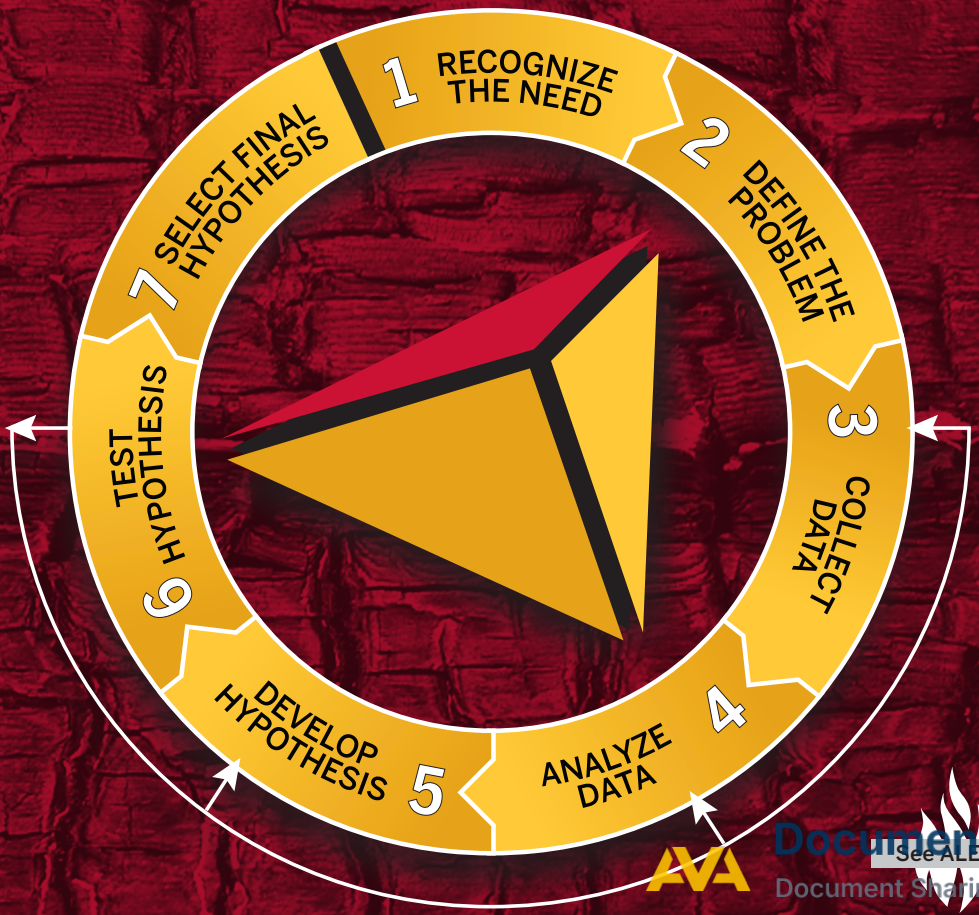
NFPA® 921

Guide for Fire and Explosion Investigations

2017



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NFPA® 921

Guide for

Fire and Explosion Investigations

2017 Edition

This edition of NFPA 921, *Guide for Fire and Explosion Investigations*, was prepared by the Technical Committee on Fire Investigations. It was issued by the Standards Council on November 11, 2016, with an effective date of December 1, 2016, and supersedes all previous editions.

This document has been amended by one or more Tentative Interim Amendments (TIAs) and/or Errata. See "Codes & Standards" at www.nfpa.org for more information.

This edition of NFPA 921 was approved as an American National Standard on December 1, 2016.

Origin and Development of NFPA 921

NFPA 921, *Guide for Fire and Explosion Investigations*, was developed by the Technical Committee on Fire Investigations to assist in improving the fire investigation process and the quality of information on fires resulting from that process. The goal of the committee is to provide guidance to both public and private investigators based on accepted scientific principles and scientific research.

The first edition of the document, issued by NFPA in 1992, focused largely on the determination of the origin and cause of fires and explosions involving structures. The 1995 edition of the document included revised chapters on safety, explosions, and the collection and handling of physical evidence. NFPA 907M, *Manual for the Determination of Electrical Fire Causes*, was withdrawn as an individual document and integrated, with revisions, into NFPA 921.

The 1998 edition of the document included a new chapter on fuel gas systems in buildings and the impact of fuel gases on fire and explosion investigations. Revisions were made to the chapters on electricity and fire, fire patterns, and physical evidence. The 1998 edition also included new text regarding ignitible liquid detection canine/handler teams.

The 2001 edition of NFPA 921 was reorganized for usability and included new chapters on building systems, fire-related human behavior, failure analysis and analytical tools, fire and explosion deaths and injuries, and wildfire investigations. The 2004 edition included a revision of the document to comply with the new *Manual of Style for NFPA Technical Committee Documents*. A new chapter, "Analyzing the Incident for Cause and Responsibility," was included, and chapters relating to legal considerations and recording the scene were revised.

The 2008 edition included rewrites of Chapter 5, Basic Fire Science; Chapter 6, Fire Patterns; Chapter 17, Origin Determination; Chapter 25, Motor Vehicle Fires; and Chapter 27, Management of Complex Investigations. A new Chapter 28, Marine Fire Investigations, was added to the document.

The 2011 edition saw changes to Chapter 4, Basic Methodology, and a new section on Report Review Procedures. Chapter 12, Safety, was revised to include chemical and contamination exposure to the fire investigator. Chapter 18, Fire Cause Determination, was revised to mirror Chapter 17, following the scientific method. This edition also saw the introduction of *negative corpus* and significant rewrites of Chapter 21, Explosions; Chapter 23, Fire and Explosion Deaths and Injuries; and Chapter 26, Wildfire Investigations. Chapter 25, Motor Vehicle Fires, was substantially expanded to further address recreational vehicles and agricultural equipment. The members of the NFPA Technical Committee on Fire Investigations dedicated the 2011 edition of NFPA 921 to the memory of long-time staff liaison Frank Florence (1943–2010). Frank passed away on July 27, 2010, after a brief illness. Frank served with the Salt Lake City Fire Department for 31 years before retiring as Fire Chief. He then joined NFPA in the Public Fire Protection Division and served as the Staff Liaison for the 2001, 2004, and 2008 editions of NFPA 921. Frank was an invaluable resource to the committee and a strong supporter of the fire investigation profession.

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The 2014 edition was the first NFPA Standard to be published in color. The color photographs greatly enhance the effectiveness of the document and are especially beneficial in the chapter on Fire Patterns. In addition, the concept of negative corpus was further clarified with additional information.

A new chapter, Fire Protection Systems, was added based on the 16 knowledge topics found in NFPA 1033, *Standard for Professional Qualifications for Fire Investigator*. The chapter Analyzing the Incident for Cause and Responsibility was divided into two chapters, and the committee added information and photographs that further illustrate concepts of electrical arcing.

The 2017 edition of NFPA 921 includes many updates to accurately reflect current practices, technologies, research, and concepts. Chapter 8, Fire Protection Systems, was renamed Active Fire Protection Systems since passive systems are addressed in Chapter 7, Building Systems. The changes to Chapter 16, Documentation of the Investigation, brings the document up to date with current technology in the area of digital photography and 3D scanning. The concept of the origin matrix was included in Chapter 18, Origin. That concept addresses the impact of ventilation on origin determination. One of the most important changes can be found in the scope of NFPA 921. Chapter 1 was revised to address the misapplication of reports from the National Fire Incident Report System (NFIRS) as Fire Investigation Reports.

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Committee Scope: This Committee shall have primary responsibility for documents relating to techniques to be used in investigating fires, and equipment and facilities designed to assist or be used in developing or verifying data needed by fire investigators in the determination of the origin and development of hostile fires.

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Guide for

Fire and Explosion Investigations

2017 Edition

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NOTICE: An asterisk (*) following the number or letter designating a paragraph indicates that explanatory material on the paragraph can be found in Annex A.

This edition includes the following usability features as aids to the user. Technical changes are indicated by gray shading of the sections. An entire figure caption or table title with gray shading indicates a change to an existing figure or table. New sections, figures, and tables are indicated by a bold, italic ***N*** in a gray box to the left of the new material. Where one or more sections have been deleted, the deletion is indicated by a bullet (•) between the sections that remain.

A reference in brackets [ ] following a section or paragraph indicates material that has been extracted from another NFPA document. As an aid to the user, the complete title and edition of the source documents for extracts in advisory sections of this document are given in Chapter 2 and those for extracts in the informational sections are given in Annex C. Extracted text may be edited for consistency and style and may include the revision of internal paragraph references and other references as appropriate. Requests for interpretations or revisions of extracted text should be sent to the technical committee responsible for the source document.

Information on referenced publications can be found in Chapter 2 and Annex C.

Chapter 1 Administration

1.1 Scope. This document is designed to assist individuals who are charged with the responsibility of investigating and analyzing fire and explosion incidents and rendering opinions as to the origin, cause, responsibility, or prevention of such incidents and the damage and injuries that arise from such incidents.

N **1.1.1** The completion of reports for the United States National Fire Incident Reporting System (NFIRS) are outside the scope of this guide.

N **1.1.2** This guide considers NFIRS reports as incident reports and not as investigation reports. The information contained in an NFIRS report should generally be considered as the preliminary report of the fire department concerning any fire or explosion incident. An NFIRS report should not be used as a fire investigation report.

1.2 Purpose.

1.2.1 The purpose of this document is to establish guidelines and recommendations for the safe and systematic investigation or analysis of fire and explosion incidents. Fire investigation or analysis and the accurate listing of causes are fundamental to the protection of lives and property from the threat of hostile fire or explosions. It is through an efficient and accurate determination of the cause and responsibility that future fire incidents can be avoided. This document has been developed as a model for the advancement and practice of fire and explosion investigation, fire science, technology, and methodology.

1.2.2 Proper determination of fire origin and cause, as well as the cause of and responsibility for property damage, injuries, or deaths, is also essential for the meaningful compilation of fire statistics. Accurate statistics form part of the basis of fire prevention codes, standards, and training.

1.3 Application. This document is designed to produce a systematic, working framework or outline by which effective fire and explosion investigation and origin and cause analysis can be accomplished. It contains specific procedures to assist in the investigation of fires and explosions. These procedures represent the judgment developed from the NFPA consensus process system that if followed can improve the probability of reaching sound conclusions. Deviations from these procedures, however, are not necessarily wrong or inferior but need to be justified.

1.3.1 The reader should note that frequently the phrase *fire investigation* is used in this document when the context indicates that the relevant text refers to the investigation of both fires and explosions.

1.3.2 As every fire and explosion incident is in some way unique and different from any other, this document is not designed to encompass all the necessary components of a complete investigation or analysis of any one case. The scientific method, however, should be applied in every instance.

1.3.3 Not every portion of this document may be applicable to every fire or explosion incident. It is up to investigators (depending on their responsibility, as well as the purpose and scope of their investigation) to apply the appropriate recommended procedures in this guide to a particular incident.

1.3.4 In addition, it is recognized that the extent of the fire investigator's assignment, time and resource limitations, or existing policies may limit the degree to which the recommendations or techniques in this document will be applied in a given investigation.

1.3.5 This document is not intended as a comprehensive scientific or engineering text. Although many scientific and engineering concepts are presented within the text, the user is cautioned that these concepts are presented at an elementary level and additional technical resources, training, and education may often need to be utilized in an investigation.

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1.4 Units of Measure. Metric units of measurement in this guide are in accordance with the modernized metric system known as the International System of Units (SI). The unit of liter is outside of but recognized by SI and is commonly used in international fire protection. These units are listed in Table 1.4.

