	195
2.41	300
User Specified Value	Enter Value

Select Charge Current Value

Scroll to desired value then Click on selection

* (milliamperes per 100 AH @ 8-hr. rate)

Old Antimony Charge Voltage (VPC)	F_c* Antimony Old
2.15	60
2.17	80
2.20	105
2.23	150
2.25	185
2.27	230
2.33	450
2.37	700
2.41	1100
User Specified Value	Enter Value

Select Charge Current Value

Scroll to desired value then Click on selection

* (milliamperes per 100 AH @ 8-hr. rate)

Calcium Charge Voltage (VPC)	F_c* Antimony Calcium
2.15	
2.17	4
2.20	6
2.23	8
2.25	11
2.27	12
2.33	24
2.37	38
2.41	58
User Specified Value	Enter Value

Select Charge Current Value

Scroll to desired value then Click on selection

* (milliamperes per 100 AH @ 8-hr. rate)

METHOD OF YUSHA, INC.

Reference: Yuasa, Inc., Safety Storage, Installation, Operation and Maintenance Manual, Section 58.00, Heritage Series, Flooded Lead-Acid Batteries, 2000.

Estimating Hydrogen Gas Generation Rate

$H_{2(gen)} = F_C/1000 \times A_H/100 \times K \times N$

This equation is based on when electrolyte temperature is 77 °F (25 °C)
For every 15 °F (8 °C) electrolyte temperaturte rise the equation will multiply by 2

Where
$H_{2(gen)}$ = hydrogen gas generation rate (ft^3/min)
F_C = float current (mA per 100 A_H @ 8-hr. rate)
A_H = ampere hours (normal 8 hour)
K = constant - 1 A_H = 0.000267 ft^3
N = number of cells

$H_{2(gen)} = F_C/1000 \times A_H / 100 \times K \times N \times 2$

Since electrolyte temperature is 92 °F (33 °C) the equation is multiply by 2

$H_{2(gen)}$ =	0.538 ft^3/min	0.015230 m^3/min	Answer

Estimating Hydrogen Gas In Compartment Based on Given Flammability Limit

$H_{2(comp)} = V \times FL$

Where
$H_{2(comp)}$ = hydrogen gas in compartment (ft^3)
V = volume of compartment (ft^3)
FL = hydrogen gas flammability limit

Volume of Compartment

$V = w_c \times l_c \times h_c$

Where
V = compartment volume (ft^3)
w_c = compartment Width (ft)
l_c = compartment Length (ft)
h_c = compartment Height (ft)

V = 15600 ft^3

$H_{2(comp)} = V \times FL$

$H_{2(comp)}$ = 624 ft^3

Estimating Time Required to Reach Hydrogen Concentration on Given Flammability Limit

$t_{H2} = H_{2(comp)} / H_{2(gen)}$

Where
t_{H2} = time require to reach on given flammability limit (min)
$H_{2(comp)}$ = hydrogen gas in compartment (ft^3)
$H_{2(gen)}$ = hydrogen gas generation rate (ft^3/min)

t_{H2} =	1160.30 min. or approximately	19 hours	Answer

NOTE

The above calculations are based on method presented in the Yuasa, Inc., Safety Storage, Installation, Operation, and maintenance Manual, Section 58.00, Heritage Series, Flooded Lead-Acid Batteries, 2000.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 16-2

Problem Statement

Consider an enclosure (10ft wide x 10ft long x 10ft high) 1,000 ft^3 (28 m^3) in turbine generator area of a nuclear facility in which hydrogen gas is accumulated. Calculate the concentration of hydrogen gas by volume reaching its LFL of 4 percent.

Solution

Purpose:

(1) Estimate the concentration of hydrogen gas in the compartment at LFL.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 16_Battery_Room_Flammable _Gas_Conc.xls
(click on Flammable_Gas_Buildup)

FDT^s Input Parameters:

-Compartment Width (w_c) = 10 ft
-Compartment Length (l_c) = 10 ft
-Compartment Height (h_c) = 10 ft
-Select Hydrogen

Results*

Volume	40 ft^3 (1.13 m^3)

*see spreadsheet on next page

Therefore, the concentration of hydrogen gas in the 1000 ft^3 compartment is 4% (40/1000).

Spreadsheet Calculations
FDT[s]: 16_Battery_Room_Flammable _Gas_Conc.xls (Flammable_Gas_Buildup)

CHAPTER 16. CALCULATING THE RATE OF HYDROGEN GAS GENERATION IN BATTERY ROOMS

Version 1805.0

The following calculations estimate the flammable concentration of gases and vapors in enclosures.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Gas or Vapor Selected.
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

Lower Flammability Limit of Flammable Gas or Vapor (LFL)	4.00	Percent	0.040
Compartment Width (w_c)	10.00	ft	
Compartment Length (l_c)	10.00	ft	
Compartment Height (h_c)	10.00	ft	

Calculate

LOWER FLAMMABILITY DATA FOR GASES AND VAPORS

Gases and Vapors	LFL Volume Percent
Hydrogen	4.00
Carbon Monoxide	12.50
Methane	5.00
Ethane	3.00
Propane	2.10
n-Butane	1.80
n-Pentane	1.40
n-Hexane	1.20
n-Heptane	1.05
n-Octane	0.95
n-Nonane	0.85
n-Decane	0.75
Ethene	2.70
Propane	2.40
Butene-1	1.70
Acetylene	2.50
Methanol	6.70
Ethanol	3.30
n-Propanol	2.20
Acetone	2.60
Methyl Ethyl Ketone	1.90
Diethyl Ketone	1.60
Benzene	1.30
User Specified Value	Enter Value

Select Gas or Vapor
Hydrogen
Scroll to desired gas or vapor then **Click** on selection

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 2-175.

ESTIMATING FLAMMABLE CONCENTRATION OF GASES USING LIMITS OF FLAMMABILITY

Volume of Gas or Vapor for Deflagration = V x LFL

Where V = volume of enclosure (ft^3)

LFL = lower flammability of a gas or vapor (percent-volume)

Volume of Compartment

$V = w_c \times l_c \times h_c$

Where V = compartment volume (ft^3)

w_c = compartment width (ft)

l_c = compartment length (ft)

h_c = compartment height (ft)

V = 1000.00 ft^3

Volume of Gas or Vapor for Deflagration = V x LFL

Volume of Gas or Vapor for Deflagration =	40 ft^3	1.13 m^3	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

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Example Problem 16-3

Problem Statement
Assume a leak of 100 ft^3/min of a 15-percent hydrogen gas/air mixture in a compartment that is 29 ft wide x 15 ft long x 12 ft high (w_c x l_c x h_c). How long would it take to reach a hydrogen concentration of 2 percent throughout the enclosure, assuming infiltration through multiple compartment cracks?

Solution

Purpose:

(1) Estimate the time until the room reaches 2% hydrogen concentration.

Assumptions:

(1) Infiltration through compartment leaks.
(2) The mass rate of the fuel is neglected in the conversion of mass.
(3) The specific heat is constant with temperature.
(4) The hydrostatic pressure difference over the height oft he compartment is negligible compared to the dynamic pressure.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 16_Battery_Room_Flammable _Gas_Conc.xls
(click on Flammable_Gas_Buildup_Time)

FDT^s Input Parameters:

-Compartment Width (w_c) = 29 ft
-Compartment Length (l_c) = 15 ft
-Compartment Height (h_c) = 12 ft
-Enter 100 ft^2/min as the Leakage Rate
-Enter 15% as Percent of Combustible Gas/Air Mixture
-Enter 2% as Combustible Gas Concentration (C)
-Click on Infiltration Through Cracks and select 0.3 from the drop-down menu

Results*

Time	20.9 minutes

*see spreadsheet on next page

Spreadsheet Calculations
FDT[s]: 16_Battery_Room_Flammable_Gas_Conc.xls (Flammable_Gas_Buildup_Time)

CHAPTER 16. CALCULATING THE RATE OF HYDROGEN GAS GENERATION IN BATTERY ROOMS

Version 1805.0

The following calculations estimate the combustible gas concentration buildup time in enclosed compartments.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Infiltration Selected.
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

COMPARTMENT INFORMATION HYDROGEN LEAK INFORMATION

Compartment Width (w_c)	29.00	ft	
Compartment Length (l_c)	15.00	ft	
Compartment Height (h_c)	12.00	ft	
Leakage Rate	100.00	ft^3/min	
Percent of Combustible Gas/Air Mixture	15.00	percent	0.15
Combustible Gas Concentration (C)	2.00	percent	0.02
Mixing Efficiency Factor (K)	0.3		

Calculate

Mixing Efficiency (K Values) for Various Ventilation Arrangements

Reference: *NFPA 69, "Standard on Explosion Prevention Systems," 1997 Edition.*

Infiltration Through Cracks	K
Single Exhaust Opening	0.2
Multiple Exhaust Openings	0.3

Select Ventilation Arrangement
0.3
Scroll to desired arrangement then Click on selection

Open Door, or Windows	K
Single Exhaust Opening	0.2
Multiple Exhaust Openings	0.4

Select Ventilation Arrangement
Scroll to desired arrangement then Click on selection

Grill and Registers	K
Single Exhaust Opening	0.3
Multiple Exhaust Openings	0.5

Select Ventilation Arrangement
Scroll to desired arrangement then Click on selection

Diffusers	K
Single Exhaust Opening	0.5
Multiple Exhaust Openings	0.7

Select Ventilation Arrangement
Scroll to desired arrangement then Click on selection

Perforated Ceiling	K
Single Exhaust Opening	0.8
Multiple Exhaust Openings	0.9

Select Ventilation Arrangement
Scroll to desired arrangement then Click on selection

User Specified Value	K
Single Exhaust Opening	Enter Value
Multiple Exhaust Openings	Enter Value

Select Ventilation Arrangement
Enter Value
Scroll to desired arrangement then Click on selection

METHOD OF NFPA 69, STANDARD ON EXPLOSION PREVENTION SYSTEMS

Reference: NFPA 69, "Standard on Explosion Prevention Systems, 1997 Edition, Appendix D.

Estimating Number of Theoretical Air Changes

ln [1 - (CQ / G)] = - K N

Where
- C = combustible gas concentration
- Q = volume of air in enclosure (ft^3/min)
- G = combustible gas leakage rate (ft^3/min)
- K = mixing efficiency factor (constant)
- N = number of theoretical air changes

Q = volume of air in enclosure

Q = 85.00 ft^3/min

G = combustible gas leakage rate

G = 15 (ft^3/min)

N = number of theoretical air changes

ln [1 - (CQ / G)] = - K N

or

N = - [ln(1 - (CQ/G))]/ K

N = 0.40

Estimating Combustible Gas Concentration Buildup Time

t = (V/ leakage rate) * N

Where
- t = buildup time (min)
- V = compartment volume (ft^3)
- leakage rate (ft^3/min)
- N = number of theoretical air changes

Volume of Compartment

$V = w_c \times l_c \times h_c$

Where
- V = compartment volume (ft^3)
- w_c = compartment Width (ft)
- l_c = compartment Length (ft)
- h_c = compartment Height (ft)

V = 5220.00 ft^3

Combustible Gas Concentration Buildup Time

t = (V/ leakage rate) * N

t = 20.93 minute **Answer**

NOTE

The above calculations are based on method presented in the NFPA 69, "Standard on Explosion Prevention Systems, 1997 Edition.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 17. CALCULATING THE FIRE RESISTANCE OF STRUCTURAL STEEL MEMBERS

17.1 Objectives

This chapter has the following objectives:

- Describe the testing procedures for fire resistance protection of structural steel members.
- Describe the failure criteria for structural steel members.
- Explain how to calculate the fire resistance (failure time) of protected and unprotected structural steel members.

17.2 Introduction

The fire resistance of structures is important in protecting life and property against the hazards of fires. Building codes regulate the fire resistance of structures in a number of ways, including requirements for fire resistance classifications based on such factors as building size, location, and occupancy. In the United States, fire resistance classifications (fire ratings) of floors, roofs, beams, partitions, walls, and columns are based on the results of the "Standard Test Method for Fire Tests of Building Construction and Materials" as defined in ASTM E119. This standard specifies that test specimens must be "truly representative of the design, material, and workmanship for which classification is desired." Testing laboratories throughout North America use gas burners to heat the furnace in such a manner that the temperature inside the furnace follows the time-temperature curve illustrated in Figure 17-1. Table 17-1 identifies the points on this curve that determine its characteristics.

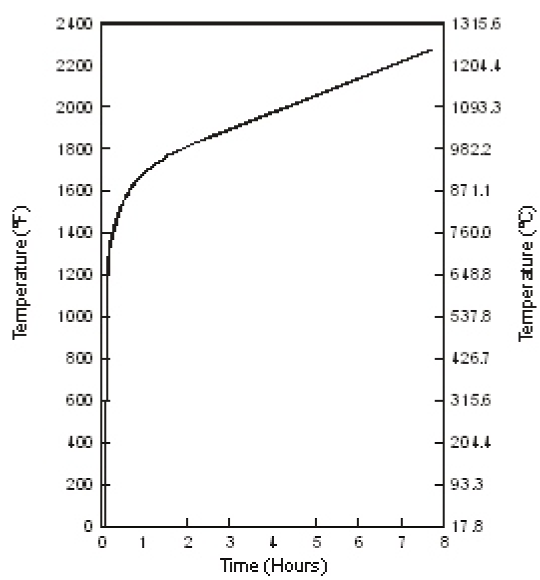


Figure 17-1 Standard Time-Temperature Curve (ASTM E-119)

Table 17-1. Standard Time-Temperature Curve Points

Time	**Temperature °C (°F)**
5 min	38 (100)
10 min	704 (1,300)
30 min	843 (1,550)
1 hr	927 (1,700)
2 hr	1,010 (1,850)
3 hr	1,052 (1,925)
4 hr	1,093 (2,000)
8 hr	1,260 (2,300)

The floors, roofs, beams, partitions, walls, and columns being tested must remain structurally intact and limit heat transmission to the unexposed surfaces. Moreover, for fire barriers such as walls the average temperature increase on the unexposed surfaces cannot exceed 121 °C (250 °F) and cotton waste on the unexposed surface cannot be ignited. Furnace temperature readings are taken as an average of at least eight thermocouples at intervals not exceeding 1 minute during the test period.

A hose stream test is also required for walls and partitions with a rating of at least 1-hour. This test can be conducted immediately after the fire exposure test or, alternatively, it can be conducted on a duplicate sample after exposure to fire for half of the rating period, but not more than 1 hour. If openings develop that permit a projection of water beyond the unexposed surface, the test is considered a failure.

Load-bearing walls or partitions support a portion of the vertical (gravity) loads from a floor or roof. During fire test, such assemblies are not restrained on vertical edges and are loaded to the maximum design load for the test duration. Nonbearing walls or partitions are restrained on all four edges.

If structural steel members supporting floors or roofs are spaced more than 4 feet apart, the maximum temperature at any location cannot exceed 704 °C (1,300 °F) and average temperature cannot exceed 593 °C (1,100 °F) for the following scenarios:

(1) A restrained assembly with up to a 1-hour classification for the full period. For ratings greater than 1 hour, the temperature limitation applies for half the hourly rating, but not less than 1 hour.

(2) An unrestrained assembly cannot exceed the temperature criteria shown above for the full classification or rating period.

If steel structural members are 4 feet or less on center, the average temperature cannot exceed 593 °C (1,100 °F) for the following scenarios:

(1) A restrained assembly with up to a 1-hour classification for the full period. For ratings greater than 1 hour, the temperature limitation applies for half the hourly rating, but not less than 1 hour.

(2) An unrestrained assembly cannot exceed the temperature criteria shown above for the full classification period.

For steel floor or roof units with spans longer than those tested, the average temperature cannot exceed 593 °C (1,100 °F) during the classification period. Floors and roofs are loaded to the maximum design conditions for the classification period.

Columns are loaded to the full design stress and exposed on all four sides to the standard time-temperature curve. The columns must sustain the structural design load for the test period. Where column protections are not required to carry any of the column load (e.g., the fire-resistive covering on a steel column), an alternative column test method uses unloaded columns with the following pass-fail criteria:

(1) The average temperature increase cannot exceed 538 °C (1,000 °F).

(2) The maximum temperature increase of any thermocouple is 649 °C (1,200 °F).

Individual ratings for loaded beams can be established if the beams are tested as part of a floor assembly; however, the beams must sustain the applied load for the full classification period. The listing is applicable to beams with a weight-to-heated perimeter (W/D) ratio greater than or equal to that of the beam tested. This W/D ratio is the factor that allows the interpolation of coating thicknesses, where W is the weight (lb/ft of length) and D is the heated perimeter (inches) of the structural member.

17.3 Fire Resistance of Buildings

Buildings consist of various structural elements that have unique fire resistance ratings and belong to various combustibility groups. The ability of a building to resist collapse during a fire, is called the fire resistance rating. It is characterized by the fire resistance of structural elements such as floor, roof, beams, partitions, fire walls or barriers, bearing walls, and columns. Figure 17-2 illustrates typical methods of protecting structural steel elements from fire. Light protection, using low-density material applied either to the profile of a section or in a box form is the most popular from an economic point of view. Massive protection, particularly concrete encasement, is used in special cases. External protections, referred to as complex protection, include such examples as box protection H-columns with core filling or very thick counter protection. Liquid filling is a special protection method, in which fire resistance is achieved by filling hollow steel members with water. This method is a less common but, an effective way of preventing rapid heating of hollow steel sections. However, a plumbing system is necessary to ensure that the water can flow by convection from member to member and to avoid excessive pressure when the water is heated.

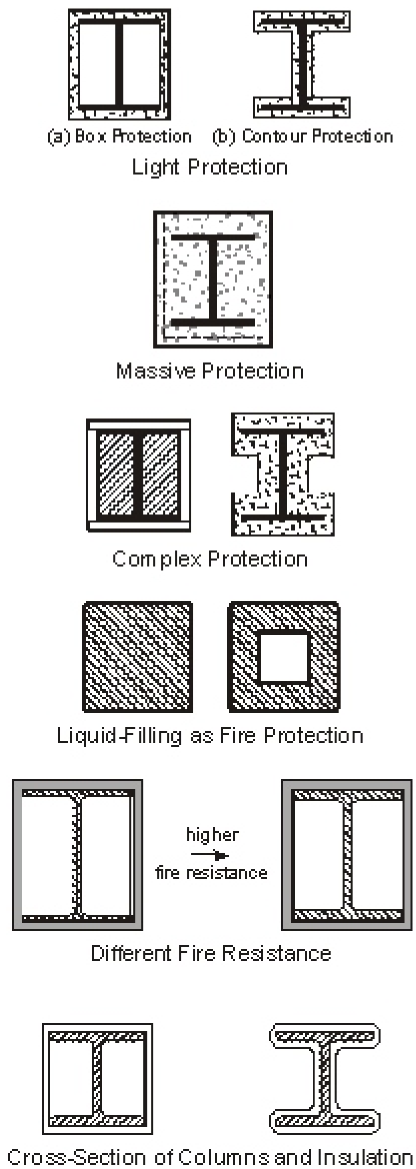


Figure 17-2 Typical Methods of Protecting Various Structural Steel Elements from Fire

It is important to distinguish between the actual and required fire resistance ratings of a building. The actual rating of a building is determined by the minimum actual fire resistance rating and combustibility group of one of the building's structural elements. The required fire resistance rating of a building is standardized and understood to be the minimum rating that the building has to satisfy given safety requirements. This rating accounts for fire hazards involved in the production processes within the building, the purpose for which the building is intended, the area, the number of stories, and the presence of automatic fire detection and extinguishing systems.

17.4 Fire Resistance of Structural Members

The term fire resistance is used to denote the ability of a building component to resist the thermal insult of a standard rest fire. This rating is usually given in units of time(e.g., 1 hour, 3 hours, etc.). The retention load-bearing capacities by structural members during a fire is very important. Buildings collapse when load-bearing members lose their load-bearing capacity.

The fire resistance of structural members is characterized by their fire resistance ratings, which are defined as the time elapsed from the start of the fire until the time the structure loses its load-bearing or protective capacity. The failure of structural members begins when they are heated to critical temperatures. The fire resistance ratings of structural members are determined either experimentally or by calculations. Experimental methods for determining the fire resistance of structural members have been standardized (e.g., ASTM E119).

17.4.1 Fire Resistance and Temperature Limits of Steel Elements

Steel is a non-combustible material, however, heat effects the material properties and strength of structural steel. For structural elements, the only criterion to be considered is the point where the thermal insult from the fire has weakened the member enough to allow structural collapse of the element.

The fire resistance (or fire endurance) of steel elements varies greatly. The temperature limits for structural steel members are based on the criteria contained in ASTM E119. The maximum single point temperature in a steel beam, column, or girder is 649 °C (1,300 °F) and the allowable average temperature in these members is 530 °C (1,000 °F). During the testing, failure is assumed to occur if either the maximum single point temperature or average temperature is exceeded.

17.4.2 Fire Resistance and Temperature Limits of Reinforced Concrete Elements

The fire resistance or fire endurance of reinforced concrete floors, roofs, and walls is often governed by the criteria for the temperature increase of the unexposed surface, rather than by structural considerations. The ASTM E119 criteria for the temperature rise of the unexposed surface, referred to as heat transmission requirements, limit the increase to an average of 121 °C (250 °F) or a maximum at any one point of 163 °C (325 °F). The purpose of these criteria is to guard against ignition of combustibles on the non-fire side that may be in contact with the fire barrier.

A classical method for estimating the maximum surface temperature reached by reinforced concrete elements is based on of the permanent color changes observed in concrete containing aggregates of siliceous or limestone rock after exposure to high temperatures. Such color changes depend upon the maximum temperature. The surface takes on a pink or red hue when exposed to temperatures of 300–600 °C (572–1,112 °F); dark grey, when exposed temperatures of 600–900 °C (1,112–1,652 °F); brown, when the maximum temperature reached 900–1,200 °C (1,652–2,192 °F); or yellow if the temperature exceeds 1,200 °C (2,192 °F) (Neville, 1975).

Table 17-2 summarizes the ASTM E119 temperature endpoint criteria for structural members. The endpoint temperatures are selected according to conservative estimates of the maximum allowable reduction in load-bearing capacity of the structural member, based on an average reduction in strength attributable to elevated temperatures.

Table 17-2. Temperature Endpoint Criteria for Structural Members (ASTM E119)

Structural Member	Location	Maximum Temperature °C (°F)
Walls/Partitions (bearing and non-bearings)	Unexposed side	139 (250)
Steel Columns	Average	530 (1,000)
	Single point	649 (1,200)
Floor/Roof Assemblies and Loaded Beams	Unexposed side	139 (250)
	Steel beam (average)	593 (1,100)
	Steel beam (single point)	704 (1,300)
	Pre-stressing steel	426 (800)
	Reinforced steel	593 (1,100)
	Open-web steel joist	593 (1,100)
Steel Beams/Girders (not loaded)	Average	530 (1,000)
	Single point	649 (1,200)

17.5 Failure Criteria for Structural Members

Structural members that are exposed to fire will ultimately fail if the fire is of sufficient duration and intensity. Failure can occur when the member collapses because it can no longer support the design load, or when the deflection is so severe that the member can no longer function in the capacity for it was intended. The failure results from major changes in the mechanical properties of steel, concrete, and other structural materials as they heat up. The ability of a building to remain stable during a fire is equated to the temperature increase in the exposed structural elements. This is based on the fact that the mechanical properties of the structural elements deteriorate as the temperature of the structural materials increases to some critical level. The changes in material properties that are most significant to the performance of structural steel members include the yield strength, modulus of elasticity, and coefficient of thermal expansion. The critical level is generally defined as the temperature at which the yield strength of the material is reduced to the design strength and, therefore, the factor of safety approaches unity.

17.6 Fire Walls and Fire Barrier Walls

NFPA 221, "Standard for Fire Walls and Fire Barrier Walls," contains design and construction requirements for fire walls and fire barriers. The basic difference between the two is that fire walls must remain stable and uncompromised throughout an uncontrolled fire (with sprinklers lacking or assumed to be ineffective), while a fire barrier is intended to help prevent the passage of fire *in conjunction with* other protective measures (such as sprinkler protection).

Fire walls and fire barriers are rated for the number of hours of fire exposure that they can withstand. Table 17-3 summarizes some rules of thumb to estimate the fire resistance ratings for walls based on some common construction materials.

Table 17-3. Typical Fire Resistance of Walls

Material	Thickness (inches) and Construction Details	Fire Resistance (Hours)
Brick	12, all materials	10
	8, sand and lime	7
	8, clay and shale	5
	8, concrete	6
	4, clay and shale	1¼
	4, concrete, sand, and lime	1½
Hollow partition tile	12, two 6-in. tiles	4
	12, unknown number of cells	3
	8, all tile arrangements	2
Concrete block	16 nominal, 15⅝ actual	4
	12 nominal. 11⅝ actual	3
	8 nominal, 7⅝ actual	1¾

A fire wall is defined as a wall that separates buildings or subdivides buildings and is intended to prevent the spread of fire, by providing fire resistance and structural stability. A fire barrier is a wall that extends to the roof or floor deck above and is intended to restrict the spread of fire by providing fire resistance.

In addition to proper structural design, other design considerations are required to maintain the integrity of the subdividing fire wall or fire barriers, as follows:

- routing of pipes, conduits, and cables to floor level to help prevent the fire wall from being damaged by collapse on either side
- fire-resistant penetration seals at pipes, conduits, cable trays, and HVAC penetrations
- fire doors for personnel or vehicle openings
- fire resistant exterior wing walls at the ends of the fire walls to prevent fire from spreading around its ends
- provision of a parapet, which consists of the fire wall penetrating the roof deck and extending above it

Some fire walls are designed to remain stable after the collapse of a building structure on either side in the event of an uncontrolled fire.

Fire walls must be designed for a minimum uniform lateral load of 5 pounds per square foot (psf) from either direction (applied perpendicular to the face of the wall). Where seismic loading governs, the design load may be considerably higher.

17.7 Fire Resistance Coatings for Structural Steel

Unprotected structural steel loses its strength at high temperatures and, therefore, must be protected from exposure to the heat generated by building fires. This protection, often referred to by the misnomer "fireproofing," insulates the steel from heat. As previously noted, the most common methods of insulating steel are encasement of the member, application of a surface treatment, or installation of a suspended ceiling as part of a floor-ceiling assembly capable of providing fire resistance. Additional methods include sheet steel membrane shields around members and box columns filled with liquid.

Encasement of structural steel members has been a common and satisfactory method of insulating steel to increase its fire resistance. In floor systems composed of reinforced concrete slabs supported by structural steel beams, the encasement can be placed within the floor. Figure 17-3 illustrates this old encasement technique. The major disadvantages of this procedure are the increased weight and cost, which are attributable to increased framework, concrete, and structural support. To reduce the weight and cost of encasement, surface treatment utilizing lath and plaster or gypsum board, or any of a variety of spray-on coatings have been developed, as shown in Figure 17-4. Sprayed-on mineral fiber coatings are widely used to protect structural steel. If applied correctly, such coatings provide excellent protection; however, the coating can easily be knocked off the member during construction or plant modification. Consequently, sprayed-on mineral coatings are suspect with regard to their effectiveness over long-term use.

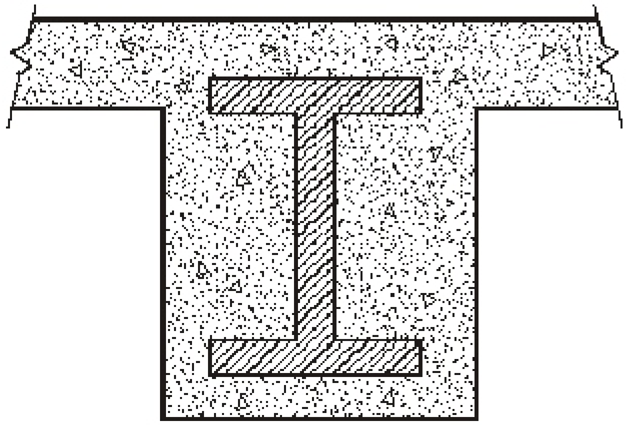
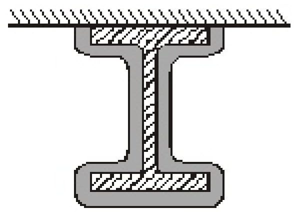
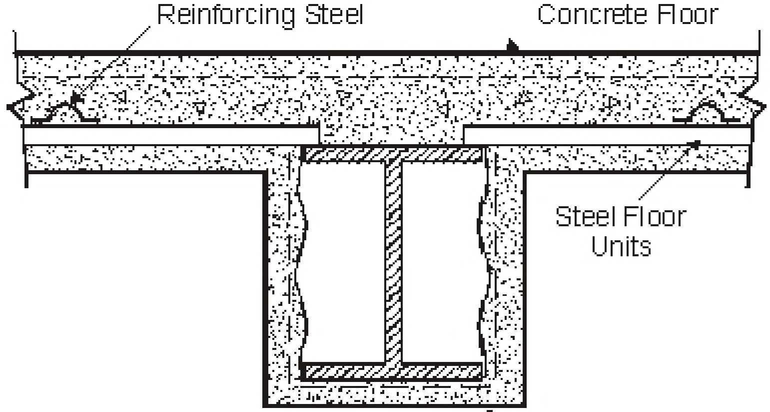


Figure 17-3 Encasement of a Steel Beam by Monolithic Casting of Concrete Around the Beam



Spray-on Fire Proofing



Furred Steel Beams with Non-combustible Protection

Figure 17-4 Spray-On Mineral Fiber and Noncombustible Protective Coatings

Cementitious materials also have been used as sprayed-on coatings, despite the fact that they can spall during a fire and have experienced adhesion problems in actual use. Thus, effective application, complete coverage, and long-term maintenance are attributes that must be evaluated in considering the use of sprayed-on coatings.

The latest advancements have been made with intumescent paints and coatings. These coatings swell to many times their installed thickness when heated to form an insulation barrier which increases the fire endurance of the structural steel. They are primarily used for non-exposed steel subject to elevated temperatures, because prolonged exposure to flame can destroy the char coating.

17.8 Calculating Fire Resistance or Endurance

The traditional approach to structural fire protection is to specify the fire resistance or fire endurance ratings for construction classifications identified in the building codes. The individual fire resistance or endurance ratings are established by subjecting various structural members and assemblies to the standard fire test (ASTM E119 or NFPA 251, “Standard Methods of Tests of Fire Endurance of Building Construction and Materials”).[1]

During the past three decades, a substantial amount of research has conducted to develop and validate computer models of the mechanical and thermal properties of structural members, as well as compartment fire behavior, heat transfer, and structural performance at elevated temperatures. These studies have resulted in more realistic predictions of structural behavior in fires than was possible with the traditional code and standard fire test procedures of the past.

As a result, several empirically derived correlations are available to calculate the fire resistance of steel columns, beams, and trusses. The correlations are based on curve-fitting techniques using data gathered by performing the standard test numerous times on variations of a standard assembly. In some cases, a best-fit line has been drawn for the data point; in other cases, lines have been drawn conservatively to estimate the fire resistance by connecting the two lowest points. Numerical methods are also available to estimate the temperature increase in steel structural elements. The equations in these methods are derived from simplified heat transfer approaches.

Compared to the traditional test approaches, modern calculation methods offer the advantages of economy and better predictability. These calculation methods calculate either (1) the fire resistance or endurance that would have been obtained in the standard fire test or (2) structural or thermal performance in an actual building fire compartment.

17.8.1 Equivalent Fire Resistance of Structural Steel

Fire testing of the structural steel has been ongoing for many years and has yielded substantial data and experience. The procedures described in the following subsections reflect the methods for calculating equivalent fire resistance. It should be noted that many of these calculation methods are obtained from test data. Consequently, one should be cautious when applying these methods to materials that have not been used in the tests that form the basis for the calculation methods. For example, the data for structural steel are based on testing of A7 and A36 structural steel, which have different mechanical properties at both normal and elevated temperatures than the high-strength steels that have become popular in recent years. Consequently, when we use the term structural steel for fire resistance calculations in this section, we mean A7 and A36 steels.

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[1] ASTM E119 and NFPA 251 utilize virtually identical testing methods.

17.8.2 Steel Column (Unprotected)

In general, unprotected steel columns of small cross-sectional area have a fire resistance of not more than 10–20 minutes (ASCE, 1992). However, heavier columns are capable of much better fire performance. Figure 17-2 illustrates typical sections of unprotected structural steel columns. Based on theoretical and experimental studies, the following formulae have been developed for calculating the fire resistance of unprotected steel columns (Milke, 1995):

$$R = 10.3\left(\frac{W}{D}\right)^{0.7} \text{ for } \frac{W}{D} < 10 \qquad (17\text{-}1)$$

and

$$R = 8.3\left(\frac{W}{D}\right)^{0.8} \text{ for } \frac{W}{D} \geq 10 \qquad (17\text{-}2)$$

Where:

R = fire resistance time (minutes)
W = weight of steel column per linear foot (lb/ft)
D = heated perimeter (in) as shown in Figure 17-5

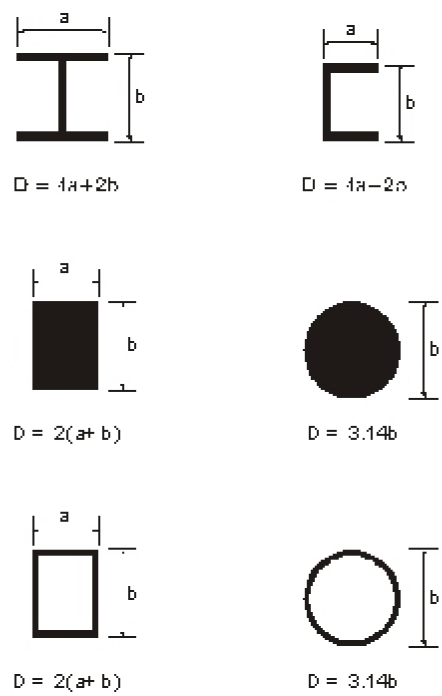


Figure 17-5 Sections of Unprotected Steel Columns

The fire resistance or endurance of structural steel columns can be improved by insulating the members. The next few subsections discuss the fire resistance of steel members protected by various insulation materials.

17.8.3 Steel Column (Protected with Gypsum Wallboard)

A common protective method is to box in steel columns using gypsum wallboard. Based on the accumulated fire-test results, the following empirical equation has been developed to determine resistance or endurance of steel columns protected by gypsum wallboard (Milke, 1995):

$$R = 130\left(\frac{h}{2}\frac{W'}{D}\right)^{0.75} \qquad (17\text{-}3)$$

Where:

R = fire resistance time (minutes)
h = thickness of protection (in)
W' = weight of steel column and gypsum wallboard protection per foot of length (lb/ft)
D = heated perimeter (in) as shown in Figure 17-6

The following formula can be used to derive the total weight of both the column and its gypsum wallboard protection (W'):

$$W' = W + \frac{50hD}{144} \qquad (17\text{-}4)$$

Where:

W' = weight of steel column and gypsum wallboard protection per foot of length (lb/ft)
W = weight of steel column per linear foot (lb/ft)
h = thickness of protection (in).
D = heated perimeter (in) as shown in Figure 17-6

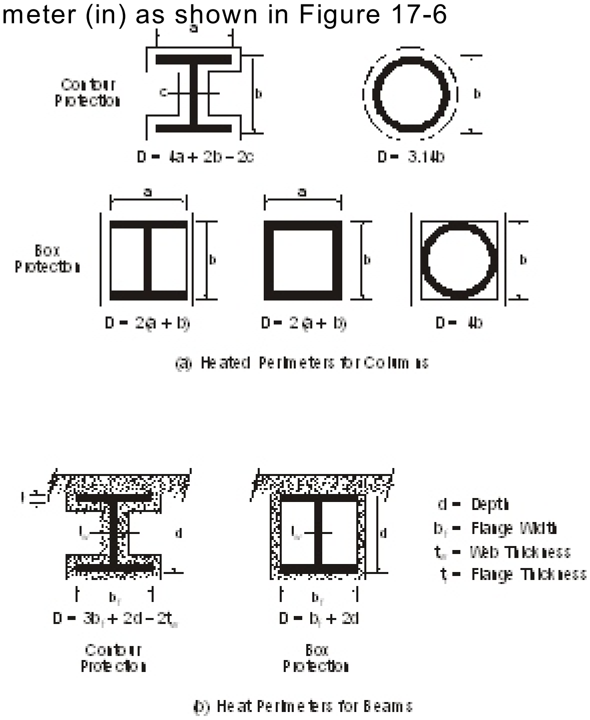


Figure 17-6 Heat Perimeters for Common Column and Beam Shapes

To improve the structural integrity during exposure to fire, gypsum wallboard can be reinforced with inorganic fiber. Such reinforced gypsum wall board is usually classified by the accredited testing laboratories, such as Underwriters Laboratories (UL) in North America.

17.8.4 Steel Column (with Low-Density Protection)

Based on experimental and theoretical studies, the following expression has been derived for the fire resistance of steel sections protected by light (low-density) insulating materials (Milke, 1995):

$$R = \left(C_1 \frac{W}{D} + C_2 \right) h \qquad (17\text{-}5)$$

Where:

R = fire resistance (minutes)
C_1, C_2 = material constants that are known for a specific protecting material
W = weight of steel column per linear foot (lb/ft)
D = heated perimeter (in) as shown in Figure 17-6
h = thickness of protection (in)

As noted above, the material constants $C_1$and C_2 are specific to a given protection material. For cases in which the values of $C_1$and C_2 are not known, conservative assessment of the fire resistance of protected steel columns can be conservatively assessed using the following equations (ASCE, 1992):

For protection material with a density ( ) of 20 < $\leq$ 50 lb/ft^3

$$R = \left(1200 \frac{W}{D\rho} + 30 \right) h \qquad (17\text{-}6)$$

Equation 17-6 applies to protections consisting of chemically stable materials, such as vermiculite, perlite, and sprayed material fiber with various binders, and dense mineral wool.

$$R = \left(1200 \frac{W}{D\rho} + 72 \right) h \qquad (17\text{-}7)$$

Equation 17-7 applies to protections consisting of cement pastes or gypsum, such as cementitious mixtures and plasters.

Where:

R = fire resistance (minutes)
W = weight of steel section per linear foot (lb/ft)
D = heated perimeter (in) shown in Figure 17-6
 = density of protected material (lb/ft^3)
h = thickness of protection (in)

For protection material with a density ( ) of 10 ≤ ≤ 20 lb/ft^3

$$R = \left(45\frac{W}{D} + 30\right)h \qquad (17\text{-}8)$$

Equation 17-8 applies to small round and square columns (less than 6 in.) and thick protection (h ≥ 1.5 in.).

$$R = \left(60\frac{W}{D} + 30\right)h \qquad (17\text{-}9)$$

Equation 17-9 applies to any shape, sizes, and thickness of protection.

Where:

R = fire resistance (minutes)
W = weight of steel section per linear foot (lb/ft)
D = heated perimeter (in) as shown in Figure 17-6
 = density of protected material (lb/ft^3)
h = thickness of protection (in)

17.8.5 Steel Column (Protected with Spray-On Materials)

The American Iron and Steel Institute (AISI, 1980) has developed the following formula for two types of spray-on low-density fire protection known as cementitious and mineral fiber insulation:

Cementitious insulation

$$R = \left(69\frac{W}{D} + 31\right)h \qquad (17\text{-}10)$$

Mineral fiber insulation

$$R = \left(63\frac{W}{D} + 42\right)h \qquad (17\text{-}11)$$

Where:

R = fire resistance (minutes)
W = weight of steel column per linear foot (lb/ft)
D = heated perimeter (in) as shown in Figure 17-6
h = thickness of protection (in)

17.8.6 Steel Column (Protected by Concrete)

Concrete encasement is another means of protecting for steel columns. The following empirical formulae have been developed to predict the fire resistance of concrete encased steel columns:

Normal weight concrete protection of uniform thickness on all sides and square shape

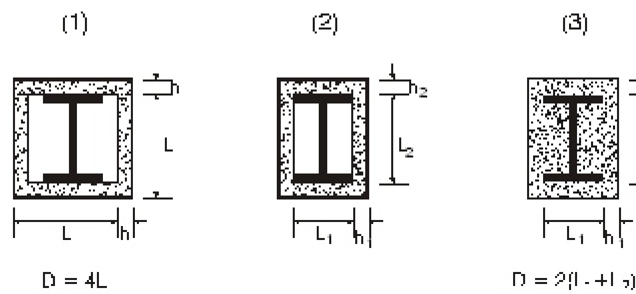
$$R = 11\left(\frac{W}{D}\right)^{0.7} + 19h^{1.6}\left[1 + 94\left(\frac{H}{\rho_c h(L+h)}\right)^{0.8}\right] \qquad (17\text{-}12)$$

Lightweight concrete protection

$$R = 11\left(\frac{W}{D}\right)^{0.7} + 23h^{1.6}\left[1 + 94\left(\frac{H}{\rho_c h(L+h)}\right)^{0.8}\right] \qquad (17\text{-}13)$$

Where:

R = fire resistance time at equilibrium moisture condition, here assumed to be 4-percent of the concrete by volume (minutes)
W = weight of steel column per linear foot (lb/ft)
D = developed heated perimeter of steel columns (in) shown in Figure 17-7
h = thickness of concrete protection (in)
H = thermal capacity of steel section at ambient temperature (0.11W Btu/ft-°F)
$_c$ = density of concrete at ambient temperature (lb/ft^3)
L = interior dimension of one side of square concrete box protection (in) (see note if the box protection is not square).



(1) Square shape protection with a uniform thickness of concrete cover on all sides
(2) Rectangular shape with varying thickness of concrete cover
(3) Encasement having all re-entrant spaces filled with concrete

Figure 17-7 Concrete-Protected Structural Steel Columns

Notes:

(1) If the concrete box protection is not square, or if the concrete cover thickness is not constant, h and L are taken as average values [i.e., $h = ½ (h_1 + h_2)$ and $L = ½ (L_1 + L_2)$.]

(2) If the steel column is completely encased in concrete, with all re-entrant spaces filled, the thermal capacity of the concrete within the re-entrant space may be added to the thermal capacity of the steel column, thereby increasing the value of H as follows:

$$H = 0.11W + \frac{\rho_c}{720}\left(L_1 L_2 - A_s\right) \qquad (17\text{-}14)$$

Where:

H = thermal capacity of steel section at ambient temperature (0.11W Btu/ft-°F)
W = weight of steel column per linear foot (lb/ft)
ρ_c = density of concrete at ambient temperature (lb/ft^3)
L_1 = steel column flange width (in)
L_2 = depth of steel column (in)
A_s = cross-sectional areas of steel column (in^2)

17.8.7 Steel Beams

When a beam is fire tested alone or as a part of a floor or roof assembly, it expands as it is heated. Floor test furnaces encase the specimen in a rigid restraining frame. If the beam is built tightly into the frame, the frame resists its expansion and moments are generated in the beam. The critical temperature of beams is much better understood and has limits of 593 °C (1,100 °F) when the beam is tested as part of an assembly, and 538 °C (1,000 °F) when the beam is tested alone.

W/D concepts can also be applied to assess protection requirements for steel beams in both restrained and unrestrained assemblies. To determine the fire resistance of steel beams protected by low-density protection, we can use the same formulae as for steel columns (Equations 17-5 through 17-11), as shown in Figure 17-6.

In the case of beams, only three sides of the beam are exposed to fire Figure 17-6b. The top of the beam is assumed to be a floor or roof slab, made of a perfectly insulating material. Thus, there is no heat exchange between the floor or roof slab and the steel. Because only three sides of the beam are exposed to heat, the values of the heated perimeter (D) of beams in these formulas are smaller than those of the corresponding column. As a result, the fire resistance of a beam, (i.e., the time to reach a specific failure temperature in the steel) is longer than that for a column. In addition, because the floor or roof on the top of the beam normally absorbs heat transmitted through the beam, which is not taken into account in the formulae the fire resistance calculated using these formulae, are more conservative for beams than for columns.

17.8.7.1 Beam Substitution Correlation for Structural Steel Beams Protected by Spray-On Materials

For beams protected by spray-on protections, the International Committee for the Study and Development of Tubular Structures (ICSDTS) (1976) has developed a scaling formula that enables substitution of one beam for another by varying the thickness of the protection.

Provided the deck is the same and D is calculated only for three-sided exposure, the following beam substitution equation has achieved code acceptance (Milke, 1995, and UL, 1995):

$$h_1 = \left(\frac{\frac{W_2}{D_2} + 0.6}{\frac{W_1}{D_1} + 0.6} \right) h_2 \qquad (17\text{-}15)$$

Where:

h = thickness of spray-applied protection (in)
W = weight of the structural beam per linear foot (lb/ft); see note
D = heated perimeter of the beam (in) as shown in Figure 17-6; see note

Note: h_1, W_1, and D_1 refer to the substitute (unrated) beam and required thickness of fire protection material.

h_2, W_2, and D_2 refer to the beam and fire protection thickness in the approved assembly (rated beam).

Use of above the equation is subject to the following limitations:

- The unrestrained beam in the tested design has a rating of not less than 1-hour.
- The equation is limited to beams with a weight-to-heated-perimeter ratio (W/D) of 0.37 or greater.
- The thickness of the spray-on protection (h_1) cannot be less than 0.95 cm (⅜ inch).

The above equation pertains only to the determination of the protection thickness for a beam in a floor or roof assembly.

17.8.7.2 Column Substitution Correlation for Structural Steel Columns Protected by Spray-On Materials

A scaling substitution correlation has also been developed to calculate the required thickness of spray-on protection for columns (UL, 1995) as follows:

$$h_2 = 1.25h_1\left(\frac{W_1}{D_1}\right)\left(\frac{D_2}{W_2}\right) \qquad (17\text{-}16)$$

Where:

h_1 = thickness of spray-on protection on the approved assembly (rated column), (in)
h_2 = required thickness of spray-on protection on substitute column (in) (smaller wide flange section)
W_1 = weight of the structural column per linear foot for the approved assembly (rated column (lb/ft)
W_2 = weight of the structural column per linear foot for the smaller wide flange section (lb/ft)
D_1 = heated perimeter of the column (in), for the approved assembly (rated column) as shown in Figure 17-6
D_2 = heated perimeter of the column (in) for the smaller wide flange section as shown in Figure 17-6

Use of the above column substitution correlation is subject to following limitations:

- The unrestrained beam in the tested design has a rating of not less than 1-hour.
- The equation is limited to beams with a weight-to-heated-perimeter ratio (W/D) of 0.95 cm (⅜ inch) or greater.
- The thickness of the spray-on protection (h_1) cannot be less than 0.95 cm (⅜ inch).

17.8.8 Numerical Method to Estimate the Temperature Increase in Structural Steel Elements

For structural steel elements, there is a critical temperature at which the steel loses so much strength that it can no longer support its design load. In such cases, calculations of the fire resistance of the steel members can be reduced to calculating the temperature of the steel. North American standards assume that the critical temperature condition is reached when the average temperature in a steel section reaches 538 °C (1,000 °F).

The simple numerical method is based on the principle that the heat entering the steel over the exposed surface area in a small time step, t (sec), is equal to the heat required to raise the temperature of the steel by T_s (°C or °F), assuming that the steel section is a lumped mass at uniform temperature. This numerical method can be further simplified by considering the steel to be a heat sink, with negligible resistance to heat flow; thus, any heat supplied to the steel section is considered to be instantly distributed to give a uniform steel temperature.

17.8.8.1 Unprotected Structural Steel Sections

The following equation calculates the temperature development of an unprotected steel member, using a quasi-stationary approach, iterated for successive time steps of t (sec):

$$\Delta T_s = \frac{F}{V}\frac{1}{\rho_s c_s}\left[h_c\left(T_f - T_s\right) + \sigma\varepsilon\left(T_f^4 - T_s^4\right)\right]\Delta t \qquad (17\text{-}17)$$

Where: T_s = temperature in the steel member (°F)
F/V = ratio of weight of steel section per linear foot and heated perimeter (m^{-1})
$_s$ = density of steel (kg/m^3)
c_s = specific heat of steel (J/kg-K)
h_c = convective heat transfer coefficient (W/m^2-/K)
= Stefan Boltzmann constant (kW/m^2-K^4)
= flame emissivity
c_s = specific heat of steel (Btu/lb-°F)
T_f = fire temperature (°F)
T_s = steel temperature (°F)
t = time step (sec)

Emissivities for various types of construction are given in Table 17-4 (Buchanan 2001).

Table 17-4. Resultant Emissivity for Different Types of Construction

Type of Construction	Resultant Emissivity
Column exposed to fire on all sides	0.7
Column outside facade	0.3
Floor girder with floor slab of concrete (only the underside of the bottom flange being directly exposed to fire)	0.5
Floor girder with floor slab on the top flange girder of I section for which the width-depth ratio is not less than 0.5	0.5
Girder of I section for which the width-depth ratio is less than 0.5	0.7
Box girder and lattice girder	0.7

The fire temperature (T_f) is evaluated at the midpoint of each time step. If the exposure under consideration is that associated with the ASTM E119 test, T_f at any time (t) is obtained from the following expression:

$$T_f = C_1 LOG(0.133t + 1) + T_a \qquad (17\text{-}18)$$

Where:

C_1 = 620 with a fire temperature T_f
T_a = ambient temperature (°F) (Milke, 1995)

The maximum time step (t) can be determined from the following relationship (Molhotra, 1982):

$$\Delta t > 15.9 \frac{W}{D} \text{ (English units)} \qquad (17\text{-}19)$$

Table 17-5 shows a spreadsheet for calculating steel temperature using this method (Buchanan, 2001). Kay et al., (1996) have shown that this type of calculation can give a good prediction of steel temperatures in standard fire resistance tests.

Table 17-5. Spreadsheet Calculation for the Temperature of Steel Sections (Buchanan, 2001)

Time	**Steel Temperature (T_s)**	**Fire Temperature (T_f)**	**Difference in Temperature**	**Change in Steel Temperature T_s)**
t_1 = t	Initial steel temperature (T_{s0})	Fire temperature halfway through time step (at t/2)	T_f - T_{s0}	Calculate from Equation (17-17) with values of T_f and T_{s0} from this row
$t_2 = t_1 +$ t	T_s from previous time step + T_s from previous row	Fire temperature halfway through time step (at $t_1 +$ t/2)	T_f - T_s	Calculate from Equation (17-17) with values of T_f and T_s from this row

17.8.8.2 Protected Structural Steel Sections

Protected steel members heat up more slowly than unprotected members because of the applied thermal insulation, which protects the steel from rapid absorption of heat. The calculation method for protected steel members is similar to that for unprotected steel members. However, the equation is slightly different and does not require a heat transfer coefficient because it is assumed that the external surface of the insulation is at the same temperature as the fire gases, while the internal surface of the insulation is at the same temperature as the steel.

The thermal capacity of the insulation material may be neglected if the following inequality is true:

$$c_s \frac{W}{D} > 2 c_i \rho_i h \qquad (17\text{-}20)$$

Where:

W/D = ratio of weight of steel section per linear foot and heated perimeter (lb/ft^2)
c_i = specific heat of insulation (Btu/lb-°F)
$_i$ = density of insulation (lb/ft^3)
h = thickness of insulation (in)

If the thermal capacity of the insulation layer is neglected, the temperature rise in the structural steel element can be calculated using the following equation:

$$\Delta T_s = k_i \left(\frac{(T_f - T_s)}{c_s h \frac{W}{D} + \frac{1}{2} c_i \rho_i h^2} \right) \Delta t \qquad (17\text{-}21)$$

Where:

T_s = temperature increase in steel (°F)
k_i = thermal conductivity of insulation material (Btu/ft-hr-°F)
$_i$ = density of insulation (lb/ft^3)
c_i = specific heat of insulation material (Btu/lb-°F)
c_s = specific heat of steel (Btu/lb-°F)
h = thickness of insulation (in)
W/D = ratio of weight of steel section per linear foot and heated perimeter (lb/ft^2)
T_f = fire temperature (°F)
T_s = steel temperature (°F)
t = time step (sec)

If the thermal capacity of the insulating material must be accounted for, as in the case of gypsum and concrete insulating materials, Equation 17-21 can be modified as follows:

$$\Delta T_s = \frac{k_i}{h}\left(\frac{T_f - T_s}{c_s \frac{W}{D} + \frac{1}{2} c_i \rho_i h}\right)\Delta t \qquad (17\text{-}22)$$

The fire temperature (T_f) is evaluated at the midpoint of each time step. If the exposure under consideration is that associated with the ASTM E119 test, T_f at any time (t) is obtained from the following expression:

$$T_f = C_1 LOG(0.133t + 1) + T_a \qquad (17\text{-}23)$$

Where:

C_1 = 620 with a fire temperature T_f
T_a = ambient temperature (°F) (Milke, 1995)

The maximum time step (t) can be determined from the following relationship (Molhotra, 1982):

$$\Delta t > 15.9 \frac{W}{D} \text{ (English units)} \qquad (17\text{-}24)$$

Table 17-6 summarizes the typical thermal properties of various insulation materials.

Table 17-6. Thermal Properties of Insulation Materials (Buchanan, 2001)

Insulation Material	**Density** $_i$ **(lb/ft^3)**	**Thermal Conductivity k_i (Btu/ft-hr-°F)**	**Specific Heat c_i (Btu/lb-°F)**
Sprays			
Sprayed mineral fiber	19	0.06936	0.2868
Perlite or vermiculite plaster	22	0.06936	0.2868
High-density perlite or vermiculite plaster	35	0.06936	0.2868
Boards			
Fiber-silicate or fiber-calcium silicate	38	0.0867	0.2868
Gypsum plaster	50	0.1156	0.4063
Compressed fiber board			
Mineral wool or fiber silicate	10	0.1156	0.2868

The spreadsheets for calculating steel temperature using this method are based on Table 15-5 (Buchanan, 2001).

17.9 Assumptions and Limitations

The methods discussed in this chapter are subject to several assumptions and limitations:

(1) The heat transfer analysis is one dimensional.
(2) Correlations are based on the analysis of data resulting from performing the standard test numerous times, using curve-fitting techniques to establish the various correlations.
(3) As the structural member heats up, its structural properties can change substantially.
(4) Equation-specific limitations apply (see the various equations throughout this chapter).

17.10 Required Input for Spreadsheet Calculations

The user must obtain the following information to using the spreadsheet:
(1) dimensions of the steel member in question
(2) thermal properties of the applied insulation

17.11 Cautions

(1) Use the appropriate spreadsheet:
(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,
or 17.4_FR_Beams_Columns_Quasi_Steady_State_Uninsulated.xls)
on the CD-ROM for calculating the fire resistance of structural steel members.
(2) Make sure you are on the correct page of the spreadsheet (for columns or beams).
(3) Make sure to enter all input parameters using the correct units.
(4) Equation (23) is only valid up to 1,000 °F (538 °C) where the carbon steel structural members begin to fail. Predicted temperatures above 1,000 °F (538 °C) are neither accurate nor valid.

17.12 Summary

The fire resistance/endurance of the beams, girders, and columns that comprise the structural frame of the walls, partitions, floor/ceiling assemblies, and roof/ceiling assemblies that serve as barriers to flame movement have been a historical basis for classifying buildings and rating frame and barrier capabilities.

The selection of building materials and the design details of construction have always played an important role in building fire safety. Two of the important structural fire considerations are the ability of the structural frame to avoid collapse and the ability of the barrier to prevent ignition and resulting flame spread into adjacent spaces.

Heat transfer analyses are applied to determine the time period required to heat structural members to a specified critical temperature. The required time period is then defined as the fire resistance/endurance time of the member.

The critical temperature of a structural member can be determined by referring to the temperature endpoint criteria cited in ASTM E119 or by a structural assessment, as discussed in this chapter.

17.13 References

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17.14 Problems

Example Problem 17.14-1

Problem Statement
Calculate the thickness of spray-on fire protection required to provide a 2-hour fire resistance for a W12 x 16 beam to be substituted for a W8 x 18 beam requiring 1.44 in. of protection for the same rating.

Solution

Purpose:

(1) Estimate the spray-on thickness required for the beam substitution.

Assumptions:

(1) The 1.44 in. of spray-on provides the W8 x 18 beam 2 hours of fire resistance.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 17.1_FR_Beams_Columns_Substitution_Correlation.xls
(click on Beam)

FDT^s Input Parameters:

-Known beam insulation thickness
-Select W8 x 18 for Rated Beam
-Select W12 x 16 for Substitute Beam

Results*

Substitute Beam Spray on Thickness	1.6 in

*see spreadsheet on next page

Spreadsheet Calculations
FDT[s]: 17.1_FR_Beams_Columns_Substitution_Correlation.xls (Beam)

CHAPTER 17. ESTIMATING THICKNESS OF FIRE PROTECTION SPRAY-APPLIED COATING FOR STRUCTURAL STEEL BEAMS (SUBSTITUTION CORRELATION)

Version 1805.0

For beams protected by spray-applied protections, following correlation enables substitution of one beam from another by varying the thickness of the fire protection insulation.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Beam Selected.
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

Rated Design Thickness of Beam Insulation (T_2)	1.44	in
<u>Known Insulation Rating</u>		
Weight of the Beam (W_2)	18	lb/ft
Heated Perimeter of Beam (D_2)	31.57	in
<u>Unknown Insulation Rating</u>		
Weight of the Beam (W_1)	16.00	lb/ft
Heated Perimeter of Beam (D_1)	35.51	in

SECTIONAL FACTORS FOR STEEL BEAMS

Select the Beam with <u>known</u> rating for insulation thickness

W8 x 18

Subscript 2
(Rated Beam)

Select the Beam with <u>unknown</u> rating for insulation thickness

W12 x 16

Subscript 1
(Substitute Beam)

Calculate

ESTIMATING THICKNESS OF FIRE PROTECTION INSULATION ON UNRATED BEAM

Reference: *UL Fire Resistance Directory, Volume 1, 1995, Page 10.*

$T_1 = ((W_2/D_2 + 0.6)\, T_2)/(W1/D_1 + 0.6)$

Where
- T_1 = calculated thickness of fire protection insulation on unrated beam (in)
- T_2 = design thickness of insulation on rated beam (in)
- W_1 = weight of beam with unknown insulation rating (lb/ft)
- W_2 = weight of design rated beam (lb/ft)
- D_1 = heated perimeter of unrated beam (in)
- D_2 = heated perimeter of the rated beam (in)

Required Equivalent Thickness of Fire Protection Insulation on Unrated Beam

$T_1 = ((W_2/D_2 + 0.6)\, T_2)/(W1/D1 + 0.6)$

T_1 =	1.60 in	Answer

Beams with a larger W/D ratio can always be substituted for the structural member listed with a specific fire resistive covering without changing the thickness of the covering.

NOTE

The above calculations are based on method developed in the UL Fire Resistance Directory, Volume 1, 1995. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Example Problem 17.14-2

Problem Statement

Use the quasi-steady-state heat transfer approach to determine the fire resistance of a W24 x 76 steel beam protected with 0.5 in. of spray-on mineral fiber material. Sprayed-on mineral fiber has the following thermal properties:

- Thermal Conductivity, k_i = 0.06936 Btu/ft-hr-°F
- Specific Heat, c_i = 0.2868 Btu/lb-°F
- Density, $_i$ =19.0 lb/ft^3

Solution

Purpose:

(1) Estimate the fire resistance of the beam.

Assumptions:

(1) The heat transfer is quasi-steady-state.

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 17.2_FR_Beams_Columns_Quasi_Steady_State_Spray_Insulated.xls (click on Beam)

FDT^s Input Parameters:

-Select W24 x 76 beam
-Enter 0.5 in spray-on thickness
-Select “Sprayed Mineral Fiber” from Insulation Type drop-down menu

Results*

Fire Resistance	42.5 min

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 17.2_FR_Beams_Columns_Quasi_Steady_State_Spray_Insulated.xls

CHAPTER 17. ESTIMATING FIRE RESISTANCE TIME OF STEEL BEAMS
PROTECTED BY FIRE PROTECTION INSULATION (QUASI-STEADY-STATE APPROACH)
Version 1805.0
The following calculations estimate the fire resistance time for structural steel beams protected by spray-applied fire protection insulating material.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Beam and Insulation Selected.
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

Ratio of Weight of Steel Section per Linear Foot and Heated Perimeter (W/D)		12.34	lb/ft^2	
Thickness of Spray-Applied Protection on Steel Beam (h)	h = 1/16 in	0.50	in	0.042 ft
Density of Spray-Applied Material (ρ)		19.00	lb/ft^3	
Thermal Conductivity of Spray-Applied Material (k)		0.06936	Btu/ft-hr-°F	1.92667E-05 Btu/ft-sec-°F
Specific Heat of Spray-Applied Material (c)		0.2868	Btu/lb-°F	
Ambient Air Temperature (T_a)		77	°F	
Specific Heat of Steel (c_s)		0.132	Btu/lb-°F	

Calculate

SECTIONAL FACTORS FOR STEEL BEAMS

Select Beam

24x76

Scroll to desired beam size then Click on selection

THERMAL PROPERTIES OF SPRAY-APPLIED INSULATION MATERIALS

Insulation Material Spray-Applied	Density ρ (lb/ft^3)	Thermal Conductivity k (Btu/ft-hr-°F)	Specific Heat c (Btu/lb-°F)
Sprayed mineral fiber	19	0.06936	0.2868
Perlite or vermiculite	22	0.06936	0.2868
High density perlite or vermiculite	35	0.06936	0.2868
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: Buchanan, A. H., Structural Design for Fire Safety, 2001, Page 179.

Select Insulation Type

Sprayed mineral fiber

Scroll to desired material then Click on selection

ESTIMATING FIRE RESISTANCE TIME USING QUASI-STEADY-STATE APPROACH

Reference: "Analytical Methods for Determining Fire Resistance of Steel Members,"
"SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 4-209.

c_s W/D > 2 $c_i \rho_i h$

Where
c_s = specific heat of steel (BTU/lb-°F)
W/D = ratio of weight of steel section per linear foot and heated perimeter (lb/ft^2)
ρ_i = density of spray-applied material (lb/ft^3)
c_i = specific heat of spray-applied material (BTU/lb-°F)
h = thickness of spray-applied protection on steel beam (in)

1.63 > 0

Temperature Rise in Steel Beam

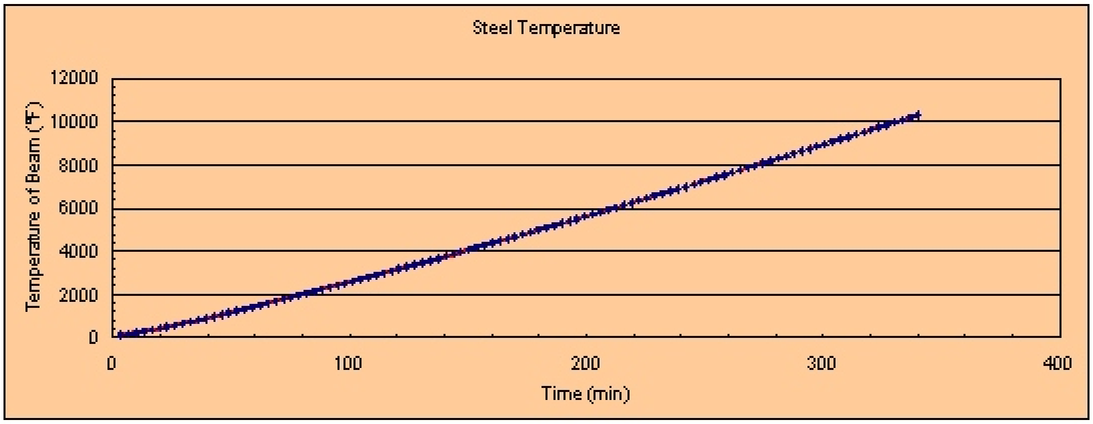
$\Delta T_s = (k_i/(c_s\, h\, W/D + 1/2 c_i \rho_i h^2)) (T_f - T_s) \Delta t$

Where
ΔT_s = temperature rise in steel (°F)
k_i = thermal conductivity of spray-applied material (Btu/ft-sec-°F)
ρ_i = density of spray-applied material (lb/ft^3)
c_i = specific heat of spray-applied material (Btu/lb-°F)
c_s = specific heat of steel (Btu/lb-°F)
h = thickness of spray-applied protection on steel beam (in)
W/D = ratio of weight of steel section per linear foot and heated perimeter (lb/ft^2)
T_f = fire exposure temperature (°F)
T_s = steel temperature (°F)
Δt = time step (sec)

Results

Time (min)	Time (sec)	ΔT_s (°F)	T_s (°F)	
3.3	196	40	117	
6.5	392	53	170	
9.8	588	60	230	
13.1	785	65	294	
16.3	981	68	362	
19.6	1177	71	433	
22.9	1373	73	506	
26.2	1569	75	581	
29.4	1765	77	658	
32.7	1961	78	737	
36.0	2158	80	817	
39.2	2354	81	898	
42.5	2550	82	980	
45.8	2746	83	1063	Failure of Beam
49.0	2942	84	1148	Failure of Beam
52.3	3138	85	1233	Failure of Beam
55.6	3334	86	1319	Failure of Beam
58.8	3531	87	1406	Failure of Beam
62.1	3727	88	1494	Failure of Beam
65.4	3923	89	1583	Failure of Beam
68.6	4119	89	1672	Failure of Beam
71.9	4315	90	1762	Failure of Beam
75.2	4511	91	1853	Failure of Beam
78.5	4707	91	1944	Failure of Beam
81.7	4904	92	2036	Failure of Beam
85.0	5100	92	2128	Failure of Beam
88.3	5296	93	2221	Failure of Beam
91.5	5492	93	2315	Failure of Beam
94.8	5688	94	2409	Failure of Beam
98.1	5884	94	2503	Failure of Beam
101.3	6080	95	2598	Failure of Beam
104.6	6277	95	2693	Failure of Beam
107.9	6473	96	2789	Failure of Beam
111.1	6669	96	2885	Failure of Beam
114.4	6865	97	2982	Failure of Beam
117.7	7061	97	3079	Failure of Beam
121.0	7257	97	3177	Failure of Beam
124.2	7453	98	3275	Failure of Beam
127.5	7650	98	3373	Failure of Beam
130.8	7846	99	3471	Failure of Beam
134.0	8042	99	3570	Failure of Beam
137.3	8238	99	3670	Failure of Beam
140.6	8434	100	3769	Failure of Beam
143.8	8630	100	3869	Failure of Beam
147.1	8826	100	3969	Failure of Beam
150.4	9023	101	4070	Failure of Beam
153.6	9219	101	4171	Failure of Beam
156.9	9415	101	4272	Failure of Beam
160.2	9611	102	4374	Failure of Beam
163.5	9807	102	4476	Failure of Beam
166.7	10003	102	4578	Failure of Beam
170.0	10199	102	4680	Failure of Beam

Time (min)	Time (sec)	ΔT_s (°F)	T_s (°F)	
173.3	10395	103	4783	Failure of Beam
176.5	10592	103	4886	Failure of Beam
179.8	10788	103	4989	Failure of Beam
183.1	10984	103	5092	Failure of Beam
186.3	11180	104	5196	Failure of Beam
189.6	11376	104	5300	Failure of Beam
192.9	11572	104	5404	Failure of Beam
196.1	11768	104	5508	Failure of Beam
199.4	11965	105	5613	Failure of Beam
202.7	12161	105	5718	Failure of Beam
205.9	12357	105	5823	Failure of Beam
209.2	12553	105	5928	Failure of Beam
212.5	12749	106	6034	Failure of Beam
215.8	12945	106	6139	Failure of Beam
219.0	13142	106	6245	Failure of Beam
222.3	13338	106	6352	Failure of Beam
225.6	13534	106	6458	Failure of Beam
228.8	13730	107	6565	Failure of Beam
232.1	13926	107	6671	Failure of Beam
235.4	14122	107	6778	Failure of Beam
238.6	14318	107	6886	Failure of Beam
241.9	14515	107	6993	Failure of Beam
245.2	14711	108	7101	Failure of Beam
248.4	14907	108	7208	Failure of Beam
251.7	15103	108	7316	Failure of Beam
255.0	15299	108	7424	Failure of Beam
258.3	15495	108	7533	Failure of Beam
261.5	15691	109	7641	Failure of Beam
264.8	15888	109	7750	Failure of Beam
268.1	16084	109	7859	Failure of Beam
271.3	16280	109	7968	Failure of Beam
274.6	16476	109	8077	Failure of Beam
277.9	16672	109	8186	Failure of Beam
281.1	16868	110	8296	Failure of Beam
284.4	17064	110	8406	Failure of Beam
287.7	17261	110	8516	Failure of Beam
290.9	17457	110	8626	Failure of Beam
294.2	17653	110	8736	Failure of Beam
297.5	17849	110	8846	Failure of Beam
300.8	18045	111	8957	Failure of Beam
304.0	18241	111	9067	Failure of Beam
307.3	18437	111	9178	Failure of Beam
310.6	18634	111	9289	Failure of Beam
313.8	18830	111	9400	Failure of Beam
317.1	19026	111	9512	Failure of Beam
320.4	19222	111	9623	Failure of Beam
323.6	19418	112	9734	Failure of Beam
326.9	19614	112	9846	Failure of Beam
330.2	19810	112	9958	Failure of Beam
333.4	20007	112	10070	Failure of Beam
336.7	20203	112	10182	Failure of Beam
340.0	20399	112	10294	Failure of Beam



The Failure Temperature for Steel Beams is Assumed at 1000 °F (538 °C)

NOTE

The above calculations are based on principles developed in the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering, 3rd Edition 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

18.1 Objectives

This chapter has the following objectives:

- Identify the hazard results of reduced visibility.
- Identify the factors that influence visibility.
- Describe the effects of smoke on nuclear power plants (NPPs).
- Explain how to calculate the visibility through smoke.

18.2 Introduction

As described in Chapter 9, smoke from a fire in a compartment rises in a plume to the ceiling. As the plume rises, air is entrained into it, thereby increasing the volume of smoke and reducing its temperature. The smoke spreads out beneath the ceiling and forms a layer that deepens as the compartment begins to fill with smoke. The production of smoke (smoke particulates) reduces visibility as a result of light absorption and scattering. Visibility through smoke is defined in terms of the furthest distance at which an object can be perceived (distance at which an object is no longer visible). Smoke obscures vision and causes irritation and watering of the eyes. Most notably, the intensity of smoke production has the greatest impact on reduction of visibility in a fire compartment or zone. Reduced visibility and inhaled smoke particles are the most frequent reasons of panic, which disorganizes evacuation and prolongs both rescue and firefighting operations. Moreover, in the consequence of absorption, smoke particles are ideal carriers of toxic gases and intensify the process of absorbing poisonous compounds into the human body.

The lachrymatory (causing or tending to cause tears) effects of smoke and hot gases, such as aldehydes or acids associated with smoke particles, have been shown to be important in interfering with vision. Visibility is generally much better at floor level than at higher levels in a compartment, so the possibility of crawling to safety raises the question of the height at which exit signs should be located. However, if sprinklers operate, their cooling and entrainment effects tend to bring the smoke closer to the floor. Moreover, fog (which may result from the use of sprinklers) will interfere with vision. There is currently no universally accepted position.

18.3 Smoke Obscuration

Unlike temperature, heat flux, or toxic gases, obscured visibility is not, itself, lethal. A hazard results only if the reduced visibility prevents required manual operator action or escape activity. This hazard is crucial, however, and smoke production has, therefore, been regulated longer than any other product of combustion. Evaluations have shown that personnel remote from the source of a fire are particularly at risk from fire effluent in post-flashover fire scenarios (Beitel et al., 1998).

Toxic gases kill largely because people cannot see to find escape routes and because they become disoriented and panic as a result of inhaling irritating gases. A little smoke makes people walk faster, while an increased amount slows the walking speed. Smoke also represents a psychological barrier to an occupant entering a room, often causing people to seek an alternative route and possibly causing the occupant to become trapped in a room without a safe exit (door or window). The same is true for reactor operators who may have to perform specific manual actions in a smoke-filled environment.

18.4 Effect of Smoke on Nuclear Power Plants

Sensitivity studies have shown that prolonged firefighting response times can lead to a noticeable increase in fire risk. Smoke, identified as one of the major contributors to prolonged response times, can also cause misdirected suppression efforts, hamper the ability of main control room (MCR) operators to safely shut down the plant, initiate automatic suppression systems in areas away from the fire, and fail electrical equipment.

Any number of possible fire scenarios could be considered threats to safe NPP operations. For example, a fire in turbine building, cable spreading room (CSR), or the control building can generate toxic combustion products that directly affect the habitability of the MCR or auxiliary shutdown areas. One exception would be a fire in the MCR, itself. The MCR is unique in several ways that significantly reduce the likelihood of a generalized area fire. First, the MCR is continuously manned and, hence, very rapid fire detection and intervention times are expected. This also implies that the transient fuel sources should be very effectively controlled and limited. Second, high-energy electrical equipment is not typically housed in the MCR and, hence, the number of potential high-energy fire sources is limited. Given these factors, the occurrence of a large, generalized fire in the MCR is not considered likely.

18.5 Estimating Visibility Through Smoke — Jin Method

As previously discussed, smoke particles and irritants can reduce visibility and, while loss of visibility is not directly life threatening, it can prevent or delay escape and thus expose people to the risk of being overtaken by fire. Visibility depends on many factors, including the scattering and absorption coefficient of the smoke, size and color of smoke particles, density of smoke, and the eye irritant effect of smoke. Visibility also depends on the illumination in the room, whether an exit sign is light-emitting or light-reflecting, and whether the sign is back- or front-lighted. An individual's visual acuity and mental state at the time of a fire emergency are other factors.

Most visibility measurements through smoke have relied on test subjects to determine the distance at which an object is no longer visible. However, variations in visual observation of up to 25 to 30 percent can occur with the same observer under the same test conditions but at different times. A correlation between the visibility of test subjects and the optical density of the smoke has been obtained in extensive studies by Jin (1974, 1975, 1978, and 1985) (also reported by Klote and Milke, 2002).

Based on those studies, the relationship between visibility and smoke obscuration is given by the following expression:

$$S = \frac{K}{\alpha_m m_p} \qquad (18\text{-}1)$$

Where:

S = visibility (ft)
K = proportionality constant
$_m$ = specific extinction coefficient (ft^2/lb)
m_p = mass concentration of particulate (lb/ft^3)

The proportionality constant (K) is dependent on the color of the smoke, illumination of the object, intensity of background illumination, and visual acuity of the observer (Klote and Milke, 2002). Table 18-1 provides values of the proportionality constant based on the research of Jin.

Table 18-1. Proportionality Constants for Visibility

Situation	**Proportionality Constant (K)**
Illuminated signs	8
Reflecting signs	3
Building components in reflected light	3

The specific extinction coefficient ($_m$), depends on the size distribution and optical properties of the smoke particulates. Seader and Einhorn (1976) and Seader (1943) obtained values for the specific extinction coefficient ($_m$) from pyrolysis of wood and plastics, as well as from flaming combustion of these same materials. Table 18-2 provides values of $_m$.

Table 18-2. Specific Extinction Coefficient for Visibility

Mode of Combustion	**Specific Extinction Coefficient $_m$ (ft^2/lb)**
Smoldering combustion	21,000
Flaming combustion	37,000

Jin also found that walking speed decreases as smoke density increases; i.e., visibility decreases. It can be expected that a decrease in the visibility of walls and floors would cause subjects to slow down. In thick irritating smoke, tears prevented the subjects from seeing the words on signs and caused them to walk in an irregular manner or along the wall. For low-density smoke, however, the walking speeds in irritating smoke were about the same as those in non-irritating smoke.

The mass concentration of particulate (m_p), is given by the following expression:

$$m_p = \frac{M_p}{V} \qquad (18\text{-}2)$$

Where:

m_p = mass concentration of particulate (lb/ft^3)
M_p = mass of particulates produced (lb)
V = volume of smoke in the space (ft^3)

The smoke particulates produced by a fire primarily consist of soot, and the production of particulates can be estimated as follows:

$$M_p = y_p M_f \qquad (18\text{-}3)$$

Where:

M_p = mass of particulates produced (lb)
y_p = particulate yield
M_f = mass of fuel burned (lb)

Table 18-3 lists values of particulate yield (y_p) for a number of materials from small-scale experiments of turbulent flaming combustion.

Table 18-3. Smoke Particulate Yield (Klote and Milke, 2002)

Material	**Particulate Yield - y_p**
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool (100-percent)	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylmethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118

Table 18-3. Smoke Particulate Yield (Klote and Milke, 2002)

Material	**Particulate Yield - y_p**
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylenetetrafluoroethylene (ETFE; Tefzel™)	0.042
Perfluoroalkoxy (PFA; Teflon™)	0.002
Fluorinated polyethylene-polypropylene (FEP; Teflon™)	0.003
Tetrafluoroethylene (TFE; Teflon™)	0.003

18.6 Assumptions and Limitations

The method discussed in this chapter is subject to several assumptions and limitations:

(1) This method takes into account the irritating and non-irritating effects of smoke.
(2) The correlations are developed for smoldering and flaming combustion.

18.7 Required Input for Spreadsheet Calculations

The user must obtain the following information before using the spreadsheet:

(1) compartment width (ft)
(2) compartment length (ft)
(3) compartment height (ft)
(4) fuel type (material)
(5) mass of fuel burn (lb)

18.8 Cautions

(1) Use spreadsheet (18_Visibility_Through_Smoke.xls) on the CD-ROM for estimating visibility through smoke.

(2) Make sure to enter the input parameters in the correct units.

18.9 Summary

This chapter describes a method of calculating the visibility through a smoke layer based on experimental correlations and data. The visibility through thin smoke primarily depends on physical obscuration; however, when the smoke is relatively thick, the physiological irritant becomes the dominant factor in impairing visibility. The correlation presented was obtained from laboratory-scale fires; smoke particulate production is expected to vary with the size of the fire and the orientation of the fuel. Equation 18-1 can be used to calculate visibility in such large fires.

18.10 References

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18.11 Problems

Example Problem 18.11-1

Problem Statement
A compartment is 30 ft width x 20 ft long x 15 ft high (w_c x l_c x h_c). In the center of the compartment, 1 lb of polypropylene is involved in flaming combustion:

(a) From the center of the compartment, can you see the "Reflecting Exit Sign" at either end of the compartment?

(b) What if you increase the mass of burned fuel (polypropylene) to 2 lbs?

Solution

Purpose:

(1) Determine the visibility of the exit sign.

Assumptions:

(1) Complete burning within the method specified

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 18_Visibility_Through_Smoke.xls

FDT^s Input Parameters:

-Compartment Width (w_c) = 30 ft
-Compartment Length (l_c) = 20 ft
-Compartment Height (h_c) = 15 ft
-Mass of fuel burn = 1 lb
-Select Polypropylene
-Select Reflecting Signs
-Select Flaming Combustion

Results*

	1 lb of material	**2 lb of material**
Visible Distance	12.37 ft (3.77 m)	6.18 ft (1.88 m)

*see spreadsheet on next page

Therefore, the signs placed at either end of the room (10 feet away) are visible with 1 lb of material burning, but would not be visible if 2 lb of material was burned.

Spreadsheet Calculations

(a) FDT^s: 18_Visibility_Through_Smoke.xls (1 lb polypropylene)

CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE
Version 1805.0
The following calculations estimate the smoke obscuration during a fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w)	30.00	ft
Compartment Length (l)	20.00	ft
Compartment Height (h)	15.00	ft
Mass of Fuel Burn (M)	1.00	lb
Particulates Yield (y_p)	0.0590	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (δ_m)	37000	ft²/lb

Calculate

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylmethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylenetetrafluoroethylene (ETFE; Tefzel™)	0.042
Perfluoroalkoxy (PFA; Teflon™)	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon™)	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 35.

Select Material
Polypropylene
Scroll to desired material then Click on selection

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 37.

Select Proportionality Constant (K)
Reflecting Signs
Scroll to desired situation then Click on selection

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient α_m (ft^2/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 32.

Select Specific Extinction Coefficient (α_m)

Flaming Combustion

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 32.

$S = K / \alpha_m m_p$

Where
- S = visibility through smoke (ft)
- K = proportionality constant
- α_m = specific extinction coefficient (ft^2/lb)
- m_p = mass concentration of particulate (lb/ft^3)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where
- V = volume of the compartment (ft^3)
- w_c = compartment width (ft)
- l_c = compartment length (ft)
- h_c = compartment height (ft)

$V =$ 9000.00 ft^3

Mass of Particulates Produced (airborne particulate)

$M_p = y_p M_f$

Where
- M_p = mass of particulates produced (lb)
- y_p = particulates yield
- M_f = mass of fuel consumed (lb)

$M_p = y_p M_f$

$M_p =$ 0.060 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where
- m_p = mass concentration of the particulates (lb/ft^3)
- M_p = mass of particulates produced (lb)
- V = volume of the compartment (m^3)

$m_p = M_p / V$

$m_p =$ 6.66666E-06 lb/ft^3

Visibility Through Smoke Calculation

$S = K / \alpha_m m_p$

S =	12.37 ft	3.77 m	Answer

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

The above calculations are based on principles developed in the Principles of Smoke Management by Klote and Milke 2002. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT^s: 18_Visibility_Through_Smoke.xls (2 lb polypropylene)

CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

Version 1805.0

The following calculations estimate the smoke obscuration during a fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	30.00	ft
Compartment Length (l_c)	20.00	ft
Compartment Height (h_c)	15.00	ft
Mass of Fuel Burn (M_f)	2.00	lb
Particulates Yield (y_s)	0.0590	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (σ_s)	37000	ft²/lb

Calculate

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylemethacrylate (PMMA; Plexiglas TM)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylenetetrafluoroethylene (ETFE; Tefzel TM)	0.042
Perfluoroalkoxy (PFA; Teflon TM)	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon TM)	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 35.

Select Material

Polypropylene

Scroll to desired material then Click on selection

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 37.

Select Proportionality Constant (K)

Reflecting Signs

Scroll to desired situation then Click on selection

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient δ_m (ft^2/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

Select Specific Extinction Coefficient (δ_m)

Flaming Combustion

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

$S = K / \delta_m \, m_p$

Where S = visibility through smoke (ft)
K = proportionality constant
δ_m = specific extinction coefficient (ft^2/lb)
m_p = mass concentration of particulate (lb/ft^3)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where V = volume of the compartment (ft^3)
w_c = compartment width (ft)
l_c = compartment length (ft)
h_c = compartment height (ft)

$V =$ 9000.00 ft^3

Mass of Particulates Produced (airborne particulate)

$M_p = y_p \, M_f$

Where M_p = mass of particulates produced (lb)
y_p = particulates yield
M_f = mass of fuel consumed (lb)

$M_p = y_p \, M_f$

$M_p =$ 0.118 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where m_p = mass concentration of the particulates (lb/ft^3)
M_p = mass of particulates produced (lb)
V = volume of the compartment (m^3)

$m_p = M_p / V$

$m_p =$ 1.31111E-05 lb/ft^3

Visibility Through Smoke Calculation

$S = K / \delta_m \, m_p$

S =	6.18 ft	1.88 m	Answer

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

The above calculations are based on principles developed in the Principles of Smoke Management by Klote and Milke 2002. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
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Example Problem 18.11-2

Problem Statement

A compartment is 10 ft wide x 30 ft long x 12 ft high (w_c x l_c x h_c). What is the minimum amount (lb) of rigid polyurethane foam involved in smoldering combustion necessary to obstruct the visibility for the length of the compartment to a building compartment in reflective light?

Solution

Purpose:

(1) Determine the minimum mass of burning fuel that will obscure the sign.

Assumptions:

(1) Complete burning within the method specified

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 18_Visibility_Through_Smoke.xls

FDT^s Input Parameters:

-Compartment Width (w_c) = 10 ft
-Compartment Length (l_c) = 30 ft
-Compartment Height (h_c) = 12 ft
-Mass of fuel burn = variable
-Select Polyurethane Foam (Rigid)
-Select Reflecting Signs
-Select Smoldering Combustion

Results*

Visible Distance	Mass of fuel burn
30 ft (9.42 m)	.14 lb (.064 kg)

*see spreadsheet on next page

Spreadsheet Calculations

FDT^s: 18_Visibility_Through_Smoke.xls

CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

Version 1805.0

The following calculations estimate the smoke obscuration during a fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROPDOWN MENU for the Material Selected.
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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	10.00	ft
Compartment Length (l_c)	30.00	ft
Compartment Height (h_c)	12.00	ft
Mass of Fuel Burn (M_f)	0.14	lb
Particulates Yield (y_p)	0.1180	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (D_m)	21000	ft²/lb

Calculate

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylemethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylene tetrafluoroethylene (ETFE; Tefzel™)	0.042
Perfluoroalkoxy (PFA; Teflon™)	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon™)	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 35.

Select Material

Polyurethane Foam (Rigid)

Scroll to desired material then Click on selection

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 37.

Select Proportionality Constant (K)

Reflecting Signs

Scroll to desired situation then Click on selection

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient α_m (ft^2/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

Select Specific Extinction Coefficient (α_m)

Smoldering Combustion

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 32.

$S = K / \alpha_m m_p$

Where S = visibility through smoke (ft)
K = proportionality constant
α_m = specific extinction coefficient (ft^2/lb)
m_p = mass concentration of particulate (lb/ft^3)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where V = volume of the compartment (ft^3)
w_c = compartment width (ft)
l_c = compartment length (ft)
h_c = compartment height (ft)

$V =$ 3600.00 ft^3

Mass of Particulates Produced (airborne particulate)

$M_p = y_p M_f$

Where M_p = mass of particulates produced (lb)
y_p = particulates yield
M_f = mass of fuel consumed (lb)

$M_p = y_p M_f$

$M_p =$ 0.01652 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where m_p = mass concentration of the particulates (lb/ft^3)
M_p = mass of particulates produced (lb)
V = volume of the compartment (m^3)

$m_p = M_p / V$

$m_p =$ 4.58889E-06 lb/ft^3

Visibility Through Smoke Calculation

$S = K / \alpha_m m_p$

$S =$	31.13 ft	9.49 m	Answer

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

The above calculations are based on principles developed in the Principles of Smoke Management by Klote and Milke 2002. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
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Example Problem 18.11-3

Problem Statement

An inspector finds 5 lbs of PVC pipe in a compartment 10 ft wide x 30 ft long x 12 ft high (w_c x l_c x h_c):

(a) What is the visibility to a reflecting sign given flaming combustion?

(b) What is the visibility to a reflecting sign given smoldering combustion?

Solution

Purpose:

(1) Determine the visibility under the different burning methods.

Assumptions:

(1) Complete burning within the method specified

Spreadsheet (FDT^s) Information:

Use the following FDT^s:

(a) 18_Visibility_Through_Smoke.xls

FDT^s Input Parameters:

-Compartment Width (w_c) = 10 ft
-Compartment Length (l_c) = 30 ft
-Compartment Height (h_c) = 12 ft
-Mass of fuel burn = 5 lbs
-Select PVC
-Select Reflecting Signs
-Select Flaming Combustion (get result)
-Select Smoldering Combustion (get result)

Results*

Burning Method	**Visibility**
Flaming	.34 ft (0.10 m)
Smoldering	.60 ft (0.18 m)

*see spreadsheet on next page

Spreadsheet Calculations

(a) FDT^s: 18_Visibility_Through_Smoke.xls

CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

Version 1805.0

The following calculations estimate the smoke obscuration during a fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w)	10.00	ft
Compartment Length (l)	30.00	ft
Compartment Height (h)	12.00	ft
Mass of Fuel Burn (M)	5.00	lb
Particulates Yield (y_s)	0.1720	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (σ_s)	37000	ft²/lb

Calculate

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylemethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylenetetrafluoroethylene (ETFE; Tefzel™)	0.042
Perfluoroalkoxy (PFA; Teflon™)	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon™)	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 35.

Select Material

Polyvinylchloride (PVC)

Scroll to desired material then Click on selection

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 37.

Select Proportionality Constant (K)

Reflecting Signs

Scroll to desired situation then Click on selection

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient σ_m (ft^2/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 32.

Select Specific Extinction Coefficient (σ_m)

Flaming Combustion

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 32.

$S = K / \sigma_m m_p$

Where
- S = visibility through smoke (ft)
- K = proportionality constant
- σ_m = specific extinction coefficient (ft^2/lb)
- m_p = mass concentration of particulate (lb/ft^3)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where
- V = volume of the compartment (ft^3)
- w_c = compartment width (ft)
- l_c = compartment length (ft)
- h_c = compartment height (ft)

$V =$ 3600.00 ft^3

Mass of Particulates Produced (airborne particulate)

$M_p = y_p M_f$

Where
- M_p = mass of particulates produced (lb)
- y_p = particulates yield
- M_f = mass of fuel consumed (lb)

$M_p = y_p M_f$

$M_p =$ 0.86 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where
- m_p = mass concentration of the particulates (lb/ft^3)
- M_p = mass of particulates produced (lb)
- V = volume of the compartment (m^3)

$m_p = M_p / V$

$m_p =$ 0.000238889 lb/ft^3

Visibility Through Smoke Calculation

$S = K / \sigma_m m_p$

$S =$	0.34 ft	0.10 m	Answer

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

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Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT^{s}: 18_Visibility_Through_Smoke.xls

CHAPTER 18. ESTIMATING VISIBILITY THROUGH SMOKE

Version 1805.0

The following calculations estimate the smoke obscuration during a fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROPDOWN MENU for the Material Selected.
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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	10.00	ft
Compartment Length (l_c)	30.00	ft
Compartment Height (h_c)	12.00	ft
Mass of Fuel Burn (M_f)	5.00	lb
Particulates Yield (y_s)	0.1720	
Proportionality Constant for Visibility (K)	3	
Mode of Combustion (σ_s)	21000	ft²/lb

Calculate

PARTICULATE YIELD FOR WELL-VENTILATED FIRES OF SOLID FUELS

Materials	Particulate Yield y_p
Wood (Red Oak)	0.015
Wood (Douglas Fir)	0.018
Wood (Hemlock)	0.015
Fiberboard	0.008
Wool 100%	0.008
Acrylonitrile-Butadiene-Styrene (ABS)	0.105
Polymethylmethacrylate (PMMA; Plexiglas™)	0.022
Polypropylene	0.059
Polystyrene	0.164
Silicone	0.065
Polyester	0.09
Nylon	0.075
Silicone Rubber	0.078
Polyurethane Foam (Flexible)	0.188
Polyurethane Foam (Rigid)	0.118
Polystyrene Foam	0.194
Polyethylene Foam	0.076
Phenolic Foam	0.002
Polyethylene (PE)	0.06
Polyvinylchloride (PVC)	0.172
Ethylene tetrafluoroethylene (ETFE; Tefzel™)	0.042
Perfluoroalkoxy (PFA; Teflon™)	0.002
Fluorinated Polyethylene-Polypropylene (FEP; Teflon™)	0.003
Tetrafluoroethylene (TFE; TeflonTM)	0.003
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 35.

Select Material

Polyvinylchloride (PVC)

Scroll to desired material then Click on selection

RECOMMENDED PROPORTIONALITY CONSTANTS FOR VISIBILITY

Situation	Proportionality Constant K
Illuminated Signs	8
Reflecting Signs	3
Building Components in Reflected Light	3
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 37.

Select Proportionality Constant (K)

Reflecting Signs

Scroll to desired situation then Click on selection

SPECIFIC EXTINCTION COEFFICIENT

Mode of Combustion	Specific Extinction Coefficient α_m (ft^2/lb)
Smoldering Combustion	21000
Flaming Combustion	37000
User Specified Value	Enter Value

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 32.

Select Specific Extinction Coefficient (α_m)

Smoldering Combustion

Scroll to desired combustion mode then Click on selection

ESTIMATING VISIBILITY THROUGH SMOKE
METHOD OF JIN

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 32.

$S = K / \alpha_m m_p$

Where
- S = visibility through smoke (ft)
- K = proportionality constant
- α_m = specific extinction coefficient (ft^2/lb)
- m_p = mass concentration of particulate (lb/ft^3)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where
- V = volume of the compartment (ft^3)
- w_c = compartment width (ft)
- l_c = compartment length (ft)
- h_c = compartment height (ft)

$V =$ 3600.00 ft^3

Mass of Particulates Produced (airborne particulate)

$M_p = y_p M_f$

Where
- M_p = mass of particulates produced (lb)
- y_p = particulates yield
- M_f = mass of fuel consumed (lb)

$M_p = y_p M_f$

$M_p =$ 0.86 lb

Mass Concentration of the Particulates Calculation

$m_p = M_p / V$

Where
- m_p = mass concentration of the particulates (lb/ft^3)
- M_p = mass of particulates produced (lb)
- V = volume of the compartment (m^3)

$m_p = M_p / V$

$m_p =$ 0.000238889 lb/ft^3

Visibility Through Smoke Calculation

$S = K / \alpha_m m_p$

S =	0.60 ft	0.18 m	Answer

Visibility in smoke is defined in terms of the furthest distance at which an object can be perceived.

NOTE

The above calculations are based on principles developed in the Principles of Smoke Management by Klote and Milke 2002. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

APPENDIX A. NUCLEAR POWER PLANT ELECTRICAL CABLE FUNDAMENTALS

A.1 Introduction

The function of electrical cable is to provide a medium for transmitting electrical energy (power control or signals) between two points in a common electrical circuit, while simultaneously maintaining the electrical isolation of the transmission path from other elements of the same circuit and from other co-located circuits. Cable failure, therefore, implies loss of continuity in the energy transmission path or diversion of a sufficient fraction of the available electrical energy to an unintended circuit destination such that proper function of the circuit is no longer assured. A typical boiling-water reactor (BWR) requires approximately 97 km (60 miles) of power cable, 80.5 km (50 miles) of control cable and 402 km (250 miles) of instrument cable. A pressurized-water reactor (PWR) may require far more, as illustrated by the containment building of Waterford Steam Electric Generating Station, Unit 3 which required nearly 1,609 km (1,000 miles) of cable (NUREG/CR-6384). The majority of fire dynamics, fire risk evaluations will focus on electrical cables because of their thermal fragility. It is therefore necessary to have a fundamental understanding of electrical cables.

Fire can cause cable failures in several ways. Experience from actual fire events has shown that different modes of fire-induced failures in electrical cables can in turn, produce a variety of circuit faults, leading to a range of circuit faulting behaviors. The risk implications of a given circuit fault depend upon the associated component function.

This appendix describes the types of cables commonly encountered in nuclear power plant (NPP) applications and the modes of cable failure that might be observed. It also discusses the potential impact of various cable failure modes on power, control, and instrumentation circuits. In addition, this appendix identifies the factors that can influence the potential for each of the identified cable failure modes that may result from a fire. Because of the large quantity of cable in a typical NPP and the fact that much of the cable material (e.g., polymer insulation and outer jacket) is combustible, cables frequently comprise a significant fraction of the total combustible load in many areas of an NPP.

The fire at Browns Ferry Nuclear Power Plant (BFNP) Unit 1, provides the classic example of how loss of function and spurious signals can occur as a result of a cable fire (NRC Bulletin BL-75-04). As such, it represents one of the most serious events ever experienced at a U.S. commercial NPP. In that fire, which was initiated by a candle flame igniting polyurethane foam in an improperly sealed penetration, temperatures as high as 816 °C (1,500 °F) caused damage to more than 1,600 cables routed in 117 conduits and 26 cable trays. Of these, a large number were safety-related. The number of damaged safety-related cables can be categorized by Unit as: 482 from Unit 1, 22 from Unit 2, and 114 common to both units. As a result, the reactor lost control power to a significant amount of emergency core cooling system (ECCS) equipment. In fact, at one point in the event, all power to Unit 1 ECCS motors and valves was lost.

Furthermore, fire-induced short circuits caused many instrument, alarm, and indicating circuits to provide false and conflicting indications of equipment operation, thereby impeding operators' ability to control reactor safety functions. For example, one panel indicated that all ECCS pumps were operating, while another panel indicated that there was no need for this operation. The fire was contained to a relatively small interior area of the plant [the cable spreading room (CSR) and Unit 1 reactor building] and the conditional core damage probability, for the event has been estimated to be about 0.4 (NUREG/CR-2497, "Precursors to Potential Severe Core Damage Accidents: 1969–1979, A Status Report," Volume 1 and 2).

The most intense part of the fire, which involved burning stacks of horizontal cable trays, covered an area roughly 3.3 m (10.9 ft) by 2.5 m (8.2 ft) in dimension. Because of reluctance to use water, fire suppression was considerably delayed, and the fire burned some 7 hours after it started.

A.2 Electrical Cable Construction

Cables come in a wide variety of configurations. The primary configuration features that define a given cable are the size of the individual conductors [expressed using the American Wire Gauge (AWG)], the number of conductors, shielding and/or armoring features, and the insulation/jacket materials used.

Of the materials available for use as cable insulation and jacketing, the broadest categories are thermoplastic and thermoset. Thermoplastic materials melt when heated and solidify when cooled. Thermoset materials do not melt, but do begin to smolder and burn if sufficiently heated. In general, thermoset materials are more robust, with failure temperatures of approximately 350 °C (662 °F) or higher. Thermoplastic materials typically have failure temperatures much lower than 218 °C (425 °F), where failure is typically associated with melting of the material.

Cables typically consist of one or more metallic conductors, insulation, filler, shielding, sheaths, and jacket. Each metallic conductor (generally copper or aluminum) is electrically isolated by being encased in a layer of insulation. The insulation, which is often considered the single most important component of the cable is typically made from a dielectric material (e.g., plastic, rubber, polymeric, silicone-based, or rubber-based material of some type). The term "sheath" commonly refers to an aluminum or steel jacket, rather than rubber or plastic (e.g., armored sheathed cable). Some cables may also include one or more shields consisting of metallic tape, composition tape, or a metallic braid. The shield is wrapped around the insulated conductors under the jacket or sheath. Single or multiple insulated conductors with their associated shields and sheaths are grouped together within a single integral protective jacket. The jacket serves a strictly utilitarian purpose (physical protection) and has no electrical function.

Cable jackets are typically constructed of rubber or plastic materials. The purpose of the jacket is to provide the insulated conductor(s) with physical or environmental protection, and/or increased flame retardancy. Cable jackets designed for increased flame retardancy slow the flame spread across the jacket and reduce the fuel contribution from the cable once ignited. Nevertheless, having increased flame retardancy does not ensure functionality.

Insulation plays an essential roll in a cable's overall performance at normal and elevated temperatures. The function of insulation is to electrically separate each conductor from the other conductors and from the ground plane. In some cases, cable jackets and cable insulation are constructed of the same materials. The number of insulated conductors within a cable is commonly identified as follows:

- single-conductor cable (1/C)
- multi-conductor cable [e.g., 2 conductors (2/C), 7 conductors (7/C)]
- triplex-conductor (triple-conductor) cable (3/C)

Cables are also identified by their rated power voltage as shown in Table A-1 (Salley, 2000).

Table A-1. Designation of Electrical Rated Voltages

Designation	**Voltage**
Low	Up to 600 V
Medium	601 to 15,000 V
High*	15,001 V and greater
* High voltage cables are typically not found inside the NPP. They may be used as a cable bus in trenches, or in the switchyards.	

A.3 Description of Cables

NPPs use three functional types of cables for power, control, and instrumentation. Virtually every system in an NPP depends on the continued operation of one or more electrical cables. Power cables may be single-conductor, multi-conductor, or triplex. Control and instrumentation cables are generally of a multi-conductor design.

As the name implies, a single-conductor cable is a single insulated metal conductor that typically has an integral over-jacket. A triplex cable is a grouping of three signal-conductors that are manufactured together and are often twisted around a centrally located uninsulated core wire, which may be connected to the circuit ground. Basic electrical construction and configurations are illustrated in Figure A-1.

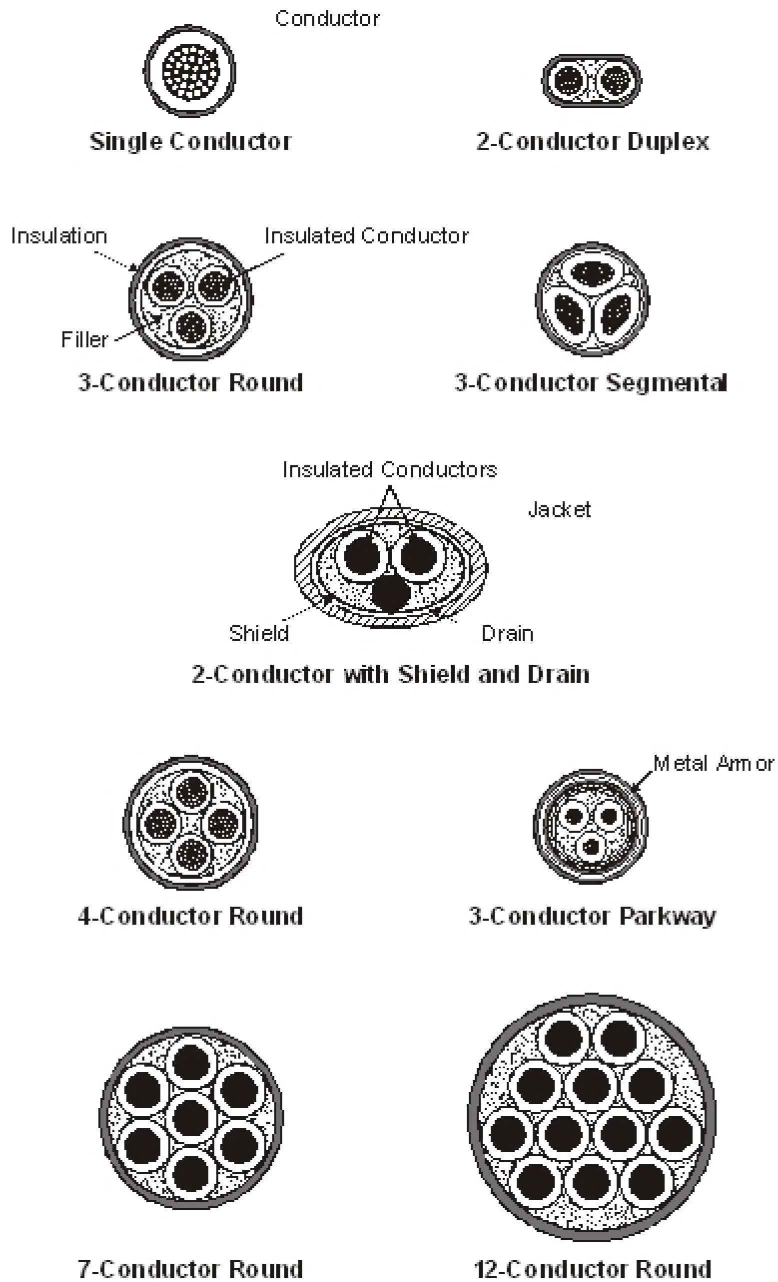


Figure A-1 Basic Electrical Cable Construction —
Common Single- and Multi-Conductor Arrangements

Multi-conductor cables are more varied and may come with virtually any number of conductors limited only by practical considerations such as overall physical diameter and handling ability. The most common configurations encountered in a NPPs are 2/C, 3/C, 7/C, and 12-conductor configurations. The 3/C, 7/C, and 12-conductor configurations are popular with manufacturers because they result in an overall cable product that maintains an essentially round outer profile. Another common configuration, particularly for instrument cables, involves some number of twisted/shielded pairs within a protective jacket. In this case, the shield refers to a conductive wrap, such as a metal foil, wrapped around, conductor pairs. This is common in sensitive instrument circuits where stray electromagnetic or radio-frequency interference (EMI/RFI) may be a concern. These cables are also commonly used in communication systems.

The size of a cable is generally expressed as the number of conductors and the AWG of the individual conductors. Hence, a 3/C 12 AWG cable is a 3-conductor 12-gauge cable. Power cables typically range from relatively small 12 AWG cables (equivalent to cables used in residential applications for household power circuits) through very large cables in which the conductor diameter can approach or even exceed 2.54 cm (1 inch) (note that a higher gauge number indicates a smaller conductor.) For power cables, the size selection is generally based on the ampacity (current-carrying capacity) required in a specific application.

Control cables are generally of a smaller gauge, commonly range from 16 AWG through 10 AWG with exceptions on the upper end of the size range. Instrumentation cables are generally of 16 AWG or smaller.

Voltage levels will also vary with the application. Instrument circuits generally use low voltages (50 volts or less). Control circuits are commonly in the 120–250-volt range. Power circuits encountered within an NPP generally range from 120 to 4,160 volts, with offsite power circuits ranging to 15 kV or higher.

Cables are generally routed through the plant in horizontally raceways (generally trays or conduits) with vertical runs as required between different elevations in the plant. The cables are generally segregated by type (power, control, and instrumentation) but cables of various voltages and functions can be found together in some plants (generally older plants). High-voltage power cables are typically routed by themselves and may use maintained spacing to address ampacity concerns. Under maintained spacing, cables are not stacked and each cable is individually strapped to the electrical raceway. Gaps between cables ensure that they do not come into physical contact with each other. For most cables, random placement within the tray is common (that is, the cables are simply laid into the tray in a more or less random manner).

Fire exposure of an electrical cable can cause a loss of insulation resistance, loss of insulation physical integrity (i.e., melting of the insulation), and electrical breakdown or short-circuiting. Fire-induced damage to a cable can result in one of the following electrical conductor failure modes (LaChance et al., 2000):

- An open circuit results in a loss of electrical continuity of an individual conductor (i.e., the conductor is broken and the signal or power does not reach its destination).
- A short to ground is experienced when an individual conductor comes into electrical contact with a grounded conducting medium (such as a cable tray, conduit, or a grounded conductor) resulting in a low-resistance path that diverts current from a circuit. The fault may be accompanied by a surge of excess current to ground (particularly in higher voltage circuits) that is often damaging to the conductor.
- A hot short is characterized by electrical faults that involve an energized conductor contacting another conductor of either the same cable (a conductor-to-conductor hot short) or an adjacent cable (a cable-to-cable hot short). A hot short has the potential to energize the affected conductor or to complete an undesirable circuit path.

It is important to note that a cable may have any number of conductors as discussed above and it is possible for more than one conductor failure mode to be active at a given time. For example, one set of three conductors may be shorted together (conductor-to-conductor hot short), while a fourth conductor shorts to ground.

Both shorts to ground and hot shorts may be manifested in the form of a low-impedance fault (often referred to as a bolted or dead-short) or as a high-impedance fault between the conductors. These two modes of shorting are distinguished on the basis of the following considerations:

- A high-impedance fault may allow power to pass from one conductor to another (or to ground) even between circuits with dissimilar voltages, while a low-impedance short between circuits of dissimilar voltage or between a circuit and ground often trips circuit protection features (fuses or breakers) in one or both circuits.
- A single low-impedance short in a power circuit typically trips the lowest level of upstream circuit protection, while multiple high-impedance faults may trip a higher-level circuit protection feature (if circuit protection coordination is not provided), leading to loss of a higher-level electrical bus.
- A high-impedance fault in an instrumentation circuit may lead to a biased indication that might not be detected by operators, while low-impedance shorts typically result in a more easily detectable situation (e.g., complete loss of indication or an indication at the extreme high or low scale).

A.4 Cable Materials

For fire risk analysis, cable insulation and jacket materials can be separated into two broad categories, as discussed in the following subsections.

A.4.1 Thermoplastic Materials

Thermoplastic materials are defined as high molecular weight polymers that are not cross-linked and are generally characterized by the distinct melting point of the insulation material. Thermoplastic materials can be repeatedly softened by heating and hardened by cooling within a temperature band that is a physical property of the material. This property is a function of the loose molecular bonding of the material. Some thermoplastic materials have a low melting point, which can be a disadvantage in that melting insulation can lead to conductor failures (e.g., conductor-to-conductor shorts and conductor-to-ground shorts) at relatively low temperatures. Some thermoplastic insulations are also problematic in that they produce dripping, flaming fires after ignition. Cables using thermoplastic insulation ***are not*** usually qualified to survive the full environment qualification exposure condition of IEEE Std. 383. Many thermoplastic cables will however, pass the limited flame spread test included in the IEEE Std. 383.

Thermoplastic insulation is generally easy to manufacture and economical to use. Common thermoplastic insulations include cellular; low and high polyethylene (PE); polyvinyl chloride (PVC); polyurethane; polypropylene (PPE); nylon; chlorinated polyethylene (CPE); tetrafluoroethylene (TFE), Teflon, and fluorinated polymers such as DuPont’s TFE copolymers with ethylene (known as Tefzel®), DuPont’s PFA (perfluoroalkoxy branched polymers), Allied Chemical’s Halar (ethylene copolymer with chlorotrifluoroethylene), and Dynamit Nobel’s Dyflor (polyvinylidene fluoride). Figure A-2 shows typical thermoplastic (PVC) insulated cable construction. In general, cables that do not pass IEEE 383 rating (i.e., non-IEEE qualified) are thermoplastic.

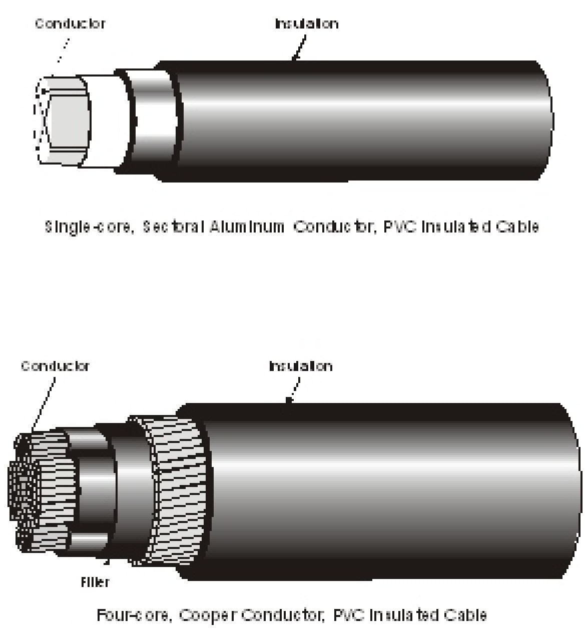
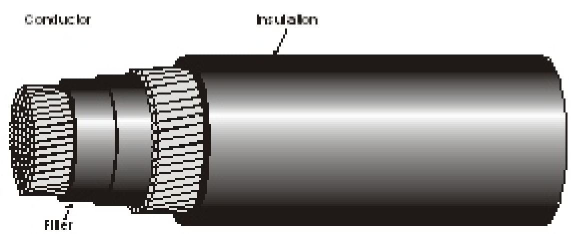


Figure A-2 Thermoplastic Insulated Cable Construction

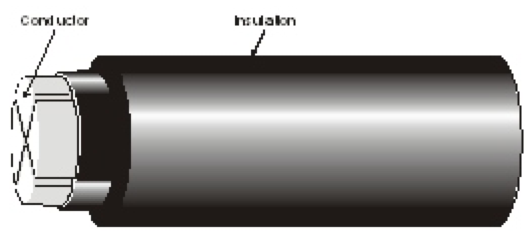
A.4.2 Thermoset Materials

The molecular consist of chains that are tied together with covalent bonds in a network (crosslinked). Thermoset insulations are generally characterized as softening, but not melting, during higher-than-normal temperature exposures. While they soften, they tend to maintain the mechanical properties of the insulator. As a result, thermoset insulations generally exhibit better low-and-high temperature properties, thermal aging resistance, and overload resistance than thermoplastic insulations. Thermoset materials are vulcanized by heat (or other methods) during their fabrication process. As such, the materials are substantially infusible and insoluble. The molecular structure is tightly interlocked (in contrast to thermoplastic insulations). Common thermosetting insulations include ethylene propylene rubber (EPR); crosslinked polyethylene (XLPE); DuPont's Hypalon (chlorosulphonated polyethylene); nitrile or rubber butadiene nitrite (NBR); styrene butadiene rubber (SBR); polybutadiene; neoprene; and silicone rubber. Cables using thermoset insulation *are* usually qualified to IEEE Std. 383. In general, cables that do pass IEEE 383 rating (i.e., IEEE 383 qualified) are thermoset cables.

In summary, thermoplastic materials are high molecular weight polymers that are not cross-linked, while the polymer chain of thermoset materials are crosslinked in covalent bonded networks. When thermoset resins are heated during manufacture, from ambient to upward of 232 °C (450 °F), they undergo an irreversible chemical reaction, referred to as "curing" or "polymerization," to make the final cross-linked thermoplastic product. While thermoplastic materials can be reshaped by heating and cooling within the proper temperature ranges for the materials, thermoset materials cannot be reshaped once they have been crosslinked. Figure A-3 shows typical thermoset (XLPE) insulated cable construction.



Single-core, XLPE Insulated Cable with Standard Conductor, Taped Bedding and Aluminum Wire Armor



Four-core Unarmored, XLPE Insulated Cable with Solid Aluminum Conductor

Figure A-3 Thermoset Insulated Cable Construction

A.5 Cable Failure Threshold and Time to Damage

A.5.1 Theory

In a very basic, first order analysis, one can assume thermal damage occurs the instant the target reaches its minimum failure temperature. For example, if the target is an electrical cable and it is known that the cable fails at 425 °F (218 °C), the analyst can assume failure as soon as the cable is exposed to a 425 °F (218 °C) hot gas layer. However, there are more realistic methods of analysis.

We know from thermal detector and sprinkler response (see Chapter 12), that all materials have a mass that must be heated before they can reach a target temperature. This thermal inertia is quantified as the response time index (RTI) for detection and suppression devices and the same principle applies to electrical cables, however with a number of complications. For example, is the cable in free air (e.g., air drop) conduit or in a cable tray? Where is the cable located in the cable tray; top, bottom, against a side rail, or in the center of the cable mass? Does the cable have any fire retardant coating? If so, which brand? These are just a sampling of the possible variables that complicate the thermal impact on a cable. At this writing, many of these factors are unknown; however, we can use what information is currently available to provide a much more accurate method of determining cable failure threshold and time to damage. The following information was developed by the authors in conjunction with Mr. Steve Nowlen of Sandia National Laboratories for use in fire protection risk analysis by the NRC.

A.5.2 Temperature Thresholds — Thermoset Cables

Thermoset represents a very broad class of cables. Of the thermoset cables, crosslinked polyolefin (XLPO) insulated cables are generally the weakest in this cable family in terms of susceptibility to thermal damage (see discussion of Kerite FR below). Of the general class XLPO, the specific material crosslinked polyethylene (XLPE) is the most widely used. XLPE-insulated cables are used extensively in the U.S. nuclear power industry. For example, based on surveys of nuclear industry practices conducted in support of the NRC's Equipment Qualification research programs, one of the most popular cable products is the widely used Rockbestos Firewall III line of nuclear qualified cable products. In general, the XLPO and XLPE cables can be taken as representative of the weaker thermoset materials. Fairly extensive evidence for thermal damage to thermoset cables in general, and the XLPO and XLPE materials in particular, exists based on a number of public sources.

Perhaps the earliest source of direct evidence on thermal failure thresholds for thermoset cables is provided in NUREG/CR-5384 which reports thermal damage test results from the early 1980's for an XLPE-insulated cable. The tested cable was specifically IEEE-383 qualified, including the flammability testing protocol. The samples were taken from excess stocks of cables purchased to support NRC-sponsored testing in the late 1970s. Hence, these cables are a very early vintage IEEE-383-qualified cable given that the flame spread test was first introduced in IEEE-383 in the 1975 revision. During high temperature exposure tests, electrical failures were observed at temperatures as low as 518 °F (270 °C). At this temperature damage times were relatively long ranging from 30 to 82 minutes, and averaging 56 minutes. At an exposure temperature of 662 °F (350 °C) the damage times ranged from 7 to 28 minutes, averaging 13 minutes.

