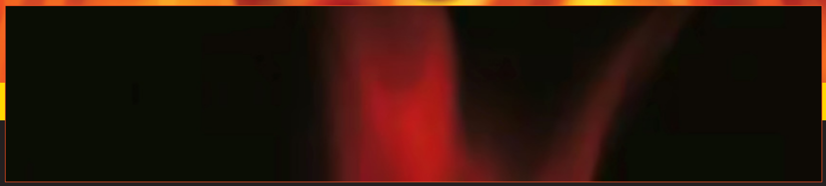

Fire Dynamics Tools (FDT^{s})

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

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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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Figures (continued)

Tables

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

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.

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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