Table 1.4 SI Units and Equivalent U.S. Customary Units

SI	U.S.
Distance	
1 cm	0.394 in.
2.54 cm	1 in.
1 m	3.28 ft
0.305 m	1 ft
Area	
1 cm^2	0.155 in^2
6.45 cm^2	1 $in.^2$
1 m^2	10.8 ft^2
0.093 m^2	1 ft^2
Volume	
1 cm^3	0.34 fluid oz
29.6 cm^3	1 U.S. fluid oz
1 L	1.06 U.S. qt
0.95 L	1 U.S. qt
1 m^3	35.3 ft^3
0.028 m^3	1 ft^3
Mass	
1 g	0.353 oz.
28.25 g	1 oz.
1 kg	2.20 lb
0.454 kg	1 lb
Density	
1 g/cm^3	8.35 lb/U.S. gal
0.12 cm^3	1 lb/U.S. gal
1 kg/m^3	0.063 lb/ft^3
Flow	
1 L/sec	15.9 U.S. gal/min
0.063 L/sec	1 U.S. gal/min
Pressure	
1 bar (750 mmHg)	14.5 lb/in^2
0.069 bar	1 lb/in^2 (27.7 in. water column)
1 kPa	0.145 lb/in^2
Energy	
1 J	9.48×10^{-4} Btu
1055 J	1 Btu
1 kJ	0.948 Btu
Power	
1 kW	0.952 Btu/sec
1.06 kW	1 Btu/sec

Note: Converting from one system of measurement to another usually introduces additional significant figures to a value. The converted values should be rounded off, so that they include no more significant figures than the original measured or reported values.

1.5 Measurement Uncertainty. The reproducibility of measurements reported in this guide may be very high, such as density measurements of pure substances, or more variable, such as gas temperatures, heat release rates, or event times in test fires. Therefore, all reported measurements, or factors in equations should be evaluated to assess whether the level of precision expressed is appropriate or broadly applicable.

Chapter 2 Referenced Publications

2.1 General. The documents or portions thereof listed in this chapter are referenced within this guide.

2.2 NFPA Publications. National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02169-7471.

NFPA 13, *Standard for the Installation of Sprinkler Systems,* 2016 edition.

NFPA 13D, *Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes,* 2016 edition.

NFPA 13R, *Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies,* 2016 edition.

NFPA 30, *Flammable and Combustible Liquids Code,* 2015 edition.

NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials,* 2016 edition.

NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals,* 2015 edition.

NFPA 54, *National Fuel Gas Code,* 2015 edition.

NFPA 58, *Liquefied Petroleum Gas Code,* 2014 edition.

NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* 2013 edition.

NFPA 70®, *National Electrical Code®,* 2014 edition.

NFPA 72®, *National Fire Alarm and Signaling Code,* 2016 edition.

NFPA 77, *Recommended Practice on Static Electricity,* 2014 edition.

NFPA *101*®, *Life Safety Code®,* 2015 edition.

NFPA 120, *Standard for Fire Prevention and Control in Coal Mines,* 2015 edition.

NFPA 170, *Standard for Fire Safety and Emergency Symbols,* 2015 edition.

NFPA 220, *Standard on Types of Building Construction,* 2015 edition.

NFPA 260, *Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture,* 2013 edition.

NFPA 261, *Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes,* 2013 edition.

NFPA 302, *Fire Protection Standard for Pleasure and Commercial Motor Craft,* 2015 edition.

NFPA 303, *Fire Protection Standard for Marinas and Boatyards,* 2016 edition.

NFPA 400, *Hazardous Materials Code,* 2016 edition.

NFPA 501, *Standard on Manufactured Housing,* 2013 edition.

NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover,* 2013 edition.

NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids,* 2013 edition.

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NFPA 1033, *Standard for Professional Qualifications for Fire Investigator,* 2014 edition.

NFPA 1144, *Standard for Reducing Structure Ignition Hazards from Wildland Fire,* 2013 edition.

NFPA 1192, *Standard on Recreational Vehicles,* 2015 edition.

NFPA 1194, *Standard for Recreational Vehicle Parks and Campgrounds,* 2014 edition.

NFPA 1403, *Standard on Live Fire Training Evolutions,* 2012 edition.

NFPA 1404, *Standard for Fire Service Respiratory Protection Training,* 2013 edition.

NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program,* 2013 edition.

NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting,* 2013 edition.

NFPA 1977, *Standard on Protective Clothing and Equipment for Wildland Fire Fighting,* 2016 edition.

NFPA 1852, *Standard on Selection, Care, and Maintenance of Open-Circuit Self-Contained Breathing Apparatus (SCBA),* 2013 edition.

NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services,* 2013 edition.

NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems,* 2015 edition.

Fire Protection Handbook, 5th (1981), 17th (1991), 18th (1997), 19th (2003), and 20th (2008) edition.

Fire Protection Guide to Hazardous Materials, 2015 edition.

National Fuel Gas Code Handbook, 2015 edition.

National Fire Alarm and Signaling Code Handbook, 2016 edition.

The SFPE Engineering Guide to Human Behavior in Fire, 2003 edition.

SPP 51 Flash Point Index of Trade Name Liquids, 1978 edition.

2.3 Other Publications.

2.3.1 ABYC Publications. American Boat and Yacht Council, 613 Third Street, Suite 10, Annapolis, MD 21403.

ABYC A-3, *Galley Stoves*, 2013.

ABYC A-7, *Liquid and Solid Fueled Boat Heating Systems*, 2014.

ABYC A-26, *LPG and CNG Fueled Appliances*, 2012.

ABYC A-30, *Cooking Appliances with Integral LPG Cylinders*, 2013, RFI.

ABYC E-11, *AC & DC Electrical Systems on Boats*, 2012, RFI.

ABYC H-24.13, *Gasoline Fuel Systems*, 2012.

ABYC H-32, *Ventilation of Boats Using Diesel Fuel*, 2013 reaffirmed.

ABYC P-1, *Installation of Exhaust Systems for Propulsion and Auxiliary Engines*, 2014.

2.3.2 ANSI Publications. American National Standards Institute, Inc., 25 West 43rd Street, 4th Floor, New York, NY 10036.

ANSI Z400.1/Z129.1, *Hazardous Workplace Chemicals — Hazard Evaluation and Safety Data Sheet and Precautionary Labeling*, 2010.

ANSI Z400.1, *Material Safety Data Sheets — Preparation*, 1998.

ANSI Z535.1, *Safety Colors*, 2006, reapproved 2011.

ANSI Z535.2, *Environmental and Facility Safety Signs*, 2011.

ANSI Z535.3, *Criteria for Safety Symbols*, 2011.

ANSI Z535.4, *Product Safety Signs and Labels*, 2011.

ANSI Z535.5, *Safety Tags and Barricade Tapes (for Temporary Hazards)*, 2011.

2.3.3 API Publications. American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005-4070.

API RP 2003, *Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents,* 7th edition, 2008.

API RP 2216, *Ignition Risk of Hydrocarbon Vapors by Hot Surfaces in the Open Air,* 3rd edition, 2003, reaffirmed 2010.

2.3.4 ASME Publications. American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990.

Boiler and Pressure Vessel Code, 2013.

2.3.5 ASTM Publications. ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959.

ASTM D56, *Standard Test Method for Flash Point by Tag Closed Tester*, 2005 (2010).

ASTM D86, *Standard Test Method for Distillation of Petroleum*, 2012.

ASTM D92, *Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester*, 2012b.

ASTM D93, *Standard Test Method for Flash Point by Pensky-Martens Closed Cup Tester*, 2015a.

ASTM D1230, *Standard Test Method for Flammability of Apparel Textiles*, 2010.

ASTM D1265, *Standard Practice for Sampling Liquefied Petroleum (LP) Gases, Manual Method*, 2011.

ASTM D1310, *Standard Test Method for Flash Point and Fire Point of Liquids by Tag Open-Cup Apparatus*, 2014.

ASTM D1929, *Standard Test Method for Determining Ignition Temperature of Plastics*, 2014.

ASTM D2859, *Standard Test Method for Flammability of Finished Textile Floor Covering Materials*, 2015.

ASTM D2887, *Standard Test Method for Boiling Range Distribution of Petroleum Fractions by Gas Chromatography*, 2014.

ASTM D3065, *Standard Test Methods for Flammability of Aerosol Products*, 2001 (2013).

ASTM D3828, *Standard Test Methods for Flash Point by Small Scale Closed Tester*, 2012a.

ASTM D4809, *Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)*, 2013.

ASTM D5305, *Standard Test Method for Determination of Ethyl Mercaptan in LP-Gas Vapor*, 2012.

ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials*, 2015b.

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ASTM E108, *Standard Test Method for Fire Tests of Roof Coverings*, 2011.

ASTM E119, *Standard Methods for Fire Tests of Building Construction and Materials*, 2015.

ASTM E603, *Standard Guide for Room Fire Experiments*, 2013.

ASTM E648, *Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source*, 2015e1.

ASTM E659, *Standard Test Method for Autoignition Temperature of Liquid Chemicals*, 2015.

ASTM E681, *Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gasses)*, 2009 (2015).

ASTM E800, *Standard Guide for Measurement of Gases Present or Generated During Fires*, 2014.

ASTM E860, *Standard Practice for Examining and Preparing Items that Are or May Become Involved in Criminal or Civil Litigation*, (2013)e1.

ASTM E906/E906M, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using a Thermopile Method*, 2014.

ASTM E1188, *Standard Practice for Collection and Preservation of Information and Physical Items by a Technical Investigator*, 2011.

ASTM E1226, *Standard Test Method for Explosibility of Dust Clouds*, 2012a.

ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, 2015a.

ASTM E1355, *Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models*, 2012.

ASTM E1459, *Standard Guide for Physical Evidence Labeling and Related Documentation*, 2013.

ASTM E1491, *Standard Test Method for Minimum Autoignition Temperature of Dust Clouds*, 2006 (2012).

ASTM E1492, *Standard Practice for Receiving, Documenting, Storing, and Retrieving Evidence in a Forensic Science Laboratory*, 2011.

ASTM E1618, *Standard Guide for Ignitible Liquid Residues in Extracts from Fire Debris Samples by Gas Chromatography–Mass Spectrometry*, 2014.

ASTM E2019, *Standard Test Method for Minimum Ignition Energy of a Dust Cloud in Air*, 2003 (2013).

ASTM E2021, *Standard Test Method for Hot-Surface Ignition Temperature of Dust Layers*, 2009 (2013).

ASTM E2067,*Standard Practice for Full-Scale Oxygen Consumption Calorimetry Fire Tests*, 2012.

2.3.6 FM Global Publications. FM Global, 270 Central Avenue, P.O. Box 7500, Johnston, RI 02919.

FMC Product Safety Sign and Label System Manual, 1985.

2.3.7 Military Standards Publications. SAE, 1620 I Street, NW, Suite 210, Washington, DC 20006.

MIL-STD-202G, *Test Method for Electronic and Electrical Component Parts*, (w. Change 2) 2013.

2.3.8 SAE International Publications. SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J2578, *Recommended Practice for General Fuel Cell Vehicle Safety*, 2014.

2.3.9 UL Publications. Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096.

UL 263, *Standard for Safety Fire Tests of Building Construction and Materials*,14th edition, 2011, revised 2014.

UL 969, *Standard for Marking and Labeling Systems*, 4th edition, 1995, revised 2014.

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2.3.10 USFA Publication. U.S. Fire Administration, 16825 S. Seton Avenue, Emmitsburg, MD 21727.

"Minimum Standards on Structural Fire Fighting Protective Clothing and Equipment," 1992.

2.3.11 U.S. Government Publications. U.S. Government Publishing Office, Washington, DC 20402.

"Consumer Safety Act" (15 USC, Sections 2051–2084, and Title 16, Code of Federal Regulations, Part 1000).

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"Flammable Fabrics Act" (15 USC, Sections 1191–1204 and Title 16, Code of Federal Regulations, Parts 1615, 1616, and 1630–1632.

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NIOSH Pocket Guide to Chemical Hazards, 2010.

OSHA Regulations (Title 29, Code of Federal Regulations, Part 1910).

Title 24, Code of Federal Regulations, Part 3280, "Manufactured Home Construction and Safety Standards (HUD Standard.)"

Title 29, Code of Federal Regulations, Part 1910, "Federal Hazards Communication Standard."

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Title 33, Code of Federal Regulations, Part 181, "Manufacturer Requirements."

Title 33, Code of Federal Regulations, Part 183, "Boats and Associated Equipment."

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2.4 References for Extracts in Advisory Sections.

NFPA 3, *Recommended Practice for Commissioning of Fire Protection and Life Safety Systems,* 2015 edition.

NFPA 13, *Standard for the Installation of Sprinkler Systems,* 2016 edition.

NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres,* 2016 edition.

NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* 2013 edition.

NFPA 70®, National Electrical Code®, 2014 edition.

NFPA 72®, National Fire Alarm and Signaling Code, 2016 edition.

NFPA 318, *Standard for the Protection of Semiconductor Fabrication Facilities,* 2015 edition.

NFPA 654, *Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids,* 2013 edition.

Chapter 3 Definitions

3.1 General. The definitions contained in this chapter shall apply to the terms used in this guide. Where terms are not defined in this chapter or within another chapter, they shall be defined using their ordinarily accepted meanings within the context in which they are used. *Merriam-Webster's Collegiate Dictionary,* 11th edition, shall be the source for the ordinarily accepted meaning.

3.2 NFPA Official Definitions.

3.2.1* Approved. Acceptable to the authority having jurisdiction.

3.2.2* Code. A standard that is an extensive compilation of provisions covering broad subject matter or that is suitable for adoption into law independently of other codes and standards.

3.2.3* Guide. A document that is advisory or informative in nature and that contains only nonmandatory provisions. A guide may contain mandatory statements such as when a guide can be used, but the document as a whole is not suitable for adoption into law.

3.2.4* Recommended Practice. A document that is similar in content and structure to a code or standard but that contains only nonmandatory provisions using the word "should" to indicate recommendations in the body of the text.

3.2.5* Standard. An NFPA Standard, the main text of which contains only mandatory provisions using the word "shall" to indicate requirements and that is in a form generally suitable for mandatory reference by another standard or code or for adoption into law. Nonmandatory provisions are not to be considered a part of the requirements of a standard and shall be located in an appendix, annex, footnote, informational note, or other means as permitted in the *NFPA Manual of Style.* When used in a generic sense, such as in the phrase "standards development process" or "standards development activities," the term "standards" includes all NFPA Standards, including Codes, Standards, Recommended Practices, and Guides.

3.3 General Definitions.

3.3.1* Absolute Temperature. A temperature measured in Kelvins (K) or Rankines (R).

3.3.2 Accelerant. A fuel or oxidizer, often an ignitible liquid, intentionally used to initiate a fire or increase the rate of growth or spread of fire.

3.3.3 Accident. An unplanned event that interrupts an activity and sometimes causes injury or damage or a chance occurrence arising from unknown causes; an unexpected happening due to carelessness, ignorance, and the like.

N **3.3.4 Active Fire Protection System.** A system that uses moving mechanical or electrical parts to achieve a fire protection goal. [**3,** 2015]

3.3.5 Ambient. Someone's or something's surroundings, especially as they pertain to the local environment; for example, ambient air and ambient temperature.

3.3.6 Ampacity. The maximum current, in amperes, that a conductor can carry continuously under the conditions of use without exceeding its temperature rating. [**70,** Article 100]

3.3.7 Ampere. The unit of electric current that is equivalent to a flow of one coulomb per second; one coulomb is defined as 6.24×10^{18} electrons.

3.3.8 Arc. A high-temperature luminous electric discharge across a gap or through a medium such as charred insulation.

3.3.9 Arc Mapping. The systematic evaluation of the electrical circuit configuration, spatial relationship of the circuit components, and identification of electrical arc sites to assist in the identification of the area of origin and analysis of the fire's spread.

3.3.10 Arc Site. The location on a conductor with localized damage that resulted from an electrical arc.

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3.3.11 Arcing Through Char. Arcing associated with a matrix of charred material (e.g., charred conductor insulation) that acts as a semiconductive medium.

3.3.12 Area of Origin. A structure, part of a structure, or general geographic location within a fire scene, in which the "*point of origin*" of a fire or explosion is reasonably believed to be located. *(See also 3.3.142, Point of Origin.)*

3.3.13 Arrow Pattern. A fire pattern displayed on the cross-section of a burned wooden structural member.

3.3.14 Arson. The crime of maliciously and intentionally, or recklessly, starting a fire or causing an explosion.

3.3.15 Autoignition. Initiation of combustion by heat but without a spark or flame.

3.3.16 Autoignition Temperature. The lowest temperature at which a combustible material ignites in air without a spark or flame.

3.3.17 Backdraft. A deflagration resulting from the sudden introduction of air into a confined space containing oxygen-deficient products of incomplete combustion.

3.3.18 Bead. A rounded globule of re-solidified metal at the end of the remains of an electrical conductor that was caused by arcing and is characterized by a sharp line of demarcation between the melted and unmelted conductor surfaces.

3.3.19 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.

3.3.20 BLEVE. Boiling liquid expanding vapor explosion.

3.3.21 Bonding. The permanent joining of metallic parts to form an electrically conductive path that ensures electrical continuity and the capacity to conduct safely any current likely to be imposed.

3.3.22 British Thermal Unit (Btu). The quantity of heat required to raise the temperature of one pound of water 1°F at the pressure of 1 atmosphere and temperature of 60°F; a British thermal unit is equal to 1055 joules, 1.055 kilojoules, and 252.15 calories.

3.3.23 Burning Rate. See 3.3.105, Heat Release Rate (HRR).

3.3.24* Calcination of Gypsum. A fire effect realized in gypsum products, including wallboard, as a result of exposure to heat that drives off free and chemically bound water.

3.3.25 Calorie. The amount of heat necessary to raise 1 gram of water 1°C at the pressure of 1 atmosphere and temperature of 15°C; a calorie is 4.184 joules, and there are 252.15 calories in a British thermal unit (Btu).

3.3.26 Cause. The circumstances, conditions, or agencies that brought about or resulted in the fire or explosion incident, damage to property resulting from the fire or explosion incident, or bodily injury or loss of life resulting from the fire or explosion incident.

3.3.27 Ceiling Jet. A relatively thin layer of flowing hot gases that develops under a horizontal surface (e.g., ceiling) as a result of plume impingement and the flowing gas being forced to move horizontally.

3.3.28 Ceiling Layer. A buoyant layer of hot gases and smoke produced by a fire in a compartment.

3.3.29 Char. Carbonaceous material that has been burned or pyrolyzed and has a blackened appearance.

3.3.30 Char Blisters. Convex segments of carbonized material separated by cracks or crevasses that form on the surface of char, forming on materials such as wood as the result of pyrolysis or burning.

3.3.31 Clean Burn. A distinct and visible fire effect generally apparent on noncombustible surfaces after combustible layer(s) (such as soot, paint, and paper) have been burned away. The effect may also appear where soot has failed to be deposited because of high surface temperatures.

3.3.32* Combustible. Capable of undergoing combustion.

3.3.33* Combustible Gas Indicator. An instrument that samples air and indicates whether there are ignitible vapors or gases present.

3.3.34 Combustible Liquid. Any liquid that has a closed-cup flash point at or above 37.8°C (100°F). *(See also 3.3.85, Flammable Liquid.)*

3.3.35 Combustion. A chemical process of oxidation that occurs at a rate fast enough to produce heat and usually light in the form of either a glow or flame.

3.3.36 Combustion Products. The heat, gases, volatilized liquids and solids, particulate matter, and ash generated by combustion.

3.3.37 Competent Ignition Source. An ignition source that has sufficient energy and is capable of transferring that energy to the fuel long enough to raise the fuel to its ignition temperature. (See 19.4.2.)

3.3.38 Conduction. Heat transfer to another body or within a body by direct contact.

3.3.39 Convection. Heat transfer by circulation within a medium such as a gas or a liquid.

3.3.40 Creep. The tendency of a material to move or deform permanently to relieve stresses.

3.3.41 Current. A flow of electric charge.

3.3.42 Deductive Reasoning. The process by which conclusions are drawn by logical inference from given premises.

3.3.43 Deflagration. Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium. [**68,** 2013]

3.3.44 Density. The mass of a substance per unit volume, usually specified at standard temperature and pressure. The density of water is approximately one gram per cubic centimeter. The density of air is approximately 1.275 grams per cubic meter.

3.3.45 Detection. (1) Sensing the existence of a fire, especially by a detector from one or more products of the fire, such as smoke, heat, infrared radiation, and the like. (2) The act or process of discovering and locating a fire.

3.3.46 Detonation. Propagation of a combustion zone at a velocity greater than the speed of sound in the unreacted medium. [**68,** 2013]

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3.3.47 Diffuse Fuel. A gas, vapor, dust, particulate, aerosol, mist, fog, or hybrid mixture of these, suspended in the atmosphere, which is capable of being ignited and propagating a flame front.

3.3.48 Diffusion Flame. A flame in which fuel and air mix or diffuse together at the region of combustion.

3.3.49 Drop Down. The spread of fire by the dropping or falling of burning materials. Synonymous with "fall down."

3.3.50 Effective Fire Temperatures. Temperatures reached in fires that produce physical effects that can be related to specific temperature ranges.

3.3.51 Electric Spark. A small, incandescent particle created by some arcs.

3.3.52* Empirical Data. Factual data that is based on actual measurement, observation or direct sensory experience rather than on theory.

N **3.3.53 Energy.** A property of matter manifested as an ability to perform work, either by moving an object against a force or by transferring heat.

3.3.54 Entrainment. The process of air or gases being drawn into a fire, plume, or jet.

N **3.3.55 Explosible.** A material with a pressure ratio (maximum pressure/pressure at ignition, in absolute units) equal to or greater than 2.0 in any test when tested using the explosibility or Go/No-Go screening test described in Section 13 of ASTM E1226, *Standard Test Method for Explosibility of Dust Clouds.* [**68,** 2013]

3.3.56 Explosion. The sudden conversion of potential energy (chemical or mechanical) into kinetic energy with the production and release of gases under pressure, or the release of gas under pressure. These high-pressure gases then do mechanical work such as moving, changing, or shattering nearby materials.

N **3.3.57 Explosion Dynamics.** Study of how chemistry, physics, fire science, engineering disciplines of fluid and solid mechanics, and heat transfer interact to influence explosion behavior.

3.3.58 Explosive. Any chemical compound, mixture, or device that functions by explosion.

3.3.59 Explosive Material. Any material that can act as fuel for an explosion.

3.3.60 Exposed Surface. The side of a structural assembly or object that is directly exposed to the fire.

3.3.61 Extinguish. To cause to cease burning.

3.3.62 Failure. Distortion, breakage, deterioration, or other fault in an item, component, system, assembly, or structure that results in unsatisfactory performance of the function for which it was designed.

3.3.63 Failure Analysis. A logical, systematic examination of an item, component, assembly, or structure and its place and function within a system, conducted in order to identify and analyze the probability, causes, and consequences of potential and real failures.

3.3.64 Fall Down. See 3.3.49, Drop Down.

3.3.65 Finish Rating. The time in minutes, determined under specific laboratory conditions, at which the stud or joist in contact with the exposed protective membrane in a protected combustible assembly reaches an average temperature rise of 121°C (250°F) or an individual temperature rise of 163°C (325°F) as measured behind the protective membrane nearest the fire on the plane of the wood.

3.3.66 Fire. A rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities.

3.3.67 Fire Analysis. The process of determining the origin, cause, development, responsibility, and, when required, a failure analysis of a fire or explosion.

N **3.3.68 Fire Area.** The boundary of fire effects within a scene in which the area of origin will be located. The fire area is characterized by identifying the border between damaged and undamaged areas, which are distinguishable by fire effects and patterns created by flame, heat, and smoke.

3.3.69 Fire Cause. The circumstances, conditions, or agencies that bring together a fuel, ignition source, and oxidizer (such as air or oxygen) resulting in a fire or a combustion explosion.

3.3.70* Fire Dynamics. The detailed study of how chemistry, fire science, and the engineering disciplines of fluid mechanics and heat transfer interact to influence fire behavior.

N **3.3.71 Fire Effects.** The observable or measurable changes in or on a material as a result of a fire.

3.3.72 Fire Hazard. Any situation, process, material, or condition that can cause a fire or explosion or that can provide a ready fuel supply to augment the spread or intensity of a fire or explosion, all of which pose a threat to life or property.

3.3.73 Fire Investigation. The process of determining the origin, cause, and development of a fire or explosion.

3.3.74 Fire Patterns. The visible or measurable physical changes, or identifiable shapes, formed by a fire effect or group of fire effects.