Direct evidence is also provided in NUREG/CR-5546 (1991) which reports thermal damage results for a XLPE-insulated Rockbestos Firewall III cable, an extremely common cable in the U.S. nuclear industry. At a temperature of 617 °F (325 °C) no failures were observed for two samples during exposures lasting approximately 80 minutes. At 626 °F (330 °C) failures were observed in all four samples tested. The failure times ranged from 33 to 79 minutes, and averaged 55 minutes. At a temperature of 635 °F (335 °C), damage times ranged from 16 to 30 minutes and averaged about 20 minutes.

A third source of direct evidence is gained from superheated steam exposure tests conducted under severe accident simulation tests in the equipment qualification (EQ) domain (e.g., NUREG/CR-5655, 1991). The dry superheated steam environments look much like the dry hot environment of a fire, and a previous study has concluded that these results might be applied as indicators of fire damage thresholds as well (SAND92-1404C). A direct correlation has been made between the damage criteria applied in fire testing to those applied in the EQ tests. All products tested were explicitly qualified for use in U.S. nuclear industry applications. Interpretation of the EQ test results requires selection of a failure criterion. NUREG/CR-5655 reports results for four separate failure criteria, each representing a progressively more severe level of degradation. Using the worst case failure threshold (i.e., that indicative of the highest level of degradation), the failure threshold for an XLPE cable was estimated at about 610 °F (320 °C). For the more general class of XLPO materials, failures at the same threshold were noted at temperatures as low as 572 °F (300 °C).

A fourth source for direct evidence on the electrical performance of XLPE-insulated cables is a series of tests performed in 1984 by TVA[1]. The TVA tests involved six different cable types each insulated with XLPE. The maximum temperature reached by the cables during the test was 570 °F (299 °C) at the end of a 1-hour exposure protocol. None of the XLPE cables experienced electrical failure at these temperatures.

A fifth source of direct evidence regarding failure for thermoset cables is the recently completed NEI/EPRI Cable Failure Modes and Effects Tests. As a part of an expert panel activity (EPRI TR1006961) some panel members examined the cable failure data in the context of temperature, and estimated the minimum failure threshold for the thermoset cables tested. Each panelist was left to their own approach to analysis and interpretation of the test data, and each reached somewhat different conclusions. Furthermore, the cable types (insulation material in particular) are not identified beyond thermoset versus thermoplastic. Nonetheless, the results do provide some insights into cable failure thresholds for at least some cable types as follows:

- Mowrer noted thermoset cable failures at a minimum temperature of 680 °F (360 °C). (See pg. B-21 of the EPRI TR1006961.)
- Funk concluded that, for thermoset cables, 550 °F (288 °C) was a “reasonably conservative” estimate of the “threshold of thermal insult below which cable failure (either partial or complete) does not occur, or is extremely unlikely.” (See pg. B-3, ibid.)
- Salley noted at least one thermoset cable that failed at a temperature of 591 °F (311 °C) and others in the range of 660–680 °F (349–360 °C). (See pg. B-64, ibid.)

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[1] As reported by M.H. Salley in “An Examination of the Methods and Data Used to Determine Functionality of Electrical Cables when Exposed to Elevated Temperatures as a Result of a Fire in a Nuclear Power Plant,” University of Maryland, MS Thesis, 2000.

The Fire Performance of Electrical Cables (FIPEC) study provides indirect evidence based on the piloted ignition thresholds. The reported ignition temperatures for a range of XLPE cable products ranged from 429-885 °F (220-474 °C). The average ignition temperature reported was 630 °F (332 °C). The results again illustrate a wide variability in performance. However, ignition behavior is dominated by the outer jacket material, rather than the cable insulation material. The FIPEC cable samples involved a range of jacket materials, and many of these were PVC-based thermoplastic materials. Hence, the lower threshold values cited might be more an indication of the performance of the thermoplastic jackets than of the thermoset insulation. Note that in the U.S. nuclear industry it is not common practice to utilize thermoplastic or PVC jackets on a thermoset-insulated cable. Rather, thermoset cables will typically have neoprene, rubber-based, or chloro-sulfanated polyethylene (hypalon) jackets. These materials are all thermoset.

It is worth noting that in the IPEEEs, a commonly applied screening failure threshold for IEEE-383 qualified cables applied by licensees was 700 °F (370 °C). Note that IEEE-383 involves both LOCA electrical performance testing and a flame spread test. Virtually all cables fully qualified to both aspects of the IEEE-383 test standard are thermoset materials.[2] The 700 °F (370 °C) value is recommended in the EPRI FIVE method (EPRI TR-100370), and appears again in the EPRI Fire PRA Implementation Guide (EPRI TR-105928). The original source cited for this value is the EPRI cable damage tests reported in a series of Factory Mutual Research Corporation (FMRC) studies from the early 1980s (see in particular, EPRI NP-1767, March 1981). The method used to estimate the cable "critical" threshold values cited in the original FMRC work, and repeated in FIVE, has since been discredited, and has been disavowed by FMRC (see letter from A. Tewarson of FMRC to R. Kasawara of EPRI, dated May 10, 1995). There appears little basis for the continued reliance on 700 °F (370 °C) as a screening threshold for thermoset/qualified cables given the direct evidence of failures at substantially lower temperatures for a broad and common class of thermoset/qualified cable products.

<u>Suggested Method for Evaluating Generic Thermoset Cables</u>: A failure threshold of 625 °F (330 °C) is recommended for the generic class of thermoset cables.

<u>Summary of Basis</u>

- The recommended SDP practice ***does not*** bound all of the data on cable failure thresholds for all thermoset cable types. In particular, it does not bound the performance of some XLPO cable types (e.g., Polyset) and it does not bound one specific test data point related to XLPE. It also does not bound the proprietary material "Kerite FR" (see discussion below).
- Given their widespread use in the U.S. nuclear industry, failure thresholds for thermoset materials are based on XLPE-insulated cables.
- 330 °C is representative of clearly demonstrated and documented test results showing failures within an average time of well under one hour for a widely used specific XLPE-insulated cable product, Rockbestos Firewall III.

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2 Various thermoplastic materials will pass the flame spread portion of the IEEE-383 test, but not electrical performance requirement of the LOCA portions of the testing protocol. Such cables would not be considered "IEEE-383 qualified" in this context.

- The lower threshold values implied by the earlier tests in NUREG/CR-5384 are not recommended for this application given the relatively long failure times reported (average time of nearly one hour) and the very early vintage of the cables tested. The TVA results also provide evidence that the failure thresholds for most XLPE cables should be expected to exceed 570 °F (299 °C).
- The lower threshold values associated with the specific XLPO cable product tested in NUREG/CR-5655 is not recommended as a general criterion because this particular material/product is not widely used as an insulation material in the U.S. nuclear industry.
- It is recommended that the consideration of higher threshold values based on knowledge of a specific cable product being used in a specific case should be deferred to the Phase 3 analysis should such an analysis be pursued.

Special Exception: There is a particular proprietary cable insulation material called "Kerite FR." While this material is a thermoset, experimental evidence suggests it is substantially more vulnerable to thermal damage than are other thermoset materials. In particular, NUREG/CR-5655 reports substantial degradation of the cable's insulation value at temperatures as low as 307 °F (153 °C). Testing by SCE&G cites average temperatures at failure of 458 °F (237 °C) (as reported by Salley). Hence, it is recommended that the material Kerite FR should be analyzed using the failure criteria for a thermoplastic cable, not the values reported for a thermoset material.

A.5.3 Temperature Thresholds — Thermoplastic Cables

The typical thermoplastic cable is polyethylene-insulated (PE) often with a polyvinyl-chloride (PVC) jacket. This configuration is also considered representative of the weaker members of the thermoplastic group. The evidence for thermal failure threshold for PE-insulated cables can be taken from a number of sources.

Direct evidence of thermally induced electrical failure is provided in NUREG/CR-5384 (see Figure 6.3 in that reference). The failures for this cable were observed at temperatures as low as 482 °F (250 °C). At this exposure temperature, failure times ranged from 1.5 to 23.5 minutes and averaged about 9 minutes. At exposures of 356 °F (180 °C) no failures were observed in six test samples during two separate tests with exposures lasting approximately two hours. Given the relatively short failure times observed in some of the 482 °F (250 °C) exposure tests, the actual failure threshold likely lies somewhat below the cited 482 °F (250 °C) value, but certainly above 356 °F (180 °C).

Direct evidence of functional failure is also provided by testing conducted by Tennessee Valley Authority (TVA). Two samples of a PE/PVC (dual layer) insulated cables tested. The failure temperature in the first test was estimated as 346 °F (175 °C), and in the second test as 440 °F (227 °C). During the TVA tests, weights were placed on top of the sample cables to simulate the weight of a load of cables in a raceway. The first test utilized a load approximately 4 times larger than the second test. During the second test, the cables were examined immediately following the initial failure, and showed signs of substantial melting. A second series of tests in 1996 demonstrated satisfactory electrical performance for the same cable type exposed to temperatures peaking at 282 °F (139 °C) at the end of a one-hour exposure protocol.

A third source of direct evidences is testing by VTT Finland (ibid). Failures of a PVC-insulated cable were reported at temperatures as low as 385 °F (196 °C). These results might be discounted to some extent by the fact that these are tests of a European cable formulation, and likely a Russian formulation (given its use in the Finish nuclear industry). Hence, its formulation in comparison to typical U.S. material would be unknown. It is also uncommon to encounter a PVC-insulated cable in the U.S. nuclear industry. This result is taken as a general indication of marginal performance for these materials at temperatures exceeding 390 °F (200 °C).

A fourth source of direct evidence is the above cited EPRI expert panel report (TR1006961). The following damage insights are noted:

- Mowrer noted thermoplastic cable failures at a minimum temperature of 400 °F (205 °C). (See pg. B-21 of the EPRI TR1006961.)
- Funk concluded that, for thermoplastic cables, 400 °F (205 °C) was a "reasonably conservative" estimate of the "threshold of thermal insult below which cable failure (either partial or complete) does not occur, or is extremely unlikely." (See pg. B-3, ibid.)
- Salley noted at least one thermoset cable that failed at a temperature of 390 °F (200 °C) and recommended a threshold value of 400 °F (205 °C) for "garden variety thermoplastic cables." (See pg. B-64, ibid.)

Indirect evidence is provided based on the FIPEC piloted ignition thresholds. The minimum temperature reported for piloted ignition of a PE/PVC cable was 388 °F (197 °C) for one sample. All other samples showed ignition temperatures of 476 °F (246 °C) or greater. The average temperature for piloted ignition for the six cable types tested was 487 °F (253 °C).

It is worth noting that the EPRI FIVE method (EPRI TR-100370) recommended use of a failure threshold for non-qualified cables[3], generally corresponding to thermoplastic cables, of 425 °F (218 °C)[4]. This value was widely used by licensees in their IPEEE analyses. The basis for the value is not explicitly cited in the FIVE documentation. The value appears in Reference Table 1E (pg. 10.4-47).

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3 In this context, "qualified" refers a cable shown to pass all aspects of the IEEE-383 performance standard. An "un-qualified" or "non-qualified" cable is a cable that does not meet one or more aspects of the IEEE-383 standard. Note that a cable that has been shown to pass the IEEE-383 flame spread test but has not been shown to pass the LOCA electrical performance tests in IEEE-383 is considered "un-qualified" in this context.

4 See FIVE Reference Table 1E (pg. 10.4-67).

Recommended SDP practice: Continue the use of the commonly applied IPEEE failure threshold of 205 °C (400 °F) for non-qualified or thermoplastic cables.

Summary of Basis:
The recommended value is based on the available experimental evidence for PE and PVC-insulated cables.

- A value of 482 °F (250 °C) is known to yield damage times of on the order of 2-20 minutes.
- The TVA results for the heavily weighted cables in their first test can be discounted to some extent as being a grossly conservative loading configuration. However, the observation of cable failure at 346 °F (175 °C) does provide evidence of marginal performance at these temperatures.
- The loading configuration in the second TVA test cannot be discounted and yielded failures at 440 °F (227 °C) in an exposure of well under 1-hour duration.
- The recommended value is largely consistent with the piloted ignition results for the FIPEC study excluding only one test sample with a disproportionately lower ignition threshold.

A.5.4 Radiant Heating Failure Criteria — Cables

The available data for the electrical failure of cables under radiant heating conditions remains relatively sparse. While substantive data is available for higher heat flux conditions, the threshold conditions in particular have only been explored directly in a handful of cases.

The primary source of direct evidence is EPRI-sponsored tests conducted at Factory Mutual Research Corp. during the late 1970s and early 1980s (see for example, EPRI NP-1200). These tests involved a fairly wide range of NPP cable products. Unfortunately, the threshold exposure levels were only explored in a limited number of cases, and were extrapolated for most tests. The extrapolation method used in the data analysis has since been discredited.

There was also a limited set of early NRC-sponsored radiant exposure tests at Sandia National Laboratories in the late 1970s (see NUREG/CR-5384). These tests were conducted in a manner similar to the EPRI tests, but at a more representative scale using a loaded cable tray.

Some additional insights were gained from the FIPEC study. The FIPEC study involved primarily thermoplastic cables and focused on ignition properties with no direct monitoring of electrical failure. However, the ignition of a cable is taken as indirect evidence that electrical failure is imminent. Hence, these data are taken as indicators of threshold, but not timing (see discussion of failure timing).

Finally, current PRA practice as documented in the EPRI *FIVE* methodology and in the more recent EPRI *Fire PRA Implementation Guide*, was considered.

Based on the available information, threshold heat flux damage limits of 0.5 BTU/ft^2s (6 kW/m^2) have been recommended for thermoplastic cables. For thermoset cable the recommended damage threshold is 1.0 BTU/ft^2s (11 kW/m^2).

A.5.5 Basis for Cable Damage Timing Estimates

The data sources available to support the assessment of cable damage times are essentially identical to those described in the discussion of cable damage thresholds. The specific objective here is to estimate the damage time for a given exposure condition at or above the damage threshold. The following describes how the recommended damage time estimates were developed.

A.5.6 Temperature Exposures — Thermoset Cables

Damage timing for thermoset cables is based primarily on the data reported in NUREG/CR-5546 for XLPE-insulated cables (the Rockbestos Firewall III product). As previously discussed, the use of XLPE as representative of the thermoset class does not bound all of the thermoset products (see discussion of Polyset) but does bound the vast majority of thermoset products. XLPE is also the most popular single product used in the U.S. nuclear industry.

A review of the NUREG/CR data also showed that they were broadly consistent with more recent tests, including in particular the recent EPRI/NEI circuit failure tests (EPRI TR-1003326). The EPRI/NEI tests often involved temperatures very near the expected threshold of cable damage. Hence, the damage times were relatively prolonged, often in excess of 1 hour. This is consistent with the NUREG/CR data in that the damage times at the threshold temperature were also in excess of 1 hour. Hence, use of the specific information in the NUREG/CR appears appropriate.

These data are plotted in two figures. Figure A-4 shows the direct time to failure versus exposure temperature as directly recorded in the tests. In order to extrapolate between the recorded data points, the data are re-plotted as shown in Figure A-5.

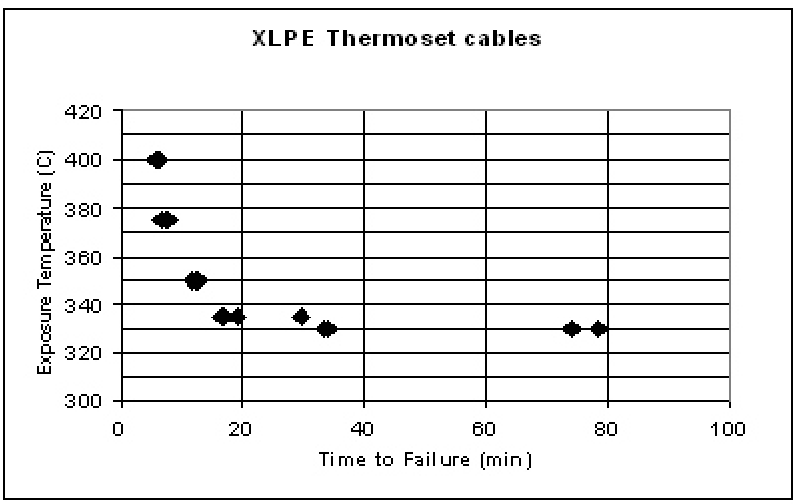

Figure A-4 Raw Time to Damage Chart for Thermoset XLPE Cables

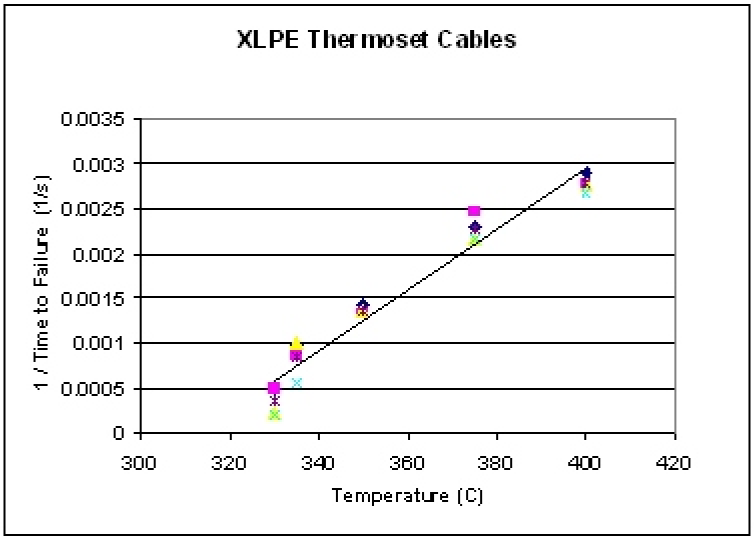

Figure A-5 Time to Damage Plot for Thermoset Cables with Linear Regression Curve

In this second plot the exposure temperature is plotted against the inverse of the time to failure. This inversion provides a near-linear relationship between the exposure temperature and the inverse of time to damage. This relationship is characterized by the following linear regression curve:

$$1/(\text{time to damage : seconds}) = 3.343\text{E-}05 \times (\text{Temp: °C}) - 1.044\text{E-}02$$

Using this relationship, a table of time to damage values was generated as previously presented. Note that the results of the linear regression were adjusted modestly for values that fell outside the data range where extrapolation is necessary. Also note that for the purposes of SDP analysis, the maximum damage times (at the threshold) were limited to 30 minutes. Table A-2 provides a time vs. temperature relationship for thermoset cables.

Table A-2. Failure Time-Temperature Relationship for Thermoset Cables

Exposure Temperature		Time to Failure (minutes)
°C	°F	
330	625	28
350	660	13
370	700	9
390	735	7
410	770	5
430	805	4
450	840	3
470	880	2
490 (or greater)	915 (or greater)	1

A.5.7 Temperature Exposures — Thermoplastic Cables

Damage timing for thermoplastic cables is, again, based primarily on the data reported in NUREG/CR-5384 for PE-insulated cables. These data were analyzed in a manner similar to that used in the analysis of the Thermoset cable response as discussed above. However, in the case of the thermoplastic cables, there was considerable scatter in the data. In particular, very short damage times are reported for some cases at the lowest exposure temperatures. The reasons for this scatter are not clear.

The data used in the analysis are again shown in two figures essentially identical to those discussed in the thermoset section above. Figure A-6 shows the direct time to failure versus exposure temperature as directly recorded in the tests for those cases used in the analysis. Figure A-7 shows the inverse of the time to failure - temperature relationship.

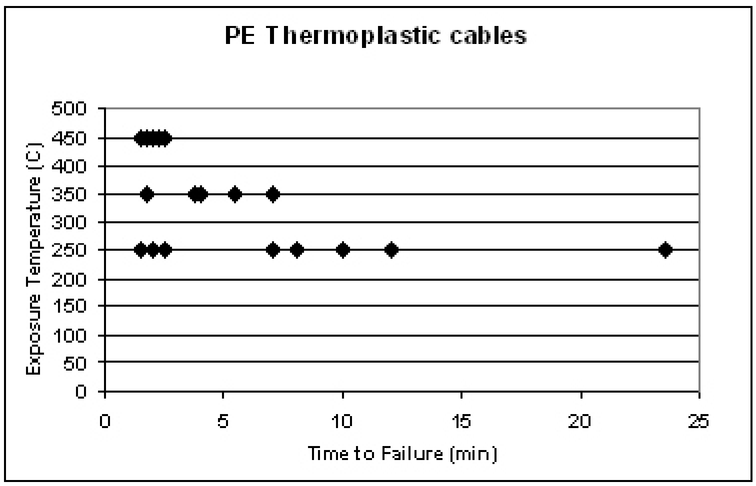

Figure A-6 Raw Time to Damage Plot for Thermoplastic PE Cables

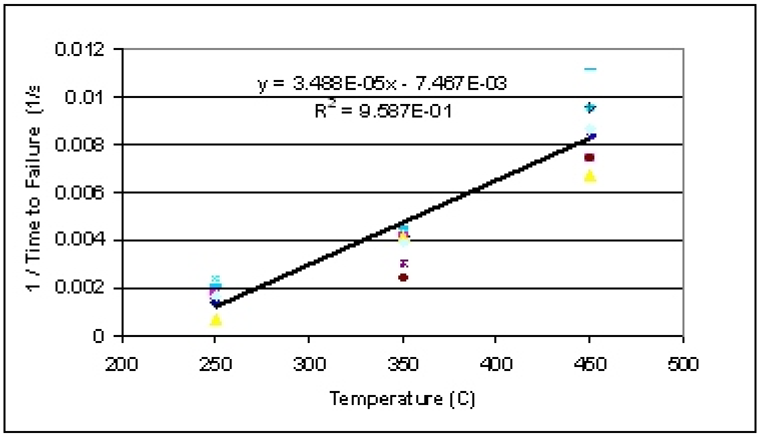

Figure A-7 Time to Damage Plot for Thermoplastic Cables with Linear Regression Curve

Using a similar analysis approach, the following linear regression curve was obtained:

$$1/(\text{time to damage : seconds}) = 3.488E\text{-}05 \times (\text{Temp: °C}) - 7.467E\text{-}03$$

Using this relationship, a table of time to damage values was generated. Again, results of the linear regression were adjusted for values that fell outside the data range where extrapolation is necessary. Table A-3 provides a time vs. temperature relationship for thermoplastic cables.

Table A-3. Failure Time-Temperature Relationship for Thermoplastic Cables

Exposure Temperature		**Time to Failure (minutes)**
°C	**°F**	
205	400	30
220	425	25
230	450	20
245	475	15
260	500	10
275	525	8
290	550	7
300	575	6
315	600	5
330	625	4
345	650	3
355	675	2
370 (or greater)	700 (or greater)	1

A.5.8 Radiant Exposures — Thermoset and Thermoplastic Cables

As previously noted, the available data for radiant exposure of cables is less complete than that for convective exposures. Most radiant heat tests have been conducted at relatively high heat flux levels, often representative of flashover conditions. This leads to relatively short damage times. The available tests generally reported damage times ranging from as short as a few seconds up to no more than 5–10 minutes. Fire risk analysis is also interested in marginal exposure conditions where damage times are expected to be upwards of 30 minutes or more. Given the data limitations, expert judgement has been applied to fill in our gaps in the understanding of radiant heating exposure conditions and the timing of cable damage.

Tables A-4 and A-5 provided below, document the recommended cable damage time/heat flux relationship for thermoset and thermoplastic cables.

Table A-4. Estimated Time to Damage for Radiant Heating Exposures for Thermoset Cables

Exposure Heat Flux		**Time to Damage (minutes)**
BTU/ft²s	**kW/m²**	
<1.0	<11	No Damage
1.0	11	19
1.2	14	12
1.4	16	6
1.6	18	1
1.75 or greater	20 or greater	1

Table A-5. Estimated Time to Damage for Radiant Heating Exposures for Thermoplastic Cables

Exposure Heat Flux		**Time to Damage (minutes)**
BTU/ft²s	**kW/m²**	
<0.5	<6	No Damage
.5	6	19
.7	8	10
0.9	10	6
1.0	11	4
1.25	14	2
1.4 or greater	16 or greater	1

A.6 References

LaChance, J., S.P. Nowlen, F. Wyant, and V. Dandini, “Circuit Analysis-Failure Mode and Likelihood Analysis,” A Letter Report to USNRC, Sandia National Laboratory, Albuquerque, New Mexico, ADAMS Accession #ML010450362, May 8, 2000.

BL-75-04, “Cable Fire at Browns Ferry Nuclear Power Station,” U.S. Nuclear Regulatory Commission, Washington, DC, March 24, 1975.

Salley, M.H., “An Examination of the Methods and Data Used to Determined Functionality of Electrical Cables When Exposed to Evaluated Temperatures as a Result of a Fire in a Nuclear Power Plant,” Master of Science Thesis, Department of Fire Protection Engineering, University of Maryland, College Park, Maryland, 2000.

NUREG/CR-6384, “Literature Review of Environmental Qualification of Safety-Related Electric Cables,” Volume 1, U.S. Nuclear Regulatory Commission, Washington, DC, April 1996.

NUREG/CR-2497, “Precursors to Potential Severe Core Damage Accidents: 1969–1979, A Status Report,” Volume 1 and 2, U.S. Nuclear Regulatory Commission, Washington, DC.

A.7 Additional Readings

Grayson, S.J., P.V. Hess, U. Vercellotti, H. Breulet, and A. Green, “Fire Performance of Electric Cables — New Test Methods and Measurements Techniques,” Interscience Communications, Limited, United Kingdom, 2000.

Zalosh, R.G., *Industrial Fire Protection Engineering*, Chapter 9, “Electrical Cables and Equipment,” John Wiley & Sons, New Jersey, 2003.

APPENDIX B. FUNDAMENTALS OF FIRE PROTECTION

This appendix reviews some selected fundamentals and most relevant characteristics of fire chemistry and physics (temperature, combustion products, smoke, toxicity, and fire extinguishing agents, etc.). Those inspectors who have never been exposed to fire protection will benefit from studying these fundamentals.

B.1 T-Squared (t^2) Fire Power Law Heat Release Rate

B.1.1 Introduction

The primary mechanism driving the growth of a fire is the flame spreading across a fuel item or between multiple fuel items. This growing fire will continue until one or more of the following conditions exist(s):

- Flashover occurs and all combustible materials are involved simultaneously.
- The fire cannot spread further due to lack of combustible materials.
- The fire uses all available oxygen for combustion.
- The fire is extinguished by intervention.

B.1.2 t^2 Heat Release Rate

Fire development varies depending on the combustion characteristics of the fuel(s) involved, the physical configuration of the fuel(s), the availability of combustion air, and the influences associated with the compartment. Once a stable flame is attained, most fires grow in an accelerating pattern, reach a steady state characterized by a maximum heat release rate (HRR), and then enter into a decay period as the availability of either fuel or combustion air becomes limited. Fire growth and development are limited by factors such as the quantity and arrangement of fuel, quantity of oxygen, and effect of manual and automatic suppression systems.

The primary parameter for describing fire growth is the HRR of the fire and how it changes with time. The fire growth rate depends on the ignition process; flame spread, which defines its perimeter; and the mass burning flux over the area involved. Once a combustible surface has ignited, the fire size increases as the flame spreads across the surface or as additional items in the room become involved. An important aspect is that the time required for the fire to grow is driven by the ignition source and the combustible or flammable materials present.

For most materials, a local ignition eventually involves the entire fuel item by flame-spreading processes. A typical sofa, for example, involves some combustion of horizontal, upward vertical, and downward vertical flame spread. For furniture and commodities, this complex fire growth process cannot be predicted by a simple formula. However, each item can have a characteristic growth time consistent with its composition and configuration. For example, a given item is ignited, it may achieve a heat release of 1 MW (1,000 kW) in 130 seconds, while another object might take 80 seconds. A complete mathematical description of this process is quite involved and relatively unpredictable given the range of ignition scenarios and the complexity of describing the burning item(s).

Nonetheless, testing has shown, that the overall HRR during the fire growth phase of many fires can often be characterized by simple-time dependent polynomial or exponential functions (Heskestad, 1997). The total heat release of fuel packages can be well approximated by the power law fire growth model for both single item burning and multiple items involved in a fire. Testing has also indicated that most growing fires can be expected to grow indefinitely until intervention by fire fighters, and the fires have an early incubation period where fire does not conform to a power law approximation, as shown in Figure B.1-1. That figure illustrates that following an incubation period, the HRR of the fire grows continuously, proportional to the square of time.

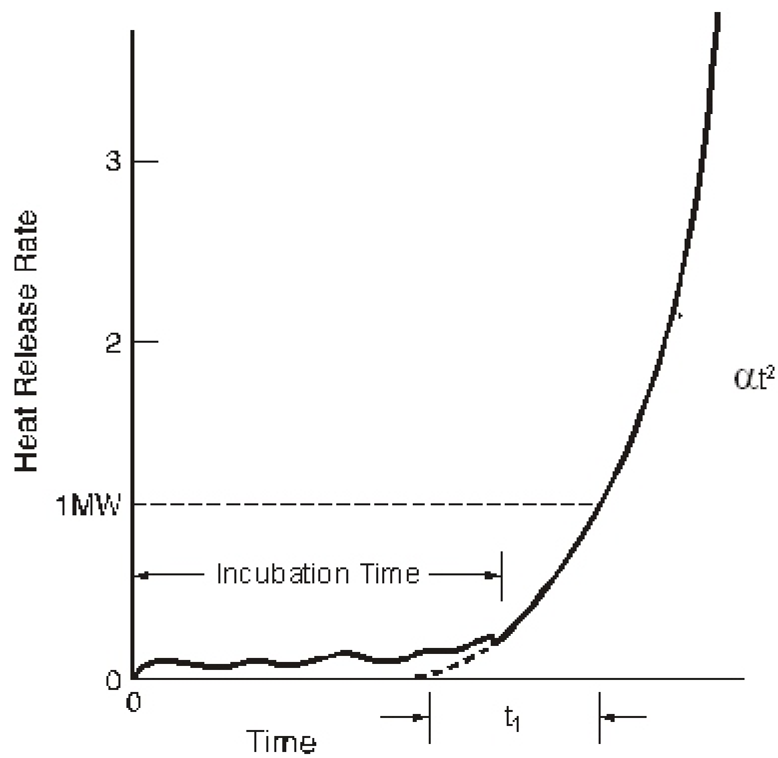

Figure B.1-1 Fire Growth of t^2 Fitted to Data
(Heskestad, 1997, © NFPA. With permission.)

The proposed model of the environment generated by fire in an enclosure is dependent on the assumption that the fire grows according to the following equation:

$$\dot{Q} = \alpha t^2 \qquad \text{(B-1)}$$

Where:

$\dot{Q}$ = the heat release rate (HRR) of fire (kW)
  = a constant governing the speed of fire growth (kW/sec^2)
t = the time (sec)

The proposed model of the environment generated by fire in an enclosure is dependent on the assumption that the fire grows according to the following equation:

$$\dot{Q} = \alpha t^2 \qquad \text{(B-2)}$$

Where:

$\dot{Q}$ = the rate of heat release of fire (kW)
  = a constant governing the speed of fire growth (kW/sec^2)
t = the time (sec)

The growth rate approximately follows a relationship proportional to time squared for flaming and radially spreading fires, which are consequently called t-squared (t^2) fires. Such fires are classed by the speed of growth, identified as ultra-fast, fast, medium, and slow. Where these classes are used, they are defined on the basis of the time required for the fire to grow to a heat release rate (HRR) of 1,000 kW (1 MW). Table B.1-1 summarizes the fire intensity constant ( ) and the growth time (t_g) for each of these classes.

Table B.1-1. Summary of t^2 Fire Parameters

Class of Fire Growth	**Intensity Constant (kW/sec^2)**	**Growth Time t_g (sec)**
Slow	0.00293	600
Medium	0.01172	300
Fast	0.0469	150
Ultra-Fast	0.1876	75

Figure B.1-2 plots the t^2 fire growth rate curves that have been developed. The t^2 relationship has proven useful and has therefore been adopted into NFPA 72, "National Fire Alarm Code®," to categorize fires for siting of detectors as well as NFPA 92B "Guide for Smoke Management Systems in Mall, Atria, and Large Areas," for design of smoke control systems.

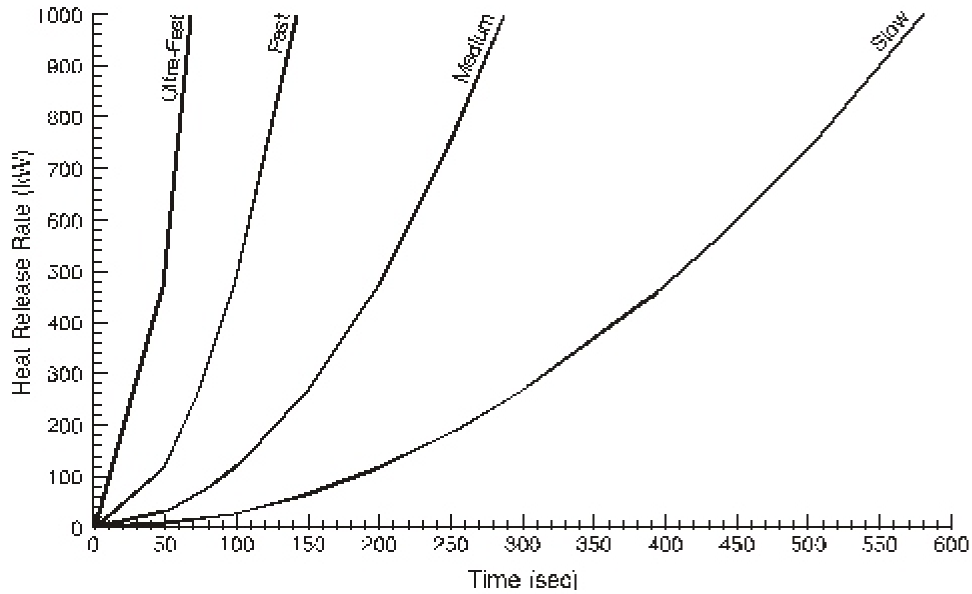

Figure B.1-2 Growth Rate Curves for t^2 Fire (NFPA, 72 and NFPA, 92B)

A t^2 fire can be viewed as one in which the HRR per unit area is constant over the entire ignited surface and the fire spreads as a circle with a steadily increasing radius. In such cases, the burning area increases in proportion to the square of the steadily increasing fire radius. Of course, fires that do not have such a conveniently regular fuel array and consistent burning rate might or might not actually produce a t^2 curve, but the t^2 approximation appears to be close enough for reasonable design decisions.

Figure B.1-3 provides the HRR results of various full-scale free burn tests performed at Factory Mutual Research Corporation (FMRC) (also reported by Nelson, 1987), superimposed on the t^2 HRR curves, using various standard test commodities for fuel arrays. Figure B.1-4 relates the classes of t^2 fire growth curves to a selection of actual fuel arrays. Figure B.1-5 plots the HRR curves for various upholstered furniture items. Figures B.1-3 to B.1-5 show that the actual fire growth curves for many common fuel arrays tend to be greater than the medium fire growth curve.

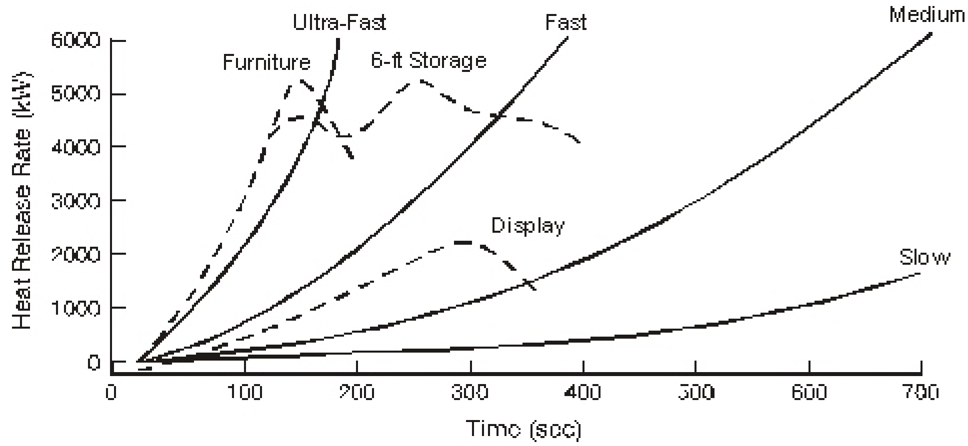

Figure B.1-3 Comparison of t^2 Heat Release Rate with Full-Scale Free-Burn Heat Release Rate (Nelson, 1987)

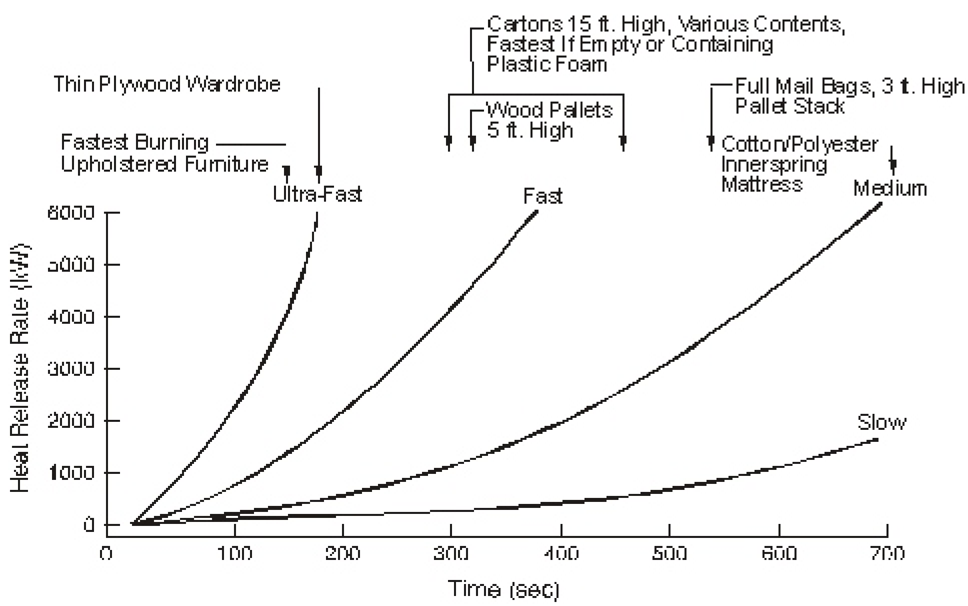

Figure B.1-4 Relation of t^2 Heat Release Rate to Some Fire Tests (Nelson, 1987)

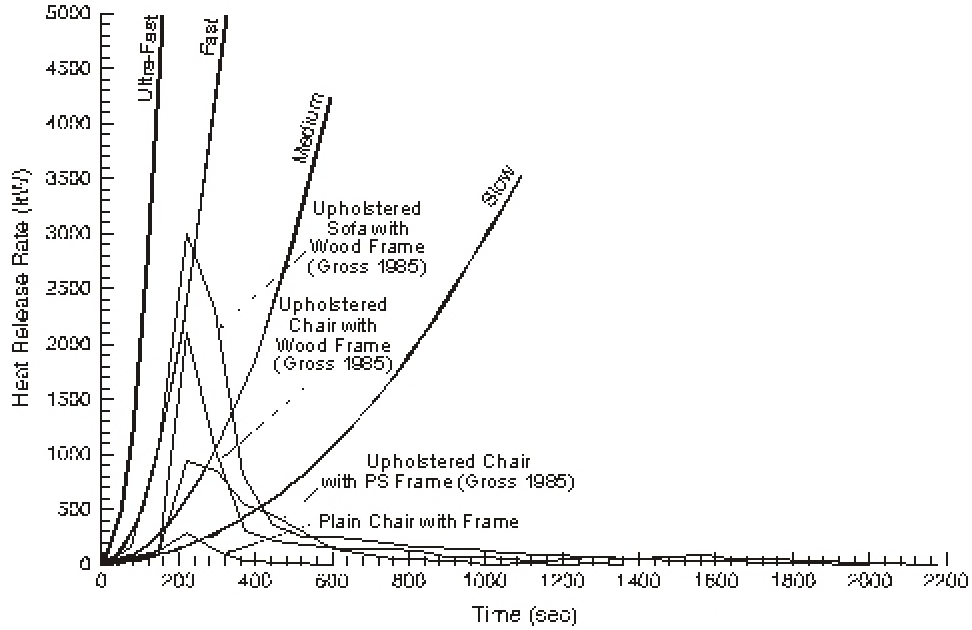

Figure B.1-5 Comparison of t^2 Heat Release Rates
with Full-Scale Furniture Heat Release Rate

Table B.1-2 tabulates the maximum HRR for various warehouse materials. As shown, the majority of these materials exhibit fire growth rates in the fast or ultra-fast ranges. The preponderance of actual fire testing over the 1990's has shown that common fuel arrays exhibit fire growth rates that tend to exceed the medium t^2 fire growth rate.

Table B.1-2. Maximum Heat Release Rates of Warehouse Materials
(NFPA 72, 1999 Edition, Appendix B)

Warehouse Material (See Notes 1 and 2)	**Growth Time (sec)**	**Heat Release Rate ($\dot{Q}$) (Btu/sec-ft²) (See Note 3)**	**Fire Growth Classification**
Wood pallets, stacked, 1½ ft high (6%–12% moisture)	150–310	110	Fast-Medium
Wood pallets, stacked, 5 ft high (6%–12% moisture)	90–190	330	Fast
Wood pallets, stacked, 10 ft high (6%–12% moisture)	80–110	600	Fast
Wood pallets, stacked, 16 ft high (6%–12% moisture)	75–105	900	Fast
Mail bags, filled and stored 5 ft high	190	35	Medium
Cartons, compartmented and stacked 15 ft high	60	200	Fast

Table B.1-2. Maximum Heat Release Rates of Warehouse Materials
(NFPA 72, 1999 Edition, Appendix B)

Warehouse Material (See Notes 1 and 2)	**Growth Time (sec)**	**Heat Release Rate ($\dot{Q}$) (Btu/sec-ft^2) (See Note 3)**	**Fire Growth Classification**
Paper, vertical rolls, stacked 20 ft high	15–28	-	(See Note 4)
Cotton (also PE, PE/cot, acrylic/nylon/PE), garments in 12 ft high racks	20–42	-	(See Note 4)
Cartons on pallets, rack storage, 15 ft–30 ft high	40–280	-	Fast-Medium
Paper products, densely packed in cartons, rack storage, 20 ft high	470	-	Slow
PE letter trays, filled and stacked 5 ft high on cart	190	750	Medium
PE trash barrels in cartons, stacked 15 ft high	55	250	Fast
FRP shower stalls in cartons, stacked 15 ft high	85	110	Fast
PE bottles, packed in item 6	85	550	Fast
PE bottles in cartons, stacked 15 ft high	75	170	Fast
PE pallets, stacked 3 ft high	130	-	Fast
PE pallets, stacked 6 ft–8 ft high	30–55	-	Fast
Methyl alcohol	-	65	-
Gasoline	-	200	-
Kerosene	-	200	-
Diesel oil	-	180	-

Notes:
(1) For SI units, 1 ft = 0.305 m.
(2) FRP = fiberglass-reinforced polyester; PE = polyethylene; PS = polystyrene; PP = polypropylene; PU = polyurethane; PVC = polyvinyl chloride.
(3) The HRRs per unit floor area are for fully involved combustibles, assuming 100-percent combustion efficiency. The growth times shown are those required to exceed 1,000 Btu/sec HRR for developing fires, assuming 100-percent combustion efficiency.
(4) Fire growth rate exceeds design data.

Madrzykowski (1996), compared HRR data for office work stations with standard t^2 HRR fire curves. Figure B.1-6 shows the HRR time history of the fire growth of a three-sided office work station compared to t^2 fire curves. Notice how the fire begins as a slow-medium growth rate fire, and then the slope increases to be representative of a fast-ultra-fast fire. As shown in Figure B.1-6, one can use the t^2 fire growth model to determine the HRR of similar fuel packages.

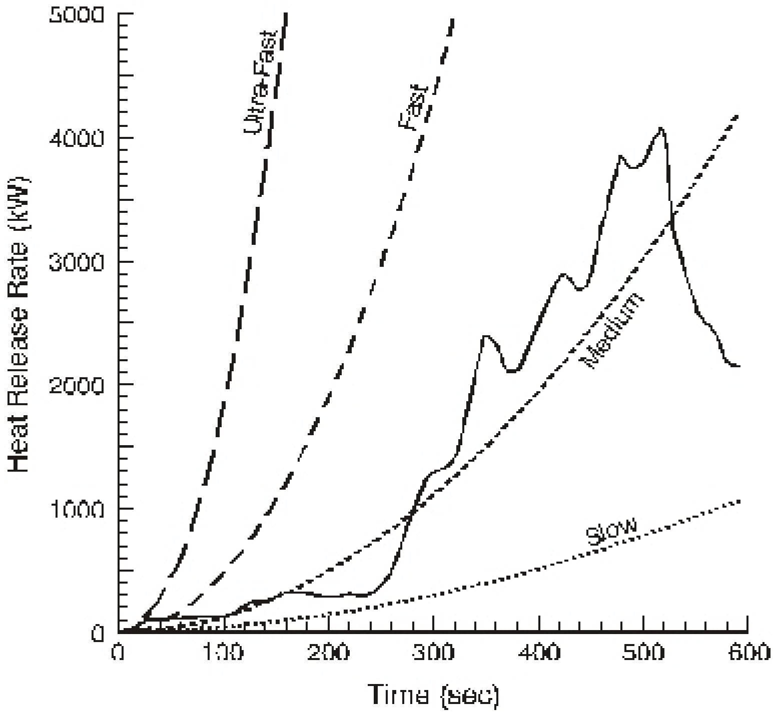

Figure B.1-6 Three-Sided Work Station Heat Release Rate Curve Compared with t^2 Curves (Madrzykowski, 1996)

Figure B.1-7 shows the relationship between t^2 fire curves and six 1.2-m (4-ft) high stacks of mixed wooden pallets (8 to 9 pallets per stack) arranged in two rows of three stacks, with the three stacks in each row forming an unbroken line with 100-mm between the front and back rows. Figure B.1-7 shows that both tests exhibited there was an incubation period following which the fire growth rate was approximately parallel to the t^2 fast fire growth curve.

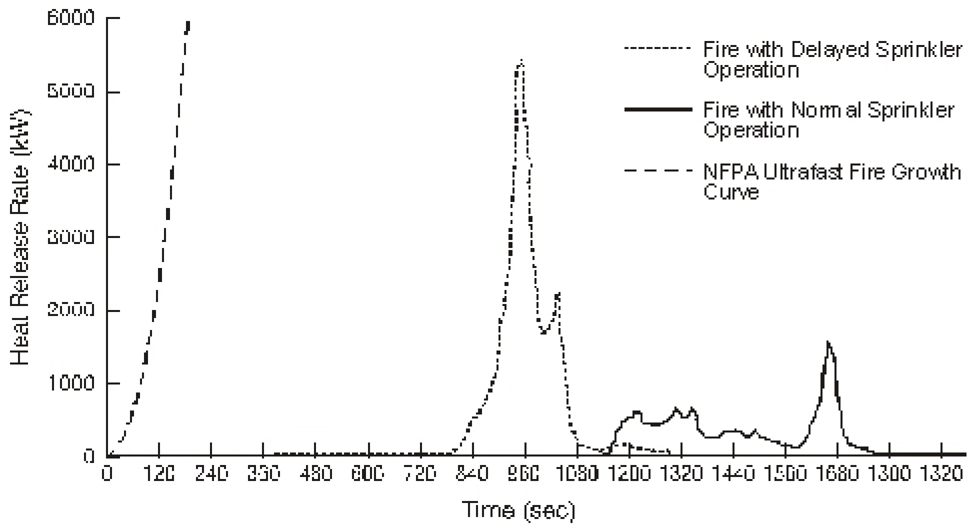

Figure B.1-7 Heat Release Rate Curve for Idle Pallets Compared with t^2 Curves (Garred and Smith, 1999, Interscience and Interflam. With permission.)

Figure B.1-8 shows the relationship between t^2 fire curves and six 12-m (4-ft) high stacks of cardboard boxes arranged in two rows of three stacks, with no gaps between the stacks. The boxes were ignited by setting light to a ball of crumpled newspaper pushed 100 mm under the front of the central stack in the front row of the array. Figure B.1-8 shows that both tests exhibited a long incubation period, as the ball of newspaper proved to be slow burning. However, the fire did break into the boxes immediately above the ignition source, and the flames eventually burst from the front of those boxes and then rapidly up the front of the central (ignition) stack. Thereafter the fire growth rate was similar to the ultra-fast t^2 fire curve.

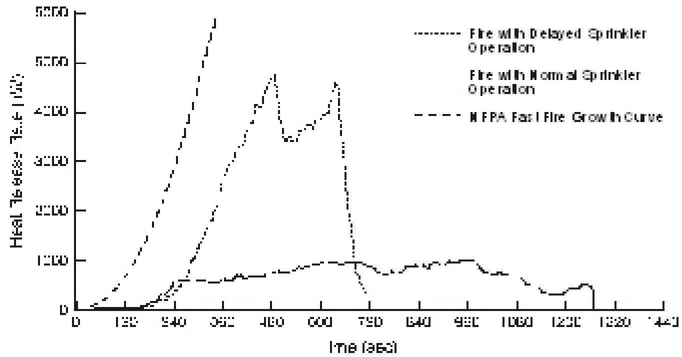

Figure B.1-8 Heat Release Rate for Stacked Box Fires Compared with t^2 Curves
(Garred and Smith, 1999, Interscience and Interflam. With permission.)

B.1.3 References

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Heskestad, G. “Venting Practice,” Section 7, Chapter 7, *NFPA Fire Protection Handbook*, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, pp. 7–105, 1997.

Madrzykowski, D., “Office Station Heat Release Study: Full Scale vs. Bench Scale,” Interflam 1996, Conference Proceedings of the 7th International Interflam Conference, Interscience Communication Limited, England, Compiled by C.A. Franks, pp. 47–55, 1996.

Nelson, H.E., “An Engineering Analysis of the Early Stages of Fire Development: The Fire at the Dupont Plaza Hotel and Casino on December 31, 1986,” NBSIR 87-3560, U.S. Department of Commerce, National Bureau of Standards (NBS), Gaithersburg, Maryland, May 1987.

NFPA 72, “National Fire Alarm Code,” 1999 Edition, National Fire Protection Association, Quincy, Massachusetts.

NFPA 92B, “Guide for Smoke Management Systems in Malls, Atria, and Large Areas,” 2000 Edition, National Fire Protection Association, Quincy, Massachusetts.

B.2 Elements of Hydraulic and Electrical Systems

Table B.2-1 provides the basic elements of a hydraulic system along with the corresponding elements of an electrical system.

Table B.2-1. Corresponding Elements of Hydraulic and Electrical Systems (NFPA 921, 2002 Edition)

Elements of a Hydraulic System	**Elements of an Electrical System**
Pump	Generator
Pressure	Voltage (potential or electromotive force)
Pounds per square inch (psi)	Volts (V)
Pressure gauge	Voltmeter
Water	Electrons
Flow	Current
Gallons per minute (gpm)	Amperes (A)
Flowmeter	Ammeter
Valve	Switch
Friction	Resistance (Ohms)
Friction loss	Voltage drop
Pipe size (inside diameter)	Conductor size (AWG No.)

Hydraulic systems use a pump to create the hydraulic pressure necessary to force water through pipes. The amount of hydraulic pressure is expressed in pounds per square inch (psi) and can be measured with a pressure gauge. By contrast, electrical systems use a generator to create the necessary electrical pressure (voltage) to force electrons through a conductor. The amount of electrical pressure is expressed in volts and can be measured with a voltmeter.

In hydraulic systems, water flows in a useful way. The amount of water flow is expressed in gallons per minute (gpm) and may be measured with a flowmeter. By contrast, electrical systems, it is electrons that flow in a useful way in the form of electrical current. The amount of electrical current is expressed in amperes (A) and may be measured with an ammeter. Electric current can be either direct current (dc), such as supplied by a battery, or alternating current (ac), such as supplied by an electrical utility company.

In hydraulic systems, water pipes provide the pathway for the water to flow. By contrast, electrical systems, conductors such as wires provide the pathway for the current to flow.

In a closed circulating hydraulic system (as opposed to a fire hose delivery system, where water is discharged out of the end of the hose), water flows in a loop, returning to the pump, where it again circulates through the loop. When the valve is closed, the flow stops everywhere in the system. When the valve is opened, the flow resumes. By contrast, an electrical system *must* be a closed system, in that the current must flow in a loop known as a complete circuit. When the switch is turned on, the circuit is completed and the current flows. When the switch is turned off, the circuit is open (incomplete) and the current flow stops everywhere in the circuit. This voltage drop is called the potential or electromotive force.

Friction losses in the pipes of a hydraulic system result in pressure drops. By contrast, electrical friction (i.e., resistance) in conductors and other parts of an electrical system results in electrical pressure drops or voltage drops. Ohm's law must be used to express resistance as a voltage drop.

When electricity flows through a conducting material, such as a conductor, a pipe, or any piece of metal, heat is generated. The amount of heat depends on the resistance of the material through which the current is flowing and the amount of current. Some electrical equipment, such as heating units, are designed with appropriate resistance to convert electricity to heat.

The flow of water in a pipe at a given pressure drop is controlled by the pipe size. A larger pipe allows a greater volume (more gallons per minute) of water to flow than a smaller pipe at a given pressure drop. Similarly, larger conductors allow more current to flow than smaller conductors. Conductor sizes are given in American Wire Gauge (AWG) numbers. The larger the number, the smaller the conductor diameter. The larger the diameter (and hence the larger the cross-sectional area) of the conductor, the lower the AWG number and the less resistance the conductor has.

B.2.1 Reference

NFPA 921, "Guide for Fire and Explosion Investigations," 2001 Edition, National Fire Protection Association, Quincy, Massachusetts.

B.3 Classes of Fires

Generally the purpose of a letter designation given to a particular fire category is to classify it according to the type of fuel and possible spread of the fire. The letter classification also provides a general indication of the severity and type of the hazard. NFPA 10, "Standard for Portable Fire Extinguishers," classifies fires as either Class A, Class B, Class C, Class D, or Class K according to the fuel involved.

Class A Fires

Fires in ordinary combustible materials, such as wood, cloth, paper, rubber, and many plastics.

Class B Fires

Fires in flammable or combustible liquids, petroleum greases, tars, oils, oil-based paints, solvents, lacquers, alcohols, and flammable gases.

Class C Fires

Fires that involve energized electrical equipment where the electrical nonconductivity of the extinguishing media is of importance. (When electrical equipment is de-energized, fire extinguishers designed for Class A or Class B fires can be safely used).

Class D Fires

Fires in combustible metals, such as magnesium, titanium, zirconium, sodium, lithium, and potassium.

Class K Fires

Fires in cooking appliances that involve combustible cooking media (vegetable or animal oils and fats).

B.3.1 Reference

NFPA 10, "Standard for Portable Fire Extinguishers," 2002 Edition, National Fire Protection Association, Quincy, Massachusetts.

B.4 Classification of Hazards

B.4.1 Light (Low) Hazard

Light hazard occupancies are locations where the total amount of Class A combustible materials (including furnishings, decorations, and content), is a minor quantity. This can include some buildings or rooms occupied as offices, classrooms, churches, assembly halls, guest room areas of hotels/motels, and so forth. This classification anticipates that the majority of content items are either noncombustible or so arranged that a fire is not likely to spread rapidly. Small amounts of Class B flammables used for duplicating machines, art departments, and so forth, are included, provided that they are kept in closed containers and safely stored (Conroy, 1997 and NFPA 10).

B.4.2 Ordinary (Moderate) Hazard

Ordinary hazard occupancies are locations where of Class A combustibles and Class B flammables are present in greater total amounts than expected under light (low) hazard occupancies. These occupancies could consist of dining areas, mercantile shops, and allied storage; light manufacturing, research operations, auto showrooms, parking garages, workshop or support service areas of light (low) hazard occupancies; and warehouses containing Class I or Class II commodities as defined by NFPA 231, "Standard for General Storage," (Conroy, 1997 and NFPA 10).

B.4.3 Extra (High) Hazard

Extra hazard occupancies are locations where the total amount of Class A combustibles and Class B flammable (in storage, production, use, finished product, or combination thereof) is over and above those expected in occupancies classed as ordinary (moderate) hazard. These occupancies could consist of woodworking, vehicle repair, aircraft and boat servicing, cooking areas, individual product display showrooms, product convention center displays, and storage and manufacturing processes such as painting, dipping, and coating, including flammable liquid handling. Also included is warehousing or in-process storage of other than Class I or Class II commodities (Conroy, 1997 and NFPA 10).

B.4.4 References

Conroy, M.T. "Fire Extinguisher Use and Maintenance," Section 6, Chapter 23, *NFPA Fire Protection Handbook*, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts. 1997.

NFPA 10, "Standard for Portable Fire Extinguishers," 2002 Edition, National Fire Protection Association, Quincy, Massachusetts.

NFPA 231, "Standard for General Storage," National Fire Protection Association, Quincy, Massachusetts.

B.5 Classes of Fires and Extinguishing Agents

One or more of the following mechanisms—more often, several of them simultaneously—can be used to extinguish fire:

- Physically separating the combustible substance from the flame
- Removing or diluting the oxygen supply
- Reducing the temperature of the combustible or of the flame
- Introducing chemicals that modify the combustion chemistry

For example, when water is applied to a fire of a solid combustible burning in air, several extinguishing mechanisms are involved simultaneously. The solid is cooled by the contact with water, causing its rate of pyrolysis, or gasification, to decrease. The gaseous flame is cooled, causing a reduction in heat feedback to the combustible solid and a corresponding reduction in the endothermic pyrolysis rate. Steam is generated, which, under some confined conditions, may prevent oxygen from reaching the fire. Water in the form of fog may block radiative heat transfer.

As another example, consider the application of a blanket of aqueous foam to a burning pool of flammable liquid. Several mechanisms may be operative. The foam prevents the fire's radiant heat from reaching the surface and supplying the needed heat of vaporization. If the fire point of the flammable liquid is higher than the temperature of the foam, the liquid is cooled and its vapor pressure decrease. If the flammable liquid is water soluble, such as alcohol, then, by a third mechanism, it will become diluted by water from the foam, and the vapor pressure of the combustible will be reduced.

As yet an example, when dry chemical is applied to a fire, the following extinguishing mechanisms may be involved:

- Chemical interaction with the flame
- Coating of the combustible surface
- Cooling of the flame
- Blocking of radiative energy transfer

The agent mentioned above—water, foam, and dry chemicals—each work by a combination of several mechanisms, and the relative importance of the various contributions varies with circumstances. Table B.5-1 provides the classes of fires with examples and extinguishing agent.

Table B.5-1. Fire Classes with Extinguishing Agents

Fire Class	Description	Examples	Extinguishing Agents
A	Ordinary combustibles	Wood, cloth, paper, rubber, and many plastics	Water, dry chemicals, foam, some Halon
B	Flammable liquids, gases, and liquid-derived solids	Gasoline, oils, LPG, paraffin or heavy lubricants, grease	CO_2, dry chemical agents, Halon, foam (Class B extinguishers isolate the fuel from the heat by cutting off oxygen to the combustion zone or by inhibiting and interrupting the formation of molecular chain reactions)
C	The same fuels as Class A and B fires, together with energized electrical equipment	Energized Class A material, such as household appliances	CO_2, dry chemical agents, Halon (Extinguishers for Class C fires are rated according to the nonconductive properties of the extinguishing agent)
D	Combustible metals or metallic alloy elements with combustible metal components	Magnesium, sodium, potassium, titanium, zirconium, and lithium	Dry chemical agents (Water and water-based extinguishers should never be used on Class D fires. To be effective on a Class D fire, an extinguisher must suppress the fire without reacting physically or chemically with the combustible metal materials)
K	Cooking appliances that involve combustible cooking media	Vegetable or animal oils and fats	Dry chemical agents, CO_2, wet chemical agents

B.6 Classification of Flammable and Combustible Liquids

In common usage, *flammable* refers to a liquid that is readily ignited, burns rapidly and vigorously, and produces a lot of thermal energy—in other words, heat. *Combustible* usually refers to a liquid that is less easily ignited, burns less rapidly, and is, therefore, relatively safer. In simple terms, *flammable liquids* produce vapors at normal room temperature in concentrations that can be easily ignited by a small spark or flame. *Combustible liquids* ***do not*** produce vapors that can be ignited at normal room temperature. However, if a combustible liquid is heated up to or above its flash point, the vapors generated by the now-heated liquid can be ignited. In these cases, combustible liquids can be just as dangerous as flammable liquids. And, some of them, hydrocarbon fuels for examples, can burn just rapidly and evolve just much heat once they are ignited. Some common combustible liquids—mineral spirits and paint thinners, for example—are blended so they are just above the accepted dividing line between flammable and combustible. So, moderate heating of these liquids or storing them in a very warm environment can also present a fire hazard.

B.6.1 Flammable Liquid

According to most fire safety codes (NFPA 30, "Flammable Combustible Liquids Code"), a flammable liquid is generally defined as any liquid that has a closed-cup flash point below 37.8 °C (100 °F). Flash points may be determined by procedures and apparatus set forth in ASTM D56, D92, D93, D1310, or D3278.

NFPA 11 defined flammable liquids as any liquid having flash point below 37.8 °C (100 °F) and having a vapor pressure not exceeding 276 kPa (40 psi) (absolute) at 37.8 °C (100 °F).

Flammable liquids can be divided into classes (which are further divided into sub-classes), based on their flash points as summarizes in Table B.6-1. Class I - Liquids have a flash point below 38 °C (100 °F) and subdivided as follows:

Table B.6-1. Flammable Liquid Classifications
(NFPA 30, 2000 Edition)

Classification	**Flash Point (°F)**	**Boiling Point (°F)**	**Example(s)**
Class IA Flammable	< 73	< 100	Ethyl ether Acetic aldehyde, Dimethyl sulfide, Furan
Class IB Flammable	< 73	≥ 100	Ethyl alcohol, gasoline-92 octane, Cyclohexane
Class IC Flammable	≥73 and < 100	N/A	Butyl ether

B.6.2 Combustible Liquid

A combustible liquid is defined as any liquid that has a closed-cup flash point above 37.8 °C (100 °F). Combustible liquids can be divided into classes (which are further divided into sub-classes), based on their flash points as summarizes in Table B.6-2.

Class II Combustible liquids with flash points at or above 38 °C (100 °F), but below 60 °C (140 °F).

Class III Combustible liquids with flash points at or above 60 °C (140 °F).

Table B.6-2. Combustible Liquid Classifications
(NFPA 30, 2000 Edition)

Classification	Flash Point (°F)	Boiling Point (°F)	Examples
Class II Combustible	≥ 100	N/A	Fuel oil # 1 (kerosene), diesel fuel oil # 1-D/2-D/4-D, glacial acetic acid, and jet fuel (A & A-1)
Class III A Combustible	≥ 140 and < 200	N/A	Fuel oil # 6, creosote oil, and butyl carbitol
Class III B Combustible	≥ 200	N/A	Fuel oil # 4, mineral oil, olive oil, and lubricating oil (motor oil)

Assume that a liquid spill occurs on a summer day when the ground has been heated by the sun to 35 °C (95 °F). Clearly, a spill of Class I (flammable) liquid is extremely hazardous with regard to fire; however, a spill of a Class II liquid is dangerous from a fire viewpoint only if a heat source exists that is capable of moderately raising the temperature of the liquid and a spill of Class III liquid is safe from ignition unless a heat source exists that can substantially raise its temperature.

Table B.6-3 lists the flash points of some common flammable and combustible liquids. Notice the wide range, from -43 °C to +243 °C (-45 °F to +469 °F). These values are meaningful only for bulk liquids. If a liquid with a high flash point is in the form of a spray, a froth, or a foam, with air present, and comes into contact with even a very small ignition flame, the tiny amount of liquid in contact will be immediately heated to above its flash point and will begin to burn. The combustion energy released will vaporize the surrounding spray or foam, and the fire will propagate (spread).

Table B.6-3. Flash Points of Flammable and Combustible Liquids (Benedetti, 1997)

Liquid Fuel	**Flash Point °C (°F)**
Class I (Flammable) Liquids	
Gasoline	-43 (-45)
n-Hexane	-26 (-15)
JP-4 (jet aviation fuel)	-18 (0)
Acetone	-16 (3)
Toluene	9 (48)
Methanol	11 (52)
Ethanol	12 (54)
Turpentine	35 (95)
Class II (Combustible) Liquids	
No.2 fuel oil (domestic)	>38 (>100)
Diesel fuel	40–50 (104–131)
Jet A (jet aviation fuel)	47 (117)
Kerosene	52 (126)
No. 5 fuel oil	>54 (>130)
Class III (Combustible) Liquids	
JP-5 (jet aviation fuel)	66 (151)
SAE No. 10 lube oil	171 (340)
Triresyl phosphate	243 (469)

B.6.3 Storage of Flammable and Combustible Liquids

Flammable and combustible liquids are packed, shipped, and stored in bottle, drums, and other containers ranging in size up to 60 gal (225 L). Additionally, liquids are shipped and stored in intermediate bulk containers up to 793 gal (3,000 L) and in portable intermodal tanks up to 5,500 gal (20,818 L). Storage requirements for each these containers are covered in the NFPA 30 chapters entitled, “Containers and Portable Tank Storage,” with the exception of those portable tanks larger than 793 gal (3,000 L) that are required to meet the applicable requirements covered in the NFPA 30 chapter entitled, “Tank Storage.”

Examples of containers types used for the storage of liquids include glass, metal, polyethylene (plastic), and fiberboard. The maximum allowable size for the different types of containers is governed by the class of flammable or combustible liquid to be stored in it. Table B.6-4 lists the maximum allowable size (capacity) of a container or metal tank used to store flammable and combustible liquids.

Table B.6-4. Maximum Allowable Size of Containers and Portable Tanks for Flammable and Combustible Liquids (NFPA 30, 2000 Edition)

Liquid Container Type	**Flammable Liquid**			**Combustible Liquid**	
	Class IA	**Class IB**	**Class IC**	**Class II**	**Class III**
Glass	1 pt	1 qt	1 gal	1 gal	5 gal
Metal (other than DOT drum) or approved plastic	1gal	5 gal	5 gal	5 gal	5 gal
Safety cans	2 gal	5 gal	5 gal	5 gal	5 gal
Metal drum (DOT specification)	60 gal	60 gal	60 gal	60 gal	60 gal
Approved metal portable tank and IBC	793 gal	793 gal	793 gal	793 gal	793 gal
Rigid plastic IBC (UN 31H1 or 31H2) or composite IBC (UN 31HZ1)	NP	NP	NP	793 gal	793 gal
Polyethylene (DOT specification 34, UN 1H1, or as authorized by DOT exemption)	1 gal	5 gal	5 gal	60 gal	60 gal
Fiber drum (NMFC or UFC Type 2A; Types 3A, 3B-H, or 3B-L; or Type 4A)	NP	NP	NP	60 gal	60 gal

SI Units - 1pt = 0.473 L; 1 qt = 0.95 L; 1 gal = 3.8 L
NP = Not Permitted
IBC = Intermediate Bulk Container
DOT = U.S. Department of Transportation

B.6.4 Flammable Combustible Storage Cabinets

Most commercially available and approved storage cabinets are built to hold 60 gallons (227 liters) or less of flammable and/or combustible liquids.

Not more than 120 gal (454 L) of Class I, Class II, and Class IIIA liquids shall be stored in a storage cabinet. Of this 120 gal total, not more than 60 gal (227 L) shall comprise Class and Class II liquids.

B.6.5 Definitions

Flash Point
The minimum temperature to which a liquid must be heated in a standardized apparatus, so that a transient flame moves over the liquid when a small pilot flame is applied.
Alternately, the flash point of a liquid may be defined as the temperature at which the vapor and air mixture lying just above its vaporizing surface is capable of just supporting a momentary flashing propagation of a flame prompted by a quick sweep of small gas pilot flame near its surface (hence the term flash point). The flash point is mainly applied to liquids. The flash point of liquid is one of its characteristics that normally determines the amount of fire safety features required for its handling, storage, and transport.

Fire Point
The minimum temperature to which a liquid must be heated in a standardized apparatus, so that sustained combustion results when a small pilot flame is applied, as long as the liquid is at normal atmospheric pressure.

Boiling Point
The temperature at which the transition from the liquid to the gaseous phase occurs in a pure substance at fixed pressure. Alternatively, the boiling point may be defined as the temperature at which the vapor pressure of a liquid equals the surrounding atmospheric pressure. For purposes of defining the boiling point, atmospheric pressure shall be considered to be 14.7 psia (760 mm Hg). For mixtures that do not have a constant boiling point, the 20-percent evaporated point of a distillation performed in accordance with ASTM D86, “Standard Method of Test for Distillation of Petroleum Products,” shall be considered to be the boiling point.

Autoignition
Initiation of fire or combustion by heat but without the application of a spark or flame.

Autoignition Temperature
The lowest temperature at which a mixture of fuel and oxidizer can propagate a flame without the aid of an initiating energy source (pilot, spark, or flame).

High-Risk Fuel
Class IA, IB, IC, or II liquids as defined by NFPA 30, “Flammable and Combustible Liquids Code,” or Class IIIA, or III B liquids heated to within 10 °C (50 °F) of their flash point, or pressurized to 174.4 kPa (25.3 psi) or more.

B.6.6 Hazardous Materials

A substance (solid, liquid, or gas) capable of creating harm to people, property, and the environment. The general category of hazard assigned to a hazardous material under the U.S. Department of Transportation (DOT) regulation. Table B.6-5 lists the hazardous material classification.

Table B.6-5. Hazardous Material Classification

Hazard Class	Description
Class 1 - Explosives	
Division 1.1	Explosive with a mass explosion hazard
Division 1.2	Explosives with a projection hazard
Division 1.3	Explosives with predominantly a fire hazard
Division 1.4	Explosives with no significant blast hazard
Division 1.5	Very insensitive explosives
Division 1.6	Extremely insensitive explosive articles
Class 2	
Division 2.1	Flammable gas
Division 2.2	Nonflammable, non-poisonous compressed gas
Division 2.3	Poison gas
Division 2.4	Corrosive gas
Class 3 - Flammable Liquid	
Division 3.1	Flammable liquids, flash point < 0 °F
Division 3.2	Flammable liquids, flash point 0 °F and above but < 73 °F
Division 3.3	Flammable liquids, flash point 73 °F and up to < 141 °F combustible liquid
Class 4	
Division 4.1	Flammable solid
Division 4.2	Spontaneously combustible material
Division 4.3	Dangerous when wet material
Class 5	
Division 5.1	Oxidizer
Division 5.2	Organic peroxide
Class 6	
Division 6.1	Poisonous material
Division 6.2	Infectious material
Class 7	Radioactive material
Class 8	Corrosive material
Class 9	Miscellaneous hazardous material, ORM-D material

B.6.7 References

Benedetti, R.P., Editor, "Flammable and Combustible Liquids Code Handbook," 6th Edition, National Fire Protection Association, Quincy, Massachusetts, 1997.

NFPA 11, "Standard for Low-Expansion Foam," 2002 Edition, National Fire Protection Association, Quincy, Massachusetts.

NFPA 30, "Flammable and Combustible Liquids Code," 2000 Edition, National Fire Protection Association, Quincy, Massachusetts.

B.7 Classification of Flammable Gases

B.7.1 Classification

Flammable gases are classified according to the maximum experimental safe gap (MESG), which prevents flame passage. MESG is determined by test IEC 79-1A, "Electrical Apparatus for Explosive Gas Atmospheres," International Electrotechnical Commission (IEC), 1975 (Senecal, 1997).

Class I	Group A - acetylene Group B - hydrogen Group C - ethylene Group D - propane
Division 1	Flammable gases or combustible dust may be present at ignitable concentrations, under normal operating conditions.
Division 2	Where hazardous materials may be handled, processed, or used; ignitable atmospheres not normally present due to containment or ventilation of hazardous materials; areas adjacent to Division 1 locations.

B.7.2 Definitions

Flammable Limits
The minimum and maximum concentration of combustible material in a homogeneous mixture with a gaseous oxidizer that will propagate a flame.

Upper and Lower Flammability Limits
Concentration of fuel in air in which a premixed flame can propagate.

Lower Flammability Limit
The lowest concentration of fuel in air at normal temperature and pressure that can support flame propagation is known as the lower flammability limit (LFL) or lower explosive limit (LEL).

Upper Flammability Limit
The highest concentration of fuel in air at normal temperature and pressure that can support flame propagation is known as the upper flammability limit (UFL) or upper explosive limit (UEL).

B.7.3 Reference

Senecal, J.A., "Explosion Prevention and Protection," Section 4, Chapter 14, *NFPA Fire Protection Handbook*, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1997.

B.8 Flammability Hazards of Gases

B.8.1 Flammability Potential of Gases

Flammability hazards in a tank or vessel dependent upon the potential for developing a flammable fuel/oxidant/inert gas mixture in the tank or vessel head space. Mixtures of fuel and air are only flammable for limited fuel-to-air ratio. The most flammable mixture is a stoichiometric mixture, in which the fuel and air (oxygen) are present in exactly the right proportions for oxidation, as dictated by the stoichiometry of the fuel/oxygen combustion reaction. Mixtures with some excess oxygen or excess fuel are also flammable, the lowest concentration of fuel in air that can support flame propagation at normal temperature and pressure is known as the lower explosive limit (LEL). Similarly, the highest concentration of fuel in air that can support flame propagation at normal temperature and pressure is known as the upper explosive limit (UEL). Mixtures of fuel in air with intermediate fuel concentrations will support flame propagation.

The flammability of gas mixtures is determined by one of two widely utilized laboratory methods. The first method uses a 5-foot-long tube that is filled with the test mixture, and a spark is used to ignite the mixture at one end to observe whether ignition occurs and whether the flame can propagate to the other end of the tube. The second method uses a spherical tank or vessel that is filled with the test mixture, and a spark is used to ignite the mixture at the center of the tank or vessel to measure the pressure increase to determine whether flame propagation occurred throughout the tank or vessel (Beyler, 1995). The spherical vessel test method is more representative of an actual tank or vessel than is the tube method.

The terms “explosive limits” and “flammable limits” are used interchangeably in the technical literature. Explosive limits simply refer to compositions, which define when flame propagation is possible. The flame propagation is known as a deflagration and results in a pressure increase as the flame passes through a vessel. This resulting overpressure is the origin of the term explosive limit, where an explosion is any event, that results in a sudden overpressure in the vessel.

When the LEL mixture has excess oxygen and insufficient fuel for complete burning, the mixture is known as “fuel lean.” The potential heat output, which defines how hot the products of combustion can be is limited not by oxygen, but by fuel concentration. The ideal “no heat loss” post-combustion temperature is known as the “adiabatic flame temperature” (AFT). For most flammable gases, the AFT at atmospheric pressure is about 2,300 K (3,680 °F) for stoichiometric mixtures of fuel in air, and is reduced to about 1,600 K (2,420 °F) for LEL mixtures. The AFT can be calculated using any of a number of chemical equilibrium computer programs, like STANJAN (Reynolds, 1986). The use of such a computer program allows the analysis to be performed for a tank-specific mixture, so that the results are representative of the actual tank environment.

B.8.2 Flammability Potential of Hydrogen

Hydrogen is a highly flammable gas with novel flammability properties and unusually broad explosive limits. Based on upward propagation in the standard flammability tube, the LEL is 4-percent hydrogen in air and the UEL is 75-percent (Zabetaskis, 1965). For most gases, the LELs for upward and downward propagation do no differ greatly. However, for hydrogen, the LEL for downward propagation is 8-percent (Furno et al., 1971). The significance of this difference is that in order for the flame to propagate throughout a tank or a vessel, it must propagate in all directions. As such, overpressures associated with hydrogen explosions are not observed at hydrogen concentrations below 8-percent. This behavior was observed by Furno et al., 1971, in 12-foot spherical vessel experiments using lean hydrogen/air mixtures. Overpressures were only measured above 8-percent hydrogen, and the pressures did not match the theoretical overpressures until about 10-percent hydrogen. Thus, while the LEL of hydrogen is widely quoted as 4-percent, explosion hazards will not occur below 8-percent.

The novel behavior of hydrogen is not reflected in documents like NFPA 69, “Standard on Explosion Prevention Systems.” As such, standards of care like NFPA 69, provide an implicit additional safety factor for hydrogen that should be understood in assessing hazards.

B.8.3 Flammable Limits, Detonable Limits, and Potential for Deflagration-to-Detonation Transitions

The formation of flammable fuel/oxidant mixtures within a tank can lead to premixed flame propagation in the form of deflagration or a detonation. The formation of a flammable mixture can result from steady-state generation and transport of flammable gases and oxidizers from an aqueous solution or waste containing radioactive isotopes, from episodic releases of such gases trapped within the waste, or from the formation of large gas bubbles within the waste which contain flammable mixtures of fuels and oxidizers.

Before assessing the potential flammable gas generation rates and resulting flammable gas mixture, it is useful to assess the relevant limits. In mixtures with fuel gas concentrations above the LEL indefinite propagation of a deflagration is possible. Above the detonable limit, indefinite propagation of a detonation is possible given a source that is capable of directly detonating the mixture. While LELs are a property of the mixture alone, the detonable limits are also impacted by the environment. The ability for a deflagration-to-detonation transition (DDT) is contingent upon both the mixture and the environment. The primary flammable gas is hydrogen.

B.8.4 Flammable Gas Generation

Flammable gases are generated with the aqueous solution or waste by several processes within a tank or a vessel. Specifically, these processes may include (1) radiolysis of the water and waste to produce hydrogen and ammonia, (2) corrosion of the steel liner to produce hydrogen, and (3) chemical decomposition of the waste. These processes generate hydrogen, methane, ammonia, and nitrous oxide, the first three of which are flammable gases, while the fourth is an oxidizer.

B.8.5 Explosion Prevention Methods

The flammability of a tank or vessel can be managed by controlling either the flammable gas concentration or oxygen concentration. Where the oxygen concentration is to be controlled, it needs to be maintained below the limiting oxidant concentration (LOC) (NFPA 69). (LOC is defined as the concentration of oxidant below which deflagration cannot occur is a specified mixture). Safety margins require maintaining the oxygen at 60-percent of the LOC if the LOC is above 5-percent, or 4-percent of the LOC if the LOC is below 5-percent. Where flammability is measured by controlling the flammable gas concentration, it needs to be maintained below 25 percent of the LEL.

Control of the oxygen concentration is achieved through the use of an inert purge gas. By contrast, control of flammable gas concentration is normally achieved through air dilution or by controlling of flammable gas evolution or regeneration or by catalytic oxidation of flammable gases.

While NFPA 69, provides standards for inerting the tanks, such inerting is not required by codes and standards for flammable liquid storage containers, such as the Uniform Fire Code Article 79; 1997, NFPA 30, 1996 Edition; 49 CFR; FM Data Sheet 7-88, “Storage Tanks for Flammable and Combustible Liquids,” 1999; and FM Data Sheet 7-29, “Flammable Liquid Storage,” 1999. These codes and standards recognize that ignition sources will not be present in passive containers, so that it is not necessary to control the composition of gases in the tank. By contrast, FM Data Sheet 7-32, “Flammable Liquids Operation,” 1993, recommends that processing equipment with the potential for an explosion should have at least one of the following characteristics:

- equipped with explosion venting
- designed to withstand the explosion overpressure
- fitted with an inerting system
- fitted with an explosion suppression system

Tank inerting is recognized as a means of preventing explosions in processing vessels, which are inherently dynamic systems where ignition sources can be limited but not excluded.

B.8.6 References

Beyler, C.L., "Flammability Limits of Premixed and Diffusion Flames," Section 2, Chapter 2-9, *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, P.J. DiNenno, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1995.

FM Data Sheet 7-29, "Flammable Liquid Storage," Factory Mutual Engineering Corporation, Norwood, Massachusetts.

FM Data Sheet 7-32, "Flammable Liquid Operations," Factory Mutual Engineering Corporation, Norwood, Massachusetts.

FM Data Sheet 7-88, "Storage Tanks for Flammable and Combustible Liquids," Factory Mutual Engineering Corporation, Norwood, Massachusetts.

Furno, A., E. Cook, J. Kuchta, and D. Burgess, "Some Observations on Near-Limit Flames," Thirteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, pp. 593–599, 1971.

NFPA 30, "Flammable and Combustible Liquids Code," 2000 Edition National Fire Protection Association, Quincy, Massachusetts.

NFPA 69, "Standard on Explosion Prevention Systems," 1997 Edition, National Fire Protection Association, Quincy, Massachusetts.

Reynolds, W.C., "The Element Potential Method for Chemical Equilibrium Analysis: Implementation in the Interactive Program STANJAN, Version 3, Department of Mechanical Engineering, Stanford University, 1986.

Uniform Fire Code (UFC), Article 79, "Flammable and Combustible Liquids," International Fire Code Institute, 1997.

Code of Federal Regulations, Title 49, Part 100–177, "Hazardous Materials Transportation," U.S. Government Printing Office, Washington DC.

Zabetakis, M.G., "Flammability Characteristics of Combustible Gases and Vapors," Bulletin 627, U.S. Bureau of Mines, Washington, DC, 1965.

B.9 Combustion Properties of Pure Metals in Solid Form

Nearly all metals will burn in air under certain conditions. Some oxidize rapidly in the presence of air or moisture, generating sufficient heat to reach their ignition temperatures. Others oxidize so slowly that heat generated during oxidation dissipates before the metal becomes hot enough to ignite. Certain metals (notably magnesium, titanium, sodium, potassium, lithium, zirconium, hafnium, calcium, zinc, plutonium, uranium, and thorium) are referred to as “combustible metals” because of the ease of ignition when they reach a high specific area ratio (thin sections, fine particles, or molten states). However, the same metals are comparatively difficult to ignite in massive solid form. Some metals (such as aluminum, iron, and steel) that are not normally thought of as combustible, may ignite and burn when in finely divided form. Clean fine steel wool, for example, may ignite. Particle size, shape, quantity, and alloy are important factors to be considered when evaluating metal combustibility. Combustibility of metallic alloys may differ and vary widely from the combustibility characteristics of the alloys’ constituent elements. Metals tend to be most reactive when in finely divided form and may require shipment and storage under inert gas or liquid to reduce fire risks.

Hot or burning metals may react violently upon contact with other materials, such as oxidizing agents and extinguishing agents used on fires involving ordinary combustibles or flammable liquids. Temperatures produced by burning metals can be higher than temperatures generated by burning flammable liquids. Some metals can continue to burn in carbon dioxide, nitrogen, water, or steam atmospheres in which ordinary combustibles or flammable liquids would be incapable of burning.

Properties of burning metal cover a wide range. Burning titanium, for example, produces little smoke, while burning lithium exudes dense and profuse smoke. Some water-moistened metal powders (such as zirconium) burn with near-explosive violence, while the same powder wet with oil burns quiescently. Sodium melts and flows while burning; calcium does not. Some metals (such as uranium) acquire an increased tendency to burn after prolonged exposure to moist air, while prolonged exposure to dry air makes it more difficult to ignite.

The toxicity of certain metals is also an important factor in fire suppression. Some metals (especially heavy metals) can be toxic or fatal if they enter the bloodstream or their smoke fumes are inhaled. ***Metal fires should never be approached without proper protective equipment (clothing and respirators)***.

A few metals (such as thorium, uranium, and plutonium) emit ionizing radiation that can complicate fire fighting and introduce a radioactive contamination problem. Where possible, radioactive materials should not be processed or stored with other pyrophoric materials because of the likelihood of widespread radioactive contamination during a fire. Where such combinations are essential to operations, appropriate engineering controls and emergency procedures should be in place to prevent or quickly suppress fires in the event that the controls fail.

Because extinguishing fires in combustible metals involves techniques not commonly encountered in conventional fire fighting operations, it is necessary for those responsible for controlling combustible metal fires to be thoroughly trained before an actual fire emergency arises. Table B.9-1 lists the melting, boiling, and ignition temperatures of pure metals in solid form.

Table B.9-1. Melting, Boiling, and Ignition Temperatures of Pure Metals in Solid Form
(Tapscott, 1997, © NFPA. With permission.)

Pure Metal	Melting Point		Boiling Point		Solid Metal Ignition Temperature	
	°C	°F	°C	°F	°C	°F
Aluminum	660	1,220	2,452	4,445	555[b, c]	1,832[b, c]
Barium	725	1,337	1,140	2,084	175[b]	347[b]
Calcium	824	1,548	1,440	2,625	704	1,300
Hafnium	2,223	4,023	5,399	9,750	-	-
Iron	1,535	2,795	3,000	5,432	930[b]	1,706[b]
Lithium	186	367	1,336	2,437	180	356
Magnesium	650	1,202	1,110	2,030	623	1,153
Plutonium	640	1,184	3,315	6,000	600	1,112
Potassium	62	144	760	1,400	69b	156[b]
Sodium	98	208	880	1,616	115[d]	239[d]
Strontium	774	1,845	1,150	2,102	720[b]	1,328[b]
Thorium	1,845	3,353	4,500	8,132	500[b]	932b
Titanium	1,727	3,140	3,260	5,900	1,593	2,900
Uranium	1,132	2,070	3,815	6,900	3,815[b, e]	6,900[b, e]
Zinc	419	786	907	1,665	900[b]	1,652[b]
Zirconium	1,830	3,326	3,577	6,470	1,400[b]	2,552[b]

Notes:
(a) Variation of test conditions may produce different results
(b) Ignition in oxygen
(c) Spontaneous ignition on moist air
(d) Above indicated temperature
(e) Below indicated temperature

B.9.1 Reference

Tapscott, R.E. "Metals," Section 4, Chapter 16, *NFPA Fire Protection Handbook*, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts. 1997.

B.10 Extinguishing Agents for Metal Fires

Water is not usually recommended for fires involving metals since a number of metals can react exothermically with water to form hydrogen, which, of course, burns rapidly. Furthermore, violent steam explosions can result if water enters molten metal. As an exception, fires have been successfully extinguished when large quantities of water were applied to small quantities of burning magnesium in the absence of pools of molten magnesium.

Table B.10-1 lists extinguishing agents used for various metal fires. In general, metal fires are difficult to extinguish because of the very high temperatures involved and the correspondingly long cooling times required. Note that certain metals react exothermically with nitrogen or carbon dioxide, so the only acceptable inert gases for these metals are helium and argon. Halons should not be used on metal fires.

Table B.10-1. Extinguishing Agents for Metal Fires
(Tapscott, 1997, © NFPA. With permission.)

Extinguishing Agent	Main Ingredient	Used On
Powders		
Metal Guard®	Graphite	Al, Ca, Hf, K, Li, Mg, Na, Pu, Th, Ti, U, Zr
Met-L-X®	NaCl	Al, K, Mg, Na, Ti, U, Zr
TEC® powder	KCl, NaCl, $BaCl_2$	K, Mg, Na, Pu, U
Lith-X®	Graphite	Li, Mg, Na, Zr
Na-X®	Sodium carbonate	Na
Copper powder	Cu	Al, Li, Mg
Salt	NaCl	K, Mg, Na
Soda ash	Sodium carbonate	K, Na
Gases		
Argon	Ar	Any metal
Helium	He	Any metal
Nitrogen	N_2	K, Na
Boron trifluoride	BF_3	Mg
Al-Aluminum, Ca-Calcium, Hf-Hafnium, K-Potassium, Li-Lithium, Mg-Magnesium, Na-Sodium, Pu-Plutonium, Th-Thorium, Ti-Titanium, U-Uranium, Zr-Zirconium		

B.10.1 References

Friedman, R., *Principles of Fire Protection Chemistry and Physics*, "Fire-Fighting Procedures," Chapter 14, 3rd Edition, National Fire Protection Association, Quincy, Massachusetts, 1998.

Tapscott, R.E., "Combustible Metal Extinguishing Agents and Application Techniques," Section 6, Chapter 26, *NFPA Fire Protection Handbook*, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1997.

B.11 Occupancy Classification and Use Groups

National Fire Code (NFC) requirements are occasionally tied to specific type of occupancy. While NPPs are fundamentally industrial occupancy, it is important to have a basic understanding of other occupancy classifications in order to be able to recognize this connection.

The use group classification of a building is probably the most significant design factor that affects the safety of the occupants and fire suppression forces that are called upon in the event of fire. The building's height and size, type of construction, type and capacity of exit facilities, and fixed fire suppression systems are all dependent on this classification. The use group classification system as the foundation for the building and fire prevention codes.

B.11.1 Occupancy Classification

The model building codes[1] and NFPA 101 (Life Safety Code®) separate buildings into about 10 general uses:

- Assembly
- Business
- Educational
- Factory or Industrial
- High Hazard or Hazardous
- Institutional
- Mercantile
- Residential
- Storage
- Utility, Miscellaneous, or Special

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[1] Model Building Codes; National Fire Protection Association, NFPA 5000; International Code Council, Inc., International Building Code (IBC).

The uses are further separated into use groups based on specific characteristics. A church, a nightclub, and a family restaurant are all assemblies, but the specific characteristics of their occupants and functions differ drastically, requiring different built-in levels of protection. The occupants of a church are probably very familiar with the building that they occupy. They have been there before and they know the locations of alternative exits. The occupants of a nightclub may not be so familiar with the building. Dim lighting, loud music, and impairment by alcohol are all common features that may further compromise the ability of the occupants to identify a fire emergency and take appropriate measures to escape:

- Assembly (A) occupancies are subdivided by function, as well as the number of occupants they hold. Assemblies that hold fewer than 50 persons are generally considered to be less-restrictive business uses. The International Building Code (IBC) further subdivides assemblies that hold many people. Such assemblies include churches, restaurants with occupant loads that exceed 50 persons, auditoriums, armories, bowling alleys, courtrooms, dance halls, museums, theaters, and college classrooms that hold more than 50 persons.
- Business (B) areas include college classrooms with occupant loads up to 50, doctor's and other professional offices, fire stations, banks, barber shops, and post offices. Dry cleaners who use noncombustible solvents (Types IV and V) also qualify as Business uses.
- Educational (E) areas include facilities that are *not* used for business or vocational training (shop areas) for students up to and including the twelfth grade. Colleges and universities are Business or Assembly areas (depending on the number of occupants). Day care facilities may be classified as Educational or Institutional depending on the model code.
- Factory or Industrial (F) areas include industrial and manufacturing facilities and are subdivided into moderate and low-hazard facilities. High-hazard factory and industrial areas are bumped up from the F Use Group to the H Use Group. Dry cleaners employing combustible solvents (types II and III) are moderate-hazard factory and industrial uses.
- High Hazard or Hazardous (H) areas are those in which more than the exempt amount of a hazardous material or substance is used or stored. Exempt amounts of hazardous materials are not exempt from the provisions of the code. They are threshold amounts by material, above which the occupancy must comply with the stringent requirements of the H Use Group.
- Institutional (I) areas may include halfway houses and group homes, hospitals and nursing homes, and penal institutions. The model codes differ in their breakdown. Care must be taken when considering homes for adults and day care centers as to whether the occupants are ambulatory or capable of self-preservation. The model codes all contain significantly more stringent requirements for institutional occupancies where a "defend-in-place" strategy is necessary because of the inability of the occupants to flee the structure without assistance.
- Mercantile (M) uses include retail shops and stores and areas that display and sell stocks of retail goods. Automotive service stations that do minor repairs are considered Mercantile uses.
- Residential (R) areas include hotels and motels, dormitories, boarding houses, apartments, townhouses, and one- and two-family dwellings.

- Storage (S) areas are used for to store goods and include warehouses, storehouses, and freight depots. Storage uses are separated into low- and moderate-hazard storage uses. Auto repair facilities that perform major repairs, including engine overhauls and body work or painting, are considered Moderate-Hazard Storage Occupancies by the International Building Code (IBC). Occupancies that store more than the exempt amounts of hazardous materials or substances are considered H Use Group Occupancies.
- Utility (U), Miscellaneous, or Special Structures, depending on the model code, include those that are not classified under any other specific use. Such structures may include tall fences cooling towers, retaining walls, and tanks.
- Mixed-use buildings often contain multiple occupancies with different uses. For example, a three-story building might have a restaurant (assembly) and computer store (mercantile) on the first floor and professional offices throughout the rest of the building. The model code provides for such situations either by requiring that the whole building be constructed to all requirements of the most restrictive use group or by separating the areas with fire-rated assemblies, or by separating the building with fire walls, thereby creates separate buildings. By far the least expensive and most attractive method of separating mixed uses is by using fire separating assemblies, but this method is sometimes impossible because of building height and area requirements.

B.11.2 Special Use and Occupancy Requirements

For most buildings and structures, assigning a use group and then specifying building requirements for all buildings within that use group works relatively well. Most mercantile occupancies share common hazards. Most business occupancies have similar occupants and processes. But what if a given business happens to be on the twenty-sixth floor of a high-rise building? Or what if the men's clothing store is in the middle of a giant shopping mall? The relative hazards suddenly change, and we begin comparing apples to oranges.

Building codes provide an enhanced level of protection for certain occupancies to compensate for special hazards over and above those posed by the use of the building. The inherent hazards posed by being located 26 stories above the ground or in a large open area with high fire loading such as a shopping mall are addressed as special use requirements.

B.11.3 Code Advances/Changes

It is important to recognize that NPPs have their design basis rotted in 1970's era code requirements. In some cases, fire science advances revise, or establish new code requirements. A good example is carpeting found in the MCR. The original NPPs required ASTM E84, "Standard Test for Surface Characteristics of Building Materials," Class A flame spread requirements. Fire science advances have developed more specialized test methods for carpeting, ASTM E648, "Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source." As a result of this, manufacturers do not test the material to 1970's vintage test method. When NPPs perform a plant modification (e.g., replace the carpet in the MCR, since ASTM E84 rated carpet is no longer manufactured), the licensee will either have to perform their own ASTM E84 testing on the proper carpet or prepare an engineering analysis on the commercially available carpeting that is tested to newer test methods recognized by NFPA 101, "Life Safety Code®."

Another area of change is cable flame spread testing. Since no new NPPs are being built there is little incentive for cable vendors to qualify electrical cables to IEEE 383 requirements. In parallel, the building code groups are recognizing by grouped electrical cables and testing organizations prepared specialized test methods and rating systems based on application of the cable: UL 910, "Test Method for Fire and Smoke Characteristics of Electrical and Optical-Fiber Cables Used in Air Handling Spaces"; UL 1581, "Reference Standard for Electrical Wires, Cables, and Flexible Cords"; UL 1666, "Standard Test for Flame Propagation Height of Electrical and Optical-Fiber Cable installed Vertically in Shafts"; and UL 1685, "Fire Test of Limited-Smoke Cables."

B.11.4 References

ASTM Fire Test Standard, Fifth Edition, American Society of Testing and Materials, West Conshohocken, Pennsylvania, pp. 765-780, 1999.

ASTM E 648-98$^{\epsilon 1}$, "Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source," ASTM Fire Test Standard, Fifth Edition, American Society of Testing and Materials, West Conshohocken, Pennsylvania, pp. 894-907, 1998.

International Building Code, Sixth Edition, International Code Council, Inc., Falls Church, Virginia.

NFPA 101®, "Life Safety Code®," 2003 Edition, National Fire Protection Association, Quincy, Massachusetts.

NFPA 5000, "Building Construction and Safety Code," 2003 Edition, National Fire Protection Association, Quincy, Massachusetts.

UL 910, "Test Method for Fire and Smoke Characteristics of Electrical and Optical-Fiber Cables used in Air Handling Spaces."

UL 1581, "Reference Standard for Electrical Wires, Cables, and Flexible Cords."

UL 1666, "Standard Test for Flame Propagation Height of Electrical and Optical-Fiber Cable Installed Vertically in Shafts."

UL 1685, "Fire Test of Limited-Smoke Cables."

B.12 Building Limitations and Types of Construction

Two of the most effective methods used over the years to limit potential fire spread and prevent conflagration have been limiting the size of buildings and regulating the materials used in their construction. One of the primary purposes of a building code is to prescribe standards that will keep buildings from falling down. Besides gravity, there are many forces that act against a building. Snow loads, wind loads, and potential earthquake loads are provided for in the building code for design and construction of buildings. It can be considered that the potential force that requires the most extensive code provisions is fire. Large portions of the model building codes address fire protection issues, fire safety, emergency egress, and structural stability.

The key to understanding building code provisions for structural protection from fire is the concept of fire resistance. In broad terms, fire resistance (also called fire endurance) it is the ability of a building to resist collapse or total involvement in fire. Fire resistance is measured by the length of time typical structural members and assemblies resist specified temperatures. The building codes define fire resistance as that property of materials or their assemblies which prevents or retards the passage of excessive heat, hot gases, or flames under conditions of use.

B.12.1 Types of Construction

There are three key points to remember when dealing with building construction types:

- All construction is either combustible (it will burn) or noncombustible (it won't).
- When applied to construction materials, "protected" refers to measures to reduce or eliminate the effects of fire encasement. Concrete, gypsum, and spray-on coatings are all used to protect construction elements. When the code means "protected with a sprinkler system," it will say just that.
- Having the ability to determine the construction type by eyeballing a building is not a requirement.

B.12.2 Five Construction Types

The model building codes and NFPA 220, "Standard on Types of Building Construction," recognize five construction types. The Standard Building Code subdivides noncombustible construction and uses six types. The terms vary a little between the different codes, but the concept is the same, based on the classifications from NFPA 220.

Type I Fire Resistive

In Type I construction, the structural elements are noncombustible and protected. Type I is divided into two or three subtypes, depending on the model code. The difference between them is the level of protection for the structural elements (expressed in hours). Only noncombustible materials are permitted, and structural steel must not be exposed. A high-rise building with an encased steel structure is an example of a Type I building.

Type II Noncombustible

In Type II construction, the structural elements are either noncombustible or limited combustible. Type II is subdivided into subtypes, dependent upon the level of protection (in hours) for the structural elements. The buildings are noncombustible, but afford limited or no fire resistance to the structural elements. A strip shopping center, with block walls, steel bar joists, unprotected steel columns, and a steel roof deck is an example of a Type II building.

Type III

Limited Combustible (Ordinary) In Type III construction, the exterior walls are noncombustible (masonry) and may be rated based on the horizontal distance to exposure. The interior structural elements may be combustible or a combination of combustible and noncombustible. Type III is divided into two subtypes (protected and unprotected). The brick, wood joisted buildings that line city streets are of Type III (ordinary) construction. Buildings with a masonry veneer over combustible framing are not Type III.

Type IV

Heavy Timber In type IV construction, the exterior walls are noncombustible (masonry) and the interior structural elements are unprotected wood of large cross-sectional dimensions. Columns must be at least 8 inches if they support a floor load, joists, and beams must be a minimum of 6 inches in width and 10 inches in depth. Type IV is not subdivided. The inherent fire-resistant nature of large-diameter wood members is taken into account. Concealed spaces are not permitted.

Type V

Wood Frame In Type V construction, the interior structure may be constructed of wood or any other approved material. Brick veneer may be applied, but the structural elements are wood frame. Type V is divided into two subtypes (protected and unprotected), again depending on the protection provided for the various structural elements.

B.12.3 Fire Resistance Ratings

The various model codes and NFPA 220 each have a table containing the rating (in hours) of the various structural elements. Table B.12-1 summarizes the required ratings by building component type, depending upon the construction classification of the building. The construction type classifications used by the International Building Code (IBC) and NFPA 220 do not exactly match, type for type. The National Fire Protection Association is consistent, however, within its different standards; therefore, the construction type classifications in NFPA 5000 and NFPA 220 are identical. Table B.12-1 provides an approximate comparison. A notational system was developed to identify the fire resistance required for the three basic elements of the building. These elements are (1) the exterior wall, (2) the primary structural frame, and (3) the floor construction. A three-digit notation was developed, as follows:

(1) First digit: Hourly fire resistance requirement for exterior bearing wall fronting on a street or lot line.

(2) Second digit: Hourly fire-resistance requirement for a structural frame or columns and girders supporting loads from more than one floor.

(3) Third digit: Hourly fire resistance requirement for floor construction.

Thus, for example, a "332" building would have 3-hour fire-resistant exterior bearing walls, a 3-hour fire resistant structural frame, and 2-hour fire-resistant floor construction, and would correspond to the NFPA 220 Type I (332) building and the International Building Code (IBC) Type IA building.

Table B.12-1. Construction Classifications of the Model Codes and NFPA 220

NFPA 220 & NFPA 5000	I 443	I 332	II 222	II 111	II 000	III 211	III 200	IV 2HH	V 111	V 000
IBC Table 601	-	IA	IB	IIA	IIB	IIIA	IIIB	IV	VA	VB

B.12.4 Reference

NFPA 220, "Standard on Types of Building Construction," National Fire Protection Association, Quincy, Massachusetts, 1999 Edition.

International Building Code, Sixth Edition, International Code Council, Inc., Falls Church, Virginia.

NFPA 5000, "Building Construction and Safety Code," 2003 Edition, National Fire Protection Association, Quincy, Massachusetts.

B.13 Deep-Seated Fires in Class A Solid Materials

B.13.1 General Information

Two types of fires can occur in Class A (ordinary) combustibles materials (e.g., wood, cloth, paper, rubber, and many plastics including cable insulation). In the first type, commonly known as flaming combustion, the source of combustion is volatile gases resulting from heating or decomposition of the fuel surface. In the second type, commonly called smoldering or glowing combustion oxidation occurs at the surface of, or within, the mass of fuel. These two types of fires frequently occur concurrently, although one type of burning may precede the other. For example, a wood fire may start as flaming combustion and become smoldering as burning progresses. Conversely, spontaneous ignition in a pile of oily rags may begin as a smoldering fire and break into flames at some later time (Friedman, 1997).

Smoldering combustion cannot be immediately extinguished like flaming combustion. This type of combustion is characterized by a slow rate of heat loss from the reaction zone. Thus, the fuel remains hot enough to react with oxygen, even though the rate of reaction, which is controlled by diffusion processes, is extremely slow. Smoldering fires can continue to burn for many weeks, for example in bales of cotton and jute and within heaps of sawdust or mulch. A smoldering fire ceases to burn only when all of the available oxygen or fuel has been consumed, or when the temperature of the fuel surface becomes too low to react. These fires are usually extinguished by reducing the fuel temperature, either directly by applying a heat absorbing medium (such as water), or indirectly by blanketing the fuel with an inert gas. In the latter case, the inert gas slows the rate of reaction to the point at which heat generated by oxidation is less than the heat lost to the surroundings. This causes the temperature to fall below the level necessary for spontaneous ignition following removal of the inert gas atmosphere.

Smoldering fires are divided into two classes, in which the fire is either deep-seated or not. Basically, “deep-seated” implies the presence of sub-surface smoldering combustion that may continue for some time after surface flaming is suppressed. Deep-seated fires may become established beneath the surface of fibrous or particulate material. This condition may result from flaming combustion at the surface or from the ignition within the mass of fuel. Smoldering combustion then progresses slowly through the mass. Whether a fire will become deep-seated depends, in part, on the length of time it has been burning before the extinguishing agent is applied. This time is usually called the “pre-burn” time (Nolan, 2001).

As described above, a deep-seated fire is embedded in the material being consumed by combustion. To extinguish deep-seated fires, an individual must investigate the interior of the material once the surface fire has been extinguished to determine whether interior smoldering has also been extinguished by a gaseous agent. It should be noted, however, that the concentration of the extinguishing agent must be adequate—and must be applied for an adequate duration—to ensure that the smoldering has been effectively suppressed.

B.13.2 Deep-Seated Cable Fires

A deep-seated fire occurs in cables when the burning involves pyrolysing beneath the surface, in addition to a surface phenomenon. This is postulated to occur when the cable fire reaches the stage of a fully developed fire. Extinguishing a cable surface fire does not guarantee that a deep-seated fire is also eliminated. A deep-seated fire is very difficult to suppress since fire suppressing agent cannot easily get to the seat of the fire, and it is also difficult to detect since combustion is primarily under the cooler surface.

Electrical cable fire tests have been conducted at the Sandia Fire Research Facility (Schmidt and Krause, 1982) in order to evaluate cable tray fire safety criteria. A burn mode concept was developed in order to describe and classify the thermodynamic phenomena which occur in the presence of smoke and to compare the fire growth and recession of different cable types under otherwise unchanged fire test conditions. The importance of deep-seated fires in cables trays from the standpoint of propagation, detection, and suppression is emphasized. The cable tray fire tests demonstrate that fire recession and deep-seated fires can result from a decreasing smoke layer and that reignition and secondary fire growth is possible by readmission of fresh air.

B.13.3 Deep-Seated Charcoal Fires

The use of activated charcoal in NPPs presents a potential for deep-seated fires. Simply, that if it says that it is combustible, that it may be ignited, and that if it does become ignited, it is likely to become a deep-seated fire. It does not predict the frequency of those fires, nor form of ignition (Holmes, 1987). On July 17, 1977, a fire occurred at the Browns Ferry Nuclear Power Plant (BFNP) in Unit 3 off-gas system charcoal adsorber bed (Crisler, 1977). The elevation in adsorber bed temperature caused temperature rises of sufficient magnitude to cause carbon ignition.

B.13.4 References

Crisler, H.E. Jr., "July 17, 1977, Off-Gas System Charcoal Adsorber Bed Fire at Browns Ferry Nuclear Plant," Proceedings of the CSNI Specialist Meeting on Interaction of Fire and Explosion with Ventilation Systems in Nuclear Facilities, Volume II, Report Number: LA-9911-C, Vol.2; CSNI-83, pp. 309-316, October 1983.

Friedman, R., "Theory of Fire Extinguishment," Section 1, Chapter 8, NFPA Fire Protection Handbook, 18th Edition, A.E. Cote, Editor-in-Chief, National Fire Protection Association, Quincy, Massachusetts, 1997.

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Schmidt, W.H., and F.R. Krause, "Burn Mode Analysis of Horizontal Cable Tray Fires," NUREG/CR-2431, U.S. Nuclear Regulatory Commission, Washington, DC, February 1982.

B.14 Special Hazard Gaseous Fire Extinguishing Agents

B.14.1 Introduction

A gaseous (or gas phase) fire suppression agent remains in the gaseous state at normal room temperature and pressure. It has low viscosity, can expand or contract with changes in pressure and temperature, and has the ability to diffuse readily and distribute itself uniformly throughout an enclosure. Gaseous fire extinguishing agents are categorized into two distinct classes, including halocarbon and inert gases (such as nitrogen and mixtures containing argon). Halocarbon agents (e.g., Halon 1301) act largely by absorbing although they also have some chemical effect on flame combustion reactions. Inert agents contain unreactive gases that act primarily by oxygen depleting. One important advantage of gaseous agents is that no cleaning is required if the agent is released in the absence of a fire; a couple of minutes of venting is all that is required. However, gaseous agents with the exception of Halon require a rather large storage area; this is particularly for nitrogen and argon, which are usually stored as compressed gases.

Halogenated extinguishing agents are hydrocarbons in which one or more hydrogen atoms in an organic compound (carbon) have been replaced by atoms from halogens (the chemicals in group 7 of the periodic table of the elements) chlorine (Cl), fluorine (F), bromine (Br), or iodine (I). This substitution confers flame extinguishing properties to many of the resulting compounds that make them useable for certain fire protection applications. The three halogen elements commonly found in Halon extinguishing agents used for fire protection are fluorine, chlorine, and bromine. Compounds containing combinations of fluorine, chlorine, and bromine can possess varying degrees of extinguishing effectiveness, chemical and thermal stability, toxicity, and volatility. These agents appear to extinguish fire by inhibiting the chemical chain reaction that promotes the combustion process.

Carbon dioxide (CO_2) has a long history as an extinguishing agent, which is primarily used for flammable liquid fires and electrical equipment fires. CO_2 is noncombustible and does not react with most substances. It is a gas, but it can be easily liquified under pressure and is normally stored as a pressure-condensed gas. CO_2 provides its own pressure for release and blankets the fire area when released in sufficient amounts. CO_2 is extremely toxic since it replaces the oxygen in the air; humans become unconscious at a 10-percent volume concentration followed by loss of life. Therefore, CO_2 cannot be released while people are present.

B.14.2 Halogenated Agent Extinguishing Systems

Halogenated extinguishing agents are currently known simply as Halons, and are described by a nomenclature that indicate the chemical composition of the materials without the use of chemical names. In this nomenclature the first digit of the number definition represents the number of carbon atoms in the compound molecule; the second digit is the number of fluorine atoms; the third digit is the number of chlorine atoms; the fourth digit is the number of bromine atoms; and the fifth digit is if any, the number of iodine atoms.

For example, the number definition for the chemical composition of Halon 1301, perhaps the most widely recognized halogenated extinguishing agent, is 1 (carbon), 3 (fluorine), 0 (chlorine), 1 (bromine), and 0 (iodine). This simplified system, proposed in 1950 by James Malcolm of the U.S. Army Corps of Engineers Laboratory, avoids the use of possibly confusing names. By contrast, the United Kingdom and parts of Europe still use the initial capital alphabet system [i.e., bromotrifluoromethane (Halon 1301) is BTM and bromochlorodifuoro-methane (Halon 1211) is BFC].

Due to the many chemical combinations available, the characteristics of halogenated fire extinguishing agents differ widely. It is generally agreed, however, that the agents most widely used for fire protection applications are Halon 1011, Halon 1211, Halon 1301, Halon 2402, and (to a lesser degree) Halon 122, which has been used as a test gas because of its economic advantages. However, because of its widespread use as a test agent, many individuals have wrongly assumed that Halon 122 is an effective fire extinguishing agent. Table B.14-1 illustrates the halogenated hydrocarbons most likely to be used today. Of all of these types, however, the most popular halogenated agent is Halon 1301, which offers superior fire extinguishing characteristics and low toxicity. Because Halon 1301 inhibits the chain reaction that promotes the combustion process, it chemically suppresses the fire very quickly, unlike other extinguishing agents that work by removing the fire's heat or oxygen. Stored as a liquid under pressure and released as a vapor at normal room temperature, Halon 1301 readily spreads into blocked and baffled spaces and leaves no corrosive or abrasive residue after use. A high liquid density permits compact storage containers, which on a comparative weight basis, makes Halon 1301 approximately 2.5 times more effective as an extinguishing agent than CO_2 (Grand, 1995).

Table B.14-1. Halogenated Hydrocarbons Commonly Used for Fire Protection

Common Name	**Chemical Name**	**Formula**
Halon 1001	Methyl Bromide	CH_3Br
Halon 10001	Methyl Iodide	CH_3I
Halon1011	Bromochloromethane	CH_2BrCl
Halon 1202	Dibromodifluoromethane	CF_2Br_2
Halon 1211	Bromochlorodifluoromethane	CF_2BrCl
Halon 122	Dichlorodifluoromethane*	CF_2Cl_2
Halon 1301	Bromotrifluoromethane	CF_3Br
Halon 104	Carbon Tetrachloride	CCl_4
Halon 2402	Dibromotetrafluoroethane	$C_2F_4Br_2$

* A popular test gas without substantial fire extinguishing properties.

Although halogenated agents may be applied using a variety of methods, the most common is the total flooding system. According to the NFPA 12A, 1997 Edition, Section 2-3.1.1, a Halon 1301 total flooding system shall be automatically actuated for fires involving Class A ordinary combustible materials (e.g., wood, cloth, paper rubber, and many plastics including cables), with the exception that manual actuation shall be permitted if acceptable to the authority having jurisdiction (AHJ). NFPA 12A, 1997 Edition, Section 3-7.1.2, also indicate that the agent discharge shall be substantially completed in a nominal 10 seconds or as otherwise required by the AHJ. The rapid discharge is specified to prevent the fire from becoming deep-seated, minimize unwanted decomposition products, and achieve complete dispersal of the agent throughout the enclosure so that the Halon quickly knocks down the flames and extinguishes the fire. When exposed to deep-seated fires for long period of times, Halon 1301 decomposes into decomposition products, that are toxic to personnel and corrosive to electronic components (See Section B.18 for further discussion). Therefore, to extinguish fire effectively, while limiting the formation of hazardous decomposition products, it is important to disperse the agent during the incipient stage of the fire.

A significant problem in using of Halon 1301 is that, in the normal firefighting concentrations of 5-percent to 6-percent, it may fail to completely extinguish fires which originate in Class A solid materials (e.g., wood, cloth, paper, rubber, and many plastics). External and visible flame is instantly extinguished by Halon 1301, but internal and unseen flameless (but glowing) combustion may continue. As defined by the NFPA, if a 5-percent concentration of Halon 1301 will not extinguish a fire within 10 minutes of application, it is considered to be deep-seated, as described above. Such deep-seated fires usually require concentrations much higher than 10-percent and soaking times much higher than 10 minutes (NFPA 12A, 1971 Edition). The technical literature does not provide any satisfactory explanation for the ineffectiveness of Halon 1301 in deep-seated fires (Fielding and Woods, 1975).

Sandia National Laboratories (SNL) investigation of the effectiveness of the Halon 1301 fire suppression agent on electrical cables fires in 1981 and again in 1986 at the behest NRC. These full-scale fire suppression tests were performed to determine the concentration and minimum soaking time necessary to suppress electrical cable tray fires and prevent reignition of those fires. Halon 1301 was very effective in suppressing surface fires, but took much longer to suppress deep-seated cable tray fires. The results of Test 60 depicted on Figure B.14-1 indicated that even after Halon 1301 is discharged, the interior temperature of the cable bundle continues to rise, probably as a resulting of continued combustion of the cable insulation. Moreover, a second increase in temperature occurs, air is readmitted during ventilation, thereby causing reignition of the cable insulation (Klamerus, 1981).

As illustrated in Figure B.14-1 the Halon 1301 concentration applied to the fire has a direct relationship to the time required to completely extinguish the fire. When the agent is first applied to the cable trays, the flames are immediately extinguished, but the deep-seated combustion (or glow), continues and the fire will reignite if the enclosure is then ventilated.

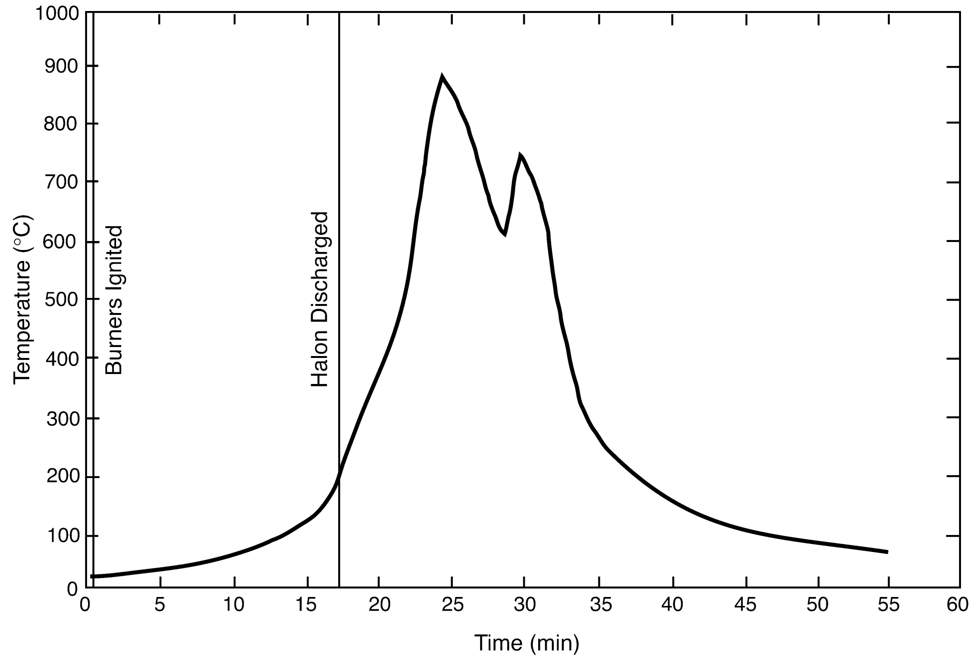

Figure B.14-1 Indication of Deep-Seated Fire and Reignition of Cables, Test # 60, IEEE-383-Qualified Cables, Horizontal Trays, 4-Minute Halon Soak Acceptor Tray Center Temperature (Klamerus, 1981)

B.14.2.1 Halon Concentration and Soaking Time

Soaking time is an important requirement for a Halon 1301 total flooding system. This is especially true for Class A fires that may reflash. A minimum soaking period of 10-minutes is typically required for fires in these applications, based on the full-scale total flooding fire suppression tests for electrical cable tray fires conducted by Klamerus (1981), and Chavez and Lambert (1986). A 6-percent Halon 1301 concentration with a 10-minute soak time successfully extinguished all cable fires in horizontally and vertically oriented trays filled with IEEE-383 unqualified cables, while IEEE-383 qualified cables required a 15-minute soaking time. The measure concentrations in these tests were based on a completely air-tight enclosure during discharge (see Figure B.14-2 for Halon 1301 concentration requirements) with 15-minute soak time successfully extinguished all cable fires in horizontal and vertical oriented tray filled. The measured concentrations in this testing are based on completely tight enclosure during discharge and soaking time of Halon 1301 (see Figure B.14-2 for Halon 1301 concentration requirements).

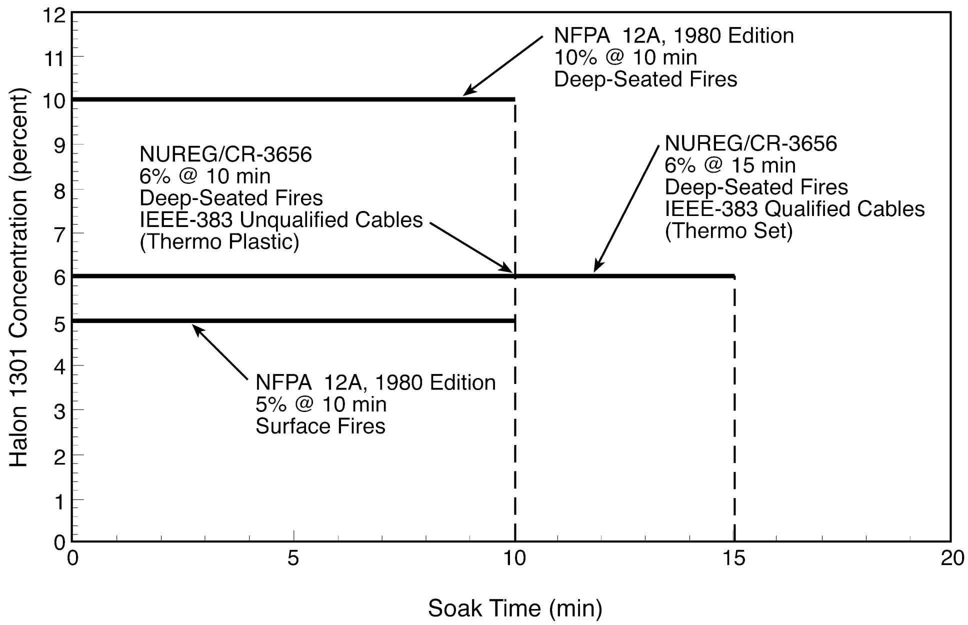

Figure B.14-2 Soaking Time vs. Halon 1301 Concentration
for Deep-Seated and Surface Fires

B.14.2.2 Agent Leakage

Because Halon 1301 is approximately five times heavier than air (with molecular weight 148.93 g/mol compared to 29 g/mol for air), there is a risk of Halon leakage from the protected space if the space is not completely airtight. Therefore, it is important to know the Halon percent and soak time at the highest combustible in the protected enclosure. NFPA 12A requires that the leakage rate should be low enough so that the design concentration is held in the hazard area long enough to ensure that the fire is completely extinguished. Reignition of the fire is a potential concern if the effective concentration is not maintained. In case of leakage during and after discharge, a greater amount of the agent is required to develop a given concentration. To maintain the agent concentration at a given level requires continuous agent discharge for the duration of the soaking period. The leakage rate from an enclosure could be predicted from the detailed knowledge of the size, location, and geometry of any leaks. However, these details are rarely known, as leakage may occur around doors and door seals; wall; ceiling; and floor cracks, duct, conduit, and cable tray penetrations; and fire and isolation dampers. Appendix B to NFPA 12A presents methods of estimating leakage area.

Discharging Halon 1301 into an enclosure to achieve total flooding results in an air/agent mixture with a higher specific gravity than the air surrounding the enclosure. Therefore, any openings in the lower portions of the enclosure will allow the heavier air/agent mixture to flow out and the lighter outside air to flow in. Fresh air entering the enclosure will collect toward the top, forming an interface between the air/agent mixture and fresh air. As the leakage proceeds, the interface will descend toward the bottom of the enclosure. The space above the interface will be completely unprotected, while the lower space will essentially contain the original extinguishing concentration. Grant (1995) presented methods of adjusting the Halon 1301 concentration to unprotected openings (leakage).

Rapid detection of a fire and prompt application of the extinguishing agent without outside assistance can help to prevent a Class A fire from becoming deep-seated. If a fire becomes deep-seated or (begins as a deep-seated fire), it will not likely be extinguished by Halon 1301 concentrations below 10-percent, and some deep-seated fires require concentrations above 18–30-percent to ensure that the glow is completely extinguished (Grant, 1995).

It is important to remember that in most cases, halogenated agent extinguishing systems have only a single chance to extinguish a fire. Such systems should be tested and Halon concentrations measured at various heights within the protected space (at least at the point of the highest combustible) to demonstrate the design concentrations. Timely and automatic actuation of Halon systems would also provide reasonable assurance that a fire would be extinguished before spreading through the combustible material and becoming deep-seated.

B.14.3 Carbon Dioxide Fire Extinguishing Systems

Carbon Dioxide (CO_2) is a colorless, odorless, inert, and electrically nonconductive agent that extinguishes a fire by displacing the normal atmosphere, thereby reducing the oxygen content below the 15-percent required for diffusion flame production. The CO_2 from either low-pressure or high-pressure extinguishing systems is stored and transported as a liquid through the piping system to the nozzles. With the release of pressure at the nozzles, the liquid CO_2 converts to a gas, with some minute solid particles, making it approximately 50-percent heavier than air.

Flame extinguishment by CO_2 is predominantly by a thermophysical mechanism in which reacting gases are prevented from achieving a temperature high enough to maintain the free radical population necessary for sustaining the flame chemistry. For inert gases presently used as fire suppression agent (argon, nitrogen, carbon, carbon, and mixture of these), the extinguishing concentration (as measured by the cup burner method, NFPA 2001) is observed to be linearly related to the heat capacity of the agent-air mixture. Although of minor importance in accomplishing fire suppression, CO_2 also dilutes the concentration of the reacting species in the flame, thereby reducing collision frequency of the reacting molecular species and slowing the rate of heat release.

CO_2 fire extinguishing systems are useful in protecting against fire hazards when an inert, electrically nonconductive, three-dimensional gas is essential or desirable and where clean up from the agent must be minimal. According to the NFPA, some of the types of hazards and equipment that carbon dioxide systems protect are "flammable liquid materials; electrical hazards, such as transformers, switches, circuit breakers, rotating equipment, and electronic equipment; engines utilizing gasoline and other flammable liquid fuels; ordinary combustibles such as paper, wood, and textiles; and hazardous solids" (NFPA 12).

Over the years, two methods of applying CO_2 have been developed. The first technique is the total flooding application, which involves filling an enclosure with CO_2 vapor to a prescribed concentration. In this technique, the CO_2 vapor flows through nozzles that are designed and located to develop a uniform concentration of the agent in all parts of the enclosure. The quantity of CO_2 required to achieve an extinguishing atmosphere is calculated on the basis of the volume of the enclosure and the concentration of the agent required for the combustibles material in the enclosure. This technique is applicable for both surface-type fires and potentially deep-seated fires.

For surface-type fires, as would be expected with liquid fuels, the minimum concentration is 34-percent of CO_2 by volume. Considerable testing has been done with using CO_2 on liquid fuels and appropriate minimum design concentrations have been derived at for a large number of common liquid fire hazards.

For deep-seated hazards, the minimum concentration is 50-percent of CO_2 by volume. This 50-percent design concentration is used for hazards involving electrical gear, wiring insulation, motors, and the like. Hazards involving record storage, such as bulk paper, require a 65-percent concentration of CO_2, while substances such as fur and bag-type house dust collectors require a 75-percent concentration. It should be noted that most surface burning and open flaming will stop when the concentration of CO_2 in the air reaches about 20-percent or less by volume. Thus, it should be apparent that a considerable margin of safety is built into these minimum CO_2 concentrations required by the standard. This is because those who developed the CO_2 standard never considered it sufficient to extinguish the flame. By contrast, the guidelines given in some of the standards for other gaseous extinguishing agents merely mandate concentrations that are sufficient to extinguish open flame but will not produce a truly inert atmosphere.

The other method of applying CO_2 is local application. This method is appropriate only for extinguishing surface fires in flammable liquids, gases, and very shallow solids where the hazard is not enclosed or where the enclosure of the hazard is not sufficient to permit total flooding. Hazards spray booths, printing presses, rolling mills, and the like can be successfully protected by a local application system designed to discharge CO_2 and direct the flow at the localized fire hazard. The entire fire hazard area is then blanketed in CO_2 without actually filling the enclosure to a predetermined concentration.

The integrity of the enclosure is a very important part of total flooding, particularly if the hazard has a potential for deep-seated fire. If the enclosure is air tight, especially on the sides and bottom, the CO_2 extinguishing atmosphere can be retained for a long time to ensure complete extinguishment of the fire. If there are openings on the sides and bottom, however, the heavier mixture of CO_2 and air may rapidly leak out of the enclosure. If the extinguishing atmosphere is lost too rapidly, glowing embers may remain and cause reignition when air reaches the fire zone. Therefore, it is important to close all openings to minimize leakage or to compensate for the openings by discharging additional CO_2.

An extended discharge of CO_2 is used when an enclosure is not sufficiently air tight to retain an extinguishing concentration as long as needed. The extended discharge is normally at a reduced rate, following a high initial rate to develop the extinguishing concentration in a reasonably short time. The reduced rate of discharge should be a function of the leakage rate, which can be calculated on the basis of leakage area, or of the flow rate through ventilating ducts that cannot be shut.

Extended discharge is particularly applicable to enclosed rotating electrical equipment, such as generators, where it is difficult to prevent leakage until rotation stops. Extended discharge can be applied to ordinary total flooding systems, as well to the local application systems where a small hot spot may require prolonged cooling.

B.14.3.1 Carbon Dioxide Requirements for Deep-Seated Fires (NFPA 12)

NFPA 12 recognizes two types of CO_2 extinguishing systems. The first type is the high-pressure CO_2 system, and the second is a low-pressure CO_2 system. The basic difference between the two types lies in the method of storing the CO_2.

The high-pressure system utilizes the U.S. Department of Transformation (DOT) spun steel storage cylinders, which are usually kept at room temperature. At an ambient temperature of 21 °C (70 °F), the internal pressure in such a unit reaches 850 psi. These cylinders are available in capacities of 50, 75, or 100 pounds.

By contrast, the low-pressure storage unit maintains the CO_2 in a refrigerated pressure vessel with a typical storage temperature of -18 °C (0 °F) with a corresponding CO_2 vapor pressure of 300 psi. The refrigerated storage concept uses an American Society of Mechanical Engineers (ASME) coded pressure vessel with a working pressure of 2,413 kPa (350 psi). Such units are available in standard capacities from 1.25–60 tons. Larger units have also been made for special applications.

This basic difference in storage configuration inspired different application and control methods for the two types of systems. Since the maximum capacity of a high-pressure cylinder is 100 pounds of CO_2, most systems consist of multiple cylinders manifolded together to provide the required quantity of agent. Each cylinder has its own individual discharge valve and, once opened, the cylinder contents will completely discharge.

NFPA 12 requires that the quantity of CO_2 for deep-seated fires must be based on fairly air tight enclosures. After the design concentration is reached, it shall be maintained for a substantial period of time, but not less than 20-minutes. Any possible leakage shall receive special consideration, because the basic flooding factor does not include any leakage allowance.

For deep-seated fires the design concentration shall be achieved within 7-minutes from the start of discharge, but the rate shall be not less than that required to develop a concentration of 30-percent within 2 minutes. For surface fires, the design concentration shall be achieved within 1-minute from the start of discharge.

B.14.3.2 Personnel Protection from Carbon Dioxide

The CO_2 that is used to extinguish the diffusion combustion may pose a threat to human life, and NPP personnel must recognize and plan to cope with this threat

Human subjects exposed to low concentrations (less than 4-percent) of CO_2 for up to 30-minutes, dilation of cerebral blood vessels, increased pulmonary ventilation, and increased oxygen delivery to the tissues were observed (Gibbs et al., 1943, Patterson et al., 1955). These results were used by the United Kingdom regulatory community to differentiate between inert gas systems for fire suppression that contain CO_2 and those that do not (HAG, 1995). During similar low-concentration exposure scenarios in humans, however, other researchers have recorded slight increases in blood pressure, hearing loss, sweating, headache, and dyspnea (Gellhorn and Speisman, 1934, 1935; Schneider and Schulte, 1964). 6–7-percent CO_2 is considered the threshold level at which harmful effects become noticeable in human beings. At concentration above 9-percent, most people lose consciousness within a short time. Since the minimum concentrations of CO_2 in air used to extinguish fire exceed 9-percent, adequate safety precautions must be designed into every CO_2 fire extinguishing system.

B.14.3.3 Harmful Effects of Carbon Dioxide Fire Suppression Systems

As described above CO_2 is lethal to humans at the minimum concentrations required to suppress fires. Accidents involving the discharge of CO_2 fire suppression systems have resulted in numerous deaths and injuries. Given its inherent hazard, CO_2 should not be used in areas that are subject to occupancy, except when the risk of fire is documented to be greater than the risk to personnel and no viable suppression alternatives exist.

In land-based workplace environments, the Occupational Safety and Health Administration (OSHA) regulates the use of CO_2. These regulations are provided in 29 CFR Parts 1910.160 and 1910.162, which outline the requirements for general and gaseous fixed extinguishing systems, respectively. Despite the fact that the concentration of CO_2 needed to extinguish fires is above the lethal level, OSHA does not prevent the use of CO_2 in normally occupied areas. (However, OSHA does explicitly limit the use of chlorobromomethane and carbon tetrachloride as extinguishing agents where employees may be exposed [29 CFR Part 1910.160 (b) (11)]. For CO_2 systems, OSHA requires a predischarge alarm for alerting employees of the impending release of CO_2 when the design concentration is greater than 4-percent (which is essentially true for all CO_2 systems). This predischarge alarm must allow sufficient time delay for personnel to safely exit the area prior to discharge. Although it is speculative, it is likely that these regulations would confer adequate protection only in the event of planned discharge, not accidental discharge. Accidental discharges have occurred, however, in which adherence to regulations has provided personnel protection, whereas some planned discharges have resulted in injury to personnel.

The U.S. Environmental Protection Agency (EPA) has published a report to provide information on the use and effectiveness of CO_2 in fire protection systems and describe incidents involving inadvertent exposure of personnel to the gas (EPA430-R-00-02, 2000). The results of this comprehensive review identify that from 1975 to the present, a total of 51 CO_2 incident records were located that reported a total of 72 deaths and 145 injuries resulting from accidents involving the discharge of CO_2 fire extinguishing systems. All the deaths that were attributed to CO_2 were the result of asphyxiation. Details about the injuries were generally not provided in the incident reports, although some OSHA inspections listed asphyxia as the nature of the injury. Prior to 1975, a total of 11 incident records were located that reported a total of 47 deaths and 7 injuries involving CO_2. Twenty of the 47 deaths occurred in England prior to 1963; however, the cause of these deaths is unknown. The remainder of this section presents representative examples of the hazards of CO_2 fire suppression systems:

- On July 28, 2000, a bank employee accidentally suffocated in a New York City bank vault after pulling a fire alarm that flooded the space with CO_2. The bank employee was putting stock receipts in the bank's basement vault when she accidentally became locked inside. Apparently thinking she could get help by pulling a fire alarm, she instead activated a CO_2 fire extinguishing system that sucked air from the vault. She was taken to a local hospital in extremely critical condition and was pronounced dead.

- On January 15, 1999, at 5:49 p.m., with the plant at full power, an inadvertent discharge of the CO_2 fire suppression system occurred in the Millstone Unit 3 cable spreading room (CSR), which is located in the control building directly below the control room. The actuation occurred when a non-licensed plant equipment operator trainee in the service building blew dust off a printed circuit board located in the CSR CO_2 control panel, which is located in the service building, rather than the control building. There were no plant personnel in the CSR at the time of the discharge. Shortly after the discharge, CO_2 was found to have migrated down into the switchgear rooms located directly below the CSR. Approximately 37-minutes after initiation, the licensee used a portable instrument to measure the concentration of CO_2 in one of the control building stairwells, which allows access to the control room, the CSR, and the switchgear rooms. The reading was off-scale high indicating that the CO_2 concentration was in excess of 50,000 parts per million (ppm). NRC Regulatory Guide 1.78 currently recommends a CO_2 toxicity limit of 10,000 ppm. On the basis of this indication, the licensee declared the area uninhabitable.

  Approximately 2 hours after the CO_2 discharge, operators aligned the control building purge system to remove CO_2 from the switchgear rooms. The switchgear rooms were selected for purging first because they contained important plant equipment, such as the auxiliary shutdown panel. The purge system is a non-safety-related system designed to remove CO_2 and smoke from various control building areas. Placing the purge system in service diverted air from the control room to the switchgear rooms, which reduced the pressure in the control room relative to the CSR. This pressure reduction in the control room may have allowed CO_2 from the CSR room to migrate up through penetrations into the control room. When the concentration of CO_2 reached 5,000 ppm in the control room, the operators donned self-contained breathing apparatus (SCBA), as required by the plant procedures. The concentration of CO_2 in the control room reached a peak level in excess of 17,000 ppm before it began to decrease. The operators wore SCBA for approximately 6 hours until the CO_2 was successfully purged from the control room.

- On July 29, 1998, a high-pressure, total flooding CO_2 extinguishing system discharged without warning during routine maintenance of electrical equipment, resulting in one fatality and several serious injuries in Building 648 of the Idaho National Engineering and Environmental Laboratory (INEEL) (EH2PUB/09-98/01A1). At the time of the accident, the newly installed CO_2 system releasing panel was electronically disabled and considered to be out of service. The work crew began opening circuit breakers in preparation for the preventive maintenance work. Shortly after the last breaker was opened, the CO_2 system discharge, creating near zero visibility. While the evacuation alarms may have briefly sounded for less than one second, they did not continuously sound in conjunction with CO_2 release. After the CO_2 discharge, the worker ran toward the exits, which were visible since they were held open by cables running into the building from portable generators. Eight of the workers were able to exit on their own; however, five remained inside of the building and were rendered unconscious by the CO_2. Three were later rescued by the workers who had earlier escaped, which left two people remaining in the building. One of the remaining workers was later revived, and the other perished.

- At Duane Arnold Unit 1 on March 22, 1992 (LER 331/92-004), the licensee performed a special test of the CO_2 fire suppression system in the CSR. This test was conducted to check corrective actions taken following a CO_2 discharge in 1990. At the time of this test, the reactor had been shut down and defueled. As a result of this test, CO_2 intruded into the control room, and this intrusion led to an unacceptable reduction in the oxygen level in the area within a few minutes. The operator recorded oxygen levels of 17-percent (at chest level) and 15-percent (at floor level), both of which were below the plant's acceptance criterion of 19.5-percent. Essential control room personnel donned SCBA and were able to remain in the control room. The reduced oxygen levels resulted from increased pressure in the CSR, which is directly beneath the control room. Sealed penetrations between the two rooms leaked under the high differential pressure.

  In this incident, the migration of CO_2 into various fire zones may have adversely affected the operators' ability to shut down the plant during a fire in the CSR. Consequently, one can conclude that a severe fire in the CSR may adversely affect the operators' ability to safely shut down the plant from the control room. In the event that the operators are required to evacuate the control room, plant procedures require operators to shut down the plant from the auxiliary shutdown panel and other panels, which are located in the switchgear rooms. During this event, the CO_2 concentration at the auxiliary shutdown panel would prohibit access without SCBA.

- At Surry Nuclear Power Station on December 9, 1986, an accidental discharge of both the CO_2 and Halon extinguishing systems was caused by water damage to the extinguishing system control panels. The water came from a pipe break in the feedwater system. Four died and four were injured in a fire associated with the accident. However, it is not clear if the release of the gases from fire extinguishing systems were responsible for these injuries and deaths (Warnick, 1986).

- At Hope Creek Generating Station, on September 4, 1984, a 10-ton CO_2 system was inadvertently discharged into a diesel generator fuel storage area. The warning bell and beacon light did not operate and workers who were cleaning the corridor walls outside of the fuel storage room with air/water guns under pressure were not alerted. The cause of the discharge was determined to be moisture (that entered the CO_2 control panel through openings at the top of an inadequately installed protective panel) that shorted the CO_2 control panel circuitry. The moisture was believed to have originated from the workers cleaning the corridor walls (PNO-I-85-64a).

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B.15 Dry Chemical Extinguishing Agents

Dry chemicals or powders, or solid phase agents provide an alternative to water or gaseous agents for extinguishing fire. Table B.15-1 lists the chemical names, formulae, and (commercial) names of the various dry chemical agents. In each case, the particles of powder (10–76 m in size) are coated with an agent (such as zinc stearate or a silicone) to prevent caking and promote flowing, and are projected by an inert gas. The effectiveness of any of these agents depends on the particle size. The smaller the particles, the less agent is needed as long as particles are larger than a critical size. The reason for this fact is believed to be that the agent must vaporize rapidly in the flame to be effective. However, if an extremely fine agent were used, it would be difficult to disperse and apply to the fire.

Table B.15-1. Dry Chemical Agents

Chemical Name	**Formula**	**Popular Name(s)**
Sodium bicarbonate	$NaHCO_3$	Baking soda
Sodium chloride	$NaCl$	Common salt
Potassium bicarbonate	$KHCO_3$	Purple K
Potassium chloride	KCl	Super K
Potassium sulfate	K_2SO_4	Karate Massive
Monoammonium phosphate	$(NH_4)H_2PO_4$	ABC or multipurpose
Urea and Potassium bicarbonate	$NH_2CONH_2 + KHCO_3$	Monnex

It is difficult to draw a precise comparison of effectiveness of one dry chemical with another because a comparison based on chemical differences would require each agent to have identical particle size. Furthermore, gaseous agents can be compared by studying the flammability limits of uniform mixtures at rest; however, if particles were present, they would settle out unless the mixture is agitated, thus modifying the combustion behavior. Nonetheless, some general comparisons of various powders have been made:

- Sodium bicarbonate (standard dry chemical) and sodium chloride have comparable effectiveness and are several times as effective (on a weight basis) as powders such as limestone or talc, which are supposedly chemically inert in a flame. Sodium bicarbonate (standard dry chemical) primarily consists of sodium bicarbonate (over 90-percent) with additives to improve fluidity, non-caking, and water-repellent characteristics.
- Potassium bicarbonate or potassium chloride is up to twice as effective (on a weight basis) as the corresponding sodium compounds.

- Under some conditions, monoammonium phosphate is more effective than potassium bicarbonate, however, it can be less effective under other conditions.
- Monnex is twice as effective as potassium bicarbonate because of the rapid thermal decomposition of the complex formed between urea and potassium bicarbonate, which cause a breakup of the particles in the flame to form very fine fragments, which then rapidly gasify.

Dry chemical formulations may be ranked with regard to their effectiveness in extinguishing fires according to their performance in tests. As previously described, this performance is a function of both the chemical composition and the particle size. It seems clear that the effective powders act on a flame through some chemical mechanism, presumably forming volatile species that react with hydrogen atoms or hydroxyl radicals. However, science has not yet firmly established the precise reactions. Although the primary action is probably removal of active species, the powders also discourage combustion by absorbing heat, blocking radiative energy transfer, and in the case of monoammonium phosphate, forming a surface coating.

Of the seven types of dry chemicals commonly in use, only monoammonium phosphate is considered effective against deep-seated fires because of a glassy phosphoric acid coating that forms over the combustible surface. All seven types of dry chemical extinguishing agents act to suppress the flame of a fire (Friedman, 1998), but require significant cleaning after use. As a result their use is limited almost exclusively to environments where this is not a serious concern. Dry chemicals are very common in manual extinguishers and to some extent for local applications. The most common application of these agents is for relatively small flammable liquid fires. Dry chemical total flooding suppression systems are designed to reach the design concentration within the entire protected volume in less than 30 seconds (NFPA 17, "Standard for Dry Chemical Extinguishing System"). Additional dry chemical is required to compensate for losses attributable to openings and ventilation in a compartment.

One reason for the popularity of dry chemical extinguishing agents other than monoammonium phosphate has to do with corrosion. Any chemical powder can produce some degree of corrosion or other damage, but monoammonium phosphate is notably acidic and corrodes more readily than other dry chemicals, which are neutral or mildly alkaline. Furthermore, corrosion by the other dry chemicals is stopped by a moderately dry atmosphere, while phosphoric acid has such a strong affinity for water that an exceedingly dry atmosphere would be needed to stop corrosion. Monoammonium phosphate is also not recommended for kitchen fires involving hot fat because of its acidic nature; an alkaline dry chemical (such as potassium bicarbonate) is preferred.

Application of a dry chemical extinguishing agent on an electrical fire is safe (from the viewpoint of electric shock) for fire fighters. However, these agents (especially monoammonium phosphate) can damage delicate electrical equipment.

B.15.1 Hazards Associated with Dry Chemicals

One hazard associated with the use of dry chemical extinguishing agents is attributable to the sudden release of the agent. Another hazard is unexpected reignition. The main toxic hazards following the use of dry chemical agents will generally be those attributable to the combustion processes, since dry chemicals themselves are non-toxic. According to Hague (1997), the ingredients used in dry chemical agents are nontoxic but can cause temporary breathing difficulty and can interfere with visibility.

B.15.2 References

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B.16 Fire Protection Using Foam

Extinguishing foams provide a primary alternative to water, particularly for large fires. Foams are widely used to control and extinguish fires involving flammable and combustible Class B liquids (e.g., solvents, oil-based paints, petroleum greases, paraffin or heavy lubricants, tars, lacquers, hydrocarbons, alcohols, LPG, LNG, and cooking fats). Foams are also suitable for Class A fires involving ordinary combustible materials (e.g., wood, cloth, paper, rubber, and many plastics).

If a flammable liquid is lighter than water and is insoluble in water, application of water to extinguish a fire would simply cause the liquid to float on the water and continue to burn. Moreover, if the burning liquid is an oil or fat, the temperature of which is substantially above the boiling point of water, the water will penetrate the hot oil, turn into steam below the surface, and cause an eruption of oil (boilover) that will accelerate the burning rate and possibly spread the fire. By contrast, if the flammable liquid is water soluble (such as alcohols), addition of sufficient water will dilute the liquid to the point where it is no longer flammable. However, if the fire involves a deep pool of alcohol (rather than a shallow spill), the time required to obtained sufficient dilution might be so great that an aqueous foam would be a better choice of extinguishing agent. If the nature of a liquid is unknown, an aqueous foam might still be chosen over direct application of water. Another important application of foam is on liquids or solids that are burning in spaces that are difficult to assess (such as a room in a basement or the hold of a ship). In such instances, the foam is used to flood the compartment completely.

Fire-fighting foam is a mass of bubbles formed by various methods from aqueous solutions of specially formulated foaming agents. Some foams are thick and viscous, forming tough heat-resistant blankets over burning liquid surfaces and vertical areas. Other foams are thinner and spread more rapidly. Some are capable of producing a vapor-sealing film of surface-active water solution on a liquid surface, and others are meant to be used as large volumes of wet gas cells to inundate surfaces and fill cavities. The foam initially acts as a blanketing agent and then as a cooling agent as the water drains from the foam, as a cooling agent.

The effectiveness of foam is attributable to the following factors:

- prevents air from reaching fire
- generates steam, which dilutes the air as well as absorbed heat
- penetrates crevices because of low surface tension
- provides protection of exposed material that not yet burning

Nonetheless, foam is an unstable air-water emulsion, which can easily be broken down by physical or mechanical forces, and certain chemical vapors or fluids can quickly destroy foam. Consequently, when certain other extinguishing agents are used in conjunction with foam, severe breakdown of the foam can occur. In addition, turbulent air or violently uprising combustion gases can divert light foam from the burning area.

Foam breaks down and vaporizes its water content under attack by heat and flames. Therefore, it must be applied to a burning surface in sufficient volume and at a sufficient rate to compensate for this loss and guarantee a residual foam layer over the extinguished portion of the burning liquid. The process of foam spread over a burning liquid fuel is similar to the spread of a less dense liquid (such as oil) on a more dense liquid (such as water).

B.16.1 Properties of Foam

Foams used for fire fighting should possess certain general properties, including (1) expansion, (2) cohesion, (3) stability, (4) fluidity, (5) fuel resistance, and (6) resistance. Clearly, foam extinguishing agents must have an appreciable expansion ratio, the bubbles must adhere together to form a blanket, and the foam must retain its water and remain stable, flowing while freely over the liquid surface and around any obstacles. In addition, foam agents must not pick up so much fuel that the foam would be liable to burn, and the agent must resist the heat of flames on the liquid. Foams for use on alcohol fires must also be alcohol resistant.

Three quantitative criteria for foam are (1) the expansion (2) the fluidity and (3) the drainage time. Expansion is quantitatively measured by the expansion ratio. While fluidity is measured in terms of shear stress. A shear stress in the range 150–200 dyn/cm^2, measured on a torsional viscometer, is typical of a good foam extinguishing agent. The drainage of liquid out of the foam is usually expressed as the 25-percent drainage rate, which is the time in minutes for 25-percent of the total liquid content to drain away under standard conditions. For a good foam, this drainage time is typically 2–5 minutes.

Foam extinguishing agents can also be affected by the quality of the water used. A study by Dimaio and Lange (1984) detected deleterious effects from contaminants (such as corrosion inhibitors, anti-fouling agents, etc.). In general, however, such effects were found to be much weaker if high application rates were used.

B.16.2 Hazards Associated with Foam

Foam is water-based; consequently, hazards associated with water also apply to foam. These hazards include increased vaporization of low-boiling flammable combustible liquids, reaction with incompatible materials and electric shock from live electrical equipment. Another hazard is rupture of the foam blanket and burn back, which may put fire fighters at risk. Hazards can also arise from the use of a foam on a liquid at a temperature of 100 °C (212 °F) or above, because the formation of steam can cause a four-fold expansion of the foam with boilover of the burning liquid. In the case of the medium- and high-expansion foams used to fill spaces, there is the additional hazard of asphyxiation of personnel or visibility and spacial limitations resulting in injury.

Another hazard of foam is ignition of hydrocarbons in a storage tank roof by static electricity from foam injection, as described by Howells (1993). This author describes several incidents in which ignition of volatile refined products in a floating roof storage tank appears to have been caused by foam injection. He suggests two possible modes of charge generation, including (1) the setting of water droplets through the hydrocarbon liquid and (2) the streaming current of the foam mixture leaving the nozzle.

B.16.3 Delivery Systems for Foam

Foam is delivered to a fire by means similar to those used for water, which primarily include fixed systems such as foam-water spray systems and fixed foam-water monitors, and mobile foam-water systems such as fire hoses. For low-expansion foam, one type of fixed-foam system used for low-expansion foam is the foam-water deluge system. Fixed-foam systems are used for fire prevention, extinguishment, and control in bunds or on spills. Subsurface application of low-expansion foam to hydrocarbon storage tanks was developed in the 1960s and is now an NFPA-recognized design procedure. Relevant codes are NFPA 11, “Standard for Low-Expansion Foam”; NFPA 11A, “Standard for Medium-and High-Expansion Foam Systems”; and NFPA 16, “Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems.” There is limited use of foam in portable devices except in wildland fire situations involving Class A fuels. The Class A foams are generally mixed in 0.1% to 1.0% concentration ratios in water and are utilized in compressed air/foam systems which discharge through hose lines equipped with air aspirating foam nozzles or conventional fog nozzles.

The delivery of foam involves three stages, including (1) proportioning the foam concentrate, (2) generating foam, and (3) distributing foam. There are a number of methods for proportioning the foam concentrate. The devices for generating the foam are incorporated in the devices used for its distribution, as previously described. The basic generation method is aspiration of air into the foam.

B.16.4 Application of Foam

Fire extinction by blanketing may be achieved using foam. Foam can be used for all modern fire protection in warehouses, high storage areas, and process plants of all types for commodities such as rubber tires, rolled paper, and plastics; in bulk storage areas and conveyor tunnels, coal mines, coal handling equipment tunnels, and diked areas; in electric power plants aircraft hangars, and aboard ships. An example of application in a BWR is the use of a foam water sprinkler system (NFPA 16) to protect the large oil hazard of the recirculation pumps motor generator (MG) set.

Low expansion foam is mainly used to prevent, extinguish, or control fires in storage tank tops and bunds and on spills. Medium- and high-expansion foams are used to prevent, extinguish, or control fire in spaces such as fires below grades (e.g., basement).

Foam should be used only if compatible with the hazardous liquid. In particular, foam is essentially expanded water and, apart from its density, has the general characteristics of water. Consequently, it is just as unsuitable as water for fighting fires involving electrical equipment or substances that have undesirable reactions with water. Other prerequisites for the use of foam are that the liquid surface must be horizontal and the temperature of the liquid must be below the boiling point. In addition, the liquid temperature is below the boiling point of the given hazardous liquid, but above 100 °C (212 °F), water in the foam will turn to steam, which can result in very large expansion of the foam.

There are optimum rates of foam application. For low-expansion foam with an expansion ratio of 8:1, an application rate of 0.1 US gal/ft^2-min will give 0.8 US gal/ft^2-min of foam. Application systems for medium- and high-expansion foams comprise both (1) total flooding systems and (2) local application systems. Fighting a major fire requires a very large quantity of foam. An example quoted by Nash (1966) is a requirement of 300 x 5 UK gal drums for a 30-minute foam attack on a single 150-ft diameter oil storage tank. The supply and disposal of such a large number of drums in an area congested with appliances and hoses constitute a major problem. Consequently, Nash describes the alternative of providing a piped supply of foam concentrate.

A particularly important application of foam is the protection of storage tanks. For fixed roof tanks, some principle arrangements are foam chambers, internal tank distributors, and subsurface foam injection. Foam chambers are installed at intervals on the outside near the top of the tank wall, providing an over-the-top foam generation. An alternative is internal distributors fitted inside the tank. Application of foam at the top of the tank poses several problems. If the fire is initiated by an explosion, the explosion itself may also disable the foam system. The upward flow of air caused by the fire may also interfere with the distribution of the foam and the foam may not reach the center of a large tank. Subsurface foam injection is designed to counter these difficulties. Such systems inject under pressure up through the liquid in the tank. Injection may be through the product pipe or a dedicated line. Mobile foam trucks may be used to provide the foam supply.

Floating roof tanks may be open topped or closed. Both have a good fire record, so foam systems are generally not required. The one exception to this rule is the need to allow for rim fires, which can occur on either type of tank. An open-topped floating roof tank may be protected by a fixed foam system, which pours foam into the annulus formed by the tank wall and a foam dam. A closed floating roof tank may be protected using a top injection system similar to those used in fixed roof tanks. Subsurface foam injection is not generally used for floating roof tanks, since a tilted or sunken roof can cause poor foam distribution.

Foam trucks are the principal means of mobile foam of delivery. The trucks are typically purpose-built twin-agent trucks with the capability to deliver dry chemicals in addition to aqueous film forming foam (AFFF). Foam trucks carry a supply of foam concentrate and delivery hoses and can be equipped with telescoping booms or articulated towers. They also have low clearances to allow passage under pipe bridges. Monitor capacities are on the order of 500–1000 US gal-min.

A variety of mobile devices can be used to apply foam to the top of a storage tank that is on fire. These include mobile foam monitors and foam towers. However, using a foam monitor for this purpose poses numerous problems, such as crosswinds and fire updrafts, which can waste a significant proportion of the foam.

Use of foam extinguishing agents is not limited to fire control and extinguishment. Another important application is the suppression of vaporization from toxic liquid spills. This use of foam is treated in ASTM F1129-88, “Standard Guide for Using Aqueous Foams to Control the Vapor Hazard from Immiscible Volatile Liquids.” A 500 to 1 foam ratio can be used to control fires and reduce vaporization from liquefied natural gas (LNG) spills.

B.16.5 Types of Foam

A large family of foams of different types and applications are currently available. Water-based foams are available in the following forms:

- chemical foam
- protein-based mechanical foam
    - standard low-expansion foam
    - high-expansion foam
    - medium-expansion foam
- special foam
    - fluorochemical for light-water foam
    - fluoroprotein foam
- synthetic detergent foam
    - aqueous film-forming foam (AFFF)
    - film-forming fluoroprotein (FFFP) foam
    - alcohol-resistant foam
    - low-temperature foam

One broad distinction is the viscosity of the foam. The blanket formed by the more viscous type is resistant to rupture by flame, but the less viscous type flows more readily over a liquid surface.

- *Chemical Foam*

  Chemical foam is produced by reacting an aqueous solution of sodium bicarbonate and aluminum sulphate in the presence of a foam stabilizer. The reaction generates CO_2, which both forms foam and ejects the mixture from the apparatus. This type of foam may be generally regarded as obsolete, given that its use has long been almost entirely confined to chemical foam portable extinguishers which are no longer listed by Underwriters Laboratories.

- *Protein-Based Mechanical Foam*

  — Mechanical foam is generated by mechanical aeration of aqueous solutions of certain chemicals, which usually have a protein base. For example, one type is based on protein rich slaughter house byproducts for the foam stabilizing agent. Standard foam is made by introducing the foam compound into the water in the hose to give a 3–6-percent aqueous solution and then mixing the solution with air in an ejector nozzle to give an expansion of approximately 10:1. This type of foam is the most widely used for both fixed and mobile apparatus. Such standard low-expansion foam is often very economical.

  — High-expansion foam is generally similar to standard foam, with the exception that it has a much higher expansion of approximately 1,000:1. Because this type of foam contains little water, it acts almost entirely by blanketing rather than cooling. In addition, it is very light and become easily blown away, it is more suitable for fires in contained spaces than for those in open situations (such as bunds).

  — Medium-expansion foam is also generally similar to standard foam, with the exception that has an expansion of approximately 100–150:1. This type of foam is also light, but is not so easily blown away as high-expansion foam. Both medium- and high-expansion foams have a good three-dimensional extinction capability and can be used against fires on piles of materials (such as rubber).

  A disadvantage of protein foams is that if the foam blanket is broken, the liquid may reignite and burn back the blanket. Low-expansion foam, however, has an advantage in this regard, given that it has reasonably good heat and burnback resistance.

- *Special Foam*

  — Fluorochemical or Light-Water Foam

  Fluorochemical foam is one agent that has been developed to overcome the problem of reignition and burnback. One type is fluorochemical foam. This light-water foam contains a straight-chain fluorocarbon surface active agent. This has the effect that as the water drains from the foam, it spreads in a thin film over the liquid and seals it. Even if the film is disturbed by agitation, it reforms rapidly. Light-water foam behaves differently, however, on different liquids, and it is expensive and not universally effective.

— *Fluoroprotein Foam*

Another agent that works in a manner similar to fluorochemical light-water foam is fluoroprotein foam, which contains a branched-chain fluorocarbon. Where good burnback resistance is needed, this alternative is less expansive and appears (in many cases) to be more effective than light-water foam. In particular, fluoroprotein foam is less prone to pick up oil particles when passed through oil. This fuel-shedding property is useful in subsurface foam injection on storage tanks. This type of foam also tends to have good compatibility with dry chemicals.

- *Synthetic Detergent Foam*

  Synthetic detergent foam is generated by mechanical aeration of an aqueous solution containing 2–3 -percent detergent. This foam is less stable than protein-based foam, but it appears to be useful in massive application in a knockout attack. Despite its limitations, detergent foam has enjoyed some popularity, because it is even less expensive than protein foam.

  — *Aqueous Film-Forming Foam (AFFF)*

  AFFF has low viscosity and spreads easily over a liquid surface so it can be an effective agent against deep-seated fires. Another useful property of AFFF is that it does not need elaborate foaming devices and can be used in many water sprinkler and water spray systems.

  — Film-Forming Fluoroprotein (FFFP) Foam

  FFFP foam is another type of foam that has low viscosity and good spreading properties and can be used in many water spray systems. FFFP foam tends to drain rapidly and, therefore, is less reliable in maintaining a foam blanket.

  — *Alcohol-Resistant Foam*

  Regular air foams do not perform well on liquids that are of the polar solvent type (notably alcohol). Alcohol-resistant foams have been developed to solve that problem. The first generation of alcohol-resistant foams were not entirely satisfactory, but effective foams have since been developed. One type of alcohol-resistant foam is polymeric-alcohol resistant AFFF.

  — *Low-Temperature Foam*

  Foams have been developed for use at low ambient temperatures; one quoted temperature for such foams is -29 °C (-20 °F). These foams come in both protein and AFFF types.

B.16.6 References

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B.16.7 Additional Reading

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B.17 Harmful Properties of Toxic Gases Found in Fires

B.17.1 Introduction

Historically, more people are injured or killed by fire combustion products than by direct exposure to heat and flame. Evaluations have shown that personnel at a distance from the source of a fire are particularly at risk from fire effluent in post-flashover fire scenarios (Beitel et al., 1998). Toxic gases are lethal largely because they cause people to become disoriented and suffer respiratory distress, often losing consciousness and physical mobility. Following a period of hyperventilation, resulting from inhaling irritant gases the final cause of death is often carbon monoxide (CO) poisoning or scorching of the lungs by hot fire gases, rather than thermal exposure or flame impact.

The most significant effluent toxicants in ordinary fires are CO, hydrogen cyanide (HCN), carbon dioxide (CO_2), hydrogen chloride (HCl), and nitrogen dioxide (NO_2). Speaking very generally, CO alone accounts for half of the fire toxicity problem, although it is far less toxic than many of the other gases found in fires. Nonetheless, CO is considered to be the primary toxicant because of its copious generation by all fires. The importance of any toxic gas species to a particular fire must reflect both its toxicity and its actual concentration in that particular fire. The time of exposure is also important for determining the effects from toxic gases. In general, a higher concentration allows the same biological effect to be reached in a shorter time. For toxicity data, the exposure period normally used is 30 minutes.

The following definitions of toxicity related terms are commonly used in fire and combustion toxicology, as defined by ASTM Standard E176-98:

- ***Toxic hazard*** is the potential for physiological harm from the toxic products of combustion. Toxic hazard reflects both the quantity and quality of toxic products (quality is typically expressed as toxic potency. Toxic hazard is not the only hazard associated with fire, and is not an intrinsic characteristic of a material or product. Rather, toxic hazard depends upon the fire scenario, the condition of use of the material or product, and possibly other factors.
- ***Toxic potency*** is a quantitative expression that relates concentration and exposure time to a particular degree of adverse physiological effects (for example, death) on exposure of humans or animals. The toxic potency of the smoke from any material, product, or assembly is related to the composition of that smoke, which, in turn, depends upon the conditions under which the smoke is generated. Toxic potency of the smoke from a specimen or product is determined on a per-unit-specimen-mass basis. At present, for fire research, the dominant biological end point adopted is death and the measured quantity is the LC_{50}, which is the concentration (g/m^3) of smoke which is lethal to 50-percent of the exposed specified test animals in a specified time period. (The meaning of this variable is the amount of mass that needs to be dispersed into a volume of 1 m^3 in order to cause a 50-percent probability of lethality.) For substances where the composition is known (e.g., purge gases), the LC_{50} is usually expressed in units of ppmv. The definition here is that 1 ppmv of gas means that there is one part of gas per million parts of air. The “v” denotes parts by volume rather than weight. The LC_{50} notation must include the exposure time, generally 30 minutes (along with a 14-day post-exposure observation period) (Babrauskas et al., 1991). The toxic potency is not an intrinsic characteristic of a material.

B.17.2 Smoke and Toxic Gases

Many studies have been undertaken on toxic combustion products of organic materials, with the objective of realistically assessing the associated hazard. Toxicities of CO, CO_2, HCN, HCl, and low O_2 have been examined in depth by Babrauskas (1991), who determined that narcosis is caused by fire gases, such as CO and HCN, as well as low O_2 concentrations and high CO_2 concentrations. Narcotic gases cause incapacitation mainly by acting on the central nervous system and, to some extent, the cardiovascular system. Most narcotic fire gases produce their effects by causing brain tissue hypoxia. Since the body possesses powerful adaptive mechanisms designed to maximize oxygen delivery to the brain, it is usually possible to maintain normal body functions up to a certain concentration of a narcotic, and be unaware of the impending intoxication. However, once the threshold is reached where normal functioning can no longer be maintained, deterioration is rapid and severe, beginning with signs similar to the effects of alcohol intoxication, including lethargy or euphoria with poor physical coordination, followed rapidly by unconsciousness and death if exposure continues (Tamura, 1994).

The manual of the American Conference of Governmental Industrial Hygienists, Inc., gives the threshold limit values (TLVs) and a description of various toxic gases. The TLV is defined as the time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek to which nearly all workers may be repeatedly exposed, day after day without adverse effect. The TLVs and biological effects of concentrations above the TLV for toxic gases are discussed in the following subsections (Tamura, 1994).

B.17.2.1 Carbon Monoxide (CO)

CO is a common product of combustion generated in a fire environment. This highly toxic, non-irritating gas has long been recognized as a primary cause of fatalities related to combustion sources including fire. In fact, the majority of all fire fatalities are attributed to CO inhalation. CO is produced as a result of incomplete combustion of materials containing carbon and is present in large quantities in most fires. Invisible, odorless, tasteless, and slightly lighter than air, CO is the most significant toxicant as it can cause occupants to become incapacitated if the concentration is high enough and the exposure is long enough. CO acts by combining with hemoglobin in the blood to form carboxyhemoglobin (COHb). This is important because hemoglobin carries oxygen throughout the body, and it cannot do this if it is tied up as COHb and, therefore, unavailable for oxygen transport. In the absence of other contributing factors, a COHb concentration of 50-percent or greater is generally considered lethal in the blood of fire victims.

The highest concentration of CO to which people can be exposed day after day without adverse effect is 50 ppm. This concentration keeps the COHb level below 10-percent. Concentrations of 400 to 500 ppm can be inhaled for 1 hour without appreciable effect. Concentrations of 1,000 to 1,200 ppm cause unpleasant symptoms after 1 hour of exposure. Concentrations of 1,500 to 2,000 ppm for 1 hour of exposure are dangerous, and concentrations above 4,000 ppm are fatal in exposure of less than 1 hour (Sumi and Tsuchiya, 1971).

B.17.2.2 Hydrogen Cyanide (HCN)

HCN is one of the most rapidly acting toxicants, being approximately 20 times more toxic than CO. HCN is produced when materials involved in a fire contain nitrogen [for example, polyacrylonitrile (Orlon®), polyamide (nylon), wool, polyurethane, urea-formaldehyde, and acrylonitrile-butadiene-styrene (ABS)]. Inhalation of HCN may cause severe toxic effects and death within a few minutes up to several hours, depending upon the concentration inhaled. The action of HCN is attributable to the cyanide ion, which is formed by hydrolysis in the blood. Unlike CO, which remains primarily in the blood, the cyanide ion is distributed throughout the body fluids, bringing it into contact with the cells of vital tissues and organs.

The TLV for HCN is 10 ppm, and it can be inhaled for several hours without appreciable effect at concentrations of 20–40 ppm. The maximum amount that can be inhaled for 1 hour without serious reaction is 50–60 ppm. Concentrations of 120–150 ppm are dangerous in 30–60 minutes, and concentrations of 3,000 ppm or more are rapidly fatal (Sumi and Tsuchiya, 1971).

B.17.2.3 Carbon Dioxide (CO_2)

CO_2 usually evolves in large quantities from fires. While not particularly toxic at observer levels, moderate concentrations of CO_2 (on the order of 2-percent) increase both the rate and depth of breathing by about 50-percent, thereby increasing the respiratory minute volume (RMV). This condition contributes to the overall hazard of a fire gas environment by causing accelerated inhalation of toxicants and irritants. If 4-percent CO_2 is breathed, the RMV is approximately doubled, but the individual may scarcely notice the effect. Given any further increase in CO_2 from 4 percent up to 10-percent, the RMV may be 8 to 10 times the resting level (Hartzell, 1989).

The TLV of CO_2 is 5,000 ppm. Stimulation of respiration is pronounced at a concentration of 5-percent (50,000 ppm), and a 30-minute exposure produces signs of intoxication. Above 70,000 ppm, unconsciousness results in a few minutes (Sumi and Tsuchiya, 1971).

B.17.2.4 Hydrogen Chloride (HCl)

HCl is formed from the combustion of materials containing chlorine, the most notable of which is polyvinyl chloride (PVC) as used in common thermoplastic electrical cables. HCL is both a potent sensory irritant and potent pulmonary irritant. It is a strong acid, being corrosive to sensitive tissue, such as the eyes. If inhaled, HCl will irritate and damage the upper respiratory tract and lead to asphyxiation or death.

The TLV for HCl is 5 ppm. Concentrations as low as 75 ppm are extremely irritating to the eyes and upper respiratory tract, and behavioral impairment has been suggested. The maximum concentration allowable for short exposures of 30–60 minutes is 50 ppm. Concentrations of 1,000–2,000 ppm are dangerous even for short exposures (Sumi and Tsuchiya, 1971).

B.17.2.5 Nitrogen Dioxides

Nitrogen dioxides (NO_2 and N_2O_4) are the common oxides of nitrogen (N) that are produced in a fire. (The other is nitric oxide, or NO.) Nitrogen dioxide, which is very toxic, can be produced from the combustion of N-containing material. Nitric oxide has a short life in atmospheric air because it is converted into dioxide in the presence of oxygen. These compounds are strong irritants, particularly to mucous membranes. When inhaled, they damage tissues in the respiratory tract by reacting with moisture to produce nitrous and nitric acids. The TLV for nitrogen dioxide is 5 ppm. Immediate throat irritation can begin at 62 ppm. Short-exposure concentrations of 117–154 ppm are dangerous, and rapidly fatal at 140–775 ppm (Sumi and Tsuchiya, 1971).

B.17.3 Toxicity Data

Toxicity or toxic data usually reflect the results of animal testing. The table of relative acute toxicity criteria given below was published by the National Institute for Occupational Safety and Health (NIOSH) in the Registry of the Toxic Effects of Chemical Substances (RTECS) in 1967. It is widely used to interpret animal toxicity data; the lower the dose number, the greater the toxicity. The measures of toxicity used in the Table B.17-1, LD_{50} and LC_{50} are explained in the discussion following the table (Spero, Devito, and Theodore, 2000).

Table B.17-1. Toxicity Data

Rating	Keywords	LD_{50} Single Oral Dose* (mg/kg)	LC_{50} Inhalation Vapor Exposure* (ppm)	LD_{50} Skin** (mg/kg)
4	Extremely hazardous	#1	#10	#5
3	Highly hazardous	50	100	43
2	Moderately hazardous	500	1000	340
1	Slightly hazardous	5,000	10,000	2,800
0	No significant hazard	>5,000	>10,000	>2,800

* Rats
**Rabbits

Data on animal toxicity usually identify the route of entry into the body (oral ingestion, inhalation, adsorption through the skin, etc.) first, followed by the test animal (mouse, rat, human, etc.), followed by the measure of toxicity. The most common measures of toxicity are as follows:

- Lethal Dose 50-percent (LD_{50}) is the dose required to kill 50-percent of the test animals when administered by a route of entry other than inhalation. The dose of the chemical (usually solids or liquids) is given as mg/kg, which represents milligrams of chemical per kilogram of body weight of the test animal. The LD_{50} is expressed in this manner because more chemical is needed to kill a larger animal. For example, the oral rat LD_{50} for the HAP calcium cyanamide is 159 mg/kg.
- Lethal Concentration 50-percent (LC_{50}) is similar to LD_{50} except that the route of entry is inhalation. The concentrations of the inhaled chemicals (usually gases) are expressed as parts per million (ppm) or milligrams per cubic meter (mg/m^3).
- Lethal Dose Low (LDL_o) is the lowest dose required to kill any of the animals in the study when administered by a route of entry other than inhalation.
- Lethal Concentration Low (LCL_o) is the same as LDL_o except that the route of entry is inhalation.
- Toxic Dose Low (TDL_o) is the lowest dose used in the study that caused any toxic effect (not just death) when administered by a route of entry other than inhalation.
- Toxic Concentration Low (TCL_o) is the same as TDL_o except that the route of entry is inhalation.
- EC_{50} is the concentration required to cause a 50-percent reduction in growth.
- Acute Risks are the risks associated with brief exposures to high concentrations.
- Chronic Risks are the risks associated with long-term exposures to low concentrations.

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B.18 Effects of Decomposition Products of Halogenated Fire Extinguishing Agents

B.18.1 Introduction

When an ineffective Halon fire extinguishing system that is incapable of extinguishing its design-basis fire is installed in a compartment, the system discharge will actually degrade environmental conditions by introducing additional toxic gases.

The 18th Edition of the National Fire Protection Association (NFPA) Fire Protection Handbook (Taylor, 1997) identifies the effects of the decomposition products of Halon 1301 and 1211 fire extinguishing agents, as follows:

> *Consideration of life safety during the use of halogenated agents must also include the effects of decomposition (or breakdown) products, which are relatively more toxic to humans. Decomposition of halogenated agents takes place on exposure to flame or surface temperatures above approximately 482 °C (900 °F). In the presence of available hydrogen (from water vapor or the combustion process itself), the main decomposition products of Halon 1301 are hydrogen fluoride (HF), hydrogen bromide (HBr), and free bromine (Br_2). Although small amounts of carbonyl halides (COF_2, $COBr_2$) were reported in the early tests, more recent studies have failed to confirm the presence of these compounds.*

Table B.18.1-1 summarizes the major decomposition products of Halon 1301 and 1211. The approximate lethal concentrations (ALCs) for a 15-minute exposure to some of these compounds are given in Column 2 of Table B.18-1. Column 3 gives the concentrations of these materials that have been quoted as "dangerous" for short exposure.

Even in minute concentrations of only a few parts per millions (ppm), the decomposition products of the halogenated agents have a characteristically sharp, acrid odor. This characteristic provides a built-in warning system for the agent, but also creates a noxious, irritating atmosphere for those who must enter the hazard area following a fire. It also serves as a warning that other potentially toxic products of combustion (such as CO) will be present.

B.18.2 Toxicity of Decomposition Products of Halogenated Fire Suppression Agents

Hill (1977) summarizes the effects of hydrogen fluoride (HF) on humans at various concentrations. At concentrations as low as 32 ppm, irritation of eyes and nose occurs. At 60 ppm, irritation of the respiratory tract occurs after 60 seconds. At concentrations of 120 ppm, irritation of the conjunctival and respiratory tracts is tolerable for only 60 seconds. Concentrations between 50 and 100 ppm are considered dangerous to life after several minutes of exposure. Generally, the HF containing atmospheres are so irritating that personnel will be forced to evacuate before serious health risk is incurred. Decomposition product data clearly indicate that life-threatening concentrations of HF likely. HF concentrations of 300 ppm are typically measured in full-scale tests.

Table B.18-1. Approximate Lethal Concentrations (ALCs)
for Predominant Halon 1301 and Halon 1211 Decomposition Products

Compound	**ALC for 15-minute Exposure (ppm by Volume in Air)**	**Dangerous Concentrations (ppm by Volume in Air)**
Hydrogen fluoride, HF	2,500	50–250
Hydrogen bromide, HBr	4,752	-
Hydrogen chloride, HCl	-	-
Bromine, Br_2	550	-
Chlorine, Cl_2	-	50
Carbonyl fluoride, COF_2	1,500	-
Carbonyl chloride, $COCl_2$	100–150	-
Carbonyl bromide, $COBr_2$	-	-

DeMonburn and McCormick (1973) have reported on the design and testing of Halon 1301 in extinguishing a wool bag filter fire in an industrial baghouse situation. The baghouse studied has an area of approximately 13.3 m^2 (144 ft^2). These studies indicate that using rate-of-rise thermal detectors and the complete shutdown of the air flow through the baghouse, a 4-percent concentration of Halon 1301 would extinguish a fully developed fire. However, it should be noted that following extinguishment and 20 minutes soaking time, toxic levels of hydrogen fluoride, hydrogen cyanide, and hydrogen sulfide were detected in the unoccupied baghouse as shown in Table B.18-2.

Table B.18-2. Concentration of Hazardous Gases Attributable to Decomposition of Halon 1301 in Industrial Baghouse Fire Situation

Time (minutes)	**Decomposition Product Concentration (ppm)**		
	Hydrogen Fluoride (HF)	**Hydrogen Cyanide (HCN)**	**Hydrogen Sulfide (H_2S)**
0–4	55	1,643	2,452
20–24	10	194	112

The National Research Council Advisory Center reviewed the toxicity of Halon 1301 for consideration by NASA. In a letter to Dr. G.J. Stopps of the Haskell Laboratory, dated September 22, 1967, R.C. Wands, Director of the Toxicology Center, stated:

> *Personnel can be exposed without significant hazard for a maximum of 5 minutes to normal air at 1 atmosphere and mixed with up to 6-percent mean concentration by volume of bromotrifluoromethane [CF_3Br (Halon 1301)] as a fire extinguishing agent. This assumes appropriate engineering design to sense the fire and deliver the agent so as to extinguish the fire promptly in order to minimize that pyrolysis products* (Atomic Energy Commission, 1970).

Ford (1975) has evaluated the issue of the decomposition of Halon 1301, and believes caution and limitations should be applied to the utilization of extinguishing systems containing that agent:

- Although safe at a design concentration of 5–7-percent, the Halon 1301 agent will not extinguish deep-seated Class A fires with these concentrations. Thus, water systems should be provided and higher concentrations of Halon 1301 should be used for extinguishment in these situations. If higher concentrations of Halon 1301 are provided, the design of the system should incorporate all of the requirements of the NFPA Standard 12A, and the operation of the system in relation to the personnel hazard should be identical to that of a CO_2 extinguishing system.
- Halon 1301 may decompose to untenable concentrations of hydrogen fluoride and hydrogen bromide when the vapor is in contact with a heated surface above 482 °C (900 °F), or when the agent is applied to a large fire in a small enclosure. Table B.18-3 summarizes the relationship between the flame shield exposure and room size. Note in Situation One that the ratio of flame dimension to room size is 0.60, while in Situation Two, the ratio of flame dimension to room size is 6.0. The concentrations of the hydrogen fluoride and hydrogen bromide acid gases in situation two are beyond tolerable limits for human exposure. However, it must be remembered in this situation and the previous industrial baghouse situation presented by DeMonburn and McMormick, that the toxic products of combustion from the fire would in all probability also create an intolerable atmosphere for human exposure. The primary life hazard involves the entry of personnel into the area immediately following extinguishment. These characteristics of the Halon agent under intense thermal or flame exposure make the installation of these systems for an oven or furnace chamber unsuitable where the temperature is above 260 °C (500 °F).

B.18.3 Physical Properties of Halon 1301

Under normal conditions, Halon 1301 is a colorless, odorless gas with a density approximately 5 times that of air. It can be liquefied upon compression for convenient shipping and storage. Unlike CO_2, Halon 1301 cannot be solidified at temperatures above -167.8 °C (-270 °F). The molecular weight of Halon 1301 is 148.93 (see Table B.18-4).

B.18.4 Physical Properties of Halon 1211

Under normal conditions, Halon 1211 is a colorless gas with a faintly sweet smell and a density about 5 times that of air. It can be readily liquefied by compression for storage in closed vessels. The molecular weight of Halon 1211 is 165.38 (see Table B.18-4 for properties of Halon).

Table B.18-3. Halon 1301 Decomposition Produced by n-Heptane Fires

Situation One: 1,695-foot Enclosure Volume; 4-Percent Halon 1301 by Volume					
Fire pan size (ft^2)	**Fuel area to volume ft^2/1000 ft^2**	**Discharge time (sec)**	**Extinguishment time (sec)**	**Decomposition products (ppm volume in air)**	
				Hydrogen Fluoride (HF)	**Hydrogen Bromide (HBr)**
0.1	0.06	23.0	11.5	1.8	3.5
0.1	0.06	13.5	7.1	1.8	2.1
0.1	0.06	5.7	4.8	1.4	2.8
Situation Two: 1,695-foot Enclosure Volume; 4-Percent Halon 1301 by Volume					
Fire pan size (ft^2)	**Fuel area to volume ft^2/1000 ft^2**	**Discharge time (sec)**	**Extinguishment time (sec)**	**Decomposition products (ppm volume in air)**	
				Hydrogen Fluoride (HF)	**Hydrogen Bromide (HBr)**
10.0	6.0	25.0	20.0	1,907	397
10.0	6.0	15.0	16.3	1,206	382
10.0	6.0	6.0	10.0	666	112
10.0	6.0	6.0	5.2	320	38

Table B.18-4. Selected Properties of Halon 1301, 1211, and 2402

Extinguishing Agent	**Halon 1301 (CF_3Br)**	**Halon 1211 (CF_2ClBr)**	**Halon 2402 ($C_2F_4Br_2$)**
Boiling point °C (°F)	-58 (-72.5 °F)	-4 (25 °F)	47 (117 °F)
Liquid density at 20 °C (g/cc)	1.57	1.83	2.17
Latent heat of vaporization (J/g)	117	134	105
Vapor pressure at 20 °C (atm)	14.5	2.5	0.46

B.18.5 References

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B.19 An Introduction to Computer Fire Models

B.19.1 Introduction

ASTM E176 defines a fire model as a physical or mathematical representation of burning or other processes associated with fire. Physical models attempt to reproduce fire phenomena in a simplified physical situation. For example, scale models are a very widespread form of modeling, as full-scale experiments are expensive, difficult, and sometimes wholly infeasible. Insight can often be gained by studying fire phenomena at a reduced physical scale. Mathematical fire models include one or more empirical equation(s) that can be solved analytically or a set of complex differential and algebraic equations that must be solved numerically on a computer. A computer program to accomplish the numerical solution of complex set of differential and algebraic equations is called a computer fire model. Fire modeling can normally be considered as the prediction of fire characteristics by the use of a mathematical method which is expressed as a computer program.

The computer fire models have invaluable tools to assist in a wide range of uses in fire protection engineering research and development, fire-safe design of a structure, fire hazard analyses, fire spread, smoke control systems design, structural response of building members, human behavior and egress in the event of fire, actuation of thermal devices (sprinklers, detectors, ceiling vents etc.), hydraulic design of fire suppression systems, and fire investigation and reconstruction. Many building and fire regulations (including NFPA 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants") allow for use of computer fire modeling as part of the performance-based fire safety designs to help bridge the gap between building functionality and fire code. The performance-based fire safety engineering is defined as "an engineering approach to fire protection design based on (1) agreed fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and fire effluents; and (4) quantitative assessment of the effectiveness of design alternatives against loss objectives and performance objectives" (Meacham and Custer, 1995 and Custer and Meacham, 1997).

B.19.2 Categories of Computer Fire Model

Fire models can be grouped into two categories: probabilistic or stochastic fire model and deterministic fire models. Probabilistic fire models involve the evaluation of the probability of risk due to fire based on the probabilities of all parameters influencing the fire such as human behavior, formation of openings and distribution of fuel load in the compartment of fire origin. The results of the models are in terms of the statistical likelihood of the occurrences of fires and fire outcomes, based on the random nature of fire and the likelihood of occurrence. Little or no information is given with respect to production and distribution of combustion products. In contrast to the probabilistic fire models, deterministic fire models are based on physical, chemical and thermodynamic relationship and empirical correlation to calculate the impact of fire. Deterministic fire models can be very simple requiring a short computing time or highly complex requiring hours of computation. Typically deterministic fire models can be classified as zone models, field models, and other models. The most commonly used computer fire models simulate the consequences of a fire in an enclosure are zone and field models. Other models are special purpose models such as building evacuation (egress) models, models of thermal actuation devices (sprinklers and detection systems), models of structural fire resistance/endurance, fire sprinkler hydraulic design models, smoke movement/migration models, and fire-sprinkler interaction models.

A large number of fire computer models have been developed in recent years indicating the interest of researchers in the computer fire modeling field. A complete listing of these fire models is available in the fire model survey Web site, www.firemodelsurvey.com. This Web site contains information about the latest survey of computer fire models as completed by the developers of these models.

B.19.2.1 Zone Models

A zone model is essentially a one-dimensional model that solves the basic conservation equation for distinct volumes as a function of time. This type of model is used to predict fire growth and smoke spread in single or multi-enclosure structures. The model calculates the temperature and concentration of gas species (oxygen, carbon dioxide, etc.) as a function of time throughout the spaces modeled.

Zone model usually divide each room into two spaces or zones; an upper hot zone that contains the gases produced by the fire and a lower cool zone that is the source of the air for combustion. Zone sizes change during the course of the fire. The upper zone can expand and occupy virtually the entire room volume. By definition, zone models will always be approximate. The primary advantage of a zone model is its relative simplicity, which permits the inclusion of more phenomena. Also, cases may be run more rapidly and inexpensively on a personal computer.

A zone model requires input of the basic geometry of the space(s) being modeled, including physical dimensions, thermal properties of bounding materials, vent opening sizes and locations, mechanical ventilation, and position and growth rates of the specified fire. Output includes the upper and lower smoke layer temperature, interface location between zones (smoke layer height), oxygen and carbon monoxide concentrations, visibility, smoke flow in and out of openings, and heat flux from the hot gas layer to a target in the compartment as a function of time. Some examples of zone models are CFAST, FASTlite, ASET, COMPBRN-III, BRI-2, MAGIC, BRANZFIRE, FIGRO-II, FIREWIND, and FLAMME-S.

B.19.2.2 Field Models

Field models avoid the simplifications inherent in zone models and, consequently, their results are very refined compared to those of a zone fire model. Some field model calculations can be made on fast PCs; however, more complex problems are best run on powerful workstations and advanced computers. Such models numerically solve the conservation of mass, energy, and momentum, as well as diffusion and species equations associated with fire. The temperature, velocity, and gas concentration are calculated in two- or three-dimensional fields by using a finite difference, finite element, or boundary element method. A compartment or space (domain) is descretized into computational cells. The greater the number of cells, the more refined the solution. The model determines the temperature, pressure, velocity, and species concentration within each cell at each time step.

The advantage of field models over zone models is that they can provide detailed information on fluid motions. The application of field modeling to fire problems has been dramatically increased over time. The ready availability of commercial computational fluid dynamics (CFD) software packages with increasing sophistication enable more widespread application. Applications of field models to fire problems include aircraft terminal atria spaces, air-supported structures, electrical generating stations, aircraft cabins, tunnels, hospitals wards, shopping malls, and warehouses. Some examples of field models are FDS, FLUENT, STAR-CD, JASMINE, PHOENICS, KOBRA-3D, FIRE, VESTA, and SOFIE.

B.19.2.3 Building Evacuation Model

Egress models are not truly fire models. They were developed in response to the need to evaluate the impact of fires on the occupants of a building. Most egress models describe the building as a network of paths along which the occupants travel. The occupants travel rates are usually derived from studies on people movement and vary with the age and ability of the occupants, crowding, and the types of travel paths. Model inputs include the geometry of the building and rooms, the openings between rooms, the number of occupants located each floor throughout the building, and the smoke data if the effect of smoke blockage is to be considered. The outputs include the location of each occupant with time, floor clearing time, stairwell clearing time, exit clearing time, and how many occupants used an exit. Some examples of evacuation models are EVACNET, EVACS, EGRASS, EXIT89, buildingEXODUS, BFIRII, Allsafe, EgressPro, and EESCAPE.

B.19.2.4 Models of Thermal Actuation Devices

Sprinkler and detection activation models are used to calculate the response time of sprinklers and detectors installed below unconfined smooth ceilings. These models also are used to estimate the size of a fire when a detection system activates, at which point egress can begin. Sprinkler and detection activation models use a heat transfer equation to calculate the temperature increase of detector sensing elements. These models assume that the thermal devices are located in a relatively large area and are heated by the ceiling jet flows (convective heat transfer), and predict the device actuation time for a user-specified heat release rate history. The sensitivity of the sprinkler/detector sensing element to an elevated temperature is often characterized by a constant parameter known as the response time index (RTI) which is derived experimentally. The required model inputs are the height of the ceiling above the fuel, distance of the thermal device from the axis of the fire, actuation temperature of the thermal device, RTI for the device, and heat release rate of the fire. The model outputs are the ceiling gas temperature at the device location and the device temperature (both as a function of time), time required for the device to actuate, and heat release rate at actuation. Some examples of thermal actuation modeled are DETACT-QS, DETACT-T2, LAVENT, JET, G-JET, and SPRINK.

B.19.2.5 Models of Structural Fire Resistance/Endurance

Structural fire resistance models estimate the structural fire endurance of a building system or member exposed to a fire environment by numerically solving the conservation of energy equations using a finite difference or finite element technique. The solution techniques are very similar to those used with field models. The structural fire resistance models evaluate the time-temperature history within a solid exposed to a fire environment. The solid region is divided into elements in much the same way that the field models divide a compartment into regions.

Steel and concrete configurations are most commonly analyzed with and without fire protection insulation. The models allow nonlinear material properties and boundary conditions. An effective analysis makes use of a mesh that finds where there are large temperature gradients. The thermal properties that are necessary to perform such an analysis are the thermal conductivity and specific heat. The density is also required, as are phase change (intumescent) data. The time-temperature history of the fire environment is considered by specifically defining the temperature at each time step during the solution. The heat transfer process attributable to the fire exposure is modeled using convection and/or radiation in the fire boundary and conduction through the solid. Some examples of PC-based structural fire resistance models are FIRES-T3, HEATING 7, FASBUS, TASEF, FIRES-RC , and SAFIR.

B.19.2.6 Fire Sprinkler Hydraulic Design Models

Fire sprinkler hydraulic design models are used to perform all necessary calculations to design a sprinkler system with a grid or loop, as required by NFPA 13, “Standard for Installation of Sprinkler Systems,” to ensure that water supplies will meet the water density requirements for the control and extinguishment of fire. These models estimate sprinkler head requirements, water supply pressure, the lowest supply pressure that can adequately drive the sprinkler system, pipe sizes, and equivalent lengths for fittings. These models use conservation of mass and momentum equations based on the principles of hydraulic (fluid) motion. The fire sprinkler models work by dividing a sprinkler system network into a series of nodes and links. The nodes represent pipe junctions of sprinklers, while links represent pipes. The user can specify which sprinklers are open and the model balance the flow and pressure. The inputs to the model are pipe junctions, diameters, and length; the locations and types of fittings; and the sprinkler locations. Some examples of fire sprinkler hydraulic design models are FIRE, HCALC, HP4M-Grid Fire Sprinkler Design, HP6M-Tree and Loop Fire Sprinkler Design, THE, HASS, HyperCalc, and Sprinkler-CALC.

B.19.2.7 Smoke Movement Models

Smoke movement/migration models calculate the airflow and pressure differences throughout a building in which a smoke control system is operating in a fire situation. In these modes, a building is represented as a network of spaces or nodes, each at a specific pressure and temperature. The stairwells and other shafts are modeled by a vertical series of spaces, one for each floor. The air flow is a function of pressure differences across the leakage paths. That is, air flows through leakage paths from regions of high pressure to regions of low pressure. These leakage paths are doors and windows that may be opened or closed. Leakage can also occur through partitions, floors, and exterior walls and roofs. The model inputs include the interior and exterior building temperatures, a description of the building flow network, and the flow produced by the ventilation or smoke control system. The outputs include the steady-state pressure and flows throughout the building. These models are capable of modeling the stack effect created in taller buildings during extreme temperature conditions. Some examples of smoke movement/migration models are ASCOS, CONTAMW, AIRNET, and ASMET.

B.19.2.8 Fire-Sprinkler Interaction Models

Fire-sprinkler interaction models simulate the environment and the response of sprinkler actuation links in compartment fires with draft curtains and fusible link-operated ceiling vents. They include the effects of the ceiling jet and upper layer of hot gases beneath the ceiling. The program inputs include the compartment geometry, thermo-physical properties of the ceiling, fire elevation, fire heat release rate, fire diameter, ceiling vent area, fusible link RTI and actuation temperature, fusible link positions along the ceiling, link assignment to each ceiling vent, and ambient temperature. The model outputs include the temperature, mass, and height of the upper layer; temperature of each link; ceiling jet temperature and velocity at each link; radial temperature distribution along the interior surface of the ceiling; radial distribution of heat flux to the interior and exterior surfaces of the ceiling; fuse time of each link; and vent area that has been open. Examples of fire-sprinkler interaction models include LAVENT and JET.

B.19.2.9 Specialized Fire Models

Special-purpose fire simulation programs include (1) BREAK1 (Berkeley Algorithm for Window Glass in a Compartment Fire), a program which calculates the temperature history of a glass window exposed to user-described fire conditions, and (2) ELVAC (Elevator Evacuation), an interactive computer program that estimates the time required to evacuate people from a building with the use of elevators and stairs. It is cautioned that elevators generally are not intended as a means of fire evacuation, and they should not be used during fires except when under fire service operation and control. However, it is possible to design elevator systems that for fire emergencies, and ELVAC can be used to evaluate the potential performance of such a system. A third special-purpose fire simulation program, known as FIRDEMND, simulates the suppression of post-flashover charring and non-charring solid-fuel fire in compartments using water sprays from portable hose-nozzle equipment used by the fire department.

The output of the Fire Demand Model (FDM) shows the extinguishment effects of water spray at various flow rates and droplet sizes. The Subway Environment Simulation(SES) computer program and subway environmental design handbook were developed in the early 1970s under sponsorship of the Urban Mass Transportation Administration (former name of the Federal Transit Administration (FTA)) to assist in the planning, design, and construction of subway ventilation systems. The SES fulfilled an unmet need in the transit engineering community, and has been widely used in the design of new rail systems or line extensions in Washington, DC, Atlanta, Buffalo, Baltimore, Dallas, Los Angeles, San Francisco, Montreal, Toronto, the Seattle Bus Tunnel, and rail transit systems around the world. The SES provides tunnel designers with the tools to: properly size and locate ventilation shafts, evaluate tunnel geometry and fan size, optimize temperature, and model the effects of heat and smoke resulting from fires and other sources. The most recent enhancement is the validation of the subroutine which describes the behavior of smoke in emergency conditions.

B.19.3 Limitations and Uncertainties Associated with Computer Fire Modeling

Fire model permit development of a better understanding of the dynamics of building fires, to quantify the performance of a building, and can aid in the fire safety decision making process. This evaluation gives an overall fire assessment of the building systems in terms of preventing fire growth, providing for safe evacuation, providing for fire-resistance design, and predicting occupant behavior.

Nonetheless, there are certain limitations and uncertainties associated with fire modeling predictions. The decision to use a particular fire model should be based on the understanding of the limitations and assumptions of the model. The limits of applicability of any fire model must be clearly stated and known to the user so that the user does not go beyond the boundaries of realistic application of the theory utilized. The input uncertainty is primarily attributable to error and assumptions in the input data. Sensitivity analyses are used to identify the critical input parameters, which must be specified with much greater care than the parameters to which the model is relatively insensitive. The model uncertainty is primarily attributable to the assumptions made by the model, and can be quantified as a result of the validation process. Full-scale fire test data are subject to experimental uncertainty. Therefore, discrepancies between model predictions and experimental data might be at least partly, attributable to measurement errors. There are many problems in comparing the results from fire model simulations to data from full-scale experiments. Some of the problems are attributable to the difference between the form of the recorded experimental data and the form needed for computer model predictions. For example, contrary to the assumption of pre-flashover compartment zone models, there often is not a clear and sharp change distinguishing the lower and upper gas layers.

Extreme care must be exercised in interpreting the fire modeling results. For scenarios where the level of predicted hazard is well below the damage threshold, the results can be used with a high level of confidence, provided that there is a high level of confidence that all risk-significant scenarios have been considered. For scenarios where the level of predicted hazard is near the damage threshold, the results should be used with caution in view of the inherent uncertainties.

A primary method of handling modeling uncertainties is the use of engineering judgment. Among other things, this judgment is reflected in the selection of appropriate fire scenarios, hazard criteria, and fire modeling techniques. A slightly more formal application of engineering judgment is the use of safety factors, which can be applied in the form of fire size, increased or decreased fire growth rate, or conservative hazard criteria (Custer and Meacham, 1997). Experimental data obtained from fire tests, statistical data from actual fire experience, and other expert judgment can also be used to improve judgment and potentially decrease the level of uncertainty.

When using a fire model, it is wise to perform a sensitivity analysis of the output to changes in the input to determine if changes in the data or the model assumptions and applicability will lead to a different decision. The sensitivity analysis will determine the most dominant and significant variables. It will also determine whether the user should pay careful attention to particular input values that might affect the result significantly.

B.19.4 Fire Models

A variety of computer fire models employing different features are currently available. Table B.19-1 provides a short description for some common fire models.

Table B.19-1. Computer Fire Models

Model Name	Classification	Model Use
CFAST **C**onsolidated Model of **F**ire **G**rowth and **S**moke **T**ransport	Zone model	CFAST is a zone model that predicts the effect of a specified fire on temperatures, various gas concentrations and smoke layer heights in a multi-compartment structure.
FPETool **F**ire **P**rotection **E**ngineering **Tool**	Zone model	FPETool is a set of engineering equations useful in estimating potential fire hazard and the response of the space and fire protection systems to the developing hazard. Version 3.2 incorporates an estimate of smoke conditions developing within a room receiving steady-state smoke leakage from an adjacent space. Estimates of human viability resulting from exposure to developing conditions within the room are calculated based upon the smoke temperature and toxicity.
FASTLite	Zone model	FASTLite is a user-friendly software package which builds on the core routines of FPEtool and the computer model CFAST to provide calculations of fire phenomena for use by the building designer, code official, fire protection engineer, and fire-safety related practitioner.
ASET, ASET-B, ASET-C **A**vailable **S**afe **E**gress **T**ime	Zone model	A simple, user-friendly, one-room, smoke-filling model computer code that simulates the smoke layer thickness, temperature, and concentrations of products of combustion attributable to fire of time-dependent, user-specified energy and product release rate.
BRANZFIRE	Zone model	A zone model to predict the environment in a compartmented structure.
COMPBRAN III	Zone model	Zone model for compartment fires, compatible with probabilistic analysis.
MAGIC	Zone model	Two zone mode, able to handle up to 24 compartments. MAGIC is designed for nuclear power plants. MAGIC is being extended to include non-rectangular room, convex and sloping ceiling, room cluttered with objects, spread of fire through ventilation ducts, and extinction.

Table B.19-1. Computer Fire Models

Model Name	Classification	Model Use
FireWind	Zone model	FireWind is a collection of 18 programs that include one- and two-room zone models, heat radiation calculation, egress calculations, a heat conductivity model and more.
FIGARO II **F**ire and **G**as Spread in **R**oom	Zone model	FIGARO II is a two-layer model that can be used for single-room and multi-room fire simulation.
FDS **F**ire **D**ynamics **S**imulator	CFD model	General-purpose, low-Mac number CFD code specific to fire-related flows.
Star-CD	CFD model	General-purpose CFD code that contains industry standard models for modeling fire and smoke movement.
JASMINE Analysis of Smoke Movement in Enclosures	CFD model	A CFD or field model for predicting consequences of fire to evaluate design issues as the assessment of smoke ventilation design and/or interaction with HVAC and other fire protection measures.
PHOENICS	CFD model	PHONICS is a general purpose CFD code for use by academia and industry as a design and analysis tool for any process involving fluid flow, combustion, and heat and mass transfer.
SOFIE **S**imulation of **F**ire in **E**nclosures	CFD model	SOFIE is a field modeling code based upon the solution of the Reynolds average Navier-Stokes equations using a finite volume approach.
KOBRA-3D	CFD model	Three-dimensional CFD model for complex geometries to be used for smoke spread and heat transfer analyses.
FIRE	CFD model	CFD model with water sprays and coupled to solid/liquid phase fuel to predict burning rate and extinguishment.
DETACT-QS **DET**ector **ACT**uation-**Q**uasi **S**teady	Detector actuation	A program for calculating the actuation time of thermal devices below unconfined ceilings for fires with arbitrary heat release rates.
DETACT-T2 **DET**ector **ACT**uation-**T**ime Squared	Detector actuation	A program for calculating the actuation time of thermal devices below unconfined ceilings for fires with heat release rates which grow with time squared.

Table B.19-1. Computer Fire Models

Model Name	Classification	Model Use
LAVENT **L**ink **A**ctuation **VENT**s	Zone model	A zone model which predicts the actuation of fusible links as a function of depth below the ceiling and distance from the plume center in response to a ceiling jet produced by a user-specified fire.
JET	Zone model	JET is a single compartment zone model for use in spaces where the lower layer remains close to ambient temperature and the fire is not ventilation limited. The model provides temperature predictions for the plume, ceiling jet, upper layer and ceiling as well as the upper layer depth.
G-JET	Smoke detection model	Design tool for all categories of smoke detectors to predict their response to performance requirements in applications.
EVACNET4	Evacuation/ egress model	EVACNET4 is a user-friendly interactive computer program that models building evacuations. The program accepts a network description and information on its initial contents at the beginning of the evacuation.
ELVAC	Elevator evacuation	Calculates emergency evacuation time using elevators.
EGRESS	Evacuation simulation model	Versatile model for predicting the evacuation of crowds which may be used in a large variety of situations.
EXIT89	Evacuation model	An evacuation model designed to handle the evacuation of a large population of individuals from a high-rise building.
buildingEXODUS	Human behavior/ evacuation model	A PC-based evacuation model that simulates individual people, behavior, and enclosure details. The model includes various aspects and is capable of simulating thousands of people in large geometries.
FIRES-T3 **FI**re **RE**sponse of **S**tructures - **T**hermal **Three**-Dimensional Version	Finite element method (FEM) heat transfer	FEM conduction heat transfer with time-varying boundary conditions and temperature-dependent material properties for concrete structure frame.
FIRES-RC Structural Analysis Program for the Fire Response of Reinforced Concrete Frame	Finite element heat transfer	FEM for 1-, 2- or 3-D conduction heat transfer with time-varying boundary conditions and temperature-dependent material properties.

Table B.19-1. Computer Fire Models

Model Name	**Classification**	**Model Use**
TASEF **T**emperature **A**nalysis of **S**tructures **E**xposed to **F**ire	Structural	TASEF is a computer program for temperature of structures exposed to fire. This program is based on the finite element method. It is developed for temperature analysis of two dimensional and axisymmetrical structures.
SAFIR A Computer Program for Analysis of Structures at Elevated Temperature Conditions	Structural model	Transient analysis of the temperature distribution in the structure; 2D or 3D, Steel, concrete, gypsum and insulating material models; Eurocode models; water evaporation; radiation in internal cavities (2D). Mechanical analysis of the structure during the fire; 2D and 3D, beam, truss and shell F.E.; large displacements; any cross-section type for the beams, concrete, and steel eurocode models.
HEATING	Structural model	
ASCOS **A**nalysis of **S**moke **CO**ntrol **S**ystems	Network air flow analysis	ASCOS is a program for steady air flow analysis of smoke control system
CONTAMW Multizone Airflow and Contaminant Transport Analysis Software	Airflow model	CONTAMW is a multizone indoor air quality and ventilation analysis program that is useful in a variety of applications. For smoke management purposes, the program can be used to help calculate room-to-room airflow and pressure differences induced by mechanical and natural forces.
ASMET **A**tria **S**moke **M**anagement **E**ngineering **T**ools	Package of engineering tools	ASMET consists of a set of equations and a zone fire model for analysis of smoke management systems for large spaces such as atria, shopping malls, arcades, sports arenas, exhibition halls and airplane hangers
BREAK1 Berkeley Algorithm for Breaking Window Glass in a Compartment Fire		BREAK1 is a program which calculates the temperature history of a glass window exposed to user-described fire conditions. The calculations are stopped when the glass breaks.

B.19.5 References

ASTM E176, "Standard Terminology of Fire Standards," ASTM Fire Test Standard, 5th Edition, American Society of Testing and Materials, West Conshohocken, Pennsylvania, 1999.

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B.19.6 Additional Readings

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APPENDIX C. SOURCES OF FIRE

This appendix discusses the various topics related to fire phenomena.

C.1 Heat Sources

Heat sources may vary widely in size, intensity, and duration. For instance, a tiny spark, a hot pin head, an exposure fire, and sun are all heat sources as are the following representative examples:

- A paper match contains about 1 kilojoule (kJ) of heat energy released at a heat of about 45 watts (W).
- A standard laboratory candle contains about 1,500 kJ of heat energy released at a heat power of about 50 W.
- A small wooden match contains about 1.5 kJ of heat energy released at a heat of about 50 W.
- A large wooden safety match contains about 3 kJ of heat energy released at a heat of about 90 W.
- A common butane-type cigarette lighter contains about 230 kJ of heat energy. A 10-cm flame releases energy at a power of about 150 W; a 5-cm flame about 90 kW.
- A handheld plumber's propane torch contains up to 20 MJ of heat energy. A 10-cm flame releases energy at a power of about 1,800 W, or 1.8 kW.
- The heat energy required to ignite a flammable gas or vapor may be as low as 0.3 millijoules (mj).
- The heat energy required to ignite a flammable dust cloud may be as low as 20 mJ.

Table C.1-1 summarizes the common engineering terms and symbols related to heat sources, as they apply to fire hazard analysis.

Table C.1-1. Common Engineering Terms Related to Heat Sources

Term	**Term Symbol***	**Basic Unit**	**Recommended Units**	
			Symbol	**Name**
Heat quantity is the total amount of heat energy released by the heat source.	Q	joules	kJ	Kilojoules
Heat flux is the rate of heat energy released from the igniter per second.	$\dot{Q}$	watt	W	watt
Heat flux density is the amount of heat energy per unit area emitted from the heat source per second.	$\dot{q}''$	watt per square meter	kW/m^2	kilowatt per square meter
Heat intensity is the temperature of a heat source.	T	Kelvin	K	Kelvin
Duration is the length of time between any two events (e.g., initial ignition to full room involvement). When a duration is specified, the beginning and ending events should be identified. Duration can also be used to represent the length of time the heat source is present.	t	second	s	second

*In fire protection engineering, Q and q are usually reserved for heat energy. Lower case t is conventionally used for time; capital T is usually used for temperature, but *never* time.

C.1.1 Reference

"SI Units Fire Protection Engineering," *1980 Report of the Measurement of Fire Phenomena Committee*, Society of Fire Protection Engineers (SFPE), Boston, Massachusetts, March 1980.

C.2 Incident Heat

Table C.2-1 summarizes the common engineering terms and symbols related to incident heat (heat arriving at the surface of the target fuel).

Table C.2-1. Incident Heat

Term	**Term Symbol**	**Basic Unit**	**Recommended Units**	
			Symbol	**Name**
Incident heat flux is the heat energy arriving at the target fuel surface from the igniter per second.	Q_i	watt	W	watt
Incident heat flux density is the amount of heat energy per unit area arriving at the target fuel surface from the igniter per second.	q_i''	watt per square meter	kW/m^2	kW/m^2
Heat intensity is the incident temperature near the target fuel surface.	T	Kelvin	K	Kelvin
Incident duration is the length of time the heat is received at the target fuel surface.	t	second	s	second

C.2.1 Reference

"SI Units Fire Protection Engineering," *1980 Report of the Measurement of Fire Phenomena Committee*, Society of Fire Protection Engineers (SFPE), Boston, Massachusetts, March 1980.

C.3 Target Fuel

Table C.3-1 summarizes the common engineering terms related to target fuel, focusing on heat-producing materials (i.e., combustibles) that may be driven to ignition by the incident heat source.

Table C.3-1. Target Fuel

Term*	Term Symbol	Basic Unit	Recommended Units	
			Symbol	Name
Heat power resistance is the maximum heat energy that the exposed surface of an initial target fuel can receive per second without causing initial ignition.	$\dot{Q}$	watt	W	watt
Heat power density resistance is the amount of heat energy per unit area received from an igniter (heat source) each second without causing ignition.	$\dot{q}''$	watt per square meter	W/m^2	kilowatt per square meter
Heat Intensity resistance is the maximum surface temperature that the target fuel will tolerate without experiencing self-sustained burning with a pilot flame present.	T	Kelvin	K	Kelvin
Duration resistance is the length of time a target fuel can receive heat energy from an igniter at a given level without igniting.	t	second	s	second
*Target fuels generally respond on a time and energy basis. The higher the energy, the lower the time to ignition. This phenomenon is extremely complex (e.g., it depends on geometry, heat balance, and pilot ignition).				

C.3.1 Reference

"SI Units Fire Protection Engineering," *1980 Report of the Measurement of Fire Phenomena Committee*, Society of Fire Protection Engineers (SFPE), Boston, Massachusetts, March 1980.

C.4 Flame/Heat Growth

Table C.4-1 summarizes common engineering terms related to flame/heat growth, focusing on burning within a space, room, or enclosure.

Table C.4-1. Flame/Heat Growth

Term	Term Symbol	Basic Unit	Recommended Units	
			Symbol	Name
Heat flux is the heat energy released from the igniter per second.	$\dot{Q}$	watt	MW	megawatt
Heat flux density is the amount of heat energy per unit area delivered from the burning material into the surrounding space per second.	$\dot{q}''$	watt per square meter	kW/m^2	kilowatt per square meter
Heat intensity is the temperature within the burning space. The location of this reading within the space should be identified.	T	Kelvin	K	Kelvin
Duration is the length of time between two identical events during the fire growth within the space (e.g., time from ignition to first steady flame out the door).	t	Second	s	kilo-second
Duration to full room involvement is the length of time the fire takes to reach full room involvement (from ignition).	t	Second	s	kilo-second
Ventilation rate is the volume of air (oxygen) entering the burning space per second.	$\dot{V}$	m	m^3/s	cubic meters per second

C.4.1 Reference

"SI Units Fire Protection Engineering," *1980 Report of the Measurement of Fire Phenomena Committee*, Society of Fire Protection Engineers (SFPE), Boston, Massachusetts, March 1980.

C.5 Fire Resistance

The fire resistance of a building may be defined as (1) its ability to withstand exposure to fire without losing its load bearing function and (2) its ability to act as a barrier to the spread of fire. These two abilities confine the fire to the compartment where it started and provide time for people to evacuate a building before it collapses as a result of a fire. Before the room is fully involved, the temperatures are relatively low and they have a negligible influence on the fire resistance of building elements. The risk that structural members or fire barriers will fail actually begins when the fire reaches the fully developed stage. During this stage, temperatures of 1,300 K or 1,027 °C (1,881 °F) or higher can be reached, and the heat transferred to building elements may substantially reduce their strength and ability to perform as a fire barrier. This risk also continues to exist during the decay period of the fire.

The behavior of fire-exposed building elements depends, in part on the fire severity and in part on the properties of the fire-exposed elements. The following tables summarize the most important quantities that determine fire severity and the fire performance of building elements.

Table C.5-1. Common Engineering Terms Related to Fire Severity

Term	Symbol	Basic Unit	Recommended Units	
			Symbol	Name
Total load is the total amount of heat energy available for possible release.	Q	joules	kJ	kilojoules
Heat load density is the amount of heat energy available possible release per unit area (floor or bounding room surface area).	Q''	joule per square meter	MJ/m^2	megajoule per square meter
Heat flux density is the amount of heat energy per unit area emitted from the heat source per second.	$\dot{Q}$	watt	MW	magawatt
Heat intensity is the temperature of the fire. The specific point of measurement should be identified (e.g., flame temperature, average ceiling temperature, average hot gas layer temperature).	T	Kelvin	K	Kelvin
Duration of severity is the length of time heat is produced by the fire that could expose building elements to the fire.	t	second	ks	kilosecond
Opening factor is the measure of the rate of temperature increase associated with the fire, defined as the area of the openings multiplied by the square root of the height of the openings, divided by the total bounding surface area of the room.	F	square root meter	$\sqrt{m}$	square root meter
Emissivity is the ratio of the intensity of radiation emitted by the fire to that emitted by a blackbody of the same temperature.		dimensionless	-	-

Table C.5-2. Common Engineering Terms Related to Fire Performance

Term	Term Symbol	Basic Unit	Recommended Units	
			Symbol	Name
Heat load resistance is the heat load required to cause the failure of a structural member or fire barrier.	Q_r	joules	MJ	megajoules
Heat flux density is the amount of heat energy received from the fire per unit area of the element per unit time.	$\dot{q}''$	watt per square meter	kW/m^2	kilowatt per square meter
Heat intensity is the temperature of the element at various locations during exposure to fire.	T	Kelvin	K	Kelvin
Thermal conductivity is the length of time the fire produces heat that could expose building elements to the fire.	k	watt per meter Kelvin	W/m-k	watt per meter Kelvin
Specific heat capacity is the heat necessary to increase the temperature of unit mass one degree	c_p	joule per kilogram Kelvin	kJ/Kg-K	kilojoule per kilogram Kelvin
Density is the mass per unit volume of a material.		kilogram per cubic meter	kg/m^3	kilogram per cubic meter
Thermal diffusivity is one of the quantities that determine the rate of temperature increase in a material at points away from the surface. It is equal to the thermal conductivity divided by the product of the specific heat and density		square meter per second	mm^2/s	square millimeter second
Emissivity absorbed is the ratio of the intensity of radiation absorbed by the element to that absorbed by a blackbody of the same temperature.		dimensionless	-	-
Coefficient of thermal expansion (linear) is the expansion of length per unit degree increase in temperature.		reciprocal degree Kelvin	1/K	reciprocal degree Kelvin
Modulus of elasticity is a measure of elastic deformation, defined as the stress needed to produce a unit strain.	E	Pascal	MPa	mega-pascal
Yield strength is the stress at which material exhibits a specified permanent deformation.	F_y	Pascal	MPa	mega-pascal
Ultimate strength is the highest stress a material can sustain before its ruptures.	F_u	Pascal	MPa	mega-pascal

C.5.1 Reference

"SI Units Fire Protection Engineering," *1980 Report of the Measurement of Fire Phenomena Committee*, Society of Fire Protection Engineers (SFPE), Boston, Massachusetts. March 1980.

C.6 Fire Resistance/Endurance Ratings

This section identifies some of the most common fire-resistance ratings used in construction and industry. "A," "B," and "C" ratings were originally defined by the Safety of Lives at Sea (SOLAS) regulations. Most tests utilize a test specific furnace which simulates a cellulosic fire exposure (slower growing fire but could ultimately grow hotter than a hydocarbon fire). Specific hydrocarbon fire exposures for pool and jet fires have recently evolved.

Fire Barriers (NFPA 251, "Fire Tests of Building Construction and Materials")

The average temperature increase of any set of thermocouples for each class of element protected is more than 121 °C (250 °F) above the initial temperature; or the temperature increase of any one thermocouple of the set for each class of element protected is more than 163 °C (325 °F) above the initial temperature. Where required by the conditions of acceptance, a duplicate specimen shall be subjected to a fire exposure test for a period equal to one-half of that indicated as the resistance period in the fire endurance test, but not for more than 1 hour. Immediately there after, the specimen shall be subjected to the impact, erosion, and cooling effects of a hose stream directed first at the middle and then at all parts of the exposed face, with changes in direction made slowly. *However,* The hose stream test shall not be required in the case of construction having a resistance period, as specified in the fire endurance test, of less than 1 hour.

A Barriers (SOLAS or Title 46, Section 72.05–75.10, of the* Code of Federal Regulations*)

- **A 0** Cellulosic Fire, 60-minute barrier against flame/heat passage, no temperature insulation.
- **A 15** Cellulosic Fire, 60-minute barrier against flame/heat passage, 15-minute temperature insulation.
- **A 30** Cellulosic Fire, 60-minute barrier against flame/heat passage, 30-minute temperature insulation.
- **A 60** Cellulosic Fire, 60-minute barrier against flame/heat passage, 60-minute temperature insulation.

Class A divisions are those divisions formed by decks and bulkheads that comply with the following:

- constructed of steel or material of equivalent properties
- suitably stiffened
- constructed to prevent the passage of smoke and flame for a 1-hour standard fire test
- insulated with approved noncombustible materials so that the average temperature of the unexposed side will not rise more than 180 °C (356 °F) above the original temperature within the time listed (A60: 60 minutes; A30: 30 minutes; A15: 15 minutes; A0: 0 minutes)

B Barriers (SOLAS or Title 46, Sections 72.05–72.10, of the* Code of Federal Regulations*)

- **B 0** Cellulosic Fire, 30-minute barrier against flame/heat passage, no temperature insulation.
- **B 15** Cellulosic Fire, 30-minute barrier against flame/heat passage, 15-minute temperature insulation.

Class B divisions are those divisions formed by decks and bulkheads that comply with the following:

- constructed to prevent the passage of flame for a 30-minutes standard fire test
- have an insulation layer such that the average temperature on the unexposed side will not rise more than 139 °C (282 °F) above the original temperature, nor will the temperature at any one point, including any joint, rise more than 225 °C (437 °F) above the original temperature (B15: 15 minutes; B0: 0 minutes)
- constructed of noncombustible materials

C Barriers (SOLAS or Title 46, Sections 72.05–72.10 of the* Code of Federal Regulations*)

- **C** construction of noncombustible materials; not rated to provide any smoke, flame, or temperature passage restrictions.

H Barriers (UL 1709)

An exposure rating to a hydrocarbon (petroleum) fire is typically given one of the following H ratings:

- **H 0** Hydrocarbon Fire, 120-minute barrier against flame/heat passage, no temperature insulation.
- **H 60** Hydrocarbon Fire, 120-minute barrier against flame/heat passage, 60-minute temperature insulation.
- **H 120** Hydrocarbon Fire, 120-minute barrier against flame/heat passage, 120-minute temperature insulation.
- **H 240** Hydrocarbon Fire, 120-minute barrier against flame/heat passage, 240-minute temperature insulation.

J Ratings

Jet fire exposure or impingement (“J” ratings) are specified by some vendors or property owners for resistance to hydrocarbon jet fire exposures. Currently, no standardized test or test specification has been adopted by an industry or governmental body. Some recognized fire testing and experimental laboratories (SINTEF, Shell Research, etc.) have conducted extensive research on jet fire exposures and have proposed a test standard based on these studies (Ref. Offshore Technology Report OTO 93028, “Interim Jet Fire Test Procedure for Determining the Effectiveness of Passive Fire Protection Materials”).

Fire Doors (NFPA 252, “Standard Methods of Tests of Door Assemblies”)

A fire door assembly, which can consist of single doors, doors in pairs, special-purpose doors (e.g., dutch doors, double-egress doors), or multisection door assembly for which a fire protection rating is determined and that is intended for installation in door openings in fire-resistive walls and provides a specific degree of fire protection to the opening.

The fire test can be conducted until the desired fire protection rating period is reached or until failure to meet any of the performance criteria specified in Chapter 5 of NFPA 252 as follows:

- 0.3 hour (20 minutes), Cellulosic fire
- 0.5 hour (30 minutes), Cellulosic fire
- 0.75 hour (45 minutes), Cellulosic fire
- 1.0 hour (60 minutes), Cellulosic fire
- 1.5 hour (90 minutes), Cellulosic fire
- 3.0 hour (180 minutes), Cellulosic fire
- Over 3.0 hours (in hourly increments), Cellulosic fire

Except for 20-minute rated door assemblies, for which it is optional, immediately following the fire endurance test, the door test assembly shall be subjected to the impact, erosion, and cooling effects of a hose stream. Temperature increases are listed at 121 °C, 232 °C, and 343 °C (250 °F, 450 °F, and 650 °F); absence of a temperature rating indicates an increase of more than 343 °C (650°F) on the unexposed surface of the door after 30 minutes of testing.

Fire Windows (NFPA 257, “Standard on Fire Test for Window and Glass Block Assemblies”)

Fire ratings of windows were normally limited to the failure of wired glass at approximately 870 °C (1,600 °F); however, advances in glazing technology have increased the available fire-resistance ratings of window assemblies, as follows:

- 0.3 hour (20 minutes), Cellulosic fire
- 0.5 hour (30 minutes), Cellulosic fire
- 0.75 hours(45 minutes), Cellulosic fire

Higher ratings are also available based on the application of other fire-resistance standard fire tests (NFPA 251, “Fire Tests of Building Construction and Materials”).

- 1.0 hour (60 minutes), Cellulosic fire
- 1.5 hour (90 minutes), Cellulosic fire
- 3.0 hours (180 minutes), Cellulosic fire
- Over 3.0 hours (in hourly increments), Cellulosic fire

Within 2 minutes following the fire endurance test, the fire-exposed side of the fire window assembly is subjected to the impact, erosion, and cooling effects of a standard hose stream.

Fire Dampers (UL Std. 555)

The fire test can be conducted on the fire dampers until the desired fire protection rating period is reached or until failure to meet any of the performance criteria specified in UL Standard 555 as follows:

- 0.3 hour (20 minutes), Cellulosic fire
- 0.75 hour (45 minutes), Cellulosic fire
- 1.0 hour (60 minutes), Cellulosic fire
- 1.5 hours (90 minutes), Cellulosic fire

Smoke Dampers (UL Std. 555S)

Smoke dampers are specified on the basis of the leakage class, maximum pressure, maximum velocity, installation mode (horizontal or vertical), and degradation test temperature of the fire.

Roof Coverings (NFPA 256, “Standard Tests of Fire Tests of Roof Coverings”)

The fire test can be conducted on the fire dampers until the desired fire protection rating period is reached or until failure to meet any of the performance criteria specified in NFPA Standard 256 as follows:

- Class A: flame spread less than 6 feet (1.82 meters)
- Class B: flame spread less than 8 feet (2.44 meters)
- Class C: flame spread less than 13 feet (3.96 meters)

For all classes of roof coverings, there is to be no significant lateral flame spread, no flying brands or particles are to continue to flame or glow after reaching the floor, no flaming is to be produced on the underside of the deck of the test sample, and the roof deck should not be exposed.

Fusible Links

Fusible links are available in temperature ratings of 51.6 °C–260 °C (125 °F–500 °F) and in various load ratings.

The following tables summarize the fire-resistance test standards for building materials, aerosol, liquid paints, and plastics.

Table C.6-1. Fire-Resistance Test Standards for Building Materials

Organization and Test Specification	**Name of Test**	**Sample**	**Property Measured**
ASTM E69	Crib test	Treated wood	Combustible properties
ASTM E84	Surface burning of building materials	Building materials	Flame spread index, Smoke developed
ASTM E108 Building Codes, UBC 32-7 UL-790	Fire rating of roof coverings	Coatings, shingle shake, insulation, etc.	Spread of flame, intermittent flame, burning brand, flying brand
ASTM E119, NFPA 251	Building and construction materials	Walls, partitions, columns, horizontal assemblies	Flame and hot gas passage, structural stability
ASTM E136	Behavior of materials in vertical tube furnace	Building materials	Combustibility or non-combustibility of building materials
ASTM E160	Crib test	Treated wood	Combustible properties
ASTM E162	Surface flammability of materials using a radiant heat source	Sheet laminates, tiles, fabrics, liquids, films	Flame spread index, visual characteristics
ASTM E648 NFPA 253	Critical radiant flux of floor covering systems	Floor covering systems	Critical radiant flux at flameout
ASTM E662	Specific optical density of smoke generated by solid materials	Solid materials (e.g., wood, plastic)	Specific optical density
ASTM E970, CPSC HH-I-515D, HH-I-521F, HH-I-1030B 16CFR 1209.6	Critical radiant flux of attic insulation	Exposed attic floor insulation	Critical radiant flux at flameout

Table C.6-1. Fire-Resistance Test Standards for Building Materials

Organization and Test Specification	**Name of Test**	**Sample**	**Property Measured**
ASTM E2010, NFPA 257	Positive pressure of windows	Windows, glass block assemblies	Retention in place
ASTM E2074, NFPA 252	Fire test of doors	Doors: side hinged, pivoted, swinging, sliding, overhead	Retention in place
Organization and Test Specification	Name of Test	Sample	Property Measured
NIST NBSIR-82-2532	Combustion product toxicity	All materials	Inhalation toxicity
NY State, Dept. of State 15,1120	Modified Pittsburgh Test	All materials	Inhalation toxicity

Table C.6-2. Fire-Resistance Test Standards for Aerosol and Liquid Paints

Organization and Test Specification	**Name of Test**	**Sample**	**Property Measured**
ASTM D56, D92, D93, D1310	Flash point	Liquids	Flash point
ASTM D3243 D3278	Flash point-set a flash	Liquids, aviation turbine fuels	Flash point
ASTM D1360	Fire retardancy of paint	Paint	Fire retardancy
FHSA ASTM-API 16 CFR 500.43	Flash point (tag open cup)	Aerosols	Flash point
FHSA CSMA 16 CFR 500.45	Flame projection	Aerosols	Flame projection
CSMA Aerosol Guide	Drum test	Aerosols	Inhalation toxicity
NIST NBSIR-82-2532	Combustion product toxicity	All materials	Inhalation toxicity
NY State, Dept. of State 15, 1120	Modified Pittsburgh test	All materials	Inhalation toxicity

Table C.6-3. Fire-Resistance Test Standards for Plastics

Organization and Test Specification	**Name of Test**	**Sample**	**Property Measured**
ASTM D568	Flammability of plastics 0.050" and under	Plastic sheets and film	non-burning, self-extinguishing, burning rate, visual characteristics
ASTM D635	Rate of burning (self- supporting plastics)	Rigid plastics	Burning rate, visual characteristics
ASTM D757	Incandescence resistance (rigid plastics)	Rigid plastics	Burning rate, visual characteristics
ASTM D1929, Procedure B	Ignition properties of plastics	Plastic sheets and films, thermo-plastic pellets	Flash ignition temperature, self-ignition temperature, visual characteristics
ASTM D2843	Smoke density from the burning of plastics	Plastic material	Percent of light absorption
Bureau of Ships NObs 84814 MIL-M-14g	Flammability and toxicity	Generally melamine plastic; any material	Flash ignition, self-ignition, composition and toxicity gases evolved
CPSC CS 192-53 16- CFR 1611.4 ASTM D-1433	Flammability of plastic film	Plastic films, coated fabrics	Ignition time, rate of burning
Federal Test Method Std. FTMS 406 Method 2023	Flame resistance of plastics	Plastics difficult to ignite	Ignition time, burning time, flame travel
NIST NBSIR-82-2532	Combustion product toxicity	All materials	Inhalation toxicity
NY State, U.S. Department of State 15,1120	Modified Pittsburgh test	All materials	Inhalation toxicity

C.6.1 Reference

Nolan, D.P., *Encyclopedia of Fire Protection*, Delmar Publishers, Albany, New York, 2001.

C.7 FIRE TEST STANDARDS

This section lists the empirical standard tests for fire-resistance, flame spread, and flammability.

The following list identifies the empirical standard fire-resistance tests.

Test Standard	Title
API 6 FA	Fire Tests for Valves
API 607	Fire Tests of Quarter-Turn Valves
ASTM E119	Fire Test of Building Constructions and Materials
ASTM E814	Fire Tests of Through-Penetration Fire Stops (Penetration Seals)
ASTM E1529	Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies
ASTM E1623	Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate-Scale Calorimeter (ICAL)
ASTM E2010	Fire Tests of Window Assemblies
ASTM E2074	Fire Tests of Door Assemblies
BS 476, Part 20, 21	Fire Test of Building Construction and Materials, Window Assemblies, and Door Assemblies (BSI)
ISO 834	Fire Tests of Building Constructions and Materials
ISO 3008	Fire Tests of Door Assemblies
ISO 3009	Fire Tests of Window Assemblies
NFPA 251	Fire Tests of Building Constructions and Materials
NFPA 252	Fire Tests of Door Assemblies
NFPA 257	Fire Tests of Window Assemblies
UL 9	Fire Test of Window Assemblies
UL 10A/10B/10C	Fire Test of Door Assemblies
UL 72	Fire Resistance of Record Protection Equipment
UL 155	Fire Test of Door Assemblies
UL 263	Fire Test of Building Construction and Materials
UL 555	Fire Dampers
UL 555C	Ceiling Dampers
UL 555S	Leakage-Rated Dampers for use in Smoke Control Systems
UL 1479	Fire Test of Through Penetration Fire Seals
UL 1709	Rapid Rise Fire Tests of Protection Materials for Structural Steel
UL 2079	Tests for Fire Resistance of Building Joint Systems
UL 2085	Insulated Above Ground Tanks for Flammable and Combustible Liquids

The following list identifies the empirical standard flame spread tests.

Test Standard	Title
ASTM E84	Surface Burning Characteristics of Materials
ASTM E162	Surface Flammability of Materials Using a Radiant Heat Energy Source
ASTM E648	Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source
ASTM E970	Critical Radiant Flux of Exposed Attic Floor Insulation Using a Radiant Heat Energy Source
IEEE 383	Standard for Type Test of Class 1E Electric Cables, Field Splices, and Connections for Nuclear Power Generating Stations
IEEE 634	Standard Cable Penetration Fire Stop Qualification Test
IEEE 1202	Standard for Flame Testing of Cable for Use in Cable Tray in Industrial and Commercial Occupancies
NFPA 255	Surface Burning Characteristics of Materials
NFPA 262	Fire and Smoke Characteristics of Electrical and Optical Fiber Cables in Air Handling Spaces
NFPA 265	Full-Scale Test for Room Fire Growth Contribution of Textile Wall Coverings
UL 910	Fire and Smoke Characteristics of Electrical and Optical Fiber Cables in Air Handling Spaces
UL 1256	Under-Deck Roof Construction Test
UL 1581	Reference Standard for Electrical Wires, Cables, and Flexible Cords, 1080, VW-1 Vertical Wire Flame Test.
UL 1581	Reference Standard for Electrical Wires, Cables, and Flexible Cords, 1160, UL Vertical-Tray Flame Test.
UL 1715	Room Fire Test Standard of Interior of Foam Plastic Systems
UL 1820	Fire Test of Pneumatic Tubing for Flame and Smoke Characteristics
UL 1887	Fire Test of Plastic Sprinkler Pipe for Flame and Smoke Characteristics

The following list identifies the empirical standard small-scale flammability tests.

Test Standard	**Title**
16 CFR 1610.4 (CPSC)	Flammability of Wearing Apparel
16 CFR 1630.4 (CPSC)	Flammability of Finished Textile Floor Covering Materials
16 CFR 1653.4 (CPSC)	Flammability of Finished Textile Floor Covering Materials
ASTM C 1166	Flame Propagation of Dense and Cellular Elastomeric Gaskets and Accessories
ASTM D635	Rate of Burning and/or Extent and Time of Burning of Self-Supporting Plastics in a Horizontal Position
ASTM D1692	Flammability of Plastic Sheeting and Cellular Plastics
ASTM D1929	Ignition Properties of Plastics
ASTM D2584	Ignition Loss of Cured Reinforced Plastics
ASTM D2859	Flammability of Finished Textile Floor Covering Materials
ASTM D2863	Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics
ASTM D3801	Method for Measuring the Comparative Extinguishing Characteristics of Solid Plastics in a Vertical Position
ASTM D3806	Small-Scale Evaluation of Fire-Retardant Paints
ASTM D3894	Evaluation of Fire Response of Rigid Cellular Plastics Using a Small Corner Configuration
ASTM D4804	Flammability Characteristics of Nonrigid Solid Plastics
ASTM D4986	Horizontal Burning Characteristics of Cellular Polymeric Materials
ASTM D5048	Comparative Burning Characteristics and Resistance to Burn-Through of Solid Plastics Using a 125-mm Flame
ASTM E136	Behavior of Materials in a Vertical Tube Furnace at 750 °C
ASTM E662	Specific Optical Density of Smoke Generated by Solid Materials
ASTM E1354	Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter
ASTM F501	Aerospace Materials Response to Flame, With Vertical Test Specimen
Boston Fire Dept. Code Sec.11.2 & 11.3	Fire Tests of Flame Resistant Textiles and Films
Boston Fire Dept. IX-I	Classification Fire Tests of Fabrics
Boston Fire Dept. IX-II	Mattresses, Portable Mattresses, and Mattress Pads
Calif. Title 19	Fire Tests of Flame-Resistant Textiles & Films; Intermediate-Scale
CS 191	Flammability of Wearing Apparel
FAA OSU	Rate of Heat Release Evaluation
FAR 25.853	Test Procedure of Showing Compliance with §§ 25.853, 25.855 and 25.1359 (Aircraft Compartment Interior Fire Test)
FMVSS 302	Flammability of Interior Materials—Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Buses
FTMS 191	Flame Resistance of Cloth
ISO 5660	Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter

Test Standard	Title
NFPA 253	Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source
NFPA 258	Specific Optical Density of Smoke Generated by Solid Materials
NFPA 263	Rate of Heat Release Evaluation
NFPA 264	Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter
NFPA 701	Fire Tests for Flame Resistant Textiles and Films
NFPA 702	Flammability of Wearing Apparel
NFPA 703	Fire-Retardant Treated Wood
UL 94	Flammability of Plastic Materials
UL 214	Tests for Flame Propagation of Fabrics and Films
UL 1975	Fire Tests for Foamed Plastics Used for Decorative Purposes

APPENDIX D. NRC DOCUMENTS RELATED TO FIRE PROTECTION

This appendix provides the various NRC reference documents related to fire protection.

D.1 *Code of Federal Regulations* Related to Nuclear Regulatory Commission Fire Protection

The *Code of Federal Regulations* is a codification of the general and permanent rules published in the *Federal Register* by the Executive departments and agencies of the Federal Government. The code is divided into 50 titles, which represent broad areas subject to Federal regulation. Each title is divided into chapters, which usually bear the name of the issuing agency. Each chapter is further subdivided into parts covering specific regulatory areas. Title 10, “Energy,” is composed of four volumes. These volumes are subdivided as Parts 1–50, 51–199, 200–499, and 500–end. The first and second volumes containing parts 1–199 comprise Chapter I, “Nuclear Regulatory Commission.” The U.S. Nuclear Regulatory Commission sets requirements for the safe operation of commercial nuclear power reactors, licenses the construction and operation of the reactors, and inspects them to ensure that they are operating safely within the agency’s regulations. NRC resident inspectors are stationed at each nuclear power plant and additional safety reviews are done by experts from NRC regional offices and headquarters.