3.3.75 Fire Propagation. See 3.3.78, Fire Spread.

3.3.76 Fire Scene Reconstruction. The process of recreating the physical scene during fire scene analysis investigation or through the removal of debris and the placement of contents or structural elements in their pre-fire positions.

3.3.77* Fire Science. The body of knowledge concerning the study of fire and related subjects (such as combustion, flame, products of combustion, heat release, heat transfer, fire and explosion chemistry, fire and explosion dynamics, thermodynamics, kinetics, fluid mechanics, fire safety) and their interaction with people, structures, and the environment.

3.3.78 Fire Spread. The movement of fire from one place to another.

3.3.79 First Fuel Ignited. The first fuel ignited is that which first sustains combustion beyond the ignition source.

3.3.80 Flame. A body or stream of gaseous material involved in the combustion process and emitting radiant energy at specific wavelength bands determined by the combustion chemistry of the fuel. In most cases, some portion of the emitted radiant energy is visible to the human eye. [**72,** 2013]

3.3.81 Flame Front. The flaming leading edge of a propagating combustion reaction zone.

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3.3.82 Flameover. The condition where unburned fuel (pyrolysate) from the originating fire has accumulated in the ceiling layer to a sufficient concentration (i.e., at or above the lower flammable limit) that it ignites and burns; can occur without ignition of, or prior to, the ignition of other fuels separate from the origin.

3.3.83 Flammable. Capable of burning with a flame.

3.3.84 Flammable Limit. The upper or lower concentration limit at a specified temperature and pressure of a flammable gas or a vapor of an ignitible liquid and air, expressed as a percentage of fuel by volume that can be ignited.

3.3.85 Flammable Liquid. A liquid that has a closed-cup flash point that is below 37.8°C (100°F) and a maximum vapor pressure of 2068 mm Hg (40 psia) at 37.8°C (100°F). *(See also 3.3.34, Combustible Liquid.)*

3.3.86 Flammable Range. The range of concentrations between the lower and upper flammable limits. [**68,** 2013]

3.3.87 Flash Fire. A fire that spreads by means of a flame front rapidly through a diffuse fuel, such as dust, gas, or the vapors of an ignitible liquid, without the production of damaging pressure.

3.3.88 Flash Point of a Liquid. The lowest temperature of a liquid, as determined by specific laboratory tests, at which the liquid gives off vapors at a sufficient rate to support a momentary flame across its surface.

3.3.89 Flashover. A transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full room involvement or total involvement of the compartment or enclosed space.

3.3.90 Forensic (Forensic Science). The application of science to answer questions of interest to the legal system.

3.3.91 Fuel. A material that will maintain combustion under specified environmental conditions. [**53,** 2011]

3.3.92 Fuel Gas. Natural gas, manufactured gas, LP-Gas, and similar gases commonly used for commercial or residential purposes such as heating, cooling, or cooking.

3.3.93 Fuel Load. The total quantity of combustible contents of a building, space, or fire area, including interior finish and trim, expressed in heat units or the equivalent weight in wood.

3.3.94 Fuel-Controlled Fire. A fire in which the heat release rate and growth rate are controlled by the characteristics of the fuel, such as quantity and geometry, and in which adequate air for combustion is available.

3.3.95* Full Room Involvement. Condition in a compartment fire in which the entire volume is involved in combustion of varying intensities.

3.3.96 Gas. The physical state of a substance that has no shape or volume of its own and will expand to take the shape and volume of the container or enclosure it occupies.

3.3.97 Glowing Combustion. Luminous burning of solid material without a visible flame.

3.3.98 Ground. A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and earth or to some conducting body that serves in place of the earth.

3.3.99 Ground Fault. An unintended current that flows outside the normal circuit path, such as (a) through the equipment grounding conductor; (b) through conductive material in contact with lower potential (such as earth), other than the electrical system ground (metal water or plumbing pipes, etc.); or (c) through a combination of these ground return paths.

3.3.100 Hazard. Any arrangement of materials that presents the potential for harm.

3.3.101* Heat. A form of energy characterized by vibration of molecules and capable of initiating and supporting chemical changes and changes of state.

3.3.102 Heat and Flame Vector. An arrow used in a fire scene drawing to show the direction of heat, smoke, or flame flow.

3.3.103 Heat Flux. The measure of the rate of heat transfer to a surface or an area, typically expressed in kW/m^2, or W/cm^2.

3.3.104* Heat of Ignition. The heat energy that brings about ignition.

3.3.105* Heat Release Rate (HRR). The rate at which heat energy is generated by burning.

N **3.3.106 Heat Transfer.** The exchange of thermal energy between materials through conduction, convection, and/or radiation.

3.3.107 High Explosive. A material that is capable of sustaining a reaction front that moves through the unreacted material at a speed equal to or greater than that of sound in that medium [typically 1000 m/sec (3000 ft/sec)]; a material capable of sustaining a detonation. *(See also 3.3.46, Detonation.)*

3.3.108 High-Order Damage. A rapid pressure rise or high-force explosion characterized by a shattering effect on the confining structure or container and long missile distances.

N **3.3.109* Hybrid Mixture.** An explosible heterogeneous mixture, comprising gas with suspended solid or liquid particulates, in which the total flammable gas concentration is ≥10 percent of the lower flammable limit (LFL) and the total suspended particulate concentration is ≥10 percent of the minimum explosible concentration (MEC). [**68,** 2013]

3.3.110 Hypergolic Material. Any substance that will spontaneously ignite or explode upon exposure to an oxidizer.

3.3.111 Ignitible Liquid. Any liquid or the liquid phase of any material that is capable of fueling a fire, including a flammable liquid, combustible liquid, or any other material that can be liquefied and burned.

3.3.112 Ignition. The process of initiating self-sustained combustion.

3.3.113 Ignition Energy. The quantity of heat energy that should be absorbed by a substance to ignite and burn.

3.3.114* Ignition Temperature. Minimum temperature a substance should attain in order to ignite under specific test conditions.

3.3.115 Ignition Time. The time between the application of an ignition source to a material and the onset of self-sustained combustion.

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3.3.116 Incendiary Fire. A fire that is intentionally ignited in an area or under circumstances where and when there should not be a fire *(see 20.1.3, Chapter 24, and 28.8.2).*

3.3.117 Inductive Reasoning. The process by which a person starts from a particular experience and proceeds to generalizations. The process by which hypotheses are developed based upon observable or known facts and the training, experience, knowledge, and expertise of the observer.

3.3.118 Interested Party. Any person, entity, or organization, including their representatives, with statutory obligations or whose legal rights or interests may be affected by the investigation of a specific incident.

3.3.119 Investigation Site. For the purpose of Chapter 29, the terms "site" and "scene" will be jointly referred to as the "investigation site," unless the particular context requires the use of one or the other word.

3.3.120 Investigative Team. A group of individuals working on behalf of an interested party to conduct an investigation into the incident.

3.3.121 Isochar. A line on a diagram connecting points of equal char depth.

3.3.122 Joule. The preferred SI unit of heat, energy, or work. A joule is the heat produced when one ampere is passed through a resistance of one ohm for one second, or it is the work required to move a distance of one meter against a force of one newton. There are 4.184 joules in a calorie, and 1055 joules in a British thermal unit (Btu). A watt is a joule/second. *[See also 3.3.22, British Thermal Unit (Btu), and 3.3.25, Calorie.]*

3.3.123 Kilowatt. A measurement of energy release rate.

3.3.124 Kindling Temperature. See 3.3.114, Ignition Temperature.

3.3.125 Layering. The systematic process of removing debris from the top down and observing the relative location of artifacts at the fire scene.

3.3.126 Low Explosive. An explosive that has a reaction velocity of less than 1000 m/sec (3000 ft/sec).

3.3.127 Low-Order Damage. A slow rate of pressure rise or low-force explosion characterized by a pushing or dislodging effect on the confining structure or container and by short missile distances.

3.3.128 Material First Ignited. The fuel that is first set on fire by the heat of ignition; to be meaningful, both a type of material and a form of material should be identified.

N **3.3.129 Minimum Explosible Concentration (MEC).** The minimum concentration of a combustible dust cloud that is capable of propagating a deflagration through a uniform mixture of the dust and air under the specified conditions of test. [**68,** 2013]

3.3.130* Noncombustible Material. A material that, in the form in which it is used and under the condition anticipated, will not ignite, burn, support combustion, or release flammable vapors when subjected to fire or heat.

3.3.131 Nonflammable. (1) Not readily capable of burning with a flame. (2) Not liable to ignite and burn when exposed to flame. Its antonym is *flammable.*

3.3.132 Ohm. The SI unit of electrical impedance or, in the direct current case, electrical resistance.

3.3.133 Origin. The general location where a fire or explosion began. *(See 3.3.142, Point of Origin, or 3.3.12, Area of Origin.)*

3.3.134 Overcurrent. Any current in excess of the rated current of equipment or the ampacity of a conductor; it may result from an overload *(see 3.3.136),* short circuit *(3.3.167),* or ground fault *(3.3.99).*

3.3.135 Overhaul. A fire fighting term involving the process of final extinguishment after the main body of the fire has been knocked down. All traces of fire must be extinguished at this time.

3.3.136* Overload. Operation of equipment in excess of normal, full-load rating or of a conductor in excess of rated ampacity that,where it persists for a sufficient length of time would cause damage or dangerous overheating. A fault, such as a short circuit or ground fault, is not an overload.

3.3.137 Oxygen Deficiency. Insufficiency of oxygen to support combustion. *(See also 3.3.200, Ventilation-Controlled Fire.)*

N **3.3.138 Passive Fire Protection System.** Any portion of a building or structure that provides protection from fire or smoke without any type of system activation or movement. [**3,** 2015]

3.3.139 Piloted Ignition Temperature. See 3.3.114, Ignition Temperature.

3.3.140* Plastic. Any of a wide range of natural or synthetic organic materials of high molecular weight that can be formed by pressure, heat, extrusion, and other methods into desired shapes.

3.3.141 Plume. The column of hot gases, flames, and smoke rising above a fire; also called *convection column, thermal updraft,* or *thermal column.*

3.3.142 Point of Origin. The exact physical location within the area of origin where a heat source and a fuel first interact, resulting in a fire or explosion.

N **3.3.143 Power.** A property of a process, such as fire, which describes the amount of energy that is emitted, transferred, or received per unit time and is measured in joules per second (J/s) or watts (W).

3.3.144 Premixed Flame. A flame for which the fuel and oxidizer are mixed prior to combustion, as in a laboratory Bunsen burner or a gas cooking range; propagation of the flame is governed by the interaction between flow rate, transport processes, and chemical reaction.

3.3.145 Preservation. Application or use of measures to prevent damage, change or alteration, or deterioration.

3.3.146 Products of Combustion. See 3.3.36, Combustion Products.

3.3.147 Protocol. A description of the specific procedures and methodologies by which a task or tasks are to be accomplished.

3.3.148 Proximate Cause. The cause that directly produces the effect without the intervention of any other cause.

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3.3.149 Pyrolysate. Product of decomposition through heat; a product of a chemical change caused by heating.

3.3.150 Pyrolysis. A process in which material is decomposed, or broken down, into simpler molecular compounds by the effects of heat alone; pyrolysis often precedes combustion.

3.3.151 Pyrophoric Material. Any substance that spontaneously ignites upon exposure to atmospheric oxygen.

3.3.152 Radiant Heat. Heat energy carried by electromagnetic waves that are longer than visible light waves and shorter than radio waves; radiant heat (electromagnetic radiation) increases the sensible temperature of any substance capable of absorbing the radiation, especially solid and opaque objects.

3.3.153 Radiation. Heat transfer by way of electromagnetic energy.

3.3.154 Rate of Heat Release. See 3.3.105, Heat Release Rate (HRR).

3.3.155 Rekindle. A return to flaming combustion after apparent but incomplete extinguishment.

3.3.156 Responsibility. The accountability of a person or other entity for the event or sequence of events that caused the fire or explosion, spread of the fire, bodily injuries, loss of life, or property damage.

3.3.157 Risk. The degree of peril; the possible harm that might occur that is represented by the statistical probability or quantitative estimate of the frequency or severity of injury or loss.