(1) *Code of Federal Regulations*, Title 10, “Energy,” Section 50.12, “Specific Exemption”, U.S. Government Printing Office, Washington DC.

(2) *Code of Federal Regulations*, Title 10, “Energy,” Section 50.48, “Fire Protection,” U.S. Government Printing Office, Washington DC.

(3) *Code of Federal Regulations*, Title 10, “Energy,” Part 50, Appendix A, “General Design Criterion 3 - Fire Protection,” U.S. Government Printing Office, Washington DC.

(4) *Code of Federal Regulations*, Title 10, “Energy,” Part 50, Appendix R, “Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979,” U.S. Government Printing Office, Washington DC.

(5) *Code of Federal Regulations*, Title 10, “Energy,” Part 54, “Requirements for Renewal of Operating Licenses for Nuclear Power Plants,” U.S. Government Printing Office, Washington DC.

D.2 Branch Technical Positions Related to Fire Protection

A branch technical position (BTP) sets forth a solution found to be acceptable by the NRC staff in dealing with a safety problem or safety-related problem. BTPs are included in the standard review plan (SRP) to serve as guides for the NRC staff reviewers as a means of achieving uniformity of interpretation and application of NRC requirements. Like regulatory guides, a BTP sets forth ***an*** acceptable method of complying with applicable regulations and not the ***only*** acceptable method.

The BTPs related to fire protection has been developed to provide comprehensive review guidance for nuclear power plant (NPP) fire protection programs (FPPs). These guidance identifies the scope and depth of fire protection that the Commission considers acceptable for NPPs. BTPs may be used for review of existing fire protection programs and program elements, proposed changes to existing programs that are subject to NRC review, new applications, fire vulnerability analyses [e.g., fire probabilistic risk assessments (PRA)], and programs for plant shutdown and decommissioning. Risk-informed and performance-based alternatives to the guidance presented in this regulatory guide may be acceptable and are evaluated on a case-by-case basis.

(1) BTP APCSB 9.5-1, “Guidelines for Fire Protection for Nuclear Power Plants,” May 1, 1976, February 24, 1977.

(2) Appendix A to BTP APCSB 9.5-1, “Guidelines for Fire Protection for Nuclear Power Plants, Docketed Prior to July 1, 1976,” (August 23, 1976), February 24, 1977.

(3) BTP ASB 9.5-1, “Guidelines for Fire Protection for Nuclear Power Plants,” Revision 1, March 1979.

(4) BTP CMEB 9.5-1 (Formerly ASB 9.5-1), “Guidelines for Fire Protection for Nuclear Power Plants,” Revision 2, July 1981.

(5) BTP SPLB 9.5-1, (Formerly CMEB 9.5-1), “Guidelines for Fire Protection for Nuclear Power Plants,” Draft, Revision D, December 2002.

Abbreviations:

APCSB	Auxiliary and Power Conversion Systems Branch
ASB	Auxiliary Systems Branch
CMEB	Chemical and Mechanical Engineering Branch
SPLB	Plant Systems Branch

D.3 NRC Regulatory Guides Related to Fire Protection

The Regulatory Guide (RG) provides guidance to licensees and applicants on implementing specific parts of the NRC's regulations, techniques used by the staff in evaluating specific problems or postulated accidents, and data needed by the staff in its review of applications for permits or licenses. Some guides delineate techniques used by the NRC to evaluate specific situations. Other provide guidance to applicants concerning information needed by the NRC in its review of construction permit (CP) and operating license (OL) applications. Many guides refer to or endorse national codes or standards [e.g., American Society of Mechanical Engineers (ASME), American National Standard Institute (ANSI), National Fire Protection Association (NFPA) etc.] that are developed by recognized national organizations. The guides are issued in the following 10 broad divisions:

(1) Power Reactors
(2) Research and Test Reactors
(3) Fuels and Materials Facilities
(4) Environmental and Siting
(5) Materials and Plant Protection
(6) Products
(7) Transportation
(8) Occupational Health
(9) Antitrust and Financial Review
(10) General

Draft RGs are issued for public comment in the early stages of the development of a regulatory position. They have not received complete staff review and do not present an official NRC staff position until finalized and issued. Table D.3-1 provide the list of RGs related to fire protection.

Table D.3-1. NRC Regulatory Guides Related to Fire Protection

Regulatory Guide	**Title**	**Issue Date**
3.16	General Fire Protection Guide for Plutonium Processing and Fuel Fabrication Plants	January 1974
1.39	Housekeeping Requirements for Water-Cooled Nuclear Power Plants, Revision 2	September 1977
1.120	Fire Protection Guidelines for Nuclear Power Plants, Revision 1	November 1977 “Withdrawn August 2001)
1.52	Design, Testing, and Maintenance Criteria for Post -accident Engineered Safety-Feature Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants, Revision 2	March 1978
1.75	Physical Independence of Electric Systems, Revision 2	September 1978

Table D.3-1. NRC Regulatory Guides Related to Fire Protection

Regulatory Guide	Title	Issue Date
1.91	Evaluations of Explosions Postulated To Occur on Transportation Routes Near Nuclear Power Plants, Revision 1	February 1978
RTS 809-5	Qualification Test for Cable Penetration Fire Stops for Use in Nuclear Power Plants	July 1979
1.175	An Approach for Plant-Specific, Risk-Informed Decisionmaking: Inservice Testing, August 1998, RS809-5 Qualification Test for Cable Penetration Fire Stops for Use in Nuclear Power Plants	September 1979
RS 902-4	Fire Stops for Use in Nuclear Power Plants (Second Proposed Revision 3 to Regulatory Guide 1.33) Quality Assurance Program Requirements (Operation)	November 1980
1.10	Emergency Planning and Preparedness for Nuclear Power Reactors, Revision 3	August 1992
1.174	An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions On Plant-Specific Changes to the Licensing Basis	July 1998
1.184	Decommissioning of Nuclear Power Reactors (Draft was issued as DG-1067)	August 2000
1.189	Fire Protection for Operating Nuclear Power Plants (Draft was issued as DG-1097)	April 2001
1.191	Fire Protection Program for Nuclear Power Plants during Decommissioning and Permanent Shutdown (Draft was issued as DG-1069)	May 2001
DG-1110	(Proposed Revision 1 to Regulatory Guide 1.174), "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis	June 2001
1.188	Standard Format and Content for Applications to Renew Nuclear Power Plant Operating Licenses (Drafts were DG-1104 issued 8/00, DG-1047 issued 8/96, Draft DG-1009 issued 12/90)	July 2001
1.170.4	Fire Protection Considerations for Nuclear Power Plants	
DG-1138	Risk-Informed, Performance-Based Fire Protection for Existing Light-Water Nuclear Power Plants	September 2004

D.4 NRC Generic Communications Related to Fire Protection

A generic communication is a transmittal to one or more classes of licensees. There are 6 types of generic communications, i.e., administrative letters, bulletins, circulars, generic letters, information notices, and regulatory issue summaries. Circulars were discontinued in February 1985.

D.4.1 NRC Administrative Letters Related to Fire Protection

An administrative letter (AL) is a type of generic communication issued to:

- Inform addressees of any of the following:
  - (1) Administrative procedure changes relating to implementation of the regulations or NRC staff positions.
  - (2) The issuance of a topical report evaluation or a NUREG-type document that is not technical in nature, does not contain a new or revised staff position, and is not appropriate for inclusion in either a generic letter or an information notice.
  - (3) Changes in NRC internal procedures or organizations.
- Request voluntary submittal of information of an administrative nature which will assist NRC in the performance of its function.
- Announce events of interest such as workshops or Regulatory Information Conferences.
- Other purposes of a strictly administrative nature.

Table D.4-1 provide the list of administrative letters related to fire protection.

Table D.4-1. NRC Administrative Letters Related to Fire Protection

Administrative Letter Number	Title	Issue Date
94-03	Announcing An NRC Inspection Procedure On Licensee Self-Assessment Programs For NRC Area-Of-Emphasis Inspections	03-17-1994
94-07	Distribution of Site-Specific and Site Emergency Planning Information	05-06-1994
95-06	Relocation of Technical Specification Administrative Controls Related to Quality Assurance	12-12-1995
96-04	Efficient Adoption of Improved Standard Technical Specifications	10-09-1996
98-02	Revisions to Event Reporting Guidelines for Power Reactors	03-17-1998
98-09	Priority for NRR Review of Risk-Informed Licensing Actions	10-30-1998
98-10	Dispositioning of Technical Specifications That Are Insufficient to Assure Plant Safety	12-29-199

D.4.2 NRC Bulletins Related to Fire Protection

A bulletin (BL) is used to address significant issues having generic applicability that also have great urgency. A BL requests information from, requests specified action by, and requires a written response in accordance with Section 182.a of the Atomic Energy Act of 1954, as amended, and 10 CFR 50.54(f), from the addresses regarding matters of safety, safeguards, or environmental significance. Addressees may be asked to take compensatory action that is commensurate with urgency of the issue being addressed, and provide requested information and perform and submit analyses by a specific time. A BL may not request long term actions. A BL may request new or revised license commitments that are based on analyses performed and license-proposed corrective action. A BL may not require license commitments. To extent that circumstances permit, NRC staff will interact with the nuclear industry on the issue being addressed. Table D.4-2 provide a list of NRC BLs related to fire protection.

Table D.4-2. NRC Bulletins Related to Fire Protection

BL No.	Title	Issue Date
75-04	Cable Fire at Browns Ferry Nuclear Power Station	03-24-1975
75-04A	Cable Fire at Browns Ferry Nuclear Power Station	04-03-1975
75-04B	Cable Fire at Browns Ferry Nuclear Power Station	11-03-1975
77-08	Assurance of Safety and Safeguards During an Emergency-Locking Systems	12-28-1977
78-01	Flammable Contact-Arm Retainers in G.E. CR120A Relays.	01-16-1978
78-03	Potential Explosive Gas Mixture Accumulation Associated with BWR Offgas System Operations	02-08-1978
81-03	Flow Blockage of Cooling Water to Safety System Components by Corbicula Sp. (Asiatic Clam) and Mytilus Sp. (Mussel)	04-10-1981
92-01	Failure of Thermo-Lag 330 Fire Barrier System to Maintain Cabling in Wide Cable Trays and Small Conduits Free From Fire Damage	06-24-1992
92-01 Supp-1	Failure of Thermo-Lag 330 Fire Barrier System to Perform Its Specified Fire Endurance Function	08-28-1992

D.4.3 NRC Circulars Related to Fire Protection

A circular (CR) is a type of generic communication used to transmit information to licensees or permit holders when the information is of safety, safeguards, or environmental interest but replies from licensees are not necessary for IE to assess the significance of the matter. A CR does not involve a specific response to the NRC but, rather, informs the licensees or permit holder. Table D.4-3 provide a list of NRC CRs related to fire protection.

Table D.4-3. NRC Circulars Related to Fire Protection

Circular Number	**Title**	**Issue Date**
77-03	Fire Inside a Motor Control Center	02-28-1977
78-04	Installation Error that Could Prevent Closing of Fire Doors	05-15-1978
78-18	UL Fire Test	11-02-1978
79-13	Replacement of Diesel Fire Pump Starting Contactors	07-16-1979

D.4.4 NRC Generic Letters Related to Fire Protection

A generic letter (GL) is used to address an emergent or routine technical issue having generic applicability that is a matter on which NRC staff has interacted with the nuclear industry and has concluded that a genetic communication is an appropriate means to effect resolution, or a risk significant, compliance, or adequate protection matter that NRC staff has concluded should be brought to the attention of the nuclear industry without extensive, prior interaction. A GL may request information from and/or request specific action by the addressees regarding matters of safety, safeguards, or environmental significance. The addressee may ask to accomplish the actions and report their completion by letter, with or without prior NRC approval of the action taken. Information requests typically will be on a voluntary basis, i.e., will not require a written response in accordance with Section 182.a of the Atomic Energy Act of 1954, as amended, and 10 CFR 50.54(f). A GL may request that the analyses be performed and, as appropriate, submitted for staff review, that description of proposed corrective action and other information be submitted for staff review, and that corrective actions be taken by a specified time. A GL may request new or revised license commitments based on analyses performed and proposed corrective actions, but may not require license commitments. Table D.4-4 provide the list of NRC GLs related to fire protection.

Table D.4-4. NRC Generic Letters Related to Fire Protection

Generic Letter	Title	Issue Date
77-02	Fire Protection Functional Responsibilities, Administrative Control and Quality Assurance	08-29-1977
80-45	Fire Protection Rule	05-19-1980
80-48	Revision To 5/19/80 Letter On Fire Protection	05-22-1980
80-56	Commission Memorandum And Order On Equipment Qualification	06-25-1980
80-96	Fire Protection	11-14-1980
80-100	Appendix R to 10 CFR 50 Regarding Fire Protection-Federal Register Notice	11-24-1980
80-103	Fire Protection - Revised Federal Register Notice	11-25-1980
81-12	Fire Protection Rule (45 FR 76602, November 19, 1980), February 20, 1981, and Clarification Letter	03-31-1982
82-21	Technical Specifications for Fire Protection Audits	10-06-1982
83-33	NRC Positions on Certain Requirements of Appendix R to 10 CFR Part 50	10-19-1983
85-01	Fire Protection Policy Steering Committee Report,January 9, 1985 (GL 85-01 was issued only as a DRAFT for comment at public meetings which were held in 1984. However, GL 85-01 was never issued as a final and therefore is not available.)	01-09-1985
86-10	Implementation of Fire Protection Requirements	04-24-1986

Table D.4-4. NRC Generic Letters Related to Fire Protection

Generic Letter	Title	Issue Date
86-10 Supp-1	Fire Endurance Test Acceptance Criteria for Fire Barrier Systems Used to Separate Redundant Safe Shutdown Trains Within the Same Fire Area	03-25-1994
88-12	Removal of Fire Protection Requirements from Technical Specifications	08-02-1988
88-20	Individual Plant Examination for Severe Accident Vulnerabilities	11-23-1988
88-20 Supp-1	Initiation of the Individual Plant Examination for Severe Accident Vulnerabilities (10 CFR 50.54)	
88-20 Supp-2	Accident Management Strategies for Consideration in the Individual Plant Examination Process	04-04-1990
88-20 Supp-4	Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities	06-29-1991
88-20 Supp-5	Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities - 10 CFR50.54(f)	09-08-1995
89-13	Service Water System Problems Affecting Safety-Related Equipment	07-18-1989
89-13 Supp-1	Service Water System Problems Affecting Safety-Related Equipment	04-04-1990
91-18	Information to Licensees Regarding Two NRC Inspection Manual Sections on Resolution of Degraded and Nonconforming Conditions and Operability	11-07-1991
91-18 Rev. 1	Information to Licensees Regarding Two NRC Inspection Manual Sections on Resolution of Degraded and Nonconforming Conditions and Operability	10-08-1997
92-08	Thermo-Lag 330-1 Fire Barriers	12-17-1992
93-03	Verification of Plant Records	10-20-1995
93-06	Research Results on Generic Safety Issue 106, Piping and the Use of Highly Combustibles Gases in Vital Areas	10-25-1993
95-01	NRC Staff Technical Position on Fire Protection for Fuel Cycle Facilities	01-26-1995

D.4.5 NRC Information Notices Related to Fire Protection

An information notice (IN) is a type of generic communication used to inform the nuclear industry of recently-identified, significant safety, safeguards, or environmental issues. Licensees are expected to review the information for applicability to their facilities or operations and consider actions, as appropriate, to avoid similar problems. INs do not convey changes in NRC policy or guidance and do not recommend specific courses of action. The suggestions contained in INs do not constitute NRC requirements and, therefore, no specific action or written response is required. The are rapid transmittals of information that may not yet have been completely analyzed by the NRC but that licensees should be aware of. Table D.4-5 provide the list of all INs related to fire protection.

Table D.4-5. NRC Information Notices Related to Fire Protection

IN Number	Title	Issue Date
79-32	Separation of Electrical Cables for HPCI and ADS	12-18-1979
80-11	Generic Problems with ASCO Valves in Nuclear Applications Including Fire Protection Systems	03-14-1980
80-25	Transportation of Pyrophoric Uranium	05-30-1980
81-27	Flammable Gas Mixtures in the Waste Gas Decay Tanks in PWR Plants	09-03-1981
82-28	Hydrogen Explosion while Grinding in the Vicinity of Drained and Open Reactor Coolant System	07-23-1982
82-53	Main Transformer Failures at the North Anna Nuclear Power Station	12-22-1982
83-41	Actuation of Fire Suppression System Causing Inoperability of Safety-Related Equipment	06-22-1983
83-69	Improperly Installed Fire Dampers at Nuclear Power Plants	10-21-1983
83-83	Use of Portable Radio Transmitters Inside Nuclear Power Plants	12-19-1983
84-09	Lessons Learned From NRC Inspections of Fire Protection Safe Shutdown Systems (10 CFR Part 50, Appendix R)	02-13-1984
84-09r1	Lessons Learned From NRC Inspections of Fire Protection Safe Shutdown Systems (10 CFR Part 50, Appendix R)	03-07-1984
84-16	Failure of Automatic Sprinkler System Valves to Operate	03-02-1984
84-42	Equipment Availability For Conditions During Outages not Covered by Technical Specifications	06-05-1984
84-92	Cracking of Flywheels On Cummins Fire Pump Diesel Engines	12-17-1984
85-09	Isolation Transfer Switches and Post-Fire Shutdown Capability	01-31-1985
85-30	Microbiologically Induced Corrosion of Containment Service Water System	04-19-1985

Table D.4-5. NRC Information Notices Related to Fire Protection

IN Number	Title	Issue Date
85-85	Systems Interaction Event Resulting in Reactor System Safety Relief Valve Opening Following a Fire-Protection Deluge System Malfunction	10-31-1985
86-13	Standby Liquid Control System Squib Valves Failure to Fire	02-21-1986
86-13 Supp-1	Standby Liquid Control System Squib Valves Failure to Fire	08-05-1985
86-17	Update of Failure of Automatic Sprinkler System Valves to Operate	03-24-1986
86-35	Fire in Compressible Material at Dresden Unit 3	05-15-1986
86-106	Feedwater Line Break	12-16-1986
86-106 Supp-1	Feedwater Line Break	02-13-1987
86-106 Supp-2	Feedwater Line Break	03-18-1987
86-106 Supp-3	Feedwater Line Break	11-10-1988
87-14	Actuation of Fire Suppression System Causing Inoperability of Safety-Related Ventilation Equipment	03-27-1987
87-20	Hydrogen Leak in Auxiliary Building	04-20-1987
87-50	Potential LOCA at High- and Low-Pressure Interfaces from Fire Damage	10-09-1987
88-04	Inadequate Qualification and Documentation of Fire Barrier Penetration Seals	02-05-1988
88-04 Supp-1	Inadequate Qualification and Documentation of Fire Barrier Penetration Seals	08-09-1988
88-05	Fire in Annunciator Control Cabinets	02-12-1988
88-45	Problems in Protective Relay and Circuit Breaker Coordination	07-07-1988
88-56	Potential Problems with Silicone Foam Fire Barrier Penetration Seal	08-04-1988
88-60	Inadequate Design and Installation of Watertight Penetration Seals	08-11-1988
88-61	Control Room Habitability - Recent Reviews of Operating Experience	08-11-1988
88-64	Reporting Fires in Nuclear Process Systems at Nuclear Power Plants	08-18-1988
89-44	Hydrogen Storage on the Roof of the Control Room	04-27-1989
89-52	Potential Fire Damper Operational Problems	06-08-1989
90-70	Pump Explosions Involving Ammonium Nitrate	11-06-1990

Table D.4-5. NRC Information Notices Related to Fire Protection

IN Number	Title	Issue Date
91-17	Fire Safety of Temporary Installations or Services	03-11-1991
91-20	Electrical Wire Insulation Degradation Caused Failure in a Safety-Related Motor Control Center	03-19-1991
91-37	Compressed Gas Cylinder Missile Hazards	06-19-1991
91-47	Failure of Thermo-Lag Fire Barrier Material to Pass Fire Endurance Test	08-06-1991
91-53	Failure of Remote Shutdown System Instrumentation Because of Incorrectly Installed Components	09-04-1991
91-77	Shift Staffing at Nuclear Power Plants	11-26-1991
91-79	Deficiencies in the Procedures for Installing Thermo-Lag Fire Barrier Materials	12-06-1991
91-79 Supp-1	Deficiencies Found in Thermo-Lag Fire Barrier Installation	08-04-1994
92-14	Uranium Oxide Fires at Fuel Cycle Facilities	02-21-1992
92-18	Potential for Loss of Remote Shutdown Capability During a Control Room Fire	02-28-1992
92-28	Inadequate Fire Suppression System Testing	04-08-1992
92-46	Thermo-Lag Fire Barrier Material Special Review Team Final Report Findings, Current Fire Endurance Tests, and Ampacity Calculation Errors	06-23-1992
92-55	Current Fire Endurance Test Results For Thermo-Lag Fire Barrier Material	07-27-1992
92-82	Results of Thermo-Lag 330-1 Combustibility Testing	12-15-1992
93-40	Fire Endurance Test Results for Thermal Ceramics FP-60 Fire Barrier Material	05-26-1993
93-41	One Hour Fire Endurance Test Results for Thermal Ceramics Kaowool, 3M Company FS-195, and 3M Company Interam E-50 Fire Barrier Systems	05-28-1993
93-71	Fire At Chernobyl Unit 2	09-13-1993
94-12	Insights Gained From Resolving Generic Issue 57: Effects of Fire Protection System Actuation on Safety-Related Equipment	02-09-1994
94-22	Fire Endurance and Ampacity Derating Test Results for 3-hour Fire-Rated Thermo-Lag 330-1 Fire Barriers	03-16-1994
94-26	Personnel Hazards and Other Problems From Smoldering Fire-Retardant Material in the Drywell of a Boiling-Water Reactor	03-28-1994

Table D.4-5. NRC Information Notices Related to Fire Protection

IN Number	Title	Issue Date
94-28	Potential Problems With Fire-Barrier Penetration Seals	04-05-1994
94-31	Potential Failure of Wilco, Lexan-Type HN-4-L Fire Hose Nozzles	04-14-1994
94-34	Thermo-Lag 330-660 Flexi-Blanket Ampacity Derating Concerns	05-13-1994
94-53	Hydrogen Gas Burn Inside Pressurizer During Welding	07-18-1994
94-58	Reactor Coolant Pump Lube Oil Fire	08-16-1994
94-59	Accelerated Dealloying of Cast Aluminum-Bronze Valves Caused by Microbiologically Induced Corrosion	08-17-1994
94-86	Legal Actions Against Thermal Science, Inc., Manufacturer of Thermo-Lag	12-22-1994
94-86 Supp-1	Legal Actions Against Thermal Science, Inc., Manufacturer of Thermo-Lag	11-15-1995
95-27	NRC Review of Nuclear Energy Institute, Thermo-Lag Combustibility Evaluation Methodology Plant Screening Guide	05-31-1995
95-32	Thermo-lag 330-1 Flame Spread Test Results	08-10-1995
95-33	Switchgear Fire and Partial Loss of Offsite Power at Waterford Generating Station, Unit 3	08-23-1995
95-36	Potential Problems with Post-Fire Emergency Lighting	08-29-1995
95-36 Supp-1	Potential Problem in Post-Fire Emergency Lighting	06-10-1997
95-48	Results of Shift Staffing Study	10-10-1995
95-49	Seismic Adequacy of Thermo-Lag Panels	10-27-1995
95-49 Supp-1	Seismic Adequacy of Thermo-Lag Panels	12-10-1997
95-52	Fire Endurance Test Results for Electrical Raceway Fire Barrier Systems Constructed From 3M Company Interam Fire Barrier Material	11-14-1995
95-52 Supp-1	Fire Endurance Test Results for Electrical Raceway Fire Barrier Systems Constructed from 3M Company Interam Fire Barrier Materials	03-17-1998
96-23	Fires in Emergency Diesel Generator Exciters During Operation Following Undetected Fuse Blowing	04-22-1996
96-33	Erroneous Data from Defective Thermocouple Results in a Fire.	05-24-1996
96-34	Hydrogen Gas Ignition During Closure Welding of a VSC-24 Multi-Assembly Sealed Baske	05-31-1996

Table D.4-5. NRC Information Notices Related to Fire Protection

IN Number	Title	Issue Date
97-01	Improper Electrical Grounding Results in Simultaneous Fires in the Control Room and the Safe-Shutdown Equipment Room	01-08-1997
97-23	Evaluation and Reporting of Fires and Unplanned Chemical Reactor Events at Fuel Cycle Facilities	05-07-1997
97-37	Main Transformer Fault with Ensuring Oil Spill into Turbine Building	06-20-1997
97-48	Inadequate or Inappropriate Interim Fire Protection Compensatory Measures	07-09-1997
97-59	Fire Endurance Test Results of Versawrap Fire Barriers	08-01-1997
97-70	Potential Problems with Fire Barrier Penetration Seals	09-19-1997
97-72	Potential for Failure of the Omega Series Sprinkler Heads	09-22-1997
97-73	Fire Hazard in the Use of a Leak Sealant	09-23-1997
97-82	Inadvertent Control Room Halon Actuation Due to a Camera Flash	11-28-1997
98-31	Fire Protection System Design Deficiencies and Common-Mode Flooding of Emergency Core Cooling System Rooms at Washington Nuclear Project Unit 2	08-18-1998
99-03	Exothermic Reactions Involving Dried Uranium Oxide Powder (Yellowcake)	01-29-1999
99-05	Inadvertent Discharge of Carbon Dioxide Fire Protection System and Gas Migration	03-08-1999
99-07	Failed Fire Protection Deluge Valves and Potential Testing Deficiencies in Pre-Action Sprinkler Systems	03-22-1999
99-17	Problems Associated with Post-Fire Safe-Shutdown Circuit Analyses	06-03-1999
99-28	Recall of Star Brand Fire Protection Sprinkler Heads	09-30-1999
99-28 Supp-1	Recall of Star Brand Fire Protection Sprinkler Heads	03-22-2002
99-34	Potential Fire Hazard in the Use of Polyalphaolefin in Testing of Air Filters	12-28-1999
00-12	Potential Degradation of Firefighter Primary Protective Garments	09-21-2000
00-14	Non-Vital Bus Fault Leads to Fire and Loss of Offsite Power	09-27-2000
01-04	Neglected Fire Extinguisher Maintenance Causes Fatality	04-11-2001
01-10	Failure of Central Sprinkler Company Model GB Series Fire Sprinkler Head	06-28-2001
01-12	Hydrogen Fire at Nuclear Power Station	07-13-2001

Table D.4-5. NRC Information Notices Related to Fire Protection

IN Number	Title	Issue Date
01-12 (Errata)	Hydrogen Fire at Nuclear Power Station	08-08-2001
02-01	Metalclad Switchgear Failures and Consequent Losses of Offsite Power	01-08-2002
02-04	Wire Degradation at Breaker Cubicle Door Hinges	01-10-2002
02-07	Use of Sodium Hypochlorite for Cleaning Diesel Fuel Oil Supply Tanks	01-28-2002
02-15	Hydrogen Combustion Events in Foreign BWR Piping	04-12-2002
02-15 Supp. 1	Potential Hydrogen Combustion Events in BWR Piping	05-06-2003
02-24	Potential Problems With Heat Collectors on Fire Protection Sprinklers	07-19-2002
02-27	Recent Fires at Commercial Nuclear Power Plants in the United States	09-20-2002
03-19	Unanalyzed Condition of Reactor Coolant Pump Seal Leakoff Line During Postulated Fire Scenarios or Station Blackout	10-06-2003

D.4.6 NRC Regulatory Issue Summaries Related to Fire Protection

A regulatory issue summary (RIS) is an informational document that is used to communicate with the nuclear industry on a board spectrum have generic applicability. It dose not involve a request for action or information unless it is stickily voluntary. Listed below are examples of way in which a RIS may be used:

- Document NRC endorsement of industry-developed resolutions to issues.
- Document NRC endorsement of industry guidance on technical or regulatory matters.
- Provide the status of staff interaction with the nuclear industry on a matter.
- Request the voluntary participation of licensees in staff-sponsored pilot programs.
- Inform licensees of opportunities for regulatory relief.
- Announce staff technical or policy positions on matters that have not been broadly communicated to the nuclear industry or are not fully understood.
- Provide guidance to licensees on regulatory matters, such as the scope and detail of information that should be provided in licensing applications to facilitate staff review.
- Announce the issuance and availability of regulatory documents [(topical reports, NUREG-series documents, and memoranda documenting the closeout of generic safety issues (GSIs)].
- Request the voluntary submittal of information which will assist the NRC in the administration of the regulatory process.
- Announce events of interest such as workshops and conferences.
- Announce changes in regulatory practices that could impact licensees.
- Announce changes in agency practices that could impact licensees.

Table D.4-6 provide the list of regulatory summaries related to fire protection.

Table D.4-6. NRCRegulatory Issue Summaries Related to Fire Protection

Regulatory Issue Summary Number	Title	Issue Date
99-02	Relaxation of Technical Specification Requirements for Porc Review of Fire Protection Program Changes	10-13-1999
01-09	Control of Hazard Barriers	04-02-2001
04-03	Risk-Informed Approach for Post-Fire Safe-Shutdown Associated Circuit Inspections	03-02-2004
04-03, Rev. 1	Risk-Informed Approach for Post-Fire Safe-Shutdown Associated Circuit Inspections	12-29-2004

D.5 Commission (SECY) Papers Related to Fire Protection

The primary decision-making tool of the Commission is the written issue paper submitted by the Offices of the Executive Director for Operations (EDO), Chief Financial Officer (CFO), Chief Information Officer (CIO), or other offices reporting directly to the Commission. Policy, rulemaking, and adjudicatory matters, as well as general information, are provided to the Commission for consideration in a document style and format established specifically for the purpose. Such documents are referred to as "SECY Papers". A SECY paper gains its nomenclature through the designation (e.g., SECY-95-189) assigned to it by the Secretariat. Headings on the first page designate whether the subject matter relates to the formulation of policy (Policy Issue papers), or to the promulgation of agency rules (Rulemaking Issue papers), or to the granting, suspending, revoking, or amending of licenses (Adjudicatory Issue paper). As described below, each paper also indicates the type of action expected of the Commission:

- Commission Meeting Paper indicates a major issue on which collegial deliberation and vote at a Commission meeting, usually in a public session, is anticipated.
- Notation Vote Paper indicates an issue requiring consideration by the Commission or consultation with the Commission prior to action by the staff, but not requiring discussion among Commissioners or a formal vote in a meeting.
- Affirmation Paper indicates Commission business that does not require discussion among the Commissioners in a meeting mode, but by law must be voted by the Commissioners in the presence of each other.
- Negative Consent Paper indicates a relatively minor action proposed to be taken by the staff in the future. The Commission is authorized a period of time (usually 10 days) in which to make its contrary views known; otherwise, SECY will advise the staff that the action proposed in the paper may be taken.
- Information Paper provide information on policy, rulemaking, or adjudicatory issues.

As a general policy, SECY papers will be released to the public immediately after Commission action is completed unless they contain specific, limited types of information which warrant protection (adjudicatory, enforcement or investigatory, lawyer-client or legal work product, classified or proprietary, and personal privacy information). Table D.5-1 provide the list of SECY papers related to fire protection.

Table D.5-1. Commission (SECY) Papers Related to Fire Protection

SECY	Title	Issue Date
80-438A	Commission Approval of the Final Rule on Fire Protection Program	09-30-1980
81-513	Plan for Early Resolution of Safety Issues	08-25-1991
82-267	Fire Protection Role for Future Plants	1982
83-133	Integrated Safety Assessment Program (ISAP)	03-23-1983
83-269	Memorandum from W. J. Dircks to the Commissioners, "Fire Protection Role for Future Plants (SECY 82-267)"	07-1983
89-081	Final Report on Chernobyl Implications.	03-07-1989
89-170	Fire Risk Scoping Study: Summary of Results and Proposed Staff Actions	06-07-1989
89-244	Training Symposium on Firearms and Explosives Recognition and Detection	08-21-1989
90-16	Evolutionary Light-Water Reactor (LWR) Certification Issues and Their Relationship to Current Regulatory Requirements	01-12-1990
91-283	Evaluation of Shutdown and Low Power Risk Issues	09-09-1991
92-263	Staff Plans for Elimination of Requirements Marginal to Safety	08-26-1992
93-049	Implementation of 10 CFR Part 45, Requirements for Renewal of Operating Licenses for Nuclear Power Plants	03-01-1993
93-087	Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light-Water Reactor (LWR) Designs	04-02-1993
93-143	NRC Staff Actions to Address the Recommendations in the Report on the Reassessment of the NRC Fire Protection Program	05-21-1993
94-084	Policy and Technical Issues Associated with the Regulatory Treatment of Non-Safety Systems in Passive Plant Design.	03-28-1994
94-090	Institutionalization of Continuing Program for Regulatory Improvement	03-31-1994
94-127	Options for Resolving the Thermo-Lag Fire Barrier Issue	05-12-1994
94-219	Proposed Agency-Wide Implementation Plan for Probabilistic Risk Assessment (PRA)	08-19-1994
95-034	Status of Recommendations Resulting from the Reassessment of the NRC Fire Protection Program	02-13-1994
99-079	Status Update of the Agency-Wide Implementation Plan for Probabilistic Risk Assessment	03-30-1995
96-134	Option for Pursuing Regulatory Improvement in Fire Protection Regulations for Nuclear Power Plants	06-21-1996

Table D.5-1. Commission (SECY) Papers Related to Fire Protection

SECY	Title	Issue Date
96-162	Nuclear Power Plant-Specific Time-Temperature Curves for Testing and Qualifying Fire Barriers	07-19, 1996
96-267	Fire Protection Functional Inspection Program	12-24-1996
97-127	Development of a Risk-Informed, Performance-Based Regulation for Fire Protection at Nuclear Power Plants	06-19-1997
97-278	Staff Requirements, Plans to Issue Confirmatory Orders Concerning Schedules for Corrective Actions Regarding Licensee Use of Thermo-Lag 330-1 Fire Barriers	12-24-1997
97-287	Final Regulatory Guidance on Risk-Informing Regulations: Policy Issue	12-12-1997
98-058	Development of a Risk-Informed, Performance-Based Regulation for Fire Protection at Nuclear Power Plants	03-26-1998
98-144	White Paper on Risk-Informed and Performance-Based Regulation	01-22-1998
98-161	The Westinghouse AP600 Standard Design as it Related to the Fire Protection and the Spent Fuel Pool Cooling Systems.	07-01-1998
98-187	Interim Status Report - Fire Protection Functional Inspection Program	08-03-1998
98-230	Insights from NRC Research on Fire Protection and Related Issues	10-02-1998
98-247	Risk-Informed, Performance-Based Regulation for Fire Protection at Nuclear Power Plants	10-27-1998
99-007	Recommendations for Reactor Oversight Process Improvements	01-08-1999
99-007A	Recommendations for Reactor Oversight Process Improvements	03-22-1999
00-040	Second Interim Status Report - Fire Protection Functional Inspection Program	02-05-1999
99-140	Recommendations for Reactor Fire Protection Inspections	05-20-1999
99-152	Status of Reactor Fire Protection Projects	06-07-1999
99-168	Improving Decommissioning Regulations for Nuclear Power Plants	06-30-1999
99-182	Assessment of the Impact of Appendix R Fire Protection Exemptions on Fire Risk	07-09-1999
99-183	Proposed Rule: Elimination of the Requirement for Noncombustible Fire Barrier Seal Materials and Other Minor Changes (10 CFR Part 50)	07-14-1999
99-204	Kaowool and FP6-60 Fire Barriers	08-04-1999
00-0009	Rulemaking Plan, Reactor Fire Protection Risk-Informed, Performance-Based Rulemaking	01-13-2000

Table D.5-1. Commission (SECY) Papers Related to Fire Protection

SECY	Title	Issue Date
00-0055	Status Report on The Comprehensive Fire Protection Regulatory Guide For Operating Reactors	03-02-2000
00-0080	Final Rule: Elimination of the Requirement for Noncombustible Fire Barrier Penetration Seal Materials and Other Minor Changes	04-10-2000
02-131	Update of the Risk-Informed Regulation Implementation Plan	02-12-2002
02-132	Proposed Rule: Revision of 10 CFR 50.48 to Permit Light-Water Reactors to Voluntarily Adopt National Fire Protection Association (NFPA) Standard 805, "Performance-Based Standard for Fire Protection for Light-Water Reactor Electric Generating Plants," 2001 Edition (NFPA 805) as an Alternative Set of Risk-Informed, Performance-Based Fire Protection Requirements	07-15-2002
03-0002	Evaluation of the Effects of the Baltimore Tunnel Fire on Rail Transportation of Spent Nuclear Fuel	03-25-2003
03-0100	Rulemaking Plan on Post-Fire Operator Manual Actions	06-17-2003

D.6 NRC Preliminary Notifications Related to Fire Incidents

Preliminary Notifications issued by the Regions to inform the Commission and NRC staff of incidents of interest occurring at NRC regulated facilities and some state regulated facilities. The following fire incidents were last more than 10 minutes, and the reports are preliminary in nature. Table D.5.1 provide the a list of preliminary notifications related to fire incidents.

Table D.6-1. Preliminary Notifications Related to Fire Incidents

PN Number	Title	Issue Date
29713	Turkey Point 3&4 - Electrical Fire	03-04-1997
19749	Haddam Neck - Control Room Evacuation Due To Halon Activation	08-08-1997
39780	Quad Cities 1, 2 - Fire Response Safe Shutdown Procedure Deficiencies	09-29-1997
49764	General Atomics - Fire in Hot Cell Undergoing Decommissioning	11-03-1997
39799	Quad Cities 1 - Unit 1 Shut Down Because Appendix R (Fire) Safe Shutdown Analysis Not Completed	12-23-1997
29816	General Electric Company - Fire In Dumpster	03-17-1998
29818	GTS Duratek - Bag House Fire	03-25-1998
29820	Kenton Meadows Company, Inc. - Gauge Involved In Building Fire	03-30-1998
49817	Siemens Nuclear Power Corporation - Fire in Waste Handling Area	04-15-1998
49817a	Siemens Nuclear Power Corporation - Fire in Waste Handling Area (Update)	04-16-1998
29831	Turkey Point - Notice of Unusual Event Due to Fire on Site Lasting More than 10 Minutes	06-10-1998
49826	Washington Nuclear 2 - Internal Flooding Caused by Fire Header Line Valve Rupture	06-18-1998
49826a	Washington Nuclear 2 - Update to Internal Flooding Caused by Fire Water System Valve Rupture and Arrival of Augmented Inspection Team	06-19-1998
49826b	Washington Nuclear 2 - AIT Activities for Internal Flooding Caused by Fire Water System Valve Rupture and Termination of NOUE	06-23-1998
29833	Schlumberger Technology - Well Fire Involving 40 Millicurie Cesium 137 Source	07-02-1998
29833a	Schlumberger Technology - Well Fire Involving 40 Millicurie Cesium 137 Source (Update)	07-07-98
39844	Department of the Army - Tritium Contamination Event (Broken Fire Control Devices)	09-14-1998

Table D.6-1. Preliminary Notifications Related to Fire Incidents

PN Number	Title	Issue Date
19849	Safety Light Corporation - Fire in Building on Safety Light Corporation	10-19-1998 Site
19849a	Safety Light Corporation - Fire in Building on Safety Light Corporation Site (Update)	10/21/1998
39848	Fermi 2 - Decl. of Alert Cond. Due to Fire in Emerg. Diesel Gen. Control Panel	10-21-1998
39858	Portsmouth Gaseous Diffusion Plant - Fire in Process Building	12-09-1998
39858a	Portsmouth Gaseous Diffusion Plant - Fire in Process Building- Update	12/15/1998
39901	Prairie Island 1 - Station Auxiliary Transformer Explosion and Fire	01-06/1999
39858b	Portsmouth Gaseous Diffusion Plant - Fire in Process Building - Second Update	01-13-1999
19903	Fitz Patrick - Notification of Unusual Event Due to a Fire at an Onsite Hydrogen Storage Facility	01-15-1999
19904	Millstone 3 - Carbon Dioxide Discharge Into Cable Spreading Room	01-20-1999
19926	Pilgrim 1 - Main Transformer Fire - Media Interes	05-19-1999
39931	Palisades 1 - Minor Hydrogen Burns During Cask Welding Activities	06-10-1999
39932	Palisades 1 - Dry Cask Storage Project Office Damaged by Fire	06-18-1999
39945	Allied Signal, Inc. - Brush Fire on Site Property One-Fourth Mile From Plant	10-01-1999
19946	Nine Mile Point 1 - Unusual Event Declaration Due to Carbon Dioxide Discharge in Administration Building	10-8-1999
29950a	Fairfax County Government - Fixed Gauge Damaged in a Fire	12-27-1999
400011	Unusual Event Because of a Fire Lasting Greater than 15 Minutes	05-152-00
400011a	Update - Unusual Event Because of a Fire Lasting Greater Than 15 Minutes	05-16-2000
400011b	Unusual Event Because of a Fire Lasting Greater Than 15 Minutes	05-26-2000
400016	Range Fire Nearby NRC Licensed Facilities (Siemens Power Corporation and WNP-2)	06-30-2000
200031	Alert Declared by Farley Due to Fire and Trip of the 2C Service Water Pump	08-17-2000
200039	Fire in B Main Power Transformer	09-22-2000
401001	Accidental Fire Damages Three Portable Gauges	01-05-2001

Table D.6-1. Preliminary Notifications Related to Fire Incidents

PN Number	Title	Issue Date
201002	Incinerator Fire	01-6-2001
401004	Circuit Breaker Failure and Fire, Resulting in Reactor Shutdown	2-06-2001
301010	Alert Declared Due to Small Fire on an Emergency Diesel Generator Bearing Cover	03-22-2001
401025	Fire Affecting The Startup Transformer at Cooper Nuclear Station	06-25-2001
401024	Switchyard Fire Caused by the Failure of the Phase a Bus Potential Transformer.	06-25-2001
301027	Electrical Panel Fire During Plant Startup	08-06-2001
301029	Fixed Gauges Damaged in Fire	08-29-2001
301036	Potential Small Fire Event	11-06-2001
302025	Fire in D.C. Cook Unit 1 Switchyard	06-12-2002
302025A	Fire in D.C. Cook Unit 1 Switchyard (Update)	06-13-2002
302028	Fire at Decommissioned Westinghouse-Hematite Uranium Fuel Fabrication Facility	06-20-2002
302028A	Fire at Decommissioned Westinghouse-Hematite Uranium Fuel Fabrication Facility (Update)	06-21-2002
202031	Fire Trip of 1C Service Water Pump	08-21-2002
202032	Notification of Unusual Event (NOUN) Due to Fire in the Turbine Building - McGuire (Event Number 39145)	08-23-2002
202036	Unusual Event Declared, Fire in Control Building at Watts Bar Unit 1, Hydro Plant	09-26-2002
202036A	Unusual Event Declared, Fire in Control Building at Watts Bar Unit 1, Hydro Plant	09-30-2002
303014	Unusual Event Declared Due to Fire in the Main Turbine	04-29-2003

D.7 NRC Miscellaneous Documents Related to Fire Protection

"Operating Experience Assessment, Energetic Faults in 4.16 kV to 13.8 kV Switchgear and Bus Ducts That Caused Fire in Nuclear Power Plants 1986-2001," Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC, February 2002 (ADAMS Accession #ML021290358).

RES/OERAB/S02-01, Vol.1, "Fire Events - Update of U.S. Operating Experience, 1986-1999, Commercial Power Reactors," Division of Risk Analysis and Applications, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC, January 2002 (ADAMS Accession #020360172) and (ADAMS Accession #ML020450056).

AEOD/S97-03, "Special Study: Fire Events - Feedback of U.S. Operating Experience," U.S. Nuclear Regulatory Commission, Office for Analysis and Evaluation of Operational Experience, June 1997.

"Fire Protection Barriers to Effective Implementation of NRC's Safety Oversight Process," U.S. Nuclear Regulatory Commission Washington, DC, Report to the Honorable Edward J. Markey, House of Representatives, GAO/REED-0039, U.S. General Accounting Office, Washington, DC, April 2000 (ADAMS Accession #ML003718163).

"Circuit Analysis-Failure Mode and Likelihood Analysis," A Letter Report to USNRC, Sandia National Laboratory, Albuquerque, New Mexico, ADAMS Accession # ML010450362, May 8, 2000. (This letter report is available through the NRC's Public Document Room under a NRC cover memorandum from T.L. King, NRC/RES/DRAA, to G.M. Holahan, NRC/NRR/DSSA, and M.E. Mayfield, NRC/RES/DET, dated June 13, 2000.)

"A Evaluation of the Fire Barrier System Thermo-Lag 330-1," SANDIA 94-0146, Sandia National Laboratories (SNL), Albuqerque, New Mexico, September 1994.

NRC Inspection Manual, Part 9900 (IM STS-10) - Technical Guidelines, Standard Technical Specification, Section 1.0 - Operability, p. 31, 1986.

NRC Inspection Manual, Chapter 0609, Appendix F, "Determining Potential Risk Significance of Fire Protection and Post-Fire Safe Shutdown Inspection Findings", February 27, 2001.

Inspection Procedure 64100, (IP 64100) - Postfire Safe Shutdown Emergency Lighting and Oil Collection Capability at Operating and Near-term Operating Reactor Facilities.

Inspection Procedure 64150, (IP 64150) - Triennial Postfire Safe Shutdown Capability.

Inspection Procedure 64704, (IP 64704) - Fire Protection Program, June 24, 1998.

Inspection Procedure 71111.05, (IP 71111.05) - Fire Protection, April 3, 2000.

Temporary Instruction 2515/62 (TI 2515/62) - Post Fire Safe Shutdown Emergency Lighting and Oil Collection Capability at All Operating Plants, Revision 2, February 14, 1985.

Temporary Instruction 2515/XX (TI 2515/XX) - Fire Protection Functional Inspection.

NRR Office Instruction, “NRR Interface With the Office of the General Counsel”, September 11, 2002 (ADAMS Accession #ML020910237).

Memorandum for Z. Rosztoczy from S. Bajwa, “Generic Issue 148: Smoke Control and Manual Fire Fighting Effectiveness; Generic Issue 149: Adequacy of Fire Barriers,” April 3, 1991.

Letter to D. Basdekas (NRC) from L. Lambright (SNL), “Generic Issue 1480: Smoke Control and Manual Fire Fighting Effectiveness,” March 4, 1992.

Memorandum for W. Minners from E. Beckjord, “Generic Issue 148: Smoke Control and Manual Fire Fighting Effectiveness; Generic Issue 149: Adequacy of Fire Barriers,” August 26, 1992.

Memorandum from T. King to A. Thadani, “Staff Review Guidance for Generic Issue (GSI) 148: Smoke Control and Manual Fire Fighting Effectiveness; Generic Issue 149: Adequacy of Fire Barriers,” July 22, 1992.

Memorandum dated July 22 1999, from Thomas L. King, Office of Nuclear Regulatory Research, NRC, to Ashok C. Thadani, Office of Nuclear Regulatory Research, NRC, Subject: Staff Review Guidance for Generic Safety Issue (GSI) 148, “Smoke Control and Manual Fire-Fighting Effectiveness.”

Letter dated November 12, 1999, from Dana A. Powers, Chairman ACRS, NRC, to Dr. William D. Travers, Executive Director of Operations, NRC, Subject: Proposed Resolution of Generic Safety Issue (GSI)-148, “Smoke Control and Manual Fire-Fighting Effectiveness.”

Letter dated December 15, 1999, from William D. Travers, Executive Director of Operations, NRC, to Dana A. Powers, Chairman ACRS, NRC, Subject: Resolution of Generic Safety Issue (GSI)-148, “Smoke Control and Manual Fire-Fighting Effectiveness.”

NRC Letter to All Licensees Holding Operating Licenses and Construction Permits for Nuclear Power Reactor Facilities, “Individual Plant Examination for Severe Accident Vulnerabilities - 10 CFR § 50.54(f), (Generic Letter 88-20),” November 23, 1988, (Supplement 1) August 29, 1989, (Supplement 2) April 4, 1990, (Supplement 3) July 65, 1990, (Supplement 4) June 28, 1991.

ZAR-791030-01, “Report of the President’s Commission on the Accident at Three Mile Island,” J G. Kemeny, et al., November 30, 1979.

Memorandum for E. Beckjord from J. Murphy, “Staff Review Guidance for Generic Safety Issue (GSI) 147, Fire-Induced Alternate Shutdown/Control Room Panel Interactions,” March 9, 1994.

Memorandum for W. Russell from T. Murley, “Final Report-Special Review Team for the Review of Thermo-lag Fire Barrier Performance,” April 21, 1992.

Memorandum to Dr. Dana A. Powers, Chairman Fire Protection Subcommittee from, A. Singh, “Proposed Resolution of Generic Safety Issue 148, Smoke Control and Manual Fire-Fighting Effectiveness,” September 17, 1999.

Koski, J.A., J.G. Bobbe, M. Arviso, S.D. Wix, D.E. Beene, R. Byrd, and J. Graupmann, "Experimantal Determination of the Shipboard Fire Environment for Simulated Radioactive Material Packages," SAND 97-0606, Sandia National Laboratories, Albuquerque, New Mexico, 1997.

Dey, M., A. Hamins, and M. Steward, "International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications: Summary of 5th Meeting," NISTIR 6986, National Institute of Standards and Technology, Gaithersburg, Maryland, September 2003.

D.8 NRR Staff Presentations and Publications Related to Fire Protection

Connell, E.A., “Individual Plant Examination of External Events Program: Perspectives on The Fire Risk Assessment of Operating Reactors,” Second International Conference on Fire Research and Engineering on August 12, 1997, at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland.

Connell, E.A., “Fire PRA Needs—Regulators Perspective,” Proceedings from International Workshop on Fire Risk Assessment, Organized by the Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installation (CSNI) Helsinki, Finland, 29 June–2 July 1999, NEA/CSNI/R(99)26.

Iqbal, N., and M.H. Salley, “Development of a Quantitative Fire Scenario Estimating Tool for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program,” Structural Mechanics in Reactor Technology (SMiRT) Post-Conference Fire Protection Seminar No. 1, August 20-23, 2001, at the Millstone Nuclear Power Station Conference Facility in Waterford, Connecticut.

Iqbal, N., and M.H. Salley, “First Applications of a Quantitative Fire Hazard Analysis Tool for Inspection in the U.S. Commercial Nuclear Power Plants,” 5th Meeting, International Collaborative Project to Evaluate Fire Models for Nuclear Power Plants Applications, Building and Fire Research Laboratory (BFRL), National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, May 2–3, 2002.

Madden, P.M., “Defense-In-Depth: A Regulatory Approach for Assuring Post-Fire Safe-Shutdown Capability,” Proceedings, Specialist Meeting on Fire Protection and Fire Protection Systems in Nuclear Power Plants, Committee on the Safety of Nuclear Installation (CSNI), Organization for Economic Co-Operation and Development (OECD), Cologne, Germany, 6–9 December 1993.

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NUREG-1723, "Safety Evaluation Report Related to the License Renewal of Oconee Nuclear Station, Units 1, 2, and 3," March 2000.

NUREG-1743, "Safety Evaluation Report Related to the License Renewal of Arkansas Nuclear One, Unit 1," May 2001.

NUREG-1803, "Safety Evaluation Report Related to the License Renewal of Edwin I. Hatch Nuclear Plant, Units 1 and 2," December 2001.

NUREG-1759, "Safety Evaluation Report Related to the License Renewal of Turkey Point Nuclear Plant, Units 3 and 4," April 2002.

NUREG-1766, "Safety Evaluation Report Related to the License Renewal of North Ann Power Station, Units 1 and 2, and Surry Power Station, Units 1 and 2," December 2002.

NUREG-1772, "Safety Evaluation Report Related to the License Renewal of McGuire Nuclear Station, Units 1 and 2, and Catawba Nuclear Station, Units 1 and 2, March 2003.

NUREG-1769, "Safety Evaluation Report Related to the License Renewal of Peach Bottom Atomic Power Station, Units 2 and 3," March 2003.

NUREG-1782, "Safety Evaluation Report Related to the License Renewal of Fort Calhoun Station, Unit 1," October 2003.

NUREG-1785, "Safety Evaluation Report Related to the License Renewal of the H.B. Robinson Steam Electric Plant, Unit 2," March 2004.

NUREG-1787, "Safety Evaluation Report Related to the License Renewal of the Virgil C. Summer Nuclear Station," March 2004.

NUREG01796, "Safety Evaluation Report Related to the License Renewal of the Dresden Nuclear Power Station, Units 2 and 3, and Quad Cities Nuclear Power Station, Units 1 and 2," October 2004.

D.11 National Fire Protection Association (NFPA) Codes and Standards for Nuclear Facilities

(1) NFPA 801, "Standard for Fire Protection for Facilities Handling Radioactive Materials," 1998 Edition, National Fire Protection Association, Quincy, Massachusetts.

(2) NFPA 804, "Standard for Fire Protection for Advanced Light Water Reactor Electric Generating Plants," 2001 Edition, National Fire Protection Association, Quincy, Massachusetts.

(3) NFPA 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," 2001 Edition, National Fire Protection Association, Quincy, Massachusetts.

APPENDIX E. CURRENT NATIONAL FIRE PROTECTION ASSOCIATION (NFPA) CODES AND STANDARDS

NFPA develops, publishes, and disseminates timely consensus codes and standards intended to minimize the possibility and effects of fire and other risks. Virtually every building, process, service, design, and installation in society today is affected by NFPA documents. More than 300 NFPA codes and standards are used around the world. This series is referred to as the National Fire Codes (NFC).

NFPA codes and standards have great influence because they are widely used as a basis of legislation and regulation at all levels of government, from local to international. Several NFPA codes have received worldwide recognition, such as the *Life Safety Code®*, the *National Electrical Code®*, and the *National Fuel Gas Code*. Many codes are referenced by Federal Government agencies, such as the regulations of the U.S. Nuclear Regulatory Commission (NRC), General Services Administration (GSA), and U.S. Occupational Safety and Health Administration (OSHA). The documents are also used by insurance authorities for risk evaluation and premium rating and as references in designs and specifications. Table E-1 provides titles of all current NFPA codes, standards, and recommended practices. It is important to recognize that the NFPA codes and standards are constantly revised and updated on 3 to 5 year cycles. The code or standard in effect at the time of design or implementation is the code of record (COR) for that application.

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
1	Uniform Fire Code™	2003
10	Standard for Portable Fire Extinguishers	2002
11	Standard for Low-Expansion Foam	2002
11A	Standard for Medium-and High-Expansion Foam Systems	1999
12	Standard on Carbon Dioxide Extinguishing Systems	2000
12A	Standard on Halon 1301 Fire Extinguishing Systems	1997
13	Standard for Installation of Sprinkler Systems	2002
13D	Standard for Installation of Sprinkler Systems in One-and Two1-Family Dwellings and Manufactured Homes	2002
13E	Recommended Practice for Fire Department Operations in Properties Protected by Sprinkler and Standpipe Systems	2000
13R	Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height	2002
14	Standard for the Installation of Standpipe and Hose Systems	2003
15	Standard for Water Spray Fixed Systems for Fire Protection	2001

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
16	Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems	2003
17	Standard for Dry Chemical Extinguishing System	2002
17A	Standard for Wet Chemical Extinguishing Systems	2002
18	Standard on Wetting Agents	1995
20	Standard for the Installation of Stationary Pumps for Fire Protection	1999
22	Standard for Water Tanks for Private Fire Protection	2003
24	Standard for the Installation of Private Fire Service Mains and Their Appurtenances	2002
25	Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection System	2002
30	Flammable and Combustible Liquids Code	2003
30A	Code for Motor Fuel Dispensing Facilities and Repair Garages	2000
30B	Code for the Manufacturer and Storage of Aerosol Products	2002
31	Standard for the Installation of Oil-Burning Equipment	2001
32	Standard for the Drycleaning Plants	2000
33	Standard for Spray Application Using Flammable or Combustible Materials	2000
34	Standard for Dipping and Coating Processes Using Flammable or Combustible Liquids	2000
35	Standard for the Manufacturer of Organic Coatings	1999
36	Standard for Solvent Extraction Plants	2001
37	Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines	2002
40	Standard for the Storage and Handling of Cellulose Nitrate Motion Picture Film	2001
42	Code for the Storage of Pyroxylin Plastic	2002
45	Standard on Fire Protection for Laboratories Using Chemicals	2000
50	Standard for Bulk Oxygen Systems at Consumer Sites	2001
50A	Standard for Gaseous Hydrogen Systems at Consumer Sites	1999
50B	Standard for Liquefied Hydrogen Systems at Consumer Sites	1999
51	Standard for the Design and Installation of Oxygen-Fuel Gas Systems for Welding, Cutting, and Allied Processe	2002

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
51A	Standard for Acetylene Cylinder Charging Plants	2001
51B	Standard for Fire Prevention During Welding, Cutting, and Other Hot Work	1999
52	Compressed Nature Gas (CNG) Vehicular Fuel Systems Code	2002
53	Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres	1999
54	National Fuel Code	2002
55	Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks	2003
57	Liquified Petroleum Gas (LNG) Vehicular Fuel Systems Code	2002
58	Liquified Petroleum Gas Code	2001
59	Utility LP-Plant Code	2001
59A	Standard for the Protection, Storage, and Handling of Liquefied Natural Gases (LNG)	2001
61	Standard for the Prevention of Fires and Dust Explosions in Agriculture and Food Products Facilities	2002
68	Guide for Venting of Deflagrations	2002
69	Standard on Explosion Prevention Systems	1997
70	National Electrical Code®	2002
70B	Recommended Practice for Electrical Equipment Maintenance	2002
70E	Standard for Electrical Safety Requirements for Employee Workshops	2000
72	National Fire Alarm Code®	2002
73	Electrical Inspection Code for Existing Dwellings	2000
75	Standard for the Protection of Information Technology Equipment	2003
76	Recommended Practice for the Fire Protection of Telecommunications Facilities	2002
77	Recommended Practice on Static Electricity	2000
79	Electrical Standard for Industrial Machinery	2002
80	Standard for Fire Doors and Fire Windows	1999
80A	Recommended Practice for Protection of Building from Exterior Fire Exposures	2001
82	Standard on Incinerators and Waste and Linen Handling Systems and Equipment	1999
85	Boiler and Combustion Systems Hazards Code	2001

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
86	Standard for Oven and Furnaces	1999
86C	Standard for Industrial Furnaces Using a Special Processing and Equipment	1999
86D	Standard for Industrial Furnaces Using Vacuum as an Atmosphere	1999
88A	Standard for Parking Structures	2002
88B	Standard for Repair Garages	1997
90A	Standard for the Installation of Air-Conditioning and Ventilating Systems	2002
90B	Standard for the Installation of Warm Air Heating and Air-Conditioning Systems	2002
91	Standard for Exhaust Systems for Air Conveying of Vapor, Gases, Mists, and Noncombustibles Particulate Solids	1999
92A	Recommended Practice for Smoke-Control Systems	2000
92B	Guide for Smoke Management Systems in Mall, Atria, and Large Areas	2000
96	Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations	2001
97	Standard Glossary of Terms Relating to Chimneys, Vents, and Heat-Producing Appliances	2003
99	Standard for Health Care Facilities	2002
99B	Standard for Hypobaric Facilities	2002
101®	Life Safety Code®	2003
101A	Guide to Alternative Approaches to Life Safety	2001
101B	Code for Mean of Egress for Buildings and Structures	2002
102	Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures	1995
105	Standard for the Installation of Smoke Door Assemblies	2003
110	Standard for Emergency and Standby Power Systems	2002
111	Standard on Stored Electrical Energy Emergency and Standby Power Systems	2001
115	Recommended Practice on Laser Fire Protection	1999
120	Standard for Coal Preparation Plants	1999
121	Standard on Fire Protection for Self-Propelled and Mobile Surface Mining Equipment	2001
122	Standard for Fire Prevention and Control in Underground Metal and Nonmetal Mines	2000

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
123	Standard for Fire Prevention and Control in Underground Bituminous Coal Mines	1999
130	Standard for Fixed Guideway Transit and Passenger Rail Systems	2000
140	Standard on Motion Picture and Television Production Studio Soundstages and Approved Production Facilities	1999
150	Standard on Fire Safety in Racetrack Stables	2000
160	Standard for Flame Effects Before an Audience	2001
170	Standard for Fire Safety Symbols	2002
203	Guide on Roof Coverings and Roof Deck Constructions	2000
204	Guide for Smoke and Heat Venting	2002
211	Standard for Chimneys, Fireplace, Vents, and Solid Fuel-Burning Appliances	2003
214	Standard on Water-Cooling Towers	2000
220	Standard on Types of Building Construction	1999
221	Standard for Fire Walls and Fire Barrier Walls	2000
225	Model Manufactured Home Installation Standard	2003
230	Standard for the Fire Protection of Storage	2003
232	Standard for the Protection of Records	2000
241	Standard for Safeguarding Construction, Alteration, and Demolition Operations	2000
251	Standard Methods of Tests of Fire Endurance of Building Construction and Materials	1999
252	Standard Methods of Fire Tests of Door Assemblies	1999
253	Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source	2000
255	Standard Method of Test of Surface Burning Characteristics of Building Materials	2000
256	Standard Methods of Fire Tests of Roof Coverings	1998
257	Standard on Fire Test for Window and Glass Block Assemblies	2000
258	Recommended Practice for Determining Smoke Generation of Solid Materials	2001
259	Standard Test Method for Potential Heat of Building Materials	2003
260	Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture	1998

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
261	Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes	1998
262	Standard Method of Test for Flame Travel and Smoke of Wires and Cables for Use in Air-Handling Spaces	2002
265	Standard Methods of Fire Tests for Evaluating Room Fire Growth Contribution of Textile Wall Coverings on Full Height Panels and Walls	2002
267	Standard Method of Test for Fire Characteristics of Mattresses and Bedding Assemblies Exposed to Flaming Ignition Source	1998
268	Standard Test Method for Determining Ignitability of Exterior Wall Assemblies Using a Radiant Heat Energy Source	2001
269	Standard Test Method for Developing Toxic Potency Data for Use in Fire Hazard Modeling	2000
270	Standard Test Method for Measurement of Smoke Obscuration Using a Conical Radiant Source in a Single Closed Chamber	2002
271	Standard Method of Test for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter	2001
272	Standard Method of Test for Heat and Visible Smoke Release Rates for Upholstered Furniture Components or Composites and Mattresses Using an Oxygen Consumption Calorimeter	2003
285	Standard Method of Test for the Evaluation of Flammability Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components Using the Intermediate-Scale, Multistory Test Apparatus	1998
286	Standard Methods of Fire Tests for Evaluating Contribution of Wall and Ceiling Interior Finish to Room Fire Growth	2000
287	Standard Test Methods for Measurement of Flammability of Materials in Cleanrooms Using a Fire Propagation Apparatus (FPA)	2001
288	Standard Methods of Fire Tests of Floor Fire Door Assemblies Installed Horizontally in Fire Resistance–Rated Floor Systems	2001
291	Recommended Practice for Fire Flow Testing and Marking of Hydrants	2002
295	Standard for Wildfire Control	1998
301	Code for Safety to Life from Fire on Merchant Vessels	2001
302	Fire Protection Standard for Pleasure and Commercial Motor Craft	1998
303	Fire Protection Standard for Marinas and Boatyards	2000
306	Standard for the Control of Gas Hazards on Vessels	2001

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
307	Standard for the Construction and Fire Protection of Marine Terminals, Piers, and Wharves	2000
312	Standard for Fire Protection of Vessels During Construction, Repair, and Lay-Up	2000
318	Standard for the Protection of Cleanrooms	2000
326	Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair	1999
329	Recommended Practice for Handling Releases of Flammable and Combustible Liquids and Gases	1999
385	Standard for Tank Vehicles for Flammable and Combustible Liquids	2000
402	Guide for Aircraft Rescue and Fire Fighting Operations	2002
403	Standard for Aircraft Rescue and Fire-Fighting Services at Airports	1998
405	Recommended Practice for the Recurring Proficiency Training of Aircraft Rescue and Fire-Fighting Services	1999
407	Standard for Aircraft Fuel Servicing	2001
408	Standard for Aircraft Hand Portable Fire Extinguishers	1999
409	Standard on Aircraft Hangars	2001
410	Standard on Aircraft Maintenance	1999
412	Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment	1998
414	Standard for Aircraft Rescue and Fire-Fighting Vehicles	2001
415	Standard on Airport Terminal Buildings, Fueling Ramp Drainage, and Loading Walkways	2002
418	Standard for Heliports	2001
422	Guide for Aircraft Accident Response	1999
423	Standard for Construction and Protection of Aircraft Engine Test Facilities	1999
424	Guide for Airport/Community Emergency Planning	2002
430	Code for the Storage of Liquid and Solid Oxidizers	2000
432	Code for the Storage of Organic Peroxide Formulations	2002
434	Code for the Storage of Pesticides	2002
450	Guide for Emergency Medical Services and Systems	2003
471	Recommended Practice for Responding to Hazardous Materials Incidents	2002

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
472	Standard on Professional Competence of Responders to Hazardous Materials Incidents	2002
473	Standard for Competencies for EMS Personnel Responding to Hazardous Materials Incidents	2002
484	Standard for Combustible Metals, Metal Powders, and Metal Dusts	2002
490	Code for the Storage of Ammonium Nitrate	2002
495	Explosive Materials Code	2001
496	Standard for Purged and Pressurized Enclosures for Electrical Equipment	1998
497	Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas	1997
498	Standard for Safe Havens and Interchange Lots for Vehicles Transporting Explosives	2001
499	Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas	1997
501	Standard on Manufactured Housing	2003
501A	Standard for Fire Safety Criteria for Manufactured Home Installations, Sites, and Communities	2003
502	Standard for Road Tunnels, Bridges, and Other Limited Access Highways	2001
505	Fire Safety Standard for Powered Industrial Trucks Including Type Designations, Areas of Use, Conversions, Maintenance, and Operation	2002
520	Standard on Subterranean Spaces	1999
550	Guide to the Fire Safety Concepts Tree	2002
551	Guide for the Evaluation of Fire Risk Assessments	2003
555	Guide on Methods for Evaluating Potential for Room Flashover	2000
560	Standard for the Storage, Handling, and Use of Ethylene Oxide for Sterilization and Fumigation	2002
600	Standard on Industrial Fire Brigades	2000
601	Standard for Security Services in Fire Loss Prevention	2000
610	Guide for Emergency and Safety Operations at Motorsports Venues	2003
654	Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids	2000

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
655	Standard for Prevention of Sulfur Fires and Explosions	2001
664	Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities	2002
701	Standard Methods of Fire Tests for Flame Propagation of Textiles and Films	1999
703	Standard for Fire Retardant Impregnated Wood and Fire Retardant Coatings for Building Materials	2000
704	Standard System for the Identification of the Hazards of Materials for Emergency Response	2001
705	Recommended Practice for a Field Flame Test for Textiles and Films	1997
720	Recommended Practice for the Installation of Household Carbon Monoxide (CO) Warning Equipment	2003
730	Premises Security Code	2003
731	Installation of Premises Security Equipment	2003
750	Standard on Water Mist Fire Protection Systems	2003
780	Standard for the Installation of Lightning Protection Systems	2000
801	Standard for Fire Protection for Facilities Handling Radioactive Materials	2003
804	Standard for Fire Protection for Advanced Light Water Reactor Electric Generating Plants	2001
805	Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants	2001
820	Standard for Fire Protection in Wastewater Treatment and Collection Facilities	1999
850	Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations	2000
851	Recommended Practice for Fire Protection for Hydroelectric Generating Plants	2000
853	Standard for the Installation of Stationary Fuel Cell Power Plants	2000
900	Building Energy Code	2003
901	Standard Classifications for Incident Reporting and Fire Protection Data	2001
906	Guide for Fire Incident Field Notes	1998
909	Code for the Protection of Cultural Resources	2001
914	Code for Fire Protection of Historic Structures	2001
921	Guide for Fire and Explosion Investigations	2001

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
1000	Standard for Fire Service Professional Qualifications Accreditation and Certification Systems	2000
1001	Standard on Fire Fighter Professional Qualifications	2002
1002	Standard for Fire Apparatus Driver/Operator Professional Qualifications	1998
1003	Standard for Airport Fire Fighter Professional Qualifications	2000
1006	Standard for Rescue Technician Professional Qualifications	2003
1021	Standard on Fire Officer Professional Qualifications	1997
1031	Standard for Professional Qualifications for Fire Inspector and Plan Examiner	1998
1033	Standard for Professional Qualifications for Fire Investigator	1998
1035	Standard for Professional Qualifications for Public Fire and Life Safety Educator	2000
1041	Standard for Fire Service Instructor Professional Qualifications	2002
1051	Standard for Wildland Fire Fighter Professional Qualifications	2002
1061	Standard for Professional Qualifications for Public Safety Telecommunicator	2002
1071	Standard for Emergency Vehicle Technician Professional Qualifications	2000
1081	Standard for Industrial Fire Brigade Member Professional Qualifications	2001
1122	Code for Model Rocketry	2002
1123	Code for Fireworks Display	2000
1124	Code for the Manufacture, Transportation, Storage, and Retail Sales of Fireworks and Pyrotechnic Articles	2003
1125	Code for the Manufacture of Model Rocket and High Power Rocket Motors	2001
1126	Standard for the Use of Pyrotechnics before a Proximate Audience	2001
1127	Code for High Power Rocketry	2002
1141	Standard for Fire Protection in Planned Building Groups	1998
1142	Standard on Water Supplies for Suburban and Rural Fire Fighting	2001
1145	Guide for the Use of Class A Foams in Manual Structural Fire Fighting	2000
1150	Standard on Fire-Fighting Foam Chemicals for Class A Fuels in Rural, Suburban and Vegetated Area	1999
1192	Standard on Recreational Vehicles	2002
1194	Standard for Recreational Vehicle Parks and Campgrounds	2002

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
1201	Standard for Developing Fire Protection Services for the Public	2000
1221	Standard for Installation, Maintenance, and Use of Emergency Service Communications Systems	2002
1250	Recommended Practice in Emergency Service Organization Risk Management	2000
1401	Recommended Practice for Fire Service Training Reports and Records	2001
1402	Guide to Building Fire Service Training Centers	2002
1403	Standard on Live Fire Training Evolutions	2002
1404	Standard for a Fire Department Self-Contained Breathing Apparatus Program	2002
1405	Guide for Land-Based Fire Fighters Who Respond to Marine Vessel Fires	2001
1410	Standard on Training for Initial Emergency Scene Operations	2000
1451	Standard for a Fire Service Vehicle Operations Training Program	2002
1452	Guide for Training Fire Service Personnel to Conduct Dwelling Fire Safety Surveys	2000
1500	Standard on Fire Department Occupational Safety and Health Program	2002
1521	Standard for Fire Department Safety Officer	2002
1561	Standard on Emergency Services Incident Management System	2002
1581	Standard on Fire Department Infection Control Program	2000
1582	Standard on Medical Requirements for Fire Fighters and Information for Fire Department Physicians	2000
1583	Standard on Health-Related Fitness Programs for Fire Fighters	2000
1584	Recommended Practice on the Rehabilitation of Members Operating at Incident Scene Operations and Training Exercises	2003
1600	Standard on Disaster/Emergency Management and Business Continuity Programs	2000
1620	Recommended Practice for Pre-Incident Planning	1998
1670	Standard on Operations and Training for Technical Rescue Incidents	1999
1710	Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Department	2001
1720	Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments	2001

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
1851	Standard on Selection, Care, and Maintenance of Structural Fire Fighting Protective Ensembles	2001
1852	Standard on Selection, Care, and Maintenance of Open-Circuit Self Contained Breathing Apparatus (SCBA)	2002
1901	Standard for Automotive Fire Apparatus	1999
1906	Standard for Wildland Fire Apparatus	2001
1911	Standard for Service Tests of Fire Pump Systems on Fire Apparatu	2002
1912	Standard for Fire Apparatus Refurbishin	2001
1914	Standard for Testing Fire Department Aerial Devices	2002
1915	Standard for Fire Apparatus Preventive Maintenance Program	2000
1925	Standard on Marine Fire-Fighting Vessels	1998
1931	Standard on Design of and Design Verification Tests for Fire Department Ground Ladders	1999
1932	Standard on Use, Maintenance, and Service Testing of Fire Department Ground Ladders	1999
1936	Standard on Powered Rescue Tool Systems	1999
1951	Standard on Protective Ensemble for USAR Operations	2001
1961	Standard on Fire Hose	2002
1962	Standard for the Inspection, Care, and Use of Fire Hose, Couplings, and Nozzles and the Service Testing of Fire Hose	2003
1963	Standard for Fire Hose Connections	1998
1964	Standard for Spray Nozzles	2003
1971	Standard on Protective Ensemble for Structural Fire Fighting	2000
1975	Standard on Station/Work Uniforms for Fire and Emergency Services	1999
1976	Standard on Protective Ensemble for Proximity Fire Fighting	2000
1977	Standard on Protective Clothing and Equipment for Wildland Fire Fighting	1998
1981	Standard on Open-Circuit Self-Contained Breathing Apparatus for the Fire Service	2002
1982	Standard on Personal Alert Safety Systems (PASS)	1998
1983	Standard on Fire Service Life Safety Rope and System Components	2001
1989	Standard on Breathing Air Quality for Fire and Emergency Services Respiratory Protection	2003

Table E-1-1. NFPA Codes and Standards

NFPA	Title	Edition
1991	Standard on Vapor-Protective Ensembles for Hazardous Materials Emergencies	2000
1992	Standard on Liquid Splash-Protective Ensembles and Clothing for Hazardous Materials Emergencies	2000
1994	Standard on Protective Ensembles for Chemical/Biological Terrorism Incidents	2001
1999	Standard on Protective Clothing for Emergency Medical Operations	2003
2001	Standard on Clean Agent Fire Extinguishing Systems	2000
2112	Standard on Flame-Resistant Garments for Protection of Industrial Personnel Against Flash Fire	2001
2113	Standard on Selection, Care, Use, and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel Against Flash Fire	2001
5000	Building Construction and Safety Code™	2003

APPENDIX F. GLOSSARY OF FIRE PROTECTION TERMS

The purpose of this appendix is to provide definitions and meanings of fire protection engineering term being used in the field of fire science, engineering, and technology today. This appendix contains a collection of terminology and a description of terms and can be used as reference source to understand basic terminology used in fire protection engineering. The reference for the definition is provided in parentheses.

accelerant—a material (gas, liquid, or solid) used to initiate or promote the spread of fire incident. Most accelerants are highly flammable. (Nolan, 2000)

access door—a fire door smaller than conventional doors provides access to utility shafts, chases, manways, plumbing, and various other concealed spaces and equipments. (NFC Online Glossary)

abort switch—a manually activated switch provided for fixed gaseous fire suppression system to cancel the signal to release and discharge the system agent. The use of an abort switch is preferred over other manual means, such as portable fire extinguishers or when a false alarm condition is immediately known, to avoid the unnecessary release of large quantities of fire suppression agent. An abort switch is only practical where individuals may be present to immediately investigate the cause of the system activation and have time to activate the switch.

absolute temperature—a temperature measured in Kelvin (K) or degree Rankine (R). Zero is the lowest possible temperature and 273 K corresponds to 0 °F and 460 °R corresponds to 0 °F.
K = °C + 273 and °R = °F + 460. (Nolan, 2000)

access door, horizontal—an access door installed in the horizontal plane used to protect openings in fire-rated floors or ceilings of floor–ceiling or roof–ceiling assemblies. (NFC Online Glossary)

access door, vertical—an access door installed in the vertical plane used to protect openings in fire-rated walls. (NFC Online Glossary)

access floor system—an assembly consisting of panels mounted on pedestals to provide an under-floor space for the installations of mechanical, electrical communication, or similar systems or to serve as an air supply or return-air plenum. (NFC Online Glossary)

access openings—a window, panel, or similar opening meeting the following criteria: (a) The opening has minimum dimensions of not less than 22 in. (55.9 cm) in width and 24 in. (61 cm) in height and is unobstructed to allow for ventilation and rescue operations from the exterior, and (b) The bottom of the opening is not more than 44 in. (112 cm) above the floor, and (c) The opening is readily identifiable from both the exterior and interior, and (d) The opening is readily openable from both the exterior and interior. (NFC Online Glossary)

access panel—a closure device used to cover an opening into a duct, an enclosure, equipment, or an appurtenance. (NFC Online Glossary)

accessible—having access to but which first may require the removal of a panel, door, or similar covering of the item described. (NFC Online Glossary) *accessible (as applied to wiring methods)*—capable of being removed or exposed without damaging the building structure or finish, or not permanently closed in by the structure or finish of the building. (NFC Online Glossary)

accessible—(as applied to equipment.) Admitting close approach; not guarded by locked doors, elevation, or other effective means. (NFC Online Glossary)

accessible means of egress—a path of travel, usable by a person with a severe mobility impairment, that leads to a public way or an area of refuge and that complies with the accessible route requirements of ICC/ANSI A117.1, "American National Standard for Accessible and Usable Buildings and Facilities".(NFC Online Glossary)

accommodation area—a group of accommodation spaces and interconnecting corridors or spaces. (NFC Online Glossary)

accommodation space—spaces designed for living purposes.
(NFC Online Glossary)

accommodation spaces—accommodation spaces shall include, but are not limited to, all portions of a vessel used for such purposes as overnight residence, deliberation, worship, entertainment, dining, or amusement. Accommodation spaces shall include the following: (a) passenger or crew cabins (b) lounge areas (c) athletic facilities (d) gaming areas (e) office spaces (f) spaces for religious worship (g) theaters (h) restaurants/messing areas (i) public toilets/washrooms (j) public sales/shops. (NFC Online Glossary)

active fire barrier—a fire barrier element that must be physically repositioned from its normal configuration to an alternate configuration in order to provide its protective function. Example include ventilation system fire dampers and normally open fire door.

activation energy—the minimum energy that colliding fuel and oxygen molecules must possess to permit chemical interaction. (NFC Online Glossary)

active fire protection—a fire protection method that requires manual, mechanical, or other means of initiation, replenishment, or sustenance for its performance during a detected hazard or fire incident. Typical activations include switching on, directing, injecting, or expelling in order to combat smoke, flame, or thermal loadings. Fire sprinkler systems and manual firefighting efforts are examples. Active systems are commonly composed of an integrated detection, signaling, and automated fire control system. (Nolan, 2000)

active smoke detection system—a fire detection system where smoke is transported to and into a sampling port to aspirate smoke into the detector-sensing chamber rather than relying totally on outside forces such as fire plume strength or environmental air flows. These systems actively draw smoke into the sensing chamber through the use of suction fans. Smoke in the immediate vicinity of the sampling ports is drawn into the detector-sensing chamber. (Nolan, 2000)

adiabatic—Referring to any change in which there is no gain or loss of heat. (McGraw-Hill) *adiabatic flame temperature*—the maximum possible flame temperature that can be achieved by a particular combustion process (with no hat loss from the combustion). For example, the adiabatic flame temperatures for hydrocarbon fuels burning in air range from 2,000 °C to 2,300 °C (3,632 °F to 4,172 °F). (Nolan, 2000)

advanced light-water reactors (ALWR)—advanced light water reactors are divided into two types: (a) evolutionary plants. These are simpler, improved versions of conventional designs employing active safety systems. (b) revolutionary plants. These are the result of completely rethinking the design philosophy of conventional plants. Revolutionary plants currently being proposed replace mechanical safe shutdown systems with passive features that rely on physical properties such as natural circulation, gravity flow, and heat sink capabilities. (NFC Online Glossary)

aerosol—A gaseous suspension of ultramicroscopic particles of a liquid or a solid. (McGraw-Hill)

aerosol detector—a detector designed to be activated by the liquid and solid particulates in smoke.

AFFF-Aqueous Film Forming Foam—a foam that forms a spreading aqueous film over the surface of a flammable liquid. AFFF is a combination of fluorocarbon surfactants and synthetic foam agents. They produce a foam that slides across the surface of hydrocarbon fuels. This is accomplished by the formation of a film that spreads ahead of the foam bubbles. (NFC Online Glossary)

air sampling-type detector—a detector that consists of a piping or tubing distribution network that runs from the detector to the area(s) to be protected. An aspiration fan in the detector housing draws air from the protected area back to the detector through air sampling ports, piping, or tubing. At the detector, the air is analyzed for fire products.

air/fuel ratio, air-rich—the ratio of air to fuel by weight or volume which is significant for proper oxidative combustion of the fuel. (McGraw-Hill)

alarm—a signal indicating an emergency that requires immediate action, such as a signal indicative of fire. (Nolan, 2000)

alarm signal—a signal indicating a concentration of carbon monoxide that could pose a risk to the life safety of the occupants in the family living unit, requiring immediate action. (NFC Online Glossary)

alarms and indicators—any device capable of providing audible, visual, or olfactory indication.

alternative shutdown capability—the ability to safely shut down the reactor and maintain shutdown using equipment and processes outside the normal reactor shutdown process.

ambient temperature—the temperature of the surrounding medium; usually used to refer to the temperature of the air in which a structure is situated or a device operates.

American Wire Gauge (AWG)—a standardized system used to designate the size or "gauge" of wire. As the diameter of wire gets smaller, the "AWG" number of the wire gets larger. The smallest AWG size is 40 and looks like a metal thread. "Four ought" (0000) is the largest AWG wire size designation. Wires larger than this size are designated by the Thousand Circular Mill system or "KCMIL" sizes (known until recently as MCM).

ampacity—the current, in amperes, that a conductor can carry continuously under the conditions of use without exceeding its temperature rating.

analysis, sensitivity—an analysis performed to determine the degree to which a predicted output will vary given a specified change in an input parameter, usually in relation to models. (NFC Online Glossary)

analysis, uncertainty—an analysis performed to determine the degree to which a predicted value will vary. (NFC Online Glossary)

analyzer, gas—a device that measures concentrations, directly or indirectly, of some or all components in a gas or mixture. (NFC Online Glossary)

annunciator—a unit containing two or more identified targets or indicators lamps in which each target or lamp indicates the circuit, condition, or location to be annunciated. (NFC Online Glossary)

antifreeze sprinkler system—a wet pipe sprinkler system employing automatic sprinklers that are attached to a piping system that contains an antifreeze solution and that are connected to a water supply. The antifreeze solution is discharge, followed by water, immediately upon operation of sprinklers opened by heat from a fire. (NFC Online Glossary)

Appendix R cables—the set of cables that must remain free of fire damage to ensure safe shutdown conditions can be achieved within established criteria.

Appendix R fire area—an area, as defined in the Appendix R analysis, sufficiently bounded by fire barriers that will withstand the fire hazards within the fire area and, as necessary, to protect important equipment within a fire area from a fire outside the area the area. A fire area must be made up of rated fire barriers with openings in the barriers provided with fire doors, fire dampers, and fire penetration seal assemblies having a fire resistance rating at least equivalent to the barrier in which it is installed.

Appendix R fire zones—subdivisions of a fire area.

Appendix R requirements—fire protection requirements specified in Appendix R to 10 CFR 50, "Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979," (It should be noted that while some specific Appendix R requirements apply to all plants operating prior to January 1, 1979, plants licensed after January 1, 1979, are not subject to Appendix R requirements. These plants must meet the fire protection condition of their licenses which are based upon the guidelines of NUREG-0800, specifically Branch Technical Position CMEB 9.5-1, which mirrors Appendix R with additional information).

approach fire fighting—limited, specialized exterior fire fighting operations at incidents involving fires producing very high levels of conducted, convective, and radiant heat, such as bulk flammable gas and bulk flammable liquid fires. Speciality thermal protection from exposure to high levels of radiant heat is necessary for the persons involved in such operations due to the limited scope of these operations and greater distance from the fire that these operations are conducted. Not entry, proximity, or structural, or wildland fire-fighting. (NFC Online Glossary)

approved—tested and accepted for a specific purpose or application by a recognized testing laboratory. (Regulatory Guide 1.189)

approved—acceptable to authority having jurisdiction. (NFPA 805)

aqueous film-forming foam (AFFF) concentrate—a concentrated aqueous solution of fluorinated surfactant(s)and foam stabilizers that is capable of producing an aqueous fluorocarbon film on the surface of hydrocarbon fuels to suppress vaporization. (NFC Online Glossary)

arcing—the flashing occurring at electrical terminals when the circuit has been opened or closed.

armored cable—type AC armored cable is a fabricated assembly of insulated conductors in a flexible metallic enclosure. (NFC Online Glossary)

assembly—a unit or structure composed of a combination of materials or products, or both.
(NFC Online Glossary)

assembly occupancy—an occupancy (1) used for a gathering of 50 or more persons for deliberation, worship, entertainment, eating, drinking, amusement, awaiting transportation, or similar uses; or (2) used as a special amusement building, regardless of occupant load.
(NFC Online Glossary)

associated circuits—circuits that do not meet the separation requirements for safe shutdown systems and components and are associated with safe shutdown systems and components by common power supply, common enclosure, or the potential to cause spurious operations that could prevent or adversely affect the capability to safely shutdown the reactor as a result of fire induced failure (hot shorts, open circuits, and short to ground). (Regulatory Guide 1.189)

associated circuit analysis—a documented, systematic, evaluation of associated circuits of concern to post-fire safe shutdown.

atmospheric pressure—the pressure of the weight of air and water vapor on the surface of the earth, approximately 14.7 pounds per square inch (psia) (101 kPa absolute) at sea level.
(NFC Online Glossary)

atmospheric tank—a storage tank that has been designed to operate at gauge pressures from atmospheric through 0.5 psi (3.45 kPa). (NFC Online Glossary)

atmospheric vents—all points where pipes, stacks, or ducts are open to the atmosphere including discharge points from emissions control devices, vent pipes from safety valves, vent pipes from filters or pumps, and other vents. (NFC Online Glossary)

Authority Having Jurisdiction (AHJ)—the organization, office, or individual responsible for approving equipment, materials, an installation, or a procedure. (NFPA 805)

autoignition—the initiation of fire or combustion process by external heat without the application of a spark or flame. (NFC Online Glossary)

autoignition temperature—the lowest temperature at which a mixture of fuel and oxidizer can propagate a flame without the aid of an initiating energy source (pilot, a spark or flame).

autoignition temperature—the lowest temperature at which a vapor/air mixture within its flammability limits can undergo spontaneous ignition.

automatic closing device—a mechanism that can be fitted to a door which will cause the door to close if there is a fire.

automatic door release—a device on a self-closing door that holds the door open during normal operation but causes it to close by releasing electromagnetic holders when activated by a signal, such as from a fire alarm. The closed door prevents the spread of fire and smoke. For personnel exit applications and other locations where smoke spread is a concern, fusible links or other similar heat-activated door-closing devices are not recommended because smoke may pass through the door opening before there is sufficient heat to melt the fusible device. (Nolan, 2000)

automatic fire alarm system—a system of controls, initiating devices, and alarm signals in which all or some of the initiating circuits are activated by automatic devices, such as smoke detectors. (Nolan, 2000)

automatic fire detection system—an arrangement of detectors that ascertains the presence of a combustion process by sensing heat, smoke, or flames. The detectors can be self-annunciating or connected to a fire alarm control panel (FACP) to initiate other alarm devices or signaling systems. Various codes and standards are used to design and provide a fire alarm system, notably NFPA 72, "National Fire Alarm Code®". (Nolan, 2000)

automatic fire door—a fire door that closes immediately following the detection of a fire incident. Most fire doors that automatically close are held open by electromagnetic holders. When the fire is detected by a fire detection system, power is removed from the magnetic holders, and the doors swing closed from their self-closer. It may also be called an automatic-closing fire door. (Nolan, 2000)

automatic fire extinguishing system—a fire suppression system that automatically senses the occurrence of a fire and signals a control device for the application of extinguishing agents. It is designed to distribute and apply the extinguishing agents in sufficient quantities and densities to effect fire control and extinguishment. No human intervention is required. Almost all automatic fire extinguishing systems are required to be designed and installed according to prescribed rules and regulations that ensure they are reliable and effective for fire protection applications. (Nolan, 2000)

automatic fire protection—active fire protection measures that are activated immediately following a fire incident without human intervention. Automatic fire protection systems pro-vide for both fire detection and extinguishment. (Nolan, 2000) *automatic sprinkler*—a water spray device, commonly a nozzle with a perpendicular spray deflector attached, used to deflect the water spray to a predetermined area at a predetermined density for the purpose of fire protection. Automatic sprinklers for fire protection applications are available in a variety of configurations and decorative features. The sprinklers for fire protection are normally required to be tested or approved by an independent testing agency (UL or FM). Sprinklers may be installed with an open orifice (dry sprinklers) or provided with an element that contains the system water supply (wet sprinklers). Water is sprayed from the sprinkler once the heat from a fire causes a fusible element in the sprinkler head to melt. Once the element has melted it releases a tension mounted cap on the outlet of the sprinkler. The sprinkler outlet is connected to a water distribution pipe network. Water pressure in the pipe network directs water onto the sprinkler deflector, providing the water spray. (Nolan, 2000)

auxiliarized local system—a local system that is connected to the municipal alarm facilities.

auxiliarized proprietary system—a proprietary system that is connected to the municipal alarm facilities.

auxiliary protective signaling system—a connection to the municipal fire alarm system to transmit an alarm of fire to the municipal communication center. Fire alarms from an auxiliary center on the same equipment and by the same alerting methods as alarms transmitted from municipal fire alarm boxes located on streets.

back pressure—pressure against which a fluid is flowing, resulting from friction in lines, restrictions in pipes or valves, pressure in vessel to which fluid is flowing, hydrostatic head, or other impediment that causes resistance to fluid flow. (NFC Online Glossary)

Backdraft—limited ventilation during an enclosure fire can lead to the production of large amount of unburnt gases. When an opening is suddenly introduced, the inflowing air may mix with these, creating a combustible mixture of gases in some part of the enclosure. Any ignition sources, such as a flowing ember, can ignite this flammable mixture, resulting in an extremely rapid burning of the gases. Expansion due to the heat created by the combustion will expel the burning gases out through the opening and cause a fireball outside the enclosure. The phenomenon can be extremely hazardous. (NFC Online Glossary)

backfire arrester—a flame arrester installed in fully premixed air–fuel gas distribution piping to terminate flame propagation therein, shut off fuel supply, and relieve pressure resulting from a backfire. (NFC Online Glossary)

barrier —a part providing protection against direct contact from any usual direction of access. (IEC 50-826.) (NFC Online Glossary)

barrier failure—the breach of a fire barrier, by a fire or other cause, which could permit propagation of a fire or its combustion products across the barrier.

barrier material—a single-layer fabric or a laminated or coated, multilayer material considered as a single-layer fabric that limits transfer from the face of the layer to the other side.
(NFC Online Glossary)

barrier, smoke—a continuous membrane, or a membrane with discontinuities created by protected openings, where such membrane is designed and constructed to restrict the movement of smoke. (NFC Online Glossary)

barrier, thermal—a material that limits the average temperature rise of an unexposed surface to not more than 120 °C (250 °F) for a specified fire exposure complying with the standard time-temperature curve of NFPA 251, "Standard Methods of Tests of Fire Endurance of Building Construction and Materials". (NFC Online Glossary)

blackbody temperature—the temperature of a perfect radiator; a surface with an emissivity of unity and, therefore, a reflectivity of zero. (NFC Online Glossary)

blanketing (or padding)—a technique of maintaining an atmosphere that is either inert or fuel-enriched in the vapor space of a container or vessel. (NFC Online Glossary)

blast—a transient change in the gas density, pressure, and velocity of the air surrounding an explosion point. The initial change can be either discontinuous or gradual. A discontinuous change is referred to as a shock wave, and a gradual change is known as a pressure wave. Blast is also called pressure wave. (Nolan, 2000)

blast area—the area including the blast site and the immediate adjacent area within the influence of flying rock, missiles, and concussion. (NFC Online Glossary)

blast pressure front—the expanding leading edge of an explosion reaction that separates a major difference in pressure between normal ambient pressure ahead of the front and potentially damaging high pressure at and behind the front. (NFC Online Glossary)

blast site—the area where explosive material is handled during loading of the blasthole, including 15.3 m (50 ft) in all directions from the perimeter formed by loaded holes. A minimum of 9.15 m (30 ft) can replace the 15 m (50 ft) requirement if the perimeter for loaded holes is marked and separated from nonblast site areas by a barrier. The 15.3 m (50 ft) or 9.15 m (30 ft) distance requirements, as applicable, apply in all directions along the full depth of the blasthole. In underground mines, at least 4.6 m (15 ft) of a solid rib, pillar, or broken rock can be substituted for the 15.3 m (50 ft) distance. (NFC Online Glossary)

blasting agent—a material or mixture intended for blasting that meets the requirements of the DOT "Hazardous Materials Regulations," as set forth in Title 49, Code of Federal Regulations, Parts 173.56, 173.57, and 173.58, Explosive 1.5D. (NFC Online Glossary)

blaze—terminology for a free-burning fire characterized as spectacular in flame evolution.

Boiling Liquid Expanding Vapor Explosion (BLEVE) —a catastrophic rupture of a pressurized vessel containing a liquid at a temperature above its normal boiling point with the simultaneous ignition of the vaporizing fluid. A short-duration, intense fireball occurs if the liquid is flammable. During the rupture of the vessel, a pressure wave may be produced and fragments of the containment vessel will be thrown considerable distances. (Nolan, 2000) *boilover*—a phenomenon that can occur during a fire over an open tank containing a blend of flammable liquids, such as crude oil; water must be present at the bottom of the tank for boilover to occur. (Friedman, 1998)

boiling point—the maximum temperature at which a liquid can evaporate under normal; atmospheric conditions; equilibrium temperature for a liquid and its vapor to coexist at 1 atmosphere of pressure.

boiling point—the temperature at which the vapor pressure of a liquid equals the surrounding atmospheric pressure. For purposes of defining the boiling point, atmospheric pressure shall be considered to be 14.7 psia (760 mm Hg). For mixtures that do not have a constant boiling point, the 20 percent evaporated point of a distillation performed in accordance with ASTM D86, Standard Method of Test for Distillation of Petroleum Products, shall be considered to be the boiling point. (NFC Online Glossary)

bounding analysis—an analysis that intentionally makes use of methods and assumptions (e.g., those pertaining to parameters describing a hazard, a resulting initiating event, and a plant's resistance to the initiator) designed to result in an upper-bound or demonstrably conservative estimate of risk.

British Thermal Unit (Btu)—the quantity of heat required to raise the temperature of one pound of water -17 °C (1 °F) at the pressure of one atmosphere and the temperature of 60 °F (15.5 °C).
building characteristics—a set of data that provides a detailed description of a building, such as building layout (geometry), access and egress, construction, building materials, contents, building services, and fire safety (hardware) systems. (NFC Online Glossary)

building code—a set of requirements intended to ensure that an acceptable level of safety (including fire safety) is incorporated into a building at the time of construction.

building construction types—there are five general types of building construction classifications defined for fire protection purposes. They are classified according to their fire resistive properties. They include the following (Nolan, 2000):

- *fire resistive*—a broad range of structural systems capable of withstanding fires of specified intensity and duration without failure. Common fire-resistive components include masonry load- bearing walls, rein-forced concrete or protective steel columns, and poured or precast concrete floors and roofs (Ref. NFPA 220, Type I).
- *noncombustible*—type of structure made of noncombustible materials in lieu of fire-resistant materials. Steel beams, columns, and masonry or metal walls are used (Ref. NFPA 220, Type II).
- *ordinary*—consists of masonry exterior load-bearing walls that are of noncombustible construction. Interior framing, floors, and roofs are made of wood or other combustible materials, whose bulk is less than that needed to qualify as heavy-timber construction. If the floor and roof construction and their supports have a one-hour fire resistance rating and all openings through the floors (stairwells) are enclosed with partitions having a one-hour fire resistance rating, then the construction is classified as "protected ordinary construction" (Ref. NFPA 220, Type III).
- *heavy timber*—characterized by masonry walls, heavy-timber columns and beams, and heavy plank floors. Although not immune to fire, the large mass of the wooden members slows the rate of combustion. Heavy timber construction can be used where the smallest dimension of the members exceeds 5.5 in. (14 cm). When timbers are this large, they are charred but not consumed in a fire and are generally considered akin to a fire-resistant type of construction (Ref. NFPA 220, Type IV).
- *wood frame*—building construction characterized by use of wood exterior walls, partitions, floors, and roofs. Exterior walls may be sheathed with brick veneer, stucco, or metal-clad or asphalt siding (Ref. NFPA 220, Type V).

building occupancy—the primary activity for which a building is designed and built. Fire code requirements are based on the risk a building occupancy represents, and, therefore, various building occupancies are normally defined by a fire code. Common building occupancies include assembly, business, educational, factory or industrial, hazardous or high hazard, institutional, mercantile, residential, storage and utility, special, or miscellaneous. (Nolan, 2000)

building services—provisions, such as heating, plumbing, electrical and air handling systems, that render a building habitable.

burning rate—the combustion rate of a fuel, expressed either as the rate of mass consumption per unit exposed area.

burnout—point at which flames cease. (Nolan, 2000)

burning velocity—the speed with which a laminar flame moves in a direction normal to its surface, relative to the unburned portion of combustible gas mixture, at constant pressure. Its value depends on mixture composition, temperature, and pressure.

buoyancy—an effective force on fluid due to density or temperature differences in a gravitational field. (NFC Online Glossary)

burn injury—an injury to the skin and deeper tissues caused by hot liquids, flames, radiant heat, and direct contact with hot solids, caustic chemicals, electricity, or electromagnetic (nuclear) radiation. A first-degree burn injury occurs with a skin temperature of about 48 °C (118 °F), and a second-degree burn injury occurs with a skin temperature of 55 °C (131 °F). Instantaneous skin destruction occurs at 72 °C (162 °F). Inhaling hot air or gases can also burn the upper respiratory tract.

The severity of a burn depends on its depth, its extent, and the age of the victim. Burns are classified by depth as first, second, and third degree. First-degree burns cause redness and pain (sun-burn) and affect only the outer skin layer. Second-degree burns penetrate beneath the superficial skin layer and are marked by edema and blisters (scalding by hot liquid). In third-degree burns, both the epidermis and dermis are destroyed, and underlying tissue may also be damaged. It has a charred or white leathery appearance and initially there may be a loss of sensation to the area. The extent of a burn is expressed as the percent of total skin surface that is injured. Individuals less than 1 year old and over 40 years old have a higher mortality rate than those between 2 and 39 years old for burns of similar depth and extent. Inhalation of smoke from a fire also significantly increases mortality. Thermal destruction of the skin permits infection, which is the most common cause of death for extensively burned individuals. Body fluids and minerals are lost through the wound. The lungs, heart, liver, and kidneys may be affected by infection and fluid loss. First aid for most burns involves the application of cool water as soon as possible after the burn. Burns of 15-percent of the body surface or less are usually treated in hospital emergency rooms by removing dead tissue (debridement), dressing with antibiotic cream (often silver sulfadiazine), and administering oral pain medication. Burns of 15 to 25-percent of the body surface often require hospitalization to provide intravenous fluids and avoid complications. Burns of more than 25-percent of the body surface are usually treated in specialized burn centers. Aggressive surgical management is directed toward early skin grafting and avoidance of such complications as dehydration, pneumonia, kidney failure, and infection. Pain control with intravenous narcotics is frequently required. The markedly increased metabolic rate of severely burned patients requires high-protein nutritional supplements given intravenously and by mouth. Extensive scarring of deep burns may cause disfigurement and limitation of joint motion. Plastic surgery is often required to reduce the effects of the scars. Psychological problems often result from scarring. Investigations are underway to improve burn victims' nutritional support, enhance the immune response to infection, and grow skin from small donor sites in tissue culture to cover large wounds. Since over 50 percent of all burns are preventable (separation, barriers, protective clothing, etc.), safety programs can significantly reduce the incidence of burn injuries.
(Nolan, 2000)

cable failure—a breakdown in the physical and/or chemical properties (e.g., electrical continuity, insulation integrity) of cable conductor(s) such that the functional integrity of the electrical circuit can not be assured (e.g., interrupted or degraded).

cable jacket—a protective covering over the insulation, core, or sheath of a cable.
(IEEE Std.100-1988).

cable penetration—an assembly or group of assemblies for electrical conductors to enter and continue through a fire-rated structural wall, floor, or floor-ceiling assembly.
(IEEE Std. 100-1988).

cable routing—the pathway electrical wiring takes through the plant from power source or control point to component location.

cable-to-cable fault—a fault condition of relatively low impedance between conductors of one cable and conductors of a different cable.

cable tray fire break—a noncombustible or limited-combustible material used for vertical cable trays to limit fire spread.

carbon dioxide—colorless, odorless, electrically nonconductive inert gas that is a suitable medium for extinguishing Class B and Class C fires. Liquid carbon dioxide forms dry ice (snow) when released directly into the atmosphere. Carbon dioxide gas is 1½ times heavier than air. Carbon dioxide extinguishers fire by reducing the concentrations of oxygen, the vapor phase of the fuel, or both in the air to the point where combustion stops. (NFC Online Glossary)

C-factor—a relative roughness coefficient used in mathematical calculations of friction losses for water flow in pipes for fire protection systems when using the Hazen-Williams friction loss formula. C-factors are dependent on the smoothness of the internal surfaces of pipes and are features of the pipe material and system age. A high C factor (120) represents a smooth internal pipe and a low C-factor (80 or 90) is a rough internal pipe surface. The C- factor decreases as the level of friction within the pipe interior surface increases. When computerized hydraulic programs are used to determine water pressures and flow conditions within a water distribution system, the friction coefficients to use are specified as part of the input data. Common piping C factors used for fire protection applications include the following (Nolan, 2000):

- Unlined Cast or Ductile Iron - 100
- Asbestos Cement, Cement-Lined
- Cast or Ductile Iron, Cement-Lined
- Steel and Concrete - 140
- Polyethylene, Polyvinyl Chloride (PVC), and Fiberglass
- Epoxy-150 Copper - 150

calorimetry—the heat release rate for a fire is the most significant measure of the magnitude and destructive potential of a fire. The growth rate of the fire is determined by the burning rate characteristics of the fuel as well as the ignitability, flame spread, and geometry of the item. Given the significant complexities of the fire growth process, there is a need to be able to experimentally measure the heat release rate history of combustibles materials. The method for measuring heat release rates are collectively referred to as calorimetry.

While it is in principle to possible to measure the heat output of a fire by thermal means, early attempts to use thermal methods were generally unsatisfactory due to practical details of instrument design. Modern calorimeters makes use of the empirical fact that the heat released per unit of oxygen consumed is a constant, 13 kJ/g of oxygen. This direct relationship between oxygen consumption and heat release means that a measurement of oxygen depletion can be used to measure the heat release rate.

cavitation—formation of a partial vacuum (creating gas bubbles), in a liquid by a swiftly moving solid body (a propeller). Cavitation may occur in a firewater pumping system due to improper design, arrangement, or installation. The generation and collapse of the gas bubbles produce a vibration and sometimes severe mechanical strain on the pumping system, reducing performance and causing accelerated deterioration of the pumping components (especially the impeller). Specific design and installation requirements are set forth in NFPA 20, “Standard for the Installation of Stationary Pumps for Fire Protection,” to prevent cavitation from occurring in fixed fire-water pump installations.

ceiling jet—the radially outward flow under a ceiling resulting when a fire plume impinges on a ceiling. (Friedman, 1998)

cellulosic—a natural polymer $(C_6H_{10}O_5)_n$, which is a principle constituent of cotton, wood, and paper. (Friedman, 1998)

cellulosic fire—a fire with a fuel source com-position predominantly of cellulose (wood, paper, cotton, etc.). A fire involving these materials is relatively slow growing, although its intensity may ultimately reach or exceed that of a hydrocarbon fire. Standard building fire barriers are based on a cellulosic fire exposure as defined by ASTM E119, “Standard Test Methods for Fire Tests of Building Construction and Materials,”; ISO Standard No. 834; or BS 476 Part 20. Cellulosic fires reach a maximum temperature of just over 900 °C (1,652 °F).

central station system (or Central station firealarm system)—A fire alarm system controlled and operated by a designated business for fire alarm system operation and maintenance. All signals generated by the system report to a central station (office) and are acted upon as required. (Nolan, 2000)

Celsius temperature—a temperature scale on which pure water at sea level freezes at 0 °C and boils at 100 °C (212 °F). (Friedman, 1998)

char—the carbonaceous remains of burned materials.

charring—the production of a solid carbonaceous residue on heating or burning a solid.

circuit failure modes—open circuit - a condition that is experienced when an individual conductor within a cable loses electrical continuity.

- *short-to-ground*—a condition that is experienced when an individual conductor comes in electrical contract with a grounded conducting device, such as a cable tray, conduit , or metal housing.
- *hot short*—a condition that is experienced when individual conductors of the same or different cables come in contact with each other.

Class of fires (NFPA 10, 2002 Edition)—a letter designation given to a particular fire category for the purpose of generally classifying it accordance to the type if fuel and possible spread of fire.