3.3.158 Rollover. See 3.3.82, Flameover.

3.3.159 Scene. The general physical location of a fire or explosion incident (geographic area, structure or portion of a structure, vehicle, boat, piece of equipment, etc.) designated as important to the investigation because it may contain physical damage or debris, evidence, victims, or incident-related hazards.

3.3.160 Scientific Method. The systematic pursuit of knowledge involving the recognition and definition of a problem; the collection of data through observation and experimentation; analysis of the data; the formulation, evaluation and testing of hypotheses; and, where possible, the selection of a final hypothesis.

3.3.161 Seat of Explosion. A craterlike indentation created at the point of origin of some explosions.

3.3.162 Seated Explosion. An explosion with a highly localized point of origin, such as a crater.

3.3.163 Secondary Explosion. Any subsequent explosion resulting from an initial explosion.

3.3.164 Self-Heating. The result of exothermic reactions, occurring spontaneously in some materials under certain conditions, whereby heat is generated at a rate sufficient to raise the temperature of the material.

3.3.165 Self-Ignition. Ignition resulting from self-heating, synonymous with *spontaneous ignition*.

3.3.166 Self-Ignition Temperature. The minimum temperature at which the self-heating properties of a material lead to ignition.

3.3.167 Short Circuit. An abnormal connection of low resistance between normal circuit conductors where the resistance is normally much greater; this is an overcurrent situation but it is not an overload.

3.3.168 Site. The general physical location of the incident, including the scene and the surrounding area deemed significant to the process of the investigation and support areas.

3.3.169 Smoke. The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass. [**318**, 2012]

3.3.170 Smoke Condensate. The condensed residue of suspended vapors and liquid products of incomplete combustion.

3.3.171 Smoke Explosion. See 3.3.17, Backdraft.

3.3.172 Smoldering. Combustion without flame, usually with incandescence and smoke.

3.3.173 Soot. Black particles of carbon produced in a flame.

3.3.174 Spalling. Chipping or pitting of concrete or masonry surfaces.

3.3.175 Spark. A moving particle of solid material that emits radiant energy due either to its temperature or the process of combustion on its surface. [**654,** 2013]

3.3.176 Specific Gravity (air) (vapor density). The ratio of the average molecular weight of a gas or vapor to the average molecular weight of air.

3.3.177 Specific Gravity (of a liquid or solid). The ratio of the mass of a given volume of a substance to the mass of an equal volume of water at a temperature of 4°C.

3.3.178 Spoliation. Loss, destruction, or material alteration of an object or document that is evidence or potential evidence in a legal proceeding by one who has the responsibility for its preservation.

3.3.179* Spontaneous Heating. Process whereby a material increases in temperature without drawing heat from its surroundings.

3.3.180 Spontaneous Ignition. Initiation of combustion of a material by an internal chemical or biological reaction that has produced sufficient heat to ignite the material.

3.3.181 Suppression. The sum of all the work done to extinguish a fire, beginning at the time of its discovery.

3.3.182 Target Fuel. A fuel that is subject to ignition by thermal radiation such as from a flame or a hot gas layer.

3.3.183* Temperature. The degree of sensible heat of a body as measured by a thermometer or similar instrument.

3.3.184 Thermal Column. See 3.3.141, Plume.

3.3.185* Thermal Expansion. The increase in length, volume, or surface area of a body with rise in temperature.

3.3.186 Thermal Inertia. The properties of a material that characterize its rate of surface temperature rise when exposed to heat; related to the product of the material's thermal conductivity *(k)*, its density (ρ), and its heat capacity *(c)*.

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N **3.3.187 Thermodynamics.** The branch of physics that deals with the relationship between heat and other forms of energy.

3.3.188 Thermometry. The study of the science, methodology, and practice of temperature measurement.

3.3.189 Thermoplastic. Plastic materials that soften and melt under exposure to heat and can reach a flowable state.

3.3.190 Thermoset Plastics. Plastic materials that are hardened into a permanent shape in the manufacturing process and are not commonly subject to softening when heated; typically form char in a fire.

3.3.191 Time Line. Graphic representation of the events in a fire incident displayed in chronological order.

3.3.192 Total Burn. A fire scene where a fire continued to burn until most combustibles were consumed and the fire self extinguished due to a lack of fuel or was extinguished when the fuel load was reduced by burning and there was sufficient suppression agent application to extinguish the fire.

3.3.193 Trailer. Solid or liquid fuel used to intentionally spread or accelerate the spread of a fire from one area to another.

3.3.194 Understanding or Agreement. A written or oral consensus between the interested parties concerning the management of the investigations.

3.3.195 Upper Layer. See 3.3.28, Ceiling Layer.

3.3.196 Vapor. The gas phase of a substance, particularly of those that are normally liquids or solids at ordinary temperatures. *(See also 3.3.96, Gas.)*

3.3.197 Vapor Density. See 3.3.176, Specific Gravity (air) (vapor density).

3.3.198 Vent. An opening for the passage of, or dissipation of, fluids, such as gases, fumes, smoke, and the like.

3.3.199 Ventilation. Circulation of air in any space by natural wind or convection or by fans blowing air into or exhausting air out of a building; a fire-fighting operation of removing smoke and heat from the structure by opening windows and doors or making holes in the roof.

3.3.200 Ventilation-Controlled Fire. A fire in which the heat release rate or growth is controlled by the amount of air available to the fire.

3.3.201 Venting. The escape of smoke and heat through openings in a building.

3.3.202 Volt (V). The unit of electrical pressure (electromotive force) represented by the symbol "E"; the difference in potential required to make a current of one ampere flow through a resistance of one ohm.

3.3.203 Watt (W). Unit of power, or rate of work, equal to one joule per second, or the rate of work represented by a current of one ampere under the potential of one volt.

3.3.204 Work Plans. An outline of the tasks to be completed as part of the investigation including the order or timeline for completion. See Chapter 15, Planning the Investigation.

Chapter 4 Basic Methodology

4.1* Nature of Fire Investigations. A fire or explosion investigation is a complex endeavor involving skill, technology, knowledge, and science. The compilation of factual data, as well as an analysis of those facts, should be accomplished objectively, truthfully, and without expectation bias, preconception, or prejudice. The basic methodology of the fire investigation should rely on the use of a systematic approach and attention to all relevant details. The use of a systematic approach often will uncover new factual data for analysis, which may require previous conclusions to be reevaluated. With few exceptions, the proper methodology for a fire or explosion investigation is to first determine and establish the origin(s), then investigate the cause: circumstances, conditions, or agencies that brought the ignition source, fuel, and oxidant together.

4.2 Systematic Approach. The systematic approach recommended is based on the scientific method, which is used in the physical sciences. This method provides an organizational and analytical process that is desirable and necessary in a successful fire investigation.

4.3 Relating Fire Investigation to the Scientific Method. The scientific method *(see Figure 4.3)* is a principle of inquiry that forms a basis for legitimate scientific and engineering processes, including fire incident investigation. It is applied using the following steps outlined in 4.3.1 through 4.3.10.

4.3.1 Recognize the Need. First, one should determine that a problem exists. In this case, a fire or explosion has occurred and the cause should be determined and listed so that future, similar incidents can be prevented.

4.3.2 Define the Problem. Having determined that a problem exists, the investigator or analyst should define the manner in which the problem can be solved. In this case, a proper origin

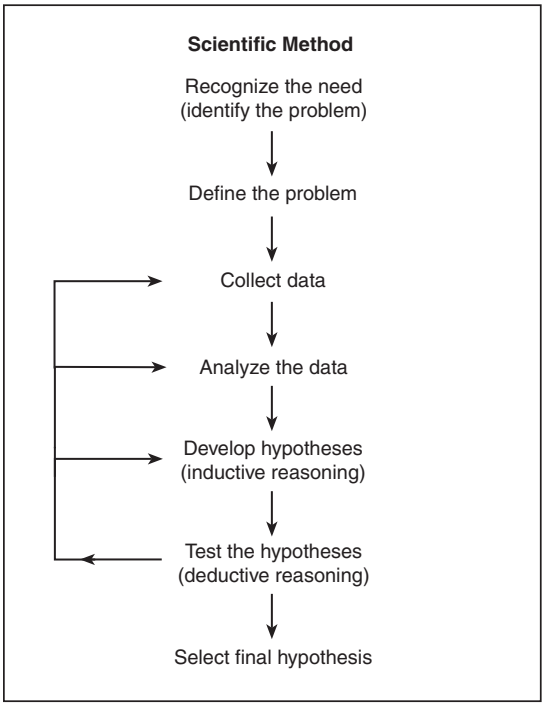


FIGURE 4.3 Use of the Scientific Method.

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and cause investigation should be conducted. This is done by an examination of the scene and by a combination of other data collection methods, such as the review of previously conducted investigations of the incident, the interviewing of witnesses or other knowledgeable persons, and the results of scientific testing.

4.3.3 Collect Data. Facts about the fire incident are now collected by observation, experiment, or other direct data-gathering means. The data collected is called empirical data because it is based on observation or experience and is capable of being verified or known to be true.

4.3.4* Analyze the Data. The scientific method requires that all data collected be analyzed. This is an essential step that must take place before the formation of the final hypothesis. The identification, gathering, and cataloging of data does not equate to data analysis. Analysis of the data is based on the knowledge, training, experience, and expertise of the individual doing the analysis. If the investigator lacks expertise to properly attribute meaning to a piece of data, then assistance should be sought. Understanding the meaning of the data will enable the investigator to form hypotheses based on the evidence, rather than on speculation.

4.3.5* Develop a Hypothesis (Inductive Reasoning). Based on the data analysis, the investigator produces a hypothesis, or hypotheses, to explain the phenomena, whether it be the nature of fire patterns, fire spread, identification of the origin, the ignition sequence, the fire cause, or the causes of damage or responsibility for the fire or explosion incident. This process is referred to as inductive reasoning. These hypotheses should be based solely on the empirical data that the investigator has collected through observation and then developed into explanations for the event, which are based upon the investigator's knowledge, training, experience, and expertise.

4.3.6* Test the Hypothesis (Deductive Reasoning). The investigator does not have a valid or reliable conclusion unless the hypothesis can stand the test of careful and serious challenge. Testing of the hypothesis is done by the principle of deductive reasoning, in which the investigator compares the hypothesis to all known facts as well as the body of scientific knowledge associated with the phenomena relevant to the specific incident. Testing of a hypothesis should be designed to disprove, or refute, the hypothesis. This may also be referred to as falsification of the hypothesis. Working to disprove a hypothesis is an attempt to find all the data or reasons why the hypothesis is not supported or not true, rather than simply finding and relying on data that support the hypothesis or why the hypothesis is true. This method of testing the hypothesis can prevent "confirmation bias," which can occur when the hypothesis or conclusion relies only on supporting data *(see 4.3.10)*. A hypothesis can be tested physically by conducting experiments, analytically by applying accepted scientific principles, or by referring to scientific research. When relying on the research of others, the investigator or analyst must ensure that the conditions, circumstances, and variables of the research and those of the hypothesis are sufficiently similar. Whenever the investigator relies on research as a means of hypothesis testing, references to the research relied upon should be acknowledged and cited. If the hypothesis is refuted or not supported, it should be discarded and alternate hypotheses should be developed and tested. This may require the collection of new data or the reanalysis of existing data. The testing process needs to be continued until all feasible hypotheses have been tested and one is determined to be uniquely consistent with the facts and with the principles of science. If no hypothesis can withstand an examination by deductive reasoning, the issue should be considered undetermined.

4.3.6.1* Any hypothesis that is incapable of being tested either physically or analytically, is an invalid hypothesis. A hypothesis developed based on the absence of data is an example of a hypothesis that is incapable of being tested. The inability to refute a hypothesis does not mean that the hypothesis is true.

N **4.3.7 Select Final Hypothesis.** The final step in applying the scientific method is to select the final hypothesis. Once the hypothesis has been tested, the investigator should review the entire process to ensure that all credible data are accounted for and all feasible alternate hypotheses have been considered and eliminated. When using the scientific method, the failure to consider alternate hypotheses is a serious error. A critical question to be answered is, "Are there any other hypotheses that are consistent with the data?" The investigator should document the facts that support the final hypothesis to the exclusion of all other reasonable hypotheses.