- *Class A Fires*—fires in ordinary combustible materials, such as , wood, cloth, paper, rubber, and many plastics.
- *Class B Fires*—fires in flammable liquids, combustibles liquids, petroleum greases, tars, oils, oil-based paints, solvents, lacquers, alcohols, and flammable gases,.
- *Class C Fires*—fires that involve energized electrical equipment where the electrical non-conductivity of the extinguishing media is of importance. (When electrical equipment is de-energized, fire extinguishers foe Class A or Class B fires can be use safely).
- *Class D Fires*—fires in combustible metals, such as magnesium, titanium, zirconium, sodium, lithium, and potassium.
- *Class K Fires*—fires in cooking appliances that involve combustible cooking media (vegetable or animal oils and fats).

circuit—a conductor or system of conductors through which electrical current flows.
(IEEE Std.100-1988)

circuit—interconnection of components to provide an electrical path between two or more components.
circuit breaker—a device designed to open and close a circuit by nonautomatic means, and to open the circuit automatically on a predetermined overload of current without injury to itself when properly applied within its rating.
(IEEE Std 100-1988)

*circuit breake*r—a mechanical switching device capable of making, carrying and breaking currents under normal circuit conditions and also, making, carrying for a specified period of time, and breaking currents under specified abnormal circuit conditions such as those of short circuit.
(IEEE Std. 100-1988)

clean agent—a volatile or gaseous fire extinguishing agent that is not electrically conductive and does not leave any residue during or after its application following evaporation. Common clean agents include carbon dioxide, Halon, Inergen, and FM-200. Although Halon is considered a clean agent, it may contribute to the Earth's ozone depletion and therefore is considered environmentally harmful. (Nolan, 2000)

clean agent fire suppression system (CAFSS)—a fire suppression application system that utilizes a volatile or gaseous fire extinguishing agent that is not electrically conductive and does not leave any residue during or after its application following evaporation. (Nolan, 2000)

closed-circuit self-contained breathing apparatus (SCBA)—a recirculation-type SCBA in which the exhaled gas is rebreathed by the wearer after the carbon dioxide has been removed from the exhalation gas and the oxygen content within the system has been restored from sources such as compressed breathing air, chemical oxygen, liquid oxygen, or compressed gaseous oxygen.

code—comprehensive set of requirements intended to address fire safetyin a facility. Code may reference numerous standards.

code of record—the codes and standards refer to the edition of the code or standard in effect at the time of fire protection systems or features was designed or specifically committed to the authority having jurisdiction.

cold smoke—smoke that is produced from a smoldering fire. The fire itself does not generate adequate quantities of heat to produce a flaming fire. Cold smoke therefore lacks the buoyancy of smoke from a flaming fire because its low heat content does not generate a strong convection current. Cold smoke may be more difficult to detect by ceiling mounted smoke detectors due to its lack of buoyancy. (Nolan, 2000)

combustion—the burning of gas, liquid, or solid, in which the fuel is oxidized, evolving heat and often light. (McGraw-Hill)

combustion efficiency—the ratio of heat actually developed in a combustion process to the heat that would be released if the combustion were perfect. (McGraw-Hill)

combustible gas detector—an instrument designed to detect the presence or concentration of combustible gases or vapors in the atmosphere. It is usually calibrated to indicate the concentration of a gas as a percentage of its lower explosive limit (LEL) so that a reading of 100-percent indicates that the LEL has been reached. They use either a solid-state circuit, infrared (IR) beam, electrochemical, or dual catalytic bead for the detection of gas in an area. Portable monitors are used for personnel protection and fixed installations are provided for property protection.

combustible liquid—as generally defined, it is any liquid that has a closed-cup flash point at or above 100 °F (37.8 °C). Combustible liquids are classified as Class II or Class III, and flammable liquids are classified as IA, IB or IC. (NFPA 30)

- *Class II Liquid*—any liquid tested with a flash point at or above 37.8 °C (100°F) and below 60 °C (140°F).
- *Class III A*—any liquid tested with a flash point at or above 60 °C (140 °F), but below 93 °C (200 °F).
- *Class III B*—any liquid tested with a flash point at or above 93 °C (200 °F).

combustible liquid area-fixed—an area used for storage of Class II and Class III combustible liquids that is infrequently moved, and where the aggregate quantity present shall not exceed 5,000 gallon (18, 925 L). Handling of liquids incidental to transfer can take place within a storage area.
(NFC Online Glossary)

combustible liquid area-large—an area used for storage of Class II and Class III combustible liquids where the aggregate quantity present shall not exceed 1,000 gallon (3,785 L). Handling of liquids incidental to transfer can take place within a storage area. (NFC Online Glossary)

combustible liquid area-mobile—self-propelled or mobile equipment fitted with suitable containers or tanks and other related fixtures used for the storage, transport, and dispensing of Class II and Class III combustible liquids. The aggregate quantity of combustible liquid carried on such equipment shall not exceed 1,000 gallon (3,785 L). (NFC Online Glossary) *combustible liquid area-portable*—an area used for storage of Class II and Class III combustible liquids that is periodically moved, and where the aggregate quantity present shall not exceed 1,000 gallon (3,785 L). Handling of liquids incidental to transfer can take place within a storage area. (NFC Online Glossary)

combustible liquid area-small—an area used for storage of Class II and Class III combustible liquids that is periodically moved, and where the aggregate quantity present shall not exceed 60 gallon to 1,000 gallon (227 L to 3,785 L). Handling of liquids incidental to transfer can take place within a storage area. (NFC Online Glossary)

combustible material—any material that will burn or sustain the combustion process when ignited or otherwise exposed to fire conditions. (Regulatory Guide 1.189)

common enclosure—an enclosure (e.g., cable tray, conduit, junction box) that contains circuits required for the operation of safe shutdown components and circuits for non-safe shutdown components.

common-mode failure—multiple failures that are attributable to a common cause.
(IEEE Std. 100-1988.

common power supply/source—a power supply that feeds safe shutdown circuits and non-safe shutdown circuits (Regulatory Guide 1.189)

common path of travel—the portion of an exit access that building occupants must traverse before two distinct paths of travel or two exits are available. (NFC Online Glossary)

compartmentation—a type of building design in which a building is divided into sections that can be closed off from each other so that there is resistance to fire spread beyond the area of origin.

compartmentation—a fire protection strategy whereby a building is subdivided into compartments that are separated from one another by fire resistant barriers.

complete combustion—refers to the chemical reaction where all the product components are in their most stable state.

compressed breathing gas—a respirable gas mixture stored in a compressed state and supplied to the user in a gaseous form. (NFC Online Glossary)

compressed gas—any material or mixture having, when in its container, an absolute pressure exceeding 40 psia (an absolute pressure 276 kPa) at 21.1 °C (70 °F) or, regardless of the pressure at 21.1 °C (70 °F), having an absolute pressure exceeding 104 psia (an absolute pressure of 717 kPa) at 54.4 °C (130 °F). (NFC Online Glossary)

computer fire model—a computer fire model is normally realized as a computer program for predicting fire. This is most common, but not necessarily always true. A computer fire model, for example, could be realized as only a flowchart.

concentration—the percentage of material per unit mass (or volume) of its mixture.

conduction—the mode of heat transfer associated with solid in direct contact, or heat transfer due to molecular energy transfer following Fourier's Law.

conductor—a substance or body that allows a current of electricity to pass continuously along it. (IEEE Std. 100-1988)

conductor—a wire or combination of wires, not insulated from one another, suitable for carrying an electric current. (IEEE Std. 100-1988)

conductor-to-conductor fault—a circuit fault condition of relatively low impedance between two or more conductors of the same or different circuit.

conductor-to-conductor fault—a cable failure mode of relatively low impedance between two or more conductors of the same multi-conductor cable (Intra-cable fault) or between two or more separate cables (Inter-cable fault).

configuration factor—fraction of radiation received by a target compared to the total emitted by the source.

conflagration or mass fire—a fire over a large tract of land where generally the flames are much shorter than the horizontal extent of the fire.

construction joint—see seismic gap penetration seal.

contain a fire—to take suppression action that can reasonably be expected to check the fire spread under prevailing and predicted conditions.

control of burning—application of water spray to equipment or areas where a fire can occur to control the rate of burning and thereby limit the heat release from a fire until the fuel can be eliminated or extinguishment effects.

control cable—cable applied at relatively low current levels or used for intermittent operation to change the operating status of a utilization device of the plant auxiliary system.
(IEEE Std. 100-1988)

control circuit—the circuit that carries the electrical signals directing the performance of the controller but does not carry the main power circuit (IEEE Std. 100-1988).

control panel—an assembly of man/machine interface devices (IEEE Std. 100-1988).

control power/voltage—the voltage applied to the operating mechanism of a device to actuate it. (IEEE Std. 100-1988)

control-power transformer—a transformer which supplies power to motors, relays, and other devices used for control purposes. (IEEE Std. 100-1988)

control a fire—to complete a control line around a fire, any spot fire therefrom, or any interior island to be saved; to burn out any unburned area adjacent to the fire side of the control line and cool down all hot spots that are an immediate threat to the control line.(NFC Online Glossary) *convection*—the heat transfer associated with fluid movement around the heated body. Warmer, less dense fluid rises and is replaced by cooler, more dense fluid. Convection current rise during a fire event due to heat transfer to the surrounding air, causing it to rise and allow cooler air to enter the fire environment at the base of the fire.

convective heat—energy that is carried by a hot moving fluid.

convective heat transfer coefficient—a quantity that represent the ability of heat to be transformed from a moving fluid to a solid surface expressed in terms of heat flux per unit temperature difference.

consequences—consequences are expected effects from the realization of the hazard and severity, usually measured in terms of property damage, business interruption, life safety exposure, environmental impact, company image etc.

corrosion-resistant material—materials such as brass, copper, monel, stainless steel, or other equivalent corrosion-resistant materials. (NFC Online Glossary)

cracking—pyrolysis; breaking gaseous molecules into other molecules.

credited shutdown equipment—the set of equipment that is relied on (credited in the SSA) for achieving post-fire safe shutdown conditions in the event of fire in a specific fire area.

creep—the high temperatures [over 500 °C (1,000 °F)] reached during fire greatly accelerate the creep strain rate (gradual degradation) in a building element. Although this time-dependent strain is important in all building elements, its effects are critical in the case of tension loads in structural steel members are reinforcing steel. The influence of creep strain on elements should be considered in all but the most gross estimates of fire resistance. An increase in creep strain rate will have the net effect of increased deformation. In general, the stress relief provided by increased creep strain may preclude catastrophic failures in steel beams.

critical heat flux—a threshold level of heating below which ignition (or in other context, flame spread) is not possible.

critical temperature—the temperature at which a structural metal (such as steel) softens when heated and can no longer support load. It is usually below its melting temperature.

cross-linked polymer—a polymer in which the long chains are bonded to one another at intermediate points. Cross-linked reduces flexibility and tendency to melt, and increase the tendency to form char on heating. (Friedman, 1998)

cross-zoning—a method of fire detection whereby adjacent fire detectors are connected to different sensing circuits to the fire alarm control panel. Confirmed fire detection is only achieved if two detectors are activated, one from each of the separate alarm circuits. Cross-zoning is used primarily as a deterrent against false alarms and in particular where a fixed fire suppression system (such as a CO_2 system) is arranged to automatically discharge upon fire detection to avoid accidental release of the suppression gas. It may also be referred to as a voting system.
(Nolan, 2000)

cross-zone analysis—the analysis of a potential fire scenario involving fire propagation between adjacent fire zones.

cryogenic gas—a refrigerated, liquid gas having a boiling point below -90 °C (-130 °F) at atmospheric pressure. (NFC Online Glossary)

current licensing basis (CLB)—the set of NRC requirements applicable to a specific plant and a licensee's written commitments for ensuring compliance with and operation within applicable NRC requirements and the plant-specific design basis (including all modifications and additions to such commitments over the life of the license) that are docketed and in effect. The CLB includes the NRC regulations contained in 10 CFR Parts 2, 19, 20, 21, 26, 30, 40, 50, 51, 54, 55, 70, 72, 73, 100 and appendices thereto; orders; license conditions; exemptions; and technical specifications. It also includes the plant-specific design-basis information defined in 10 CFR 50.2 as documented in the most recent final safety analysis report (FSAR) as required by 10 CFR 50.71 and the licensee's commitments remaining in effect that were made in docketed licensing correspondence such as licensee responses to NRC bulletins, generic letters, and enforcement actions, as well as licensee commitments documented in NRC safety evaluations or licensee event reports. (10 CFR 54.3) *See also:* Regulatory Guide 1.189.

curtain wall—an exterior wall non-load bearing prefabricated wall, usually more than one story high supported by the structural frame, which protects the building’s interior from weather, noise, or fire.

damper, fire—a device (damper) arranged to seal off airflow automatically through part of an air distribution system to resist the passage of heat and flame. It is usually an assembly of louvers arranged to close from the heat of a fire by melting a fusible link or through a remote activation signal. Fire dampers are required by all building codes to maintain the required level of fire resistance rating for walls, partitions, and floors when they are penetrated by air ducts or other ventilation openings. There are two significant ratings when applying a fire damper; the fire resistance rating and the airflow closure rating. The fire rating is dependent on meeting the fire resistant rating of the fire barrier being penetrated by the airflow duct and the airflow rating is either static or dynamic, depending on whether the air flow is automatically shut down upon fire detection. (NFC Online Glossary)

damper, smoke—a damper arranged to restrict the spread of smoke in a heating, ventilation and air conditioning (HVAC) air duct system. It is designed to automatically shut off air movement in the event of a fire. It is usually applied in a Passive Smoke Control System or as part of an Engineered Smoke Control System to control the movement of smoke within a building when the HVAC is operational in an engineered smoke control system. HVAC control fans are used to create pressure differences in conjunction with fixed barriers (walls and floors). Higher pressures surround the fire area and prevent the spread of smoke from the fire zone into other areas of the building. A smoke damper also can be a standard louvered damper serving other control functions, provided the location lends itself to the dual purpose. A smoke damper is not required to meet all the design functions of a fire damper. Smoke dampers are classified according to leakage rates: Class 1 (lowest), 2, 3, and 4 (highest); elevated temperature 250 °F (121 °C), 350 °F (177 °C) or higher; and prescribed pressure and velocity differences at the damper (specific velocity of airflow when open and to close against a specific pressure differential). (NFC Online Glossary)

dead end—a corridor, hallway, or passageway open to a corridor that can be entered from the exit access without passage through a door, but which does not lead to an exit.

dedicated smoke control systems—systems that are intended for the purpose of smoke control only. They are separate systems of air moving and distribution equipment that do not function under normal building operating conditions. Upon activation, these systems operate specifically to perform the smoke control function.

dedicated shutdown—the ability to shut down the reactor and maintain shutdown conditions using structures, systems, or components dedicated to the purpose of accomplishing post-fire safe shutdown functions. (Regulatory Guide 1.189)

deep-seated fire—a deep-seated fire occurs when the burning solid material (e.g., cable) is not just a surface burning phenomena but pyrolysing beneath the surface. This is postulated to occur when the cable fire has reached the stage of a fully developed fire. Extinguishment of a surface does not guarantee a deep-seated fire may also be eliminated. Extinguishment of deep-seated fires requires an individual to investigate the interior of a material once the surface fire has been extinguished to determine if interior extinguishment has also been accomplished. If a deep-seated fire in an enclosed area is to be extinguished by a gaseous agent, the period of agent concentration has to be adequate to ensure suppression has been accomplished.

deep-seated fire—a deep-seated fire may become established beneath the surface of fibrous or particulate material. This condition may result from flaming combustion at the surface or from the ignition within the mass of fuel. Smoldering combustion then progresses slowly through the mass. A fire of this kind is referred to in this standard as a “deep-seated” fire. The burning rate of these fires can be reduced by the presence of Halon 1301, and they may be extinguished if a high concentration can be maintained for an adequate soaking time. However, it is not normally practical to maintain a sufficient concentration of Halon 1301 for a sufficient time to extinguish deep-seated fires.

defense-in-depth—a principle aimed at providing a high degree of fire protection by achieving a balance of (a) preventing fores from starting (b) detecting fires quickly and suppressing those fires that occur, thereby limiting damage; and (c) designing the plant to limit the consequences of fire to life, property, environment, continuity of plant operation, and safe shutdown capability. It is recognized that, independently, no one of these items is complete in itself. Strengthening any item can compensate for weaknesses, known or unknown, in the other items.

deflagration—mechanism for the propagation of an explosion reaction through a flammable gas mixture that is thermal in nature. The velocity of the reaction is always less than the speed of sound in the mixture but is capable of causing damage. A deflagration is possible if a gases concentration rises above its lower flammability limit (LFL). (Nolan, 2000)

deflagration pressure containment—the technique of specifying the design pressure of a vessel and its appurtenances so they are capable of withstanding the maximum pressure resulting from an internal deflagration. (Nolan, 2000)

deflagration suppression—the technique of detecting and arresting combustion in a confined space while the combustion is still in its incipient stage, thus preventing the development of pressure that could result in an explosion. (Nolan, 2000)

deluge—the immediate release of a commodity, usually referring to a water spray release for fire suppression purposes. (Nolan, 2000) *deluge sprinkler system*—a system that uses open sprinklers or nozzles so that all flow water is discharged when the deluge valve actuates.

deluge water mist system—water mist system with open nozzles that discharge water mist simultaneously from all nozzles on the system.

density—the property of a substance which is expressed by the ratio of its mass to its volume.

design fire curve—an engineering description of the development of a fire for use in a design fire scenario. Design fire curves might be described in terms of heat release rate versus time.

design fire scenario—a set of conditions that defines or describe the critical factors for determining outcomes of trial designs.

detonation—propagation of a combustion zone at a velocity that is greater than the speed of sound in the un-reacted medium. (NFC Online Glossary)

developing fire—the early stage of growth (in a compartment fire) before flashover and full involvement.

diffusion—process of species transport in a mixture from its high to low concentration.

diffusion flame—a flame in which the fuel and oxygen are transported (diffused) from opposite sides of the reaction zone (flame). (Nolan, 2000)

dimensionless—having no units of measure (terms combine to produce no units).

draft curtains—barriers suspended from the roof of a structure to limit the spread of smoke.

dry chemicals—a power composed of very small particles, usually sodium bicarbonate, potassium bicarbonate, or ammonium phosphate-based with added particulate supplemented by special treatment to provide resistance to packing, resistance to moisture absorption (caking), and the proper flow capabilities. (NFC Online Glossary)

Early Suppression Fast Response (ESFR) sprinkler—an automatic fire sprinkler designed to activate quickly from fire conditions. ESFR sprinklers have a thermal element with a response time index (RTI) of 50 $(\text{meters-seconds})^{1/2}$ or less. Standard sprinklers have a thermal element with an RTI of 80 $(\text{meters-seconds})^{1/2}$ or more. ESFR sprinklers are used for special high hazard applications. Large drop ESFR sprinklers are specifically designed for wet pipe sprinkler systems protecting high-piled storage commodity applications. They were developed by the Factory Mutual Research Corporation (FMRC) in the late 1970s and early 1980s. (Nolan, 2000)

egress—a way out or exit. (NFC Online Glossary)

electrical fire—a fire involving energized electrical equipment. They are usually propagated by electrical short circuits, faults, arcs, and sparks, and the equipment remains energized during the fire event. Due to the possibility of electrical shock, nonconductive extinguishing agents, Class C (carbon dioxide), must be used for fire control and suppression efforts. When the equipment is de-energized, Class A or B extinguishing agents may be used. (Nolan, 2000) *ember*—a particle of solid material that emits radiant energy due to its temperature or the process of combustion on its surface. (NFC Online Glossary)

emergency voice/alarm communication system—a system that provides dedicated manual or automatic, or both, facilities for originating and distributing voice instructions, as well as alert and evacuation signals pertaining to a fire emergency to the occupants of a building.
(NFC Online Glossary)

emissivity—the ratio of radiant energy emitted by a surface to that emitted by a black body of the same temperature (the property (0 to 1) that gives the fraction of being a perfect radiator).

emissive power—the total radiative power discharged from the surface of a fire per unit area (also referred to as surface emissive power).

emissive power—the rate at which radiant energy is emitted by unit surface area of an object.

energy—a state of matter representative of its ability to do work or transfer heat.

energy balance—three modes of heat transfer (i.e., conduction, convection, and radiation) can be combined by adding gains and losses to determine the temperature at some point. This combination of energy gains and energy losses is called an energy balance. The exact form of the energy balance will differ for each situation evaluated.

entrainment—the process of air or gases being drawn into a fire, plume, or jet.

equivalent length—a length of pipe of a given diameter whose friction loss is equivalent to the friction loss of a pipe of differing diameter.

equivalent fitting length—a length of straight pipe that has the same friction loss as a fitting where the water changes direction.

evaporation—the process of gas molecules escaping from the surface of a liquid.

exit—the portion of the means of egress that leads from the interior of a building or structure to the outside at ground level, or an area of refuge. (NFC Online Glossary)

exit access—any portion of an evacuation path that leads to an exit. (NFC Online Glossary)

exit discharge—that portion of a means of egress between the termination of the exit and the exterior of the building at ground level. (NFC Online Glossary)

explosion—a sudden violent expansion or production of gases which may be accompanied by heat, shock waves, and the disruption or enclosing of nearby structural materials.

exposed (cables/circuits /equipment/structures)—structures, systems and components (SSCs), that are subject to the effects of fire and/or fire suppression activities.

exposed (cables/circuits/equipment/structures)—SSC not provided with fire protection features sufficient to satisfy Section III.G.2 of Appendix R or Position C.5.b of SRP 9.5.1.

exposure fire—a fire in a given area that involves either in situ or transient combustibles and is external to any structures, systems, and components located in or adjacent to that same area. The effects of such fire (e.g., smoke, heat, or ignition) can adversely affect those structures, systems, and components important to safety. Thus, a fire involving one success path of safe shutdown equipment may constitute an exposure fire for the redundant success path located in the same area, and a fire involving combustibles other than either redundant success path may constitute an exposure fire to both redundant trains in the same area. (Regulatory Guide 1.189)

exposure hazard—a structure at a location (15.24 m (50 ft) of another building and 9.3 m^2 (100 ft^2) or larger in area.

extinguish—to cause a material to cease burning; to completely control a fire so that no abnormal heat of smoke remains, or to cause to cease burning, or completely put out a fire. (Nolan, 2000)

extinguish—to cause a material to cease burning; to completely control a fire so that no abnormal heat or smoke remains. Fire extinguishment may be obtained by several methods: cooling, oxygen depletion or removal, inhibition of chemical reaction, and flame removal (blowout).

extinguisher rating—the numerical rating given to an extinguisher which indicates the extinguishing potential of the unit based on standardized tests developed by Underwriters' Laboratories, Inc.

Extra large orifice (ELO) sprinkler—a fire suppression sprinkler for automatic sprinkler systems that has an orifice size of 0.675 in. (1.59 cm). Standard sprinklers have an orifice size of 0.5 in. (1.27 cm). ELO sprinklers are used for hazards requiring a higher density of water application such as those with a high fuel loading. (Nolan, 2000)

failsafe circuits—circuits designed in such a way that fire-induced faults will result in logic actuation(s) to a desired, safe, mode which can not be overridden by any subsequent circuit failures.

failure mode—the action of a device or system to revert to a specified state upon failure of the utility power source that normally activates or controls the device or system. Failure modes are normally specified as fail open (FO), fail closed (FC), or fail steady (FS) which will result is a fail to danger arrangement.

fault—any undesired state of a component or system. A fault does not necessarily require failure (for example, a pump may not start when required because its feeder breaker was inadvertently left open. (IEEE Std. 100-1988)

fault—a partial or total local failure in the insulation or continuity of a conductor.
(IEEE Std. 100-1988)

fault—a physical condition that causes a device, a component or an element to fail to perform in a required manner, for example a short-circuit, a broken wire, an intermittent connection.
(IEEE Std.100-1988)

fault current—a current that flows from one conductor to ground or another conductor owing to an abnormal connection (including an arc) between the two. (IEEE Std. 100-1988)

fault current—a current that results from the loss of insulation between conductors or between a conductor and ground. (NEMA Std. ICS-1, 1988)

fire—the process of an advancing fire front: smoldering or flaming or an uncontrolled chemical reaction producing light and sufficient energy.

fire—a processing entailing rapid oxidative, exothermic reactions in which part of the released energy sustains the process.

fire—a rapid oxidation process with the evoluation of light and heat in varying intensities.
(NFC Online Glossary)

firebrand—a flaming or smoldering airborne object emerging from a fire, which can sometimes ignite remote combustibles.

fire area—the portion of a building or plant that is separated from other areas by rated fire barriers adequate for the fire hazards. (Regulatory Guide 1.189)

fire area boundaries—the term “fire area” as used in Appendix R means an area sufficiently bounded to withstand the hazards associated with the area and, as necessary, to protect important equipment within the area from a fire outside the area. In order to meet the regulation, fire area boundaries need not be completely sealed floor-to-ceiling, wall-to-wall boundaries. However, all unsealed openings should be identified and considered the evaluating the effectiveness of the overall barrier. Where fire area boundaries are not wall-to-wall, floor-to-ceiling boundaries with all penetrations sealed to the fire rating required of the boundaries, licensees must perform an evaluation to assess the adequacy of fire boundaries in their plants to determine if the boundaries will withstand the hazards associated with the area. This analysis must be performed by at least a fire protection engineer and, if required, a systems engineer.
(Generic Letter 86-10)

fire ball—a burning fuel-air cloud whose energy is emitted primarily in the form or radiant heat. The inner core of the cloud consists almost completely of fuel, whereas the outer layer (where ignition first occurs) consists of a flammable fuel-air mixture. As the buoyancy forces of hot gases increases, the burning cloud tends to rise, expand, and assume a spherical shape.

fire barrier—components of construction (wall, floor, and their supports), including beams, joists, columns, penetration seals or closures, fire doors, and fire dampers that are rated by approving laboratories in hours of resistance to fire, that are used top prevent the spread of fire.

fire characteristics—a set of data that provides a description of a fire.

fire control—limiting the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage. (NFC Online Glossary) *fire control*—the stage is firefighting whereby a fire incident is controlled and not allowed to escalate in magnitude. Following fire control, suppression or extinction of the fire incident will occur. Fire control limits the growth of a fire by pre-wetting adjacent combustibles and controlling ceiling gas temperatures to prevent structural damage.

fire department connection—device that allows the fire department to pump water into a fire a fire protection system from their trucks.

fire dynamics—fire dynamics is the scientific description of fire phenomena (e.g., ignition, flame spread, burning, smoke spread) in quantitative terms. It encompasses chemistry, physics, mathematics, fluid mechanics as well as heat and mass transfer.

fire dynamics—the interaction among the complex phenomena involved in a building fire.

fire endurance—the length of time that a structural element can resist fire either up to the point of collapse, or alternatively, to the point when the deflection reaches a limiting value. (Nolan, 2000)

fire extinguishment—the complete suppression of a fire until there are no burning combustibles material. (NFC Online Glossary)

fire extinguisher rating—a rating set forth in NFPA 10, Standard for Portable Fire Extinguishers. This rating is identified on an extinguisher by number (e.g., 5, 20, 70), indicating relative effectiveness, followed by a letter (e.g., A, B, C, or D) indicating the class or classes of fires for which the extinguisher has been found to be effective. (NFC Online Glossary)

fire-fighting foam—a fire fighting medium that is created by adding a foaming agent to a liquid (usually water).

fire growth potential—the potential size or intensity of a fire over a period of time based on the available fuel and the fire's configuration. (NFC Online Glossary)

fire growth rat—rate of change of the heat release rate. Some factors that affect the fire growth rate are exposure, geometry, flame spread, and fire barrier. (NFC Online Glossary)

fire hazard—the existence of conditions that involve the necessary elements to initiate and support combustion, including in situ or transient combustible materials, ignition sources (e.g., heat, sparks, open flame), and an oxygen environment.

fire hazard analysis—an analysis used to evaluate the capability of a nuclear power plant to perform safe shutdown functions and minimize radioactive releases to the environment in the event of a fire. The analysis includes the following features (Regulatory Guide 1.189):

- Identification of fixed and transient fire hazards.
- Identification and evaluation of fire prevention and protection measures relative to the identified hazards.
- Evaluation of the impact of fire in any plant area on the ability to safely shutdown the reactor and maintain shutdown conditions, as well as to minimize and control the release of radioactive material.

fire hazard analysis—a comprehensive assessment of the potential for a fire at any location to ensure that the possibility of injury to people or damage to buildings, equipment, or the environment is within acceptable limits. (NFC Online Glossary)

fire hydraulic—term for the science or study of water in motion (fluid mechanics) as applied to fire protection application (firefighting, fire suppression, fixed water-based suppression systems etc.)

fire hydrant—a device that provides a water supply to fire department pumpers for use in combating structure fires.

fire growth rate—the periodic increase in a fire, dependent on the ignition process, flame spread, and mass burning rate over the area involved.

fire-induced fault—an electrical failure mode (e.g., hot short, open circuit, or short to ground) that may result from circuit/cable exposure to the effects of fire (e.g., heat and smoke) and/or subsequent fire suppression activities (e.g., water spray, hose streams).

fire-induced vulnerability evaluation (FIVE)—five is a semi-quantitative method of fire risk and hazard analysis for screening purposes. The methodology has been used to perform risk-based fire-induced vulnerability evaluations for NPPs. This technique was developed by the Electric Power Research Institute (EPRI) under the guidance of the Severe Accident Working Group of the Nuclear Management and Resources Council (NUMARC) and the industry's experts, for the purpose of addressing the fire portion of licensee's Individual Plant Examination of External Events (IPEEE) studies.

fire load—the fire load for an enclosure is a measure of the total energy released by the combustion of all combustible materials in the enclosure. It is assigned the symbol W, and is given in joules (J).

fire loading—the amount of combustible present in a given area, expressed in kJ/m^2 (Btu/ft^2). (NFC Online Glossary)

fire load density—the fire load density is the fire load per unit area. The fire load density is assigned the symbol Q" and is given in J/m^2. Some times the fire load is given is per unit floor area of the enclosure or some times in terms of the total enclosure surface area.

fire model—a physical or mathematical procedure that incorporates engineering and scientific principles in the analysis of fire and fire effects to simulate or predict fire characteristics and conditions of the fire environment.

fire modeling—fire modeling can normally be considered as the predication of fire characteristics by the use of a mathematical method which is expressed as a computer program.

fire performance—the response of a material or product to a source of heat or flame under controlled fire conditions. Fire performance includes: ease of ignition, flame spread, smoke generation, fire resistance and toxicity of smoke.

fire plume—a buoyant column of fire gases and smoke rising above, usually with flames in the lower portion. In a confined area a fire plume rises almost vertically. In an outside, unconfined area the configuration of a fire plume is affected by ambient conditions (wind, temperature etc.)

fire point—the minimum temperature to which a liquid must be heated in a standardized apparatus, so that sustained combustion results when a small pilot flame is applied, as long as the liquid is at normal atmospheric pressure.

fire point—the lowest temperature at which flaming can be sustained at the liquid's surface.

fireproofing—a common industry term used to denote materials or methods of construction that provide fire resistance for a defined fire exposure and specific time.

fireproof—common trade name for materials used to provide resistance to a fire exposure. Essentially nothing is fireproof, but some materials are resistant to effects of fire (heat flame etc.) for limited periods.

fire prevention code—a set of requirements intended to ensure that, following construction, building, buildings are equipped, operated and maintained to provide an acceptable level of protection from potential hazards created by fires or explosions.

fire prevention research engineer—conducts research to determine cause and methods of preventing fires and prepares educational materials concerning fire prevention for insurance companies, performing duties as described under Research Engineer. ("Dictionary of Occupational Titles," Volume 1, 14th Edition, U.S. Department of Labor Employment and Training Administration, 1991.)

fire protection engineer—advises and assists private and public organization and military services for purpose of safeguarding life and property against fire, explosion, and related hazards. Make studies of industrial, mercantile. And public buildings, homes, and other property before and after construction, considering factors, such as fire resistance of construction, usage or contents of buildings, water supplies and water delivery, and egress facilities. Designs or recommends materials or equipment, such as structural components protection, fire detection equipment, alarm systems, fire extinguishing devices and systems, and advises on location, handling, installation, and maintenance. Recommends materials, equipment, or methods for alleviation of conditions conductive to fire. Devices fire protection programs, and organizes and trains personnel to carry out such programs. May evaluate fire departments and adequacy of laws, ordinances, and regulations affecting fire prevention or fire safety. Conducts research and test on fire retardants and fire safety of materials and devices and to determine fire causes and methods of fire prevention. May determine fire causes and methods of fire prevention. May teach courses on fire prevention and protection at accredited educational institutions. May advise and plan for prevention of destruction by fire, wind, water, or other causes of damage. ("Dictionary of Occupational Titles," Volume 1, 14th Edition, U.S. Department of Labor Employment and Training Administration, 1991.)

fire protection rating—a designation of fire resistance duration for a material or assembly when exposed to standard test conditions, having met all acceptance criteria. (Nolan, 2000) *fire resistance*—the ability of an element of building construction, component, or structure to fulfill, for a stated period of time, the required load-bearing functions, integrity, thermal insulation, or other expected duty specified in a standard fire-resistance test.

fire resistive construction—construction in which the structural members, including walls, columns, floors, and roofs are noncombustible or limited-combustible materials, and have fire resistance rating not less than those specified in NFPA 220; fire resistive construction has more ability to resist structural damage from fire than any other construction type.

fire-retardant coating—a coating that reduces that flame spread of combustible materials surfaces to which it is applied, by at least 50 percent or to a flame spread classification value of 75 or less, whichever is the lesser value, and smoke developed rating not exceeding 200. (Nolan, 2000)

fire-retardant material—means materials that has been coated or treated with chemical, paints, or other materials that designed to reduce the combustibility of the treated material. The retardants are intended to make the material ignite less readily or burn more slowly, once ignited.

fire risk—refers to the combination of the probability of a given fire event occurring and the estimated consequences of the event should it occur. (Regulatory Guide 1.189)

fire-rated cable—electrical cable with a fire resistance rating on maintaining functionality when exposed to fire tests.

fire-resistant cable—electrical cable that has been tested and found resistant to the spread of flames.

fire resistance rating —the time that a particular construction will withstand a standard fire exposure in hours as determined by ASTM E119.

fire resistance rating—the time that materials or assemblies have withstood a fire exposure as established in accordance with the test procedures of NFPA 251 and ASTM E119.
(Regulatory Guide 1.189)

fire-resistive joint system—see seismic gap penetration seal.

fire pump—a device that provides the required water flow and pressure for a fire protection system.

fire scenario—a set of conditions that defines the development of fire and the spread of combustion products throughout a building or part of a building.

fire separation—a fire-resistive barrier to restrict the spread of fire, provided in a horizontal or vertical orientation.

fire severity—the maximum effects that can be caused by a fire event. Usually described in terms of temperature and duration, and may be used to described the potential for fire destruction for a particular location. The rate of heat release has also been accepted as a guide of fire severity.
(Nolan, 2000)

fire signature—a property of fire (temperature, smoke concentration, etc.) that is used to detect the presence of fire.

fire spread—the process of an advancing flame front through smoldering or flaming.

fire stop—a feature to the construction that prevents fire propagation along the length of cables or prevents spreading of fire to nearby combustibles within a given fire area or fire zone.

fire suppression—control and extinguishing of fire (fire-fighting). Manual fire suppression is the use of hoses, portable extinguishers, or manually actuated fixed systems by plant personnel. Automatic fire suppression is the use of automatically actuated systems such as water, Halon, or carbon dioxide systems (Regulatory Guide 1.189). Firefighting activity concerned with controlling and reducing a fire prior to its actual extinguishment. Fire suppression is generally taken as the sharp reduction of the rate of heat release of a fire and the prevention of its growth. Fire extinguishment activities encompass the actual direct fire extinction process.

fire suppression—all the work of confining and extinguishing wildland fires.
(NFC Online Glossary)

fire suppression—sharply reducing the heat release rate of a fire and preventing its regrowth by means of direct and sufficient application of water through the fire plume to the burning fuel surface. (NFC Online Glossary)

fire suppression—the activities involved in controlling and extinguishing fires. Fire suppression shall include all activities performed at the scene of a fire incident or training exercise that expose fire department members to the dangers of heat, flame, smoke, and other products of combustion, explosion, or structural collapse. (NFC Online Glossary)

fire suppression—control and extinguishing of fires (firefighting). Manual fire suppression employs the use of hoses, portable extinguishers, or manually actuated fixed systems by plant personnel. Automatic fire suppression is the use of automatically actuated fixed systems such as water, Halon, or carbon dioxide systems. (Regulatory Guide 1.189).

fire suppression—actions taken with the intend to control the growth of a fire.

fire suppression impacts—the susceptibility of structures, systems and components and operations response to suppressant damage (due to discharge or rupture) (NFPA 805).

fire triangle—a concept describing fire as consisting of three ingredients: fuel, oxygen, and energy.

fire tetrahedron—a schematic representation of fire in which the four elements required to initiate and maintain fire (fuel, oxidant, heat and chain reactions) are depicted as the four corners of a tetrahedron.

fire watch—individuals responsible for providing additional (e.g., during hot work) or compensatory (e.g., for system impairments) coverage of plant activities or areas for the purposes of detecting fires or for identifying activities and conditions that present fire hazard. The individuals should be trained in identifying conditions or activities that present potential fire hazards, as well as the use of fire extinguishers and the proper notification procedures. (Regulatory Guide 1.189) *fire zones*—a subdivisions of fire areas (Regulatory Guide 1.189)

fixed fire suppression system—a total flooding or local application system consisting of a fixed supply of extinguishing agent permanently connected for fixed agent distribution to fixed nozzles that are arranged to discharged an extinguishing agent in an enclosure (total flooding), directly onto a hazard (local application), or a combination of both; or an automatic sprinkler system. (NFC Online Glossary)

fixed fire suppression system—a fire suppression system that provides local application, area coverage, or total flooding protection. It consists of a fixed supply of extinguishing agent, permanently connected distribution piping, and fixed nozzles that are arranged to discharge an extinguishing agent into an enclosure (total flooding), directly onto a hazard (local application), over an entire area (area coverage), or a combination of application.

FIVE—a fire-induced vulnerability evaluation - a quantitative screening technique sponsored by EPRI under the guidance of the Severe Accident Working Group of the Nuclear Management and Resources Council (NUMARC) and the industry's experts, for the purpose of addressing the fire portion of licensees' IPEEE studies.

fire PRA methodology—the set of procedures, based on probabilistic risk analysis, for estimating core damage frequency due to fire events.

fire zones—subdivisions of fire areas.

flare—a flame condition of a fire in which burning occurs with an unsteady flame.

flame arrester—a device installed in a pipe or duct to prevent the passage of smoke.

flame arrester—a device that prevents the transmission of a flame through a flammable gas/air mixture by quenching the flame on the surface of an array of small passages through which the flame must pass. The emerging gases are sufficiently cooled to prevent ignition on the protected side. (NFC Online Glossary)

flame burning velocity—the burning velocity of a laminar flame under stated conditions of composition, temperature, and pressure of the unburned gas. (NFC Online Glossary)

flame detector—a detector that is activated by electromagnetic radiation emitted by flames.

flame height—the vertical measurement of the combustion region.

flame speed—the speed of a flame front relative to a fixed reference point. It is dependent on the turbulence, the equipment geometry, and the fundamental burning velocity.

flame spread—the increase in the perimeter of a fire. Flame spread depends on orientation and the surrounding fluid flow. It can be associated with solids, liquids, forest fuels, smoldering, and gas-phase propagation for premixed systems. Flame spread is influenced by gravity (flame buoyancy) and wind effects. Relative flame spread speeds are indicated below (Nolan, 2000):

Phenomenon	**Speed (cm/sec)**
smoldering	10^{-3} to 10^{-2}
downward or horizontal spread (thick solids)	10^{-1}
upward spread (thick solids)	1 to10^{2}
wind-driven spread through forest debris	1 to 30
horizontal spread on liquids	1 to 10^{2}
laminar deflagration	10 to 10^{2}
detonation	$\sim 10^{5}$

flame spread index—a relative performance of fire travel over the surface of a material when tested in accordance with the provisions of NFPA 255, Standard method of Test of Surface Burning Characteristics of Building Materials. (Nolan, 2000)

flame spread rating—flame spread rating is a numerical classification determined by the test method ASTM E84, which indexes the relative burning behavior of a material by quantifying the spread of flame of at test specimen. The surface burning characteristic of a material is not a measure of resistance to fire exposure. (NFC Online Glossary)

flammable limits—the minimum and maximum concentration of combustible material in a homogeneous mixture with a gaseous oxidizer that will propagate a flame.

flammable—capable of being ignited.

flammable liquid—as defined by the most fire safety codes (NFPA 30, "Flammable Combustible Liquids Code"), generally a flammable liquid is any liquid that has a closed-cup flash point below 37.8 °C (100 °F). Flash points are determined by procedures and apparatus set fort in ASTM D56, "Standard Method of Test for Flash Point by the Tag Closed Tester."

- *Class I Flammable Liquid*—any liquid that has a defined closed-cup flash point below 37.8 °C (100 °F) and a Reid vapor pressure not exceeding 40 psi (2,068.6 mm Hg) at 37.8 °C (100 °F), as determined by the ASTM D323, "Standard Method of Test for Vapor Pressure of Petroleum Products (Reid Method)".
- Class I liquids are further sub-classified into A and B as follows:
- *Class IA flammable liquids*—liquids that have a defined flash point below 22.8 °C (73 °F) and boiling points below 37.7 °C (100 °F).
- *Class IB flammable liquids*—liquids that have a defined flash point below 22.8 °C (73 °F) and boiling points at or above 37.7 °C (100 °F).
- *Class II flammable liquids*—any liquid that has a flash point at or above 37.8 °F (100 °F) and below 60 °C (140 °F).
- *Class IIIA* flammable liquids—any liquid that has a flash point at or 60 °C (140 °F), but below 93 °C (200 °F).
- *Class IIIB flammable liquids*—any liquid that has a flash point at or 93 °C (200 °F).

flame temperature—most open flames of any type produce a flame temperature in the region of 1,093 °C (2,000 °F). The hottest burning substance is carbon subnitride (C_4N_2), which at one atmospheric pressure can produce a flame calculated to reach 4,988 °C (9,010 °F). (Nolan, 2000)

flash—a quick spreading flame or momentary intense outburst of radiant heat. It may also be used to refer to a spark or intense light of short duration.

flash fire—a fire that spreads rapidly through a diffuse fuel, such as dust, gas, or the vapors of an ignitable liquid, without the production of damaging pressure. (NFC Online Glossary)

flash point—the minimum temperature to which a liquid must be heated in a standardize apparatus, so that a transient flame moves over the liquid when a small pilot flame is applied.
(NFC Online Glossary)

flash point—the flash point of a liquid is the temperature at which the vapor and air mixture laying just above its vaporizing surface is capable of just supporting a momentary flashing propagation of a flame prompted by a quick sweep of small gas pilot flame near its surface, hence the term flash point. The flash point is mainly applied to a liquid. The flash point of liquid is one of its characteristics that normally determines the amount of fire safety features requires for its handling, storage and transport.

flashover—the transition from fire growth period to the full developed stage in the enclosure fire development that is the demarcation point between two stages of a compartment fire, pre-flashover and post-flashover. Flashover is a phenomenon which defines the point in a compartment fire where all combustibles in the compartment are involved and flames appears to fill the entire volume. Gas temperatures of 300 to 650 °C (572 to 1,202 °F) have been associated with the onset of flashover, although temperatures of 500 to 600 °C (932 to 1,112 °F) are more widely used.

flashover—when a fire in a compartment is allowed to grow without intervention, assuming sufficient fuel in the burning item, temperatures in the hot upper lager will increase, with increasing radiant heat flux to all objects in the room. If a critical level of heat flux is reached, all exposed combustible items in the room will begin to burn, leading to a rapid increase in both heat release rate and temperatures. This transition is “flashover”. The fire is then referred to as “post-flashover fire”, a “fully developed fire” or a fire which has reached “full room involvement”.

flashover—the formal definition of flashover, from International Standards Organization (ISO), is given as, “the rapid transition to a state of total surface involvement in a fire of combustion material within an enclosure”. Flashover is the term given to the relatively abrupt change from a localized fire to the complete involvement of all combustibles within a compartment. This is from ISO, “Glossary of Fire Terms and Definitions,” ISO/CD 13943, International Standards Organization, Geneva, 1996.

flash vaporization—the instantaneous vaporization of some or all a liquid whose temperature is above its atmospheric boiling point when its pressure is suddenly reduced to atmosphere.

flow hydrant—a hydrant selected to measure the water flow available from the water supply.

flux—pertains to mass or heat flow rates per unit area.

forced flow—refers to air flow produced by wind or a fan.

*free-burnin*g—burning in open-air.

free of fire damage—the structure, system, or component under consideration is capable of performing its intended function during and after the postulated fire, as needed without repair (Regulatory Guide 1.189). In promulgating Appendix R, the Commission has provided methods acceptable for assuring that necessary structures, systems and components are free of fire damage (see Section III.G.2a, b and c), that is, the structure, system or component under consideration is capable of performing its intended function during and after the postulated fire, as needed. Licensees seeking exemptions from Section III.G.2 must show that the alternative proposed provides reasonable assurance that this criterion is met. The term "damage by fire" also includes damage to equipment from the normal or inadvertent operation of fire suppression systems. (Generic Letter 86-10).

Note: Section III.G.2 of Appendix R and Position C.5.b of Standard Review Plan (SRP) Section 9.5.1 establish fire protection features necessary to ensure that systems needed to achieve and maintain hot shutdown conditions remain free of fire damage.

fuel-controlled or fuel-limited fire—after ignition and during the initial fire growth stage, the fire is said to be fuel-controlled, since in the initial stages there is sufficient oxygen available for combustion and the growth of the fire entirely depends on the characteristics of the fuel and its geometry. The fire can also be fuel-controlled in later stages.

fuel lean—description of fuel burning in an excess supply of air.

fuel-limited—state of a compartment fire where the air supply is sufficient to maintain combustion.

fully developed—state of a compartment fire during which the flames fill the room involving all the combustibles, or the state of maximum possible energy release in a room fire.

fundamental burning velocity—the burning velocity of a laminar flame under stated conditions of composition, temperature, and pressure of the unburned gas.

fuse—a device that protects a circuit by fusing open its current responsive element when an overcurrent or short-circuit current passes through it. (IEEE Std. 100-1988).

fuse—a protective device that opens by the melting of a current-sensitive element during specified overcurrent conditions (NEMA Std. FU-1 1986).

fuse current rating—the ac or dc ampere rating which the fuse is capable of carrying continuously under specified conditions. (NEMA Std. FU-1 1986)

fuse voltage rating—the maximum rms ac voltage or the maximum dc voltage at which the fuse is designed to operate. (NEMA Std. FU-1 1986)

fusible link—a system of levers and links held together with a metal alloy which melts at a predetermined temperature.

fusible link—a connecting link of a low-melting alloy that holds an automatic sprinkler head in the closed position and melts at a predetermined temperature; it may also be used to hold a fire door or fire damper in the open position.

gas combustible—gas that is capable of being ignited and burned, such as hydrogen, methane, propane, etc.

gas sensing detector—a detector activates when a critical concentration of some gaseous product of combustion is reached.

generic issue (GI)—a concern that may affect the design, construction, or operation of all, several, or a class or nuclear power plants, which either does not affect safe operation of the plant or the safety significance of the issue has not yet been determined.

generic safety issue (GSI)—according to the NUREG-0933, "A Prioritization of Generic Safety Issues," a GSI is a safety concern that may affect the design, construction, or operation of all, several, or a class of nuclear power plants, and may have the potential for safety improvements and promulgation of new or revised requirements or guidance.

glove box—a sealed enclosure in which items inside the box are handled exclusively using long rubber or neoprene gloves sealed to ports in the walls of the enclosure. The operator places his or her hands and forearms into the gloves from the room outside of the box in order to maintain physical separated from the glove box environment. This allows the operator to retain the ability to manipulate items inside the box with relative freedom while viewing the operation through a window. (NFC Online Glossary)

glowing combustion—luminous burning of solid material without a visible flame. A stage in the ignition of a solid material that occurs before sufficient volatile fuel has evolved to sustain a gas-phase flame. (NFC Online Glossary)

gravity—the force of mutual attraction between masses.

gravity—the force that causes a body to accelerate while falling, usually expressed as 32.2 ft/sec^2 (9.81 m/sec^2).

ground—a conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth, or to some conducting body of relatively large extent that serves in place of the earth. (IEEE Std. 100-1988)

grounded circuit—a circuit in which one conductor or point (usually the neutral conductor or neutral point of transformer or generator windings) is intentionally grounded, either solidly or through a non-interrupting current limiting grounding device. (IEEE Std.100-1988)

Halon—any one of several halogenated hydrocarbon compounds, two of which (bromotriflioromethane and bromochlorodifuoromethane) are commonly used as extinguishing agents; they are inert to almost all chemicals, and resistant to both high and low temperatures.

Halon—as employed in the fire protection industry, a gaseous fire suppression agent. Halon is an acronym for halogenated hydrocarbons, commonly bromotriflioromethane Halon 1301) and bromochlorodifuoromethane (Halon 1201). Consider obsolete for fire protection purposes due to a possible environmental impact to the Earth's atmosphere ozone layer and beginning to be phased out or eliminated. In order for a Halon fire suppression system to be an effective fire suppression, the system must provide a very rapid response and be completely discharged while the fire is in its incipient stages (i.e., the fire is still controllable). The system discharge enough of the agent to effectively actively the chemical chain breaking mechanism of the diffusion flame combustion process and that discharge be contained in the area for a long enough period for this to be accomplished.

hazard—a possible source of danger that can initiate or cause undesirable consequences if uncontrolled.

hazard—hazard is a chemical or physical condition that has the potential for causing damage to people, property, or the environment. An example would be flammable liquids or explosive gases or dusts used in the process or in storage.

hazardous material—a substance that, upon release, has the potential of causing harm to people, property, or the environment.

HAZOP—an acronym for the hazard and operability study in which the hazards and operability of a system are identified and analyzed in a systematic manner to determine if adequate safe guards are in place. (Nolan, 2000)

heat—energy transfer due to temperature difference.

heat capacity—the energy that must be added to a unit mass of a substance in order to rise its temperature by 1 °C (34 °F) (as long as no phase change occurs). Also called thermal capacity.

Heat collector plate or Canopy—a covering provided over a heat detector or automatic sprinkler placed in the open, to trap and collect updrafts of heat from a fire incident to aid in its detection or sprinkler activation. They commonly consist of a sheet of steel (Nolan, 2000). Heat collectors were intended to reduce the time a fire takes to activate sprinklers located too far below the ceiling. When sprinklers are too far below the ceiling, most of the heat energy rises past the sprinklers and heat collectors and the sprinklers are not activated. Locating the sprinkler close to the ceiling ensures that the sprinkler will be in the hot gas layer, minimizing activation time and enabling the sprinkler to provide a fully developed water spray pattern to control the fire. In addition, the water from the sprinkler cools the upper gas layer (preventing flashover conditions) and cools the structural steel supports of the compartment boundaries (preventing structural collapse).

heat flux—the rate of heat transfer per unit area that is normal to the direction of heat flow. It is a total of heat transmitted by radiation, conduction, and convection. A radiant heat flux of 1 kW/m^2 (312.5 Btu/ft^2-hr) (that is, direct sunlight) will be felt as pain to exposed skin. A radiant heat of 4 kW/m^2 (1,250 Btu/ft^2-hr) will cause a burn on exposed skin. A heat flux density of 10–20 kW/m^2 (3,125–6,250 Btu/ft^2-hr) may cause objects to ignite, and a heat flux density of 37.8 kW/m^2 (11,813 Btu/ft^2-hr) will cause major damage. Heat flux may also be called heat flow rate. (Nolan, 2000)

heat of combustion—the energy released by the fire per unit mass of fuel burned.
(Quintiere, 1998)

heat of condensation—the energy released when a unit mass of vapor condenses to a liquid. (Friedman, 1998)

heat of decomposition—the amount of heat released during a chemical decomposition reaction. (Nolan, 2000)

heat of fusion—the energy absorbed when a unit mass of a solid melts. (Friedman, 1998)

heat of gasification—energy required to produce a unit mass of fuel vapor from a solid or liquid. (Quintiere, 1998)

heat of solidification—the energy released when a unit mass of a liquid solidifies. (Friedman, 1998)

heat of sublimation—the energy absorbed when a unit mass of a solid gasifies directly, without forming a liquid and without chemical change. (Friedman, 1998)

heat of vaporization—the energy absorbed when a unit mass of liquid vaporizes. (Friedman, 1998)

heat release rate—the rate at which heat energy is generated by burning. The heat release rate of a fuel is related to its chemistry, physical form, and availability of oxidant and is expressed as kW (kJ/sec) or Btu/sec. (Nolan, 2000)

heat resistance—the property of a foam to withstand exposure to high heat fluxes without loss of stability. (NFC Online Glossary)

heat transfer—the branch of physics dealing with the calculation of the rate at which thermal energy (heat) moves from a hotter to a cooler region or the transport of energy from a high-to a low-temperature object.

high/low pressure interface—reactor coolant boundary valves whose spurious operation due to fire could: (a) potentially rupture downstream piping on an interfacing system, or (b) result in a loss of reactor coolant inventory in excess of the available makeup capability.

high-impedance fault—an electrical fault of a value that is below the trip point of the breaker on each individual circuit. (Generic Letter 86-10)

high-impedance fault—a circuit fault condition resulting in a short to ground, or conductor to conductor hot short, where residual resistance in the faulted connection maintains the fault current level below the component's circuit breaker long-term setpoint. (Regulatory Guide 1.189)

horizontal exit—an exit from one building to another on approximately the same level; or a passage through or around a rated wall or partition that affords protection from fire or smoke coming from the area from which escape is made. (NFC Online Glossary) *hot short*—an electric cable failure mode, resulting from a fire, which involves making an electrical connection between a conductor with power and a conductor that does not currently have power, without a simultaneous short to ground or open-circuit condition. Such failure might, for example, simulate the closing of a control switch, cause errors in an instrument reading, or result in the application of power to an unpowered circuit. ndividual conductors of the same or different cables come in contact with each other and may result in an impressed voltage or current on the circuit being analyzed. (Regulatory Guide 1.189)

Clarification: The term "hot short" is used to describe a specific type of short circuit fault condition between energized and de-energized conductors. Should a de-energized conductor come in electrical contact with an energized conductor (or other external source), the voltage, current or signal being carried by the energized conductor(or source) would be impressed onto one or more of the de-energized conductors.

hot work—activities that involve the use of heat, sparks, or open flame such as cutting, welding, and grinding. (Regulatory Guide 1.189)

humidity—the property of the water-air mixture that measure the amount of water present relative to the equilibrium concentration.

hybrid mixture—a mixture of a combustible gas with either a combustible dust or combustible mist.

hyperthermia—heat stress.

hypergolic—property of a material which describes its ability to spontaneously ignite or explode upon contact with an oxidizing agent.

Ignition process—ignition is broadly defined as the initiation of the chemical process of combustion (burning) in any fuel. In most fire protection problems, ignition involves both a heat source and target fuel. A burning wastebasket can be an ignition source for a nearby chair. The burning chair subsequently can be ignition source for another fuel.
In an otherwise free-free environment, the first unwanted burning is the initial ignition, and the initial heat source is called an igniter.
In the environments where gases, vapors, or dust are present, the initial ignition may yield combustion fast enough to generate a pressure or shock wave. This type of sudden over-pressure requires different fire defense than spread from combustible to combustible without a pressure wave.

ignition temperature—the surface temperature needed to cause ignition in solids. (Quintiere, 1997)

ignition temperature—temperature at which an element or compound will catch fire in air (atmospheric oxygen).

impairment—the degradation of a fire protection system or feature that adversely affects the ability to the system or feature to perform its intended function. (Regulatory Guide 1.189)

impulse—a measure that can be used to define the ability of a blast wave to do damage. It is calculated by the integration of the pressure-time curve.

important to safety—nuclear power plant structures, systems, and components "important to safety" are those required to provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public. (Regulatory Guide 1.189)

incipient stage—refers to the severity of a fire where the progression is in early stage and has not developed beyond that which can be extinguished using portable fire extinguishers or handlines flowing up to 125 gpm (473 L/min). A fire is considered to be beyond the incipient stage when the use of thermal protective clothing or self-contained breathing apparatus is required or an industrial fire brigade member is required to crawl on the ground or floor to stay below smoke and heat. (NFC Online Glossary)

incipient stage fire—a fire which is in the initial or beginning stage and which can be controlled or extinguished by portable fire extinguishers, Class II standpipe or small hose systems without the need for protective clothing or breathing apparatus.

incomplete combustion—a combustion process that does not go the most stable species such as H_2O and CO_2. (Quintiere, 1997)

inflammable—not a permissible word, because it introduces confusion as to whether flammable or nonflammable is meant. (Friedman, 1998)

Inflammable—identical meaning as flammable, however the prefix "in" indicates a negative in many words and can cause confusion, therefore the use of flammable is preferred over inflammable. (Nolan, 2000)

indicating appliance—any audible or visible signal employed to indicate a fire, supervisory, or trouble condition. Example of audible signal appliances are bells, horns, sirens, electronic horns, buzzers, and chimes. A visible indicators consists of a lamp, target, meter deflection, or equivalent.

indicating appliance circuit—a circuit or path directly connected to an indicating deflection, or equivalent.

inert gas—gases, such as carbon dioxide or nitrogen, that will not support combustion.

inert gas agents—an agents that contains one or more inert gases, such as helium, neon, argon, nitrogen, and carbon dioxide. (NFC Online Glossary)

inerting—the process of removing an oxidizer (usually air or oxygen) to prevent a combustion process from occurring normally accomplished by purging.

inerting—adding an agent within an enclosure to reduce a flammable concentration of gas or vapor.

initiating device (appliance)—a manually or automatically operated device, the normal intended operation of which results in a fire alarm or supervisory signal indication from the control unit. Example of alarm signal indicating devices are thermostats, manual boxes, smoke detectors, and water flow switches. Examples of supervisory signal initiating devices are water level indicators sprinklers system, valve position switches, pressure supervisory transmitters, and water temperature switches.

individual plant examination (IPE)—an evaluation to identify any plant-specific vulnerabilities to severe accidents initiated by internal events, including flooding, during full power operation. (Generic Letter 88-20 has requested each licensee of a U.S. power plant to perform such evaluation for its plant(s).

individual plant examination of external events (IPEEE)—an evaluation to identify any plant-specific vulnerabilities to severe accidents initiated by external events during full power operation. [Generic Letter 88-20, Supplement 4, has requested each licensee of a U.S. power plant to perform such evaluation for its plant(s).]

internal fire—a fire initiated anywhere within the plant boundaries, including both areas within plant structure and buildings, and contiguous outdoor areas such as the electrical switchyard and transformer areas.

inter-cable fault—a fault between conductors of two or more separate cables.

inter-cable fault—a fault between two or more conductors within a single multi-conductor cable.

Interlock—a device actuated by the operation of some other device with which it is directly associated to govern succeeding operations of the same or allied devices. Note: Interlocks may be either electrical or mechanical. (IEEE Std.100-1988)

interrupting device—a breaker, fuse, or similar device installed in an electrical circuit to isolate the circuit (or a portion of the circuit) from the remainder of the system in the event of an overcurrent or fault downstream of the interrupting device. (Regulatory Guide 1.189)

isolating device/isolation device—a device in a circuit which prevents malfunctions in one section of the circuit from causing unacceptable influences in other sections of the circuit or other circuits. (IEEE Std. 100-1988; Regulatory Guide 1.189)

isolation transfer switch—a device used to provide electrical isolation from the fire affected area and transfer control of equipment from the main control room to the local control station (alternate shutdown panel).

insulated conductor—a conductor covered with a dielectric(other than air) having a rated insulating strength equal to or greater than the voltage of the circuit in which it is used. (IEEE Std. 100-1988).

insulation (cable, conductor)—that which is relied on to insulate the conductor or other conductors or conducting parts from ground. (IEEE Std. 100-1988)

intumescent coating—a protective chemical coating, which, when heated, internally generates gases and expands, resulting in a thermally insulating crust that contains cavities.

in situ combustibles—combustibles materials that constitute part of the construction, fabrication, or installation of plant structure, systems, and components and as such are fixed in place.

irritants—toxicant that irritate the eyes, upper respiratory tract and/or lungs.

irritant gases—acid gases and other hydrocarbon byproducts that can cause pain on contact or inhalation.

jet—a discharge pressurized liquid, vapor, or gas into free space from an orifice, the momentum of which induces the surrounding atmosphere to mix with the discharged material.

jet fire—combustion occurring at the release of liquid, vapor, or gas under pressure from a leakage point (orifice), the momentum of which causes entrainment of the surrounding atmosphere. The jet fire has a high heat flux, turbulent flame, and capability of eroding the material it impacts.

jet flame—flame due to high velocity fuel supply.

K-factor—coefficient specified for individual sprinklers based on their orifice design and used for hydraulic calculations of the sprinkler system. K-factors are determined by the design and manufacturer of the sprinkler head. (Nolan, 2000)

K-factor—the thermal conductivity coefficient of materials. It is a measurement in standard terms of the amount of heat conducted per the thickness of the material per the degree of temperature.

Kelvin (K)—absolute Celsius temperature, 273 + °C.

laminar—refers to orderly, unfluctuating fluid motion. (Quintiere, 1997)

latent heat—the characteristic amount of energy absorbed or released by a substance during a change in its physical state that occurs without changing its temperature. The latent heat associated with melting a solid or freezing a liquid is called the heat of fusion; that associated with vaporizing a liquid or a solid or condensing a vapor is called the heat of vaporization. (Nolan, 2000)

leakage current (Insulation)—the current that flows through or across the surface of insulation and defines the insulation resistance at the specified direct current potential (IEEE Std. 100-1988).

lean mixture—a mixture of flammable gas or vapor and air in which the fuel concentration is below of fuel's lower limit of flammability.

lean mixture—a mixture of air and gas that contains too much air for the amount of gas present to cause an explosion and is thus below the lower flammable limit.

limited sprinkler system—an automatic sprinkler system that is limited to a single fire area and consists of not more than twenty sprinklers.

line fire—elongated fires on a horizontal fuel surface. (Nolan, 2000)

listed—equipment or materials included on a list published by a recognized testing laboratory, inspection agency, or other organization concerned with product evaluation that maintains periodic inspection of production of listed equipment or materials, and whose listing states that certain specific equipment or materials meet nationally recognized standards and have been tested and found suitable for use in a specific manner. (Regulatory Guide 1.189, NFC Online Glossary) *local control*—operation of shutdown equipment using remote controls (e.g., control switches) specifically designed for this purpose from a location other than the main control room.

local control station—a control panel located in the plant which allows operation and monitoring of plant equipment from outside of the main control room. For post-fire safe shutdown control functions and monitoring variables on these panels must be independent (physically and electrically)from those in the main control room.

local operation—manipulation of plant equipment from a location outside of the main control room. For example, manual operation of the circuit breakers or turning the handwheel on the valve to change its position.

load breaker—a circuit breaker that is located on the load side of a power source. Synonym: branch breaker.

LOI—the limiting oxygen index, a characteristic of solid combustibles measured in a standards apparatus in which the O_2/N_2 ratio of the atmosphere is varied, to provide a measure of relative flammability. Also called oxygen index (OI).

lower flammability limit—the lowest concentration of fuel in air at normal temperature and pressure that can support flame propagation is known as the lower flammability limit (LFL) or lower explosive limit (LEL).

lowe flammability limit—the lowest concentration of a vapor/air mixture which can be ignited by a pilot.

manual action—physical manipulation (operation) of equipment when local or remote controls are no longer available of a plant component such as a valve, switch or circuit breaker.

manual valve—a valve that does not have the capability of being manipulated remotely.

manually operated valve—term used to denote a valve credited in the SSA or shutdown procedures for being manually manipulated.

Note: A manually operated valve may be a manual valve or a remotely operated valve (e.g., MOV) that has its power and control capability disabled or removed.

mass burning flux—burning rate per unit area. (Quintiere, 1997)

mass loss rate—the mass of fuel vaporized but not necessarily burned per unit time. (Quintiere, 1998)

mass optical density—a normalized value of the optical density of a smoke cloud, which is intended to be independent of measuring apparatus.

material safety data sheets—a document, prepared in accordance with DOL 29 CFR, that contains information regarding the physical and health hazards associated with a given product or substance and a recommended emergency action.

means of egress—a safe, continuous, and unobstructed way of travel out of any building or structure; this include the exit access, exit, and exit discharge.

model—a model of anything is, simply, a systematic representation of that thing. For example, we can have: thought models (or conceptual models), scale models, and mathematical models. These three examples are probably the main representation which are used by scientists. A thought or conceptual model is simply a proposed schema explaining how something works. Scale models are often used in structural engineering, fluid dynamics, and have occasionally been used in fire science. Model trains are familiar to all. A scale model in scientific work is simply a reduced-size object on which certain measurements will be made. The mathematical model is a series of equations which describe a certain process. If the equations are simple enough, they can be solved on the hand calculator. More commonly, the equations are not so simple. Consequently, a computer is required for their solution. Thus, in the fire field, we would speak of computer fire model.

molded-case circuit breaker—a circuit breaker that is assembled as an integral unit in a supporting and enclosing housing of molded insulating material. (IEEE Std. 100-1988)

modulus of elasticity—as with yield strength, the modulus of elasticity degrades with temperature, causing deformations at elevated temperatures. This degradation has serious impact on the buckling behavior of columns and the midspan deflection of beams.

moisture content—moisture content will affect the thermal transmission qualities of an element significantly, and in rigorous analysis becomes a very complex problem. Methods for idealizing the treatment of moisture have been developed successfully. Water evaporation can also cause chemical changes in material, usually resulting in discontinuous values of thermal properties. Concrete and gypsum materials are good examples. Moisture content also affects the shrinkage and modulus elasticity properties of concrete. Moisture condensation on reinforced and prestressed cables also affects the temperature in these elements.

multi-conductor cable (multiple conductor cable)—a combination of two or more conductors cabled together and insulated from one another and from sheath or armor where used.
Note: Specific cables are referred to as 3-conductor cable, 7-conductor cable, 50-conductor cable, etc. (IEEE Std. 100-1988).

National Fire Protection Association (NFPA) codes and standards—consensus codes and standards intended to minimize the possibility and adverse consequences of fires.

negative phase —that portion of a blast wave whose pressure is below ambient.

neutral plane—the height in a compartment above which smoke will or can flow out during a fire event. A neutral plane may change from one-half to one-third of the compartment height as the fire becomes fully involved in flames. However, the smoke interface can extend very close to the floor of the compartment.

non-combustible material—(a) material that, in the form in which it is used and under conditions anticipated, will not ignite, burn, support combustion, or release flammable vapors when subjected to fire or heat or (b) material having a structural base of noncombustible material, with a surfacing not over 1/8 inch thick that has a flame spread rating not higher than 50 when measured in accordance with the ASTM E84, "Standard Test Method for Surface Burning Characteristics of Building Materials."

non-essential (conductor, cable, component or system)—structures, systems, and components (Class 1E, Non-Class 1E, safety related or non-safety related) whose operation is not required to support the performance of systems credited in the SSA for accomplishing post-fire safe shutdown functions.

norcotic effect—the effect of producing drowsiness and ultimately unconsciousness. Chemical substances in smoke, when inhaled, can enter the bloodstream and interfere with the oxygen supply to the brain, causing narcosis and possible death.

nonflammable—not capable of being ignited.

normally closed or normally open—the component status during normal operating modes of the plant. This terminology is usually applied to valve, circuit breaker, and relay operating positions.

open circuit—a failure condition that results when a circuit (either a cable or individual conductor within a cable) loses electrical continuity.

open circuit—a failure condition that results when a circuit (either a cable or individual conductor within a cable) loses electrical continuity. (Regulatory Guide 1.189)

Clarification: A circuit fault condition where the electrical path has been interrupted or "opened" at some point so that current will not flow. Open circuits may be caused by a loss of conductor integrity due to heat or physical damage (break).

optical density—a number quantifying the fraction of a beam of light that is unable to pass through a given smoke cloud.

overpressure—any pressure above atmospheric caused by a blast.

overcurrent—any current in excess of the rated current of equipment or the rated ampacity of a conductor. It may result from overload, short-circuit, or ground-fault. A current in excess of rating may be accommodated certain equipment and conductors for a given set of conditions. Hence, the rules for overcurrent protection are specific for particular situations (IEEE Std. 100-1988).

overcurrent protection—a form of protection that operates when current exceeds a predetermined value. (IEEE Std. 100-1988)

overcurrent relay—a relay that operates when its input current exceeds a predetermined value. (IEEE Std. 100-1988).

overload—loading in excess of normal rating of equipment (IEEE Std. 100-1988).

overload—generally used in reference to an overcurrent that is not of sufficient magnitude to be termed a short circuit. (IEEE Std. 100-1988).

oxidization—removal electrons from an atom or molecule, usually by chemical reaction with oxygen.

oxidizing agent—chemical substance that gives up oxygen easily, removes hydrogen from another substance, or attracts electrons.

oxygen starvation—for the case where there are no openings in the enclosure or only small leakages areas, the hot gas layer will soon descend toward the flame region and eventually cover the flame. The air entrained into the combustion zone now contains little oxygen and fire may die out due to oxygen starvation.

paired cable—a cable in which all the conductors are arranged in the form of twisted pairs (IEEE Std. 100-1988).

passive fire barriers—a fire barrier that provides its protective function while in its normal orientation, without any need to be repositioned. (Examples of passive fire barriers include walls and normally closed fire doors).

passive fire protection (PFP)—protection measures that prolong the fire resistance of an installation before an eventual fire occurrence from the effects of smoke, flames, and combustion gases. These can consist of insulation (fireproofing) of a structure, choice of noncombustible materials of construction, use of fire-resistant partitions, and compartmentation to resist the passage of fire. It includes coatings, claddings, or free-standing systems that provide thermal protection in the event of fire and that require no manual, mechanical, or other means of initiation, replenishment, or sustainment for their performance during a fire incident. Passive systems also embrace the basic requirements for area separation and classification. (Nolan, 2000)

passive smoke detection system—a fire detection system where smoke is transported to and into a sensing chamber by outside forces, that is, fire plume strength or environmental air-flows. A passive smoke detection system may have difficulty detecting smoke from smoldering types of fires because this smoke may not be hot enough to rise to the smoke detector location. (Nolan, 2000)

penetration seal—a purposely made seal (or seals) formed in situ to ensure that penetrations or “poke through” to fire barriers do not impair its fire resistance. Wiring, cable or piping openings, ducting through floors, ceilings, walls, and building joints must be provided with fire-rated penetration seals to prevent the spread of fire or its effects. The penetration sealing material is to be made of limited-combustible or noncombustible material that meets the requirements of ASTM E 814, “Fire Tests of Through-Penetration Fire Stops,” or UL 147*9,* “Standard for Safety Fire Tests of Through-Penetration Firestops”. (Nolan, 2000)

performance-based fire protection design—an engineering approach to fire protection design based on (1) agreed upon fire safety goals, loss objectives, and design objectives; (2) deterministic and probabilistic evaluation of fire initiation, growth, and development; (3) the physical and chemical properties of fire and growth effluents; and (4) a quantitative assessment of the effectiveness of design alternatives against objectives. One primary difference between a prescriptive and a performance based design is that a fire safety goal life safety, property protection, mission continuity, and environmental impact is explicitly stated. Prescriptive requirements may inhibit fire safety components from effectively meeting the fire safety goals as an integrated system. (Nolan, 2000)

performance codes—regulations providing for engineering analysis.

performance-based requirements—codes and standards that require design solution be engineered to address the expected hazard in such a fashion that an acceptable level of safety (performance) is ensured.

photoelectric (light scattering) smoke detector—a method of smoke detection that uses the scattering of a light beam from the presence of smoke particles onto a photosensitive detector to sense a fire condition and send a signal for alarm. (Nolan, 2000)

piloted ignition—ignition of flammable fuel-air mixture by a hot spot spark, or small flame (pilot). (Quintiere, 1998)

pilot head detection system—a fire detection system that uses fusible heads on a pneumatic charged system placed over the area of protection or hazard. Activation of the fusible head releases the system pressure, which normally is linked by a pressure switch to a water suppression trip valve to activate water flow to a deluge water spray system. The system provides forautomatic fire detection and activation of protective devices or alarms. (Nolan, 2000)

plume—the column of hot gases, flames, and smoke rising above a fire. In a confined area a fire plume rises almost vertically. In an outside, unconfined area the configuration of a fire plume is affected by ambient conditions (wind, temperature, etc.). A fire plume consists of a flame plume, a thermal column of combustion gases, and smoke particles. A fire plume's temperature decreases rapidly after the combustion process due to the entrainment of air. Therefore, the ignition hazard from a fire plume is primarily dependent on the flame height of the plume. Objects located above a flame are not likely to ignite unless large amounts of radiated heat are present or flame contact is made. It may also be called a convection column, thermal updraft, or thermal column. (Nolan, 2000)

pneumatic fire detection system—a fire detection system that detects fire from heat, which either melts fusible elements (spot-type detection) in the system or a low melting point pneumatic (plastic) tubing (linear detection). Loss of pressure in the system activates a pressure switch that sends a signal for an alarm and fixed fire suppression system activation. (Nolan, 2000)

pool fire—a turbulent diffusion fire burning above an upward facing horizontal of vaporizing liquid fuel (usually symmetrical) under conditions where the fuel vapor or gas has zero or very low initial momentum. (Nolan, 2000)

positive phase—that portion of blast wave whose pressure is above ambient.

premixed flame—a flame in which fuel and air are mixed first before combustion. (Quintiere, 1998)

pre-flashover fire—the growth stage of a fire, where the emphasis in the fire safety engineering design is on the safety of humans. The design load is in this case characterized by a heat release rate curve, where the growth phase of the fire is most important.

potential transformer—a special class of transformer used to step down high distribution system level voltages (typically 480V and above) to a level that can be safely measured by standard metering equipment. PT's have a voltage reduction ratio given on their nameplate. A PT with a voltage reduction ratio of 200: 5 would reduce the voltage by a ratio of 200 divided by 5 or 40 times.

post-flashover fire—when the objective of fire safety engineering design is to ensure structure stability and safety of firefighters, the post-flashover fire is of greatest concern. The design load in this case is characterized by the temperature-time curve assumed for the full developed fire stage.

positive-pressure breathing apparatus—self-contained breathing apparatus in which the pressure in the breathing zone is positive in relation to the immediate environment during inhalation and exhalation.

positive pressure ventilation (PPV)—the application of positive air ventilation to an enclosed fire event to influence the degree of ventilation, aid in firefighting activities, and influence burning activity. Mechanical ventilators (fans) are used to blow fresh air into an enclosure in sufficient amounts to create a pressure differential within the enclosure that forces the existing air or products of combustion through an exit opening in the enclosure. Positive pressure ventilation has been used to assist in firefighting operations. (Nolan, 2000)

power cable/circuit—a circuit used to carry electricity that operates a load.

pre-discharge employee alarm—an alarm which will sound at a set time prior to actual discharge of an extinguishing system so that employees may evacuate the discharge area prior to system discharge.

pre-fire position/operating mode—terminology used to indicate equipment status prior to a fire.

prescriptive requirements—detailed and often rigid measures mandated in codes and standards as the means to ensure fire safety.

probable maximum loss (PML)—the loss due to a single fire scenario, which assumes an impairment to one suppression system and a possible delay in manual fire-fighting response.

probabilistic safety assessment (PSA)—a comprehensive evaluation of the risk of a facility or process; also referred to a probabilistic risk assessment (PRA).

product safety engineer—develops and conducts tests to evaluate product safety levels and recommends measures to reduce or eliminate hazards. Establishes procedures for detection and elimination of physical and chemical hazards and avoidance of potential toxic effects and other product hazards. Investigates causes of accidents, injuries, and illnesses resulting from product usage and develops solution. Evaluates potential health hazards or damage which could result from misuse of products and applies engineering principles and product standards to improve safety. May participate in preparation of product usage and precautionary label instructions. ("Dictionary of Occupational Titles," Volume 1, 14^{th} Edition, U.S. Department of Labor Employment and Training Administration, 1991.)

protective relay—a device whose function is to detect defective lines or apparatus or other power system conditions of an abnormal or dangerous nature and to initiate appropriate control action. A protective relay may be classified according to its input quantities, operating principal, or performance characteristics. (IPEEE Std. 100-1988)

Clarification: Protective relays are small, fast acting, automatic switches designed to protect an electrical system from faults and overloads. A single 4160V switchgear have many relays, each with a specific purpose. Protective relays are classified by the variable they monitor or the function they perform. When a relay senses a problem (e.g., short circuit) it quickly sends a signal to one or many circuit breakers to open, or trip, thus protecting the remainder of distribution system.

pyrolysis—the process of heating fuel to cause decomposition.

pyrophoricity—spontaneous combustion of a material upon exposure to air (atmospheric oxygen).

qualitative—measuring or describing with regards to characteristics, generalities, or trends.

quantitative—measuring or describing based on number or quantity.

qualitative risk analysis—an evaluation of risk based on the observed hazards and protective systems that are in place, as opposed to an evaluation that uses specific numerical techniques

quantitative risk analysis—an evaluation of both the frequency and the consequences of potential hazardous events to make a logical decision on whether the installation of a particular safety measure can be justified on grounds of safety and loss control. Frequency and consequences are usually combined to produce a measure risk that can be expressed as the average loss per year in terms of injury or damage arising from an accidental event. The risk calculations of different alternatives can be compared to determine the safest and most economical options. Calculated risk may be compared to set criteria that have been accepted by society or required by law.

qualified cable—a cable that is certified to meet all of the requirements of the IEEE-383 standard (including both the flame spread and the LOCA exposure test protocols).

quick disconnect valve—a device which starts the flow of air by inserting of the hose (which leads from the facepiece) into the regulator of self-contained breathing apparatus, and stops the flow of air by disconnection of the hose from the regulator.

raceway—an enclosure channel of metal or nonmetallic materials designed expressly for holding wires, cables, or busbars, with additional functions as permitted by code. Raceways include, but are not limited to, rigid metal conduit, rigid nonmetallic conduit, intermediate metal conduit, liquid-tight flexible conduit, flexible metallic tubing, flexible metal conduit, electrical nonmetallic tubing, electrical metallic tubing, underfloor raceways, cellular concrete floor raceways, cellular metal floor raceways, surface raceways, wireways, and busways.
(Regulatory Guide 1.189; IEEE Std. 100-1988).

raceway fire barrier—non-load-bearing partition type envelope system installed around electrical components and cabling that are rated by test laboratories in hours of fire resistance and are used to maintain safe shutdown functions free of fire damage. (Regulatory Guide 1.189)

radiation—heat transfer due to electromagnetic energy transfer such as light. (Quintiere, 1998)

Rankine (°R)—absolute Fahrenheit temperature scale, 460 °F. (Quintiere, 1998)

radiant energy (heat) shield—a non-combustible or fire resistive barrier installed to provide separation protection of redundant cables, equipment, and associated non-safety circuits within containment. (Regulatory Guide 1.189)

rated fire barrier—a fire barrier with a fire endurance rating established in accordance with the test procedure of NFPA 251, “Standard Methods of Fire Test of Building Construction and Materials”.

rated voltage—the voltage at which operating and performance characteristics of apparatus and equipment are referred. (IEEE Std. 100-1988).

rated voltage—for cables, either single-conductor or multiple conductor, the rated voltage is expressed in terms of phase-to-phase voltage of a three phase system. For single phase systems, a rated voltage of $\sqrt{3}$ * the voltage to ground should be assumed. (IEEE Std. 100-1988).

redundant shutdown—if the system is being used to provide its design function, it generally is considered redundant. If the system is being used in lieu of the preferred system because the redundant components of the preferred system do not meet the separation criteria of Section III.G.2, the system is considered an alternative shutdown capability.

redundant shutdown—for the purpose of analysis to Section III.G.2 criteria, the safe shutdown capability is defined as one of the two normal safe shutdown trains. If the criteria of Section III.G.2 are not met, an alternative shutdown capability is required. (Generic Letter 86-10)

Note: For BWRs, the use of safety relief valves and low pressure injection systems has been found to meet the requirements of a redundant means of post-fire safe shutdown under Section III.G.2 of 10 CFR 50, Appendix R.

regression rate—the burning rate of a solid or liquid, usually measured in centimeters per second measured perpendicular to the surface.

relay—an electrically controlled, usually two-state, device that opens and closes electrical contacts to effect the operation of other devices in the same or another electric circuit.
(IEEE Std. 100-1988)

re-radiation—the radiation re-emitted from a heated surface.

reflected pressure—impulse or pressure experienced by an object facing a blast.

remote shutdown—the capability, including necessary instrumentation and control, to safely shutdown the reactor and maintain shutdown conditions from outside the main control room.
(Regulatory Guide 1.189)

remote control—control of an operation from a distance: this involves a link, usually electrical, between the control device and the apparatus to be operated. (IEEE Std. 100-1988)
Note: Remote control may be accomplished from the control room or local control stations.

remote shutdown location—a plant location external to the main control room that is used to manipulate or monitor plant equipment during the safe shutdown process. Examples include the remote shutdown panel or valves requiring manual operation.

repair—to restore by replacing a part or putting together what is broken.
(Webster's Ninth New Collegiate Dictionary).

Response Time Index (RTI)—a relative measure of the sensitivity of an automatic fire sprinkler's thermal element as installed in a specific sprinkler. It is usually determined by plunging a sprinkler into a heated laminar airflow within a test oven. This type of "plunge" test is not currently applicable to certain sprinklers. These sprinklers must have their thermal sensitivity determined by other standardized test methods. A response time index is also used to quantify the responses of heat detectors used in a fire detection system. A normal RTI for a sprinkler is 300. Early suppression fast response (ESFR) sprinklers have an RTI of 50 or less. (Nolan, 2000) *restricted area*—any area to which access is controlled by the licensee for purposes of protecting individuals from exposure to radiation and radioactive materials.

rich mixture—a mixture of flammable gas or vapor and air in which the fuel concentration is above the fuel's upper limit of flammability.

risk—risk is a quantitative measure of fire or explosion incident loss potential in terms of both the event likelihood and aggregate consequences.

risk-informed—the risk-informed approach the analyst factors is not just the severity of a fire but also the likelihood that the fire will occur.
For example, based on the knowledge and experience of the equipment operator, a fire in a given turbine generator is likely to occur 80-percent of the time. Or, based on the knowledge and experience of the fire protection engineer, the sprinkler system protecting that generator is 90-percent likely to be contain and control that fire. Because the risk-informed, performance-based methodology quantifies the likelihood of a fire hazard and the likelihood that the fire protection system will contain or control the fire it provides a more realistic prediction of the actual risk.

risk reduction—risk reduction in define as the application of technological or administrative measures to reduce fire and explosion risk to a tolerable level.

safety engineer—develops and implements safety program to prevent or correct unsafe environmental working conditions, utilizing knowledge of industrial processes, mechanics, chemistry, psychology, and industrial health and safety laws. Examines plans and specifications for new machinery or equipment to determine if all safety precautions have been included. Determines amount of weight that can be safely placed on plant floor. Tour to inspect fire and safety equipment, machinery, and facilities to identify and correct potential hazards and enclothing and devices, and designs, builds, and installs, or directs installation or safety devices on machinery. Conducts or coordinates safety and first aid training to educate workers about safety policies, laws, and practices. Investigates industrial accidents to minimizes recurrence and prepares accident reports. May conduct air quality tests for presence of harmful gases and vapors. ("Dictionary of Occupational Titles," Volume 1, 14th Edition, U.S. Department of Labor Employment and Training Administration, 1991.)

safety factor—safety factors have been used in most engineering designs to account for uncertainties in calculations. Safety factors are also used in fire protection engineering designs, especially for evacuation times and structural fire safety performance design. The addition of safety factors to performance criteria permits the designer to make a conservative assessment while allowing for smaller margin of error by accounting for uncertainty in the models, the input data and the assumptions.

safe shutdown—for fire events, those plant conditions specified in the plant Technical Specifications as Hot Standby , Hot Shutdown, or Cold Shutdown. (Regulatory Guide 1.189)

safe shutdown analysis (post-fire safe shutdown analysis)—a documented evaluation of the potential effects of a postulated fire (including an exposure fire) and fire suppression activities in any single area of the plant (fire area), on the ability to achieve and maintain safe shutdown conditions in a manner that is consistent with established performance goals and safety objectives. (i.e., Sections III.G and III.L of Appendix R or Position C.5.b of SRP 9.5.1).

safe shutdown system—all structures, equipment (components, cables, raceways cable enclosures etc.), and supporting systems (HVAC, electrical distribution, station and instrument air, cooling water, etc.) needed to perform a shutdown function.

self-heating—the result of exothermic reaction, occurring spontaneously in some materials under certain conditions, whereby heat is liberated at a rate sufficient to rise the temperature of the material.

seismic gap penetration seal—material to fill joints between fire resistance rated walls, floors, or floor/ceiling assemblies which maintains continuity of the assembly. The seal system is often multifunctional having fire, flood, and pressure ratings.

severity—severity is a qualitative estimate of the hazard intensity in terms of source intensity, time, and distance; for example heat flux, temperature, toxic or corrosive smoke concentration, explosion over-pressure versus distance.

short circuit—a failure condition that results when a circuit (either a cable or individual conductor within a cable) comes into electrical contact with another circuit. (Regulatory Guide 1.189)

short circuit—an abnormal connection (including an arc) of relatively low impedance, whether made accidentally or intentionally, between two points of different potential. (IEEE Std. 100-1988)

short-to-ground—a short circuit between conductor(s) and a grounded reference point (e.g., grounded conductor, conduit, raceway, metal enclosure, shield wrap or drain wire within a cable).

short-to-ground—a failure condition that results when a circuit (either a cable or individual conductor within a cable) comes into electrical contact with a grounded conducting device such as a cable tray, conduit, grounded equipment, or grounded component. (Regulatory Guide 1.189)

solid conductor self-ignited cable fire—a conductor consisting of a single wire. (IPEEE Std.100-1988). Electrical cables are often considered as a source of fire because they carry electric power (a potential source of ignition) and are constructed of materials that can sustain combustion. A fire that initiates from a cable, either due to a fault in the cable or due to a current overload, is refereed to as a self-ignited cable fire.

SI units—an internationally accepted systems of measurement units.

small hose system—a system of hose ranging in diameter from 5/8" up to 1½" which is for the use of employees and which provides a means for the control and extinguishment of incipient stage fires.

smoke (from fire)—the mixture of tiny particles and gases produced by a fire. The particles consist mainly of soot, aerosol mist, or boot, or gases, no longer chemically reacting, that emanate from the fire.

smoke barrier—a continuous surface (wall, floor, HVAC damper, or ceiling assembly) that is designed and constructed to restrict the movement of smoke. A smoke barrier may or may not also have a fire resistance rating. Such barriers might have protected openings. (Nolan, 2000) *smoke bomb*—a device for generating smoke from a chemical source (a pyrotechnic device) to simulate fire conditions. Smoke bombs are used in confined spaces for testing and training purposes (testing smoke detection, smoke management systems, or firefighter training). They usually produce smoke at a standard rate and quality and can be supplied in various durations. Smoke bombs are sometimes called smoke candles. (Nolan, 2000)

smoke chaser—terminology used for a forest firefighter who is lightly equipped to enable him or her to get to a fire quickly. (Nolan, 2000)

smoke compartment—an area enclosed by smoke barriers on all sides, including the top and bottom. (Nolan, 2000)

smoke condensate—the condensed residue of suspended vapors and liquid products of incomplete combustion. (Nolan, 2000)

smoke control—the control of smoke movement by the use of the airflow by itself, if it is of sufficient velocity and application of air pressure differences of sufficient strength across a barrier. Dilution of a smoke environment by only supplying air and extracting air is not considered a method of smoke control within an enclosure for fire safety concerns. (Nolan, 2000)

smoke control system—a system to limit and direct smoke movement within a building to protect occupants and assist with evacuation measures. It consists of mechanical fans that are engineered to produce air flows and pressure differences within the building compartments to achieve smoke control. (Nolan, 2000)

smoke control zone—the subdivision of a building to inhibit the movement of smoke from one area to another for the purpose of life safety, evacuation, and property protection. A smoke control zone can consist of one or more floors, or a floor can consist of more than one smoke control zone. Each zone is separated from the others by partitions, floors, and doors that can be closed to prevent the spread of smoke. (Nolan, 2000)

smoke curtain—salvage covers placed around an area by the fire service to prevent the spread of smoke that may cause further damage. (Nolan, 2000)

smoke damage—the harmful effects to property from the occurrence of unwanted smoke exposure and combustion gases, consisting of stains, odors, and contamination. Exposure of combustion gases and smoke in some locations may cause property damages higher than physical fire damages. High technology clean rooms and the food processing industry, for example, require high cleanliness standards for their products and smoke damage may cause harmful chemicals to deposited on the products, making them unsuitable for use or salvage. (Nolan, 2000)

smoke damper—a device to restrict the passage of smoke through a duct that operates automatically and is controlled by a smoke detector. (Nolan, 2000)

smoke density—the relative quantity of solid and gaseous airborne products of combustion in a given volume. (Nolan, 2000)

smoke detection—the sensing of the products of combustion and sending a signal or an alarm for the purpose of safeguarding life or property. Various devices are available that can sense the presence of smoke, which is considered evidence of unwanted combustion. (Nolan, 2000) *smoke detector*—a device that senses visible or invisible particles of combustion. They are very effective for a slow smoldering fire and will generally provide an alarm before a heat detector. They may cause a false alarm or be ineffective if not sited and installed where air currents from ventilation or air conditioning systems are likely to carry smoke and other products of combustion away from the detectors. Usually used to warn occupants of a building of the presence of a fire before it reaches a rapidly spreading stage and inhibits escape or attempts to extinguish it. On sensing smoke, the detectors emit a loud, high-pitched alarm tone, usually warbling or intermittent, and are usually accompanied by a flashing light. There are two types of smoke detector: photoelectric and ionization. Photoelectric smoke detectors utilize a light-sensitive cell in either of two ways. In one type, a light source (a small spotlight) causes a photoelectric cell to generate current that keeps an alarm circuit open until visible particles of smoke interrupt the ray of light or laser beam, breaking the circuit and setting off the alarm. The other photoelectric detector widely used in private dwellings employs a detection chamber shaped so that the light-sensitive element cannot ordinarily "see" the light source (usually a light-emitting diode, LED). When particles of smoke enter a portion of the chamber that is aligned with both the LED and the photocell, the particles diffuse or scatter the light ray so it can be "seen" by the photocell. Consequently, a current is generated by the light-sensitive cell, producing an alarm.

- Ionization detectors employ radioactive material in quantities so tiny they are believed to pose no significant health hazard to ionize the air molecules between a pair of electrodes in the detection chamber. This enables a minute current to be conducted by the ionized air. When smoke enters the chamber, particles attach them-selves to ions and diminish the flow of current by attaching themselves to the ions in the air from the radioactive source. The reduction in current sets off the alarm circuit.
- Photoelectric smoke detectors are relatively slow to respond and are most effective in sensing the larger smoke particles generated by a smoldering, slow-burning fire. Ionization detectors are much faster to respond and are best at sensing the tiny smoke particles released by a fast-burning fire. Ionization smoke detection is also more responsive to invisible particles (smaller than 1 micron in size) produced by most flaming fires. It is somewhat less responsive to the larger particles typical of most smoldering fires. For this reason, some manufacturers produce combination versions of detectors. Many fire prevention authorities recommend the use of both photoelectric and ionization types in various locations in a private home. Either type of detector can be powered by batteries or by household current. Air sampling smoke detectors is a fire detection system where smoke is transported to and into a sampling port but they aspirate smoke into the detector sensing chamber rather than chamber using suction fans. Smoke in the immediate vicinity of the sampling ports is drawn into the detector sensing chamber. Air sampling smoke detectors have been employed in zero gravity environments (space vehicles) to detect the presence of smoke. The first smoke alarm was invented by W. Jaeger and E. Meili of Switzerland in 1941. The alarm was part of a project named Minerva Fire Alarm System. It was battery powered and had a flashing light and audible alarm when activated. It was also capable of sending a signal to the local fire station. (Nolan, 2000)

smoke detector, duct—a device located within a building air-handling duct, protruding into the duct, or located outside the duct that detects visible or invisible particles of combustion flowing within the duct. Actuation of the device may allow operation of certain control functions. National and local fire codes recognize the hazard posed by building air-handling systems to spread smoke, toxic gases, and flame from one area to another unless they are shut down. The primary purpose of duct smoke detection is to prevent injury, panic, and property damage by preventing the spread (re-circulation) of smoke. Duct smoke detection can also assist in protecting the air-handling system itself as well as sensitive equipment such as computer hardware. Duct smoke detectors may also be used to activate smoke exhaust dampers. Duct smoke detectors are not rated to be used as general area protection nor are general area detectors listed as duct smoke detectors. It may also be called a duct detector (DD). (Nolan, 2000)

smoke developed index (SDI)—a relative index of smoke produced during the burning of a material as measured by a recognized test. The smoke developed rating of materials is deter-mined by NFPA 25*5,* "Standard Test of Surface Burning Characteristics of Building Materials"; ASTM E84, "Surface Burning Characteristics of Building Materials"; and UL 723, "Tests for Surface Burning Characteristics of Building Materials." (Nolan, 2000)

smoke developed rating—a relative index for the smoke produced from a building material test sample as measured and calculated by the Steiner Tunnel Tests (NFPA 255, "Standard Method of Test of Surface Burning Characteristics of Building Materials"; ASTM E84, "Surface Burning Characteristics of Building Materials"; or UL 72*3,* "Tests for Surface Burning Characteristics of Building Materials"). Red oak has a rating of 100, whereas cement board has a rating of zero. It may also be called a smoke density index (SDI). (Nolan, 2000)

smoke eater—slang terminology referring to a firefighter. It has been applied due to the consequences of firefighters inhaling smoke during a fire incident. (Nolan, 2000)

smoke ejector—a device similar to a fan used to exhaust heat, smoke, and harmful combustion gases from a post-fire enclosed environment and to induct fresh air to the affected enclosure. Smoke ejectors are usually carried as part of the complement of equipment on a fire-fighting vehicle and are commonly electrically powered. (Nolan, 2000)

smoke exhaust system—natural (chimney) or mechanical (fans) ventilation for the removal of smoke from an enclosure to its exterior. The provision of a tenable environment for human life is not considered within the capability of a smoke exhaust system. (Nolan, 2000)

smoke extraction—the removal of smoke from an enclosed structure to aid firefighting operations. It is generally acknowledged that correct ventilation in fire conditions reduces (lateral) fire spread and resultant damage, enables firefighters to enter a building fire more easily, and provides greater visibility for fire-fighting activities. Manual efforts at the time of the fire may be employed, either through rapidly cut openings or the use of portable smoke extraction fans. Where smoke production may be anticipated in buildings, they are provided with automatic smoke extraction devices. (Nolan, 2000)

smoke extractor—machine or fan blower device for extracting or removing smoke and gases from a building or an enclosure.

smokehouse—a structure used to provide simulated smoke conditions for the training of firefighters. Training is provided in smoke environments where conditions can be monitored and observations made to improve performance. Simulated smoke is used as a safety measure and real fires are avoided. (Nolan, 2000)

smoke gas explosion—when unburnt gases from an unventilated fire flow through leakages into an closed space connected to the fire room, the gases there can mix very well with air to form a combustible gas mixture. A small spark is then enough to cause a smoke gas explosion, which can have very serious consequences. This phenomenon is, however, very observed in enclosure fires.

smoke inhalation—the breathing of the combustion products into the lungs. It is considered an injury that damages the respiratory system. The main dangers of smoke inhalation to the lungs are the presence of narcotic gases, principally carbon monoxide (CO), hydrogen cyanide (HCN), carbon dioxide (CO_2), and the asphyxiating effects of an oxygen-depleted atmosphere. Inhalation of narcotic gases often leads to hyperventilation, leading to an increase in the amount of narcotic gases taken into the lungs.

Narcotic gases also cause incapacitation by attacking the central nervous system. A low level of oxygen in the blood results in low oxygen levels to the brain, which causes impaired judgment and concentration. These effects may confuse, panic, or incapacitate an individual. Incapacity occurs in less than 10 minutes with a 0.2 percentage concentration of carbon monoxide (CO) if heavy activities are being performed. Carbon monoxide combines with the hemoglobin of the blood, preventing oxygen from binding with hemoglobin, which will cause death. Carbon monoxide has an affinity to hemoglobin 300 times that of oxygen. The degree of poisoning depends on the time of exposure and concentration of the combustion gases. If the percentage of carbon monoxide in the blood rises to 70 to 80-percent, death is likely to ensue. Hydrogen cyanide is also referred to as hydrocyanic acid. The cyanides are true proto-plasmic poisons, combining in the tissues with enzymes associated with cellular oxidation. They therefore render oxygen unavailable to the tissues and cause death through asphyxia. Inhaling concentrations of more than 180 ppm of HCN leads to unconsciousness in a matter of minutes, but the fatal effects would normally be caused by carbon monoxide poisoning after HCN has made the victim unconscious. Exposure to concentrations of 100 to 200 ppm for periods of 30 to 60 minutes can also cause death. Inhalation of hot smoke gases into the lungs will also cause tissue damage (burns) such that fatal effects could result in 6 to 24 hours after the exposure. Whenever the effects of smoke may affect individuals, protective measures must be provided, such as smoke management systems, smoke barriers, or fresh air supplies. (Nolan, 2000)

smoke interface—the layer in a compartment that separates the smoke layer from the non-smoke layer. A smoke layer will gradually increase as the fire increases if the smoke layer is not vented, which lowers the smoke interface and may eventually fill the compartment. Fully developed fires have a smoke interface several centimeters (inches) above the floor. Cooling, or a decrease in the fire, may allow the smoke layer to dissipate and the interface will rise. May also be called smoke layer interface. (Nolan, 2000)

smoke layer—the accumulated thickness of smoke in an enclosure. (Nolan, 2000) *smoke management system (SMS)*—natural or mechanical ventilation for the control or removal of smoke from an enclosure. Smoke management systems provide for smoke control to assist in personnel evacuation and firefighting activities. They provide pressurized areas within a building to prevent the entrance of smoke or to direct smoke to the outside of the building. Smoke control systems can be designated a dedicated or nondedicated. A dedicated smoke control system is provided for smoke control only within an enclosure. It is a separate air moving and distribution system that does not function under normal building operating conditions. It is specifically designated for smoke control functions. A nondedicated smoke control system shares its components with other building systems such as the heating, ventilation, and air conditioning (HVAC) system. Activation of it causes the system to change its mode of operation from normal building HVAC requirements to that of smoke control. (Nolan, 2000)

smoke pencil—a chemical solid that is ignited to produce smoke for testing purposes, primarily for the integrity testing of enclosures that are protected by fixed gaseous fire suppression systems. (Nolan, 2000)

smoke-proof—resistant to the spread of smoke. (Nolan, 2000)

smoke shaft—a continuous shaft extending the full height of a building, with opening at each floor and a fan at the top; during a fire, the dampers on the fire floor open and the fan vents the combustion products.

smoke seal—a flexible membrane provided around the edge of a rated fire door frame. It is used to prevent the passage of smoke particles and combustion gases through the door seam surrounding a fire-rated door when it is closed.

smoke stop—a barrier provided to stop the spread of smoke to another area. (Nolan, 2000)

smoke test—a method for confirming the integrity of a chimney and for detecting any cracks in a masonry chimney flue, or deterioration or breaks in the seal or joints of a factory-built or metal chimney flue. Smoke is generated in a fire-place or solid fuel-burning appliance while simultaneously covering the chimney termination. Smoke leakages are then checked for through the chimney walls or suspected openings. (Nolan, 2000)

smoke visibility—the ability to perceive objects through smoke at a specific distance. Smoke visibility is necessary during fire conditions for evacuation of occupants, rescue operations, and firefighting activities. The ability to see through smoke is a measure of smoke visibility and can be related to the mass optical density (the yield of solid and liquid particulates of smoke generation). Smoke reduces visibility by a reduction in available light through the absorption and scattering of light by the smoke particulates. (Nolan, 2000)

smoldering—a slow combustion process between oxygen and a solid fuel. (Quintiere, 1998)

soot—tiny particles consisting of carbon, often formed in diffusion flames and in very rich premixed flames.

spalling—generally, the breaking away or explosion of concrete materials from a fire exposure. It occurs due to stresses set up by steep temperature gradient onto aggregates in the concrete that expand, or moisture that is trapped and vaporizes without any means of venting safely. Major factors that affect spalling behavior are moisture contact, rate of temperature rise, permeability, porosity, restraint, and reinforcement. Spalling also is known to occur in fire-resistant protective coating for steel where asbestos or other fiber fillers are added to concrete or other cementitious material to increase insulation value. Spalling promotes exposure of structural steel, steel reinforcing or pre-stressing cables; thermal transmission due to decreased section thickness; fire passage due to openings caused by extreme spalling; and degradation in moment-bearing capacity due to reduced element cross sections. (Nolan, 2000)

species—another name for chemical compounds, usually gases. (Quintiere, 1998)

specific heat—property that measures the ability of matter to store energy. (Quintiere, 1998)

spot detector—a device whose detection element is concentrated at a particular location. Examples are bimetallic detectors, fusible alloy detectors, local rate-of-rise and smoke detectors, and thermoelectric detectors. Spot-type detectors have a defined area of coverage. (Nolan, 2000)

spontaneous combustion—the outbreak of fire without application of heat from an external source. Spontaneous combustion may occur when combustible matter, such as hay or coal, is stored in bulk. It begins with a slow oxidation process (bacterial fermentation or atmospheric oxidation) under conditions not permitting ready dissipating of heat, such as in the center of a haystack or a pile of oil rags. Oxidation gradually raises the temperature inside the mass to the point at which a fire starts.

spontaneous combustion—ignition of a combustible material caused by the accumulation of heat from oxidation reactions.

spontaneous heating—slow oxidation of an element or compound which causes the bulk temperature of the element/compound to rise without the addition of an external heat source.

spontaneous ignition—ignition that occurs as a result of progressive heating, as contrasted with instantaneous ignition caused by exposure to a spark or a flame. The spontaneous ignition can result from self-heating caused by slow oxidation, or from an external heat source.

sprinkler—a water deflector spray nozzle device used to provide distribution of water in specific characteristic patterns and densities for the purpose of cooling exposures exposed to unacceptable heat radiation, and controlling and suppressing fires or combustible vapor dispersions. Water droplet size from a discharging sprinkler is one key factor in deter-mining the effectiveness of its water spray. Water droplets penetrate a fire plume to reach a burning commodity by two modes: gravity and momentum. In the gravity mode, the downward velocity of the water droplets falling through a fire plume must be greater than the upward velocity of the fire plume for it to reach the base of the fire. Gravity action alone cannot accomplish this. Increased system pressure provides water droplets with greater downward thrust (momentum) to over-come the upward thrust of the fire plume. (Nolan, 2000)

sprinkler, automatic—a fire suppression or control device that operates automatically when its heat-actuated element is heated to its thermal rating or above, allowing water to discharge over a specific area. (NFC Online Glossary) *sprinkler density*—calculated by gallons per minute discharge divided by the square footage covered.

sprinkler, dry (pendent)—an automatic sprinkler that is not provided with water continuously at its inlet. It is provided where freezing conditions are a concern if the sprinkler system is seasonally drained down. A seal is provided at the main supply pipe to prevent water from entering the sprinkler assembly until the sprinkler is activated from fire conditions. Typically, it is designed so that the fusible element opens the sprinkler and releases a spring-loaded tube that breaks the glass inlet water seal. This allows water to flow to the sprinkler. pattern of the sprinkler. (Nolan, 2000)

sprinkler, on-off—a cycling (on-off), self-actuating snap-action, heat-actuated sprinkler. Water flow automatically shuts off from the sprinkler when the fire has been extinguished (no heat is available to activate the sprinkler head) and it is automatically reset for later operations. This type of sprinkler requires a water supply that is free of contaminants (potable) that could interfere with its operation. It does not have to be replaced after operation. It is provided to avoid water damage by eliminating the need to shut off the water supply after a fire has been extinguished. Typical applications include areas containing high-value inventories, materials, or equipment highly sensitive to water areas subject to flash or repeat fires, and where the water supply is limited. (Nolan, 2000)

sprinkler, open—a sprinkler device that has a permanent open orifice and is not actuated by a heat responsive element. Instead, an upstream device controls water flow from the sprinkler. Its primary purpose is to provide adequate distribution of water in a prescribed pattern. (Nolan, 2000)

sprinkler, pendent—a sprinkler designed for and installed with the head in a downward fashion from the piping, rather than placed in an upward position above the supply pipe. They are primarily used where upright sprinklers cannot be used because of lack of space (headroom) or where concealment of sprinkler piping above a false ceiling is desired because of aesthetic reasons (office areas). (Nolan, 2000)

sprinkler, pilot—an automatic sprinkler head or thermostatic fixed temperature device used in a pneumatic or hydraulic fire detection system, normally connected to an actuating valve that releases when the pilot device is activated. (Nolan, 2000)

sprinkler pintle—an indicating device on sprinklers that have small and large orifices and a standard 0.5 in. (1.27 cm) pipe thread. A pintle highlights the sprinkler orifice size difference compared to standard orifices; that is, 0.5 in. (1.27 cm) sprinklers with 0.5 in. (1.27 cm) pipe threads. It consists of a small, short cylinder centrally mounted and perpendicular to the deflector plate, on the side opposite the water discharge. (Nolan, 2000)

sprinkler, recessed—sprinklers in which all or part of the body, other than the shank thread, is mounted within a recessed housing. Recessed sprinklers are mainly provided for aesthetic reasons, although protection of the sprinkler installed, tested, and evaluated before the installation of the finished ceiling. (Nolan, 2000)

sprinkler, residential—a type of fast-response sprinkler that is well known for its ability to enhance human survivability in the room of fire origin and is used in the protection of dwelling units as specified by listing or approval agencies. The first effective fast-response sprinkler for residential use was developed by the Factory Mutual Research Corporation (under contract to the United States Fire Administration) and was demonstrated in 1979. (Nolan, 2000) *sprinkler riser*—the vertical portion of a sprinkler system piping from the ground main to the horizontal cross main that feeds the branch lines. (Nolan, 2000)

sprinkler, sidewall—sprinkler designed to be installed on piping along the sides of a room instead of the normal sprinkler spacing requirements. The sprinkler is made with a special deflector that deflects most of the water away from the nearby walls in a pattern similar to a quarter of a sphere. A small portion of the water is directed at the wall behind the sprinkler. Sidewall sprinklers are generally used because of aesthetic concerns, building construction arrangements, or installation economy considerations. (Nolan, 2000)

sprinkler spacing—distribution of automatic sprinklers to provide the area coverage specified for light, ordinary, and extra hazardous occupancies. (Nolan, 2000)

sprinkler system—for fire protection purposes, an integrated system of underground and overhead piping designed in accordance with fire protection engineering standards. The installation includes one or more automatic water supplies. The portion of the sprinkler system above ground is a network of specially sized or hydraulically designed piping installed in a building, structure, or area, generally over-head, and to which sprinklers are attached in a systematic pattern. The valve controlling each system riser is located in the system riser or its supply piping. Each sprinkler system riser includes a device for actuating an alarm when the system is in operation. The system is usually activated by heat from a fire and discharges water over the fire area.

The first recorded patented sprinkler system was developed in London in 1806 by John Carey. It consisted of a pipe fed by a gravity tank with a number of valves held closed by counterweights on strings; when a fire burned the strings, the valves were opened. The sprinkler head consisted of an outlet similar to a water can perforated nozzle that faced downward. A refined sprinkler system was patented (British Patent No. 3201) by William Congreve in 1809. His system used fusible metal on the wires controlling water supply valves and had various water distribution devices including perforated pipes, devices similar to sidewall sprinklers. Many manually operated systems were installed in 19^{th} century buildings. The first system in America was installed in a plant in Lowell, Massachusetts in about 1852. A number of perforated pipes were fed by a main riser that could be turned on in an adjoining area. James B. Francis improved the distribution of this system by using pipe with perforations about 0.1 in. (0.25 cm) in diameter and spaced 9 in. (22.86 cm) apart, alternately on different sides, to provide a spray at water at an angle slightly above the horizontal. Insurance companies of the time continued to improve on the design. These systems resulted in frequent water damage in parts of a room or building untouched by fire. An improvement was sought and found in the Parmelee sprinkler head, which was introduced in the United States in the 1870s. The Parmelee head had a normally closed orifice that was opened by heat from a fire. The first sprinkler successfully used over a long period was the Grinnel "glass button," which appeared in 1890 (previous Grinnel types were developed from 1884 to 1888). Since about 1900, most changes to sprinklers have been refinements in the design (deflector or activating mechanism improvements) rather than conceptual changes. Modern versions use a fusible link or a bulb containing chemicals that breaks at about 160 °F (70 °C) to open the orifice. Modern sprinkler heads are designed to direct a spray downward. Most sprinkler systems are wet-head; that is, they use pipes filled with water. Where there is danger of freezing, however, dry-head sprinklers are used, in which the pipes are filled with air under moderate pressure; when the system is activated, the air escapes, opening the water-feeder valves. An improved version has air under only atmospheric pressure and is activated by heat-sensing devices. Another special type, used in high-hazard locations, is the deluge system, which delivers a large volume of water quickly. The definitions of several types of sprinkler systems follow. (Nolan, 2000)

- *wet pipe system*—a sprinkler system that uses automatic sprinklers installed in a piping system containing water and connected to a water supply. Individual sprinklers discharge immediately when they are affected by the heat of a fire. Sprinklers that are not affected by the heat remain closed. It is used where there is no danger of the pipes freezing and where no other conditions require the use of a special system. A wet pipe sprinkler system that uses automatic sprinklers installed in a piping system containing an antifreeze solution and connected to a water supply. The antifreeze solution is discharged (followed by water) immediately upon operation of the sprinklers, which are opened from the heat effects from a fire.
- *dry pipe system*—a sprinkler system that uses automatic sprinklers installed in a piping system containing air or nitrogen under pressure. A release of pressure on the system (as from the opening of a sprinkler) permits the water pressure to open a valve known as a dry pipe valve. The water then flows into the piping system and out the opened sprinklers. Dry pipe systems operate more slowly than do wet pipe systems and are more expensive to install and maintain, therefore they are only used where there is an absolute necessity, such as freezing conditions.
- *pre-action system*—a sprinkler system using automatic sprinklers installed in a piping system containing air that may or may not be under pressure, with a supplemental detection system installed in the same areas as the sprinklers. Actuation of a detection system opens a valve that permits water to flow into the sprinkler piping system and to be discharged from any sprinklers that have opened from the effects of a fire. Sprinklers that are not affected by heat from a fire remain closed. They are designed to counteract the operational delay of dry pipe systems and eliminate the damage from a broken pipe or sprinkler head.
- *combined dry pipe and pre-action system*—a sprinkler system that uses automatic sprinklers installed in a piping system containing air under pressure, with a supplemental fire detection system installed in the same areas as the sprinklers. Operation of the detection system actuates tripping devices that open dry pipe valves simultaneously without a loss of air pressure in the system. Operation of the fire detection system also opens air exhaust valves at the end of the system feed main, facilitating the filling of the system with water, which normally occurs before any sprinklers open. The detection system also serves as an automatic fire alarm system for the area. Only sprinklers that are affected by heat from a fire are opened; others remain closed.
- *deluge system*—a sprinkler system using open sprinklers installed in a piping system connected to a water supply through a valve that is opened by the operation of a detection system installed in the same areas as the sprinklers. When the deluge valve opens, water flows into the system piping and discharges from all sprinklers. There are no closed sprinklers in a deluge system. Its objective is to deliver the most amount of water in the least amount of time. Deluge systems are specified for high hazard locations where a fire occurs quickly and reaches very high temperatures, such as from highly flammable fuels.
- *water spray system*—a fixed pipe system connected to a water supply and equipped with spray nozzles for specific discharge and distribution over the surface or area to be protected. The piping system is connected to the water supply through an automatic or manually activated valve that initiates the flow of water. The control valve is actuated by the operation of automatic fire detection devices installed in the same area as the water spray nozzles (in special cases the automatic detection devices may be located in another area).
- *foam-water sprinkler system*—a fire protection piping system that is connected to a source of air-foam concentrate and a water supply and is equipped with appropriate discharge devices for extinguishing agent discharge and for distribution over the area to be protected.

- *foam-water spray system*—a fire protection piping system connected to a source of air-foam concentrate and a water supply and equipped with foam-water spray nozzles (aspirating or non-aspirating) for extinguishing agent discharge and for distribution over the area to be protected.

Fire protection sprinkler systems may also have several different piping arrangements:

- *gridded system*—a sprinkler system piping arrangement where parallel cross-mains are connected by multiple branch lines. An operating sprinkler receives water from both ends of its branch line while other branch lines help transfer water between cross-mains.
- *looped system*—a sprinkler system piping arrangement where multiple cross-mains are connected to provide more than one path for water to flow to an operating sprinkler, and branch lines are connected to each other.
- *circulating closed-loop system*—a wet pipe sprinkler system that has a non-fire-protection connection to an automatic sprinkler system in a closed-loop piping arrangement. This allows the sprinkler piping to conduct water for heating or cooling in an economical fashion without impacting the ability of the sprinkler system to support its fire protection purpose. Water is not removed or used from the system, but is only circulated through the piping system.

sprinkler temperature classes—sprinklers are designated to operate at specific fire temperatures and are segregated into temperature classes. The actual temperature rating of sprinklers may be less important than is popularly perceived. Where ceiling temperatures rise rap-idly, the difference between 165 °F (74 °C) and 212 °F (100 °C) for the first sprinkler to operate may not be important, but it may affect the number of heads that operate. Higher temperature sprinklers are used where the ambient temperatures may be higher than ordinary temperature ratings.

sprinkler tong—a portable tool used to stop the flow from a sprinkler head.

sprinkler types:
- spray sprinkler
- conventional sprinkler
- fast-response sprinkler
- residential sprinkler
- extended coverage sprinkler
- quick-response sprinkler
- quick-response extended coverage sprinkler
- large-drop sprinkler
- early suppression fast response sprinkler (ESFR)
- open sprinkler
- special sprinkler
- specific application sprinkler
- flush sprinkler
- concealed sprinkler
- recessed sprinkler
- corrosion-resistant sprinkler
- in-rack sprinkler
- dry sprinkler

sprinkler, upright—a sprinkler designed for and placed in an upward position above the sup-ply pipe, rather than installed in a downward fashion from the supply pipe. It directs 100-percent of its water toward the floor. A sprinkler designated for upright installation cannot be used in the downward position because the water will be directed to the ceiling instead of toward the fire incident and will not achieve its density pattern for fire control and extinguishment. (Nolan, 2000)

spurious actuation—an undesirable actuation of a component or system due to an uncontrolled or unintended signal.

spurious actuation/operation—a change (full or partial) in the operating mode or position of equipment. These operations include but are not limited to: (a) opening or closing normally closed or open valves, (b) starting or stopping of pumps or motors, (c) actuation of logic circuits, (d) inaccurate instrument reading.

spurious operation—the undesired operation of equipment resulting from a fire that could affect the capability to achieve and maintain safe shutdown. (Regulatory Guide 1.189)

spurious indications—false indications (process monitoring, control, annunciator, alarm, etc.) that may occur as a result of fire and fire suppression activities.

spurious signals—false control or instrument signals that may be initiated as a result of fire and fire suppression activities.

suppression—the sum of all the work done to extinguish a fire from the time of its discovery.

stack effect—the air or smoke movement of migration through a tall building due to pressure differentials caused by temperature.

stair pressurization—increasing the air pressure in stair wells (usually with fan systems) to provide refuge area from fire and smoke.

standard—document that address a specific fire safety issue. There are standard practices for installing and inspecting fire protection equipment; and standard methods for testing personal protective equipment, building products and fire protection equipment.

standard sprinkler pendent (SSP)—a sprinkler designated to be installed with its outlet oriented to allow its spray to be directed upward.

standard sprinkler upright (SSU)—a sprinkler designated to be installed with its outlet orientated to allow the spray to be directed downwards.

standpipe hose cabinet—a cabinet provided for the provision of standpipe outlets and/or fire hose storage. Fire hoses are usually pre-connected and stored in a rack with release pins.

standpipe, manual—a standpipe system that relies on the fire service to supply water to it to meet its demands.

standpipe, semi-automatic—a standpipe system that is connected to an adequate water supply, but requires a control device activation to supply water to the hose outlets.

standpipe system—the provision of piping, riser pipes, valves, firewater hose connections, and associated devices for the purpose of providing or supplying firewater hose applications in a building or structure by the occupants or fire department personnel. Standpipe systems are classified according to their intended use by the building occupants, the fire department, or both. Many high-rise or other large buildings have an internal system of water mains (standpipes) connected to fire hose stations. Trained occupants or employees of the building management operate the hoses until the fire department arrives. Firefighters can also connect their hoses to outlets near the fire. The National Fire Protection Association (NFPA) classifies standpipe systems based on their intended use as Classes I, II, or III. Class I is provided for fire service use or other personnel trained in handling heavy fire streams. It is distinguished by the provision of 2.5 in. (6.35 cm) hose stations or hose connections. A Class II standpipe system is provided for use by the building occupants and by the fire service during initial attack operations. It is characterized by the provision of 1.5 in. (3.81 cm) hose stations. A Class III standpipe system combines both the features of Class I and Class II systems.

For fire protection purpose, an integrated system of underground and overhead piping designed in accordance with fire protection engineering standards. The installation includes one or more automatic water supplies. The portion of the sprinkler system aboveground is a network of specially sized or hydraulically designed piping installed in a building, structure, or area, generally overhead, and to which sprinklers are attached in a systematic pattern. The valve controlling each system riser is located in the system riser or its supply piping. Each sprinkler system riser includes a device for actuating an alarm when the system is in operation. The system is usually activated by heat from a fire and discharged water over the fire area.

standpipe systems
Class I standpipe system—a 2½" hose connection for use by fire departments and those trained in handling heavy fire streams.

Class II standpipe system—a 1½" hose system which provides a means for the control or extinguishment of incipient stage fires.

Class III standpipe system—a combined system of hose which is for the use of employees trained in the use of hose operations and which is capable of furnishing effective water discharge during the more advanced stages of fire (beyond the incipient stage) in the interior of workplaces. Hose outlets are available for both 1½" and 2½" hose.

standpipe, wet—a standpipe system that is permanently charged with water for immediate use.

static ignition hazard—an electrical charge build-up of sufficient energy to be considered an ignition source. For an electrostatic charge to be considered an ignition source, four conditions must be present: (1) a means of generating an electrostatic charge, (2) a means of accumulating an electrostatic charge of sufficient energy to be capable of producing an incendiary spark, (3) a spark gap, and (4) an ignitable mixture in the spark gap. Removal of one or more of these features will eliminate a static ignition hazard. Static charges can accumulate on personnel and metallic equipment. If the static accumulation is separated by materials that are electrically nonconducting, a dangerous potential difference may occur. These nonconducting materials or insulators act as barriers to inhibit the free movement of electrostatic charges, pre-venting the equalization of potential differences. A spark discharge can occur only when there is no other available path of greater conductivity by which this equalization can be affected (bonding or grounding).

spurious operation—the undesired of equipment resulting from a fire that could affect the capability to achieve and maintain safe shutdown.

standard time-temperature curve—curve representing the standard reproducible test fire used since 1918 to measure the fire endurance of building materials.

Stefan-Boltzmann law—an equation that specifies the intensity of radiation emitted by an object, in terms of its absolute temperature (K).

steiner tunnel test—test to determine the surface burning characteristics of building materials in which the flame spread of the test material is compared to asbestos cement board, rated 0, and red oak, rated 100. The higher the rating, the greater the potential hazard. In addition to flame spread, the test also measure smoke development and fuel contributed to the fire. (ASTM E84, NFPA 255, UL 723)

stoichiometric—refers to the amount of air needed to burn the fuel (and to combustion products formed).

stoichiometric reaction—chemical A is said to undergo a stoichiometric reaction with chemical B when the proportions of A and B are such that there is no excess of A and B remaining after the reaction.

stoichiometric air to fuel mass ratio—the ratio of air to fuel mass needed to burn all the fuel to combustion.

stoichiometry—a balance chemical equation defines the stoichiometry of a reaction; stoichiometry gives the exact proportions of the reactants for complete conversion to products, where no reactants are remaining. Stoichiometric ratio is the ideal reaction mass fuel to oxygen (or air) ratio and is given the symbol r.

stratification—the rising or setting of layers of smoke, according to the density or weight, with the heaviest layer on the bottom; smoke layers usually collect from the ceiling down.

sublimation—the evaporation of molecules from a solid to form a gas in the absence of a liquid.

surface emissive power—the heat that is radiated outward from a flame per unit surface area of the flame. It measurement and calculation units are normally kW/m^2. (Nolan, 2000)

superheat limit temperature—the temperature of a liquid above which flash vaporization can proceed explosively.

supervisory service—the service required to monitor performance of guard patrols and the operative condition of automatic sprinkler systems and of other systems for the protection of life and property.

supervisory signal—a signal indicating the need of action in connection with the supervision of guards' tours, sprinkler and other extinguishing systems or equipment, or with the maintenance features of other protective systems.

suppression—the sum of all the work done to extinguish an unwanted fire from the time of its discovery until extinguishment. (NFC Online Glossary)

temperature—measurement of heat energy content for a substance/material/fluid, etc.

thermal conductivity—the property of matter that represents the ability to transfer heat by conduction.

thermal decomposition—chemical breakdown of a material induced by the application of heat.

thermal decomposition (pyrolysis)—a process whereby chemical bonds within macromolecules forming a solid are broken by heat and flammable vapors are released.

thermal diffusivity—ratio of a material's thermal conductivity to the product of its heat capacity and density. It is the measure of a material's disposition to absorb and transmit heat to the interior of the material.

thermal energy—energy directly related to the temperature of an object.

thermal expansion—thermal expansion becomes important when an element is heated non-uniformly, as in the case of a fire. It may cause increased axial loads in columns, resulting in earlier buckling failure. In case of beams, however thermal expansion also affects the strain and subsequent stress distribution through a beam section. Normally, tensile strain is increased while compressive strain is decreased. The resulting strain distribution causes a greater deflection of the beam at midspan. The coefficient if thermal expansion varies with temperature. In case of concrete, thermal expansion is significantly affected by aggregate type. Thermal expansion also affects spalling (chipping and scaling) characteristics at the surface of an element.
If the member is partially restrained axially, any added axial thrust caused by the thermal expansion of the element will have the net effects of increasing the moment-bearing capacity (load) of the beam. Of course, the strain caused by the thermal expansion should be considered when calculating deflection histories of elements. Generally, beam-type assemblies are given restrained and unrestrained fire resistance rating.

thermal/hydraulic time line—a documented evaluation of the response of important reactor plant parameters to a postulated transient (thermal/hydraulic analysis) with respect to the time available to accomplish required shutdown functions. For example, the time available to establish Auxiliary Feedwater (AFW) following a reactor scram in a PWR would be determined by a thermal/hydraulic analysis. The objective of the thermal/hydraulic time line is to compare this time to the time needed for operators to perform all system and equipment alignments necessary to establish a secure source of AFW.
Note: All operator actions delineated in alternative shutdown procedures must be supported by a thermal/hydraulic timeline.

thermal inertia—a thermal property responsible for the rate of temperature rise, $k\rho c$. Low $k\rho c$ - Surface heats rapidly, fast ignition (b) High $k\rho c$ - Surface heats slowly, slow ignition.

thermal inertia—thermal inertia is a measure of the tendency of heat to collect on the surface of a material. It may be a better indicator of ignitability than ignition temperature. Material such as balsa wood and foamed plastics have low thermal inertia; their surfaces will heat up quickly, making them easy to ignite, and to produce rapid flame spread. By contrast, materials with relatively high thermal inertia, such as ebony wood, are difficult to ignite and do not spread fire as rapidly.

thermal inertia—thermal inertia is the resistance to temperature change in a material when the surrounding temperature changes. The lower the thermal inertia of a material, the faster its surface will heat, with accompanying increasing temperature. Thus response to exposing conditions is important in terms of how quickly a combustible material reaches its ignition temperature, how fast it burns when ignited, and the rate of flame spread across its surface. Thermal inertia also plays an important part in determining the amount of heat absorbed by wall, ceiling, and other materials in a compartment. Thermal inertia has an important effect on both the onset of flashover and eventual impact of the fire.

Thermal inertia is an intrinsic material property. Its influence on the temperature of an object is strictly a function of heat transferred to the object. As a materia's surface is heated (or cooled), heat is conducted to (or from) the material's interior. At first, this heat transfer is not constant and depends on the thermal inertia of the material. Once the rate of heat transfer from the surface to the interior is constant , the rate of surface temperature range depends only on the conductivity of the material, without regard to the material's density or specific heat. For thicker materials with high density thermal inertia, the time to reach this condition can be extensive.

thermal insulation—one or more layers of noncombustible or fire-resistant, high-density material to reduce the passage of heat for protection against exposure of an ignition source (hot surface), burn injuries, or heat damage. (Nolan, 2000)

thermal lag—when a fixed temperature device senses a rise in ambient temperature, the temperature of the surrounding air will always be higher than the operating temperature of the device itself. This difference between the operating temperature and the actual air temperature is commonly referred to as thermal lag, an is proportional to the rate at which the temperature is rising. (Nolan, 2000)

thermal layering—the process of gases to form layers based on temperature where the hottest layers in a confined space are located at the highest elevations (due to lower densities) and the lowest temperature gases are located at the lowest elevations (due to the highest densities). (Nolan, 2000)

thermal protective clothing—the protective apparel provided for and used by firefighters and other individuals as protective insulation against the adverse effects of heat. Generally consisting of helmets, boots, gloves, hoods, coats, and pants. (Nolan, 2000)

thermal penetration time—time required to be conducted through a particular object, typically to each side of the wall material.

thermal runway—an accelerating chemical reaction due to an imbalance between heat loss and energy production.

thermocouple—device made of two dissimilar metal wires to measure temperature.
(Quintiere, 1997). A temperature difference across an interface of two different metals causes a voltage proportioned to the temperature difference.

thermoplastic—a polymeric solid which melts at a temperature lower that its ignition temperature.

thermoset—a polymeric solid which does not melt but decomposes to generate vapors and char.

thermal lag—the difference between the operating temperature of a fire detection device such as sprinkler head and the actual air temperature when the device activates.

thermal transmission —among the standard criteria for the fire resistance of a building element is its ability to insulate an adjacent space from the fire zone to prevent ignition of combustibles on the unexposed side of the wall. The problem concerning the prediction of the element's temperature distribution evolves from the effects of increased temperature on thermal properties. The values of thermal conductivity, heat capacity, and density often vary considerably with temperature and material composition, as in the case of concrete. These terms define the thermal diffusivity, which is critical to the analysis of heat flux through an element.

thermoplastic cable—a cable material which will soften, flow, or distort appreciably when subjected to sufficient heat and pressure. Examples are polyvinyl chloride and polyethylene.
Note: Cables using thermoplastic insulation *are not* usually qualified to IEEE Std. 383.

thermoset cable—a cable material which will not soften, flow, or distort appreciably when subjected to heat and pressure. Examples are rubber and neoprene.

Note: Cables using thermoplastic insulation *are* usually qualified to IEEE Std. 383.

time/current characteristic curve (trip curves)—a graphic illustration of the operating characteristics of electrical protection devices (fuse, circuit breaker, or relay). The tripping characteristics of protective devices is represented by a characteristic tripping curve that plots tripping time versus current level. The curve shows the amount of time required for the protective device to trip at a given overcurrent level. The larger the overload or fault current, the faster the breaker/fuse will operate to clear the circuit (referred to as inverse time characteristics). A comparison of characteristic trip curves is necessary to determine if proper coordination exists between devices.

TNT equivalence—the amount of TNT (trinitrotoluene) that would produce observer damage effects similar to the explosion under consideration. For non-dense phase explosion, the equivalence has meaning only at a considerable distance from the explosion source, where the nature of the blast wave arising is more or less comparable with that of TNT.

total enclosure surface area—the total surface area bounding the enclosure, not including openings.

total flooding system—a fixed suppression system which is arranged to automatically discharge a predetermined concentration of agent into an enclosed space for the purpose of fire extinguishment or control.

total flooding system—a supply of dry chemical permanently connected to fixed piping and nozzles that are arranged to discharged dry chemical into an enclosure surrounding the hazard.

The provision of a fire extinguishing agent in an enclosed area that completely fills the volume to effect extinguishment or prevent a fire incident. They may be gaseous, liquid, or solid. Most common agents are gaseous, such as carbon dioxide (CO_2) or Halon; liquid types use foaming agents, such as high expansion foam, and solid form may use dry chemical systems. Gaseous agents require a particular concentration of agent to be achieved within the volume before extinguishment can be achieved. Total flooding is used where it may be difficult to immediately reach the seat of a fire, such as in machinery spaces, a computer room, and engine compartments. Because some agents (CO_2) may deplete oxygen from the enclosure to extinguish the fire, special precautions (pre-alarm, evacuation notification, reentry precautions, etc.) must be implemented where personnel may also be present. Application of a total flooding system to an enclosure requires the enclosure to be adequately sealed to prevent the release of the agent out of the enclosure once it is applied.

toxicity—the nature and extent of adverse effects of a substance upon a living organism.

transmissivity—the fraction of radiant energy transmitted from a radiating object through the atmosphere to a target after reduction by atmospheric absorption.

transient combustibles—combustibles materials that are not fixed in place or an integral part of an operating systems or components. (Regulatory Guide 1.189)

travel distance—the length of the path a building occupant must travel before reaching an exterior door or enclosed exit stairway, exit passageway, or horizontal exit. The total length of the exit access.

triplex cable—a cable composed of three insulated single conductor cables twisted together. (IEEE Std. 100-1988)

Note: AC power cables are usually of triplex design.

trouble signal—an audible signal indicating trouble of any nature, such as a circuit break or ground, occurring in the devices or wiring associated with a protective signaling system.

turbulent—refers to randomly fluctuating fluid motion around a mean flow.

under-ventilated—Less than stoichiometric air is available.

upper and lower flammability limits—Concentration of fuel in air in which a premixed flame can propagate.

unconfined vapor cloud explosion (UNVC)—unconfined vapor cloud explosion where there is a cloud of flammable gas/vapor which is within the flammable region and an ignition source creates a deflagration seen as a fireball.

unpiloted ignition—ignition point of a material due entirely to incident heat flux on object, with no pilot or spark present.

unprotected cable/circuit—a cable/circuit which is not provided with fire protection features sufficient to satisfy applicable requirements (Section III.G.2 of Appendix R or Position C.5.b of SRP 9.5.1).

unresolved safety issue (USI)—according to NUREG-0933, "A Prioritization of Generic Issues," a USI is defined as a matter affecting of nuclear power plants that poses important questions concerning the adequacy of existing safety requirements for which a final resolution has not yet been developed and that involves conditions not likely to be acceptable over the lifetime of the plants affected.

upper flammability limit—the highest concentration of fuel in air at normal temperatures and pressure that can support flame propagation is known as the upper flammability limit (UFL) or upper explosive limit (UEL).

vapor barrier—that material used to prevent or substantially inhibit the transfer of water, corrosive liquids and steam or other hot vapors from the outside of a garment to the wearer's body.

vaporization temperature—the temperature of a vaporizing fuel while burning, or needed to cause vaporization.

vent, heat, and smoke—an assembly rated for the release of heat or smoke from a fire event. Heat and smoke vents are commonly provided in the roofs of buildings. They may be activated by means of automatic detection or constructed of materials that cause the material to melt from the heat of the fire and create an opening for venting. The sizing of heat or smoke vents should be based on the anticipated fire event.

vent flow—if there is an opening to the adjacent room or out to the atmosphere, the smoke will flow out through it as soon as the hot layer reaches the top of the opening. Often, the increasing heat in the enclosure will cause the breakage of windows and thereby create an opening.

ventilation—the process of supplying or removing an atmosphere to or form any space by natural or mechanical means.

ventilation factor—the parameter controlling smoke flow rate through a door or window

ventilation-limited or ventilation-controlled—state of a compartment fire where the air supply is limited; smoke gases will have nearly zero oxygen left; under-ventilated.

ventilation-controlled fire—a fire of which the heat release rate or growth is controlled by the amount of air available to the fire. (NFC Online Glossary)

ventilation, mechanical—the use of exhaust fans, blowers, air conditioning systems, or smoke ejectors to remove products of combustion (smoke, heat, gases) from an area affected by a fire event. (Nolan, 2000)

ventilation rate—ventilation rate is based on air changes per hour and is calculated by the use of 100-percent outside air for the supply air that is exhausted. Air changes per hour is calculated on the basis of the maximum aggregate volume (under normal operating conditions) of the space to be ventilated. (NFC Online Glossary) *venting, fire*—the escape of smoke, noxious or toxic fumes, and heat through openings in a building provided as part of the structure (a chimney) or instituted during emergency fire-fighting actions for the removal of hot gases and smoke particles. In fire conditions, it is generally accepted that the efficient venting of heat, hot gases, and smoke reduces the lateral spread and subsequent damage and enables firefighters to more easily enter a building on fire and begin fire protection measures. In order for roof or ceiling vents to operate efficiently, there has to be an adequate source of low level replacement air. Ventilation through the top of a structure or its roof vents or similar devices (skylights) is called vertical ventilation or top ventilation. (Nolan, 2000)

view factor—the ratio of the incident radiation received by a surface to the emissive power from the emitting surface per unit area.

visibility—the maximum distance one can recognize objects, often referring to an exit sign in a smoke-filled compartment.

voltage—the effective root-mean-square (rms) potential between any two conductors or between a conductor and ground. Voltages are expressed in nominal values unless otherwise indicated. (IEEE Std 100-1988)

Clarification: The electrical force that causes free electrons to move from one atom to another. Similar to pressure in a water pipe.

water curtain—a screen or wide angle spray of water that is set up and used to protect exposures from fire effects mainly from radiated heat, smoke, and billowing flames. It normally consists of open or closed sprinkler heads or perforated pipes installed on the exterior of a building at eaves, cornices, window openings, or peaked roofs under manual control, or installed around the openings in floors or walls of a building with the water supply under thermostatic control. Manual firefighting operations may also provide and position water spray nozzles to provide a water curtain to protect exposures. It may also be called a water screen.

water damage—the damage sustained to a property as a direct result of water-based fire-fighting efforts or because of leakage from a fixed water-based suppression system (sprinkler system).

water flow alarm—a sounding device activated by a water-flow detector or alarm check valve and arranged to sound an alarm that is audible in all living areas over background noise levels with all intervening doors closed.

water flow detector—an electric signaling indicator or alarm check valve actuated by water flow in one direction only.

water flow switch—an assembly approved for the service and so constructed and installed that any flow of water from sprinkler system equal to or greater than that from a single automatic sprinkler of the smallest orifice size installed on the system will result in activation of this switch and subsequently indicate an alarm condition.

water flow test—an evaluation of water sup-plies and a piping distribution network to deter-mine whether it is of sufficient capacity and pressure to provide or meet fire protection needs or requirements. Static pressure, residual pressure, hydraulic profile, and flow rates may be obtained during water flow tests. (Nolan, 2000) *water horsepower*—power necessary to move water.

water supply—source of water for fire protection purposes typically described in terms of volume, flow rate, and pressure.

Watt—Power necessary to move a weight of 1 newton a distance of 1 meter in i second. One horsepower is equal to 746 watts.

wet chemical—normally a solution of water and potassium carbonate-based chemical, potassium acetate-based chemical, potassium citrate-based chemical, or a combination thereof that forms an extinguishing agent.

wet chemical—a solution of water and potassium carbonate-based chemical, potassium acetate-based chemical, or a similar combination that is used as a fire extinguishing agent. Its application may cause corrosion or staining of the protected equipment if not removed. Wet chemical solutions are generally considered relatively harmless and normally have no lasting significant effects on human skin, the respiratory system, or personal clothing. (Nolan, 2000)

wet chemical fire suppression system—an automatic fire suppression system that uses a liquid agent. It is applied through a system of piping and nozzles with an expellant gas from a storage cylinder. It is usually released by automatic mechanical thermal linkage. The agent leaves a residue that is confined to the protected area that must be removed after application. Primarily applied to having cooking range hoods and ducts and associated appliances. The wet chemical agent consist of water and usually potassium carbonate or potassium acetate. (Nolan, 2000)

wetting agent—a wetting agent is a chemical compound that, when added to water in amounts indicated by the manufacturer, will materially reduce the water's surface tension, increase its penetrating and spreading abilities, and might also provide emulsification and foaming characteristics. Decreased surface tension disrupts the forces holding the film of water together, thereby allowing it to flow and spread uniformly over solid surfaces and to penetrate openings and recesses over which it would normally flow. Water treated in this manner not only spreads and penetrates, but displays increased absorptive speed and superior adhesion to solid surfaces. Water normally has a surface tension of 73 dynes per centimeter and wetting agents can lower it to about 25 dynes per centimeter. Leaks in piping connections and pump packing can occur that would not have occurred if the wetting agent had not been used. Visual inspection should be made during wet water operations. Wet water should be applied directly to the surface of the combustible. These agents do not increase the heat absorption capacity of water, but the greater spread and penetration of the wet water increase the efficiency of the extinguishing properties of water, as more water surface is available for heat absorption and run-off is decreased. Therefore they enhance fire control and suppression applications, especially for three dimension fires. Wetting agents are broadly defined as being surfactants (surface acting agents). All wetting agents are concentrated and are mixed with a liquid at varying percentages (usually 1 to 2 per-cent). The wetting agent can be liquid or pow-der. The liquid into which it is mixed for firefighting purposes is water. However, the primary sales for some wetting agents are for use as a carrier for liquid fertilizers, fungicides, insecticides, and herbicides. These wetting agents can be, and are, used for firefighting purposes. They do not have additives that protect tanks, pumps, valves, and bushings, etc., so it is recommended that unused mixtures be drained out of the tank and a flush of all parts made with plain water. With all wetting agents, hard water usually requires a greater amount of additive to produce the same results. Wetting agents designed for fire department use will normally contain rust inhibitors to protect the tank, pump, piping, and valves. Generally, the mixture loses some of its rust-inhibiting characteristics if left in the tank. Wetting agents are best used as a soaking or penetrating agent for a three-dimensional burning mass such as wild-land fuels, coal piles, sawdust, cotton (bales, bedding, upholstery), rags, paper, etc. These agents are used very effectively on smoldering or glowing combustibles. All of the commercially available products that fall into the preceding category will satisfactorily suppress Class A fires. (Nolan, 2000)

wet water—firefighting water to which a wet-ting agent has been added to reduce its surface tension and increase its penetrating power into the fire environment. Wet water is useful in congested environments where normal water application may be blocked or restricted. Wet water can more easily seep into inaccessible areas.

worst case scenario—a scenario resulting in the worst consequence as defined by the stakeholders or a code. The criteria must be explicitly stated because worst case conditions for life safety and property protection might be incompatible.

worst credible fire—For a specific site, a fire, as defined by the stakeholders or a code, that can be reasonably expected to result in unfavorable consequences equal to or less severe than those resulting from a worst case scenario.

yield strength—yield strength, both compressive and tensile, is degraded by an increase in temperature. This loss of strength can result in the mechanical failure of an element at an elevated temperature. The temperature dependence of the yield strength is a multi-variate function.

zone smoke control—a smoke control system that provides smoke exhaust for a smoke zone and pressurization of all adjacent smoke control zones, thereby providing removal of smoke from the primary area of concern and using preventive measures to avoid additional smoke infiltration to primary area of concern. (Nolan, 2000)

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APPENDIX G. ABBREVIATIONS USED IN FIRE PROTECTION ENGINEERING

The purpose of this appendix is to provide abbreviations of the numerous engineering and scientific terms that appear in fire protection printed and electronic information. This collection has been complied from various sources [e.g., National Fire Protection Association (NFPA), Society of Fire Protection Engineers (SFPE)]. No one abbreviation is recommended to the exclusion of another because the same abbreviation may with equal validity apply to two or more terms. The following abbreviations are commonly used in the field of fire science, engineering, and technology.

ACI	American Concrete Institute
ACMV	Air Conditioning and Mechanical Ventilation
ACV	Alarm Check Valve
ADA	Americans with Disabilities Act
ADAAG	Americans with Disabilities Act Accessibility Guidelines
ADD	Actual Delivered Density
AFA	Automatic Fire Alarm
AFAA	Automatic Fire Alarm Association (USA)
AFD	Aspirating Fire Detection
AFFF	Aqueous Film-forming Foam (fire suppression agent)
AFP	Active Fire Protection
AFSA	American Fire Sprinkler Association
AFT	Adiabatic Flame Temperature
AHJ	Authority Having Jurisdiction
AIA	American Insurance Association
AIChE	American Institute of Chemical Engineers
AISC	American Institute of Steel Construction
AISI	American Iron and Steel Institute
AIT	Autoignition Temperature
ALC	Approximate Lethal Concentration
ALV	Alarm Valve
ANSI	American National Standards Institute
AOV	Air-Operated Valve
AP	Annunciator Panel (fire alarm)
AR-AFFF	Alcohol Resistant-Aqueous Film Forming Foam (fire suppression agent)
ARC	Alcohol-Resistant Concentrates
ARV	Air Release Valve
AS	Automatic Sprinkler
ASCE	American Society of Civil Engineers
ASD	Automatic Smoke Detection
ASET	Available Safe Egress Time
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASMET	Atria Smoke Management Engineering Tools
ASRS	Automatic Storage and Retrieval System
ASSE	American Society of Safety Engineers
AST	Aboveground Storage Tank
ASTM	American Society for Testing and Materials

ATC	Alcohol Type Concentrate
ATS	Automatic Transfer Switch
AWG	American Wire Gage
BCMC	Board of Coordination of the Model Code
BFRL	Building and Fire Research Laboratory (USA)
BHF	Bureau of Home Furnishings
BHP	Brake Horsepower
BI	Barrier Integrity
BLEVE	Boiling Liquid Expanding Vapor Explosion
BNBC	BOCA National Building Code
BNFPC	BOCA National Fire Prevention Code
BOCA	Building Officials and Code Administrators International, Inc.
BOMA	Building Owners and Managers Association
BOP	Blowout Preventor (valve)
BP	Boiling Point Temperature
BSD	Beam Smoke Detector
BTU	British Thermal Unit
CABO	Council of American Building Officials
CAFS	Compressed Air Foam System
CAFSS	Clean Agent Fire Suppression System
CCDS	Critical Combustible Data Sheet
CCFM	Consolidated Compartment Fire Model (computer code developed by NIST)
CCPA	Center of Chemical Process Safety (AIChE)
CDG	Carbon Dioxide Generation Calorimetry
CDS	Chemical Data System
CFAST	Consolidated Model of Fire Growth and Smoke Transport (computer code developed by NIST)
CFD	Computational Fluid Dynamics
CFI	Certified Fire Investigator (NFPA)
CFPE	Certified Fire Plan Examiner (NFPA)
CFPS	Certified Fire Protection Specialist (NFPA)
CFR	*Code of Federal Regulation*
CFSI	Congressional Fire Service Institute (USA)
CGA	Compressed Gas Association (USA)
CHF	Critical Heat Flux
CIB	Conseil International du Batiment
CLE	Coefficient of Linear Expansion
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COHB	Carboxyhemoglobin
COR	Code of Record
CSAA	Central Station Alarm Association
CSDS	Critical Screen Data Sheet
CSI	Construction Specifications Institute
CSP	Certified Safety Professional (Board of Certified Safety Professionals, USA)

CSPS	Consumer Product Safety Commission (USA)
CSRF	Construction Sciences Research Foundation
CV	Check Valve
CVD	Combustible Vapor Dispersion
DACR	Digital Alarm Communicator Receiver
DACS	Digital Alarm Communicator System
DACT	Digital Alarm Communicator Transmitter
DARR	Digital Alarm Radio Receiver
DARS	Digital Alarm Radio System
DART	Digital Alarm Radio Transmitter
DC	Dry Chemical (fire extinguisher agent)
DCVA	Double Check Valve Assembly
DD	Duct Detector
DDT	Deflagration-to-Detonation Transition
DH	Double Outlet, Fire Hydrant
DID	Defense-in-Depth
DIERS	Design Institute for Emergency Relief Systems
DP	Dry Pipe or Dry Pendant Sprinkler
DPV	Dry Pipe Valve
EC	Expansion Coefficient
EDS	Explosive Detection System
EEBD	Emergency Egress Breathing Device
EFP	Electric Fire Pump
EFS	Equivalent Fire Severity
ELO	Extra Large Orifice (sprinkler)
EMD	Electric Motor Driven
EOLR	End-of-Line Resistor
EPA	Environment Protection Agency (USA)
ER	Electrical Resistance
ERFBS	Electric Raceway Fire Barrier System
ESF	Engineered Safety Feature
ESFR	Early Suppression Fast Response (sprinkler)
ESS	Emergency Shutdown System
ETA	Event Tree Analysis
ESW	Emergency Service Water
FA	Fire Alarm
FACP	Fire Alarm Control Panel
FAG	Fire Alarm Group
FAST	Fire Growth and Smoke Transport (computer code developed by NIST)
FB	Fire Brigade
FCIA	Fire Compartment Interaction Analysis
FCP	Fire Control Plan
FD	Fire Department, Fire Damper, Fire Detection
FDC	Fire Department Connection, Functional Design Criteria
FDI	Fire Detection Institute (USA)
FDPC	Fire Department Pumper

FDU	Fire Detecting Unit
F&E	Fire and Explosion
FE	Fire Endurance, Fire Escape, Fire Extinguisher
FDMS	Fire Data Management System
FDS	Fire Dynamics Simulator (CFD computer code developed by NIST)
FED	Fractional Effective Dose
FEDB	Fire Event Data Base
FEHM	Fire and Explosion Hazard Management
FEMA	Federal Emergency Management Agency (USA)
FERP	Fire Emergency Response Plan
FFFP	Film-forming Fluoroprotein foam (fire suppression foam agent)
FFM	Furniture Fire Model
FFR	Fire-Resistance Rating
FGC	Fireground Command
FH	Fire Hydrant, Fire Hose
FHA	Fire Hazards Analysis or Assessment
FHAR	Fire Hazards Analysis Report
FHR	Fire Hose Reel
FHSR	Fire Hazards Safety Report
FHZ	Fire Hazard Zone
FID	Fractional Incapacitating Dose
FIDO	Fire Incident Data Organization (NFPA)
FIGRA	Fire Growth Rate Index
FIVE	Fire Induced Vulnerability Evaluation
FL	Friction Loss
FLC	Friction Loss Coefficient
FLD	Fractional Lethal Dose
FLED	Fire Load Energy Density
FM	Fire Modeling
FMANA	Fire Marshals Association of North America
FMEA	Failure Mode and Effect Analysis
FMRC	Factory Mutual Research Corporation (USA)
FP	Fire Protection, Fire Pump, Flash Point, Flammability Parameter
FPE	Fire Protection Engineer
FPETOOL	Fire Protection Engineering Tools for Hazard Estimation (computer code developed by NIST)
FPFG	Fire Protection Focus Group
FPFI	Fire Protection Functional Inspection
FPH	Fire Pump House
FPI	Fire Propagation Index
FPR	Fire Protection Rating
FPS	Fire Protection System
FPSS	Fire Protection and Supporting Systems
FPWG	Fire Protection Working Group
FR	Fire-Retardant
FRAM	Fire Risk Assessment Method
FRG	Fire Resisting Glazing
FRIS	Fire Research Information Services (NIST)
FS	Flow Switch (water)

FSAR	Final Safety Analysis Report
FSBBS	Fire Safety Bulletin Board System (NIST)
FSCS	Fire Fighter's Smoke-Control Station
FSES	Fire Safety Evaluation System
FSHA	Federal Hazardous Substance Act
FSI	Flame Spread Index
FSM	Fire Screening Methodology
FSR	Flame Spread Rating
FSS	Fire Suppression System
FSS	Fire Systems Services
FSSD	Fire Safe Shutdown
FTA	Fault Tree Analysis
FW	Fire Water
FWP	Firewater Pump
FWS	Firewater System
GBHP	Gross Break Horsepower
GC/MS	Gas Chromatography/Mass Spectrometry
GN_2	Gaseous Nitrogen
GPM	Gallon Per Minute
GTR	Gas Temperature Rise Calorimetry
HAD	Heat-Activated Device
HAG	Halon Alternative Group
HALON	Halogenated Hydrocarbon (Gaseous fire suppression agent)
HAZOP	Hazard and Operability Study
HC	Hose Cabinet, Hose Connection
HCFC	Hydrpchlorofluorocarbon
HCN	Hydrogen Cyanide
HCP	Halon Control Panel
HCS	Hydrogen Control System
HD	Heat Detector, Heat of Decomposition
HEPA	High-Efficiency Particulate Air
HFC	Hydrofluorocarbon
HG	Hydrogen Gas
HGL	Hot Gas Layer
HIFT	High Intensity Fire Testing
HMIS	Hazardous Materials Inventory Statement
HMIS	Hazardous Materials Identification System
HMMP	Hazardous Materials Management Plan
HMR	Hazardous Materials Regulations
HP	Heat of Polymerization
HPM	Hazardous Production Materials
HPR	Highly Protected Risk
HRC	Halon Recycling Corporation
HRP	Heat Release Parameter
HRR	Heat Release Rate
HSSC	Highly Safety Significant Component
HSSD	High Sensitivity Smoke Detection

HST	Hot-Smoke Test
HTA	High Temperature Accelerant
HTF	Heat Transfer Fluid
HTOC	Halon Technical Options Committee
HVAC	Heating, Ventilation, and Air Conditioning
HX	Heat Exchanger
IAFC	International Association of Fire Chiefs
IAFSS	International Association of Fire Safety Science
I&C	Instrumentation and Controls
ICBO	International Conference of Building Officials
ICC	International Code Council
ICE	International Electrotechnical Commission
ICS	Incident Command System
IDC	Initiating Device Circuits
IE	Initiating Events
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers, Inc.
IFCI	International Fire Code Institute
ILBP	In-Line Balanced Proportioner
IP	Inert Point, Inspection Procedure
IPA	Integrated Plant Assessment
IR	Infrared
IRI	Industrial Risk Insurers
ISDS	Ignition Source Data Sheet
ISI	Inservice Inspection
ISO	International Organization for Standardization
IST	Inservice Testing
ITM	Inspection, Testing, and Maintenance
JCAHO	Joint Commission on Accreditation of Health Organizations
LBTF	Large Building Test Facility
LC	Limited-Combustible
LC_{50}	The Concentration Lethal 50 Percent of a Population
LD_{50}	Respiratory Depression
L/D	Length to Diameter
LDH	Large Diameter Hose
LEL	Lower Explosive Limit
LES	Large Eddy Simulation
LFG	Liquefied Flammable Gas
LFL	Lower Flammability Limit
LFS	Limiting Fire Scenarios
LHD	Linear Heat Detection
LIFT	Lateral Ignition and Flame Spread Test (ASTM E1321)
LNG	Liquefied Natural Gas
LO	Large Orifice (sprinkler)
LOC	Limiting Oxidant Concentration, Lower Oxygen Concentration, Loss of Containment
LOI	Limiting Oxygen Index

LOX	Liquid Oxygen
LP	Liquefied Petroleum
LPG	Liquefied Petroleum Gas, Liquefied Propane Gas
LRFD	Load and Resistance Factor Design
LSC	Life Safety Code® (NFPA 101)
LOST	Lube Oil Storage Tank
M/A	Manual or Automatic
MAC	Manual Activation Call Point (fire alarm)
MAG	Maximum Allowable Concentration
MC	Moisture Content
MCFL	Maximum Credible Fire Loss
MCSC	Model Codes Standardization Council
MDH	Medium Diameter Hose
MEC	Minimum Explosive Concentration
MEFS	Maximum Expected Fire Scenario
MESG	Maximum Experimental Safe Gap
MFL	Maximum Allowable Fuel Loading
MIC	Minimum Ignition Current, Microbiologically Influenced Corrosion
MIE	Minimum Ignition Energy
MLR	Mass Loss Rate
MOC	Maximum Allowable Oxygen Concentration
MOD	Mass Optical Density
MOV	Motor-Operated Valve
MPFL	Maximum Possible Fire Loss
MPS	Manual Pull Station
MPV	Minimum Proper Value
MS	Mitigating Systems
MSDS	Material Safety Data Sheet
NAC	Notification Appliance Circuits
NAFED	National Association of Fire Equipment Distributors (USA)
NBFAA	National Burglar and Fire Alarm Association, Inc. (USA)
NBFU	National Board of Fire Underwriters
NBHP	Net Break Horsepower
NBS	National Bureau of Standards (now NIST)
NC	Non-Combustible, Non-Compliance
NCEES	National Council of Examiners for Engineering and Surveying
NCHRR	Normalized Chemical Heat Release Rate
NCSBCS	National Conference of States on Building Codes and Standards
NEC	National Electrical Code® (NFPA 70)
NEMA	National Electric Manufacturers Association
NFC	National Fire Code
NFD	Nominal Fire Duration
NFDC	National Fire Data Center (USA)
NFDRS	National Fire Danger Rating System (USA)
NFIC	National Fire Information Council (USA)
NFIRS	National Fire Incident Reporting System (FEMA/USFA)
NFPA	National Fire Protection Association (USA)

NFPRF	National Fire Protection Research Foundation (USA)
NFR	Non-Fire Retardant
NFSA	National Fire Sprinkler Association (USA)
NHT	National Hose Thread
NIBS	National Institute of Building Sciences (USA)
NICET	National Institute for Certification in Engineering Technologies (USA)
NIFC	National Interagency Fire Center (USA)
NIOSH	National Institute for Occupation Safety and Health (USA)
NIST	National Institute of Standards and Technology (USA)
NLE	Normal Loss Expectancy
NPP	Neutral Pressure Plane
NPSH	Net Positive Section Head
NPSHA	Net Positive Section Head Available
NPSHR	Net Positive Section Head Required
NRS	Nonrising Stem (gate valve)
NRTL	Nationally Recognized Testing Laboratory
NS	Non-Sprinklered
NSC	National Safety Council
NST	National Standard Thread
NTP	Normal Temperature and pressure
NUMARC	Nuclear Management and Resources Council
OC	Over Compliance
OD	Optical Density, Outer Diameter
ODP	Ozone Depletion Potential
ODS	Ozone Depleting Substance
OI	Oxygen Index
OS	Open Sprinkler
OSHA	Occupational Safety and Health Administration (USA)
OSR	Operational Safety Requirement
OS&Y	Outside Stem and York or Outside Screw and Yoke (valve)
OWSI	Open Web Steel Joist
PASS	Personal Alert Safety System
PAV	Pre-Action Valve
PCV	Pressure Control Valve
PDP	Pump Discharge Pressure
PDS	Point of Demand Supply
PE	Professional Engineer (NCEES)
PEL	Permissible Exposure Limit
PFC	Perfluorocarbon
PFDAS	Plant Fire Detection and Alarm System
PFHA	Preliminary Fire Hazard Analysis
PFP	Passive Fire Protection
PFPCDS	Plant Fire Protection Carbon Dioxide Subsystem
PFPHS	Plant Fire Protection Halon Subsystem
PFPS	Plant Fire Protection System
PFPWS	Plant Fire Protection Water Subsystem
PHA	Process Hazard Analysis

PHRR	Peak Heat Release Rate
P&IDs	Piping & Instrumentation Diagram, Piping & Instrumentation Drawing, Process & Instrumentation Diagram
PIM	Performance Integrity Measure
PIV	Post Indicator Valve
PLFA	Power-Limited Fire Alarm (circuits or cables)
PLG	Pressure Liquefied Gas
PML	Probable Maximum Loss
pphm	Parts Per Hundred Million
ppm	Parts Per Million
PPV	Positive Pressure Ventilation
PRA	Probabilistic Risk Assessment
PRV	Pressure Relief Valve
PS	Pressure Switch, Pull Station (fire alarm, manual)
PSA	Probabilistic Safety Analysis or Probabilistic Safety Assessment
PSF	Potential of Fire Spread
PSV	Pressure Safety Valve
PZR	Pressurizer
QH	Quadruple Outlet, Fire Hydrant
QOD	Quick Opening Devices
QR	Quick-Response (sprinkler)
QRA	Quantitative Risk Analysis or Quantitative Risk Assessment
QRES	Quick-Response Early Suppression (sprinkler)
RARSR	Radio Alarm Repeater Station Receiver
RAS	Radio Alarm System
RASSR	Radio Alarm Supervising Station Receiver
RAT	Radio Alarm Transmitter
RCAP	Root Cause Analysis Report
RDD	Required Delivered Density
RF	Radio Frequency
RHR	Rate of Heat Release
RI/PB FP	Risk-Informed and Performance-Based Fire Protection
RMV	Respiratory Minute Volume
ROR	Rate of Rise
RPE	Respiratory Protection Equipment
RPM	Revolution Per Minute
RPZ	Reduced Pressure Zone (water)
RSET	Required Safe Egress Time
RTI	Response Time Index
RV	Riser Valve, Relief Valve
RVP	Reid Vapor Pressure

SAWG	Severe Accident Working Group
SBC	Standard Building Code
SBCCI	Southern Building Code Congress International, Inc.
SCBA	Self-Contained Breathing Apparatus
SCFM	Standard Cubic Feet Per Minute
SD	Smoke Detector, Smoke Damper
SDH	Small Diameter Hose
SDI	Smoke Density Index or Smoke Developed Index or Smoke Damage Index
SDP	Significance Determination Process
SEA	Specific Extinction Area
SEI	Structural Engineering Institute (USA)
SEP	Surface Emissive Power
SEPSS	Stored Emergency Power Supply System
SF	Safety Factor
SFP	Steam Fire Pump
SFPC	Standard Fire Prevention Code
SFPE	Society of Fire Protection Engineers (USA)
SHEVS	Smoke and Heat Exhaust Ventilation System
SIS	Safety Instrumented Systems
SL	Stoichiometric Limit
SLC	Signaling Line Circuits
SMS	Smoke Management System
SMACNA	Sheet Metal and Air Conditioning Contractors' National Association, Inc. (USA)
SOP	Standard Operating Procedures
SPR	Smoke Production Rate
SRV	Safety Relief Valve
STA	Success Tree Analysis
STD	Standard Orifice Sprinkler
STP	Standard Temperature and Pressure
SSC	System, Structure, and/or Component
SSP	Standard Spray Pendant (sprinkler head)
SSU	Standard Spray Upright (sprinkler head)
STI	Steel Tank Institute
STTC	Standard Time-Temperature Curve (ASTM E119)
SV	Smoke Vent, Safety Valve
SW	Service Water
TC	Thermocouple
TDL	Threshold Damage Limit
TDR	Tender Delivery Rate
TGA	Thermogravimetric Analysis
THC	Total Unburned Hydrocarbons
THR	Total Heat Released
TLV	Threshold Limit Value
TNT	Trinitrotoluene
TPP	Thermal Protective Performance
TR	Temperature Rise
TRP	Thermal Response Parameter
TSR	Total Smoke Released

TTI	Time to Sustained Ignition
TV	Tidal Volume
TWA	Time Weighted Average
UBC	Uniform Building Code
UEL	Upper Explosive Limit
UFC	Uniform Fire Code
UFL	Upper Flammability Limit
UFSAR	Updated Final Safety Analysis Report
UL	Underwriter's Laboratories, Inc.
UPS	Uninterruptible Power Supply
USFA	United States Fire Administration
UST	Underground Storage Tank
UV	Ultraviolet
UVCE	Unconfined Vapor Cloud Explosion
VESDA	Very Early Smoke Detection and Alarm
VCE	Vapor Cloud Explosion
VOC	Volatile Organic Compound
VSP	Volume of Smoke Production
WATS	Wide Area Telephone Service
WCCE	Worst Case Creditable Event
WE	Wet Chemical (fire extinguisher agent)
WH	Wall Hydrant
WHMIS	Workplace Hazardous Materials Identification Systems
WHP	Water Horsepower
WIC	Withstand and Interrupting Current
WOBO	World Organization of Building Officials
WOM	Water Oscillating Monitor
WPIV	Wall Post Indicator Valve
WSO	World Safety Organization
ZV	Zone Valve (sprinkler)

APPENDIX H. SELECTED U.S. COMMERCIAL NUCLEAR POWER PLANT FIRE INCIDENTS

H.1 Introduction

Over the past few decades, a number of large fires have occurred in commercial nuclear power plants (NPPs), both in the United States and abroad. Particularly notable among the U.S. events was the cable spreading room (CSR) and reactor building fire at Browns Ferry Nuclear Power Plant (BFNP) in 1975, in which a single fire partially or totally disabled numerous safety- and nonsafety-related systems.

Empirical data indicate that a nuclear facility will experience event precursors (in this case, smaller fires that have no impact on nuclear safety) more frequently than actual fires affecting nuclear safety equipment (such as the BFNP fire). Many argue that no fire in an NPP is without nuclear safety implications because every fire threatens safety through its effects on either equipment or personnel operating the facility. Nevertheless, the industry expects an NPP to experience a fire that affects nuclear safety equipment every 6 to 10 years (Ramsey and Modarres, 1998).

The remainder of this appendix provides a summary table and detailed narrative discussions concerning the major fires that have occurred at U.S. commercial NPPs since 1968. The specific incidents included are those fires that led to severe or widespread damage and those that challenged nuclear safety. Additional detail concerning these fire incidents is available in the NRC inspection reports and licensee event reports (LERs)[1].

These general descriptions are provided for information only. The events can be used to develop real-life example problems for use with the fire dynamics spreadsheets.

Reference

Ramsey, C.B., and M. Modarres, *Commercial Nuclear Power Assuring Safety for The Future*, John Wiley & Sons, Inc., New York, 1997.

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[1] Licensee event reports (LERs) are form reports that are often accompanied by narratives, which licensees and the nuclear industry submit to the U.S. Nuclear Regulatory Commission, in accordance with the regulatory requirements following the occurrence of reportable events. Oak Ridge National Laboratory (ORNL) maintains all LERs in a searchable database for use of NRC and its licensees.

Table H.1-1. Summary of Selected U.S. Commercial Nuclear Power Plant Fire Incidents

Plant	**Date of Incident**	**Description of Fire Incident**
San Onofre Nuclear Generating Station, Unit 1	February 7 and March 12, 1968	Two similar incidents involving self-ignited cable fires took place within a 5-week period. On February 7, 1968, San Onofre Nuclear Generating Station (SONGS) Unit 1 experienced a self-ignited cable fire adjacent to a containment penetration and on March 12, 1968, another self-ignited cable fire occurred in a 480-volt switchgear room. These fires showed significant fire propagation beyond the initiating cable. The licensee reported that three horizontal stacked cable trays were burning at the time that the fire brigade arrived on the scene (several minutes after the apparent time of ignition).
Browns Ferry Nuclear Power Plant, Unit 1	March 22, 1975	A cable spreading room and reactor building fire challenged nuclear safety and led to important changes in the NRC's fire protection program.
North Anna Power Station, Unit 2	July 3, 1981	A severe fire involved a large transformer, but did not affect any safety-related components or electrical circuits.
Rancho Seco Nuclear Generating Station	March 19, 1984	A hydrogen fire and explosion occurring in the turbine building.
Waterford Steam Electric Generating Station, Unit 3	June 26, 1985	This main feedwater pump fire involved operator error leading to a loss of redundant trains. The plant operator at the scene called the control room with the wrong pump tag number. This error resulted in the undamaged pump being shut down from the control room.
Fort St. Vrain Nuclear Generating Station	October 2, 1987	This large turbine building fire involved hydraulic oil and affected control room habitability as a result of smoke ingress.
Oconee Nuclear Station, Unit 1	January 3, 1989	A fire in a nonsafety-related switchgear led to equipment failure. Smoke from fire propagates outside fire area (e.g., smoke control room from turbine building switchgear fire). In this incident equipment was unavailable to use water to suppress the fire, and fire induced independent failures challenge the operator.
H.B. Robinson Steam Electric Plant, Unit 2	January 7, 1989	This event involved hydrogen fires at multiple locations during an outage because of maintenance crew error.
Calvert Cliffs Nuclear Power Plant, Unit 2	March 1, 1989	This incident involved multiple initial fires, including a small fire in the control room.
Shearon Harris Nuclear Power Plant	October 9, 1989	This incident involved multiple initial and secondary fires involving one of the main transformers and electrical equipment in the turbine building.

Table H.1-1. Summary of Selected U.S. Commercial Nuclear Power Plant Fire Incidents

Plant	Date of Incident	Description of Fire Incident
Salem Nuclear Generating Station, Unit 2	November 9, 1991	This turbine building fire was caused by a turbine blade failure and ejection.
Waterford Steam Electric Generating Station, Unit 3	June 10, 1995	This incident involved a 4,160V switchgear cabinet fire. The cause of the fire was improper automatic bus transfer due to slow circuit breaker caused by hardened grease. A fire initiated inside a switchgear propagates outside of the switchgear boundary (e.g., arcing, smoke, ionized gases damaged four more switchgear cabinets; and overhead cables are damaged in part from failure of a cable tray fire barrier). The fire burned over an hour. The fire induced and independent equipment failures that challenge the operator.
Palo Verde Nuclear Generating Station, Unit 2	April 4, 1996	This incident involved multiple initial fires, including a small fire in the main control room.
San Onofre Nuclear Generating Station, Unit 3	February 3, 2001	This incident involved a circuit breaker fault resulted in a fire, loss of offsite power, and reactor trip. The damage extended to the associated electrical bus and cable trays in the switchgear room. A subsequent failure to start the turbine emergency DC lubricating (lube) oil pump resulted in extensive turbine damage. In this event, a 4.16-kV switchgear fault had an explosive release of energy and the ensuing fire was substantial enough to damage other plant equipment.

Table H.1-1. Summary of Selected U.S. Commercial Nuclear Power Plant Fire Incidents

Plant	Date of Incident	Description of Fire Incident
Point Beach Nuclear Plant, Unit 1	April 24, 2001	A small fire originated as the result of a short in a 12-Vdc communication box during a refueling outage in the steam generator (S/G) vault on the access platform to the primary side manway covers. The fire consumed a bag of rags and testing equipment debris, and lasted for approximately 23 minutes. After multiple failed attempts in which the fire brigade discharged approximately 70 pounds of dry chemical (three portable fire extinguishers), the fire was finally extinguished using 15–20 gallons of water. The dry chemical fire extinguishing agent was dispersed through large areas of the S/G and reactor coolant pump (RCP) vaults. Certain chemicals in the extinguishing agent can result in potential stress corrosion cracking on the exposed stainless steel pipe and tube surfaces in the presence of halogens (chlorides, fluorides, and sulfates) with high temperatures (greater than 250 °F) and contamination of motors, air-operated valves, safety-related snubbers, and other electrical contacts and components. This incident illustrated the importance of fire extinguishing practices and the choice and use of fire extinguishing agents.
Prairie Island Nuclear Generating Plant, Unit 1	August 3, 2001	A fire occurred in a 4,160V nonsafety-related electrical panel on Unit 1, during initial startup while plant operators were transferring the plant's electrical power from the reserve transformer to the main transformer. The breaker failure initiated a fire in cubicle 12-4 of bus 12. The failure also actuated the generator transformer protective relaying scheme, including a lockout of bus 12. The bus lockout opened breaker 12-1 (bus 12 is the source from the 1RX transformer), and actuated the protective relaying scheme. The protective relaying scheme initiated a turbine/reactor trip and actuation of the auxiliary feedwater system.

Table H.1-1. Summary of Selected U.S. Commercial Nuclear Power Plant Fire Incidents

Plant	**Date of Incident**	**Description of Fire Incident**
Fort Calhoun Station, Unit 1	December 19, 2001	A fire occurred in a corridor between safety injection pump room 22 and the containment tension stressing gallery as a result of an overloaded extension cord used to supply power to a 55-gallon grease drum heater. The fire ignited ordinary combustible materials in the area. Room 22 was completely filled with dense smoke in addition to spreading to adjacent remote areas. The smoke travel resulted in a deluge system actuating in the auxiliary building stairwell (water curtain). The ensuing water sprayed onto safety-related motor control centers (MCCs), causing shorts on safety-related circuits. The water curtain was required since there is no fixed fire barrier between the fire areas. The root cause of this fire event was determined to be unauthorized modifications to the male connection of an extension cord, which resulted in overheating and the subsequent fire.
McGuire Nuclear Station, Unit 2	August 23, 2002	A fire occurred from a leak in the hydrogen dryer associated with the Unit 2 turbine generator. The fire area was in the Unit 2 turbine building, one level below the turbine. The automatic sprinkler system activated in response to the fire alarm. A manual reactor trip was initiated and Unit 2 experienced an elevated steam generator water level. The plant fire brigade responded to the hydrogen dryer fire and isolated the hydrogen leak.

H.2 San Onofre Nuclear Generating Station, Unit 1, February 7 and March 12, 1968

Two similar incidents involving self-ignited cable fires took place within a 5-week period. On February 7, 1968, San Onofre Nuclear Generating Station (SONGS) Unit 1 experienced a self-ignited cable fire adjacent to a containment penetration and on March 12, 1968, another self-ignited cable fire occurred in a 480-volt switchgear room. These fires showed significant fire propagation beyond the initiating cable. The licensee reported that three horizontal stacked cable trays were burning at the time that the fire brigade arrived on the scene (several minutes after the apparent time of ignition).

At 4:45 p.m., on February 7, 1968, the unit was operating at 360 MWe and performing core depletion tests. All of the pressurizer heaters had been on for 96 hours when the operator noticed that the heaters were not actually operating. At about the same time, the control room received a 480-volt bus ground alarm, a loud noise was heard in the control room, and the lights flickered.

At 4:47 p.m. a security officer reported a fire at the southeast side of the containment. The reactor operator transferred the #1 480-volt bus, to the #3 480-volt bus which caused ground indications on both buses. The reactor operator then transferred the 480-volt buses back to their normal sources. The #1 480-volt bus ground cleared when the Group C pressurizer heater breaker was opened. Fire-fighting was initiated immediately, and the fire was very quickly reported to be under control at 4:47 p.m., (Just 2 minutes after the first signs of the presence of fire). The fire was fought with carbon dioxide (CO_2) and Ansul portable extinguishers.

At 5:10 p.m., the reactor and turbine (generator) were manually tripped. No spurious equipment operations were noted during the incident, and there was no apparent effect on the reactor shutdown/cooldown efforts.

On March 12, 1968, SONGS Unit 1 experienced another cable fire, this time in a cable tray in the #2 480-volt switchgear room. At the time of the fire incident, the unit was operating at 380 MWe when, at 12:21 a.m., the control room received several alarms including "Intake Structure Hi Level," "480-volt System Ground," "Station DC Bus Ground or Low Voltage," and "Hydraulic Stop Gate Trouble." These were followed by a "Sphere Heating and Ventilating System Trouble" alarm.

At 12:25 a.m., the annunciator panel for the turbine generator first out, auxiliary, and electrical boards were lost. An auxiliary operator reported smoke in the #2 480-volt switchgear room. At 12:27 a.m., operators observed blue arcing above the east door window of the #2 480-volt switchgear room. At 12:32 a.m., fire was observed in three cable trays above east door.

The reactor was tripped at 12:34 a.m., and the operator began unit shutdown actions at 12:37 a.m. The #2 480-volt was cleared by over current relay operation.

At 12:35 a.m., the licensee requested assistance from the closest outside fire department, which happened to be a Marine Corps Fire Department. At 12:45 a.m., 24 minutes after the first control room alarms were received, the fire department arrived on the scene, but the electric motor-driven fire pumps would not start. Therefore, at 12:56 a.m., the licensee started the gasoline engine driven backup emergency fire pump. The fire was declared extinguished at 1:00 a.m., 39 minutes after the initial control room alarms.

During cooldown efforts following the fire, the licensee determined that the coolant boron concentration was decreasing instead of increasing as expected. As a result, the cooldown was suspended for 3 hours and 40 minutes until the problem was diagnosed and fixed.

Post-fire investigation revealed that power and/or control circuits were affected for residual heat removal (RHR) suction and discharge valves, the component cooling water (CCW) heat exchanger outlet valve, the south primary makeup water pump, and three annunciator panels. Damaged cables rendered the following equipment electrically inoperable:

- safety injection recirculation valves
- west recirculation pump and discharge valve
- electric auxiliary feedwater pump
- safety injection train valves [west train motor-operated values (MOVs)]
- refueling water pump discharge valve to recirculation system

The following equipment was lost as a result of the relay cutout of the #2 480-volt bus:

- west RHR pump
- south transfer pump
- boric acid injection pump
- boric acid storage tank heaters and boric acid system heat tracing
- south primary plant makeup pump
- flash tank bypass valve
- east and west flash tank discharge pumps
- center component cooling water pump
- several other MOVs

While the first incident had only a minimal impact on the plant, the second incident rendered a large number of components. Nevertheless, a sufficient number of components and systems remained available to allow for orderly shutdown and core cooling. In addition, at least one of the alarms received in the control room was (namely the Intake Structure Hi Level alarm) apparently spurious. An operator reporting from the intake structure found no reason for this alarm to have sounded.

In terms of the fire cause, the two incidents shared many similarities. The investigation concluded that the most probable cause of both fires was thermally and mechanically stressed cables, coupled with the use of individual fuses to provide for clearing of faults on each phase of the three-phase 340-volt circuits. It also appeared that the cables were undersized for their design current loads under their actual installation conditions.

The initial fault was thought to be a cable-to-cable, phase-to-phase hot shot involving two separate power feeds from the same three-phase power bus. The fusing configuration allowed back-feeding of fault current through the unfaulted phases of each power feed, which led to an even more severe overcurrent condition for the conductors.

Both incidents involved self-ignited cable fires. As such, they are important because they were the earliest fire incidents at a nuclear power plant where self-ignition of cables resulted in extensive equipment damage and loss of equipment operability. While the first incident resulted in little or no fire spread, the second incident involved fire spread to three cable trays that were entirely burned for 4.60 m (15 ft). Investigation of the incidents led to recommendations that urged the industry to reexamine cable qualification and raise the standards for establishing cable ampacity limits and for improving the flammability behavior of cables.

In both incidents, the fires did not cause complete loss of core cooling capability, core damage, radiation release or any injury to plant personnel or the public. The available sources do not offer detailed discussion of fire-fighting activities, occurrence of hot shorts (other than the initial cable-to-cable fault that initiated the second incident), the nature of the other circuit failures or operator actions in response to the failures, caused by the fire.

Reference

San Onofre Nuclear Generating Station Unit 1, Report on Cable Failures—1968, Southern California Edison Company, San Diego Gas & Electric Company, Publication date unknown, but circa 1968.

H.3 Browns Ferry Nuclear Power Plant, Unit 1, March 22, 1975

At noon on March 22, 1975, both Units 1 and 2 at the Browns Ferry Nuclear Power Plant (BFNP) were operating at full power, delivering 2,200 megawatts of electricity to the Tennessee Valley Authority (TVA).

The BFNP consists of three boiling-water reactors (BWRs). Units 1 and 2 share a common cable spreading room (CSR) located beneath the control room (CR). Cables carrying electrical signals between the CR and various pieces of equipment in the plant pass through the CSR. Just below the plant's control room, two electricians were trying to seal air leaks in the CSR, where the electrical cables that control the two reactors are separated and routed through different tunnels to the reactor buildings. There were using strips of spongy foam rubber to seal the leaks. They were also using candles to determine whether or not leaks had been successfully plugged by observing how the flame was affected by escaping air. One of the electricians put the candle too close to the foam rubber, and it burst into flame.

Following ignition of the polyurethane (PU) foam in the Unit 1 CSR, the fire propagated through the penetration in the wall between the CSR and the Unit 1 reactor building. After the insulation burned off, the electrical cables shorted together and grounded to either their supporting trays or the conduits. In addition to the direct fire damage, the fire deposited an extensive amount of soot on all equipment located in the reactor building below the refueling floor. More than 600 of the burned cables contained circuits for the safe shutdown of one or both of the operating reactors. The direct fire loss was $10 million, and the cost of fossil fuel used to produce the replacement electricity over the next 18 months was $200 million.

Approximately 15 minutes passed between the time the fire started (12:20 p.m.) and the time at which a fire alarm was turned in. One of the electricians told a plant guard inside the turbine building that a fire had broken out, but confusion over the correct telephone number caused a delay in sounding the fire alarm.

This fire burned a large number of cables associated with penetrations between the CSR and the reactor building. The fire initiated in the CSR and initially involved the readily combustible and exposed PU foam of an incomplete cable penetration seal. The fire immediately propagated through a gap in the penetration seal into the adjacent reactor building. This spread was enhanced by air flow through the penetration seal gap, caused by the negative pressure in the reactor building. In this case, the penetration seal was not complete (i.e., the seal was still under construction and lacked noncombustible cover panels).

The fire at BFNP demonstrates that, given a sufficient initial source of readily combustible fuel (the PU foam in this case) in close proximity to a large concentration of cables in open cable trays, a self-sustaining and propagating cable fire may result. In this case, fire propagated both horizontally and vertically, thereby igniting and damaging cables. Cables inside conduits running near the burning cable trays were also damaged.

The fire in the Browns Ferry CSR was controlled and extinguished without the use of water. The fire in the reactor building was unsuccessfully fought for several hours with portable carbon dioxide (CO_2) and dry chemical extinguishers; however, once water was used, the fire was extinguished in a few minutes. After actuation of the CSR CO_2 fire suppression system, openings between the CR and the CSR had to be plugged to stop the entry of smoke and CO_2 into the CR. Some of these openings were in the floor of the CR at the points where the cables entered the CR. This appears to violate the design provision that these cable entryways would be sealed. Actuation of the CO_2 system in the CSR made the situation worse, driving the smoke and toxic fumes into the CR, which became uninhabitable.

The BFNP design incorporated provisions for sealing the openings between major structural divisions, such as the reactor building, the CSR and the control room. However, in the case of the Browns Ferry fire, one such seal between the CSR and the reactor building was ineffective in limiting the spread of the fire and was ultimately the primary cause of the fire. The lack of other seals, such as those between the CSR and the CR, impeded plant operation during the fire.

Notably, the smoke detectors in the Browns Ferry CSR did not alarm, despite presence of smoke possibly because the normal flow of air from the CSR to the reactor building drew the smoke away from the installed detector in the CSR. The smoke also penetrated the control room (through the unsealed cable entryways), but the fire detectors installed in the control room were of the ionization type and did not detect the combustion products generated by the cable fire and did not alarm. The reactor building also had a great deal of smoke in the vicinity of the fire, but the licensee had not installed detectors in that area.

A principal lesson learned from the BFNP fire is the failure of fire prevention. The Review Group (NUREG-0050) recommended that the licensees review the ventilation systems in all operating NPPs and upgrade them, as appropriate, to ensure their continued functioning if needed during a fire. The Review Group further recommended that the licensees should provide the capability to control ventilation systems to deal with fire and smoke, but such provisions must be compatible with requirements for the containment of radioactivity. Licensees should also protect the CR from both radioactivity and smoke or toxic gases. Adequate breathing apparati and recharging equipment should be available for operators, fire-fighters, and damage control crews who may be required to work simultaneously during a prolonged incident.

The Review Group concluded that more comprehensive regulatory guidance was needed to provide fire protection design criteria to implement the requirements of General Design Criterion (GDC) 3 as specified by Appendix A to Title 10, Part 50, of the *Code of Federal Regulation*s (10 CFR Part 50). The Browns Ferry fire and its aftermath revealed some significant inadequacies in design and procedures related to fire at the plant, including gaps in the defense against fires.

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H.4 North Anna Power Station, Unit 2, July 3, 1981

On July 3, 1981, North Anna Unit 2 was at a power level of 17.9-percent when an internal fault in one phase of main transformer B led to a catastrophic transformer failure and fire. Ceramic insulation shifted, the side of the transformer ruptured, and transformer oil sprayed from the opening over the transformer and the outside wall of the turbine building.

The fire caused the feeder breakers from a reserve station service transformer to two station service buses to trip open. The voltage transient caused by this event led to several bi-stables in the solid-state protection system to drop out, resulting in a high steam line flow signal. Since the reactor coolant temperature was low, this led to a safety injection signal.

The fire brigade was activated immediately, and the licensee also contacted the local fire department for assistance. The deluge systems on transformers B and C activated. However, the fire was too severe for the capability of the system and the fire continued to burn. It took the fire brigades about 1 hour to bring the fire under control.

Although this incident is considered a severe fire in classical fire protection terms, it affected only nonsafety components. Despite the low potential risk impact, the incident provided an interesting insight about fixed fire suppression system capabilities. Specifically, the incident demonstrated that a fixed fire suppression system can be overwhelmed even when the fire initiates in those components that the system is intended to protect. In other words, it showed that the effectiveness of the suppression system may be an important factor.

Reference

Licensee Event Report (LER) 339-81-055, North Anna Power Station, Unit 2, Docket No. 50–339, Virginia Electric and Power Company, July 15, 1981.

H.5 Rancho Seco, March 19, 1984

On March 19, 1984, Rancho Seco was operating at 85-percent power, and had been experiencing problems with the automatic level control of the de-foaming tank and hydrogen side drain regulator tank of the main generator. The licensee switched the drain regulator tank level to manual mode, requiring direct operator level control. However, operators apparently failed to pay adequate attention to the level control and this allowed the main generator seal oil pressure to decrease. This, in turn, allowed hydrogen to escape from the generator. At 9:50 p.m., hydrogen gas exploded and started a fire.

Plant personnel in the area immediately detected the fire, and it was extinguished by the fixed automatic carbon dioxide (CO_2) system within 14 minutes. Nonetheless, the fire caused significant damage in a relatively short frame, primarily because of the initial explosion and early burning.

This fire is one of few turbine building fire incidents in the United States that has caused significant damage. The incident demonstrated the unique nature of the turbine building fire hazards, which in this case, included a hydrogen gas leak and explosion and the potential for fast-developing fires that may cause damage despite effective operation of the fire suppression systems. This incident also demonstrated that turbine building analyses may warrant attention to more severe fires than might reasonably be postulated in other plant areas. This particular incident apparently had a minimal impact on plant operations and safety systems, but the impact on operators is a plant specific-factor, consistent with the presence (or absence) of safety-significant equipment in the turbine building.

H.6 Waterford Steam Electric Station, Unit 3, June 26, 1985

On June 26, 1985, the plant was operating at power when a fire occurred in one of the main feedwater pumps. An electrician notified the control room that smoke was emanating from main feedwater pump A, and an operator dispatched to the scene reported back to the control room that the pump was on fire. Control room (CR) operators tripped the cited pump, began reducing reactor power, and declared that an unusual event was underway.

Five minutes after the initial report of a fire, the operator notified the CR that the fire was actually in main feedwater pump B, rather than A as previously reported. As a result, the CR operators immediately tripped the turbine, which, in turn, caused the reactor to trip. Since both main feedwater pumps were secured, the steam generator level dropped below the emergency feedwater system setpoint.

The licensee activated the fire brigade upon confirmation of the fire. The fire brigade used a local hose station and water streams to fight the fire and managed to extinguish it in about 10 minutes. The fire was limited to a small portion of the outer wrapping of insulation on the feedwater piping and was attributed to design and fabrication errors.

In most senses, this fire was relatively small and, overall, presented a relatively minor challenge to nuclear safety (a reactor trip with all safety systems available). The interesting aspect of this incident is that operator/personnel error led to an initial report identifying the wrong pump as the one on fire. As a result, the operator initially tripped the unaffected pump, and ultimately was forced to trip both main feedwater pumps. Although this incident involved only nonsafety-related trains, it provided an interesting insight into the possibility of an indirect impact of fire on multiple train availability. That is, for various reasons, a fire may lead to unaffected trains being taken out of service. In this case, the cause was operator error and the operator’s actions were classified as an error of commission. This is, rather than failing to take a desirable action, the operator in this case took an action that was undesirable.

H.7 Fort St. Vrain Nuclear Generating Station, October 2, 1987

Fort St. Vrain is a single-unit high-temperature gas-cooled reactor (HTGR), which (like other HTGRs) reactor uses graphite as a moderator and helium gas for heat removal from the core. Fort St. Vrain had two main cooling (helium) loops. After passing through the core, the helium flowed through the two steam generators (one per cooling loop). Two steam-driven circulators for each loop provided motive power for the helium. The steam for the circulators comes from the discharge of the high-pressure turbine of the turbine-generator. The steam then passes through the steam generators once more for superheating before being taken to the intermediate and low-pressure turbines.

On October 2, 1987, the plant was coming out of a long outage and was in the midst of its initial power ascension. As part of this process, the operators closed a hydraulic valve in the turbine building, when they noticed a drop in hydraulic oil pressure. An inquiry into the causes of this drop revealed that a filter bowl (canister) had failed and high-pressure oil (about 3,000 psig) was spraying (close to a 15-ft distance) onto hot exposed steel. The petroleum-based hydraulic oil ignited, starting the fire, because the temperature of the hot surfaces was above the auto-ignition point of the oil. The equipment operator who discovered the fire initially succeeded in extinguishing it using a portable dry-chemical extinguisher. However, since he did not close the valve feeding the failed filter, the oil continued to spray and re-flashed (re-ignited). By this time, the fire was relatively large (estimated at 8 ft x 3 ft).

The licensee immediately activated the plant's fire brigade was asked an outside fire department to respond. The licensee also dispatched a reactor operator to the reactor building to close the two control valves for the hydraulic system to cut off the supply of oil to the failed filter. That operator managed to close one of the two valves immediately. However, the handle for the other valve was missing and, therefore, some delay occurred in cutting off the oil from the fire. As soon as the oil was cut off, the fire was extinguished and the operators managed to close off and isolate the failed filter and activate the available hydraulic system train.

The damage caused by this fire was limited to the immediate area of the fire at the north end of the turbine building. The fire also damaged several cables that had some effect on the control room (CR). In addition, the fire affected valves, instruments, and structural elements. However, the fire had only a minor impact on the plant shutdown and reactor cooling capabilities.

The fire also had some impact on CR habitability. Apparently, the burning oil and cables generated large quantities of smoke that hampered the initial fire-fighting efforts. The cables damaged by the fire also caused the CR ventilation system to shift to radiation emergency mode, and caused a loss of electric power at the fire location, thereby rendering the electric motor-driven smoke ejectors useless. In this mode, the system shifted to suction from the turbine building, thereby drawing some smoke into the CR. Within 2 minutes of the shift in ventilation systems, the ventilation system switched to the purge mode. However, smoke continued to enter the CR because positive pressure in the room could not be maintained as a result of frequent use of the door between the CR and the turbine building. Ultimately, the operators had to prop open the door separating the control room and Building 10 to allow fresh air to be drawn into the CR.

Reference

"Preliminary Report on the Impact of the FSV October 2nd Fire," Fort St. Vrain Nuclear Generating Station, Public Service Company of Colorado, October 30, 1987.

H.8 Oconee Nuclear Station, Unit 1, January 3, 1989

On January 3, 1989, Oconee Unit 1, was being brought up to power following a trip that had occurred a few days earlier. The unit had reached 26-percent power at 7:16 p.m., when the 6.9 kV switchgear (1TA) failed explosively and caught fire. Subsequent investigation could not establish the precise cause of this incident.

As a result of the switchgear failure, the main turbine and two reactor coolant pumps tripped, thereby initiating a reactor transient. The operators immediately began to reduce reactor power. The average reactor temperature was 302 °C (575 °F) at the beginning of the incident, and core cooling was initially maintained by the two operating reactor coolant pumps (RCPs) and main feedwater flow through the steam generators (S/Gs). The operators also started two high-pressure injection pumps to compensate for contraction of the water in the main coolant loop as it was cooling down in response to the power reduction. When the power dropped to 4-percent, the operators tripped the reactor.

Meanwhile, the control room (CR) received fire alarms and activated the fire brigade to respond to the fire. Later, the licensee called off-duty shift personnel to assist in the fire- fighting effort. The fire brigade made two initial attempts to suppress the fire using carbon dioxide (CO_2) and dry chemical fire extinguishers, but failed extinguish the fire. CR operators deenergized the DC power bus in order to isolate the impacted 1TA switchgear from all electrical sources. The fire brigade then decided to apply water to the fire using a fog nozzle. To further protect the fire-fighters, the operators also deenergized the other train of the nonsafety related 6.9 kV switchgear (i.e., 1TB), which was located near 1TA. The fire brigade used the water fog on the fire and at 8:15 p.m., about 1 hour after the switchgear failure, the fire brigade declared the fire as being completely extinguished.

Tripping of switchgear 1TB (to protect the fire fighters) caused the remaining reactor coolant pumps to trip. Under these conditions, the integrated control system (ICS) is designed to raise the water level in the S/G to 50-percent and swap the feedwater nozzles from main to auxiliary. However, because of fire damage to the signal cables, the ICS failed and the operators had to manually execute these two actions. In doing so, however, the operators forgot to close the main feedwater valve. This further accelerated the rapid cooldown process that was already underway. Furthermore, since the operators focused on in-core thermocouple readings to monitor reactor temperature, they did not properly monitor the rate of cooldown at different points of the main coolant loop. As a result cold leg temperature dropped to about 219 °C (426 °F) in about 1 hour. The shift engineer and shift supervisor determined that the temperature in parts of the reactor may have dropped faster than 38 °C (100 °F) in that hour, which means that the plant may actually have entered the thermal shock operation region (overcooling).

Because operators had started the high-pressure injection system, reactor pressure reached 2,355 psig for a short time. Later, the pressure reached 2,385 psig, also for a short time. Operations then stopped the high-pressure pumps to control the high-pressure condition. These two pressure spikes, combined with the possibility of operating in the thermal shock operation region, could have endangered the integrity of the main vessel if the conditions had persisted for an extended time.

At some point in the incident, smoke did find its way into the main control room. The available literature does not describe either the extent of the smoke or the path by which the smoke found its way into the CR. Consequently, it is not clear whether the smoke had any impact on operator performance, although one report cites the smoke (rather in passing) as a contributing factor to the error that led to the overcooling transient.

Reference

Licensee Event Report (LER) 26989002, “Fire in 1TA Switchgear Due to Unknown Cause,” Oconee Nuclear Station, Unit 1, Event Date January 3, 1989.

H.9 H.B. Robinson Steam Electric Plant, Unit 2, January 7, 1989

At the time of this incident on January 7, 1989, Robinson Unit 2, was in a refueling outage. At 10:30 p.m., as part of an air test of the main generator, a maintenance crew erroneously connected the instrument air header to the main generator hydrogen manifold using a rubber hose. This allowed the bulk hydrogen supply, which is at 120 psig, to be directly connected to the station’s 95 psig compressed air system. The configuration was such that hydrogen flow to the generator was blocked, but flow into the station air system was not. Hence, hydrogen spread into the plant’s general purpose compressed air system.

At the time the maintenance crew established the hose connection, the station air compressor was out of service and the station air system was connected to the instrument air system. The station air system was in greater demand because plant personnel were using air-driven tools throughout the plant. This caused the majority of the hydrogen to migrate into the station air system.

Approximately 1 hour after the maintenance crew established the connection, the crew noticed that generator pressure had not increased. At approximately the same time a small fire was discovered in an air junction box on the turbine deck inside the turbine building, the fire quickly extinguished and did not notice any damage. However, approximately 3 hours after the maintenance crew established the connection, a contract worker reported that flames were coming out of his air operated-grinder. Upon this discovery, the licensee ceased all work that could cause a spark and prohibited the use of the air system.

The licensee then took samples of the air at several locations and discovered that the hydrogen concentration ranged from 50-percent to 150-percent of lower explosive limit (LEL). The hydrogen had also migrated into the entire system, which encompassed practically all plant locations including the auxiliary building and the containment. No further fires occurred, and the licensee eventually purged the system of hydrogen.

This incident is of interest because it illustrates the somewhat unique point, that unexpected fire sources can arise during a refueling outage. In this case, at least two minor fires occurred, and there was clearly an inherent potential for more, and perhaps more serious, fires.

Reference

Licensee Event Report 26189001, “Hydrogen Introduced Into the Instrument Air System,” H.B. Robinson Steam Electric Plant, Unit 2, Event Date January 7, 1989.

H.10 Calvert Cliffs Nuclear Power Plant, Unit 2, March 1, 1989

On March 1, 1989, Calvert Cliffs Unit 2 was operating at 100-percent power. At 4:45 p.m., a fire was discovered in a control panel in the main control room (MCR). At the time, an operator was in the process of verifying a repair on the over-speed trip mechanism of the auxiliary feedwater pump trip/throttle valve actuator. As part of this procedure, the operator put the hand switch for the valve in the shut position. The shut position indicating light flickered, and the operator heard a buzzing noise on the control panel. The operator repeated the action with the same result. The operator opened the panel cover and discovered a fire at the hand switch. Using a hand-held Halon fire extinguisher, the operator extinguished the fire in 1–2 minutes. In the meanwhile, a 10-amp fuse in the associated circuit blew. However, because the fire was extinguished quickly, the control room supervisor did not call the fire brigade.

When the operator discovered the fire, a turbine building operator was called to reset the throttle valve. In the attempt to reset the valve, that operator discovered that a solenoid associated with the valve was smoking, but there were no visible flames. The solenoid stopped smoking, apparently when the 10-amp fuse blew. The fire in the MCR panel caused some damage to nearby wires, but the licensee did not notice any other damage resulting from this incident. Moreover, this incident did not cause a significant safety hazard and its impact was limited to an isolated part of a safety-related system. The lack of damage can be attributed, at least in part, to the immediate response of the operator whose actions led to the initiation of the fire.

This incident is one of only a very few incidents in U.S. commercial NPPs that lend insight into multiple fire ignitions in a single incident. In this case, a small fire occurred in the MCR and an incipient fire (the smoking solenoid) occurred in the auxiliary feedwater pump room; the common link between the fires was a common electrical circuit.

Reference

Licensee Event Report 31889004, “Auxiliary Feedwater Pump Trip Circuitry Fire in Control Room Due to Maintenance Error,” Calvert Cliffs Nuclear Power Plant, Unit 2, Event Date March 1, 1989.

H.11 Shearon Harris Nuclear Power Plant, October 9, 1989

On October 9, 1989, the Shearon Harris plant was operating at full power. At 11:05 p.m., a turbine generator and main power transformer differential relay tripped and started a chain of events that led to fires at three locations involving one main transformer and the main generator. As a result of the relay trip, the main generator output breaker also tripped. This, in turn, caused a turbine trip and a reactor trip. The auxiliary feedwater system actuated as designed, but the turbine-driven pump failed to operate properly so operators switched to motor-driven auxiliary feedwater pumps. The operators closed the main steam isolation valves to limit the cooldown rate.

The initial cause of the event was multiple ground faults in a bus duct near main power transformer B. The licensee event report (LER) stated that the ground faults apparently resulted from aluminum debris carried into the duct by the forced air ventilation system used to cool the bus duct. The licensee suspected that the debris entered the ventilation system as a result of two damper failures, one of which occurred on February 27, 1988, and a second one during the summer of 1989. The ground fault caused arcing over a 50-foot length of the bus, thereby reducing the dielectric strength of the air. In accordance with the air, per the design of the system, the air then entered the bushing box of the transformer, causing ground faults in the bushing box and leading to a crack in the low-voltage bushings. The bushing crack, in turn, led to a spill of oil and ignition of the first fire at the transformer.

The fault in the main transformer bushing box and bus duct A caused the voltage of the generator neutral to become elevated. A current transformer was mounted around the neutral conductor, from which it was isolated by insulating tape. However, the insulation resistance of the tape was apparently insufficient to withstand the elevated neutral voltage and an electrical breakdown occurred, causing the neutral conductor to short to ground. The arcing caused by this short burned holes in generator-related piping, which, in turn, subsequently allowed the housing above the hydrogen fire to ignite (the third fire).

At 11:09 p.m., the control room (CR) was notified of a fire at main power transformer B, and an oil fire on the second level of the turbine deck underneath the main generator. The licensee immediately activated its onsite fire brigade who also noted a hydrogen fire on the second level of the turbine deck underneath the main generator (second fire). The deluge system at the main transformer activated as designed.

The licensee also contacted offsite fire departments shortly after the initiation of the incident to assist in the fire-fighting efforts. Later, the licensee created the prompt notification of offsite fire departments as having limited the damage caused by the fires.

As previously noted, the auxiliary feedwater system automatically actuated in response to the incident. However, the turbine-driven auxiliary feedwater pump tripped shortly after it started. The licensee later identified the cause of the trip a spurious over-speed trip signal from the tachometer. No link between the failure of the auxiliary feedwater pump and the fire has been established, and this appears to have been an independent (random) failure event.

At 11:35 p.m., an alert was declared and activated the technical support center (TSC). By 12:13 a.m. on October 10 (a little more than over 1 hour after initiation of the event), the oil fire at the generator hosing was extinguished. Also, the fire at the main power transformer was believed to be under control by the deluge system. The hydrogen fire underneath the generator was also considered to be under control.

By 01:45 a.m., a small residual oil fire at the main transformer was extinguished using a portable dry chemical extinguisher. By 02:45 a.m., (2 hours and 40 minutes after incident initiation) the licensee completed walkdowns to verify that all three fires were extinguished, fire watches were posted at the fire locations, and purged the main generator CO_2.

The fires in this incident were of relatively long duration, lasting about 1 hour and 45 minutes total, and were relatively severe from a classical fire protection perspective. However, from a nuclear safety perspective, the fires had a relatively modest overall impact. The plant did trip automatically and an auxiliary feedwater pump did fail (apparently a random failure). However, the operators responded appropriately to the situation and properly controlled the plant shutdown including proper control of the cooldown rate.

The incident is of interest because it is one of the few incidents in the United States that involved multiple fires occurring concurrently. As such, the incident demonstrated that multiple fires may occur simultaneously in different areas of a plant. As seen in other such incidents, one of the common links was a common electrical system. However, the secondary hydrogen fire was apparently the result of damage caused by the failure of the current sensor on the generator neutral cable, so there were multiple contributing factors rather than simply a common electrical system that became overloaded.

Reference

Licensee Event Report # 40089017, “Electric Fault on Main Generator Output Bus Causing Plant Trip and Fire Damage in Turbine Building,” Shearon Harris Nuclear Power Plant, Event Date October9, 1989.

H.12 Salem Generating Station Unit 2, November 9, 1991

On November 9, 1991, Salem Unit 2, was operating at full power when a reactor trip occurred, causing the main generator breaker to open. The auto stop oil system was in test mode and, as result, the turbine valves cycled open while the generator was disconnected from the grid (i.e., the turbine re-started without an appropriate generator load on the system). An over-speed condition occurred, but the over-speed protection system failed to function properly and allowed the turbine's rotational speed to exceed 2,500 rpm compared to the normal operating speed of 1,800 rpm. The forces associated with this level of over-speed caused the blades to break apart, ejecting fragments from the turbine casing. Hydrogen gas escaped and caught fire because of a seal failure caused by the excessive vibration. The vibration also severed the lube oil pipes causing a release of the oil that also caught fire.

The following automatic fire suppression systems actuated promptly as designed:

- deluge system protecting the inboard generator bearing housing
- deluge system protecting the low-pressure bearing housing
- low pressure CO_2 system protecting the main generator exciter
- wet pipe sprinkler system below the main generator pedestal

The entire sequence of events leading to turbine failure lasted 74 seconds. Fires had already occurred by that time and some of the automatic suppression systems had activated. The automatic suppression systems managed to extinguish some of the fires.

By coincidence the fire brigade happened to be outside the protected area at the time of fire. With the assistance of plant security, the brigade promptly re-entered the plant proper and managed to be on the scene in full gear within 5 minutes of fire ignition. With the help of plant fire brigade personnel, the fire was contained rapidly and extinguished within 15 minutes. The fire caused relatively little damage compared to that done by the ejected blades.

The licensee subsequently determined that the fire impacted the turbine and exciter ends of the main generator. Because the main turbine generator of Salem Unit 2 is not enclosed, the hydrogen and smoke from the fire escaped directly into the atmosphere. As a result, the fire brigade did not need to be concerned with hydrogen pocketing under the structural elements of the ceiling.

This incident is considered important because despite the potential for a very severe fire, the licensee observed only very limited fire damage. In this case, catastrophic failure of a turbine led to a fire. This event is somewhat unique in that the fire suppression system was adequate to control the ensuing fire and, coupled with the response of the fire brigade, was to extinguish the fire very quickly. Some localized fire damage resulted, and the costs of replacing the failed turbine were extensive, but the fire had no impact on the safety-related elements of the plant.

Another notable aspect of this incident is that a failure related to a main turbine generator system led to turbine disintegration, which, in turn, caused the fire. It is also interesting to note that two independent events contributed directly to the initiation of the fires. First, the auto-stop oil system was in test mode and this created a condition where the turbine was, in effect, re-started without an appropriate load and this, in turn, led directly to the potential for an over-speed condition to occur. Second, the over-speed protection system failed to function, allowing the over-speed condition to progress unchecked.

Reference

Licensee Event Report 31191017, “Reactor/Turbine Trip on Low Auto-Stop Oil Pressure Followed by Turbine/Generator Failure,” Salem Generating Station Unit 2, Event Date November 9, 1991.

H.13 Waterford Steam Electric Station Unit 3, June 10, 1995

On June 10, 1995, Waterford Unit 3 was operating at 100-percent power. At 8:58 a.m., failure of a lightning arrester on a substation transformer (230 kV/34.5 kV) caused a severe electrical transient that, in combination with the failure of a breaker, led to failure of non-vital switchgear 2A and fire in the breaker cubicle for the startup transformer. This led to a reactor trip and a series of other nonsafety-related equipment trips, signal actuations, and equipment activations.

All 36 fire detectors for the turbine building switchgear room alarmed to the control room (CR) indicating panel. However, the CR operators did not become aware of the fire detector alarms because other plant alarms were sounding at the same time, the fire protection alarm board was in an area not readily visible to the operators, and the fire detector alarm panel buzzer had been covered with tape. Hence, CR operators remained unaware of the fact that a fire had started in the switchgear room.

At 9:06 a.m., the control room received a report from an auxiliary operator, who happened to be a trained fire brigade member, that heavy smoke was coming out of the switchgear room. The shift supervisor asked if the auxiliary operator could observe flames or an orange glow. The auxiliary operator responded that he could not see flames but a large amount of smoke was coming out of the switchgear room. The shift supervisor instructed the auxiliary operator to confirm the presence of an actual fire and report back.

Two auxiliary operators donned self-contained breathing apparatus (SCBA) and entered the switchgear room to verify the presence of a fire and subsequently notified the CR that a fire was indeed in progress. The exchange of information took place about 30 minutes after the first fire alarm sounded in the CR (i.e., approximately 9:30 a.m.). At that time the shift supervisor, announced the presence of fire and activated the fire brigade.

The fire brigade arrived on the scene and initially attempted to extinguish the fire using hand-held fire extinguishers charged with carbon dioxide (CO_2), Halon, and dry chemical agents. However, all of their attempts proved ineffective. According to the plant procedures, the shift supervisor, then assumed the leadership of the fire brigade and left the CR for the fire location.

The shift supervisor summoned the local offsite fire department was summoned at 9:41 a.m., and they arrived at about 9:58 a.m. (17 minutes later). Upon arrival, the offsite fire department recommended the use of water. However, the shift supervisor, in consultation with other members of plant operations team, decided to continue using non-water suppression media. The shift supervisor ultimately gave permission to use water about 90 minutes after the initiation of the fire (i.e., about 10:30 a.m.). The fire fighters brought the fire under control within 4 minutes after initial application of water and declared the extinguished about 2½ hours after initiation.

As noted, the fire was initiated as result of a failure of a switchgear breaker cubicle. The fire propagated out of the top of the cubicle and ignited vertical cable tray risers above the cubicle. (One can infer that the switchgear cubicle fire broke through the steel top of the panel and propagated to those cables. However, it is impossible to determine whether this was attributable to heat damage to the top panel or whether the top panel may have been damaged in the initial electrical fault.) In its progression, the fire jumped over a fire stop installed in the vertical section of the cable tray and continued to propagate. As a result, the fire damaged cables in a 5-foot diameter column up to a height of about 10 feet above the panel top, and the associated heat damaged the fire detectors immediately above the fire zone.

The fire eventually reached a horizontal cable tray about 17 feet above the floor (10 feet above the top of the panel). The fire then propagated horizontally until it came to a fire stop installed in the horizontal cable tray about 8 feet from the junction with the vertical trays. From the available information, one can infer that, for the horizontal segment of the cable trays, the flames were of limited height and/or limited duration. This is because the 6.9-kV power cables that were located a few inches above the burning 4.16-kV cables were not ignited and had only minor surface damage after the fire.

The fire also severely damaged two adjacent switchgear cubicles, but four other nearby cubicles experienced exterior damage only. The investigators postulated that the radiative heat reflected from the shield wall separating the two switchgear trains caused the exterior damage to those four cubicles. The fire did not damage any of the redundant train cubicles (on the opposite side of the shield wall).

It is also interesting to note that the plant's log records indicated erratic behavior of the A2 unit auxiliary transformer breaker that was involved in the fire. Operators also noted a few other erratic indications on the control board during the course of the incident. The records indicated that the transformer breaker first showed closed and then open. One can infer from this that breaker control circuit faults led to inaccurate indications on the sequence of events log.

The non-vital switchgear fire at Waterford Unit 3 had little impact on safety-related functions. Switchgear fires are considered one of the most likely fire scenario in a nuclear power plant.

This incident provides an interesting account of what can happen to the switchgear cubicles and the cables above it in the event of a switchgear fault and fire. In this case, three cubicles suffered extensive damage, and four experienced minor damage. Further, the fire propagated through the steel panel top into a vertical cable tray, about 10-ft up the vertical tray to a crossing horizontal tray, and about 8-ft along the intersecting horizontal tray before being stopped by a raceway fire barrier. The potential for fires inside closed electrical panels to propagate outside of the panel has been a point of significant recent debate. This incident clearly illustrates that this potential exists under some conditions.

A second factor of interest is the fact that fire fighting was considerably delayed in this incident. The delay was caused by three nominally unrelated factors, two of which related to decisions made by plant personnel during the incident.

One of these three factors was the decision made by the shift supervisor, who insisted on direct observation of flames before declaring a fire and activating the fire brigade. It took close to 30 minutes an hour (from time of ignition) for two operators to don protective breathing apparatus, enter the room, verify the presence of flames, seek out the source of the fire, retreat from the room and report back to the CR.

The second factor related to the strategy used to fight the fire. Once the fire was declared and the fire brigade arrived on-scene, the fire brigade resisted using water on an electrical fire until multiple attempts to extinguish the fire using portable extinguishers proved ineffective. As a result, the fire was allowed to burn far longer and observed damage was perhaps made worse than if prompt and effective fire suppression had been undertaken. The licensee did not report the reason for the failure of CO_2, Halon, and dry chemical agent to control the fire.

The final factor contributing to the delay in declaring a fire emergency is the position of the fire protection annunciator panel and the suppressed sound of the alarm. The panel was not readily visible to the operators in the CR must have diverted attention from the fire panel. It is important to note that even after receiving a verbal report of smoke in the switchgear room, the operators did not approach the fire protection panel to verify the condition of the fire detectors.

Another point of interest in this incident is the fact that operators noted a few erratic indications on the control board during the course of the incident. This indicates that control circuits can fail erratically under fire conditions. The licensee did not report the exact reasons for the observed behavior.

This incident also demonstrated that a fire stop in a horizontal cable tray can be effective in stopping the progression of the fire. In this case, the fire propagation in the horizontal tray ended at a raceway fire stop; however, a fire stop in a vertical cable tray may be ineffective. In this case the fire in the riser jumped past a fire stop and continued to propagate. It is not clear whether the fire stop delayed propagation.

References

Inspection Report 50-282/95-15, "NRC Augmented Inspection of Waterford 3," U.S. Nuclear Regulatory Commission, July 7, 1995.

Information Notice 95-33, "Switchgear Fire and Partial Loss of Offsite Power at Waterford Generating Station, Unit 3," U.S. Nuclear Regulatory Commission, August 23, 1995.

H.14 Palo Verde Nuclear Generating Station Unit 2, April 4, 1996

On April 4, 1996, Palo Verde Unit 2 was in a refueling outage. At 5:00 a.m., a fire watch detected smoke in the back panel area of the control room (CR), emanating from the Train B emergency lighting uninterruptible power supply (UPS) panel. At about the same time, an auxiliary operator discovered smoke and fire in the Train B DC equipment room at the 100-ft elevation of the auxiliary building. This second fire was discovered on the 480/120-volt essential lighting isolation transformer. However, multiple trouble alarms on the fire detectors masked the actual fire alarm coming from this equipment room such that operators did not notice the valid fire alarm signal.

The fires led to the loss of power to the Train B CR emergency lighting circuits, some of general plant essential lighting, and plant fire detection and alarm system panels. The circuit breaker supplying power to the UPS panel tripped open when cables in the conduit supplying the power supply panel overheated causing various conductors to short-circuit. The circuit breaker trip also deenergized power to the fire detection and alarm panels in the auxiliary building. The fire alarm annunciator monitor (a computer screen) indicated a large number of fire detector trouble alarms and these multiple alarms were scrolling on the monitor. This was attributed to the deenergized fire detection and alarm panels.

The fire in the equipment room was reported by the auxiliary operator to the CR and the shift supervisor activated the onsite fire brigade. The onsite fire brigade attacked the fire immediately and extinguished it in a short time. It is not entirely clear whether the fire brigade also reported to the CR or not. The operators approximately handled the fire in the CR and the CR fire was also quickly extinguished. The damaged caused by these fires was limited to the components of origin. That is, neither fire propagated beyond its point of ignition.

In this incident, the fires were not severe either from a classical fire protection standpoint or a nuclear safety standpoint. The most interesting aspect of this incident is the occurrence of multiple simultaneous fires, one of which occurred in the plant's main control room. Incidents involving multiple initial fires have been observed in several other plants. In some cases, particularly incidents at non-U.S. reactors, the fires have led to extensive damage.

The cause of simultaneous fires at Palo Verde was traced to a fault in the isolation transformer located in the Train B DC equipment room. This failure caused a short-circuit fault to the station ground through the transformer's panel ground. The neutral leg of the transformer was not connected to ground. Also, an inverter that served as the alternative essential lighting UPS was improperly grounded. The ground connection of the inverter served as the return path for the isolation transformer's ground fault, which passed through the essential lighting power supply panel. The conductors that carried the fault current were not designed to handle the high currents caused by the fault. As a result, they overheated and ignited the combustible materials around them. Clearly, the common factor leading to multiple ignitions was a common overheated electrical conductor.

It is also interesting to note that the fires in this case were, in effect, self-ignited cable fires. An electrical fault led to an ampacity overload on a particular cable, and the cable ignited in two locations as a result. The units at Palo Verde are relatively new (Unit 2 construction began in 1976 and the current U.S. cable flammability standard, IEEE-383, was adopted in 1975); hence, one can assume that the cables installed in the plant are of the low flame spread type. This incident is one of the very few incidents, if not the only incident, where a self-ignited cable fire in low flame spread cable has not self-extinguished. This incident appears to illustrate that the possibility of such fires does exist at some level, although the actual frequency of such fires remains uncertain.

Reference

Information Notice 97-01, "Improper Electrical Grounding Results in Simultaneous Fires in the Control Room and the Safe-Shutdown Equipment Room," U.S. Nuclear Regulatory Commission, January 8, 1997.

H.15 San Onofre Nuclear Generating Station, Unit 3, February 3, 2001

On February 3, 2001, San Onofre Unit 3, was operating at 39-percent power following a refueling outage. While switching offsite power sources for Unit 3, a 4160kV breaker (3A0712) faulted and initiated a fire. This resulted in a loss of power to Unit 3 nonsafety-related systems, a reactor trip, a turbine/generator trip, and an automatic start of both Unit 3 emergency diesel generators (EDGs). The main control room (MCR) received an annunciator fire alarm, along with a visual report of smoke and flames at the 30-foot elevation switchgear room of the turbine building. The incident was further complicated when the MCR annunciators were lost as a result of a tripped breaker approximately 5 minutes into the event.

The SONGS onsite fire department was dispatched upon receipt of the fire alarm in the switchgear room and arrived at the scene within 7 minutes. The on-scene fire department captain requested additional support from an offsite fire department. Firefighters observed that the room was completely filled with heavy smoke, with essentially zero visibility. The source of the heavy smoke and heat was determined to be within the closed cubicle 4160-V switchgear cabinetry. The firefighters also noted flames from burning instrument gauges on the front of cubicle 3B14, which is located directly across from the 4160-V breaker cubicle. The onsite fire department captain established a command post, initiated fire suppression using portable fire extinguishers, and began ventilating the area. Communication between the onsite fire department captain and the plant shift manager was through the technical advisor at the scene. The firefighters discharged portable Halon and dry chemical fire extinguishers through the cabinet vents in an attempt to extinguish any active fire within the cabinet. The extinguishing agents had no noticeable effect on the production of smoke. The technical advisor transmitted to the operations shift manager a report that the fire was out, although the fire department captain only advised the operations technical advisor that flames were no longer visible.

With the exception of some low-voltage circuits, all power was isolated to the 4160-V switchgear. The firefighters then determined that the cubicle door could be opened safely. Upon opening the cubicle door, the firefighters observed flames within the cubicle, and discharged additional dry chemical in another attempt to extinguish the flames. The firefighters then closed the cubicle door as a containment measure. The cubicle door was subsequently opened several times, and each time the door was opened, in-rushing air caused the fire to reflash. Firefighters then used dry chemical each time the fire reflashed.

The fire department captain advised the operations technical advisor that the fire could not be completely extinguished unless the firefighters applied water to the fire. It appeared that the dry chemical temporarily removed air from the fire, but did not reduce the heat, and the fire would reflash once air was reintroduced. The operations technical advisor relayed this request to the shift manager for permission to use water on the smoldering area inside the cubicle to prevent reflash. Because he was concerned that the buses were still energized with 125-V dc and low-voltage ac power, the shift manager initially denied the fire department captain's request to use water. However, after the fire department captain spoke directly with the shift manager to advise him that the deep-seated fire could not be extinguished unless water was applied, the shift manager granted permission to use water to extinguish the fire. The fire was ultimately extinguished after firefighters applied water. The deep-seated fire burned for approximately 3 hours before finally being extinguished. The licensee later determined that communication weaknesses in identifying the actual fire status during the event contributed to the delay in extinguishment.

Discussion

The extensive damage made it difficult to determine the exact cause of the fault. The licensee found that the 4160-V switchgear phase C arcing contact had completely melted, and concluded that the phase C circuit breaker failed to close completely during the bus transfer. The breaker was approximately 25 years old and had its last preventive maintenance performed in 1997. The licensee also believed that arcing, fire, smoke, and ionized gases in the 4160-V circuit breaker caused multiple faults on a 3A07 bus and the offsite power circuit terminal connection at circuit breaker 3A0714.

The licensee also determined that the fire event generated a much higher heat release rate (HRR) than would normally be assumed in typical fire risk modeling to perform probabilistic risk assessment (PRA). In "A Supplement to EPRI Fire PRA Implementation Guide (TR-105928)," report SU-105928, the Electric Power Research Institute (EPRI) provides data for electrical cabinet fires, indicating an HRR of either 68.60 kW or 200.50 kW (65- or 190 Btu/sec), depending on the type of cable installed. The EPRI data focus on the HRR contributions of combustibles in the electrical cabinet (only cable insulation) and neglect the large amounts of electrical energy that may be released from electrical faults. According to a report by the NRC's Office of Nuclear Regulatory Research, entitled "Operating Experience Assessment Energetic Faults in 4160-V kV to 13800-V Switchgear and Bus Ducts That Caused Fires in Nuclear Power Plants in 1986–2001" (ADAMS Accession #ML021290358, February 28, 2002) for medium- and high-voltage applications, the research indicates that these HRR values [68.60 kW and 200.50 kW (65- and 190 Btu/sec)] may be under predicted by a factor of 1,000.

This operating experience indicates that equipment rated at 4160-V and higher is vulnerable to particularly energetic electrical faults. This event demonstrates that energetic electrical faults instantaneously release large amounts of electrical energy and may bypass the normal fire initiation and growth stages. In the SONGS fire event, the equipment that caught fire was directly connected to the auxiliary transformer (AT), which is powered from the grid or main generator. If a circuit breaker is stuck or slow in responding, there is sufficient energy to cause an explosion and vaporize metal in a few cycles.

Conclusion

This event demonstrates the importance of using water to extinguish deep-seated electrical cable fires. It is similar to previous fire events (Browns Ferry 1975, Waterford 1995) in which delayed application of water on electrical fires extended the duration of the fires and delayed recovery from the events. It is essential that fire brigade and operator training address the appropriate use of water in firefighting operations in energized electrical equipment. This event also highlights that the HRR from fires in electrical cabinets may be much greater than assumed in NPP fire hazard analysis (FHA).

References

Inspection Report No. 50-362/01-05, "San Onofre Nuclear Generating Station NRC Special Team Inspection Report," U.S. Nuclear Regulatory Commission, April 20, 2001.

Preliminary Notification, PN401004, "Circuit Breaker Failure and Fire, Resulting in Reactor Shutdown," U.S. Nuclear Regulatory Commission, February 6, 2001.

Significant Event Notification, SEN 218, "Circuit Breaker Fault Results in Fire, Loss of Offsite Power, Reactor Scram, and Severe Turbine Damage," San Onofre Nuclear Generating Station Unit 3, March 9, 2001.

Significant Event Report, SER 5-01, "4-kV Breaker Failure Resulting in a Switchgear Fire and Damage to the Main Turbine Generator," San Onofre Nuclear Generating Station Unit 3, September 21, 2001.

H.16 Point Beach Nuclear Plant, Unit 1, April 24, 2001

On April 24, 2001, while Point Beach Unit 1 was shut down and defueled for refueling outage U1R26, a fire occurred in the “A” steam generator (S/G) vault on the access platform to the primary side manway covers. The fire was believed to originate as the result of a short in a 12-Vdc communication box. The fire consumed a bag of rags and testing equipment debris, and lasted for approximately 23 minutes. After multiple failed attempts in which the fire brigade discharged approximately 70 pounds of dry chemical (3 portable fire extinguishers), the fire was finally extinguished using 15–20 gallons of water. The licensee reported that approximately 50 percent of the containment basement floor (8 feet elevation), 50 percent of the “A” S/G vault, and 30 percent of the “A” reactor coolant pump (RCP) vault were covered in white dust (dry chemical fire extinguishing agent). Also, a white dust layer was visible on components on the main refueling floor (66 feet evaluation). Smoke and soot resulting from the fire left a mark about 4 feet wide by 25 feet high against the vault wall.

Discussion

The dry chemical extinguishing agent is discharged by an inert gas when a fire extinguisher is used. All forms of dry chemical act as extinguishing agents to suppress the flame of a fire (Friedman, 1998), but may require extensive cleanup after use, as illustrated by this event.

Most chemical extinguishing agents can produce some degree of corrosion or other damage, but of the seven types of dry chemicals, monoammonium phosphate is especially acidic and tends to corrode more readily than other dry chemicals, which tend to be more neutral or mildly alkaline. Furthermore, corrosion resulting from the other dry chemicals is stopped in a moderately dry atmosphere, while phosphoric acid generated by using monoammonium phosphate has such a strong affinity for water that an exceedingly dry atmosphere would be needed to stop the corrosion.

Application of dry chemical agents on electrical fires is considered a safe practice from the viewpoint of electric shock. However, these agents, especially monoammonium phosphate, can damage delicate electrical equipment.

One potential issue with using dry chemical extinguishers results from the sudden release of the agent and the large area of discharge. Dry chemicals become sticky when heated and, therefore, are not recommended for locations where it may be difficult to remove residue from equipment. It is important to note that when water is applied to the affected areas, corrosion will occur because moisture initiates a chemical reaction that accelerates corrosion of equipment exposed to the dry chemical.

Dry chemicals are generally nontoxic, but can pose a health hazard when used in closed areas. Persons who breathe concentrations of the dry chemical powder may experience respiratory irritation and coughing. When dry chemicals are discharged into an enclosed area, impaired breathing and reduced visibility should be considered.

Conclusion

Although the Point Beach incident lasted approximately 23 minutes, it was not a large fire in terms of HRR. The dry chemical extinguishing agent did suppress the fire, but failed to completely extinguish the fire (the fire reflashed twice). The fire brigade unsuccessfully attempted to extinguish the fire with dry chemical agent three times before easily extinguishing it with a hose line (water). A more thorough selection of extinguishing media should be considered in light of the cleanup effort from the small fire. It is important to recognize that the fire was successfully extinguished with a relatively small quantity of water, which required minimal post-fire cleanup.

References

Friedman, R. *Principles of Fire Protection Chemistry and Physics*, 3rd Edition, Chapter 14, "Fire-Fighting Procedures," pp. 229-230, National Fire Protection Association, Quincy, Massachusetts. 1998.

Point Beach Nuclear Plant, Inspection Report 50-266/01-08, 50-301/01-08, U.S. Nuclear Regulatory Commission, June 6, 2001 (ADAMS Accession #ML011580082).

"Point Beach Unit 1 Containment Fire," Presented by the Point Beach Senior Resident Inspector, Krohn, P.G., at the Region III Training Seminar. December 2001.

H.17 Prairie Island Nuclear Generating Plant, Unit 1, August 3, 2001

On August 3, 2001, at 8:44 p.m., an operator enroute to the Unit 1 bus 11/12 area observed fire and smoke, but could not identify the cubicle from which it was originating. The operator entered the bus 13/14 room and called the main control room (MCR) to report the fire. The MCR immediately initiated the fire alarm and activated the onsite fire brigade. The MCR also notified the offsite Red Wing Fire Department (RWFD).

The fire brigade entered the turbine building to assess the extent and exact location of the fire. They reported flames in the upper and lower compartments of the 12-4 cubicle and along the left side of the breaker. They also found that the door in both the upper and lower compartments of the cubicle were blown open.

At 8:58 p.m., the fire brigade began initial suppression of the fire using three portable carbon dioxide (CO_2) extinguishers and one Halon extinguisher through the open front door of the breaker cubicle. The fire was not extinguished, and the fire brigade observed electrical arcing in cubicle 12-4.

The fire appeared to be localized in one area and not spreading. The initial efforts to deenergize the bus from the MCR failed. The fire brigade chief reported to the MCR that breaker 12-4 was still energized, as evidenced by arcing observed in cubicle 12-4. Because of the uncertainty as to whether bus 12 was deenergized, the Unit 2 shift supervisor decided to deenergize the 1R transformer. The fire department reported to the MCR that there were small flames and heavy smoke in breakers 12-1 and 12-4. At 10:13 p.m., approximately 1.5 hours into the event, the fire brigade extinguished the fire with assistance from the RWFD.

Discussion

The fire was extinguished after 1.5 hours by using more than 20 portable CO_2 fire extinguishers in the evolution (in addition to the 3 CO_2 extinguishers and 1 Halon extinguisher used in the initial attack). One factor that complicated extinguishing the fire was the decision not to use water because of energized electrical equipment. This resulted in continued burning and elevated temperature. Because of the elevated temperature caused by this electrical fire, two fire brigade members were treated for heat exhaustion at the site, and one of them was subsequently transported to the hospital for further treatment. In addition, several inches of the copper feed stabs from the 1M transformer completely vaporized during this fire (providing additional evidence of high temperature).

The licensee determined that the cause of the event was a poor electrical connection between the breaker 12-4 C-phase primary disconnect assembly (PDA) and the 1MY bus stab, which caused the PDA to overheat. The arcing also actuated the protective relaying, which resulted in an automatic turbine/reactor trip. The arcing event at breaker 12-4 released enough energy to cause the cubicle to expand and the door to be blown open. The breaker compartment was heavily oxidized and holes were burned through the cubicle on either side of the breaker. The arcing event destroyed many of the springs and fingers in the PDAs. A few were found at the very bottom of the debris, particularly below C phase.

Conclusion

The root cause evaluation of the nonsafety-related breaker fire concluded that maintenance practices could have contributed to the failure of the PDA by creating a poor connection, which caused localized over heating of parts of the PDA. This overheating caused the PDA to disintegrate. At that point, the loose parts of the PDA created a short-to-ground path. Once the arc was struck, phase-to-phase faulting occurred between the A-B and B-C phases. The initial arcing to ground quickly interrupted the dc circuit below the breaker pan (located directly below the PDA).

In this fire event, the use of portable CO_2 and Halon fire extinguishers may not have been the most effective choice of extinguishing agent to use. Operating experience in energized electrical equipment fires shows that the use of a relatively small quantity of water was effective in successful fire extinguishment.

References

Preliminary Notification PN301027, “Electrical Panel Fire During Plant Startup,” Prairie Island Nuclear Generating Plant, Unit 1, U.S. Nuclear Regulatory Commission, August 6, 2001.

Licensee Event Report (LER) 1-01-05, “Fault and Fire in Non-Safeguards Circuit Breaker Results in Reactor Trip and Auxiliary Feedwater System Actuation,” Prairie Island Nuclear Generating Plant, Unit 1, October 2, 2001.

H.18 Fort Calhoun Station, Unit 1, December 19, 2001

In October 2001, the licensee for Fort Calhoun Station began a surveillance of the Unit 1 containment prestressing system. This surveillance included testing the tension of the containment concrete tensioning cables. It also involved pumping lubricating grease into the containment tendon sheathings to replace the grease that had been lost as a result of leakage. In support of this activity, 55-gallon drums of grease were located in the tension gallery. During this surveillance activity, the plant personnel discovered that the grease was too cold to pump and would need to be heated before use. Drum heaters were, therefore, used on the outside of the drums to heat the grease and facilitate pumping into the containment tension sheathings. Two drum heaters were used, one powered from a receptacle located in the tension gallery and the second powered from a receptacle located in room 22. In order to supply power from the outlet in room 22 to one of the drum heaters, two extension cords were connected in series and routed through the open door separating room 22 from the tension gallery. At the end of the day, the drum heater powered from the receptacle in room 22 was left energized to keep the grease warm overnight so that work could begin the next morning.

Unbeknownst to plant personnel involved in performing the surveillance, the extension cords used to power the drum heater were not rated for this application. The extension cords were rated at 15 amperes, and had male connections that would only allow them to be connected to 15-ampere receptacles. However, the 20-ampere male connection on the drum heater had been inappropriately modified to allow it to be connected to a 15-ampere plug or receptacle. The licensee later determined that the 2,000-watt drum heater drew a current of 17.39 amperes.

As a result of using underrated extension cords, the extension cords continued to heat up during the evening. The extension cords eventually overheated and ignited the plastic on the radiological control point stepoff pad and a rubber air hose.

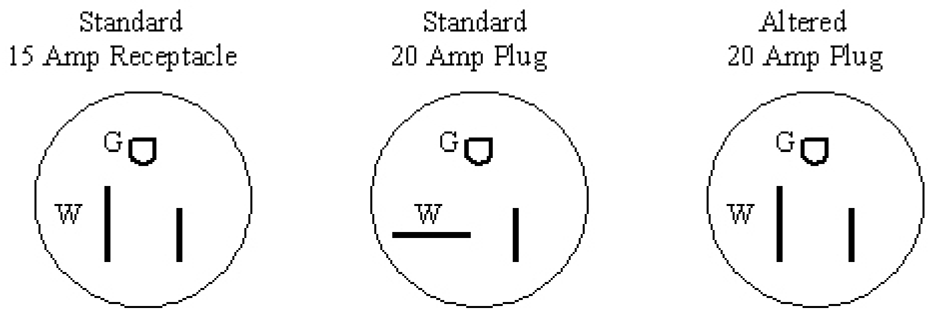
On December 19, 2001, at 2:48 a.m., the MCR operators received an alarm from an ionization smoke detector located in room 22. A control room operator dispatched the auxiliary building operator and a radiation protection technician to investigate the cause of the fire alarms. The auxiliary building operator arrived at the door to room 22, cracked the door open, and determined that there was too much smoke to enter the room without using protective firefighting bunker gear and a self-contained breathing apparatus (SCBA) and informed the MCR. The fire brigade was activated while operators entered the abnormal operating procedure for fighting fires. During this event, the MCR received another ionization smoke detector alarm in corridor 4.

The fire brigade laid out an attack line from the hose cabinet outside room 22 and a backup line from the cabinet outside room 6 before the attack team prepared to enter room 22. The attack team entered room 22 and proceeded down the stairs toward the entrance to the containment tension stressing gallery. The nozzle man described room 22 as being completely filled with smoke with no visibility. The smoke that traveled from room 22 through the open door caused the actuation of the water curtain open head deluge system on the auxiliary building stairwell, which resulted in water being sprayed onto safety-related motor control centers (MCCs), which subsequently caused actuation of the 480-V bus ground alarms in the MCR.

These MCCs are safety-related but are not required to function during a safe shutdown event, as defined by Appendix R to Title 10, Part 50, of the *Code of Federal Regulations* (10 CFR Part 50). Operators also restarted the room 22 ventilation to remove the smoke.

Discussion

Licensee personnel performed unauthorized modifications to the male connections of two drum heaters, allowing them to be inserted into underrated outlets and extension cords, which ultimately caused the fire. The licensee concluded that the root cause of the fire was the modification of the male connection on a 2,000-watt drum heater. The plug on a second 2,000-watt drum heater was also found to be modified. This unauthorized modification defeated a manufactured safety device (electrical connector standards), thereby allowing the heaters to be energized using undersized extension cords and electrical outlets. On one of the plugs, a prong was twisted 90 degrees to make it similar to a 15-ampere plug. On the other heater, the plug was completely removed and replaced with a 15-ampere plug (see illustrations below).



Conclusion

The fire was a result of modified plugs on two drum heaters, which defeated the intent of the design of electrical outlets. The licensee failed to with comply the procedural requirements for a temporary modification. The heavy smoke from the fire caused a deluge sprinkler system to actuate in a different fire area which sprayed on safety-related electrical equipment. 10 CFR 50.48(a) requires licensees to have a fire protection plan that meets General Design Criterion (GDC) 3 of Appendix A to 10 CFR Part 50. GDC 3 requires that structures, systems, and components that are important to safety shall be designed and located to minimize, the probability and effect of fires and explosions, consistent with other safety requirements.

Reference

Fort Calhoun Station NRC Special Team Inspection Report, 50-285/02-06, U.S. Nuclear Regulatory Commission, April 5, 2002 (ADAMS Accession #ML020960001).

APPENDIX I. MATHEMATICS REVIEW AND SYSTEM OF UNITS

This appendix provides the essential, mathematical foundation for quantitative fire hazard analysis.

I.1 Mathematics Review

While it was our goal to minimize the use of mathematics as much as possible, there is a need to use some relatively simple mathematics to understand the principles of fire dynamics used in this NUREG. The mathematical methods used in this NUREG hinge on an understanding of units of measurement, the ability to read various types of graphs, the ability to solve simple algebraic equations and to determine the unit consistency of an equation, and the ability to use simple functions commonly found on a basic scientific calculator. The spreadsheets were designed with this in mind, i.e., each sheet shows equations and variables being input. It was the authors' goal to further the science of fire dynamics, while not burdening the users down with complex mathematical operations. Likewise it's the users' responsibility to use the spreadsheets to gain an understanding of fire dynamics and *not* view them as "black boxes."

I.1.1 Units of Measurement

Fire dynamics most often uses units of measure from the system international (SI) metric system. While this may seem foreign at first, the transition to metric units is relatively easy and, once mastered, the metric system is much easier to use than English units of measure. Many of the spreadsheets are designed to allow the user to enter the information in English units, the spreadsheet will convert them to SI units, solve the problem and convert the answer back to English units.

Table I.1-1 summarizes the basic units of measure. These are units of length, mass, time, temperature, electric current, amount of light, and quantity of matter. All other units can be derived from these seven basic units. For instance, velocity (or speed) is a derived unit, expressed as meter per second (m/s), which is formed from the units of length and time.

Table I.1-1. Basic Units

Units of Measure	Symbol	Unit (SI)	SI Symbol
Length	L	meter	m
Mass	m	kilogram	kg
Time	t	second	s
Temperature	T	Celsius, Kelvin	°C, K
Electric current	A	ampere	A
Amount of light	cd	candela	cd
Quantity of matter	mol	mole	mol

Table I.1-2 presents a partial listing of the derived units that are useful in fire dynamics. The table does not include units relevant to electricity, magnetism, or other areas that are not relevant to fire dynamics. Note that some units named after individuals are capitalized, while other units are not. For example, because the unit of power (watt) is named for James Watt of steam engine fame; the abbreviation (W) is capitalized.

Table I.1-2. Derived Units

Unit of Measure	**Unit (SI)**	**SI Symbol**
Acceleration	meter per square second	m/s^2
Area	square meter	m^2
Density	kilogram per cubic meter	kg/m^3
Energy	joule (J)	N-m
Force	newton (N)	$Kg\text{-}m/s^2$
Frequency	hertz (Hz)	l/s
Heat (quantity)	joule (J)	N-m
Heat flux	kilowatts per square meter	kW/m^2
Illuminance	lux (lx)	lm/m^2
Luminance	candela per square meter	cd/m^2
Luminous flux	lumen (lm)	lm/m^2
Power (heat release rate)	watt (W)	J/s
Pressure	pascal (Pa)	N/m^2
Radiant intensity	watt per steradian	W/sr
Specific heat	joule per kilogram-kelvin	J/kg-K
Stress	pascal (Pa)	N/m^2
Thermal conductivity	watt per meter-kelvin	W/m-K
Velocity	meter per second	m/s
Viscosity, dynamic	pascal-second	Pa-sec
Viscosity, kinematic	square meter per second	m^2/s
Volume	cubic meter	m^3
Work	joule (J)	N-m

Simple units of the types shown in Table I.1-1 and I.1-2 can be cumbersome if the magnitudes are very large or very small. For example, it is problematic to speak of distances between cities in meters (as in "City A is 5,000 meters from City B"). While this distance may be accurate, meters is not the most convenient unit in terms of magnitude. To avoid very large and very small numbers, the metric system uses prefixes to modify the magnitude of the basic unit. For example, 5,000 m is equivalent to 5 km. The prefix k refers to kilo and indicates multiplication by 1,000. Table I.1-3 lists the common prefixes used in the metric system form names and symbols of multiples (decimal multiples and sub-multiples) of the SI units. While these prefixes are optional, they often simplify matters. The distance in the example above (5,000 m or 5 km) is a common foot race distance, which is often further simplified by referring to a 5-k race.

Table I.1-3. SI Prefixes

Multiplication Factors	**Prefix**	**SI Symbol**
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

Table I.1-4 introduces another useful concept, known as scientific notation. Rather than writing out 1,000,000, it is useful to use scientific notation, which indicates the number of zeros as an exponent. In Table I.1-3, we see an entry for the prefix mega, which refers to multiplication by 1,000,000 or, in scientific notation, 10^6 or 10E+06. Thus, a distance of 5,000,000 m could be expressed as 5×10^6 m or 5 Mm. We see that scientific notation has essentially the same function as the prefixes.

Table I.1-4. Scientific Notations, Prefixes, and Abbreviations

Multiplier	**Prefix**	**Abbreviation**
10^{12}	tera	T
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^2	hecto	h
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	
10^{-9}	nano	n
10^{-12}	pico	p
10^{-18}	atto	a

While the information required for use in fire dynamics is generally available in metric units, the data are sometimes available only in English units and conversion to metric is needed. Table I.1-5 gives some of the most common conversions required for fire dynamics. These conversions are simple to apply. For example, to convert from feet to meter, multiply the number of feet by 3.048×10^{-1} (0.3048) to get the number in meters. Many of the spreadsheets have this conversion features built into the sheet.

Table I.1-5. Selected Unit Conversions

To Convert from	**To**	**Multiply by**
Area		
foot^2	meter^2 (m^2)	9.290304×10^{-2}
inch^2	meter^2 (m^2)	6.451600×10^{-4}
Energy/Area Time watt/centimeter^2	watt/meter^2 (W/m^2)	1.0×10^4
Length		
foot	meter (m)	3.048×10^{-1}
inch	meter (m)	2.540×10^{-2}

Table I.1-5. Selected Unit Conversions

To Convert from	To	Multiply by
Mass/Area		4.882428×10^{0}
pound-mass/foot^2	kilogram/meter^2 (kg/m^2)	
Mass/Volume (including Density and Mass Capacity) pound-mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601846×10^{1}
Pressure		
atmosphere	Pascal (Pa)	1.01325×10^{5}
bar	Pascal (Pa)	1.0×10^{5}
inch of mercury	Pascal (Pa)	3.37685×10^{3}
inch of water	Pascal (Pa)	2.4884×10^{2}
pound-force/inch^2 (psi)	Pascal (Pa)	6.894757×10^{3}
torr mm Hg (°C)	Pascal (Pa)	1.33322×10^{2}
Temperature		
degree Celsius	degree Fahrenheit (°F)	9/5 °C + 32
degree Celsius	Kelvin (K)	°C + 273.15
degree Celsius	Rankine (R)	5/9 (R + 491.67)
degree Fahrenheit	degree Celsius (°C)	5/9 (°F - 32)
degree Fahrenheit	Kelvin (K)	5/9 °F + 255.37
degree Fahrenheit	Rankine (R)	°F + 459.67
Kelvin	degree Celsius (°C)	K - 273.15
Kelvin	degree Fahrenheit (°F)	9/5(K - 255.37)
Kelvin	Rankine (R)	9/5 K
Rankine	degree Celsius (°C)	5/9 (R - 491.67)
Rankine	degree Fahrenheit (°F)	R - 459.67
Rankine	Kelvin (K)	5/9 R
Time		
day (mean solar)	second (s)	8.640×10^{4}
hour (mean solar)	second (s)	3.60×10^{3}
minute (mean solar)	second (s)	6.0×10^{1}
Velocity (includes Speed)		
foot/second	meter/second (m/s)	3.0480×10^{-1}
mile/hour	meter/second (m/s)	4.4704×10^{-1}
Volume (including Capacity)		
foot^3	meter^3 (m^3)	2.831685×10^{-2}
gallon (U.S. liquid)	meter^3 (m^3)	3.785412×10^{-3}
liter	meter^3 (m^3)	1.0×10^{-3}

The approach taken in converting from customary English units to SI units has been to retain the precision of the original measurement. For example, “It is about 8-miles,” properly translates to “It is about 13 kilometers.” Thus, would be inappropriate to convert the imprecise 8-mile measurement to a precise value of 12.875 kilometers (based on the exact conversion). The degree of precision implied by such an exact conversion is simply not implied by the original measurement. Therefore, conversions have been chosen to properly reflect the precision of the original measurement. For example, a 12-foot run of sprinkler piping converts to 3.7 meters, if the piping is measured to the nearest inch. If measured to the nearest foot, the appropriate conversion is 4 meters.

For the most part the SI units into which quantities have been converted follow the SI practice of expressing a quantity so that its numerical value falls between 0.1 and 1,000. For example, 14.7 psi would be converted to 101 kPa, not 101,000 Pa. Some deviations from this practice have been allowed in instances where several values of the same quantity are being compared or presented in tabular form. For example, if four fire test samples have masses of 500 kg, 800 kg, 900 kg, and 1,200 kg, it would be inappropriate to express the last entry as 1.2 Mg.

I.1.2 Math Functions

This section discusses several mathematical functions that are common to many of the equations and empirical correlations used in fire dynamics. These functions can all be calculated using a simple scientific hand calculator.