4.3.8 Avoid Presumption. Until data have been collected, no specific hypothesis can be reasonably formed or tested. All investigations of fire and explosion incidents should be approached by the investigator without presumption as to origin, ignition sequence, cause, fire spread, or responsibility for the incident until the use of the scientific method has yielded testable hypotheses, which cannot be disproved by rigorous testing.

4.3.9 Expectation Bias. Expectation bias is a well-established phenomenon that occurs in scientific analysis when investigator(s) reach a premature conclusion without having examined or considered all of the relevant data. Instead of collecting and examining all of the data in a logical and unbiased manner to reach a scientifically reliable conclusion, the investigator(s) uses the premature determination to dictate investigative processes, analyses, and, ultimately, conclusions, in a way that is not scientifically valid. The introduction of expectation bias into the investigation results in the use of only that data that supports this previously formed conclusion and often results in the misinterpretation and/or the discarding of data that does not support the original opinion. Investigators are strongly cautioned to avoid expectation bias through proper use of the scientific method.

4.3.10* Confirmation Bias. Different hypotheses may be compatible with the same data. When using the scientific method, testing of hypotheses should be designed to disprove a hypothesis (i.e., falsification of the hypothesis), rather than relying only on confirming data that support the hypothesis. Confirmation bias occurs when the investigator relies exclusively on data that supports the hypothesis and fails to look for, ignores, or dismisses contradictory or nonsupporting data. The same data may support alternate and even opposing hypotheses. The failure to consider alternate or opposing hypotheses, or prematurely discounting seemingly contradictory data without appropriate analysis and testing can result in incorrect conclusions. A hypothesis can be said to be valid only when rigorous testing has failed to disprove the hypothesis. Disproving the hypothesis is a process in which all the evidence is compared against the proffered hypothesis in an effort to find why the hypothesis is not true.

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4.4 Basic Method of a Fire Investigation. Using the scientific method in most fire or explosion incidents should involve the steps shown in 4.4.1 through 4.4.6.

4.4.1 Receiving the Assignment. The investigator should be notified of the incident, told what his or her role will be, and told what he or she is to accomplish. For example, the investigator should know if he or she is expected to determine the origin, cause, and responsibility; produce a written or oral report; prepare for criminal or civil litigation; make suggestions for code enforcement, code promulgation, or changes; make suggestions to manufacturers, industry associations, or government agency action; or determine some other results.

4.4.2 Preparing for the Investigation. The investigator should marshal his or her forces and resources and plan the conduct of the investigation. Preplanning at this stage can greatly increase the efficiency and therefore the chances for success of the overall investigation. Estimating what tools, equipment, and personnel (both laborers and experts) will be needed can make the initial scene investigation, as well as subsequent investigative examinations and analyses, go more smoothly and be more productive.

4.4.3 Conducting the Investigation.

4.4.3.1 It is during this stage of the investigation that an examination of the incident fire or explosion scene is conducted. The fundamental purpose of conducting an examination of any incident scene is to collect all of the available data and document the incident scene. The investigator should conduct an examination of the scene if it is available and collect data necessary to the analysis.

4.4.3.2 The actual investigation may include different steps and procedures, which will be determined by the purpose of the assignment. These steps and procedures are described in detail elsewhere in the document. A fire or explosion investigation may include all or some of the following tasks: a scene inspection or review of previous scene documentation done by others; scene documentation through photography and diagramming; evidence recognition, documentation, and preservation; witness interviews; review and analysis of the investigations of others; and identification and collection of data from other appropriate sources.

4.4.3.3 In any incident scene investigation, it is necessary for at least one individual/organization to conduct an examination of the incident scene for the purpose of data collection and documentation. While it is preferable that all subsequent investigators have the opportunity to conduct an independent examination of the incident scene, in practice, not every scene is available at the time of the assignment. The use of previously collected data from a properly documented scene can be used successfully in an analysis of the incident to reach valid conclusions through the appropriate use of the scientific method. Thus, the reliance on previously collected data and scene documentation should not be inherently considered a limitation in the ability to successfully investigate the incident.

4.4.3.4 The goal of all investigators is to arrive at accurate determinations related to the origin, cause, fire spread, and responsibility for the incident. Improper scene documentation can impair the opportunity of other interested parties to obtain the same evidentiary value from the data. This potential impairment underscores the importance of performing comprehensive scene documentation and data collection.

4.4.4 Collecting and Preserving Evidence. Valuable physical evidence should be recognized, documented, properly collected, and preserved for further testing and evaluation or courtroom presentation.

4.4.5 Analyzing the Incident. All collected and available data should be analyzed using the principles of the scientific method. Depending on the nature and scope of one's assignment, hypotheses should be developed and tested explaining the origin, ignition sequence, fire spread, fire cause or causes of damage or casualties, or responsibility for the incident.

4.4.6 Conclusions. Conclusions, which are final hypotheses, are drawn as a result of testing the hypotheses. Conclusions should be drawn according to the principles expressed in this guide and reported appropriately.

4.5 Level of Certainty. The level of certainty describes how strongly someone holds an opinion (conclusion). Someone may hold any opinion to a higher or lower level of certainty. That level is determined by assessing the investigator's confidence in the data, in the analysis of that data, and testing of hypotheses formed. That level of certainty may determine the practical application of the opinion, especially in legal proceedings.

4.5.1 The investigator should know the level of certainty that is required for providing expert opinions. Two levels of certainty commonly used are probable and possible:

(1) Probable. This level of certainty corresponds to being more likely true than not. At this level of certainty, the likelihood of the hypothesis being true is greater than 50 percent.
(2) Possible. At this level of certainty, the hypothesis can be demonstrated to be feasible but cannot be declared probable. If two or more hypotheses are equally likely, then the level of certainty must be "possible."

4.5.2 If the level of certainty of an opinion is merely "suspected," the opinion does not qualify as an expert opinion. If the level of certainty is only "possible," the opinion should be specifically expressed as "possible." Only when the level of certainty is considered "probable" should an opinion be expressed with reasonable certainty.

4.5.3 Expert Opinions. Many courts have set a threshold of certainty for the investigator to be able to render opinions in court, such as "proven to an acceptable level of certainty," "a reasonable degree of scientific and engineering certainty," or "reasonable degree of certainty within my profession." While these terms of art may be important for the specific jurisdiction or court in which they apply, defining these terms in those contexts is beyond the scope of this document.

4.6 Review Procedure. A review of a fire investigator's work product (e.g., reports, documentation, notes, diagrams, photos, etc.) by other persons may be helpful, but there are certain limitations. This section describes the types of reviews and their appropriate uses and limitations.

4.6.1 Administrative Review. An administrative review is one typically carried out within an organization to ensure that the investigator's work product meets the organization's quality assurance requirements. An administrative reviewer will determine whether all of the steps outlined in an organization's procedure manual, or required by agency policy, have been followed and whether all of the appropriate documentation is

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present in the file, and may check for typographical or grammatical errors.

4.6.1.1 Limitations of Administrative Reviews. An administrative reviewer may not necessarily possess all of the knowledge, skills, and abilities of the investigator or of a technical reviewer. As such, the administrative reviewer may not be able to provide a substantive critique of the investigator's work product.

4.6.2 Technical Review. A technical review can have multiple facets. If a technical reviewer has been asked to critique all aspects of the investigator's work product, then the technical reviewer should be qualified and familiar with all aspects of proper fire investigation and should, at a minimum, have access to all of the documentation available to the investigator whose work is being reviewed. If a technical reviewer has been asked to critique only specific aspects of the investigator's work product, then the technical reviewer should be qualified and familiar with those specific aspects and, at a minimum, have access to all documentation relevant to those aspects. A technical review can serve as an additional test of the various aspects of the investigator's work product.

4.6.2.1 Limitations of Technical Reviews. While a technical review may add significant value to an investigation, technical reviewers may be perceived as having an interest in the outcome of the review. Confirmation bias (attempting to confirm a hypothesis rather than attempting to disprove it) is a subset of expectation bias *(see 4.3.9)*. This kind of bias can be introduced in the context of working relationships or friendships. Investigators who are asked to review a colleague's findings should strive to maintain a level of professional detachment.

4.6.3 Peer Review. Peer review is a formal procedure generally employed in prepublication review of scientific or technical documents and screening of grant applications by research-sponsoring agencies. Peer review carries with it connotations of both independence and objectivity. Peer reviewers should not have any interest in the outcome of the review. The author does not select the reviewers, and reviews are often conducted anonymously. As such, the term "peer review" should not be applied to reviews of an investigator's work by coworkers, supervisors, or investigators from agencies conducting investigations of the same incident. Such reviews are more appropriately characterized as "technical reviews," as described above.

4.6.3.1 The methodologies used and the fire science relied on by an investigator are subject to peer review. For example, NFPA 921 is a peer-reviewed document describing the methodologies and science associated with proper fire and explosion investigations.

4.6.3.2 Limitations of Peer Reviews. Peer reviewers should have the expertise to detect logic flaws and inappropriate applications of methodology or scientific principles, but because they generally have no basis to question an investigator's data, they are unlikely to be able to detect factual errors or incorrectly reported data. Conclusions based on incorrect data are likely to be incorrect themselves. Because of these limitations, a proper technical review will provide the best means to adequately assess the validity of the investigation's results.

4.7 Reporting Procedure. The reporting procedure may take many written or oral forms, depending on the specific responsibility of the investigator. Pertinent information should be reported in a proper form and forum to help prevent recurrence.

Chapter 5 Basic Fire Science

5.1 Introduction. The fire investigator should have an understanding of ignition and combustion principles and should be able to use them to help in the identification and interpretation of evidence at the fire scene and in the development and testing of hypotheses regarding the origin and cause of the fire. The body of knowledge associated with combustion and fire could easily fill several textbooks. The discussion presented in this chapter should be considered introductory. *(See Annex A and Annex C for additional information.)*

N **5.1.1* Fire and Energy.** Fire is a rapid oxidation process, which is an exothermic chemical reaction, resulting in the release of heat and light energy in varying intensities. It is important that the fire investigator understands the basic concepts of energy, power, and heat flux and how the units of measurement for each are used to describe the behavior of fire.

N **5.1.2 Energy.** Energy is a property of matter that manifests as an ability to perform work, either by moving over a distance against a force or by transferring heat. Energy can be changed in form (e.g., from chemical to mechanical energy), or transferred to other matter, but it can neither be created nor destroyed. Energy is measured in joules (J), calories (cal), or British thermal units (Btu). A joule is the heat produced where one ampere is passed through a resistance of one ohm for one second, or it is the work required to move over a distance of one meter against a force of one newton. A calorie is the amount of energy required to raise the temperature of 1 g of water by 1°C (e.g., from 14°C to 15°C); a calorie is equal to 4.184 J. A Btu is the quantity of heat required to raise the temperature of 1 lb of water 1°F at a pressure of 1 atmosphere and temperature of 60°F; a British thermal unit is equal to 1055 J, and 252.15 cal.

N **5.1.3 Power.** Power is a property that describes energy released per unit time. The same amount of energy is required to carry a load up a flight of stairs whether the person carrying it walks or runs, but more power is needed for running because the work is done in a shorter amount of time. Raising the temperature of a volume of water requires the same amount of energy whether the temperature increase takes place in 10 sec or in 10 min. Raising the temperature more quickly requires that the energy be transferred more quickly. Power is measured in joules per second (J/s) or watts (W).

N **5.1.4 Heat Flux.** Heat flux is a term that describes the amount of power per unit area. A kilowatt spread over 1 m^2 is approximately equal to the radiant heat flux outdoors on a sunny day. If that same kilowatt is concentrated using a magnifying glass and only spread over .05 m^2 (500 cm^2), there may be sufficient energy transferred to that area to cause ignition of combustibles. Heat flux is measured in kW/m^2 or W/cm^2.

5.1.5 Fire Tetrahedron. The combustion reaction can be characterized by four components: the fuel, the oxidizing agent, the heat, and the uninhibited chemical chain reaction. These four components have been classically symbolized by a four-sided solid geometric form called a tetrahedron *(see*

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Figure 5.1.5). Fires can be prevented or suppressed by controlling or removing one or more of the sides of the tetrahedron.