(1) A “power” is an exponent (x) that operates on a base (y) real number in the function y^x. When the power is a whole number, the function can be expressed as the base multiplied by itself the number of times indicated by the power.

$$y^x = (3.2)^3 = (3.2) \text{ x } (3.2) \text{ x } (3.2) = 32.768$$

When the same base (y) is raised to different powers and the quantities are multiplied, the “powers” are added, as illustrated by the following examples:

$$(Q)^{\frac{3}{2}}.(Q)^{\frac{4}{2}} = (Q)^{\frac{3}{2}+\frac{4}{2}} = (Q)^{\frac{7}{2}} \text{ (a)}$$

$$(Z)^2.(Z)^3 = (Z)^{2+3} = (Z)^5 \text{ (b)}$$

Similarly, when the same base (y) is raised to different powers and the quantities are divided, the powers are subtracted as illustrated by the following examples:

$$\frac{(Q)^{\frac{3}{2}}}{(Q)^{\frac{2}{2}}} = (Q)^{\frac{3}{2}-\frac{2}{2}} = (Q)^{\frac{1}{2}} \text{ (a)}$$

$$\frac{(Z)^2}{(Z)^3} = (Z)^{2-3} = (Z)^{-1} = \frac{1}{(Z)^1} = \frac{1}{Z} \text{ (b)}$$

By contrast, when a power (x) is raised to another power, they multiply, as illustrated by the following example:

$$\left(Z.Q^{\frac{1}{2}}\right)^3 = (Z)^{1x3}.(Q)^{\frac{1}{2}x3} = Z^3.Q^{\frac{3}{2}}$$

Finally when a number or variable has no "power," it is assumed to be raised to the power of 1 because any "base" raised to the "power" of 1 is equal to the "base" as illustrated by the following examples:

$$(Z)^1 = Z$$
$$(Q)^1 = Q$$

In summary, the following examples are valid mathematical equations using powers:

(a)
$$Q^x Q^r = Q^{x+r}$$

(b)
$$\frac{Q^x}{Q^r} = Q^{x-r}$$

(c)
$$\left(Q^x\right)^r = Q^{xr}$$

A scientific calculator typically has a y^x button.

(2) A logarithm is an exponent indicating the power to which a fixed number (the base) must be raised to produce a given number. For example, if $n^x = a$, then the logarithm of a, with n as the base, is x, as illustrated by the following function:

$$LOG_n(a) = x$$

Scientific calculators typically have two logarithmic buttons typically identified as LOG and LN. In such cases, LOG returns the logarithm of the imputed value using a base equal to 10. This common logarithm functions as follows:

$$LOG_{10} \text{ (value entered)} = x \text{ (value calculator returns)}$$

By contrast, LN returns the logarithm of the imputed value using the base equal to "e," which is the real number for which the natural logarithm is 1 (≈2.718). This "natural logarithm" function as follows:

$$LOG_e \text{ (value entered)} = x \text{ (value calculator returns).}$$

I.1.3 Solving Equations

"Equation solving" is a central theme in mathematics which is considerably broader than the treatment given here. The FDT^s we are using for fire hazard analysis (FHA) is simply based on algebraic equations, in which we substitute numbers for the variables and calculate a numerical result. This calculation hinges on inserting numbers for the variable names with units included, and then checking or adjusting the units to ensure dimensional consistency through a process called dimensional analysis. This process is based on the principle that units associated with numbers are operated on, just as the numerical values are, through algebraic manipulations.

Units follow the rules set forth for powers, because units can also have associated powers:

- When divided, units cancel through power subtraction, as illustrated by the following examples:

  (a) $\dfrac{kg \cdot m}{kg} = kg^{1-1} \cdot m = m$

  (b) $\dfrac{kg^3 \cdot m}{kg} = kg^{3-1} \cdot m = kg^2 \cdot m$

- When multiplied units combine through power addition, as illustrated by the following examples:

  (a) $\left(3 \ \ kg\right) \ x \ \left(5 \ \ kg^2\right) = 15 \ \ kg^3$

  (b) $\dfrac{m \cdot m}{kg^2} = \dfrac{m^2}{kg^2}$

- When raised to other powers, unit powers are multiplied, as illustrated by the following examples:

$$\left(x \ \ kg^{\frac{1}{3}} m^3 s^2\right)^{\frac{1}{2}} = x^{\frac{1}{2}} \ \ kg^{\frac{1}{3}\frac{1}{2}} m^{3\frac{1}{2}} s^{2\frac{1}{2}} = x^{\frac{1}{2}} \ \ kg^{\frac{1}{6}} m^{\frac{3}{2}} s^1$$

- The horizontal flame spread rate on thick solid fuels equation is a good illustration:

$$V = \frac{\Phi}{k\rho c\left(T_{ig} - T_a\right)^2}$$

Where:

V = flame spread rate (m/sec)
Φ = a flame spread modulus $(kW)^2/m^3$ (determined experimentally)
k c = thermal inertia $(kW/m^2\ K)^2$ sec
T_{ig} = material ignition temperature (°C)
T_a = initial material temperature (°C)

The literature provides the following data for plywood:

$\dotplus$ = 12.9 $(kW)^2/m^3$
$k\ c$ = 0.54 $(kW/m^2\ K)^2$ sec
T_{ig} = 390 °C

We cannot solve for the flame spread rate until we select a material temperature T_a. Indeed, the point of the equation is to show how the flame spread rate varies with material and material temperature. As an example, let's use T_a = 200 °C. Substituting the numerical values in the equation, we can compute the flame spread rate on plywood, as follows:

$$V = \frac{12.9\ \dfrac{(kW)^2}{m^3}}{0.54\ \left(\dfrac{kW}{m^2 K}\right)^2 \sec\ \left(390\ °C - 200\ °C\right)^2}$$

$$V = \frac{12.9}{(0.54)(190)^2}\ \frac{\dfrac{kW^2}{m^3}}{\dfrac{kW^2 \sec}{m^4 K^2}\ °C^2}$$

We can now use a calculator to perform the multiplications and division to obtain an answer as follows:

$$V = 0.00066\ \frac{\dfrac{kW^2}{m^3}}{\dfrac{kW^2 \sec}{m^4 K^2}\ °C^2}$$

It remains to check the consistency of the units. The kW^2 and m^3 in the above equation, as follows:

$$V = 0.00066\ \frac{1}{\dfrac{\sec\ °C^2}{m\ K^2}}$$

At first inspection, it does not appear that the two temperature units will cancel, even though they are both raised to the power of 2. However, because the °C^2 unit comes from a temperature difference, it will cancel because the only difference between °C and K is an added constant. Thus, to convert from °C to K, you add 273, as follows:

$$(390\ °C - 200\ °C)^2 = [(390\ °C + 273\ K) - (200\ °C + 273\ K)]^2$$
$$= [663\ K - 473\ K]^2$$
$$= 190\ K^2$$

The result in terms of temperature differentials (T), 190 °K^2 is the same as 190 °C^2. If the °C term were not different, it would require the conversion to K^2. Thus, in this case, the °C^2 and the K^2 units cancel.

$$V = 0.00066\ \frac{\frac{1}{sec}}{m}$$

The resulting unit is m/s as follows:

$$V = 0.00066\ \frac{m}{sec}$$

Thus, the result is complete and the units are consistent and reasonable. Meter/second (m/s) is the unit of velocity as the equation indicated it should be.

I.1.4 Cautions with T Conversions

A word of caution is in order about converting temperature between Celsius (°C) and Fahrenheit (°F). For conversion between the temperature scales:

$$°F = (°C \times 1.8) + 32$$

$$°C = (°F - 32) / 1.8$$

For example, to convert the temperature 250 °F to °C:

$$°C = (250\ °F - 32) / 1.8$$
$$= (218) / 1.8$$
$$= 121.11 \sim 121\ °C$$

However, to establish a ratio, such as a temperature rise (T):

$$\Delta °F = (\Delta °C \times 1.8)$$

$$\Delta °C = (\Delta °F / 1.8)$$

For example, to convert a temperature rise (T) of 250 °F to °C, instead of converting:

$$
\begin{array}{lll}
32\ °F \rightarrow 282\ °F & & (DT = 250\ °F) \\
\updownarrow \quad\quad \updownarrow & & \quad\quad \updownarrow \\
0\ °C \rightarrow 138.9\ °C & & (DT = 139\ °C)
\end{array}
$$

the same will result from:

$$
\begin{aligned}
°C &= (250\ °F / 1.8) \\
&= 138.89 \sim 139\ °C
\end{aligned}
$$

Note that ASTM E119, "Standard Test Method for Fire Tests of Building Construction and Materials," properly applies these conversions as illustrated in "Tests of Nonbearing Walls and Partitions," Section 18.1.3, "Transmission of heat through the wall or partition during the fire endurance test shall not have been such as to raise the temperature on its unexposed surface more than 250 °F (139 °C) above its initial temperature."

NFPA 251, 1995 Edition, "Standard Method of Fire Tests of Building Construction and Materials," does not make this same conversion, "Transmission of heat through the wall or partition during the fire endurance test shall not be sufficient to raise the temperature on its unexposed surface more than 250 °F (139 °C) above its initial temperature." For the purpose of this NUREG, the conversion of ASTM E119 will be used.

I.1.5 Miscellaneous Information

The following information involves measurement of geometrical quantities in the form of diameter, circumference, area, etc.

- To find the diameter of a circle, multiply the circumference by 0.31831.

$$D_c = C \quad 0.31831$$

- To find the circumference of a circle, multiply the diameter by 3.14159.

$$C_c = \pi D = 314159D$$

- To find the area of a circle, multiply the square of the diameter by 0.78539.

$$A_c = \frac{\pi}{4} D^2 = 0.78539D^2$$

- To find the surface of a sphere, multiply the square of the diameter by 3.14159.

$$A_s = \pi D^2 = 314159D^2$$

- To find the volume of a sphere, multiply the cube of the diameter by 0.52369.

$$V_s = \frac{\pi}{6} D^3 = 0.52369 D^3$$

- Doubling the diameter of a pipe or hose increases its capacity four times.

$$2D = 4Capacity$$

I.1.6 References

Fire Dynamics Course Guide, Federal Emergency Management Agency (FEMA), United States Fire Administration (USFA), National Emergency Training Center, Emmitsburg, Maryland, 1995.

Qunitiere, J.G., *Principles of Fire Behavior*, Delmar Publishers, Albany, New York, 1997.

"Standard for Use of the International System of Units (SI): The Modern Metric System," IEEE/ASTM SI 10-1997, Institute of Electrical and Electronics Engineer, Inc., (IEEE), New York, New York, and American Society of Testing and Materials (ASTM), West Conshohocken, Pennsylvania, 1997.

Taylor, B.N., "Guide for the Use of the International System of Units (SI)," NIST Special Publication 811, 1995 Edition, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland.

I.2 Notation Conventions

This section provide various notation conventions used in fire dynamics to expressed a quantity related to fire protection engineering, for example, heat flux density $(\dot{q}'')$ or heat release rate $(\dot{Q})$.

X, x — Generally letters are assigned to physical phenomena. In fire protection engineering there is often a special significance implied by either upper or lower case. The use of notation is important in fire dynamics, upper and lower case are recommended.

The following symbols indicate additional characteristics of a single quantity to simplify both memorization needs and dimensional verification of calculations.

$\dot{X}$ — A dot over a letter means that quantity "per unit time" (e.g., rate).

$\ddot{X}$ — A double dot over a letter means that quantity "per unit time per unit time" (e.g., acceleration is the change in velocity over a period of time).

X' — An apostrophe to the right of a letter means that quantity "per unit length."

X'' — Two apostrophies to the right of a letter signifies that quantity "per unit area."

X''' — Three apostrophies to the right of a letter means that quantity "per unit volume."

$\bar{X}$ — A bar over a letter means the arithmetic average value (the mean value) of varying quantity.

The following usage conventions also apply to the equations used in FHA.

$\dot{X}''$ — Notations may be combined as needed.

kW — With unit abbreviations, it is customary to use a capital letter when the abbreviation signifies a person's name (e.g., W for Watt, kW for kilowatt).

x/y — Units in the denominator are generally shown without a prefix (s, m, etc.), but there is an exception (i.e., kg).

$x/(y\ z^0)$ — Quantities with more than one unit in the denominator are shown with the denominator in parentheses and units separated by a space.

I.2.1 Reference

SI Units Fire Protection Engineering, 1980 Report of the Measurement of Fire Phenomena Committee, Society of Fire Protection Engineers (SFPE), Boston, Massachusetts, March 1980.

I.3 System of Units

When expressing a physical quantity by a numerical value, a unit must be selected for that quantity defined by appropriate notation, letters or symbols. Certain units are by convention regarded as dimensionally independent; these units are called base units, and all other units (derived units) can be expressed algebraically in terms of the base units. The following section describes the fundamental basic and derived units of measurements.

I.3.1 Length, Area, and Volume Units

The basic SI unit of length is the meter (m). Originally, the meter was selected as one ten-millionth of the distance from earth's equator to the North Pole.

The basic SI units of area are square meter (m^2), square centimeter (cm^2), and so on. Land areas are expressed in hectares (ha); 1 hectare is 10,000 m^2. The English equivalent of the hectare is 2.47 acres.

Similarly, volume is expressed in cubic meters (m^3), cubic centimeters (cm^3), and so on. The liter (L), which is also is commonly used as a unit of volume, is the same as 1 cubic decimeter (dm^3) or 1,000 cubic centimeters (cm^3). The English equivalency of the liter is 0.264 U.S. gallons.

I.3.2 Mass and Density Units

The basic SI unit of mass is the kilogram (kg). The kilogram was selected because it is approximately the mass of 1 liter of water. The gram (g), also widely used, is one one-thousandth of a kilogram, which is approximately the mass of 1 cubic centimeter of water. (Water expands or contracts slightly as its temperature changes.)

Density (mass per unit volume) is generally expressed in grams per cubic centimeter (g/cm^3) or kilograms per cubic decimeter (kg/dm^3). The numerical value of density is the same in either of these units. "Specific gravity" refers to the ratio of the density of a substance to that of liquid water.

Confusion often exists between mass and weight. Weight refers to the force acting on an object because of gravitational attraction. As such, it is a convenient way to measure mass at sea level on earth. However, if an object were on the moon, its weight would be only about one-sixth of its weight on earth and in an orbiting space station, the object would be weightless; however, its mass would be the same in each case as it is on earth. The mass of an object is the sum of masses of its constituent atoms and is invariant (except in a nuclear bomb explosion, when mass changes into energy). This fact can be proved by an experiment measuring the inertia of an object (the force needed to accelerate it the object).

I.3.3 Time Units

Units of time are the same in the SI system as in the English system. The basic unit is the second.

I.3.4 Force and Pressure Units

The basic unit of force in the SI system is the newton (N). A newton is the force needed to accelerate a mass of 1 kg at the rate of 1 m/sec^2. In the English system, 1 lb of force will accelerate 1 lb of mass at the rate of 32.2 ft/sec^2. This definition was selected so that 1 lb of mass at sea level would feel a gravitational attraction of 1 lb of force.

From the relationships between the pound and the kilogram, and between the foot and the meter, it is easy to show that a newton is equal to 0.224 lb of force. The gravitational force on 1 kg of mass at sea level is 9.81 N.

Pressure is force per unit area. The basic SI unit of pressure is the pascal (Pa), which is 1 N/m^2. One Pa is a very low pressure; therefore, we also use a unit called the bar, which is defined as 100,000 Pa or 100 kilopascals (kPa). One bar is only 1.3 percent greater than normal atmospheric pressure at sea level; therefore, 1 bar is nearly equal to 1 atmosphere (atm).

In the English system, pressure is often expressed in pounds per square inch (psi) or in inches of water (H_2O) or mercury (Hg). One bar equals 14.89 psi and kPa equals 4.02 in. of water.

I.3.5 Energy Units

The basic SI unit of energy is the joule (J). A joule is the quantity of energy expended when a force of 1 N pushes something a distance of 1 m. Both thermal and mechanical energy can be expressed as joules. One joule equals 0.239 calorie (cal), and 4.187 J equals 1 cal. (A calorie is the energy needed to heat 1 g of water 1 °C; a dietitian's calorie is actually 1,000 calories.)

Electrical energy can also be expressed in joules; in the case, 1 J equals 1 watt-second (Ws) and one megajoule (MJ) (1,000,000 J) equals 0.278 kilowatt-hour (kW-h). For example, if a power of 1 kW is released in an electric iron for 0.278 h, 1 MJ of thermal energy has been released.

In English units, energy is expressed in foot-pounds (ft-lb) or British thermal units (Btu). One ft-lb is equal to 1.355 J, and 1 Btu is equal to 1,044 J or 252 cal.

I.3.6 Power Units

Power is the rate at which energy is expended. In SI units, power is expressed in watts (W), kilowatts (1,000 W) or megawatts (MW) (1,000,000 W). One watt is 1 J/sec. In English units, power is expressed as horsepower (hp), where one horsepower equals 745 W. Also, note that 1 Btu/sec equals 1.055 kW. (For first order approximation, 1 Btu/sec roughly equals 1 kW).

I.3.7 Temperature Units

The SI system uses both the Celsius (°C) and Kelvin scale (K) temperature scales. A Celsius degree (previously called centigrade) is one one-hundredth of the difference between the temperature of melting ice and boiling water at a pressure of 1 atmosphere (atm). On the Celsius scale (at sea level), 0° is the melting point of ice (or the freezing point of water) and 100° is the boiling point of water. Negative temperatures are possible.

On the Kelvin scale (Celsius absolute), sometimes called the thermodynamic temperature, the zero point is called "absolute zero" and equals -273.15 °C. No temperature colder than this is possible; that is, negative temperatures are not possible. The Kelvin scale is expressed in Kelvin, not degrees Kelvin.

Other features of the Kelvin scale indicate its basic nature:

- The volume occupied by a gas is proportional to its temperature on the Kelvin scale, as long as its pressure is held constant (except at pressures far above atmospheric pressure).
- The thermal radiation emitted by an opening in a hot furnace is proportional to the fourth power of the Kelvin temperature.
- The velocity of sound through a gas is proportional to the square root of its Kelvin temperature.

Because of these and other scientific facts, it would be logical to use only the Kelvin scale for temperature. However, the world continues to use both scales because the Celsius was used for more than century before these facts were discovered.

By contrast, the English system uses the Fahrenheit temperature scale (°F). One Fahrenheit degree is 1one eightieth of the difference between the temperature of melting of ice and boiling water at a pressure of 1 atm. On the Fahrenheit scale (at sea level), 32 °F is the melting point of ice (or the freezing point of water), and 212 °F is the boiling point of water.

I.3.8 References

ASTM E-380-93, "Standard Practice for Use of the International System of Units (SI) (the Modernized Metric System)," American Society for Testing and Materials (ASTM), West Conshohocken, Pennsylvania.

IEEE/ASTM SI 10-1997, "Standard for Use of the International System of Units (SI): The Modern Metric System," Institute of Electrical and Electronics Engineer, Inc., (IEEE), New York, New York, and American Society of Testing and Materials (ASTM), West Conshohocken, Pennsylvania, 1997.

Taylor, B.N., "Guide for the Use of the International System of Units (SI)," NIST Special Publication 811, 1995 Edition, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland.

I.4 Physical Constants for General Use

Table I.4.1 provides common values of physical constants used in the fire dynamics and other engineering and scientific calculations. Table I.4.1 show the values of several different constants in SI units having special names and symbols.

Table I.4-1. Values of Constants for General Use

Constant Name	**Symbol**	**Value**	**SI Unit**
Standard atmospheric pressure	P_a	100	kPa
Absolute zero (temperature)	T	0	K
Standard acceleration due to gravity	g	9.80665	m/s^2
Velocity of sound in air (P_a, 20 °C, 50% R.H.)	M	344	m/s
Specific volume of perfect gas at standard temperature and pressure	V_a	22.414	$m^3/(k\text{-}mol)$
Characteristic gas constant for air	R_a	287.045	J/(kg K)
Characteristic gas constant for water vapor	R_v	461.52	J/(kg K)
Natural logarithms	e	2.7182818285	–
Pi		3.1415926536	–
Stenfan-Boltzman constant		5.67032×10^{-11}	$kW/(m^2\ K^4)$

I.4.1 Reference

SI Units Fire Protection Engineering, 1980 Report of the Measurement of Fire Phenomena Committee, Society of Fire Protection Engineers (SFPE), Boston, Massachusetts, March 1980.

APPENDIX J. PRACTICE PROBLEMS AND SOLUTIONS

This appendix contains problems to apply the principles learned in the NUREG with the FDT^s program. This appendix provides some additional practice to solve problems related to fire dynamics.

NUREG Chapter and Related Calculation Methods

Problem	NUREG Chapter	FDT^s
J-1	Chapter 2. Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire with Natural and Forced Ventilation Method of McCaffrey, Quintiere, and Harkleroad (MQH) Compartment with Thermally Thick/Thin Boundaries	02.1_Temperature_NV.xls
J-2	Chapter 2. Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire with Natural and Forced Ventilation Method of Foote, Pagni, and Alvares (FPA) Compartment with Thermally Thick/Thin Boundaries Method of Deal and Beyler Compartment with Thermally Thick/Thin Boundaries	02.2_Temperature_FV.xls
J-3	Chapter 2. Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire with Natural and Forced Ventilation Method of McCaffrey, Quintiere, and Harkleroad (MQH) Compartment with Thermally Thick/Thin Boundaries Chapter 2. Method of Predicting Hot Gas Layer Temperature in Room Fire with Forced Ventilation Method of Foote, Pagni, and Alvares (FPA) Compartment with Thermally Thick/Thin Boundaries Method of Deal and Beyler Compartment with Thermally Thick/Thin Boundaries	02.1_Temperature_NV.xls 02.2_Temperature_FV.xls
J-4	Chapter 3. Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration and Flame Height Heat Release Rate, Burning Duration, and Flame Height	03_HRR_Flame_Height_Burning _ Duration_Calculations.xls

NUREG Chapter and Related Calculation Methods

Problem	NUREG Chapter	FDT[s]
J-5	Chapter 4. Estimating Wall Fire Flame Height, Line Fire Flame Height Against the Wall, and Corner Fire Flame Height	04_Flame_Height_Calculations.xls Wall_Line_Flame_Height Corner_Flame_Height Wall_Flame_Height
J-6	Chapter 2. Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire with Natural and Forced Ventilation Method of Foote, Pagni, and Alvares (FPA) Compartment with Thermally Thick/Thin Boundaries Method of Deal and Beyler Compartment with Thermally Thick/Thin Boundaries	02.2_Temperature_FV.xls
J-7	Chapter 5. Estimating Radiant Heat Flux from Fire to a Target Fuel Solid Flame Radiation Model (Target Above Ground Level, with Wind)	05.2_Heat_Flux_Calculations_Wind_Free.xls (Solid Flame 2)
J-8	Chapter 6. Estimating the Ignition Time of a Target Fuel Exposed to a Constant Radiative Heat Flux Method of Estimating Piloted Ignition Time of Solid Materials Under Radiant Exposures. Method of (1) Mikkola and Wichman, (2) Quintiere and Harkleroad and, (3) Janssens	06_Ignition_Time_Calculations.xls (Ignition_Time_Calculations1)
J-9	Chapter 7. Estimating the Full-Scale Heat Release Rate of a Cable Tray Fire	07_Cable_HRR_Calculations.xls
J-10	Chapter 9. Estimating the Centerline Temperature of a Buoyant Fire Plume	09_Plume_Temperature_Calculations.xls
J-11	Chapter 10. Estimating Sprinkler Response Time	10_Detector_Activation_Time.xls (Sprinkler)
J-12	Chapter 12. Estimating Heat Detector Response Time	10_Detector_Activation_Time.xls (FTHDetector)

NUREG Chapter and Related Calculation Methods

Problem	NUREG Chapter	FDT[s]
J-13	Chapter 13. Predicting Compartment Flashover Compartment Post-Flashover Temperature. Method of Law. Minimum Heat Release Rate Required to Compartment Flashover. Method of (1) McCaffrey, Quintiere, and Harkleroad (MQH), (2) Babrauskas, and (3) Thomas	13_Compartment_Flashover_ Calculations.xls (Post_Flashover_Temperature) (Flashover-HRR)
J-14	Chapter 14. Estimating Pressure Rise Attributable to a Fire in a Closed Compartment	14_Compartment_Over_Pressure _Calculations.xls
J-15	Chapter 17. Calculating the Fire Resistance of Structural Steel Members Empirical Correlations	17.1_FR_Beams_Columns_Sub stitution_Correlation.xls (Beam)
J-16 (a)	Chapter 3. Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration, and Flame Height	03_HRR_Flame_Height_Burning _Duration_Calculations.xls
(b)	Chapter 2. Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire with Natural and Forced Ventilation Method of McCaffrey, Quintiere, and Harkleroad (MQH) Compartment with Thermally Thick/Thin Boundaries	02.1_Temperature_NV.xls
(c)	Chapter 9. Estimating the Centerline Temperature of a Buoyant Fire Plume	09_Plume_Temperature_ Calculations.xls
(d & e)	Chapter 5. Estimating Radiant Heat Flux from Fire to a Target Fuel Wind-Free Condition Point Source Radiation Model (Target at Ground Level) Solid Flame Radiation Model (Target Above Ground Level)	05.1_Heat_Flux_Calculations_ Wind_Free.xls (Point Source) (Solid Flame 2)
(f)	Chapter 10. Estimating Sprinkler Response Time	10_Detector_Activation_Time.xls (Sprinkler)
(g)	Chapter 13. Predicting Compartment Flashover	13_Compartment_Flashover_ Calculations.xls (Flashover-HRR)

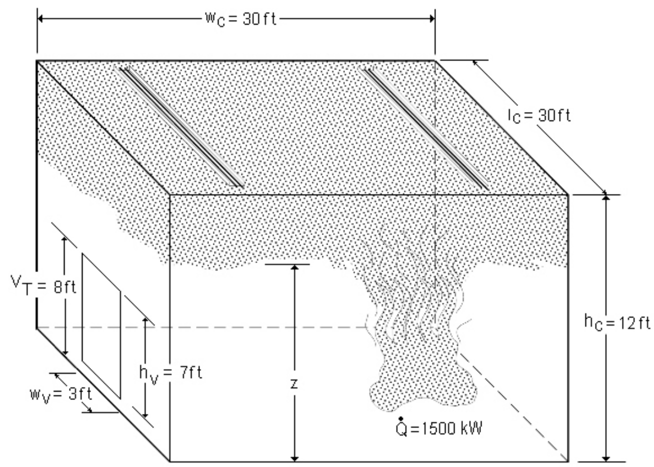
NUREG Chapter and Related Calculation Methods

Problem	NUREG Chapter	FDT^s
J-17	Chapter 3. Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration, and Flame Height Chapter 2. Predicting Hot Gas Layer Temperature and Smoke Layer Height in a Room Fire with Natural and Forced Ventilation Method of McCaffrey, Quintiere, and Harkleroad (MQH) Compartment with Thermally Thick/Thin Boundaries	03_HRR_Flame_Height_Burning_Duration_Calculations.xls 02.1_Temperature_NV.xls
J-18	Chapter 3. Estimating Burning Characteristics of Liquid Pool Fire, Heat Release Rate, Burning Duration, and Flame Height Chapter 8. Estimating Burning Duration of Solid Combustibles	03_HRR_Flame_Height_Burning_Duration_Calculations.xls 08_Burning_Duration_Solids.xls

Problem J-1

Problem Statement

Consider a compartment 9.0 m wide x 9.0 m long x 3.7 m high (30 ft wide x 30 ft long x 12 ft high) (w_c x l_c x h_c) with a door vent that is 0.92 m wide x 2.15 m high (3 ft wide x 7 ft high) (w_v x h_v). The fire is constant with an HRR of 1,500 kW (1,422 Btu/sec). Assume that the top of the vent is at 2.45 m (8 ft). Compute the hot gas temperature in the compartment, as well as the smoke layer height, at 5 minutes after the ignition, assuming that the compartment boundaries are made of 2.54 cm (1.0 in) thick gypsum board.



Problem 1: Compartment Fire with Natural Ventilation

Solution

Purpose:

(1) Determine the hot gas temperature in the compartment (T_g) at t = 5 min after ignition.
(2) Determine the smoke layer height (z) at t = 5 min after ignition.

Assumptions:

(1) Air properties (ambient) are at 25 °C (77 °F).
(2) The ceiling is unconfined, unobstructed, and flat.
(3) The heat flow through the compartment boundaries is one-dimensional.
(4) The heat release rate (HRR) is constant.
(5) The fire is located at the center of the compartment or away from the walls.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 02.1_Temperature_NV.xls

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

- Compartment Width (w_c) = 30 ft
- Compartment Length (l_c) = 30 ft
- Compartment Height (h_c) = 12 ft
- Vent Width (w_v) = 3 ft
- Vent Height (h_v) = 7 ft
- Top of Vent from Floor (V_T) = 8 ft
- Interior Lining Thickness (δ) = 1 in
- Select Material: select **Gypsum Board** from the combo box
- Fire Heat Release Rate $(\dot{Q})$ = 1,500 kW
- Time after Ignition (t) = 5 min

Note: When **Gypsum Board** is selected, its thermal properties are automatically selected from the table and entered in the corresponding input cells.

Results*

From the table of results of the spreadsheet at t = 5 minutes after ignition we obtain:

Hot Gas Layer Temperature T_g °C (°F)	Smoke Layer Height z m (ft)
351 (664)	2.44 (8.00) smoke is exiting through the vent

*spreadsheet calculations attached on next page

Spreadsheet Calculations

FDT^s: 02.1_Temperature_NV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	30.00	ft	9.144 m
Compartment Length (l_c)	30.00	ft	9.144 m
Compartment Height (h_c)	12.00	ft	3.6576 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	7.00	ft	2.134 m
Top of Vent from Floor (V_T)	8.00	ft	2.438 m
Interior Lining Thickness (δ)	1.00	in	0.0254 m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

Interior Lining Thermal Inertia ($k\rho c$)	0.18	(kW/m^2-K)^2-sec
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
Interior Lining Specific Heat (c)	1.1	kJ/kg-K
Interior Lining Density (ρ)	960	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m^2-K)^2-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Material
Gypsum Board
Scroll to desired material then Click the selection

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 270.

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q)	1500.00	kW
	Calculate	

METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})(A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

Q = heat release rate of the fire (kW)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

Area of Ventilation Opening Calculation

$A_v = (w_v)\,(h_v)$

Where A_v = area of ventilation opening (m^2)

w_v = vent width (m)

h_v = vent height (m)

A_v = 1.95 m^2

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)\,(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 1001.90 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 299.05 m^2

Compartment Hot Gas Layer Temperature With Natural Ventilation

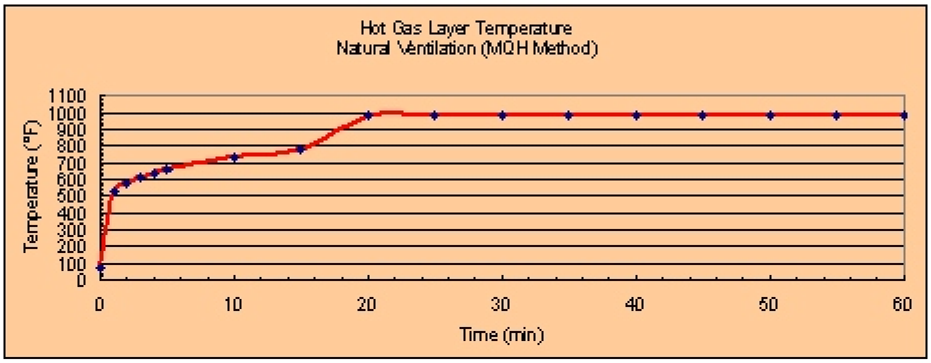
$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})(A_T h_k)]^{1/3}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0.00	-	-	298.00	25.00	77.00
1	60	0.05	249.29	547.29	274.29	525.73
2	120	0.04	279.82	577.82	304.82	580.68
3	180	0.03	299.39	597.39	324.39	615.90
4	240	0.03	314.09	612.09	339.09	642.36
5	300	0.02	325.99	623.99	350.99	663.79
10	600	0.02	365.91	663.91	390.91	735.65
15	900	0.01	391.50	689.50	416.50	781.69
20	1200	0.01	502.37	800.37	527.37	981.27
25	1500	0.01	502.37	800.37	527.37	981.27
30	1800	0.01	502.37	800.37	527.37	981.27
35	2100	0.01	502.37	800.37	527.37	981.27
40	2400	0.01	502.37	800.37	527.37	981.27
45	2700	0.01	502.37	800.37	527.37	981.27
50	3000	0.01	502.37	800.37	527.37	981.27
55	3300	0.01	502.37	800.37	527.37	981.27
60	3600	0.01	502.37	800.37	527.37	981.27



ESTIMATING SMOKE LAYER HEIGHT
METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where
z = smoke layer height (m)
Q = heat release rate of the fire (kW)
t = time after ignition (sec)
h_c = compartment height (m)
A_c = compartment floor area (m^2)
k = a constant given by $k = 0.076/\rho_g$
ρ_g = hot gas layer density (kg/m^3)
ρ_g is given by $\rho_g = 353/T_g$
T_g = hot gas layer temperature (K)

Compartment Area Calculation
$A_c = (w_c)(l_c)$
Where
A_c = compartment floor area (m^2)
w_c = compartment width (m)
l_c = compartment length (m)

A_c = 83.61 m^2

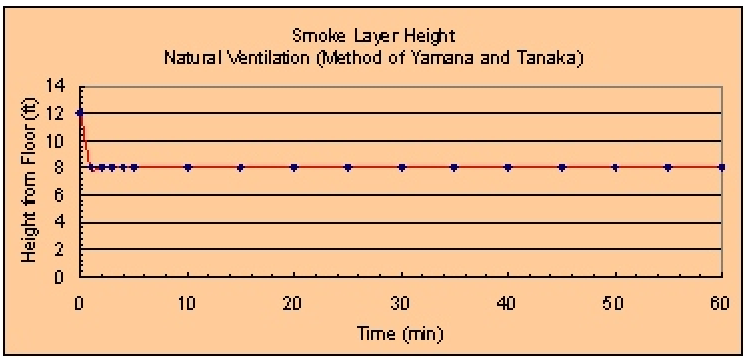
Hot Gas Layer Density Calculation
$\rho_g = 353/T_g$

Calculation for Constant K

Results

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

Time (min)	ρ_g (kg/m^3)	Constant(k) (kW/m-K)	Smoke Layer height z (m)	Smoke Layer height z (ft)	
0	1.18	0.064	3.66	12.00	
1	0.64	0.118	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
2	0.61	0.124	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
3	0.59	0.129	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
4	0.58	0.132	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
5	0.57	0.134	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
10	0.53	0.143	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
15	0.51	0.148	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
20	0.44	0.172	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
25	0.44	0.172	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
30	0.44	0.172	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
35	0.44	0.172	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
40	0.44	0.172	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
45	0.44	0.172	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
50	0.44	0.172	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
55	0.44	0.172	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
60	0.44	0.172	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT



NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

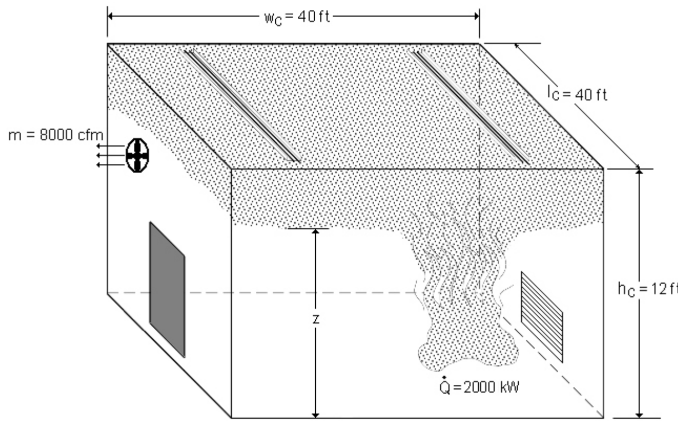
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

Problem J-2

Problem Statement

Consider a compartment 12.0 m wide x 12.0 m long x 3.7 m high (40.0 ft wide x 40.0 ft long x 12.0 ft high) (w_c x l_c x h_c) with a forced ventilation rate of 3.78 m^3/s (8,000 cfm). Calculate the hot gas layer temperature in the compartment for a fire size $(\dot{Q})$ of 2,000 kW (1,896 Btu/sec) at 5 minutes after ignition, assuming that the compartment boundaries are made of 5.10 cm (2.0 in) thick gypsum board.



Problem 2: Compartment Fire with Forced Ventilation

Solution

Purpose:

(1) Determine the hot gas temperature in the compartment (T_g) at t = 5 min after ignition.

Assumptions:

(1) Air properties (ambient) are at 25 °C (77 °F).
(2) The ceiling is unconfined, unobstructed, and flat.
(3) The heat flow through the compartment boundaries is one-dimensional.
(4) The heat release rate (HRR) is constant.
(5) The fire is located at the center of the compartment or away from the walls.
(6) The compartment is open to the outside at the inlet (pressure =1 atm).

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 02.2_Temperature_FV.xls

FDT[s] Input Parameters:

Enter the following parameters in both spreadsheets (values only):

- Compartment Width (w_c) = 40 ft
- Compartment Length (l_c) = 40 ft
- Compartment Height (h_c) = 12 ft
- Interior Lining Thickness (δ) = 2 in
- Select Material: select **Gypsum Board** from the combo box
- Compartment Ventilation Rate $(\dot{m})$ = 8,000 cfm
- Fire Heat Release Rate $(\dot{Q})$ = 2,000 kW

Note: When **Gypsum Board** is selected, its thermal properties are automatically selected from the table and entered in the corresponding input cells.

Results

From the table of results of the spreadsheet at t = 5 minutes after ignition we obtain:

Hot Gas Layer Temperature* T_g °C (°F)	
Method of Foot, Pagni, and Alvares (FPA)	Method of Deal & Beyler
203 (398)	244 (471)

*spreadsheet calculations attached on next page

Spreadsheet Calculations

FDT2: 02.2_Temperature_FV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION
COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	40.00	ft	12.19 m
Compartment Length (l_c)	40.00	ft	12.19 m
Compartment Height (h_c)	12.00	ft	3.66 m
Interior Lining Thickness (δ)	2.00	in	0.0508 m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m³	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

Interior Lining Thermal Inertia (kρc)	0.18	(kW/m²-K)²-sec
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
Interior Lining Specific Heat (c)	1.1	kJ/kg-K
Interior Lining Density (ρ)	960	kg/m³

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	kρc (kW/m²-K)²-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m³)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

Select Material

Gypsum Board

Scroll to desired material then Click on selection

COMPARTMENT MASS VENTILATION FLOW RATE

Forced Ventilation Flow Rate (m)	8000.00	cfm	3.776 m^3/sec
			4.472 kg/sec

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q)	2000.00	kW

Calculate

METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/m c_p T_a)^{0.72}(h_k A_T/m c_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

c_p = specific heat of air (kJ/kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries (m^2)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 4007.58 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where A_T = total area of the compartment enclosing surface boundaries (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_0 = area of ventilation opening (m^2)

A_T = 475.66 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

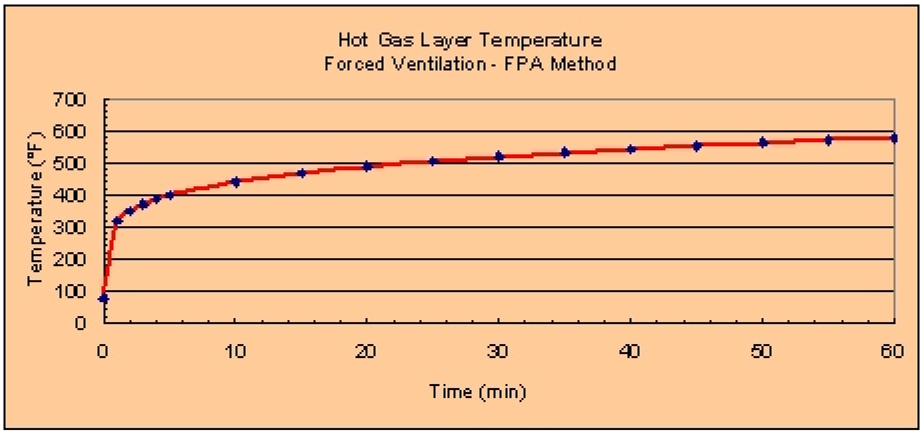
$\Delta T_g/T_a = 0.63(Q/m c_p T_0)^{0.72}(h_k A_T/m c_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	$\Delta T_g/T_a$	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)		(K)	(K)	(°C)	(°F)
0	0	-	-	-	298.00	25.00	77.00
1	60	0.05	0.45	133.34	431.34	158.34	317.01
2	120	0.04	0.51	151.06	449.06	176.06	348.90
3	180	0.03	0.55	162.49	460.49	187.49	369.49
4	240	0.03	0.57	171.13	469.13	196.13	385.04
5	300	0.02	0.60	178.14	476.14	203.14	397.66
10	600	0.02	0.68	201.82	499.82	226.82	440.27
15	900	0.01	0.73	217.10	515.10	242.10	467.77
20	1200	0.01	0.77	228.64	526.64	253.64	488.54
25	1500	0.01	0.80	238.01	536.01	263.01	505.41
30	1800	0.01	0.83	245.95	543.95	270.95	519.70
35	2100	0.01	0.85	252.87	550.87	277.87	532.16
40	2400	0.01	0.87	259.02	557.02	284.02	543.23
45	2700	0.01	0.89	264.57	562.57	289.57	553.22
50	3000	0.01	0.90	269.63	567.63	294.63	562.34
55	3300	0.01	0.92	274.30	572.30	299.30	570.74
60	3600	0.01	0.93	278.63	576.63	303.63	578.53



METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k = 0.4\sqrt{(k\rho c / t)}$ for $t < t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia (kW/m^2-K)^2-sec
(a thermal property of material responsible for the rate of temperature rise)
δ = thickness of interior lining (m)

h_k = 0.022 kW/m^2-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

A_T = 475.66 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\, c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

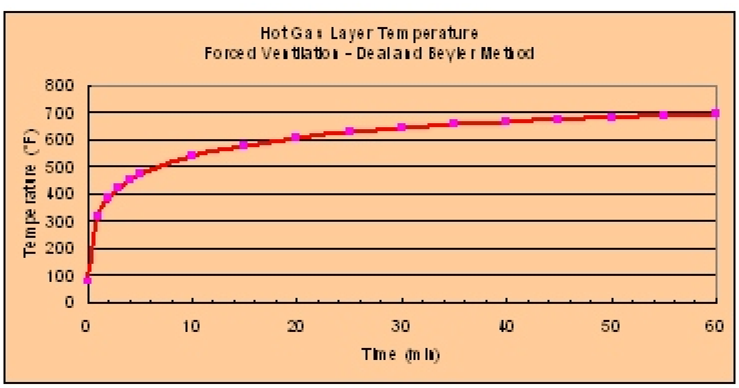
c_p = specific heat of air (kJ/kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

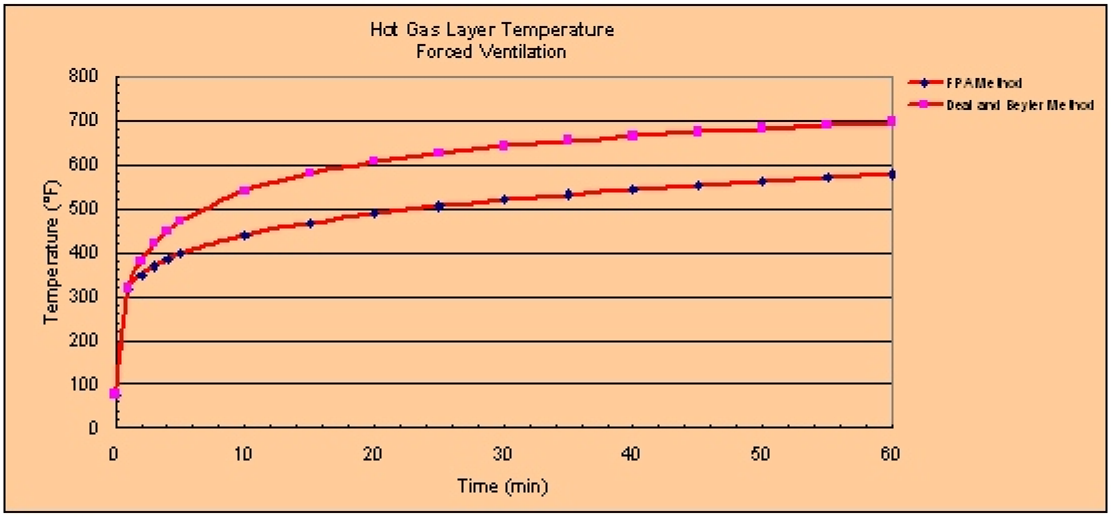
A_T = total area of the compartment enclosing surface boundaries (m^2)

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0	-	-	298.00	25.00	77.00
1	60	0.02	134.29	432.29	159.29	318.71
2	120	0.02	168.90	466.90	193.90	381.02
3	180	0.01	190.67	488.67	215.67	420.21
4	240	0.01	206.55	504.55	231.55	448.78
5	300	0.01	218.99	516.99	243.99	471.18
10	600	0.01	257.47	555.47	282.47	540.45
15	900	0.01	279.21	577.21	304.21	579.57
20	1200	0.00	294.00	592.00	319.00	606.20
25	1500	0.00	305.03	603.03	330.03	626.06
30	1800	0.00	313.72	611.72	338.72	641.70
35	2100	0.00	320.82	618.82	345.82	654.48
40	2400	0.00	326.79	624.79	351.79	665.22
45	2700	0.00	331.90	629.90	356.90	674.42
50	3000	0.00	336.35	634.35	361.35	682.43
55	3300	0.00	340.27	638.27	365.27	689.49
60	3600	0.00	343.77	641.77	368.77	695.79



Summary of Result:



NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

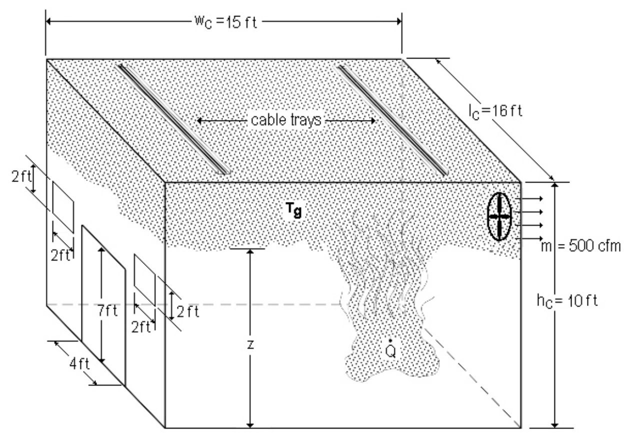
UNITED STATES NUCLEAR REGULATORY COMMISSION

Problem J-3

Problem Statement

Consider a compartment 4.6 m wide x 4.9 m long x 3.0 m high (15 ft wide x 16 ft long x 10 ft high) with multiple vents and 15.24 cm (6 in.) of gypsum board as interior boundary material. The compartment has two vents of 0.6 m wide x 0.6 m high (2 ft wide x 2 ft high) and one vent of 1.2 m wide x 2.1 m high (4 ft wide x 7 ft high), all located on the same wall. The top of the highest vent is at 2.4 m (8 ft) above the floor. If the ventilation system is not operating (natural ventilation) and at 10 minutes after a fire ignition the hot gas layer temperature reaches the failure temperature of the IEEE-383 unqualified cable [assume T_g = 218 °C (T_g = 425 °F) as failure for this example], what minimum HRR might cause this failure? Is the smoke exiting the compartment at the time of cable failure?

Consider the same compartment with a mechanical ventilation rate of 0.236 m^3/s (500 cfm) and a fire with an intensity equal to the HRR of the natural ventilation scenario. What would be the hot gas layer temperature around the cable trays at 10 minutes after ignition? (Use method of FPA and method of Deal & Beyler). What is the effect of the ventilation system on the hot gas layer temperature? Compare the results of the forced ventilation scenario as a function of time after ignition and explain the discrepancy between methods.



Problem 3: Compartment Fire with Multiple Vents

Solution

Purpose:

(1) Determine the minimum HRR that could cause the IEEE-383 unqualified cable failure at 10 min after ignition in a natural ventilation scenario.
(2) Determine if the smoke is exiting the compartment at 10 min after ignition.
(3) Determine the hot gas layer temperature (T_g) at 10 min after ignition if the mechanical ventilation system is activated and the HRR is equal to the HRR of the natural ventilation scenario (i.e., use the answer of purpose **1**).
(4) Evaluate the effect of the ventilation system in the hot gas layer temperature (i.e., increase, decrease, etc.).
(5) Analyze the discrepancy between the methods of FPA and Deal & Beyler, and mention possible causes of that discrepancy.

Assumptions:

(1) Air properties (ambient) are at 25 °C (77 °F).
(2) The ceiling is unconfined, unobstructed and flat.
(3) The heat flow through the compartment boundaries is one-dimensional.
(4) The HRR is constant.
(5) The fire is located at the center of the compartment or away from the walls.
(6) The compartment is open to the outside at the inlet (pressure = 1 atm).

Pre FDT^s Calculations:

Equivalent Vent

Since the FDT^s are designed to calculate the hot gas layer temperature and smoke layer height based in only one vent compartment, we need to calculate an equivalent vent that represents the three vent openings.

Vent Opening Characteristics			
Width w_v (ft)	Height h_v (ft)	Are A_o (ft^2)	MQH Factor $A_o \sqrt{h_v}$ ($ft^{5/2}$)
2	2	4	5.66
2	2	4	5.66
4	7	28	74.08
Total		36	84.4

The equivalent vent dimensions must satisfy the following conditions in order to have the same effect of the actual multiple vents:

Condition 1: $A_o \sqrt{h_v} = 85.4\ ft^{5/2}$

$36\ ft^2 \sqrt{h_v} = 85.4\ ft^{5/2}$

$h_v = 5.63\ ft = 5.6\ ft$

Condition 2: $w_v \times h_v = 36\ ft^2$

$w_v \times 5.63\ ft = 36\ ft^2$

$w_v = 6.39\ ft = 6.4\ ft$

Spreadsheet (FDT^s) Solution Procedure:

<u>Natural Ventilation Scenario</u>

Use the following FDT^s:

(a) 02.1_Temperature_NV.xls

FDT[s] Input Parameters:

Enter the following parameters in the spreadsheet (values only):

- Compartment Width (w_c) = 15 ft
- Compartment Length (l_c) = 16 ft
- Compartment Height (h_c) = 10 ft
- Vent Width (w_v) = 6.4 ft
- Vent Height (h_v) = 5.6 ft
- Top of Vent from Floor (V_T) = 8 ft
- Interior Lining Thickness (δ) = 6 in
- Select Material: select **Gypsum Board** from the combo box
- Fire Heat Release Rate $(\dot{Q})$ = 410 kW*

Note: When **Gypsum Board** is selected, its thermal properties are automatically selected from the table and entered in the corresponding input cells.

*The HRR value is a starting value for the trial and error procedure explained below.

Because we are looking for an HRR value that could generate a hot gas layer temperature of 218 °C (425 °F), we need to enter HRR values on the spreadsheet until get a temperature close to 218 °C (425 °F) at 10 min after ignition. This trial and error procedure is shown in the following table.

Trial and error procedure to determine the HRR Target: T_g = 425 °F for natural ventilation scenario		
Trial	Heat Release Rate $(\dot{Q})$ (kW)	Hot Gas Layer Temperature (T_g) at 10 min after Ignition (°C) (°F)
1	100	100 (213)
2	200	145 (293)
3	300	182 (360)
4	400	215 (420)
5*	410	219 (425)

*spreadsheet calculations attached on next page for last trial at t = 10 min

Results

According to the method of McCaffrey, Quintiere, and Harkleroad (MQH), an HRR of approximate **410 kW** could generate a hot gas layer temperature of 218 °C (425 °F) at 10 minutes after ignition. But, what is important for practical purposes is that for the given compartment and ventilation conditions, a fire power of about **400 kW (379 Btu/sec)** may generate a hot gas layer temperature of **204+°C (400+°F)**. Also, the smoke layer height at 10 minutes after ignition is approximately **z = 0.39 m (1.27 ft)**, based on the method of Yamana and Tanaka. That means that the smoke could be exiting the compartment because z is less than the height of the vent top (V_T).

Spreadsheet Calculations

FDT[s]: 02.1_Temperature_NV.xls (*Temperature_NV Thermally Thick*)

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Parameter	Value	Unit	Converted
Compartment Width (w_c)	15.00	ft	4.572 m
Compartment Length (l_c)	16.00	ft	4.8768 m
Compartment Height (h_c)	10.00	ft	3.048 m
Vent Width (w_v)	6.40	ft	1.951 m
Vent Height (h_v)	5.60	ft	1.707 m
Top of Vent from Floor (V_T)	8.00	ft	2.438 m
Interior Lining Thickness (δ)	6.00	in	0.1524 m

AMBIENT CONDITIONS

Parameter	Value	Unit	Converted
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C 298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

Parameter	Value	Unit
Interior Lining Thermal Inertia ($k\rho c$)	0.18	$(kW/m^2\text{-}K)^2$-sec
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
Interior Lining Specific Heat (c)	1.1	kJ/kg-K
Interior Lining Density (ρ)	960	kg/m^3

Note : Air density will automatically correct with Ambient Air Temperature (T_a) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ $(kW/m^2\text{-}K)^2$-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: Klote, J., J. Milke, *Principles of Smoke Management*, 2002, Page 270.

Select Material: Gypsum Board

Scroll to desired material then Click the selection

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) 410.00 kW

Calculate

METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})(A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

Q = heat release rate of the fire (kW)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

Where A_v = area of ventilation opening (m^2)

w_v = vent width (m)

h_v = vent height (m)

A_v = 3.33 m^2

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 36068.24 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 98.86 m^2

Compartment Hot Gas Layer Temperature With Natural Ventilation

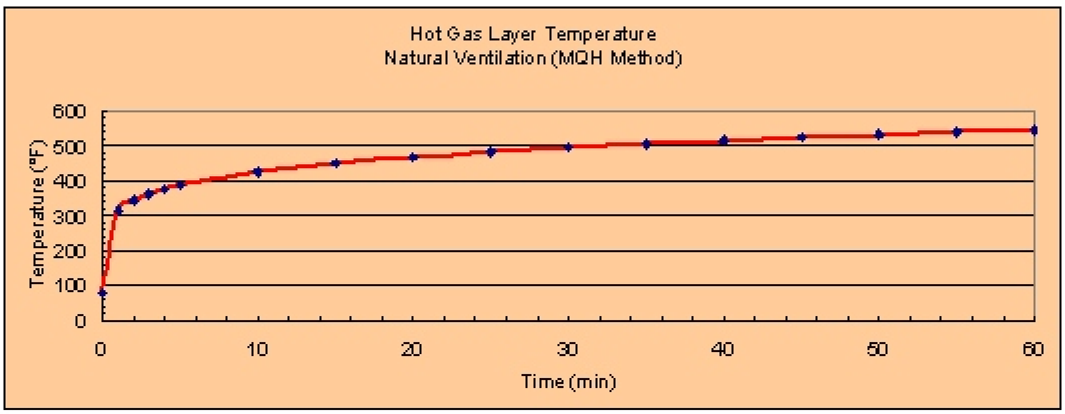
$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})(A_T h_k)]^{1/3}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0.00	-	-	298.00	25.00	77.00
1	60	0.05	131.88	429.88	156.88	314.39
2	120	0.04	148.03	446.03	173.03	343.46
3	180	0.03	158.38	456.38	183.38	362.08
4	240	0.03	166.16	464.16	191.16	376.09
5	300	0.02	172.46	470.46	197.46	387.42
10	600	0.02	193.57	491.57	218.57	425.43
15	900	0.01	207.11	505.11	232.11	449.79
20	1200	0.01	217.28	515.28	242.28	468.10
25	1500	0.01	225.51	523.51	250.51	482.92
30	1800	0.01	232.47	530.47	257.47	495.45
35	2100	0.01	238.52	536.52	263.52	506.34
40	2400	0.01	243.89	541.89	268.89	516.00
45	2700	0.01	248.72	546.72	273.72	524.70
50	3000	0.01	253.13	551.13	278.13	532.63
55	3300	0.01	257.18	555.18	282.18	539.93
60	3600	0.01	260.94	558.94	285.94	546.69



ESTIMATING SMOKE LAYER HEIGHT
METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where
- z = smoke layer height (m)
- Q = heat release rate of the fire (kW)
- t = time after ignition (sec)
- h_c = compartment height (m)
- A_c = compartment floor area (m^2)
- k = a constant given by $k = 0.076/\rho_g$
- ρ_g = hot gas layer density (kg/m^3)
- ρ_g is given by $\rho_g = 353/T_g$
- T_g = hot gas layer temperature (K)

Compartment Area Calculation

$A_c = (w_c)(l_c)$

Where
- A_c = compartment floor area (m^2)
- w_c = compartment width (m)
- l_c = compartment length (m)

A_c = 22.30 m^2

Hot Gas Layer Density Calculation

$\rho_g = 353/T_g$

Calculation for Constant K

$k = 0.076/\rho_g$

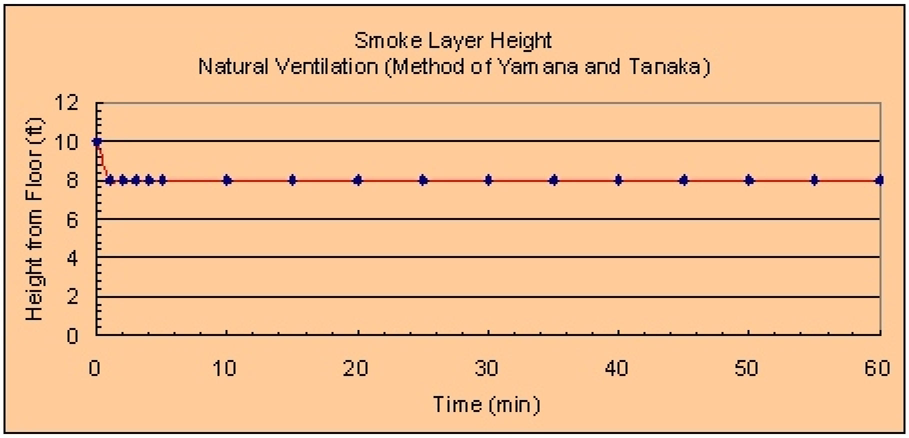
Smoke Gas Layer Height With Natural Ventilation

$z = [(2kQ^{1/3}t/3A_c] + (1/h_c^{2/3}))^{-3/2}$

Results

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

Time (min)	ρ_g (kg/m^3)	Constant (k) (kW/m-K)	Smoke Layer height z (m)	Smoke Layer height z (ft)	
0	1.18	0.064	3.05	10.00	
1	0.82	0.093	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
2	0.79	0.096	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
3	0.77	0.098	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
4	0.76	0.100	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
5	0.75	0.101	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
10	0.72	0.106	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
15	0.70	0.109	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
20	0.69	0.111	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
25	0.67	0.113	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
30	0.67	0.114	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
35	0.66	0.116	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
40	0.65	0.117	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
45	0.65	0.118	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
50	0.64	0.119	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
55	0.64	0.120	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT
60	0.63	0.120	2.44	8.00	CAUTION: SMOKE IS EXITING OUT VENT



NOTE

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Spreadsheet (FDT^s) Solution Procedure:

Forced Ventilation Scenario

Use the following FDT^s:

(a) 02.2_Temperature_FV.xls

FDT^s Input Parameters:

Enter the following parameters in both spreadsheets (values only):

- Compartment Width (w_c) = 15 ft
- Compartment Length (l_c) = 16 ft
- Compartment Height (h_c) = 10 ft
- Interior Lining Thickness (δ) = 6 in
- Material: select **Gypsum Board** from the combo box
- Compartment Ventilation Rate $(\dot{m})$ = 500 cfm
- Fire Heat Release Rate $(\dot{Q})$ = 410 kW

Note: When **Gypsum Board** is selected, its thermal properties are automatically selected from the table and entered in the corresponding input cells.

Results

From the table of results of the spreadsheet at t = 10 minutes after ignition we obtain:

Hot Gas Layer Temperature* T_g °C (°F)	
Method of Foot, Pagni, and Alvares (FPA)	Method of Deal & Beyler
329 (625)	440 (824)

*spreadsheet calculations attached on next page

These results demonstrate that the ventilation system is able to increase the hot gas layer temperature. That is, for a specific compartment and heat release rate, the ventilation system can drastically increase the hot gas layer temperature due to the oxygen supply.

Spreadsheet Calculations
FDT^s: 02.2_Temperature_FV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	15.00	ft	4.57	m
Compartment Length (l_c)	16.00	ft	4.88	m
Compartment Height (h_c)	10.00	ft	3.05	m
Interior Lining Thickness (δ)	6.00	in	0.1524	m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00	°C
			298.00	K
Specific Heat of Air (c_p)	1.00	kJ/kg-K		
Ambient Air Density (ρ_a)	1.18	kg/m^3		

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

Interior Lining Thermal Inertia (kρc)	0.18	(kW/m^2-K)^2-sec
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
Interior Lining Specific Heat (c)	1.1	kJ/kg-K
Interior Lining Density (ρ)	960	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	kρc (kW/m^2-K)^2-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

Select Material
Gypsum Board
Scroll to desired material then Click on selection

COMPARTMENT MASS VENTILATION FLOW RATE

Forced Ventilation Flow Rate (m) | 500.00 cfm | 0.236 m^3/sec | 0.280 kg/sec

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) | 410.00 kW

Calculate

METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/m c_p T_a)^{0.72}(h_k A_T/m c_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

c_p = specific heat of air (kJ/kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries (m^2)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 36068.24 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia (kW/m^2-K)^2-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where A_T = total area of the compartment enclosing surface boundaries (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 102.19 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

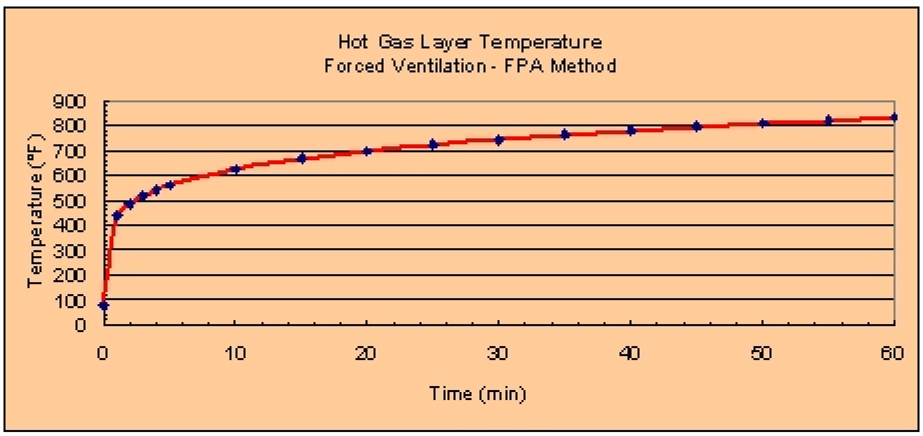
$\Delta T_g/T_a = 0.63(Q/m c_p T_0)^{0.72}(h_k A_T/m c_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t) (min)	(sec)	h_k (kW/m^2-K)	$\Delta T_g/T_a$	ΔT_g (K)	T_g (K)	T_g (°C)	T_g (°F)
0	0	-	-	-	298.00	25.00	77.00
1	60	0.05	0.67	201.07	499.07	226.07	438.92
2	120	0.04	0.76	227.78	525.78	252.78	487.01
3	180	0.03	0.82	245.03	543.03	270.03	518.06
4	240	0.03	0.87	258.05	556.05	283.05	541.50
5	300	0.02	0.90	268.63	566.63	293.63	560.53
10	600	0.02	1.02	304.33	602.33	329.33	624.79
15	900	0.01	1.10	327.37	625.37	352.37	666.26
20	1200	0.01	1.16	344.77	642.77	369.77	697.58
25	1500	0.01	1.20	358.90	656.90	383.90	723.01
30	1800	0.01	1.24	370.87	668.87	395.87	744.57
35	2100	0.01	1.28	381.30	679.30	406.30	763.35
40	2400	0.01	1.31	390.58	688.58	415.58	780.04
45	2700	0.01	1.34	398.95	696.95	423.95	795.11
50	3000	0.01	1.36	406.59	704.59	431.59	808.86
55	3300	0.01	1.39	413.62	711.62	438.62	821.52
60	3600	0.01	1.41	420.15	718.15	445.15	833.27



METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k = 0.4\sqrt{(k\rho c / t)}$ for $t < t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)
$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec
(a thermal property of material responsible for the rate of temperature rise)
δ = thickness of interior lining (m)

h_k = 0.022 kW/m^2-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

A_T = 102.19 m^2

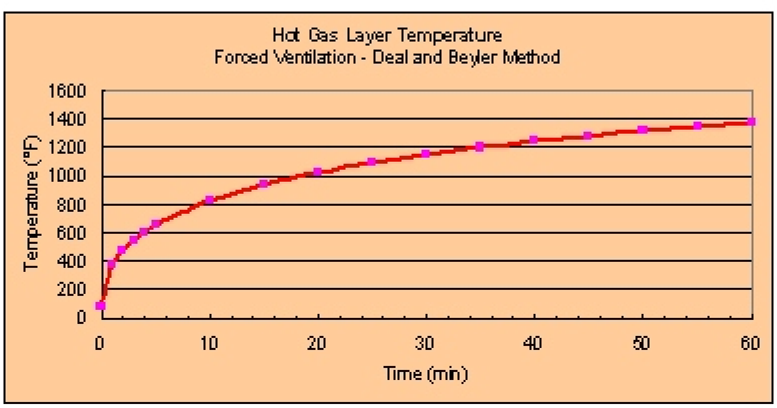
Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\ c_p + h_k A_T)$

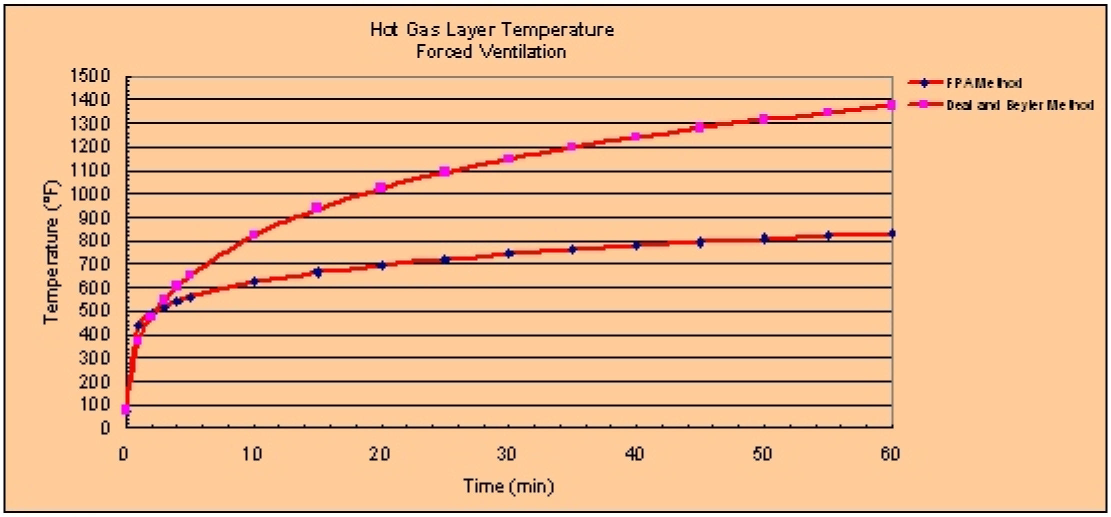
Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)
T_a = ambient air temperature (K)
Q = heat release rate of the fire (kW)
m = compartment mass ventilation flow rate (kg/sec)
c_p = specific heat of air (kJ/kg-K)
h_k = convective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surface boundaries (m^2)

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0	-	-	298.00	25.00	77.00
1	60	0.02	162.80	460.80	187.80	370.04
2	120	0.02	220.11	518.11	245.11	473.20
3	180	0.01	260.78	558.78	285.78	546.41
4	240	0.01	293.07	591.07	318.07	604.52
5	300	0.01	320.11	618.11	345.11	653.20
10	600	0.01	415.17	713.17	440.17	824.31
15	900	0.01	478.07	776.07	503.07	937.52
20	1200	0.00	525.53	823.53	550.53	1022.95
25	1500	0.00	563.72	861.72	588.72	1091.69
30	1800	0.00	595.67	893.67	620.67	1149.21
35	2100	0.00	623.12	921.12	648.12	1198.62
40	2400	0.00	647.16	945.16	672.16	1241.89
45	2700	0.00	668.53	966.53	693.53	1280.35
50	3000	0.00	687.73	985.73	712.73	1314.92
55	3300	0.00	705.16	1003.16	730.16	1346.30
60	3600	0.00	721.10	1019.10	746.10	1374.99



Summary of Result:



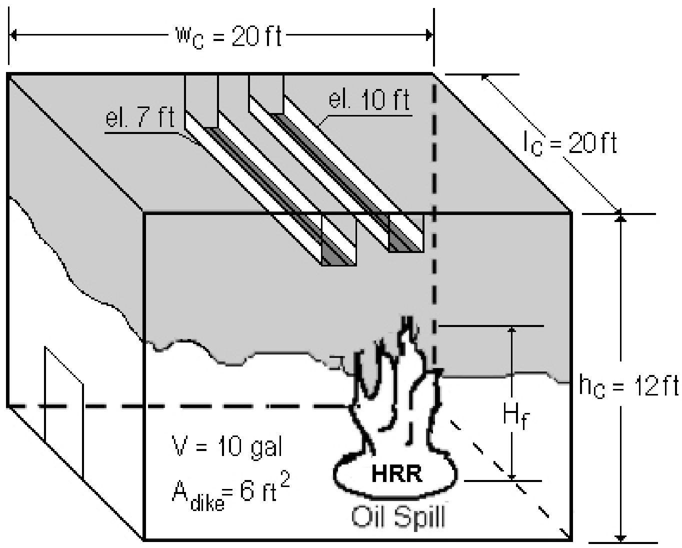
NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Problem J-4

Problem Statement

Consider a pool fire caused by a 38.0 liters (10 gallons) spill combustible liquid (kerosine oil) in a 0.55-m^2 (6.0-ft^2) dike area in a compartment with a concrete floor. The kerosine oil is ignited and spread rapidly over the surface, reaching steady burning almost instantly. Compute the HRR, burning duration, and flame height of the pool fire. The dimensions of the compartment are 6.0 m wide x 6.0 m long x 3.7 m high (20.0 ft wide x 20.0 ft long x 12.0 ft). Two cable trays are located above the pool fire at heights of 2.15 m (7.0 ft) and 3.0 m (10.0 ft), respectively. Determine whether flame will impinge upon the cable trays. Assume instantaneous, complete involvement of the liquid pool with no fire growth and no intervention by the plant fire department or automatic suppression systems.



Problem 4: Compartment with Liquid Pool Fire Scenario

Solution

Purpose:

(1) Determine the HRR of the liquid pool fire.
(2) Determine the flame duration.
(3) Determine flame height (H_f).
(4) Determine if the flame will impinge the cable trays.

Assumptions:

(1) There is instantaneous and complete involvement of the liquid in the pool fire.
(2) The pool fire is burning in the open.
(3) The pool is circular or nearly circular and contains a fixed mass of liquid volume.
(4) The pool fire is in the center of the compartment or away from the walls.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

- Fuel spill volume (V) = 10 gallons
- Fuel Spill Area or Dike Area (A_{dike}) = 6.0 ft^2
- Select Fuel Type: select **Kerosine** from the combo box

Note: When **Kerosine** is selected, its properties are automatically selected from the table and entered in the corresponding input cells.

Results

Heat Release Rate* $\dot{Q}$ kW (Btu/sec)	Burning Duration* t_b (min)	Pool Fire Flame Height* H_f m (ft)	
		Method of Heskestad	Method of Thomas
890 kW (843 Btu/sec)	24	2.7 m (8.8 ft)	2.3 m (7.6 ft)

*spreadsheet calculations attached on next page

Both methods for pool fire flame height estimation show that the flame could impinge upon the cable trays.

Spreadsheet Calculations

FDT^s: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE, HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	10.00	gallons	0.0379	m^3
Fuel Spill Area or Dike Area (A_{dike})	6.00	ft^2	0.557	m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec		
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	43200	kJ/kg		
Fuel Density (ρ)	820	kg/m^3		
Empirical Constant (kβ)	3.5	m^{-1}		
Ambient Air Temperature (T_a)	77.00	°F	25.00	°C
			298.00	K
Gravitational Acceleration (g)	9.81	m/sec^2		
Ambient Air Density (ρ_a)	1.18	kg/m^3		

Calculate

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Fuel Type: Kerosine

Scroll to desired fuel type
Click on selection

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-26.

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 3-25.

$Q = m''\Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diamter (m)

$D = \sqrt{(4A_{dike}/\pi)}$

D = 0.842 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff} (1-e^{-k\beta D}) A_{dike}$

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	889.91 kW	843.48 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference: *SFPE Handbook of Fire Protection Engineering*, 2[nd] Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where t_b = burning duration of pool fire (sec)

V = volume of liquid (m^3)

D = pool diameter (m)

v = regression rate (m/sec)

Calculation for Regression Rate

$v = m''/\rho$

Where v = regression rate (m/sec)

m'' = mass burning rate of fuel (kg/m^2-sec)

ρ = liquid fuel density (kg/m^3)

v = 0.000048 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b =	1427.85 sec	23.80 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference: *SFPE Handbook of Fire Protection Engineering*, 2[nd] Edition, 1995, Page 2-10.

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where H_f = pool fire flame height (m)

Q = pool fire heat release rate (kW)

D = pool fire diameter (m)

Pool Fire Flame Height Calculation

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

H_f =	2.70 m	8.84 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-204.

$H_f = 42\,D\,(\dot{m}''/\rho_a \sqrt{g\,D})^{0.61}$

Where H_f = pool fire flame height (m)

$\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)

ρ_a = ambient air density (kg/m^3)

D = pool fire diameter (m)

g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation

$H_f = 42\,D\,(\dot{m}''/\rho_a \sqrt{g\,D})^{0.61}$

H_f =	2.32 m	7.60 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	8.84
METHOD OF THOMAS	7.60

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft^2)	Area (m^2)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	148.32	8567.07	4.54	4.08
2	0.19	0.49	296.64	4283.54	5.89	5.19
3	0.28	0.60	444.96	2855.69	6.85	5.97
4	0.37	0.69	593.28	2141.77	7.61	6.60
5	0.46	0.77	741.60	1713.41	8.27	7.13
6	0.56	0.84	889.91	1427.85	8.84	7.60
7	0.65	0.91	1038.23	1223.87	9.36	8.02
8	0.74	0.97	1186.55	1070.88	9.83	8.40
9	0.84	1.03	1334.87	951.90	10.26	8.75
10	0.93	1.09	1483.19	856.71	10.67	9.07
11	1.02	1.14	1631.51	778.82	11.05	9.38
12	1.11	1.19	1779.83	713.92	11.40	9.67
13	1.21	1.24	1928.15	659.01	11.74	9.94
14	1.30	1.29	2076.47	611.93	12.06	10.20
15	1.39	1.33	2224.79	571.14	12.37	10.45
20	1.86	1.54	2966.38	428.35	13.73	11.55
25	2.32	1.72	3707.98	342.68	14.89	12.48
50	4.65	2.43	7415.95	171.34	19.10	15.87
75	6.97	2.98	11123.93	114.23	22.06	18.28
100	9.29	3.44	14831.91	85.67	24.43	20.20

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation doe not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Problem J-5

Problem Statement

Consider a compartment with cable trays at 4.60 m (15 ft) above the floor. The cable trays are very close to the compartment walls. If 7.6 liters (2 gallons) of lube oil spills covering an area of 1.4 m^2 (15 ft^2), what location type of fire source will allow the fire flame to impinge on the cable trays?

Solution

Purpose:

(1) Determine what type of fire source will impinge upon the cable tray.

Assumptions:

(1) Air is entrained only from one side during the combustion process.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 04_Flame_Height_Calculations.xls
select *Wall_Flame _Height* for wall fire analysis
select *Corner_Flame _Height* for corner fire analysis
select *Wall_Line_Flame _Height* for line fire analysis

FDT^s Input Parameters:

Enter the following parameters in all spreadsheets (values only):

- Fuel spill volume (V) = 2 gallons
- Fuel Spill Area or Dike Area (A_{dike}) = 15 ft^2
- Select Fuel Type: select **Lube Oil** from the combo box

Note: When **Lube Oil** is selected, its properties are automatically selected from the table and entered in the corresponding input cells.

Results

Fire Source	Flame Height* H_f m (ft)
Wall Fire	4.02 (13.18)
Corner Fire	6.07 (19.93)
Line Fire	2.01 (6.59)

*spreadsheet calculations attached on next page

Spreadsheet Calculations

FDT^s: 04_Flame_Height_Calculations.xls (Wall_Flame _Height)

CHAPTER 4. ESTIMATING WALL FIRE FLAME HEIGHT

Version 1805.0

The following calculations estimate the wall fire flame height.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	2.00	gallons	0.0076 m^3
Fuel Spill Area or Dike Area (A_{dike})	15.00	ft^2	1.394 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Empirical Constant (kβ)	0.7	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, Page 3-26.*

Select Fuel Type

Lube Oil

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

Reference : *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25.*

$Q = m''\Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diamter (m)

D = 1.332 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

Q = 1516.02 kW 1436.91 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where Q' = heat release rate per unit length (kW/m)

Q = fire heat release rate of the fire (kW)

L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 1.394 m^2

L = 1.180 m

$Q' = Q/L$

Q' = 1284.23 kW/m

ESTIMATING WALL FIRE FLAME HEIGHT

Reference : *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-134.*

$H_{(wall)} = 0.034\, Q'^{2/3}$

Where $H_{(wall)}$ = wall fire flame height (m)

Q' = rate of heat release per unit length of the fire (kW/m)

$H_{(wall)} = 0.034\, Q'^{2/3}$

$H_{(wall)}$ =	4.02 m	13.18 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, and NFPA Fire Protection Handbook, 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

CHAPTER 4. ESTIMATING CORNER FIRE FLAME HEIGHT

Version 1805.0

The following calculations estimate the corner fire flame height.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	2.00	gallons	0.0076 m^3
Fuel Spill Area or Dike Area (A_{dike})	15.00	ft^2	1.394 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Empirical Constant (kβ)	0.7	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, Page 3-26.

Select Fuel Type

Lube Oil

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-25.*

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_f$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diamter (m)

D = 1.332 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1-e^{-k\beta D}) A_{dike}$

Q = 1516.02 kW 1436.91 Btu/sec

ESTIMATING CORNER FIRE FLAME HEIGHT

Reference: *Hesemi and Tokunaga, "Modeling of Turbulent Diffusion Flames and Fire Plumes for the Analysis of Fire Growth," Growth," Proceeding of the 21th National Heat Transfer Conference, American Society of Mechanical Engineers (ASME), 1983.*

$H_{f(corner)} = 0.075\ Q^{2/5}$

Where Q = heat release rate of the fire (kW)

$H_{f(corner)} = 0.075\ Q^{2/5}$

$H_{f(corner)}$ =	6.07 m	19.93 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002 and Hesemi and Tokunage, 1983.
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CHAPTER 4. ESTIMATING LINE FIRE FLAME HEIGHT AGAINST THE WALL

Version 1805.0

The following calculations estimate the line fire flame height against the wall.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	2.00	gallons	0.0076 m^3
Fuel Spill Area or Dike Area (A_{dike})	15.00	ft^2	1.394 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Empirical Constant (kβ)	0.7	m^{-1}	

Calculate

THERMAL PROPERTIES FOR

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzene	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosene	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.034	42,600	2.8
Lube Oil	0.039	46,000	0.7
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition, Page 3-26.*

Select Fuel Type

Lube Oil

Scroll to desired fuel type then Click on selection

Heat Release Rate Calculation

Reference: *SFPE Handbook of Fire Protection Engineering, 3[rd] Edition, 2002, Page 3-26.*

$Q = m''\Delta H_{c,eff}\,(1 - e^{-k\beta D})\,A_f$

Where
- Q = pool fire heat release rate (kW)
- m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- $\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)
- $A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

(Liquids with relatively high flash point, like transformer oil require localized heating to achieve ignition)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where
- A_{dike} = surface area of pool fire (m^2)
- D = pool fire diameter (m)

D = 1.332 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}\,(1-e^{-k\beta D})\,A_{dike}$

Q = 1516.02 kW 1436.91 Btu/sec

Heat Release Rate Per Unit Length of Fire Calculation

$Q' = Q/L$

Where
- Q' = heat release rate per unit length (kW/m)
- Q = fire heat release rate of the fire (kW)
- L = length of the fire source (m)

Fire Source Length Calculation

$L \times W = A_{dike}$

L x W = 1.394 m^2

L = 1.180 m

$Q' = Q/L$

Q' = 1284.23 kW/m

ESTIMATING LINE WALL FIRE FLAME HEIGHT

Reference: *NFPA Fire Protection Handbook, 19[th] Edition, 2003, Page 3-134.*

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

Where
- $H_{f(wall\ line)}$ = wall fire flame height (m)
- Q' = rate of heat release per unit length of the fire (kW/m)

$H_{f(wall\ line)} = 0.017\ Q'^{2/3}$

$H_{f(wall\ line)}$ =	2.01 m	6.59 ft	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3[rd] Edition, 2002, and NFPA Fire Protection Handbook, 19[th] Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

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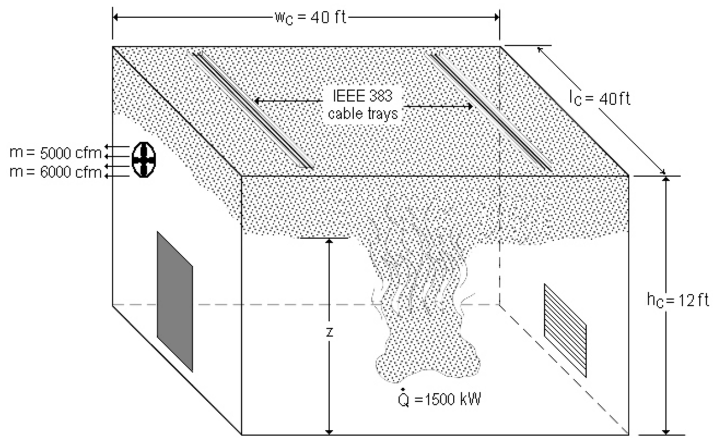
Problem J-6

Problem Statement

Consider a compartment that is 15.2 m wide x 12.20 m long x 3.70 m height (50 ft wide x 40 ft long x 12 ft height) with two forced ventilation rates: 2.4 m^3/s and 2.8 m^3/s (5,000 cfm and 6,000 cfm). If a fire scenario arises with a fire power of 1,500 kW (1,422 Btu/sec), find the average hot gas layer temperature for gypsum board (boundary material) that is ½, ⅝, ¾, 1, 1½, and 2 inch(es) thick at 15 min after ignition.



Problem 6: Compartment Fire with Forced Ventilation

Solution

Purpose:

(1) Determine the average hot gas layer temperature for two ventilation rates (5,000 cfm and 6,000 cfm) at 15 minutes after ignition.

Assumptions:

(1) Air properties (ambient) are at 25 °C (77 °F).
(2) Neglect the effect of the cable trays on the plume profile.
(3) The heat flow through the compartment boundaries is one-dimensional.
(4) The HRR is constant.
(5) The fire is located at the center of the compartment or away from the walls.
(6) The compartment is open to the outside at the inlet (pressure = 1 atm).

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 02.2_Temperature_FV.xls

FDT[s] Input Parameters:

Enter the following parameters in both spreadsheets (values only):

- Compartment Width (w_c) = 50 ft
- Compartment Length (l_c) = 40 ft
- Compartment Height (h_c) = 12 ft
- Interior Lining Thickness = 0.5 in
- Select Material: select **Gypsum Board** from the combo box
- Compartment ventilation rate $(\dot{m})$ = 5,000 cfm and 6,000 cfm
- Fire Heat Release Rate $(\dot{Q})$ = 1,500 kW

Note: When **Gypsum Board** is selected, its thermal properties are automatically selected from the table and entered in the corresponding input cells.

Results

This problem is solved using the two different ventilation rates and varying wall thicknesses at 15 minutes after ignition. The following table summarizes the results.

Ventilation rate $\dot{m}$ (cfm)	Trial	Material Thickness (in)	Hot Gas Layer Temperature T_g [°C (°F)]	
			Method of FPA	Method of Deal & Beyler
5,000	1	0.5	225 (436)	274 (525)
	2	0.63	241 (467)	274 (525)
	3	0.75	256 (492)	274 (525)
	4	1.0	220 (429)	274 (525)
	5	1.5	220 (429)	274 (525)
	6	2.0	220 (429)	274 (525)
6,000	1	0.5	212 (413)	253 (487)
	2	0.63	228 (442)	253 (487)
	3	0.75	241 (466)	253 (487)
	4	1.0	208 (407)	253 (487)
	5	1.5	208 (407)	253 (487)
	6	2.0	208 (407)	253 (487)

*spreadsheet calculations attached on next page

Following the results of the FPA and Deal & Beyler method, we see how the two methods respond to different inputs. This problem can be rerun varying time to explore the differences in methods.

Spreadsheet Calculations

Note: The following spreadsheets show the final result of the solution process. Only the 6,000 cfm case is shown; spreadsheet calculations for the 5,000 cfm scenario are similar.

FDT^s: 02.2_Temperature_FV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE IN A ROOM FIRE WITH FORCED VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	50.00	ft	15.24 m
Compartment Length (l_c)	40.00	ft	12.19 m
Compartment Height (h_c)	12.00	ft	3.66 m
Interior Lining Thickness (δ)	1.50	in	0.0381 m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES

Interior Lining Thermal Inertia ($k\rho c$)	0.18	(kW/m^2-K)^2-sec
Interior Lining Thermal Conductivity (k)	0.00017	kW/m-K
Interior Lining Specific Heat (c)	1.1	kJ/kg-K
Interior Lining Density (ρ)	960	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m^2-K)^2-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Material: Gypsum Board

Scroll to desired material then Click on selection

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002 Page 270.*

COMPARTMENT MASS VENTILATION FLOW RATE

Forced Ventilation Flow Rate (m) | 6000.00 cfm | 2.832 m^3/sec | 3.354 kg/sec

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q) | 1500.00 kW

Calculate

METHOD OF FOOTE, PAGNI, AND ALVARES (FPA)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-177.

$\Delta T_g/T_a = 0.63(Q/m c_p T_a)^{0.72}(h_k A_T/m c_p)^{-0.36}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

c_p = specific heat of air (kJ/kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries (m^2)

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 2254.26 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia (kW/m^2-K)^2-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

Where A_T = total area of the compartment enclosing surface boundaries (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 572.28 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

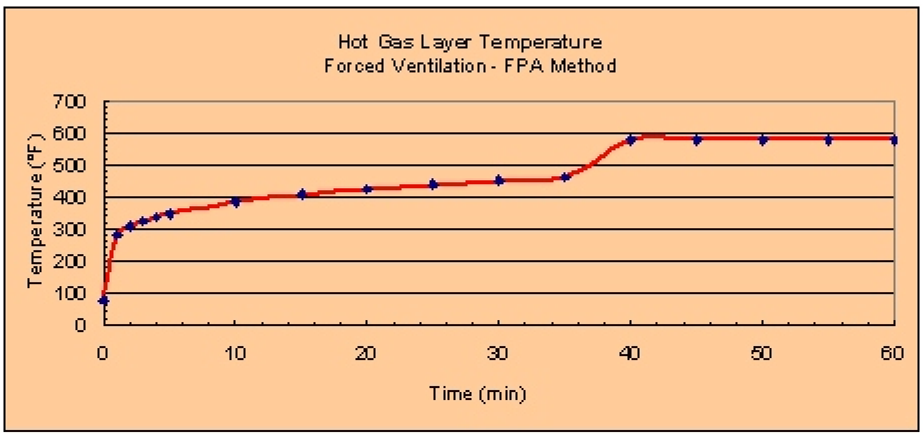
$\Delta T_g/T_a = 0.63(Q/m c_p T_o)^{0.72}(h_k A_T/m c_p)^{-0.36}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	$\Delta T_g/T_a$	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)		(K)	(K)	(°C)	(°F)
0	0	-	-	-	298.00	25.00	77.00
1	60	0.05	0.38	112.48	410.48	137.48	279.46
2	120	0.04	0.43	127.42	425.42	152.42	306.36
3	180	0.03	0.46	137.07	435.07	162.07	323.73
4	240	0.03	0.48	144.36	442.36	169.36	336.84
5	300	0.02	0.50	150.27	448.27	175.27	347.49
10	600	0.02	0.57	170.24	468.24	195.24	383.44
15	900	0.01	0.61	183.13	481.13	208.13	406.64
20	1200	0.01	0.65	192.86	490.86	217.86	424.16
25	1500	0.01	0.67	200.77	498.77	225.77	438.38
30	1800	0.01	0.70	207.47	505.47	232.47	450.44
35	2100	0.01	0.72	213.30	511.30	238.30	460.95
40	2400	0.00	0.93	277.41	575.41	302.41	576.34
45	2700	0.00	0.93	277.41	575.41	302.41	576.34
50	3000	0.00	0.93	277.41	575.41	302.41	576.34
55	3300	0.00	0.93	277.41	575.41	302.41	576.34
60	3600	0.00	0.93	277.41	575.41	302.41	576.34



METHOD OF DEAL AND BEYLER

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 3-178.

Heat Transfer Coefficient Calculation

$h_k = 0.4 \sqrt{(k\rho c / t)}$ for $t < t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia (kW/m^2-K)^2-sec

(a thermal property of material responsible for the rate of temperature rise)

δ = thickness of interior lining (m)

h_k = 0.022 kW/m^2-K

Area of Compartment Enclosing Surface Boundaries

$A_T = 2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)$

A_T = 572.28 m^2

Compartment Hot Gas Layer Temperature With Forced Ventilation

$\Delta T_g = Q / (m\, c_p + h_k A_T)$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

T_a = ambient air temperature (K)

Q = heat release rate of the fire (kW)

m = compartment mass ventilation flow rate (kg/sec)

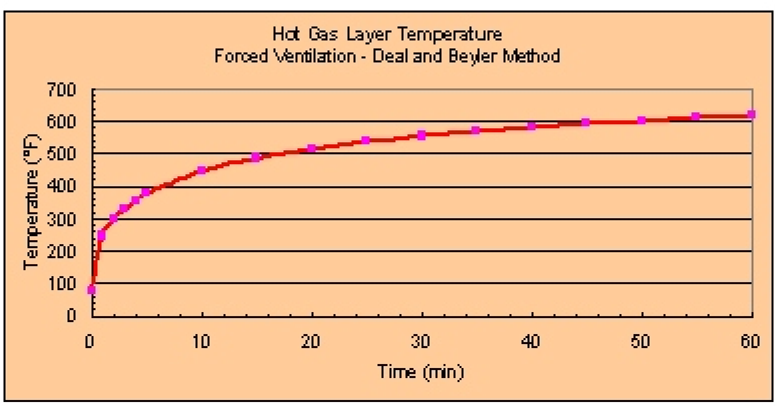
c_p = specific heat of air (kJ/kg-K)

h_k = convective heat transfer coefficient (kW/m^2-K)

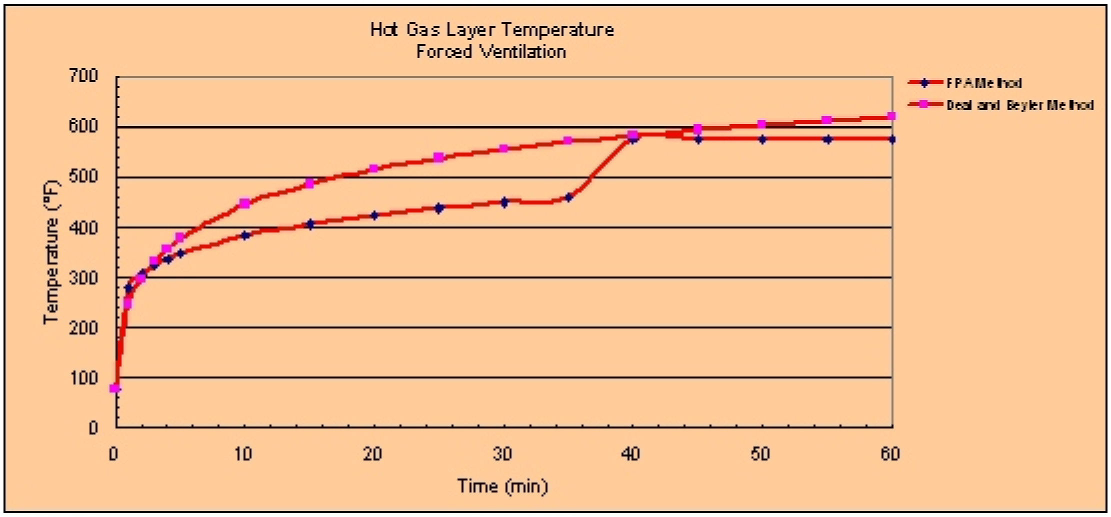
A_T = total area of the compartment enclosing surface boundaries (m^2)

Results

Time After Ignition (t) (min)	Time After Ignition (t) (sec)	h_k (kW/m^2-K)	ΔT_g (K)	T_g (K)	T_g (°C)	T_g (°F)
0	0	-	-	298.00	25.00	77.00
1	60	0.02	94.38	392.38	119.38	246.89
2	120	0.02	122.75	420.75	147.75	297.95
3	180	0.01	141.60	439.60	166.60	331.88
4	240	0.01	155.87	453.87	180.87	357.57
5	300	0.01	167.38	465.38	192.38	378.29
10	600	0.01	204.94	502.94	229.94	445.89
15	900	0.01	227.56	525.56	252.56	486.61
20	1200	0.00	243.59	541.59	268.59	515.46
25	1500	0.00	255.89	553.89	280.89	537.60
30	1800	0.00	265.80	563.80	290.80	555.43
35	2100	0.00	274.04	572.04	299.04	570.27
40	2400	0.00	281.07	579.07	306.07	582.93
45	2700	0.00	287.17	585.17	312.17	593.91
50	3000	0.00	292.54	590.54	317.54	603.58
55	3300	0.00	297.33	595.33	322.33	612.19
60	3600	0.00	301.63	599.63	326.63	619.93



Summary of Result:



NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Problem J-7

Problem Statement

Consider a compartment with an open vent that allows the air entrance at 3.60 m/s (700 ft/min). Assume that heptane from a tank spills on the concrete floor forming a 1.86 m^2 (20 ft^2) pool. The edge to edge distance from the pool fire to a certain target is about 9.0 m (30 ft). The target is 3 m (10 ft) above ground. Calculate the flame radiative heat flux at ground level using the solid flame model.

Solution

Purpose:

(1) Calculate the radiant heat flux from the pool fire to the target using the solid flame radiation model and considering the effect of the wind.

Assumptions:

(1) The pool is circular or nearly circular.
(2) The correlation for solid flame radiation model is suitable for heptane.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 05.2_Heat_Flux_Calculations_Wind.xls (select *Solid Flame 2*)

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

- Fuel Spill Area or Dike Area (A_{dike}) = 20 ft^2
- Distance between Fire and Target (L) = 30 ft
- Vertical Distance of Target from Ground Level ($H_1 = H_{f1}$) = 10 ft
- Wind Speed or Velocity (u_w) = 700 ft/min
- Select Fuel Type: select **Heptane** from the combo box

Note: When **Heptane** is selected, its thermal properties are automatically selected from the table and entered in the corresponding input cells.

Results

Radiation Model	Radiant Heat Flux* $\dot{q}''$ kW/m^2 (Btu/ft^2-sec)
Solid Flame	4.06 (0.36)

*spreadsheet calculations attached on next page

Spreadsheet Calculations

FDT[s]: 05.2_Heat_Flux_Calculations_Wind.xls (Solid Flame 2)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL ABOVE GROUND LEVEL IN PRESENCE OF WIND (TILTED FLAME) SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel in the presence of wind.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire above ground level to determine if secondary ignitions are likely in presence of wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Parameter	Value	Unit	Converted
Mass Burning Rate of Fuel (m'')	0.101	kg/m²-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	44600	kJ/kg	
Empirical Constant ($k\beta$)	1.1	m⁻¹	
Fuel Area or Dike Area (A_{dike})	20.00	ft²	1.86 m²
Distance between Fire and Target (L)	30.00	ft	9.144 m
Vertical Distance of Target from Ground Level ($H_1 = H_T$)	10.00	ft	3.048 m
Wind Speed or Velocity (u_w)	700	ft/min	3.56 m/sec
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec²	
Ambient Air Density (ρ_a)	1.18	kg/m³	

Calculate

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m'' (kg/m²-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m⁻¹)
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-26.

Select Fuel Type

Heptane

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL IN PRESENCE OF WIND

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 1995, Page 3-272.

SOLID FLAME RADIATION MODEL IN PRESENCE OF WIND

$q'' = EF_{1 \to 2}$

Where q'' = incident radiative heat flux on the target (kW/m^2)
E = emissive power of the pool fire flame (kW/m^2)
$F_{1 \to 2}$ = view factor between target and the flame in presence of wind

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4 A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)
D = pool fire diameter (m)

$D =$ 1.64 m

Pool Fire Radius Calculation

$r =$ $D/2$

$r =$ 0.77 m

Flame Emissive Power Calculation

$E = 58 (10^{-0.00823D})$

Where E = emissive power of the pool fire flame (kW/m^2)
D = diameter of the pool fire (m)

$E =$ 66.33 (kW/m^2)

View Factor Calculation in Presence of Wind

$\pi F_{1 \to 2,V1} =$ $(a_1 \cos\theta/(b - a_1 \sin\theta)) (a_1^2 + (b+1)^2 - 2b(1 + a_1 \sin\theta))/(A_1B_1)^{0.5} (\tan^{-1}(A_1/B_1)^{0.5} ((b-1)/(b+1))^{0.5} + \cos\theta/(C)^{0.5} ((\tan^{-1}(a_1 b - (b^2-1) \sin\theta)/((b^2-1)(C)^{0.5}) + \tan^{-1}(b^2-1) \sin\theta/(b^2-1)^{0.5}$

$\pi F_{1 \to 2,V2} =$ $(a_2 \cos\theta/(b - a_2 \sin\theta)) (a_2^2 + (b+1)^2 - 2b(1 + a_2 \sin\theta))/(A_2B_2)^{0.5} (\tan^{-1}(A_2/B_2)^{0.5} ((b-1)/(b+1))^{0.5} + \cos\theta/(C)^{0.5} ((\tan^{-1}(a_2 b - (b^2-1) \sin\theta)/((b^2-1)(C)^{0.5}) + \tan^{-1}(b^2-1) \sin\theta/(b^2-1)^{0.5}$

$A_1 =$ $a_1^2 + (b+1)^2 - 2a_1(b+1)\sin\theta$

$A_2 =$ $a_2^2 + (b+1)^2 - 2a_2(b+1)\sin\theta$

$B_1 =$ $a_1^2 + (b-1)^2 - 2a_1(b-1)\sin\theta$

$B_2 =$ $a_2^2 + (b-1)^2 - 2a_2(b-1)\sin\theta$

$C =$ $1 + (b^2 - 1)\cos^2\theta$

$a_1 =$ $2H_f/r = 2H_f/r$

$a_2 =$ $2H_{f2}/r = 2(H_f - H_{f1})/r$

$b =$ R/r

$F_{1 \to 2,V} = F_{1 \to 2,V1} + F_{1 \to 2,V2}$

Where $F_{1 \to 2,V}$ = total vertical view factor in presence of wind
R = distance from center of the pool fire to edge of the target (m)
H_f = height of the pool fire flame (m)
r = pool fire radius (m)
θ = flame tilt or angle of deflection (radians)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + r =$ 9.91 m

Where
- R = distance from center of the pool fire to edge of the target (m)
- L = Distance between Fire and Target
- r = pool fire radius (m)

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}\,(1 - e^{-k\beta D})\,A_{dike}$

Where
- Q = pool fire heat release rate (kW)
- m" = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ΔH_c = effective heat of combustion of fuel (kJ/kg)
- A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)
- $k\beta$ = empirical constant (m^{-1})
- D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 6828.38 kW

Pool Fire Flame Height Calculation

$H_f = 55\,D\,(m''/\rho_a\,\sqrt{(g\,D)})^{0.67}\,(u^*)^{-0.21}$

Where
- H_f = flem height (m)
- m" = mass burning rate of fuel (kg/m^2-sec)
- D = pool fire diameter (m)
- ρ_a = ambient air density (kg/m^3)
- g = gravitational acceleration (m/sec^2)
- u* = nondimensional wind velocity

Nondimensional Wind Velocity Calculation

$u^* = u_w/(g\,m''\,D/\rho_a)^{1/3}$

Where
- u* = nondimensional wind velocity
- u_w = wind velocity (m/sec)
- g = gravitational acceleration (m/sec^2)
- m" = mass burning rate of fuel (kg/m^2-sec)
- D = pool fire diameter (m)
- ρ_a = ambient air density (kg/m^3)

$u^* = u_w/(g\,m''\,D/\rho_a)^{1/3}$

u* = 3.270

$H_f = 55\,D\,(m''/\rho_a\,(\sqrt{g\,D}))^{0.67}\,(u^*)^{-0.21}$

H_f = 5.11 m

Flame Tilt or Angle of Deflection Calculation

$COS\theta = 1$ for $u^* \leq 1$

$COS\theta = 1/(u^*)^{0.5}$ for $u^* \geq 1$

Since $u^* \geq 1$

θ = ACOS(1/(u*)^0.5) =	0.985 Rad		56.42 degree
	0.985 Rad		56.42 degree
	0 Rad		0.00 degree

$A_1 = a_1^2 + (b+1)^2 - 2a_1(b+1)\sin\theta$ =	72.30
$A_2 = a_2^2 + (b+1)^2 - 2a_2(b+1)\sin\theta$ =	97.71
$B_1 = a_1^2 + (b-1)^2 - 2a_1(b-1)\sin\theta$ =	47.16
$B_2 = a_2^2 + (b-1)^2 - 2a_2(b-1)\sin\theta$ =	63.98
$C = 1 + (b^2 - 1)\cos^2\theta$ =	61.61
$a_1 = 2H_{f1}/r = 2H_1/r$ =	7.93
$a_2 = 2H_{f2}/r = 2(H - H_1)/r$ =	6.36
$b = R/r$ =	12.89

		F_{V1}	F_{V2}	F_{V3}	F_{V4}	F_{V5}	F_{V6}	F_{V7}	$F_{1\to 2,V1}$
$F_{1\to 2,V1}$	0.04306								
$F_{1\to 2,V2}$	0.02899	0.697	1.023	0.853	0.077	-0.367	0.980	0.521	0.048061

		F_{V1}	F_{V2}	F_{V3}	F_{V4}	F_{V5}	F_{V6}	F_{V7}	$F_{1\to 2,V2}$
$F_{1\to 2} = F_{1\to 2,V1} + F_{1\to 2,V2}$ =	0.07204								
		0.351	1.022	0.852	0.077	-0.367	0.980	0.262	0.028991

Radiative Heat Flux Calculation in Presence of Wind

$q'' = EF_{1\to 2}$

q'' =	4.06 kW/m²	0.36 Btu/ft²-sec	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Problem J-8

Problem Statement

Consider a compartment that has been insulated with 1.27 cm (½ in) of gypsum board, wallboard (S142M). If a pool fire scenario arises with a heat flux of 75 kW/m^2, what will be the ignition time of the gypsum board?

Solution

Purpose:

(1) Calculate the ignition time of Gypsum Board, Wallboard (S142M) for the given conditions.

Assumptions:

(1) The material is infinitely thick.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 06_Ignition_Time_Calculations.xls (select *Ignition_Time _Calculations1*)

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

-Exposure or External Radiative Heat Flux to Target Fuel $(\dot{q}_e'')$ = 75 kW/m^2

-Select Material: select **Gypsum Board, Wallboard (S142M)** from the combo box

Note: When **Gypsum Board, Wallboard (S142M)** is selected, its thermal properties are automatically selected from the table and entered in the corresponding input cells.

Results

Calculation Method	Ignition Time* t_{ig} (min)
Mikkola and Wichmann	0.34 min
Quintiere and Harkleroad	0.20 min
Janssens	0.86 min

*spreadsheet calculations attached on next page

Spreadsheet Calculations

FDT^s: 06_Ignition_Time_Calculations.xls (Ignition_Time _Calculations1)

CHAPTER 6. ESTIMATING THE IGNITION TIME OF A TARGET FUEL EXPOSED TO A CONSTANT RADIATIVE HEAT FLUX

Version 1805.0
The following calculations estimate time to ignition for flame spread of solid fuels exposed to a constant external radiative heat flux.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

MATERIAL FLAME SPREAD PROPERTIES

Parameter	Value	Unit
Material Ignition Temperature (T_{ig})	412.00	°C
Material Thermal Inertia (kρc)	0.57	$(kW/m^2\text{-}K)^2\text{-sec}$
Material Critical Heat Flux for Ignition ($q''_{critical}$)	18.00	kW/m^2
Flame Spread Parameter b	0.07	$(s)^{-1/2}$
Exposure or External Radiative Heat Flux (q''_e)	75.00	kW/m^2
Ambient Air Temperature (T_a)	77.00	°F
Heat Transfer Coefficient at Ignition (h_{ig})	0.0275	$kW/m^2\text{-K}$

Calculate

FLAME SPREAD PROPERTIES OF COMMON MATERIALS

Materials	Ignition Temperature T_{ig} (°C)	Thermal Inertia kρc $(kW/m^2\text{-}K)^2\text{-sec}$	Critical Heat Flux for Ignition $q''_{critical}$ (kW/m^2)	Flame Spread Parameter b $(s)^{-1/2}$
PMMA Polycast (1.59mm)	278	0.73	9	0.04
Hardboard (6.35mm)	298	1.87	10	0.03
Carpet (Acrylic)	300	0.42	10	0.06
Fiber Insulation Board	355	0.46	14	0.07
Hardboard (3.175mm)	365	0.88	14	0.05
PMMA Type G (1.27 cm)	378	1.02	15	0.05
Asphalt Shingle	378	0.7	15	0.06
Douglas Fire Particle Board (1.27 cm)	382	0.94	16	0.05
Plywood Plain (1.27 cm)	390	0.54	16	0.07
Plywood Plain (0.635 cm)	390	0.46	16	0.07
Foam Flexible (2.54cm)	390	0.32	16	0.09
GRP (2.24mm)	390	0.32	16	0.09
Hardboard (Gloss Paint) (3.4mm)	400	1.22	17	0.05
Hardboard Nitrocellulose Paint)	400	0.79	17	0.06
GRP (1.14mm)	400	0.72	17	0.06
Particle Board (1.27 cm Stock)	412	0.93	18	0.05
Carpet (Nylon/Wool Blend)	412	0.68	18	0.06
Gypsum Board, Wallboard (S142M)	412	0.57	18	0.07
Carpet # 2 (Wool Untreated)	435	0.25	20	0.11
Foam Rigid (2.54 cm)	435	0.03	20	0.32
Fiberglass Shingle	445	0.5	21	0.08
Polyisoyanurate (5.08cm)	445	0.02	21	0.36
Carpet # 2 (Wool Treated)	455	0.24	22	0.12
Carpet # 1 (Wool, Stock)	465	0.11	23	0.18
Aircraft Panel Epoxy Fiberite	505	0.24	28	0.13
Gypsum Board FR (1.27 cm)	510	0.4	28	0.1
Polycarbonate (1.52 mm)	528	1.16	30	0.06
Gypsum Board (Common) (1.27 mm)	565	0.45	35	0.11
Plywood FR (1.27 cm)	620	0.76	44	0.1
Polystyrene (5.08cm)	630	0.38	46	0.14
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Material
Scroll to desired material
Click on selection

METHOD OF MIKKOLA AND WICHMAN
THERMALLY THICK MATERIALS

Reference: SFPE Engineering Guide, "Piloted Ignition of Solid Materials Under Radiant Exposure," 2002, Page 7.

$t_{ig} = \pi/4\ k\rho c\ (T_{ig} - T_a)^2 / (q_e'' - q_{critical}'')^2$

Where

t_{ig} = material ignition time (sec)
$k\rho c$ = material thermal inertia $(kW/m^2\text{-}K)^2\text{-}sec$
T_{ig} = material ignition temperature (°C)
T_a = ambient air temperature (°C)
q_e'' = exposure or external radiative heat flux (kW/m^2)
$q''_{critical}$ = material critical heat flux for ignition (kW/m^2)

$t_{ig} = \pi/4\ k\rho c\ (T_{ig} - T_a)^2 / (q_e'' - q_{critical}'')^2$

t_{ig} =	20.64 sec	0.34 minute	Answer

METHOD OF QUINTIERE AND HARKLEROAD
THERMALLY THICK MATERIALS

Reference: SFPE Engineering Guide, "Piloted Ignition of Solid Materials Under Radiant Exposure," 2002, Page 12.

$t_{ig} = (q_{critical}'' / b\ q_e'')^2$

Where

t_{ig} = material ignition time (sec)
$q''_{critical}$ = material critical heat flux for ignition (kW/m^2)
b = flame spread parameter $(s)^{-1/2}$
q_e'' = exposure or external radiative heat flux (kW/m^2)

$t_{ig} = (q_{critical}'' / b\ q_e'')^2$

t_{ig} =	11.76 sec	0.20 minute	Answer

METHOD OF JANSSENS
THERMALLY THICK MATERIALS

Reference: SFPE Engineering Guide, "Piloted Ignition of Solid Materials Under Radiant Exposure," 2002, Page 15.

$t_{ig} = 0.563\ (k\rho c / h_{ig}^2)\ ((q_e'' / q_{critical}'') - 1)^{-1.83}$

Where

t_{ig} = material ignition time (sec)
$k\rho c$ = material thermal inertia $(kW/m^2\text{-}K)^2\text{-}sec$
h_{ig} = heat transfer coefficient at ignition $(kW/m^2\text{-}K)$
q_e'' = exposure or external radiative heat flux (kW/m^2)
$q''_{critical}$ = material critical heat flux for ignition (kW/m^2)

$t_{ig} = 0.563\ (k\rho c / h_{ig}^2)\ ((q_e'' / q_{critical}'') - 1)^{-1.83}$

t_{ig} =	61.48 sec	0.86 minute	Answer

Summary of Result

Calculation Method	Time to Ignition (minute)
MIKKOLA AND WICHMAN	0.34
QUINTIERE AND HARKLEROAD	0.20
JANSSENS	0.86

NOTE

The above calculations are based on principles developed in the SFPE Engineering Guide, "Piloted Ignition of Solid Materials Under Radiant Exposure," January 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Problem J-9

Problem Statement
A 75.0-liter (20-gallon) trash bag exposure fire source is located 3.0 m (10.0 ft) beneath a horizontal cable tray. Assume that the trash fire ignites an area of approximately 1.0 m^2 (11.0 ft^2) of the cable tray, and the cables in the tray are IEEE-383-qualified XPE/FRXPE cables. Compute the full-scale HRR, $(\dot{Q}_{fs})$ of the XPE/FRXPE cable insulation. The bench scale HRR $(\dot{Q}''_{bs})$ of the XPE/FRXPE is 475 kW/m^2.

Solution

Purpose:

(1) Calculate the full-scale HRR of the XPE/FRXPE for the given scenario.

Assumptions:

(1) Lee's correlation is valid for this fire scenario.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 07_Cable_HRR_Calculations.xls

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

-Exposure Cable Tray Burning Area (A_f) = 11 ft^2

-Select Cable Typel: select **XPE/FRXPE** from the combo box

Note: When **XPE/FRXPE** is selected, its thermal properties are automatically selected from the table and entered in the corresponding input cells.

Results

Cable Insulation	Full Scale HRR $\dot{Q}_{fs}$ kW (Btu/sec)
XPE/FRXPE	218 (207)

*spreadsheet calculations attached on next page.

Spreadsheet Calculations

FDT[s]: 07_Cable_HRR_Calculations.xls

CHAPTER 7. ESTIMATING THE FULL-SCALE HEAT RELEASE RATE OF A CABLE TRAY FIRE

Version 1805.0

The following calculations estimate the full-scale cable tray heat release rate.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Cable Selected.
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 Bench-Scale HRR ($\dot{Q}''_{bs}$)	475	kW/m^2	
Exposed Floor Area (Length x Width) of Burning Cable Tray (A)	11.00	ft^2	1.022 m^2

Calculate

HEAT RELEASE RATE DATA FOR CABLE TRAY FIRE

BENCH-SCALE HRR OF CABLE TRAY FIRE

Cable Type	Bench-Scale HRR per Unit Floor Area (L x W) $\dot{Q}''_{bs}$ (kW/m^2)
XLPE	1071
PE/PVC	589
XPE/FRXPE	475
PE/PVC	395
PE/PVC	359
XPE/Neoprene	354
PE, PP/Cl.S.PE	345
PE/PVC	312
XPE/Neoprene	302
PE, PP/Cl.S.PE	299
PE, PP/Cl.S.PE	271
FRXPE/Cl.S.PE	258
PE, Nylon/PVC, Nylon	231
PE, Nylon/PVC, Nylon	218
XPE/Cl.S.PE	204
Silicone, glass braid, asbestos	182
XPE/XPE	178
PE, PP/Cl.S.PE	177
Silicone, glass braid	128
Teflon	98
User Specified Value	Enter Value

Select Cable Type

XPE/FRXPE

Scroll to desired cable type then Click on selection

Reference: *"Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.*

ESTIMATING FULL-SCALE CABLE TRAY HEAT RELEASE RATE

Reference: *SFPE Handbook of Fire Protection Engineering, 3rd Edition 2002, Page 3-16.*

$Q_{fs} = 0.45\ Q_{bs}\ A$

Where Q_{fs} = cable tray full-scale HRR (kW)

Q_{bs} = cable tray bench-scale HRR (kW)

A = exposed floor area (length x width) of burning cable tray (m^2)

Heat Release Rate Calculation

$Q_{fs} = 0.45\ Q_{bs}\ A$

Q_{fs} =	218.44 kW	207.04 Btu/sec

Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and has inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Problem J-10

Problem Statement

Estimate the maximum plume temperature ($T_{p(centerline)}$) at the ceiling of a 6.0-m (20.0-ft) high compartment above a 1,420 kW fire involving a 1½ ft high stack of wood pallets in a 0.92 m^2 (10.0 ft^2) pallet area. Assume that the ambient temperature is 25 °C (77 °F).

Solution

Purpose:

(1) Estimate the maximum plume temperature for the given fire scenario.

Assumptions:

(1) All heat is released at a point.
(2) Buoyant forces are more significant than momentum forces.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 09_Plume_Temperature_Calculations.xls

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

-Heat Release Rate $(\dot{Q})$ = 1,420 kW

-Distance from the Top of the Fuel to the Ceiling (z) = 20 ft

-Area of Combustible Fuel = 10 ft^2

Results

Heat Release Rate $\dot{Q}$ (kW)	Plume Centerline Temperature $T_{p(centerline)}$ °C (°F)
1,420	164 (328)

*spreadsheet calculations attached on next page.

Spreadsheet Calculations
FDT[s]: 09_Plume_Temperature_Calculations.xls

CHAPTER 9. ESTIMATING CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

Version 1805.0

The following calculations estimate the centerline plume temperature in a compartment fire.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
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

Heat Release Rate of the Fire (Q)	1420.00	kW		
Elevation Above the Fire Source (z)	20.00	ft	6.10	m
Area of Combustible Fuel (A_c)	10.00	ft^2	0.93	m^2
Ambient Air Temperature (T_a)	77.00	°F	25.00	°C
	Calculate		298.00	K

AMBIENT CONDITIONS

Specific Heat of Air (c_p)	1.00	kJ/kg-K
Ambient Air Density (ρ_a)	1.18	kg/m^3
Acceleration of Gravity (g)	9.81	m/sec^2
Convective Heat Release Fraction (χ_c)	0.70	

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

ESTIMATING PLUME CENTERLINE TEMPERATURE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 2-6.