5.1.5.1 Fuel. A fuel is any substance that can undergo combustion. The majority of fuels encountered are organic, which simply means that they are carbon-based and may contain other elements such as hydrogen, oxygen, and nitrogen in varying ratios. Examples of organic fuels include wood, plastics, gasoline, alcohol, and natural gas. Inorganic fuels contain no carbon and include combustible metals, such as magnesium or sodium. All matter can exist in one of three states: solid, liquid, or gas. The state of a given material depends on the temperature and pressure and can change as conditions vary. If cold enough, carbon dioxide, for example, can exist as a solid (dry ice). The normal state of a material is that which exists at NTP (normal temperature and pressure) conditions: 20°C (68°F) temperature, and a pressure of 101.6 kPa (14.7 psi), or 1 atmosphere at sea level.

5.1.5.1.1 Combustion of liquid fuels and most solid fuels takes place above the fuel surface in a region of vapors created by heating the fuel surface. The heat can come from the ambient conditions, from the presence of an ignition source, or from exposure to an existing fire. The application of heat causes vapors or pyrolysis products to be released into the atmosphere, where they can burn if in the proper mixture with an oxidizer and if a competent ignition source is present or if the fuel's autoignition temperature is reached. Ignition is discussed in Section 5.7.

5.1.5.1.2 Gaseous fuels do not require vaporization or pyrolysis before combustion can occur. Only the proper mixture with an oxidizer and an ignition source are needed.

5.1.5.1.3 For the purposes of the following discussion, the term *fuel* is used to describe vapors and gases rather than solids.

5.1.5.2 Oxidizing Agent. In most fire situations, the oxidizing agent is the oxygen in the earth's atmosphere. Fire can occur in the absence of atmospheric oxygen, when fuels are mixed with chemical oxidizers. Many chemical oxidizers contain readily released oxygen. Ammonium nitrate fertilizer (NH_4NO_3), potassium nitrate (KNO_3), and hydrogen peroxide (H_2O_2) are examples.

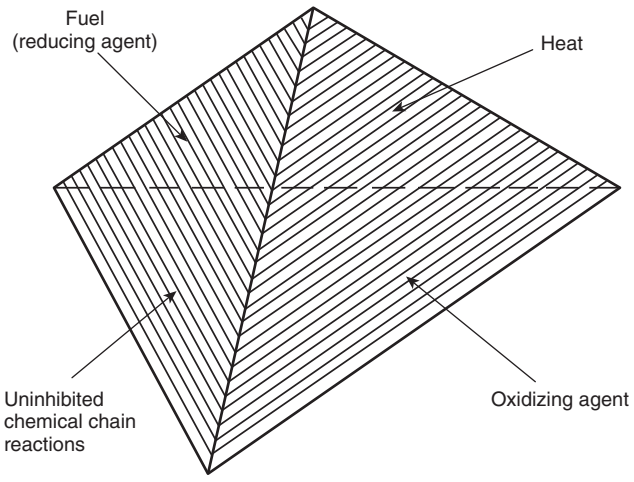


FIGURE 5.1.5 Fire Tetrahedron.

5.1.5.2.1 Certain gases can form flammable mixtures in atmospheres other than air or oxygen. One example is a mixture of hydrogen and chlorine gas.

5.1.5.2.2 Every fuel–air mixture has an optimum ratio at which point the combustion will be most efficient. This ratio occurs at or near the mixture known by chemists as the stoichiometric ratio. When the amount of air is in balance with the amount of fuel (i.e., after burning there is neither unused fuel nor unused air), the burning is referred to as stoichiometric. This condition rarely occurs in fires except in certain types of gas fires. *(See 23.8.2.1.)*

5.1.5.3 Heat. The heat component of the tetrahedron represents heat energy above the minimum level necessary to release fuel vapors and cause ignition. Heat is commonly defined in terms of intensity or heating rate (kilowatts) or as the total heat energy received over time (kilojoules). In a fire, heat produces fuel vapors, causes ignition, and promotes fire growth and flame spread by maintaining a continuous cycle of fuel production and ignition.

5.1.5.4 Uninhibited Chemical Chain Reaction. Combustion is a complex set of chemical reactions that results in the rapid oxidation of a fuel, producing heat, light, and a variety of chemical by-products. Slow oxidation, such as rust or the yellowing of newspaper, produces heat so slowly that combustion does not occur. Self-sustained combustion occurs when sufficient excess heat from the exothermic reaction radiates back to the fuel to produce vapors and cause ignition in the absence of the original ignition source. For a detailed discussion of ignition, see Section 5.7.

5.2* Fire Chemistry.

5.2.1 General. Fire chemistry is the study of chemical processes that occur in fires, including changes of state, decomposition, and combustion.

5.2.2 Phase Changes and Thermal Decomposition. The response of fuels to heat is quite varied. Figure 5.2.2 illustrates the wide range of processes that can occur.

5.2.2.1 Phase changes most relevant in fire are melting and vaporization. In melting, the material changes from a solid to a liquid with no change in the chemical structure of the material (e.g., melting of candle wax). In vaporization, the material changes from a liquid to a vapor with no change in chemical structure of the material (e.g., evaporation of molten candle wax on the wick to form the vapor that burns in the candle flame). Phase changes are reversible events, that is, upon cooling, vapors will return to the liquid state and liquids will solidify.

5.2.2.2 Thermal decomposition involves irreversible changes in the chemical structure of a material due to the effects of heat (pyrolysis). Thermal decomposition of a solid or liquid most often results in the production of gases. Wood decomposes to create char and vapors, some of which are flammable. Under vigorous heating, flexible polyurethane decomposes to form a liquid and flammable gases or vapors. At more moderate heating conditions, flexible polyurethane decomposes to a char and flammable gases or vapors.

5.2.3 Combustion. The combustion reactions can be characterized by the fire tetrahedron *(see 5.1.5)* and may occur with the fuel and oxidizing agent already mixed (premixed burning) or with the fuel and oxidizing agent initially separate

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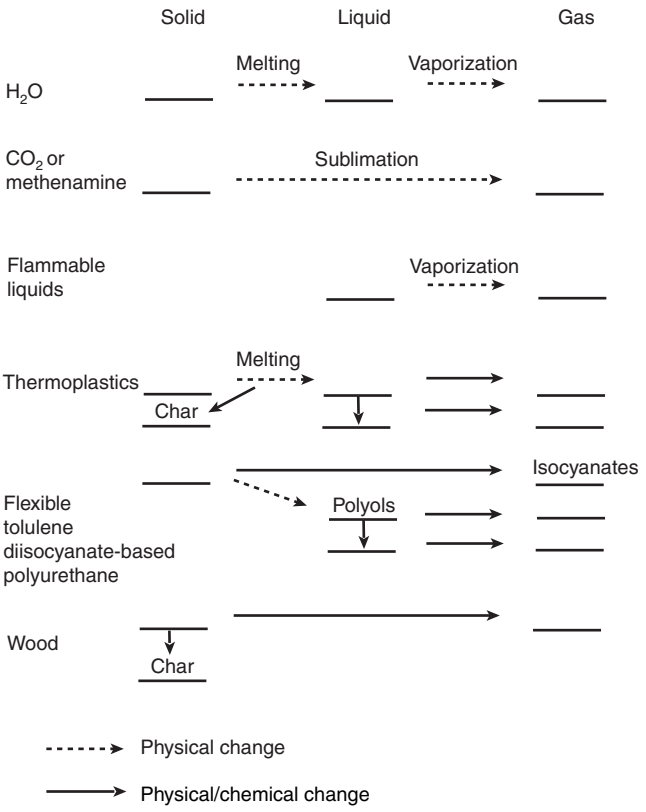


FIGURE 5.2.2 Physical and Chemical Changes During Thermal Decomposition. [*Adopted from Beyler and Hirschler (2002).*]

(diffusion burning). Both premixed and diffusion flames are important in fire.

5.2.3.1 Premixed burning occurs when fuel vapors mix with air in the absence of an ignition source and the fuel–air mixture is subsequently ignited. Examples of premixed fuel and air include a natural gas release into the environment and evaporation of gasoline. Upon application of an ignition source to the fuel–air mixture, a premixed flame quickly propagates through the volume of fuel–air. Premixed flame spread can proceed as a deflagration (subsonic combustion) or as a detonation (supersonic combustion). Deflagration velocities normally range from cm/sec to m/sec, though velocities into the hundreds of m/sec are possible. Detonation velocities are normally in the thousands of m/sec. Premixed flame propagation in a confined volume is normally termed a combustion explosion.

5.2.3.2 Gaseous Fuels. In order for flammable gases and vapors of ignitible liquids to ignite, they must be mixed with a sufficient amount of oxidizer (typically atmospheric oxygen) to allow the combustion reaction to occur. The percentage of the mixture of gaseous fuel to air by volume must be within a specific range for combustion to occur. This is known as the flammable or explosive range of the fuel.

5.2.3.2.1 Flammable/Explosive Range. The flammable or explosive range of a fuel is expressed as a percentage of ignitible gas or vapor in air by volume. In this context, the words "flammable" and "explosive" are interchangeable. The flammable or explosive range is particular to the fuel involved. Each ignitible gas or vapor has its own range or limits of flammability.

5.2.3.2.2 Lower Explosive Limit (Lower Flammable Limit). The minimum percentage of fuel in air (by volume) in which combustion can occur is the lower explosive limit (LEL) of the material. In a mixture that is below its LEL no combustion will occur. This is because below the LEL there are insufficient fuel molecules in the mixture. The mixture can be said to be "too lean."

5.2.3.2.3 Upper Explosive Limit (Upper Flammability Limit). There is also a maximum percentage of fuel in air (by volume) in which combustion can occur. This is called the upper explosive limit (UEL). This is because above the UEL combustion will not occur because there are insufficient oxygen molecules in the mixture. These mixtures can be said to be "too rich."

5.2.3.2.4 For example, the lower and upper flammable limits of methane are 5 percent and 15 percent, respectively, in air at ordinary temperatures. At concentrations below 5 percent and above 15 percent methane, methane will not burn in air at ordinary temperatures. In situations where the UEL is exceeded, there is often a point where the concentration of the gas drops off due to diffusion, and combustion can take place. Consequently, considerations of the UEL are usually only relevant in the case of a closed container or a location close to a fuel source before significant mixing with air occurs.

5.2.3.2.5 The difference between the lower and upper limits is called the flammable or explosive *range*. The extent (width) of the flammable or explosive range of a material, as well as its LEL and UEL, are among the properties that describe the fire hazard of a material. For example, the flammable range of hydrogen is 71 percent (4 percent to 75 percent). When considering the fire hazard of ignitible gases and vapors the lower the LEL, the higher the UEL, and the wider the flammable or explosive range, the greater the fire hazard of the fuel material.

5.2.3.3 Diffusion flame burning is the ordinary sustained burning mode in most fires. Fuel vapors and oxidizer are separate and combustion occurs in the region where they come together. A diffusion flame is typified by a candle flame in which the luminous flame zone exists where the air and the fuel vapors meet.

5.2.3.4* Diffusion flames can only occur for certain concentrations of the mixture components. The lowest oxygen concentration in nitrogen is termed the limiting oxygen index (LOI). For most fuel vapors, the LOI is in the range of 10 percent to 14 percent by volume at ordinary temperatures (Beyler 2002). Similarly, a fuel gas stream can be diluted with nitrogen or other inert gas to the extent where burning is no longer possible. For example, methane diluted with nitrogen to below 14 percent methane will not burn with air at normal temperatures. An underventilated compartment fire may behave like a large diffusion flame. In a ventilation-controlled compartment fire, oxygen concentrations can drop to near zero at locations away from sources of ventilation. This will limit flaming combustion within the compartment.

5.2.3.5 Transitions from premixed burning to diffusion flame burning are common during the ignition of liquid and solid fuels. For instance, if an ignition source is applied to a pan of gasoline, the ignition source ignites gasoline vapors mixed with

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air above the pan. These vapors are quickly consumed and the burning of fuel vapors from the pan of gasoline occurs as a diffusion flame.

5.3* Products of Combustion.