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

Where $T_{p(centerline)}$ = plume centerline temperature (°C)
Q_c = convective portion of the heat release rate (kW)
T_a = ambient air temperature (K)
g = acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/kg-K)
ρ_a = ambient air density (kg/m^3)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fire (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\, Q$

Where Q_c = convective portion of the heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release fraction

Q_c = 994 kW

Fire Diameter Calculation

$A_c = \pi D^2/4$

Where A_c = area of combustible fuel (m^2)
D = fire diameter (m)

$D = \sqrt{(4\,A_c/\pi)}$

D = 1.09 m

Hypothetical Virtual Origin Calculation

$z_o/D = -1.02 + 0.083\,(Q^{2/5})/D$

Where z_o = virtual origin of the fire (m)

Q = heat release rate of fire (kW)

D = fire diameter (m)

z_o/D = 0.37

z_o = **0.40** m

Centerline Plume Temperature Calculation

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

$T_{p(centerline)} - T_a$ = **139.22**

$T_{p(centerline)}$ = **437.22** K

$T_{p(centerline)}$ =	**164.22** °C	**327.59** °F	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

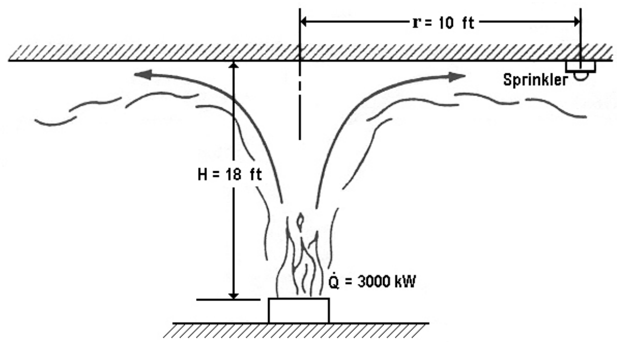
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

Problem J-11

Problem Statement

A fire with $\dot{Q}$ = 3,000 kW occurs in a makeup pump room protected with sprinkler protection. The sprinklers are rated at 74 °C (165 °F) [standard response bulb with RTI 235 $(m\text{-}sec)^{1/2}$ and located 3.0 m (10.0 ft) from the center of the fire source. The height from the top of the fuel package to the ceiling is 5.5 m (18.0 ft). Determine whether the sprinklers would activate and, if so, how long it would take for them to activate.



Problem 11: Fire Scenario with Sprinkler Protection

Solution

Purpose:

(1) Determine if the sprinklers will be activated for the given fire scenario.

(2) If the sprinkles are activated, determine how long it takes for the activation.

Assumptions:

(1) The fire is located away from walls and corners.

(2) The fire is steady state

(3) The ceiling is unconfined, unobstructed, and flat.

(4) Only convective heat transfer from the hot fire gases is considered.

(5) There is heavily obstructed overhead.

(6) The ambient temperature before the fire ignition is 70 °F

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (select *Sprinkler*)

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

- Heat Release Rate of the Fire $(\dot{Q})$ = 3,000 kW
- Distance from the Top of the Fuel Package to the Ceiling (H) = 18 ft
- Radial Distance from the Plume Centerline to the Sprinkler (r) = 10 ft
- Ambient Air Temperature (T_a) = 70 °F
- Select Type of Sprinkler = select **Standard response bulb** from the combo box
- Select Sprinkler Classification = select **Ordinary** from the combo box

Note: Ordinary classification is selected because the rated value for the sprinklers in this problem (165 °F) is within the range of temperature ratings for ordinary sprinklers (135 °F–170 °F).

Note: When the **sprinkler type** and **classification** are selected, their respective values are automatically selected from the table and entered in the corresponding input cells.

Results

Sprinkler Type	Sprinkler Activation Time* $t_{activation}$ (min.)
Standard response bulb	2.47

*spreadsheet calculations attached on next page.

Spreadsheet Calculations
FDT^s: 10_Detector_Activation_Time.xls (Sprinkler)

CHAPTER 10. ESTIMATING SPRINKLER RESPONSE TIME

Version 1805.0

The following calculations estimate sprinkler activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Sprinkler Selected.
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

Heat Release Rate of the Fire (Q) (Steady State)	3000.00	kW	
Sprinkler Response Time Index (RTI)	235	(m-sec)$^{1/2}$	
Activation Temperature of the Sprinkler ($T_{activation}$)	165	°F	73.89 °C
Height of Ceiling above Top of Fuel (H)	18.00	ft	5.49 m
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	10.00	ft	3.05 m
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		

r/H = 0.56

Calculate

GENERIC SPRINKLER RESPONSE TIME INDEX (RTI)*

Common Sprinkler Type	Generic Response Time Index (RTI) (m-sec)$^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34
User Specified Value	Enter Value

Select Type of Sprinkler
Standard response bulb
Scroll to desired sprinkler type then Click on selection

Reference: *Madrzykowski, D., "Evaluation of Sprinkler Activation Prediction Methods" ASIAFLAM'95, International Conference on Fire Science and Engineering, 1st Proceeding, March 15-16, 1995, Kowloon, Hong Kong, pp. 211-218.*

*Note: The actual RTI should be used when the value is available.

GENERIC SPRINKLER TEMPERATURE RATING ($T_{activation}$)*

Temperature Classification	Range of Temperature Ratings (°F)	Generic Temperature Ratings (°F)
Ordinary	135 to 170	165
Intermediate	175 to 225	212
High	250 to 300	275
Extra high	325 to 375	350
Very extra high	400 to 475	450
Ultra high	500 to 575	550
Ultra high	650	550
User Specified Value	–	Enter Value

Select Sprinkler Classification
Ordinary
Scroll to desired sprinkler class then Click on selection

Reference: *Automatic Sprinkler Systems Handbook, 6th Edition, National Fire Protection Association, Quincy, Massachusetts, 1994, Page 67.*

*Note: The actual temperature rating should be used when the value is available.

ESTIMATING SPRINKLER RESPONSE TIME

Reference: *NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.*

$t_{activation} = (RTI/(\sqrt{u_{jet}})) (\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = sprinkler activation response time (sec)
RTI = sprinkler response time index $(m\text{-}sec)^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$T_{activation}$ = activation temperature of sprinkler (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9 (Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38 (Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
Q_c = convective portion of the heat release rate (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the sprinkler (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c Q$

Where Q_c = convective portion of the heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release rate fraction

Q_c = **2100** kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = **0.56** r/H > 0.15

$T_{jet} - T_a$ = {5.38 (Qc/r)^2/3)/H

$T_{jet} - T_a$ = 76.49

T_{jet}= **101.49** (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96 (Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195 Q^{1/3} H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)
Q = heat release rate of the fire (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the sprinkler (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.56 r/H > 0.15

u_{jet} = (0.195 Q^1/3 H^1/2)/r^5/6

u_{jet} = 2.602 m/sec

Sprinkler Activation Time Calculation

$t_{activation} = (RTI/(\sqrt{u_{jet}})) (\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation}$ = 148.47 sec

The sprinkler will respond in approximately	2.47 minutes	Answer

NOTE: If $t_{activation}$ = "NUM" Sprinkler does not activate

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
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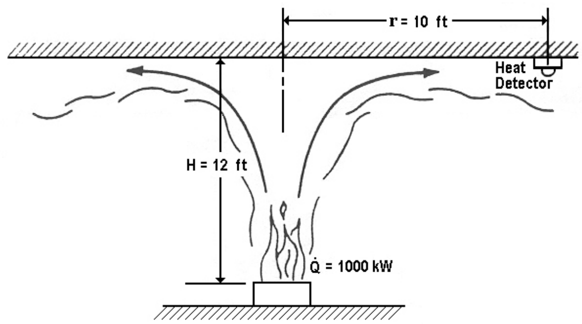
Problem J-12

Problem Statement

A trash fire with an HRR ($\dot{Q}$) of 1,000 kW occurs in a battery room protected with fixed temperature heat detectors with an RTI of 306 $(m\text{-}sec)^{1/2}$. The distance from the top of the fuel package to the ceiling 3.7 m (12 ft) and the radial distance from the plume center to the heat detector location is 10 ft. Calculate the activation time ($t_{activation}$) for the detectors, using listed spacing of 4.6 m (15.0 ft). Assume that the detector activation temperature of 54 °C (128 °F), and the ambient temperature is 20 °C (68 °F).



Problem 12: Fire Scenario with Heat Detectors

Solution

Purpose:

(1) Determine the response time of the fixed-temperature heat detectors for the given fire scenario.

Assumptions:

(1) The fire is located away from walls and corners.
(2) The fire is steady state.
(3) The ceiling is unconfined, unobstructed, and flat.
(4) Only convective heat transfer from the hot fire gases is considered.
(5) There is heavily obstructed overhead.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 10_Detector_Activation_Time.xls (select *FTHDetectors*)

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

- Heat Release Rate of the Fire $(\dot{Q})$ = 1,000 kW
- Radial Distance to the Detector (r) = 10 ft
- Distance from the Top of the Fuel Package to the Ceiling (H) = 12 ft
- Ambient Air Temperature (T_a) = 68 °F
- Select the option button (⊙) for FTH detectors with $T_{activation}$ = 128 °F
- Select Detector Spacing: select **15** from the combo box

Note: When $\mathbf{T_{activation}}$ and **Detector Spacing** are selected, their respective values are automatically selected from the table and entered in the corresponding input cells.

Results

Detector Type	Heat Detector Activation Time $t_{activation}$ (min.)
Fixed Temperature	3.03

*spreadsheet calculations attached on next page.

Spreadsheet Calculations

FDT[s]: 10_Detector_Activation_Time.xls (FTHDetectors)

CHAPTER 12. ESTIMATING HEAT DETECTOR RESPONSE TIME

Version 1805.0

The following calculations estimate fixed temperature heat detector activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Detector Selected.
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

Parameter	Value	Unit		
Heat Release Rate of the Fire (Q) (Steady State)	1000.00	kW		
Radial Distance to the Detector (r) "never more than 0.707 or 1/2√2 of the listed spacing"	10.00	ft	305	m
Activation Temperature of the Fixed Temperature Heat Detector ($T_{activation}$)	128	°F	5333	°C
Detector Response Time Index (RTI)	306.00	(m-sec)$^{1/2}$		
Height of Ceiling above Top of Fuel (H)	12.00	ft	366	m
Ambient Air Temperature (T_a)	77.00	°F	2500	°C
			29800	K
Convective Heat Release Fraction (χ_c)	0.70			

r/H = 0.83

Calculate

INPUT DATA FOR ESTIMATING HEAT DETECTOR RESPONSE TIME

Activation Temperature $T_{activation}$

(•) T= 128 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	490	128
15	306	128
20	325	128
25	152	128
30	116	128
40	87	128
50	72	128
70	44	128
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

15

Scroll to desired spacing then Click on selection

( ) T= 135 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	404	135
15	233	135
20	165	135
25	123	135
30	98	135
40	70	135
50	54	135
70	20	135
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

( ) T= 145 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	321	145
15	191	145
20	129	145
25	96	145
30	75	145
40	50	145
50	37	145
70	11	145
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 160 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	239	160
15	135	160
20	86	160
25	59	160
30	44	160
40	22	160
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 170 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	196	170
15	109	170
20	64	170
25	39	170
30	27	170
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then Click on selection

T= 196 F

UL Listed Spacing r (ft)	Response Time Index RTI (m-sec)$^{1/2}$	Activation Temperature (°F)
10	119	196
15	55	196
20	21	196
User Specified Value	Enter Value	Enter Value

Select Detector Spacing

Scroll to desired spacing then

Click on selection

Reference: *NFPA Standard 72, National Fire Alarm Code, Appendix B, Table B-3.2.5.1, 1999, Edition.*

ESTIMATING FIXED TEMPERATURE HEAT DETECTOR RESPONSE TIME

Reference: *NFPA Fire Protection Handbook*, 19[th] Edition, 2003, Page 3-140.

$t_{activation} = (RTI/(\sqrt{u_{jet}}))(\ln(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = detector activation time (sec)
RTI = detector response time index $(m\text{-}sec)^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$T_{activation}$ = activation temperature of detector (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\,(Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38\,(Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
Q_c = convective portion of the heat release rate (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the detector (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\,Q$

Where Q_c = convective heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release fraction

Q_c = 700 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.83 r/H > 0.15

>0.15	55.16	<0.15	153.45

$T_{jet} - T_a$ = 5.38 ((Qc/r)^2/3)/H

$T_{jet} - T_a$ = 55.16

T_{jet} = 80.16 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\,(Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\,Q^{1/3}\,H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)
Q = heat release rate of the fire (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the detector (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 0.83 r/H > 0.15

u_{jet} = (0.195 Q^1/3 H^1/2)/r^(5/6)

u_{jet} = 1.473 m/sec

Detector Activation Time Calculation

$t_{activation}$ = (RTI/(√u_{jet})) (ln (T_{jet} - T_a)/(T_{jet} - $T_{activation}$))

$t_{activation}$ = 181.72 sec

The detector will respond in approximately	3.03 minutes	Answer

NOTE: If $t_{activation}$ = "NUM" Detector does not activate

NOTE

The above calculations are based on principles developed in the NFPA Fire Protection Handbook 19th Edition, 2003. Calculations are based on certain assumptions and have inherent limitations.
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Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
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Problem J-13

Problem Statement

Calculate the HRR necessary for flashover $(\dot{Q}_{FO})$ and the post-flashover temperature in a long access corridor that is 30.5 m long x 5.5 m wide x 3.0 m high (100.0 ft long x 18.0 ft wide x 10.0 ft high), with an opening that is 0.91 m (3.0 ft) wide x 2.5 m (8.0 ft) high. Assume that corridor boundary material is 15 cm (6 in) thick concrete.

Solution

Purpose:

(1) Determine the HRR necessary for flashover and the post-flashover temperature for the given compartment

Assumptions:

(1) Natural Ventilation.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 13_Compartment_Flashover_Calculations.xls
select *Flashover-HRR* to calculate the HRR for flashover
select *Post_Flashover_Temperature* to calculate the post-flashover temperature

FDT^s Input Parameters:

Enter the following parameters in both spreadsheets (values only):

- Compartment Width (w_c) = 18 ft
- Compartment Length (l_c) = 100 ft
- Compartment Height (h_c) = 10 ft
- Vent Width (w_v) = 3 ft
- Vent Height (h_v) = 8 ft
- Interior Lining Thickness (δ) = 6 in (*Flashover-HRR* only)
- Select Material: select **Concrete** from the combo box (*Flashover-HRR only*)

Note: When **Concrete** is selected in *Flashover-HRR spreadsheet***,** its respective properties are automatically selected from the table and entered in the corresponding input yellow cells.

Results

Post-Flashover Temperature $T_{PFO(max)}$ °C (°F)	Flashover HRR $\dot{Q}_{FO}$ kW (Btu/sec)		
Method of Law	Method of MQH	Method of Babrauskas	Method of Thomas
478 (892)	2,739 (2,596)	2,611 (2,475)	5,618 (5,325)

*spreadsheet calculations attached on next page

Spreadsheet Calculations

FDT[s]: 13_Compartment_Flashover_Calculations.xls (Post_Flashover_Temperature)

CHAPTER 13. PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE

Version 1805.0

The following calculations estimate the compartment post-flashover temperature.
Parameters in YELLOW CELLS are Entered by the User.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	18.00	ft	5.4864 m
Compartment Length (l_c)	100.00	ft	30.48 m
Compartment Height (h_c)	10.00	ft	3.048 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	8.00	ft	2.438 m

Calculate

PREDICTING COMPARTMENT POST-FLASHOVER TEMPERATURE
METHOD OF MARGARET LAW

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-183.

$T_{PFO\ (max)} = 6000\ (1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

Where $T_{PFO\ (max)}$ = maximum compartment post-flashover temperature (°C)

Ω = ventilation factor

Where $\Omega = (A_T - A_v) / A_v\ (\sqrt{h_v})$

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

Area of Ventilation Opening Calculation

$A_v = (w_v)\ (h_v)$

Where A_v = area of ventilation opening (m^2)

w_v = vent width (m)

h_v = vent height (m)

A_v = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 551.47 m^2

Ventilation Factor Calculation

$\Omega = (A_T - A_v) / A_v\ (\sqrt{h_v})$

Where Ω = ventilation factor

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

A_v = area of ventilation opening (m^2)

h_v = vent height (m)

Ω = 157.75 $m^{-1/2}$

Compartment Post-Flashover Temperature Calculation

$T_{PFO\ (max)} = 6000\ (1 - e^{-0.1\Omega}) / (\sqrt{\Omega})$

$T_{PFO\ (max)}$ =	477.71 °C	891.88 °F	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER HEAT RELEASE RATE

Version 1805.0

The following calculations estimate the minimum heat release rate required to compartment flashover.

Parameters in YELLOW CELLS are Entered by the User.

Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	100.00	ft	30.48 m
Compartment Length (l_c)	18.00	ft	5.49 m
Compartment Height (h_c)	10.00	ft	3.048 m
Vent Width (w_v)	3.00	ft	0.914 m
Vent Height (h_v)	8.00	ft	2.44 m
Interior Lining Thickness (δ)	6.00	in	0.1524 m
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

Material	Thermal Conductivity k (kW/m-K)
Aluminum (pure)	0.206
Steel (0.5% Carbon)	0.054
Concrete	0.0016
Brick	0.0008
Glass Plate	0.00076
Brick/Concrete Block	0.00073
Gypsum Board	0.00017
Plywood	0.00012
Fiber Insulation Board	0.00053
Chipboard	0.00015
Aerated Concrete	0.00026
Plasterboard	0.00016
Calcium Silicate Board	0.00013
Alumina Silicate Block	0.00014
Glass Fiber Insulation	0.000037
Expanded Polystyrene	0.000034
User Specified Value	Enter Value

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270.*

Select Material

Concrete

Scroll to desired material then Click on selection

PREDICTING FLASHOVER HEAT RELEASE RATE
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_o\ (\sqrt{h_v}))}$

Where Q_{FO} = heat release rate necessary for flashover (kW)

h_k = effective heat transfer coefficient (kW/m²-K)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m²)

A_o = area of ventilation opening (m²)

h_v = height of ventilation opening (m)

Heat Transfer Coefficient Calculation

$h_k = k/\delta$ Assuming that compartment has been heated thoroughly before flashover, i.e., $t > t_p$.

Where h_k = effective heat transfer coefficient (kW/m²-K)

k = interior lining thermal conductivity (kW/m-K)

δ = interior lining thickness (m)

h_k = 0.010 kW/m²-K

Area of Ventilation Opening Calculation

$A_o = (w_v)(h_v)$

Where A_o = area of ventilation opening (m²)

w_v = vent width (m)

h_v = vent height (m)

A_o = 2.23 m²

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_o$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m²)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_o = area of ventilation opening (m²)

A_T = 551.47 m²

Minimum Heat Release Rate for Flashover

$Q_{FO} = 610\ \sqrt{(h_k\ A_T\ A_o\ (\sqrt{h_v}))}$

Q_{FO} =	2738.77 kW	Answer

METHOD OF BABRAUSKAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 750\ A_v\ (\sqrt{h_v})$

Where Q_{FO} = heat release rate necessary for flashover (kW)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 750\ A_v\ (\sqrt{h_v})$

Q_{FO} =	2611.29 kW	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (\sqrt{h_v})$

Where Q_{FO} = heat release rate necessary for flashover (kW)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 7.8\ A_T + 378\ A_v\ (\sqrt{h_v})$

Q_{FO} =	5617.57 kW	Answer

Summary of Result

Calculation Method	Flashover HRR (kW)
METHOD OF MQH	2739
METHOD OF BABRAUSKAS	2611
METHOD OF THOMAS	5618

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

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Problem J-14

Problem Statement

Consider a closed compartment in a facility (a pump room) 2.75 m wide x 2.75 m long x 3.7 m high (9.0 ft wide x 9.0 ft long x 12 ft high) (w_c x l_c x h_c). A fire starts with a constant power of 75 kW. Estimate the pressure increase attributable to the expansion of gases after 15 seconds.

Solution

Purpose:

(1) Estimate the pressure rise in the compartment at 15 seconds after ignition.

Assumptions:

(1) The energy release rate is constant.
(2) The mass rate of the fuel is neglected in the conversion of mass.
(3) The specific heat is constant with temperature.
(4) The hydrostatic pressure difference over the height of the compartment is negligible compared to the dynamic pressure.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 14_Compartment_Over_Pressure_Calculations.xls

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

- Compartment Width (w_c) = 9 ft
- Compartment Length (l_c) = 9 ft
- Compartment Height (h_c) = 12 ft
- Fire Heat Release Rate $(\dot{Q})$ = 75 kW
- Time After Ignition (t) = 15 sec

Results

Pressure Rise*	16.53 kPa (2.40 psi)

*spreadsheet calculations attached on next page

Spreadsheet Calculations

FDT[s]: 14_Compartment_Over_Pressure_Calculations.xls

CHAPTER 14. ESTIMATING PRESSURE RISE DUE TO A FIRE IN A CLOSED COMPARTMENT

Version 1805.0

The following calculations estimate the pressure rise in a compartment due to fire and combustion.
Parameters in YELLOW CELLS are Entered by the User.
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 guide should be read before an analysis is made.

INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	9.00	ft	2.74 m
Compartment Length (l_c)	9.00	ft	2.74 m
Compartment Height (h_c)	12.00	ft	3.66 m
Fire Heat Release Rate (Q)	75.00	kW	
Time after Ignition (t)	15.00	sec	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K

Calculate

AMBIENT CONDITIONS

Initial Atmospheric Pressure (P_a)	14.70	psi	101.35 kPa
Specific Heat of Air at Constant Volume (c_v)	0.71	kJ/kg-K	
(Note: Values of c_v ranges from 0.71 to 0.85 kJ/kg-K)			
Ambient Air Density (ρ_a)	1.18	kg/m³	

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

METHOD OF KARLSSON AND QUINTIERE

Reference: *Karlsson and Quintiere, Enclosure Fire Dynamics, 1999, Page 192.*

$(P - P_a) / P_a = Q\,t / (V \rho_a c_v T_a)$

Where
- P = compartment pressure due to fire and combustion (kPa)
- P_a = initial atmospheric pressure (kPa)
- Q = heat release rate of the fire (kW)
- t = time after ignition (sec)
- V = compartment volume (m^3)
- ρ_a = ambient density (kg/m^3)
- c_v = specific heat of air at constant volume (kJ/kg-K)
- T_a = ambient air temperature (K)

Compartment Volume Calculation

$V = w_c \times l_c \times h_c$

Where
- V = volume of the compartment (m^3)
- w_c = compartment width (m)
- l_c = compartment length (m)
- h_c = compartment height (m)

V = 27.52 m^3 972 ft^3

Pressure Rise in Compartment

$(P - P_a) / P_a = Q\,t / (V \rho_a c_v T_a)$

$(P-P_a)/P_a$ = 0.163 atm

Multiplying by the atmospheric pressure (P_a) = 101 kPa

Gives a pressure difference = 16.53 kPa 2.40 psi **Answer**

This example shows that in a very short time the pressure in a closed compartment rises to quite large value.

Most buildings have leaks of some sort. The above example indicates that even though a fire compartment may be closed, the pressure is very rapid and would presumably lead to sufficient leaks to prevent further pressure rise from occurring. We will use this conclusion when dealing with pressure rises in enclosures with small leaks.

NOTE

The above calculations are based on principles developed in the Enclosure Fire Dynamics. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Problem J-15

Problem Statement

The licensee used UL Design No. 816 to protect a number of unrestrained beams. The licensee's quality assurance (QA) program verified that there is 6.35 cm (2½ in) thickness of fire protection insulation on all of the beams. The size of the tested beam was W12 x 26. Determine whether the 6.35 cm (2½ in) thickness of fire protection insulation is acceptable for a beam that is W8 x 13.

Solution

Purpose:

(1) Determine whether the 6.35 cm (2½ in.) thickness of fire protection insulation is acceptable for a W8 x 13 beam using the data for a W12 x 26 beam.

Assumptions:

(1) The heat transfer is one-dimensional.
(2) The analysis assumes that as the structural member heats up, structural properties change substantially.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 17.1_FR_Beams_Columns_Substitution_Correlation.xls (Click on *Beam*)

FDT^s Input Parameters:

Enter the following parameters in the spreadsheet (values only):

- Rated Design Thickness of Beam Insulation (T_2) = 2.5 in
- Select Beam with ***known*** rating for insulation thickness: select **W12 x 26**
- Select Beam with ***unknown*** rating for insulation thickness: select **W8 x 13**

Note: When beam size (e.g., W12 x 26) is selected from the combo box, its properties are automatically selected from the table ("*Data*" spreadsheet) and entered in the corresponding input yellow cells.

Results

Required Equivalent Thickness*	7.09 cm (2.79 in) not appropriate

*spreadsheet calculations attached on next page

From the substitution correlation, we obtain that 6.35 cm (2.5 in.) of fire protection insulation is not appropriate for W8 x 13 because the required thickness is more than 6.35 cm (2.5 in.).

A similar problem can be analyzed for a column, the calculations for columns are included in the same FDT^s (not shown).

Spreadsheet Calculations

FDT[s]: 17.1_FR_Beams_Columns_Substitution_Correlation.xls (Beam)

CHAPTER 17. ESTIMATING THICKNESS OF FIRE PROTECTION SPRAY-APPLIED COATING FOR STRUCTURAL STEEL BEAMS (SUBSTITUTION CORRELATION)

Version 1805.0

For beams protected by spray-applied protections, following correlation enables substitution of one beam from another by varying the thickness of the fire protection insulation.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Beam Selected.
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

Rated Design Thickness of Beam Insulation (T_2)	2.5	in
Known Insulation Rating		
Weight of the Beam (W_2)	26	lb/ft
Heated Perimeter of Beam (D_2)	43.45	in
Unknown Insulation Rating		
Weight of the Beam (W_1)	13.00	lb/ft
Heated Perimeter of Beam (D_1)	27.52	in

SECTIONAL FACTORS FOR STEEL BEAMS

Select the Beam with known rating for insulation thickness

W12 x 26

Subscript 2
(Rated Beam)

Calculate

Select the Beam with unknown rating for insulation thickness

W8 x 13

Subscript 1
(Substitute Beam)

ESTIMATING THICKNESS OF FIRE PROTECTION INSULATION ON UNRATED BEAM

Reference: *UL Fire Resistance Directory, Volume 1, 1995, Page 10.*

$T_1 = ((W_2/D_2 + 0.6)\,T_2)/(W1/D_1 + 0.6)$

Where T_1 = calculated thickness of fire protection insulation on unrated beam (in)

T_2 = design thickness of insulation on rated beam (in)

W_1 = weight of beam with unknown insulation rating (lb/ft)

W_2 = weight of design rated beam (lb/ft)

D_1 = heated perimeter of unrated beam (in)

D_2 = heated perimeter of the rated beam (in)

Required Equivalent Thickness of Fire Protection Insulation on Unrated Beam

$T_1 = ((W_2/D_2 + 0.6)\,T_2)/(W1/D1 + 0.6)$

T_1 = 2.79 in Answer

Beams with a larger W/D ratio can always be substituted for the structural member listed with a specific fire resistive covering without changing the thickness of the covering.

NOTE

The above calculations are based on method developed in the UL Fire Resistance Directory, Volume 1, 1995. Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.

Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.

Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

Problem J-16

Problem Statement

During a routine fire protection inspection, an NRC inspector discovers a significant oil leak in a station air compressor in an access corridor in the fuel building. It is important to determine whether a fire involving a 76.0-liter (20.0-gallon) spill of lubricating oil from a compressor could damage the safety-related cable tray and electrical cabinet in the corridor. The compressor is on a pedestal approximately (1.0 ft) above floor level and has a 1.12 m^2 (12.0 ft^2) oil retention dike. The safety-related cable trays are located 2.5 m (8.0 ft) above the corridor floor with a horizontal distance of 1.2 m (4.0 ft) from the edge of the compressor's oil retention dike. The horizontal distance between the compressor oil dike and the electrical cabinet is 1.52 m (5.0 ft).

The access corridor has a floor area of 6.0 m wide x 4.6 m long (20 ft wide x 15 ft long) (w_c x l_c), ceiling height of 3.0 m (10.0 ft) (h_c), and a single unprotected vent opening (door) that is 1.2 m wide x 1.8 m high (4.0 ft wide x 6.0 ft high) (w_v x h_v). The corridor has no forced ventilation and it is constructed of 0.3048 m (1.0 ft) thick concrete. The corridor has a smoke and heat detection system and a wet pipe sprinkler system. The nearest sprinkler is rated at 74 °C (165 °F) with an RTI of 235 $(m\text{-}sec)^{1/2}$ and is located 2.98 m (9.8 ft) from the center of the dike. Determine whether there is a credible fire hazard to the safety-related cable trays and electrical cabinet. Evaluate the hazard of the fire scenario using the following parameters:

(a) pool fire heat release rate, $\dot{Q}$, flame height, z, and burning duration, t_b

(b) compartment hot gas layer temperature, T_g, as well as gas layer height z

(c) heat flux to the target (electrical cabinet) using the point source model, $\dot{q}''_{cabinet}$

(d) heat flux to the target (cable trays) using the solid-flame radiation model, $\dot{q}''_{cable}$

(e) centerline plume temperature, $T_{p(centerline)}$

(f) sprinkler activation time, $t_{activation}$

(g) HRR necessary to cause flashover, $\dot{Q}_{FO}$

Solution

Purpose:

(1) Determine if the given fire scenario could represent a hazard for the safety-related cable trays and electrical cabinet.

Solution Approach:

To analyze this fire scenario, we are going to use various concepts that have been presented individually in the NUREG. A logical approach for this type of problem is to analyze the heat source and then its effect over the safety-related targets and fire suppression systems. First, we are going to calculate the HRR, flame height, and the burning duration of the pool fire (see Chapter 3) in order to determine the intensity and geometrical characteristics of the fire. Then calculate the hot gas layer temperature and gas layer height (see Chapter 2). Then calculate the centerline plume temperature to obtain an estimate of the maximum temperature in the fire scenario (see Chapter 9). Then, we are going to calculate the radiative heat flux from the pool fire to the electrical cabinet and cable tray (see Chapter 5). After that, evaluate the activation time of the sprinkler system to determine if the system is able to respond to the actual developed fire (see Chapter 10). The last calculation is the required HRR for flashover (see Chapter 13). Once we get all these values, we have to use them to evaluate the hazard of the fire scenario.

Assumptions:

(1) There is instantaneous and complete involvement of the liquid in the pool fire.
(2) The pool fire is burning in the open.
(3) The pool is circular or nearly circular.
(4) The fire is located at the center of the corridor or away from the walls.
(5) All heat is released at a point
(6) Buoyant forces are more significant than momentum forces
(7) Radiation to the surroundings can be approximated as being isotropic or emanating from a point source (valid for point source radiation model only).
(8) Only convective heat transfer is considered for sprinkler activation.
(9) The ambient (or initial condition of the air) is at 25 °C (77 °F)
(10) The bottom of the oil retention dike is at ground level.
(11) The distance from the top of the fuel package (oil pool) to the ceiling is 10 ft, the pool height or oil layer thickness is negligible compared to ceiling height (about 0.22 ft).

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

- (a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls
- (b) 02.1_Temperature_NV.xls
- (c) 09_Plume_Temperature_Calculations.xls
- (d) & (e) 05.1_Heat_Flux_Calculations_Wind_Free.xls (select *Point Source* and *Solid Flame 2* for the target cabinet and cable tray heat flux analyses, respectively)
- (f) 10_Detector_Activation_Time.xls (select *Sprinkler*)
- (g) 13_Compartment_Flashover_Calculations.xls (select *Flashover-HRR* to calculate the HRR for flashover)

FDT^s Input Parameters:

Enter the following parameters in the spreadsheets (values only):

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

- Fuel spill volume (V) = 20 gallons
- Fuel Spill Area or Dike Area (A_{dike}) = 12 ft^2
- Select Fuel Type: select **Lube Oil** from the combo box

Note: When **Lube Oil** is selected**,** its properties are automatically selected from the table and entered in the corresponding input cells.

Results*

Heat Release Rate $\dot{Q}$ kW (Btu/sec)	Burning Duration t_b (min)	Pool Fire Flame Height H_f m (ft)	
		Method of Heskestad	Method of Thomas
1,131 (1,072)	22.0	2.7 (8.85)	2.95 (9.67)

*spreadsheet calculations attached at the end of the problem

(b) 02.1_Temperature_NV.xls

- Compartment Width (w_c) = 20 ft
- Compartment Length (l_c) = 15 ft
- Compartment Height (h_c) = 10 ft
- Vent Width (w_v) = 4 ft
- Vent Height (h_v) = 6 ft
- Top of Vent from Floor (V_T) = 6 ft
- Interior Lining Thickness (δ) = 12 in
- Heat Release Rate $(\dot{Q})$ = 1131 kW
- Select Material: select **Concrete** from the combo box

Note: When **Concrete** is selected**,** its properties are automatically selected from the table and entered in the corresponding input cells.

Results*

Time (min)	Hot Gas Layer Temperature T_g °C (°F)	Gas Layer Height z m (ft)
0	25 (77)	3.05 (10)
1	199 (389)	1.83 (6.0)
2	220 (428)	1.83 (6.0)
3	233 (452)	1.83 (6.0)
4	244 (471)	1.83 (6.0)
5	252 (486)	1.83 (6.0)
10	280 (536)	1.83 (6.0)
15	298 (568)	1.83 (6.0)
20	311 (592)	1.83 (6.0)

*spreadsheet calculations attached at the end of the problem

(c) 09_Plume_Temperature_Calculations.xls

- Heat Release Rate $(\dot{Q})$ = 1131 kW
- Distance from the Top of the Fuel to the Ceiling (z) = 9 ft
- Area of Combustible Fuel: 12 ft^2

Results*

Heat Release Rate $\dot{Q}$ (kW)	Plume Centerline Temperature $T_{p(centerline)}$ °C (°F)
1,131	473 (884)

*spreadsheet calculations attached at the end of the problem

(d) 05.1_Heat_Flux_Calculations_Wind_Free.xls
Point Source (heat flux to the electrical cabinet)
- Fuel Spill Area or Dike Area (A_{dike}) = 12 ft^2
- Distance between Fire and Target (L) = 5 ft
- Select Fuel Type: select **Lube Oil** from the combo box

(e) 05.1_Heat_Flux_Calculations_Wind_Free.xls
Solid Flame 2 (heat flux to the cable tray)
- Fuel Spill Area or Dike Area (A_{dike}) = 12 ft^2
- Distance between Fire and Target (L) = 4 ft
- Vertical Distance of Target from Ground (H_1 = H_{f1}) = 7 ft
- Select Fuel Type: select **Lube Oil** from the combo box

Note: When **Lube Oil** is selected**,** its properties are automatically selected from the table and entered in the corresponding input cells.

Results*

Radiation Model	Target	Radiant Heat Flux $\dot{q}''$ kW/m^2 (Btu/ft^2-sec)
Point Source	Electrical Cabinet	6.0 (0.53)
Solid Flame	Cable Tray	13.24 (1.17)

*spreadsheet calculations attached at the end of the problem

(f) 10_Detector_Activation_Time.xls
Sprinkler
- Heat Release Rate of the Fire $(\dot{Q})$ = 1,131 kW
- Distance from the Top of the Fuel Package to the Ceiling (H) = 9 ft
- Radial Distance from the Plume Centerline to the Sprinkler (r) = 9.8 ft
- Ambient Air Temperature (T_a) = 77 °F
- Select Type of Sprinkler = select **Standard response link** from the combo box
- Select Sprinkler Classification = select **Ordinary** from the combo box

Note: Standard response is selected because it corresponds with the given RTI value. Also, **Ordinary** classification has been selected because the rated value for the sprinklers in this problem (165 °F) is within the range of temperature ratings for ordinary sprinklers (135 °F–170 °F).

Results*

Sprinkler Type	Sprinkler Activation Time $t_{activation}$ (min.)
Standard response link	1.73

*spreadsheet calculations attached at the end of the problem

(g) 13_Compartment_Flashover_Calculations.xls
- Compartment Width (w_c) = 20 ft
- Compartment Length (l_c) = 15 ft
- Compartment Height (h_c) = 10 ft
- Vent Width (w_v) = 4 ft
- Vent Height (h_v) = 6 ft
- Interior Lining Thickness (δ) = 12 in
- Select Material: select **Concrete** from the combo box

Note: When **Concrete** is selected**,** its properties are automatically selected from the table and entered in the corresponding input cells.

Results*

HRR for Flashover $\dot{Q}_{FO}$ kW (Btu/sec)		
Method of MQH	Method of Babrauskas	Method of Thomas
836 (729)	2,261 (2,143)	2,064 (1,956)

*spreadsheet calculations attached at the end of the problem

Conclusions

According to the calculations the fire could represent a hazard to the safety-related targets (cable tray and electrical cabinets) due to the following results:

- From the pool fire analysis we obtain that the flame height is greater that the cable tray height. That means that the flame probably will impinge upon the cable trays since the pool is just at 4 ft from the cable tray (horizontal distance).
- The hot gas layer analysis estimates that the hot gas temperature will be over 500 °F and almost 600 °F at 10 minutes and one (1) minute, respectively. These temperature values are the critical temperatures for thermoplastic cables. Also the corridor will be almost filled with smoke at one minute after the ignition, which means that the cable tray and electrical cabinet will be rapidly exposed to the hot gas layer.
- Heat flux calculations show that the solid flame model predicts a radiant heat flux greater than the critical heat flux for IEEE-383 qualified and unqualified cables. Also, the heat flux to the electrical cabinet could represent a hazard for the integrity of the cabinet components.
- The HRR of the fire is very close to the HRR for flashover. Therefore, the whole corridor could flashover. The sprinkler should activate approximately at 2 minute after the fire development, during this time the fire should begin to be controlled. The burning time of the pool is significantly greater than the activation time of the sprinklers; thus, a complete and immediate extinguishment of the fire is not expected.

Spreadsheet Calculations

(a) FDT[s]: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE,
HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	20.00	gallons	0.0757 m^3
Fuel Spill Area or Dike Area (A_{dike})	12.00	ft^2	1.115 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Density (ρ)	760	kg/m^3	
Empirical Constant (kβ)	0.7	m^{-1}	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec^2	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Calculate

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Fuel Type

Lube Oil

Scroll to desired fuel type
Click on selection

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-26.

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-25.

$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_{dike}$

Where Q = pool fire heat release rate (kW)

$\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diamter (m)

$D = \sqrt{(4A_{dike}/\pi)}$

D = 1.191 m

Heat Release Rate Calculation

$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_{dike}$

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	1131.38 kW	1072.34 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where t_b = burning duration of pool fire (sec)

V = volume of liquid (m^3)

D = pool diameter (m)

v = regression rate (m/sec)

Calculation for Regression Rate

$v = \dot{m}''/\rho$

Where v = regression rate (m/sec)

$\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)

ρ = liquid fuel density (kg/m^3)

v = 0.000051 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b =	1323.37 sec	22.06 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 2-10.

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where H_f = pool fire flame height (m)

Q = pool fire heat release rate (kW)

D = pool fire diameter (m)

Pool Fire Flame Height Calculation

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

H_f =	2.70 m	8.85 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-204.

$H_f = 42\ D\ (\dot{m}''/\rho_a\sqrt{(g\ D)})^{0.61}$

Where H_f = pool fire flame height (m)

$\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)

ρ_a = ambient air density (kg/m^3)

D = pool fire diameter (m)

g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation

$H_f = 42\ D\ (\dot{m}''/\rho_a\sqrt{(g\ D)})^{0.61}$

H_f =	2.95 m	9.67 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	8.85
METHOD OF THOMAS	9.67

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft^2)	Area (m^2)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	94.28	15880.43	3.60	4.08
2	0.19	0.49	188.56	7940.21	4.64	5.19
3	0.28	0.60	282.84	5293.48	5.38	5.97
4	0.37	0.69	377.13	3970.11	5.97	6.60
5	0.46	0.77	471.41	3176.09	6.47	7.13
6	0.56	0.84	565.69	2646.74	6.91	7.60
7	0.65	0.91	659.97	2268.63	7.30	8.02
8	0.74	0.97	754.25	1985.05	7.66	8.40
9	0.84	1.03	848.53	1764.49	7.99	8.75
10	0.93	1.09	942.82	1588.04	8.30	9.07
11	1.02	1.14	1037.10	1443.68	8.58	9.38
12	1.11	1.19	1131.38	1323.37	8.85	9.67
13	1.21	1.24	1225.66	1221.57	9.11	9.94
14	1.30	1.29	1319.94	1134.32	9.35	10.20
15	1.39	1.33	1414.22	1058.70	9.58	10.45
20	1.86	1.54	1885.63	794.02	10.60	11.55
25	2.32	1.72	2357.04	635.22	11.46	12.48
50	4.65	2.43	4714.08	317.61	14.58	15.87
75	6.97	2.98	7071.12	211.74	16.75	18.28
100	9.29	3.44	9428.17	158.80	18.47	20.20

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation does not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT[s]: 02.1_Temperature_NV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	15.00	ft	4.572 m
Compartment Height (h_c)	10.00	ft	3.048 m
Vent Width (w_v)	4.00	ft	1.219 m
Vent Height (h_v)	6.00	ft	1.829 m
Top of Vent from Floor (V_T)	6.00	ft	1.829 m
Interior Lining Thickness (δ)	12.00	in	0.3048 m

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

Interior Lining Thermal Inertia ($k\rho c$)	2.9	(kW/m^2-K)^2-sec
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K
Interior Lining Specific Heat (c)	0.75	kJ/kg-K
Interior Lining Density (ρ)	2400	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ (kW/m^2-K)^2-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270.

Select Material

Concrete

Scroll to desired material then Click the selection

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q)	1131.00	kW
	Calculate	

METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})(A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)
Q = heat release rate of the fire (kW)
A_v = area of ventilation opening (m^2)
h_v = height of ventilation opening (m)
h_k = convective heat transfer coefficient (kW/m^2-K)
A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

Where A_v = area of ventilation opening (m^2)
w_v = vent width (m)
h_v = vent height (m)

A_v = 2.23 m^2

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)
ρ = interior construction density (kg/m^3)
c_p = interior construction heat capacity (kJ/kg-K)
k = interior construction thermal conductivity (kW/m-K)
δ = interior construction thickness (m)

t_p = 26128.98 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)
$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec
(a thermal property of material responsible for the rate of temperature rise)
t = time after ignition (sec)
See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
h_c = compartment height (m)
A_v = area of ventilation opening (m^2)

A_T = 118.54 m^2

Compartment Hot Gas Layer Temperature With Natural Ventilation

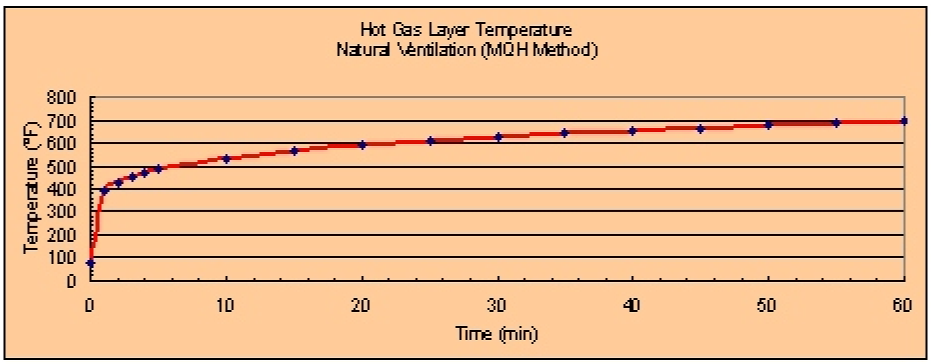
$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})(A_T h_k)]^{1/3}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t)		h_k	ΔT_g	T_g	T_g	T_g
(min)	(sec)	(kW/m^2-K)	(K)	(K)	(°C)	(°F)
0	0.00	-	-	298.00	25.00	77.00
1	60	0.22	173.60	471.60	198.60	389.48
2	120	0.16	194.86	492.86	219.86	427.75
3	180	0.13	208.49	506.49	233.49	452.27
4	240	0.11	218.73	516.73	243.73	470.71
5	300	0.10	227.01	525.01	252.01	485.62
10	600	0.07	254.81	552.81	279.81	535.66
15	900	0.06	272.63	570.63	297.63	567.73
20	1200	0.05	286.02	584.02	311.02	591.83
25	1500	0.04	296.86	594.86	321.86	611.34
30	1800	0.04	306.02	604.02	331.02	627.83
35	2100	0.04	313.98	611.98	338.98	642.16
40	2400	0.03	321.05	619.05	346.05	654.88
45	2700	0.03	327.41	625.41	352.41	666.34
50	3000	0.03	333.21	631.21	358.21	676.78
55	3300	0.03	338.55	636.55	363.55	686.38
60	3600	0.03	343.49	641.49	368.49	695.28



ESTIMATING SMOKE LAYER HEIGHT
METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where
- z = smoke layer height (m)
- Q = heat release rate of the fire (kW)
- t = time after ignition (sec)
- h_c = compartment height (m)
- A_c = compartment floor area (m^2)
- k = a constant given by $k = 0.076/\rho_g$
- ρ_g = hot gas layer density (kg/m^3)
- ρ_g is given by $\rho_g = 353/T_g$
- T_g = hot gas layer temperature (K)

Compartment Area Calculation

$A_c = (w_c)\,(l_c)$

Where
- A_c = compartment floor area (m^2)
- w_c = compartment width (m)
- l_c = compartment length (m)

A_c = 27.87 m^2

Hot Gas Layer Density Calculation

$\rho_g = 353/T_g$

Calculation for Constant K

$k = 0.076/\rho_g$

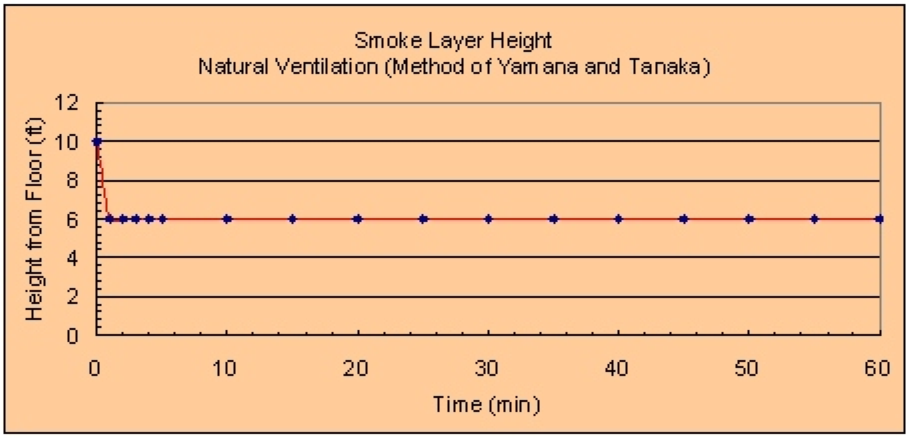
Smoke Gas Layer Height With Natural Ventilation

$z = [(2kQ^{1/3}t/3A_c] + (1/h_c^{2/3}))^{-3/2}$

Results

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

Time (min)	ρ_g (kg/m^3)	Constant (k) (kW/m-K)	Smoke Layer height z (m)	Smoke Layer height z (ft)	
0	1.18	0.064	3.05	10.00	
1	0.75	0.102	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
2	0.72	0.106	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
3	0.70	0.109	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
4	0.68	0.111	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
5	0.67	0.113	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
10	0.64	0.119	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
15	0.62	0.123	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
20	0.60	0.126	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
25	0.59	0.128	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
30	0.58	0.130	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
35	0.58	0.132	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
40	0.57	0.133	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
45	0.56	0.135	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
50	0.56	0.136	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
55	0.55	0.137	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT
60	0.55	0.138	1.83	6.00	CAUTION: SMOKE IS EXITING OUT VENT



NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
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Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

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CHAPTER 9. ESTIMATING CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

Version 1805.0

The following calculations estimate the centerline plume temperature in a compartment fire.
Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.
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

Heat Release Rate of the Fire (Q)	1131.00	kW	
Elevation Above the Fire Source (z)	9.00	ft	2.74 m
Area of Combustible Fuel (A_c)	12.00	ft^2	1.11 m^2
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
	Calculate		298.00 K

AMBIENT CONDITIONS

Specific Heat of Air (c_p)	1.00	kJ/kg-K
Ambient Air Density (ρ_a)	1.18	kg/m^3
Acceleration of Gravity (g)	9.81	m/sec^2
Convective Heat Release Fraction (χ_c)	0.70	

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

ESTIMATING PLUME CENTERLINE TEMPERATURE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 2-6.

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

Where $T_{p(centerline)}$ = plume centerline temperature (°C)
Q_c = convective portion of the heat release rate (kW)
T_a = ambient air temperature (K)
g = acceleration of gravity (m/sec^2)
c_p = specific heat of air (kJ/kg-K)
ρ_a = ambient air density (kg/m^3)
z = distance from the top of the fuel package to the ceiling (m)
z_0 = hypothetical virtual origin of the fire (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c Q$

Where Q_c = convective portion of the heat release rate (kW)
Q = heat release rate of the fire (kW)
χ_c = convective heat release fraction
Q_c = 791.7 kW

Fire Diameter Calculation

$A_c = \pi D^2/4$

Where A_c = area of combustible fuel (m^2)
D = fire diameter (m)

$D = \sqrt{(4 A_c/\pi)}$

D = 1.19 m

Hypothetical Virtual Origin Calculation

$z_0/D = -1.02 + 0.083\,(Q^{2/5})/D$

Where z_0 = virtual origin of the fire (m)
Q = heat release rate of fire (kW)
D = fire diameter (m)

$z_0/D =$ 0.14

$z_0 =$ 0.17 m

Centerline Plume Temperature Calculation

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

$T_{p(centerline)} - T_a =$ 448.21

$T_{p(centerline)} =$ 746.21 K

$T_{p(centerline)} =$	473.21 °C	883.79 °F	**Answer**

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

(d) FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Point Source)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL AT GROUND LEVEL UNDER WIND-FREE CONDITION POINT SOURCE RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from a pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire at ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Empirical Constant (kβ)	0.7	m^{-1}	
Heat Release Rate (Q)	1131.38	kW	
Fuel Area or Dike Area (A_{dike})	12.00	ft^2	1.11 m^2
Distance between Fire and Target (L)	5.00	ft	1.524 m
Radiative Fraction (χ_r)	0.30		

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-26*.

Select Fuel Type

Lube Oil

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-272*.

POINT SOURCE RADIATION MODEL

$q'' = Q \chi_r / 4 \pi R^2$

Where q'' = incident radiative heat flux on the target (kW/m^2)
Q = pool fire heat release rate (kW)
χ_r = radiative fraction
R = distance from center of the pool fire to edge of the target (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)
D = pool fire diamter (m)

D = 1.19 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D}) A_f$

Where Q = pool fire heat release rate (kW)
m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)
ΔH_c = effective heat of combustion of fuel (kJ/kg)
A_f = surface area of pool fire (area involved in vaporization) (m^2)
$k\beta$ = empirical constant (m^{-1})
D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 1131.38 kW

Distance from Center of the Fire to Edge of the Target Calculation

$R = L+D/2$

Where R = distance from center of the pool fire to edge of the target (m)
L = distance between pool fire and target (m)
D = pool fire diameter (m)

R = 2.12 m

Radiative Heat Flux Calculation

$q'' = Q \chi_r / 4 \pi R^2$

q'' =	6.01 kW/m^2	0.53 Btu/ft^2-sec	Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.
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(e) FDT[s]: 05.1_Heat_Flux_Calculations_Wind_Free.xls (Solid Flame 2)

CHAPTER 5. ESTIMATING RADIANT HEAT FLUX FROM FIRE TO A TARGET FUEL ABOVE GROUND LEVEL UNDER WIND-FREE CONDITION
SOLID FLAME RADIATION MODEL

Version 1805.0

The following calculations estimate the radiative heat flux from pool fire to a target fuel.
The purpose of this calculation is to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire above ground level to determine if secondary ignitions are likely with no wind.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Mass Burning Rate of Fuel ($\dot{m}''$)	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Empirical Constant ($k\beta$)	0.7	m^{-1}	
Heat Release Rate ($\dot{Q}$)	1131.38	kW	
Fuel Area or Dike Area (A_{dike})	12.00	ft^2	1.11 m^2
Distance between Fire and Target (L)	4.00	ft	1.2192 m
Vertical Distance of Target from Ground ($H_1 = H_2$)	7.00	ft	2.1336 m

OPTIONAL CALCULATION FOR GIVEN HEAT RELEASE RATE

Select "User Specified Value" from Fuel Type Menu and Enter Your HRR here ? [ ] kW

Calculate

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR FUELS

Fuel	Mass Burning Rate $\dot{m}''$ (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	100
Ethanol	0.015	26,800	100
Butane	0.078	45,700	2.7
Benzene	0.085	40,100	2.7
Hexane	0.074	44,700	1.9
Heptane	0.101	44,600	1.1
Xylene	0.09	40,800	1.4
Acetone	0.041	25,800	1.9
Dioxane	0.018	26,200	5.4
Diethy Ether	0.085	34,200	0.7
Benzine	0.048	44,700	3.6
Gasoline	0.055	43,700	2.1
Kerosine	0.039	43,200	3.5
Diesel	0.045	44,400	2.1
JP-4	0.051	43,500	3.6
JP-5	0.054	43,000	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	0.7
561 Silicon Transformer Fluid	0.005	28,100	100
Fuel Oil, Heavy	0.035	39,700	1.7
Crude Oil	0.0335	42,600	2.8
Lube Oil	0.039	46,000	0.7
Douglas Fir Plywood	0.01082	10,900	100
User Specified Value	Enter Value	Enter Value	Enter Value

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 3-26.

Select Fuel Type

Lube Oil

Scroll to desired fuel type then Click on selection

ESTIMATING RADIATIVE HEAT FLUX TO A TARGET FUEL

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-276*.

SOLID FLAME RADIATION MODEL

$q'' = EF_{1\to 2}$

Where q'' = incident radiative heat flux on the target (kW/m^2)

E = emissive power of the pool fire flame (kW/m^2)

$F_{1\to 2}$ = view factor between target and the flame

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

$D = \sqrt{(4A_{dike}/\pi)}$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diamter (m)

D = 1.19 m

Emissive Power Calculation

$E = 58\ (10^{-0.00823\ D})$

Where E = emissive power of the pool fire flame (kW/m^2)

D = diameter of the pool fire (m)

E = 56.71 (kW/m^2)

View Factor Calculation

$F_{1\to 2,V1} = 1/(\pi S)\tan^{-1}(h_1/(S^2-1)^{1/2})-(h_1/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_1h_1/\pi S(A_1^2-1)^{1/2}\tan^{-1}((A_1+1)(S-1)/(A_1-1)(S+1))^{1/2}$

$F_{1\to 2,V2} = 1/(\pi S)\tan^{-1}(h_2/(S^2-1)^{1/2})-(h_2/\pi S)\tan^{-1}((S-1)/(S+1))^{1/2}+A_2h_2/\pi S(A_2^2-1)^{1/2}\tan^{-1}((A_2+1)(S-1)/(A_2-1)(S+1))^{1/2}$

$A_1 = (h_1^2+S^2+1)/2S$

$A_2 = (h_2^2+S^2+1)/2S$

$B = (1+S^2)/2S$

$S = 2R/D$

$h_1 = 2H_{f1}/D$

$h_2 = 2H_{f2}/D$

$F_{1\to 2,V} = F_{1\to 2,V1} + F_{1\to 2,V2}$

Where $F_{1\to 2,V}$ = total vertical view factor

R = distance from center of the pool fire to edge of the target (m)

H_f = height of the pool fire flame (m)

D = pool fire diameter (m)

Distance from Center of the Pool Fire to Edge of the Target Calculation

$R = L + D/2$

Where R = distance from center of the pool fire to edge of the target (m)

L = distance between pool fire and target (m)

D = pool fire diameter (m)

R = L+D/2 = 1.815 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff}(1 - e^{-k\beta D})A_{dike}$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

ΔH_c = effective heat of combustion of fuel (kJ/kg)

A_{dike} = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Q = 1131.38 kW

Pool Fire Flame Height Calculation

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where	H_f = flame height (m)						
	Q = heat release rate of fire (kW)						
	D = fire diameter (m)						
H_f =	2.698 m						
$S = 2R/D$ =	3.047						
$h_1 = 2H_{f1}/D$ =	3.582						
$h_2 = 2H_{f2}/D$ =	$2(H_f - H_{f1})/D$ =	0.947					
$A_1 = (h_1^2+S^2+1)/2S$ =		3.793					
$A_2 = (h_2^2+S^2+1)/2S$ =		1.835					
$B = (1+S^2)/2S$ =		1.687					
			F_{V1}	F_{V2}	F_{V3}	F_{V4}	$F_{1\to 2,V1}$
$F_{1\to 2,V1}$ =	0.153		0.093	0.231	0.388	0.750	0.153
$F_{1\to 2,V2}$ =	0.081		F_{V1}	F_{V2}	F_{V3}	F_{V4}	$F_{1\to 2,V2}$
$F_{1\to 2,V} = F_{1\to 2,V1} + F_{1\to 2,V2}$ =	0.234		0.033	0.061	0.118	0.919	0.081

Radiative Heat Flux Calculation

$q'' = EF_{1\to 2}$

q'' =	13.24 kW/m^2	1.17 Btu/ft^2-sec

Answer

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002.

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(f) FDT^s: 10_Detector_Activation_Time.xls (Sprinkler)

CHAPTER 10. ESTIMATING SPRINKLER RESPONSE TIME

Version 1805.0

The following calculations estimate sprinkler activation time.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Sprinkler Selected.
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

Heat Release Rate of the Fire (Q) (Steady State)	1131.00	kW	
Sprinkler Response Time Index (RTI)	130	(m-sec)$^{1/2}$	
Activation Temperature of the Sprinkler ($T_{activation}$)	165	°F	73.89 °C
Height of Ceiling above Top of Fuel (H)	9.00	ft	2.74 m
Radial Distance to the Detector (r) **never more than 0.707 or 1/2√2 of the listed spacing**	9.80	ft	2.99 m
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Convective Heat Release Rate Fraction (χ_c)	0.70		

r/H = 1.09

Calculate

GENERIC SPRINKLER RESPONSE TIME INDEX (RTI)*

Common Sprinkler Type	Generic Response Time Index (RTI) (m-sec)$^{1/2}$
Standard response bulb	235
Standard response link	130
Quick response bulb	42
Quick response link	34
User Specified Value	Enter Value

Select Type of Sprinkler

Standard response link

Scroll to desired sprinkler type then Click on selection

Reference: Madrzykowski, D., "Evaluation of Sprinkler Activation Prediction Methods" ASIAFLAM95, International Conference on Fire Science and Engineering, 1st Proceeding, March 15-16, 1995, Kowloon, Hong Kong, pp. 211-218.

*Note: The actual RTI should be used when the value is available.

GENERIC SPRINKLER TEMPERATURE RATING ($T_{activation}$)*

Temperature Classification	Range of Temperature Ratings (°F)	Generic Temperature Ratings (°F)
Ordinary	135 to 170	165
Intermediate	175 to 225	212
High	250 to 300	275
Extra high	325 to 375	350
Very extra high	400 to 475	450
Ultra high	500 to 575	550
Ultra high	650	550
User Specified Value	--	Enter Value

Select Sprinkler Classification

Ordinary

Scroll to desired sprinkler class then Click on selection

Reference: Automatic Sprinkler Systems Handbook, 6th Edition, National Fire Protection Association, Quincy, Massachusetts, 1994, Page 67.

*Note: The actual temperature rating should be used when the value is available.

ESTIMATING SPRINKLER RESPONSE TIME

Reference: NFPA Fire Protection Handbook, 19th Edition, 2003, Page 3-140.

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\,(\ln\,(T_{jet} - T_a)/(T_{jet} - T_{activation}))$

Where $t_{activation}$ = sprinkler activation response time (sec)
RTI = sprinkler response time index (m-sec)$^{1/2}$
u_{jet} = ceiling jet velocity (m/sec)
T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
$T_{activation}$ = activation temperature of sprinkler (°C)

Ceiling Jet Temperature Calculation

$T_{jet} - T_a = 16.9\,(Q_c)^{2/3}/H^{5/3}$ for r/H = 0.18

$T_{jet} - T_a = 5.38\,(Q_c/r)^{2/3}/H$ for r/H > 0.18

Where T_{jet} = ceiling jet temperature (°C)
T_a = ambient air temperature (°C)
Q_c = convective portion of the heat release rate (kW)
H = height of ceiling above top of fuel (m)
r = radial distance from the plume centerline to the sprinkler (m)

Convective Heat Release Rate Calculation

$Q_c = \chi_c\, Q$

Where Q_c = convective portion of the heat release rate (kW)

Q = heat release rate of the fire (kW)

χ_c = convective heat release rate fraction

Q_c = 791.7 kW

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.09 r/H > 0.15

$T_{jet} - T_a$ = {5.38 (Qc/r)^2/3}/H

$T_{jet} - T_a$ = 80.92

T_{jet} = 105.92 (°C)

Ceiling Jet Velocity Calculation

$u_{jet} = 0.96\,(Q/H)^{1/3}$ for r/H = 0.15

$u_{jet} = (0.195\,Q^{1/3}\,H^{1/2})/r^{5/6}$ for r/H > 0.15

Where u_{jet} = ceiling jet velocity (m/sec)

Q = heat release rate of the fire (kW)

H = height of ceiling above top of fuel (m)

r = radial distance from the plume centerline to the sprinkler (m)

Radial Distance to Ceiling Height Ratio Calculation

r/H = 1.09 r/H > 0.15

u_{jet} = (0.195 Q^1/3 H^1/2)/r^5/6

u_{jet} = 1.352 m/sec

Sprinkler Activation Time Calculation

$t_{activation} = (RTI/(\sqrt{u_{jet}}))\,(\ln (T_{jet} - T_a)/(T_{jet} - T_{activation}))$

$t_{activation}$ = 103.61 sec

The sprinkler will respond in approximately	1.73 minutes	Answer

NOTE: If $t_{activation}$ = "NUM" Sprinkler does not activate

NOTE

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(g) FDT[s]: 13_Compartment_Flashover_Calculations.xls (Flashover-HRR)

CHAPTER 13. PREDICTING COMPARTMENT FLASHOVER HEAT RELEASE RATE

Version 1805.0

The following calculations estimate the minimum heat release rate required to compartment flashover.

Parameters in YELLOW CELLS are Entered by the User.

Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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).
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INPUT PARAMETERS

COMPARTMENT INFORMATION

Compartment Width (w_c)	20.00	ft	6.096 m
Compartment Length (l_c)	15.00	ft	4.57 m
Compartment Height (h_c)	10.00	ft	3.048 m
Vent Width (w_v)	4.00	ft	1.219 m
Vent Height (h_v)	6.00	ft	1.83 m
Interior Lining Thickness (δ)	12.00	in	0.3048 m
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K	

Calculate

THERMAL PROPERTIES DATA

Material	Thermal Conductivity k (kW/m-K)
Aluminum (pure)	0.206
Steel (0.5% Carbon)	0.054
Concrete	0.0016
Brick	0.0008
Glass Plate	0.00076
Brick/Concrete Block	0.00073
Gypsum Board	0.00017
Plywood	0.00012
Fiber Insulation Board	0.00053
Chipboard	0.00015
Aerated Concrete	0.00026
Plasterboard	0.00016
Calcium Silicate Board	0.00013
Alumina Silicate Block	0.00014
Glass Fiber Insulation	0.000037
Expanded Polystyrene	0.000034
User Specified Value	Enter Value

Select Material: Concrete

Scroll to desired material then Click on selection

Reference: *Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270.*

PREDICTING FLASHOVER HEAT RELEASE RATE
METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering, 3[rd] Edition, 2002, Page 3-184.*

$Q_{FO} = 610\,\sqrt{(h_k\, A_T\, A_v\, \sqrt{h_v})}$

Where
- Q_{FO} = heat release rate necessary for flashover (kW)
- h_k = effective heat transfer coefficient (kW/m^2-K)
- A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)
- A_v = area of ventilation opening (m^2)
- h_v = height of ventilation opening (m)

Heat Transfer Coefficient Calculation

$h_k = k/\delta$ Assuming that compartment has been heated thoroughly before flashover, i.e., $t > t_p$

Where
- h_k = effective heat transfer coefficient (kW/m^2-K)
- k = interior lining thermal conductivity (kW/m-K)
- δ = interior lining thickness (m)

h_k = 0.005 kW/m^2-K

Area of Ventilation Opening Calculation

$A_V = (w_V)(h_V)$

Where A_V = area of ventilation opening (m^2)

w_V = vent width (m)

h_V = vent height (m)

A_V = 2.23 m^2

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_V$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_V = area of ventilation opening (m^2)

A_T = 118.54 m^2

Minimum Heat Release Rate for Flashover

$Q_{FO} = 610 \sqrt{(h_k A_T A_V \sqrt{h_V})}$

Q_{FO} =	835.57 kW	Answer

METHOD OF BABRAUSKAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 750\, A_V \sqrt{h_V}$

Where Q_{FO} = heat release rate necessary for flashover (kW)

A_V = area of ventilation opening (m^2)

h_V = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 750\, A_V \sqrt{h_V}$

Q_{FO} =	2261.44 kW	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-184.

$Q_{FO} = 7.8\, A_T + 378\, A_V \sqrt{h_V}$

Where Q_{FO} = heat release rate necessary for flashover (kW)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

A_V = area of ventilation opening (m^2)

h_V = height of ventilation opening (m)

Minimum Heat Release Rate for Flashover

$Q_{FO} = 7.8\, A_T + 378\, A_V \sqrt{h_V}$

Q_{FO} =	2064.41 kW	Answer

Summary of Result:

Calculation Method	Flashover HRR (kW)
METHOD OF MQH	836
METHOD OF BABRAUSKAS	2261
METHOD OF THOMAS	2064

NOTE

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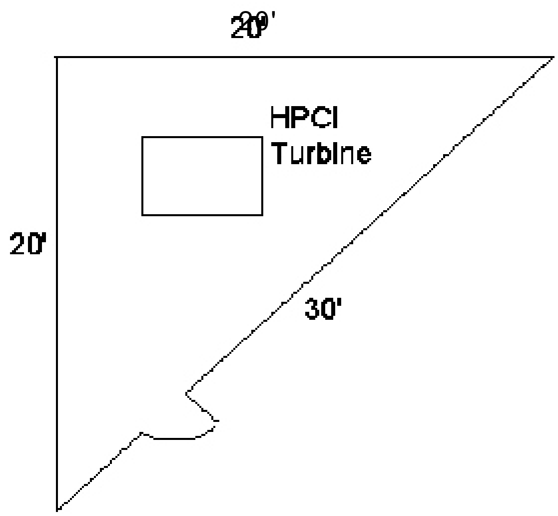
Problem J-17

Problem Statement

Consider a triangular corner compartment (as shown in the figure) in a boiling water reactor (BWR). The compartment is 4.6 m (15.0 ft) high with 0.3048 m (12.0 in) thick concrete walls, floor, and ceiling and with a door that is 2.15 m (7.0 ft) wide x 3.0 m (10.0 ft) high (w_v x h_v).



Problem 17: Pool Fire Scenario in a Triangular compartment

A fire scenario arises from a spill of lube oil from the high-pressure coolant injection (HPCI) turbine. Assume that 113.5 liters (30.0 gallons) of lube oil spills in a 1.12 m^2 (12.0 ft^2) oil retention dike. The lube oil spreads and reaches steady burning almost instantly. Two unprotected safety-related cable trays are located 3.0 m (10.0 ft) above the HPCI turbine. Determine whether there is a credible fire hazard to the unprotected safety-related cable trays.

Evaluate the hazard of the fire scenario using the following parameters:

(a) pool fire HRR, $\dot{Q}$, flame height, z, and burning duration, t_b

(b) compartment hot gas layer temperature, T_g, as well as gas layer height z

Solution

Purpose:

(1) Determine if the given fire scenario could represent a hazard for the safety-related cable trays.

Solution Approach:

The solution of this problem is very similar to the previous problem, but in this case we do not have or we are not considering any heat radiation and fire suppression system. First, we are going to calculate the heat release rate, flame height, and the burning duration of the pool fire (see Chapter 3) in order to determine the fire source characteristics. Notice that although the compartment is triangular, we are not going to consider a corner fire. It is reasonable to assume that the HPCI turbine is at a large distance away from the walls. Also, we will determine the hot gas layer temperature and the gas layer height (see Chapter 2).

Once we get all these values, we have to use them to estimate the hazard of the fire scenario.

Assumptions:

(1) There is instantaneous and complete involvement of the liquid in the pool fire.
(2) The pool fire is burning in the open.
(3) The pool is circular or nearly circular.
(4) The fire is located away from the walls.
(5) The ambient (or initial condition of the air) is at 25 °C (77 °F)
(6) The bottom of the oil retention dike is at ground level.
(7) The distance from the top of the fuel package (oil pool) to the ceiling is 15 ft, the pool height or oil layer thickness is negligible compared with the height of the ceiling.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls
(b) 02.1_Temperature_NV.xls

FDT^s Input Parameters:

Enter the following parameters in the spreadsheets (values only):

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

- Fuel spill volume (V) = 30 gallons
- Fuel Spill Area or Dike Area (A_{dike}) = 12 ft^2
- Select Fuel Type: select Lube Oil from the combo box

Note: When Lube Oil is selected, its properties are automatically selected from the table and entered in the corresponding input cells.

Results*

Heat Release Rate $\dot{Q}$ kW (Btu/sec)	Burning Duration (t_b) (min)	Pool Fire Flame Height H_f m (ft)	
1,131 (1,072)	33 min	Method of Heskestad	Method of Thomas
		2.7 (8.9)	3.0 (9.7)

*spreadsheet calculations attached at the end of the problem

(b) 02.1_Temperature_NV.xls

Equivalent Compartment:

The FDT^s for hot gas layer temperature and flame height are designed for a quadrilateral compartment. Since the compartment is triangular, we have to calculate an equivalent square compartment in order to use the FDT^s.

- ❑ Triangular Compartment Surface Area:
  SA= (½ x (base) x (width)) + ($A_{wall\ \#1}$ + $A_{wall\ \#2}$ + $A_{wall\ \#3}$)
  SA= (½ x 20 x 20) + ((20 x 15) + (30 x 15) + (20 x 15)) = 1450 ft^2
- ❑ Equivalent Rectangular Compartment with Same Height:
  SA= Area Floor + Area Ceiling + Area Walls
  SA= (L x W) + (L x W) + 2(L x 15) + 2(W x 15)
  since equivalent L = W
  SA= (L^2) + (L^2) + 4(L x 15)
  1450 = $2L^2$ + 60L => L = 15.8 ft = W

Input Parameters:

- Compartment Width (w_c) = 15.8 ft
- Compartment Length (l_c) = 15.8 ft
- Compartment Height (h_c) = 15 ft
- Vent Width (w_v) = 7 ft
- Vent Height (h_v) = 10 ft
- Top of Vent from Floor (V_T) = 10 ft
- Interior Lining Thickness (δ) = 12 in
- Select Material: select **Concrete** from the combo box
- Fire Heat Release Rate ($\dot{Q}$) = 1,131 kW

Note: When **Concrete** is selected, its thermal properties are automatically selected from the table and entered in the corresponding input cells.

Results*

Time (min)	**Hot Gas Layer Temperature T_g °C (°F)**	**Gas Layer Height z m (ft)**
0	25 (77)	4.57 (15)
1	134 (273)	3.05 (10) venting
2	147 (297)	3.05 (10) venting
3	156 (312)	3.05 (10) venting
4	162 (324)	3.05 (10) venting
5	167 (333)	3.05 (10) venting
10	185 (364)	3.05 (10) venting
15	196 (385)	3.05 (10) venting
20	204 (400)	3.05 (10) venting

*spreadsheet calculations attached at the end of the problem

Conclusions

We can note that the fire power (HRR) and the pool fire flame height values are similar to the previous problem. The reason for this similarity is because the correlations to determine the HRR and flame height are based on the type of fuel and the dike area (or dike diameter), and in this problem we are dealing with a pool fire similar to problem 16. The amount of combustible in the pool (volume) will determine the duration of the pool fire, that is, the burning time. Thus, we obtained a different burning time value because we have more fuel volume.

As problem 16, we have a high intensity fire with a flame height that probably will impinge upon the cable trays. Also, the hot gas layer temperature analysis predicts that the temperature of the gases will reach the failure temperature for thermoplastic cables ($T \cong 425$ °F) approximately at 2 minutes after ignition and the compartment will be full with smoke at this time too. If there is no intervention of any suppression system during the 33 minutes of flame exposure, there is no doubt that there is a credible hazard for the safety related cables.

Spreadsheets Calculations

(a) FDT^s: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE,
HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	30.00	gallons	0.1136 m^3
Fuel Spill Area or Dike Area (A_{dike})	12.00	ft^2	1.115 m^2
Mass Burning Rate of Fuel (m")	0.039	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	46000	kJ/kg	
Fuel Density (ρ)	760	kg/m^3	
Empirical Constant (kβ)	0.7	m^{-1}	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec^2	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Calculate

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant kβ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Fuel Type

Lube Oil

Scroll to desired fuel type
Click on selection

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-26.

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3[rd] Edition, 2002, Page 3-25.

$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D})A_{dike}$

Where Q = pool fire heat release rate (kW)
$\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)
$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)
$k\beta$ = empirical constant (m^{-1})
D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Pool Fire Diameter Calculation
$A_{dike} = \pi D^2/4$
Where A_{dike} = surface area of pool fire (m^2)
D = pool fire diamter (m)
$D = \sqrt{(4A_{dike}/\pi)}$
D = 1.191 m

Heat Release Rate Calculation
$Q = \dot{m}''\Delta H_{c,eff}(1 - e^{-k\beta D})A_{dike}$

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	1131.38 kW	1072.34 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference: *SFPE Handbook of Fire Protection Engineering*, 2[nd] Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where t_b = burning duration of pool fire (sec)
V = volume of liquid (m^3)
D = pool diameter (m)
v = regression rate (m/sec)

Calculation for Regression Rate
$v = \dot{m}''/\rho$
Where v = regression rate (m/sec)
$\dot{m}''$ = mass burning rate of fuel (kg/m^2-sec)
ρ = liquid fuel density (kg/m^3)
v = 0.000051 m/sec

Burning Duration Calculation
$t_b = 4V/\pi D^2 v$

t_b =	1985.05 sec	33.08 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT
METHOD OF HESKESTAD

Reference: *SFPE Handbook of Fire Protection Engineering*, 2[nd] Edition, 1995, Page 2-10.

$H_f = 0.235\, Q^{2/5} - 1.02\, D$

Where H_f = pool fire flame height (m)
Q = pool fire heat release rate (kW)
D = pool fire diameter (m)

Pool Fire Flame Height Calculation
$H_f = 0.235\, Q^{2/5} - 1.02\, D$

H_f =	2.70 m	8.85 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2[nd] Edition, 1995, Page 3-204.

$H_f = 42\ D\ (\dot{m}''/\rho_a \sqrt{(g\ D)})^{0.61}$

Where
- H_f = pool fire flame height (m)
- $\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m²-sec)
- ρ_a = ambient air density (kg/m³)
- D = pool fire diameter (m)
- g = gravitational acceleration (m/sec²)

Pool Fire Flame Height Calculation

$H_f = 42\ D\ (\dot{m}''/\rho_a \sqrt{(g\ D)})^{0.61}$

H_f =	2.95 m	9.67 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	8.85
METHOD OF THOMAS	9.67

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft²)	Area (m²)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	94.28	23820.64	3.60	4.08
2	0.19	0.49	188.56	11910.32	4.64	5.19
3	0.28	0.60	282.84	7940.21	5.38	5.97
4	0.37	0.69	377.13	5955.16	5.97	6.60
5	0.46	0.77	471.41	4764.13	6.47	7.13
6	0.56	0.84	565.69	3970.11	6.91	7.60
7	0.65	0.91	659.97	3402.95	7.30	8.02
8	0.74	0.97	754.25	2977.58	7.66	8.40
9	0.84	1.03	848.53	2646.74	7.99	8.75
10	0.93	1.09	942.82	2382.06	8.30	9.07
11	1.02	1.14	1037.10	2165.51	8.58	9.38
12	1.11	1.19	1131.38	1985.05	8.85	9.67
13	1.21	1.24	1225.66	1832.36	9.11	9.94
14	1.30	1.29	1319.94	1701.47	9.35	10.20
15	1.39	1.33	1414.22	1588.04	9.58	10.45
20	1.86	1.54	1885.63	1191.03	10.60	11.55
25	2.32	1.72	2357.04	952.83	11.46	12.48
50	4.65	2.43	4714.08	476.41	14.58	15.87
75	6.97	2.98	7071.12	317.61	16.75	18.28
100	9.29	3.44	9428.17	238.21	18.47	20.20

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation does not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT[s]: 02.1_Temperature_NV.xls

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Parameter	Value	Unit	Converted
Compartment Width (w_c)	15.80	ft	4.81584 m
Compartment Length (l_c)	15.80	ft	4.81584 m
Compartment Height (h_c)	15.00	ft	4.572 m
Vent Width (w_v)	7.00	ft	2.134 m
Vent Height (h_v)	10.00	ft	3.048 m
Top of Vent from Floor (V_T)	10.00	ft	3.048 m
Interior Lining Thickness (δ)	12.00	in	0.3048 m

AMBIENT CONDITIONS

Parameter	Value	Unit	Converted
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.18	kg/m³	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

Parameter	Value	Unit
Interior Lining Thermal Inertia ($k\rho c$)	2.9	$(kW/m^2-K)^2$-sec
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K
Interior Lining Specific Heat (c)	0.75	kJ/kg-K
Interior Lining Density (ρ)	2400	kg/m^3

Note : Air density will automatically correct with Ambient Air Temperature (T_a) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ $(kW/m^2-K)^2$-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Material
Concrete
Scroll to desired material then Click the selection

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270.

FIRE SPECIFICATIONS

Fire Heat Release Rate (Q)	1131.00	kW
	Calculate	

METHOD OF McCAFFREY, QUINTIERE, AND HARKLEROAD (MQH)

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, Page 3-175.

$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})(A_T h_k)]^{1/3}$

Where $\Delta T_g = T_g - T_a$ = upper layer gas temperature rise above ambient (K)

Q = heat release rate of the fire (kW)

A_v = area of ventilation opening (m^2)

h_v = height of ventilation opening (m)

h_k = convective heat transfer coefficient (kW/m^2-K)

A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

Area of Ventilation Opening Calculation

$A_v = (w_v)(h_v)$

Where A_v = area of ventilation opening (m^2)

w_v = vent width (m)

h_v = vent height (m)

A_v = 6.50 m^2

Thermal Penetration Time Calculation

$t_p = (\rho c_p/k)(\delta/2)^2$

Where t_p = thermal penetration time (sec)

ρ = interior construction density (kg/m^3)

c_p = interior construction heat capacity (kJ/kg-K)

k = interior construction thermal conductivity (kW/m-K)

δ = interior construction thickness (m)

t_p = 26128.98 sec

Heat Transfer Coefficient Calculation

$h_k = \sqrt{(k\rho c/t)}$ for $t < t_p$ or (k/δ) for $t > t_p$

Where h_k = heat transfer coefficient (kW/m^2-K)

$k\rho c$ = interior construction thermal inertia $(kW/m^2\text{-}K)^2$-sec

(a thermal property of material responsible for the rate of temperature rise)

t = time after ignition (sec)

See table below for results

Area of Compartment Enclosing Surface Boundaries

$A_T = [2(w_c \times l_c) + 2(h_c \times w_c) + 2(h_c \times l_c)] - A_v$

Where A_T = total area of the compartment enclosing surface boundaries excluding area of vent openings (m^2)

w_c = compartment width (m)

l_c = compartment length (m)

h_c = compartment height (m)

A_v = area of ventilation opening (m^2)

A_T = 127.95 m^2

Compartment Hot Gas Layer Temperature With Natural Ventilation

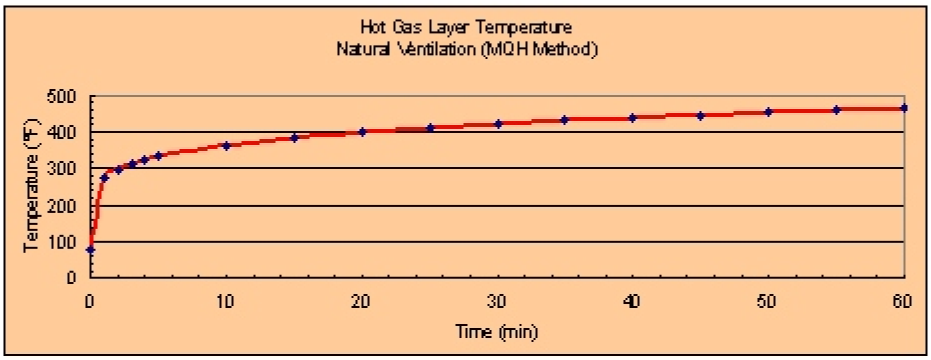
$\Delta T_g = 6.85\,[Q^2/(A_v(h_v)^{1/2})(A_T h_k)]^{1/3}$

$\Delta T_g = T_g - T_a$

$T_g = \Delta T_g + T_a$

Results

Time After Ignition (t) (min)	(sec)	h_k (kW/m^2-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	108.78	406.78	133.78	272.81
2	120	0.16	122.11	420.11	147.11	296.79
3	180	0.13	130.64	428.64	155.64	312.16
4	240	0.11	137.06	435.06	162.06	323.70
5	300	0.10	142.25	440.25	167.25	333.05
10	600	0.07	159.67	457.67	184.67	364.41
15	900	0.06	170.84	468.84	195.84	384.50
20	1200	0.05	179.23	477.23	204.23	399.61
25	1500	0.04	186.02	484.02	211.02	411.83
30	1800	0.04	191.76	489.76	216.76	422.16
35	2100	0.04	196.75	494.75	221.75	431.14
40	2400	0.03	201.17	499.17	226.17	439.11
45	2700	0.03	205.16	503.16	230.16	446.29
50	3000	0.03	208.80	506.80	233.80	452.83
55	3300	0.03	212.14	510.14	237.14	458.85
60	3600	0.03	215.24	513.24	240.24	464.43



ESTIMATING SMOKE LAYER HEIGHT
METHOD OF YAMANA AND TANAKA

$z = ((2kQ^{1/3}t/3A_c) + (1/h_c^{(2/3)}))^{-3/2}$

Where z = smoke layer height (m)
Q = heat release rate of the fire (kW)
t = time after ignition (sec)
h_c = compartment height (m)
A_c = compartment floor area (m^2)
k = a constant given by $k = 0.076/\rho_g$
ρ_g = hot gas layer density (kg/m^3)
ρ_g is given by $\rho_g = 353/T_g$
T_g = hot gas layer temperature (K)

Compartment Area Calculation
$A_c = (w_c)(l_c)$
Where A_c = compartment floor area (m^2)
w_c = compartment width (m)
l_c = compartment length (m)
$A_c =$ 23.19 m^2

Hot Gas Layer Density Calculation
$\rho_g = 353/T_g$

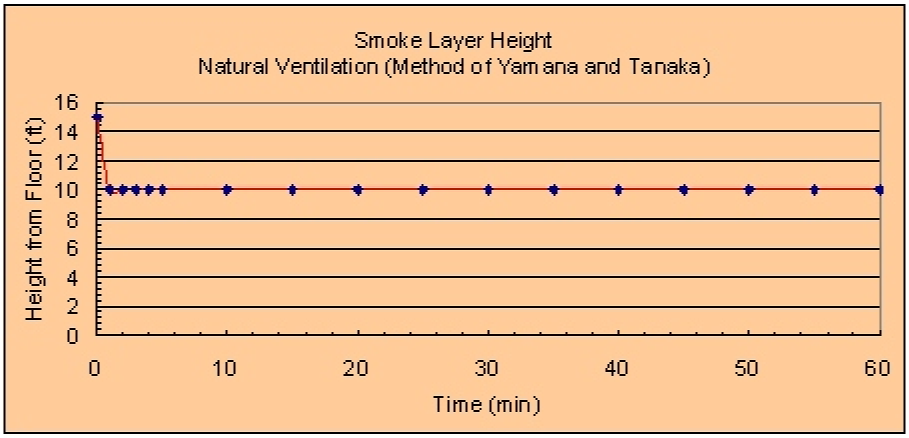
Calculation for Constant K
$k = 0.076/\rho_g$

Smoke Gas Layer Height With Natural Ventilation
$z = [(2kQ^{1/3}t/3A_c) + (1/h_c^{2/3})]^{-3/2}$

Results

Caution! The smoke layer height is a conservative estimate and is only intended to provide an indication where the hot gas layer is located. Calculated smoke layer height below the vent height are not creditable since the calculation is not accounting for the smoke exiting the vent.

Time (min)	ρ_g (kg/m^3)	Constant (k) (kW/m-K)	Smoke Layer height z (m)	Smoke Layer height z (ft)	
0	1.18	0.064	4.57	15.00	
1	0.87	0.088	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
2	0.84	0.090	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
3	0.82	0.092	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
4	0.81	0.094	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
5	0.80	0.095	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
10	0.77	0.099	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
15	0.75	0.101	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
20	0.74	0.103	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
25	0.73	0.104	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
30	0.72	0.105	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
35	0.71	0.107	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
40	0.71	0.107	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
45	0.70	0.108	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
50	0.70	0.109	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
55	0.69	0.110	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT
60	0.69	0.110	3.05	10.00	CAUTION: SMOKE IS EXITING OUT VENT



NOTE

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Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov.

Problem J-18

Problem Statement

The operators of Bywater NPP are planning their summer company picnic. A fire scenario arises from a pile of instant-lighting charcoal briquets. Ten 3.62-kg (8.0-lb) bags of these briquets have been stored on the floor of a corridor in the NPP. Assume that a strong ignition source is present and ignites the charcoal briquets. Compute the heat release rate, $\dot{Q}$, flame height, H_f, and burning duration, t_b, of pile of charcoal briquets, assuming that the area of the charcoal pile is 0.28 m^2 (3 ft^2).

Additional Information

Charcoal briquets are a combustible material and become more combustible when soaked with lighter fluid (an accelerant) during the manufacturing process (Ref. 1). The lighter fluid is usually kerosene or a petroleum distillate (Refs. 2 and 3). No direct burning rate data are available for instant-lighting charcoal briquets. A breakdown of the combustion data for plain charcoal and kerosine (Ref. 4) is provided below. Average values can be used as a composition when specific burning rate data are not available. The density of charcoal is approximately 400 kg/m^3.

Combustion Properties of Charcoal and Kerosine		
Combustible Material	Heat of Combustion H_c (kJ/kg)	Mass Loss Rate $\dot{m}''$ (kg/m^2-sec)
Charcoal	31,400	0.01082*
Kerosine	43,300	0.039
Average	**37,350**	**0.02491**
* Mass loss rate of charcoal is not available in the literature, mass loss rate of plain plywood can be used, since charcoal is a derivative of wood.		

References

1. Roblee, C.L., "Hazards of Charcoal Briquets," *Fire and Arson Investigator*, Volume 33, No. 3, March 1993.
2. Lincoln, S., "Case in Review: Charcoal Lighter Fluid Used as an Arson Accelerant," *Fire and Arson Investigator*, Volume 41, No. 1, September 1991.
3. Wiltshire, L.L., and R.S. Alger, "Carbon Monoxide Production in Charcoal Briquete Fires," NOLTR 71-104, Project MAT-03L-00/ZRO11-01-01, Naval Ordnance Laboratory, Silver Spring, Maryland, July 7, 1971.
4. SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.

Solution

Purpose:

(1) Determine the heat release rate, $\dot{Q}$ flame height, H_f, and burning duration, t_b, of the pile of charcoal briquets for the given fire scenario.

Solution Approach:

To calculate the HRR and flame height, we are going to use the pool fire approach. These calculations are just fuel type and area dependent; therefore, we are going to model the area of the charcoal pile as the area of a dike and use the average values of heat of combustion, mass loss rate and density (values are given in the problem statement). The burning duration of the pile can be calculated with the learned concepts in Chapter 8 of NUREG.

Assumptions:

(1) There is instantaneous and complete involvement of the charcoal pile.
(2) The charcoal pile is burning in the open.
(3) The charcoal pile area is circular or nearly circular.
(4) The fire is located away from the walls.
(5) The ambient (or initial condition of the air) is at 25 °C (77 °F)
(6) Combustion is incomplete and takes place entirely within the confines of the compartment.

Spreadsheet (FDT^s) Solution Procedure:

Use the following FDT^s:

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls
(b) 08_Burning_Duration_Solid.xls

FDT^s Input Parameters:

Enter the following parameters in the spreadsheets (values only):

(a) 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

- Fuel spill volume (V) = 0 gallons
- Fuel Spill Area or Dike Area (A_{dike}) = 3 ft^2
- Mass Burning Rate of Fuel $(\dot{m}'')$ = 0.02491 kg/m^2-sec
- Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$) = 37,350 kJ/kg
- Fuel Density (ρ) = 400 kg/m^3
- Empirical constant = 100 (since unknown)

Note: For this calculation, use any value of spill volume because the burning time based on the pool fire calculation is not applicable. We are just going to accept the HRR and flame height values as reasonable estimates. Mass burning rate, heat of combustion, and density values are from the given properties in the problem statement. Select User-Specified Value and enter the values in the proper areas.

Results*

Heat Release Rate $\dot{Q}$ kW (Btu/sec)	Pool Fire Flame Height H_f m (ft)	
	Method of Heskestad	Method of Thomas
259 (246)	1.56 (5.13)	1.38 (4.54)

*spreadsheet calculations attached at the end of the problem

(b) 08_Burning_Duration_Solid.xls

HRR per Unit Floor Area:

The HRR per unit of area is defined as $\dot{Q}'' = \Delta H_{c,eff} \dot{m}''$. Therefore, from the given properties in the problem statement we have:

$\dot{Q}'' = \Delta H_{c,eff} \dot{m}''$ = 37,350 kJ/kg (0.02491 kg/m^2-sec) = 930 kW/m^2

Input Parameters:

- Mass of Solid Fuel (m_{solid}) = 80 lb
- Exposed Fuel Surface Area (A_{fuel})= 3 ft^2
- HRR per Unit Floor Area $(\dot{Q}'')$ = 930 kW/m^2
- Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$) = 37,350 kJ/kg

Note: Select User-Specified Value and enter the inputs.

Results*

Material	Burning Duration t_{solid} (min.)
Charcoal briquets	87

*spreadsheet calculations attached at the end of the problem

Spreadsheet Calculations

(a) FDT^s: 03_HRR_Flame_Height_Burning_Duration_Calculations.xls

CHAPTER 3. ESTIMATING BURNING CHARACTERISTICS OF LIQUID POOL FIRE,
HEAT RELEASE RATE, BURNING DURATION, AND FLAME HEIGHT

Version 1805.0

The following calculations estimate the heat release rate, burning duration, and flame height for liquid pool fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Fuel Selected.
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

Fuel Spill Volume (V)	0.00	gallons	0.0000 m^3
Fuel Spill Area or Dike Area (A_{dike})	3.00	ft^2	0.279 m^2
Mass Burning Rate of Fuel (m")	0.02491	kg/m^2-sec	
Effective Heat of Combustion of Fuel ($\Delta H_{c,eff}$)	37350	kJ/kg	
Fuel Density (ρ)	400	kg/m^3	
Empirical Constant ($k\beta$)	100	m^{-1}	
Ambient Air Temperature (T_a)	77.00	°F	25.00 °C
			298.00 K
Gravitational Acceleration (g)	9.81	m/sec^2	
Ambient Air Density (ρ_a)	1.18	kg/m^3	

Calculate

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

THERMAL PROPERTIES DATA

BURNING RATE DATA FOR LIQUID HYDROCARBON FUELS

Fuel	Mass Burning Rate m" (kg/m^2-sec)	Heat of Combustion $\Delta H_{c,eff}$ (kJ/kg)	Density ρ (kg/m^3)	Empirical Constant $k\beta$ (m^{-1})
Methanol	0.017	20,000	796	100
Ethanol	0.015	26,800	794	100
Butane	0.078	45,700	573	2.7
Benzene	0.085	40,100	874	2.7
Hexane	0.074	44,700	650	1.9
Heptane	0.101	44,600	675	1.1
Xylene	0.09	40,800	870	1.4
Acetone	0.041	25,800	791	1.9
Dioxane	0.018	26,200	1035	5.4
Diethy Ether	0.085	34,200	714	0.7
Benzine	0.048	44,700	740	3.6
Gasoline	0.055	43,700	740	2.1
Kerosine	0.039	43,200	820	3.5
Diesel	0.045	44,400	918	2.1
JP-4	0.051	43,500	760	3.6
JP-5	0.054	43,000	810	1.6
Transformer Oil, Hydrocarbon	0.039	46,000	760	0.7
561 Silicon Transformer Fluid	0.005	28,100	960	100
Fuel Oil, Heavy	0.035	39,700	970	1.7
Crude Oil	0.0335	42,600	855	2.8
Lube Oil	0.039	46,000	760	0.7
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Select Fuel Type
User Specified Value
Scroll to desired fuel type
Click on selection

Reference: SFPE Handbook of Fire Protection Engineering, 3rd Edition, 2002, Page 3-26.

ESTIMATING POOL FIRE HEAT RELEASE RATE

Reference: *SFPE Handbook of Fire Protection Engineering*, 3rd Edition, 2002, *Page 3-26*.

$Q = m''\Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

Where Q = pool fire heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

$A_f = A_{dike}$ = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (diameter involved in vaporization, circular pool is assumed) (m)

Pool Fire Diameter Calculation

$A_{dike} = \pi D^2/4$

Where A_{dike} = surface area of pool fire (m^2)

D = pool fire diameter (m)

$D = \sqrt{(4A_{dike}/\pi)}$

$D =$ 0.596 m

Heat Release Rate Calculation

$Q = m''\Delta H_{c,eff} (1 - e^{-k\beta D}) A_{dike}$

(Liquids with relatively high flash point, like transformer oil, require localized heating to achieve ignition)

Q =	259.31 kW	245.78 Btu/sec	Answer

ESTIMATING POOL FIRE BURNING DURATION

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-197.

$t_b = 4V / \pi D^2 v$

Where t_b = burning duration of pool fire (sec)

V = volume of liquid (m^3)

D = pool diameter (m)

v = regression rate (m/sec)

Calculation for Regression Rate

$v = m''/\rho$

Where v = regression rate (m/sec)

m'' = mass burning rate of fuel (kg/m^2-sec)

ρ = liquid fuel density (kg/m^3)

$v =$ 0.000062 m/sec

Burning Duration Calculation

$t_b = 4V/\pi D^2 v$

t_b =	0.00 sec	0.00 minutes	Answer

Note that a liquid pool fire with a given amount of fuel can burn for long periods of time over small area or for short periods of time over a large area.

ESTIMATING POOL FIRE FLAME HEIGHT

METHOD OF HESKESTAD

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 2-10.

$H_f = 0.235\,Q^{2/5} - 1.02\,D$

Where
- H_f = pool fire flame height (m)
- Q = pool fire heat release rate (kW)
- D = pool fire diameter (m)

Pool Fire Flame Height Calculation

$H_f = 0.235\,Q^{2/5} - 1.02\,D$

H_f =	1.56 m	5.13 ft	Answer

METHOD OF THOMAS

Reference: *SFPE Handbook of Fire Protection Engineering*, 2nd Edition, 1995, Page 3-204.

$H_f = 42\,D\,(\dot{m}''/\rho_a\sqrt{g\,D})^{0.61}$

Where
- H_f = pool fire flame height (m)
- $\dot{m}''$ = mass burning rate of fuel per unit surface area (kg/m^2-sec)
- ρ_a = ambient air density (kg/m^3)
- D = pool fire diameter (m)
- g = gravitational acceleration (m/sec^2)

Pool Fire Flame Height Calculation

$H_f = 42\,D\,(\dot{m}''/\rho_a\sqrt{g\,D})^{0.61}$

H_f =	1.38 m	4.54 ft	Answer

Flame Height Calculation - Summary of Results

Calculation Method	Flame Height (ft)
METHOD OF HESKESTAD	5.13
METHOD OF THOMAS	4.54

ESTIMATING POOL FIRE RESULTS FOR RANDOM SIZE SPILLS USING INPUT PARAMETERS

Area (ft^2)	Area (m^2)	Diameter (m)	Q (kW)	t_b (sec)	H_f (ft) (Heskestad)	H_f (ft) (Thomas)
1	0.09	0.34	86.44	0.00	3.44	3.10
2	0.19	0.49	172.87	0.00	4.43	3.95
3	0.28	0.60	259.31	0.00	5.13	4.54
4	0.37	0.69	345.74	0.00	5.69	5.02
5	0.46	0.77	432.18	0.00	6.16	5.43
6	0.56	0.84	518.62	0.00	6.58	5.78
7	0.65	0.91	605.05	0.00	6.95	6.10
8	0.74	0.97	691.49	0.00	7.29	6.39
9	0.84	1.03	777.92	0.00	7.60	6.65
10	0.93	1.09	864.36	0.00	7.89	6.90
11	1.02	1.14	950.80	0.00	8.16	7.14
12	1.11	1.19	1037.23	0.00	8.41	7.35
13	1.21	1.24	1123.67	0.00	8.65	7.56
14	1.30	1.29	1210.10	0.00	8.88	7.76
15	1.39	1.33	1296.54	0.00	9.10	7.95
20	1.86	1.54	1728.72	0.00	10.06	8.78
25	2.32	1.72	2160.90	0.00	10.88	9.49
50	4.65	2.43	4321.80	0.00	13.81	12.08
75	6.97	2.98	6482.69	0.00	15.84	13.90
100	9.29	3.44	8643.59	0.00	17.45	15.37

Caution: The purpose of this random spill size chart is to aid the user in evaluating the hazard of random sized spills. Please note that the calculation doe not take into account the viscosity or volatility of the liquid, or the absorptivity of the surface. The results generated for small volume spills over large areas should be used with extreme caution.

NOTE

The above calculations are based on principles developed in the SFPE Handbook of Fire Protection Engineering, 2nd Edition, 1995.
Calculations are based on certain assumptions and have inherent limitations. The results of such calculations may or maynot have reasonable predictive capabilities for a given situation, and should onlybe interpreted by an informed user.
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Anyquestions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheets, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

(b) FDT^s: 08_Burning_Duration_Solid.xls

CHAPTER 8. ESTIMATING BURNING DURATION OF SOLID COMBUSTIBLES

Version 1805.0

The following calculations provides an approximation of the burning duration of solid combustibles based on free burning rate with a given surface area.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
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

COMPARTMENT INFORMATION

Mass of Solid Fuel (m_{solid})	80.00	lb	36.29	kg
Exposed Floor Area (Length x Width) of Fuel (A_{fuel})	3.00	ft^2	0.28	m^2
Heat Release Rate per Unit Floor Area (Q")	930	kW/m^2		
Effective Heat of Combustion ($\Delta H_{c,eff}$)	37350	kJ/kg		

Calculate

THERMAL PROPERTIES OF SOLID COMBUSTIBLE MATERIALS

Materials	HRR per Unit Floor Area (L x W) Q" (kW/m^2)	Heat of Combustion ΔH_c (kJ/kg)
PE/PVC	589	24000
XPE/FRXPE	475	28300
XPE/Neoprene	354	10300
PE, Nylon/PVC, Nylon	231	9200
Teflon	98	3200
Douglas fir plywood	221	17600
Fire retardant treated plywood	81	13500
Particle Board, 19 mm thick	1900	17500
Nylon 6/6	1313	32000
Polymethylmethacrylate (PMMA)	665	26000
Polypropylene (PP)	1509	43200
Polystyrene (PS)	1101	42000
Polyethylene (PE)	1408	46500
Polycarbonate	420	24400
Polyurethane	710	45000
Polyvinyl Chloride (PVC) Flexible	237	15700
Styrene-butadiene Copolymers (SBR)	163	44000
Ethylene Propylene Dien Rubber (EPDM)	956	28800
Empty Cartons 15 ft high	1700	12700
Wood pallets, stacked 1.5 ft high	1420	14000
Wood pallets, stacked 5 ft high	3970	14000
Wood pallets, stacked 10 ft high	6800	14000
User Specified Value	Enter Value	Enter Value

Select Material

User Specified Value

Scroll to desired material then Click on selection

References: "Categorization of Cable Flammability, Part 1: Laboratory Evaluation of Cable Flammability Parameters," EPRI Research Project 1165-1, NP-1200, Part 1.
Karlsson and Quintiere, Enclosure Fire Dynamics, Chapter 3,: Energy Release Rate," CRC Press, 1999.
Johnson, D. G., "Combustion Properties of Plastics," Journal of Applied Fire Science, Volume 4, No. 3, 1994-95, pp. 185-201.
Hirschler, M. M., "Heat Release from Plastic Materials," Heat Release in Fires, Babrauskas and Grayson, Editors, Elsevier Applied Science, 1992.

BURNING DURATION OF SOLID COMBUSTIBLES

Reference: *Buchanan, A.H., "Structural Design for Fire Safety," 2001, Page 38.*

The burning duration of a solid fuel can be calculated if the total energy contained in the fuel and HRR are known.

The burning duration is given by:

$Q = E / t_{solid}$

or

$t_{solid} = (E) / (Q'' A_{Fuel})$

Where t_{solid} = burning duration of solid combustible (sec)
$E = m_{Fuel} \Delta H_C$ = total energy contained in the fuel (kJ)
Q = heat releare rate of fire (kW)
Q'' = heat release rate per unit floor area of fuel (kW/m^2)
A_{Fuel} = exposed floor area (length x width) of fuel (m^2)

$t_{solid} = (m_{Fuel} \Delta H_C) / (Q'' A_{Fuel})$

Where m_{Fuel} = mass of solid fuel (kg)
ΔH_C = fuel effective heat of combustion (kJ/kg)

$t_{solid} = (m_{solid} \Delta H_C) / (Q'' A_{solid})$

t_{solid} =	5228.92 sec	87.15 minutes	Answer

NOTE

The above calculations are based on principles developed in the Structural Design for Fire Safety, 2001.
Calculations are based on certain assumptions and have inherent limitations.
The results of such calculations may or may not have reasonable predictive capabilities for a given situation, and should only be interpreted by an informed user.
Although each calculation in the spreadsheet has been verified with the results of hand calculation, there is no absolute guarantee of the accuracy of these calculations.
Any questions, comments, concerns, and suggestions, or to report an error(s) in the spreadsheet, please send an email to nxi@nrc.gov or mxs3@nrc.gov.

UNITED STATES NUCLEAR REGULATORY COMMISSION

Additional Problems

1. Consider a pool fire caused by a 38.0 liters (10 gallons) spill of flammable liquid (kerosine oil) in a 0.55-m^2 (6.0-ft^2) dike area in a compartment with a concrete floor. The kerosine oil is ignited and spreads rapidly over the surface, reaching steady burning almost instantly. Compute the HRR, burning duration, and flame height of the pool fire. The dimensions of the compartment are 6.0 m wide x 6.0 m long x 3.7 m high (20.0 ft wide x 20.0 ft long x 12.0 ft high). Two cable trays are located above the pool fire at heights of 2.15 m (7.0 ft) and 3.0 m (10.0 ft), respectively. Determine whether flame will impinge upon the cable trays. Assume instantaneous, complete involvement of the liquid pool with no fire growth and no intervention by the plant fire department or automatic suppression systems.

2. Assume that heptane from a tank spills on a concrete floor forming a 113.0 m^2 (1261.0 ft^2) pool, the distance from the center of the pool fire to the target edge is 30.0 m (98.0 ft). Calculate the radiative heat flux of the flame at ground level with no wind using—
   (a) Point Source Model
   (c) Solid Flame Radiation Model

3. A trash fire with an HRR $(\dot{Q})$ of 1,500 kW occurs in an NPP backup power battery room protected with the fixed temperature heat detectors with an RTI of 165 $(m\text{-}sec)^{1/2}$. Calculate the activation time for the detectors, using listed spacing of 3.05 m (20.0 ft) with a ceiling height of 4.60 m (15 ft). Assume that the detectors have an activation temperature of 57 °C (135 °F) and the ambient temperature is 25 °C (77 °F).

4. A fire scenario arises from the failure of a 4,160V switchgear in a cable spreading room. A stack of safety-related cable (IEEE-383 non-qualified PE/PVC) is located 4.6 m (15.0 ft) horizontally from the 4,160V breaker. Assume that the breaker fire produces a maximum flame heat flux 50 kW/m^2 and the surface of the cable trays initially at 25 °C (77 °F). Calculate the ignition time (t_{ig}) of IEEE-383 non-qualified PE/PVC cables.

5. A pool fire scenario arises from a rupture in an oil-filled transformer. This event allows the fuel contents of the transformer to spill along a wall with an area of 1.4 m^2 (15 ft^2). A safety-related cable tray is located 5.5 m (18 ft) above the pool fire. Calculate the wall flame height ($H_{f(wall)}$) of the fire, and determine whether flame will impinge upon the cable tray.

6. A fire scenario arises from a rupture in the housing of an auxiliary lube oil pump. This event allows the fuel contents of the pump to spill along a wall with an area of 0.75 m^2 (8.0 ft^2). A cable tray is located 3.0 m (10.0 ft) above the fire. Calculate the flame height of the line fire ($H_{f(wall\ line)}$), and determine whether the flame will impinge upon the cable tray.

7. A fire scenario arises from a rupture in an oil-filled transformer in a facility. This event allows the fuel contents of the transformer to spill along the corners of walls with an area of 0.55 m^2 (6.0 ft^2). A cable tray is located 5.5 m (18 ft) above the fire. Calculate the corner fire flame height ($H_{f(corner)}$), and determine whether flame will impinge upon the cable tray.

8. Consider a compartment that is 9.0 m wide x 9.0 m long x 3.7 m high (30.0 ft wide x 30.0 ft long x 12.0 ft high) (w_c x l_c x h_c) with a door vent that is 0.91 m (3.0 ft) wide x 2.15 m (7.0 ft) high (w_v x h_v). The fire is constant with an HRR $(\dot{Q})$ of 1,500 kW. Compute the hot gas temperature (T_g) in the compartment as well as smoke layer height (z) at 5 minutes after ignition, assuming that the compartment boundaries are made of 2.54 cm (1.0 in) thick gypsum board.

9. Consider a compartment that is 12.2 m wide x 12.2 m long x 3.0 m high (40.0 ft wide x 40.0 ft long x 10.0 ft high) (w_c x l_c x h_c) with a door vent that is (4.0 ft) wide x (8.0 ft) high (w_v x h_v). The fire is constant with an HRR$(\dot{Q})$ of 2,000 kW. Compute the hot gas temperature (T_g) in the compartment as well as smoke layer height (z) at 3 minutes after ignition, assuming that the compartment boundaries are made of 0.3048 (12.0 in) thick concrete.

10. Consider a compartment that is 15.25 m wide x 12.2 m long x 3.7 m high (50.0 ft wide x 40.0 ft long x 12.0 ft high) (w_c x l_c x h_c) with a forced ventilation rate of 1,500 cfm. Calculate the hot gas layer temperature (T_g) in the compartment for a fire size $(\dot{Q})$ of 1,800 kW at 5 minutes after ignition, assuming that the compartment boundaries are made of 2.54 cm (1.0 in) thick gypsum board.

11. Consider a compartment that is 13.7 m wide x 15.25 m long x 3.35 m high (45.0 ft wide x 50.0 ft long x 11.0 ft high) (w_c x l_c x h_c) with a forced ventilation rate of 1,800 cfm. Calculate the hot gas layer temperature (T_g) in the compartment for a fire size $(\dot{Q})$ of 2,200 kW at 8 minutes after ignition, assuming compartment boundaries are made of 0.245 m (10.0 in) thick concrete.

12. Consider a pool fire caused by a 30.30liters (8.0 gallons) spill of flammable liquid (lube oil) in 0.38 m^2 (4.0 ft^2) dike area in a compartment with a finished concrete floor. The lube oil is ignited and spreads rapidly over the surface reaching steady burning almost instantly. Compute the HRR, burning duration, and flame height of the pool fire. The dimensions of the compartment are 4.9 m wide x 3.7 m long x 3.0 m high (16.0 ft wide x 12.0 ft long x 10.0 ft high). Two cable trays are located above the pool fire at heights of 1.8 m (6.0 ft) and 2.5 m (8.0 ft), respectively. Determine whether flame will impinge upon the cable trays. Assume instantaneous, complete involvement of the liquid pool with no fire growth and no intervention by the plant fire department or automatic suppression systems.

13. A 75.7-liter (20.0-gallon) trash bag (transient) exposure fire source is located 2.5 m (8.0 ft) beneath a horizontal cable tray. Assumed that the trash fire ignites an area of approximately 0.92 m^2 (10.0 ft^2) of the cable tray, and the cables in the tray are Id PE. Compute the full-scale HRR of Id PE cable insulation. The bench-scale HRR $(\dot{Q}''_{b})$ of the Id PE type cable material is 1,071 kW/m^2.

14. Assume that heptane from a tank spills on a concrete floor, forming a 0.92 m^2 (10.0 ft^2) pool and exposing a safety-related electrical cabinet in a corridor. The distance from the center of the pool fire to the target (cabinet) edge is 3.7 m (12.0 ft). Calculate the radiative heat flux of the flame to the electrical cabinet with no wind using—
(a) Point Source Model
(b) Solid Flame Radiation Model

15. Estimate the maximum plume temperature ($T_{p(centerline)}$) at the ceiling of a 4.6-m (15.0-ft) high room above a 1,500-kW fire involving a 1½-ft high stack of wood pallets in a 0.92-m^2 (10.0-ft^2) pallet area. Assume that the ambient temperature is 25 °C (77 °F).

16. A fire with $\dot{Q}$ = 3,000 kW occurs in a makeup pump room protected with a wet pipe sprinkler system. Fire sprinklers are rated at 74 °C (165 °F) [standard response bulb with RTI 235 $(m\text{-}sec)^{½}$] and are located 3.0 m (10.0 ft) on the center. The compartment ceiling is 5.5 m (18.0 ft) high. Determine whether the sprinklers would activate, and if so how long it would take for them to activate.

17. A fire scenario may arise from failure of a vital 480V AC breaker in a switchgear room. A stack of safety-related cable (IEEE-383 non-qualified PE/PVC) is located 3.0 m (10.0 ft) horizontally from the 480V AC breaker. Assumed that the vital breaker fire produces a maximum flame heat flux of 30 kW/m^2 and the surface of the cable trays is initially at 25 °C (77 °F). Calculate the ignition time (t_{ig}) of IEEE-383 non-qualified PE/PVC cables.

18. A pool fire scenario arises from a rupture in an oil-filled transformer containing (5 gallons) lube oil. This event allows the fuel contents of the transformer to spill along a wall with an area of 1.4 m^2 (15.0 ft^2). A safety-related cable tray is located 4.6 m (15.0 ft) above the pool fire. Calculate the wall flame height of the fire, and determine whether flame will impinge upon the cable tray.

19. A fire scenario arises from a rupture in the housing of a makeup pump containing 30.3 liters (8 gallons) lube oil. This event allows the fuel contents of the pump to spill along a wall with an area of 0.75 m^2 (8.0 ft^2). A cable tray is located 3.7 m (12.0 ft) above the fire. Calculate the flame height of the line fire, and determine whether flame will impinge upon the cable tray.

20. A fire scenario arises from a rupture in an oil-filled transformer in a facility containing (6 gallons) lube oil. This event allows the fuel contents of the transformer to spill along the corners of the walls with an area of 0.55 m^2 (6 ft^2). A cable tray is located 4.3 m (14.0 ft) above the fire. Calculate the corner fire flame height, and determine whether flame will impinge on the cable tray.

21. Calculate the HRR necessary for flashover $(\dot{Q}_{FO})$ in a compartment that is 5.5 m wide x 6.0 m long x 3.7 m high (18.0 ft wide x 20.0 ft long x 12.0 ft high) (w_c x l_c x h_c), with an opening that is 0.60 m (2.0 ft) wide x 1.83 m (6.0 ft) high (w_v x h_v). Assume that the boundary material is concrete and the door is open.

22. Calculate the HRR necessary for flashover $(\dot{Q}_{FO})$ in a cable spreading room (CSR) that is 15.3 m wide x 24.4 m long x 6.0 m high (50.0 ft wide x 80.0 ft long x 20.0 ft high) (w_c x l_c x h_c) with a door opening 1.2 m (4.0 ft) wide x 3.0 m (10.0 ft) high (w_v x h_v). The compartment boundaries are made of concrete and the door is open.

23. Consider a compartment in a facility pump room that is 3.0 m wide x 2.7 m long x 2.5 m high (10.0 ft wide x 9.0 ft long x 8.0 ft high) (w_c x l_c x h_c). A fire starts with a constant effect of 75 kW. Estimate the pressure increase attributable to the expansion of hot fire gases after 15 seconds, assuming that the door is closed.

24. The licensee used UL Design No. 816 to protect a number of unrestrained beams. The licensee's quality assurance (QA) program verified that there is 6.35 cm (2½ in) thickness of fire protection insulation on all of the beams. The size of the tested beam was W12 x 26. Determine whether the 6.35 cm (2½ in) thickness of fire protection insulation is acceptable for a beam that is W8 x 13.

25. A hydrogen line leaks 1 lb. of hydrogen in a turbine building. What is the worst case pressure increase, blast wave, and TNT equivalent.

26. A compartment that is 15.25 m wide x 15.25 m long x 3.7 m high (50 ft wide x 50 ft long x 12 ft high) has a hydrogen leak. What is the volume of gas needed for a deflagration.

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10. SUPPLEMENTARY NOTES
Sunil Weerakkody, NRC Project Manager and Fire Protection Section Chief

11. ABSTRACT *(200 words or less)*

The U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Reactor Regulation (NRR), Division of Systems Safety and Analysis (DSSA), Plant Systems Branch (SPLB), Fire Protection Engineering and Special Projects Section has developed quantitative methods, known as “Fire Dynamics Tools (FDTs),” to assist regional fire protection inspectors in performing fire hazard analysis (FHA). These methods have been implemented in spreadsheets and taught at the NRC’s quarterly regional inspector workshops. FDTs were developed using state-of-the-art fire dynamics equations and correlations that were preprogrammed and locked into Microsoft Excel® spreadsheets. These FDTs will enable the inspector to perform quick, easy, first-order calculations for the potential fire scenarios using today’s state-of-the-art principles of fire dynamics. Each FDTs spreadsheet also contains a list of the physical and thermal properties of the materials commonly encountered in nuclear power plants. This NUREG addresses the technical bases for FDTs, which were derived from the principles developed primarily in the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering, National Fire Protection Association (NFPA) Fire Protection Handbook, and other fire science literature. The subject matter of this NUREG covers many aspects of fire dynamics and contains descriptions of the most important fire processes. A significant number of examples, reference tables, illustrations, and conceptual drawings are presented in this NUREG to expand the inspector’s appreciation in visualizing and retaining the material and understanding calculation methods.

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