5.3.1 The chemical products of combustion can vary widely, depending on the fuels involved and the amount of air available. Complete combustion of hydrocarbon fuels containing only hydrogen and carbon will produce carbon dioxide and water. Materials containing nitrogen, such as silk, wool, and polyurethane foam, can produce nitrogen oxides or hydrogen cyanide as combustion products under some combustion conditions. Literally hundreds of compounds have been identified as products of incomplete combustion of wood.

5.3.2 Where less air is available for combustion, as in ventilation-controlled fires *(see 5.10.2.8)*, the production of carbon monoxide increases as does the production of soot and unburned fuels.

5.3.3 Combustion products exist in all three states of matter: solid, liquid, and gas. Solid material makes up the ash and soot products that represent the visible "smoke." Many of the other products of incomplete combustion exist as vapors or as extremely small tarry droplets or aerosols. These vapors and droplets often condense on surfaces that are cooler than the smoke, resulting in smoke patterns that can be used to help determine the origin and spread of the fire. Such surfaces include walls, ceilings, and glass. Because the condensation of residue results from temperature differences between the smoke body and the affected surface, the presence of a deposit is evidence that smoke did engulf the surface, but the lack of deposit or the presence of a sharp line of demarcation is not evidence of the limits of smoke involvement.

5.3.4 Soot and tarry products often accumulate more heavily on ceramic-tiled surfaces than on other surrounding surfaces due to the heat conduction properties of ceramic tile. Those surfaces that remain the coolest the longest tend to collect the most condensate.

5.3.5 Some fuels, such as alcohol or natural gas, burn very cleanly, while others, such as fuel oil or styrene, will produce large amounts of sooty smoke even when the fire is fuel controlled.

5.3.6 Smoke is generally considered to be the collection of the solid, liquid, and gaseous products of incomplete combustion.

5.3.7 Smoke color is not necessarily an indicator of what is burning. While wood smoke from a well-ventilated or fuel-controlled wood fire is light-colored or gray, the same fuel under low-oxygen conditions, or ventilation-controlled conditions in a post-flashover fire, can be quite dark or black. Black smoke also can be produced by the burning of other materials, including most plastics and ignitible liquids.

5.3.8 The action of fire fighting can also have an effect on the color of the smoke being produced. The application of water can produce large volumes of condensing vapor that will appear white or gray when mixed with black smoke from the fire. This result is often noted by witnesses at the fire scene and has been misinterpreted to indicate a change of fuel being burned.

5.3.9 Smoke production rates are generally less in the early phase of a fire but increase greatly with the onset of flashover, if flashover occurs. At the beginning of a fire there is an abundance of oxygen, but after flashover the fire usually becomes significantly underventilated. This can be demonstrated by putting a glass over a candle and observing increased smoke production due to reducing oxygen in the volume surrounding the flame.

5.4* Fluid Flows.

5.4.1 General. Flows can be generated by mechanical forces (like fans) or by buoyant forces generated by temperature differences. In most instances, buoyant flows are most significant in fires. Important buoyant flows in fire include fire plumes above burning objects, ceiling jet flows when plume gases strike the ceiling and move along the ceiling, and the flow of hot gases out of a door or window (vent flows).

5.4.2 Buoyant Flows. Buoyant flows occur because hot gases are less dense than cold gases. This causes the hot gases to rise, just as a hot air balloon rises.

5.4.3 Fire Plumes. The primary engine for flows is the creation of hot gases by the fire itself. The hot gases created by the fire rise above the fire source as a fire plume. As the hot gases rise, they mix with or entrain the surrounding air so that the flow of gases in the plume increases with height above the fire and at the same time the temperature of the plume is reduced by the entrainment of air. It is the entrainment of air into the plume that causes the plume to increase in diameter as it rises.

5.4.4 Ceiling Jets. When a fire plume reaches the ceiling of a room, the gases turn to move laterally along the ceiling as a ceiling jet. The ceiling jet flows along the ceiling until the flow encounters a vertical obstruction such as a wall. The hot ceiling jet is generally responsible for the operation of ceiling-mounted detectors or sprinklers.

5.4.5 Vent Flows. The buoyancy of gases in a compartment fire causes flow into and out of a compartment through vents. In a compartment fire with a single vent opening, hot gases flow out through the upper portion of the opening, and fresh air enters in the lower portions of the opening.

5.5* Heat Transfer.

5.5.1 General. Heat transfer is classically defined as the transport of heat energy from one point to another caused by a temperature difference between those points. The heat transfer rate per unit area (also known as heat flux) is normally expressed in kW/m^2. The transfer of heat is a major factor in fires and has an effect on ignition, growth, spread, decay (reduction in energy output), and extinction. Heat transfer is also responsible for much of the physical evidence used by investigators who attempt to establish a fire's origin and cause.

5.5.1.1 It is important to distinguish between heat and temperature. Temperature is a measure that expresses the degree of molecular activity of a material compared to a reference point, such as the freezing point of water. Heat is the energy that is needed to change the temperature of an object. When heat energy is transferred to an object, the temperature increases. When heat is transferred away from an object, the temperature decreases.

5.5.1.2 Unless work is done on the system by outside forces, heat is naturally transferred from a higher temperature mass to a lower temperature mass. Heat transfer is measured in terms of energy flow per unit of time (kilowatts). The greater the temperature difference between the objects, the more energy transferred per unit of time and the higher the heat transfer

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rate. Temperature can be compared to the pressure in a fire hose and heat or energy transfer to the water flow in gallons per minute.

5.5.1.3 Heat transfer is accomplished by three mechanisms: conduction, convection, and radiation. All three mechanisms play a role in fire, and an understanding of each is necessary in the investigation of a fire.

5.5.2 Conduction. Conduction is the form of heat transfer that takes place within solids when one portion of an object is heated. Energy is transferred from the heated area to the unheated area at a rate dependent on the difference in temperature and the thermal conductivity *(k)* of the material. The thermal conductivity *(k)* of a material is a measure of the amount of heat that will flow across a unit area with a temperature gradient of 1 degree per unit of length (W/m-K, Btu/hr-ft-°F). The heat capacity (specific heat) of a material is a measure of the amount of heat necessary to raise the temperature of a unit mass 1 degree, under specified conditions (J/kg-K, Btu/lb-°F).

5.5.2.1 If thermal conductivity *(k)* is high, the rate of heat transfer through the material is high. Metals have high thermal conductivities *(k)*, while plastics and glass have low thermal conductivity *(k)* values. High-density materials conduct heat faster than low-density materials. Therefore, low-density materials make good insulators. Materials with a high heat capacity *(c)* require more energy to raise the temperature than materials with low heat capacity values.

5.5.2.2* When one portion of a solid is exposed to a high temperature and another portion of that solid is at a lower temperature, then heat energy will be transferred into and through the solid from the higher to the lower temperature areas. Initially, the heat energy moving through the solid will raise the temperature at all interior points to some level of temperature between the extreme high and extreme low. When the temperatures at all interior points have stopped increasing, the temperature and heat transfer within the solid is said to be in a steady state thermal condition. During steady state heat transfer, a condition that is rare in most fire scenarios, thermal conductivity *(k)* is the dominant heat transfer property. Figure 5.5.2.2 shows the steady state maximum surface temperature achievable as a function of the incident radiant flux. While achieving these steady state temperatures might take an unrealistic time period, the plot is illustrative of the maximum possible surface temperature for a given incident radiant heat flux.

5.5.2.3 Thermal Inertia. During transient heating, a more common condition, the result is changing rates of heat transfer and temperature. During this period, all three properties — thermal conductivity *(k)*, density (ρ), and heat capacity *(c)* — play a role. Multiplied together as a mathematical product, these properties are called the *thermal inertia*, $k\rho c$, of a material. The thermal inertia of a material is a measure of how easily the surface temperature of the material will increase when heat flows into the material. Low-density materials like polyurethane foam have a low thermal inertia and the surface temperature will increase quickly upon exposure to a heat flux. Conversely, metals have a high thermal inertia due to their high thermal conductivity and high density. As such, when exposed to a flame, the surface temperature of a metal object increases relatively slowly compared to the surface temperature of a plastic or wood object. Table 5.5.2.3 provides data for some common

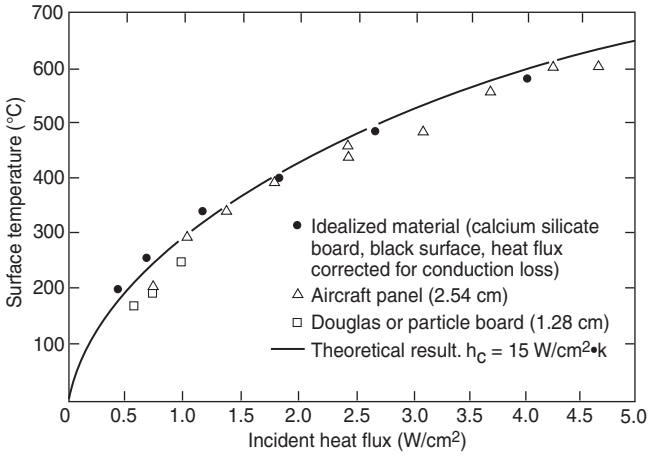


FIGURE 5.5.2.2 Maximum Surface Temperature Achievable from a Steady State Radiant Heat Flux in an Environment at Normal Ambient Temperature [20°C (68°F)].

materials at room temperature. Thermal properties are generally a function of temperature.

5.5.2.4 The influence of the thermal inertia on the surface temperature of a thick material occurs principally during the time the surface temperature is increasing. Eventually, as the material reaches a steady temperature, the effects of density (ρ) and heat capacity *(c)* become insignificant relative to thermal conductivity. Therefore, thermal inertia of a material is most important at the initiation and early stages of a fire.

5.5.2.5 The effect of conduction of heat into a material is an important aspect of ignition. Thermal inertia determines how fast the surface temperature will rise. The lower the thermal inertia of the material, the faster the surface temperature will rise.

5.5.2.6 Conduction is also a mechanism of fire spread. Heat conducted through a wall or along a pipe or beam can cause ignition of combustibles in contact with the heated object. Thermally thin materials are those materials that are physically thin or have a very high thermal conductivity. The full thickness of the material is at approximately the same temperature during heating. The rate of temperature rise is dependent on the thermal mass of the material, which is the mass per unit area multiplied by the heat capacity of the material. Subjected to the same heat source, a thin curtain will heat more rapidly than a thick drapery. This effect has a direct impact on ignitibility and flame spread.

5.5.3 Convection. Convection is the transfer of heat energy by the movement of heated liquids or gases from the source of heat to a cooler part of the environment. In most cases, convection will be present in any environment where there are temperature differences, although in a few cases a stably-stratified condition may be found that does not cause fluid movement.

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Table 5.5.2.3 Thermal Properties of Selected Materials

Material	Thermal Conductivity (k) (W/(m K))	Density (ρ) (kg/m^3)	Heat Capacity (c) (J/(kg-K))	Thermal Inertia ($k\rho c$) ($W^2 \times s/k^2 m^4$)
Copper	387	8940	380	1301×10^6
Concrete	0.8–1.4	1900–2300	880	1.34×10^6–2.83×10^6
Gypsum plaster	0.48	1440	840	0.581×10^6
Oak	0.17	800	2380	0.324×10^6
Pine (yellow)	0.14	640	2850	0.255×10^6
Polyethylene	0.35	940	1900	0.625×10^6
Polystyrene (rigid)	0.11	1100	1200	0.145×10^6
Polyvinylchloride	0.16	1400	1050	0.235×10^6
Polyurethane*	0.034	20	1400	0.000952×10^6

*Typical values and properties vary with temperature. *Source:* Drysdale (1999).

5.5.3.1 Heat is transferred by convection to a solid when hot gases pass over cooler surfaces. The rate of heat absorbed by the solid is a function of the temperature difference between the hot gas and the surface, the thermal inertia of the material being heated, the surface area exposed to the hot gas, and the velocity of the hot gas. The higher the velocity of the gas, the greater the rate of convective heat transfer. Because a flame itself is a hot gas, flame contact involves heat transfer by convection.

5.5.3.2 In the early part of a fire, convection plays a major role in heating the surfaces exposed to gases heated by the fire. As the room temperature rises, convection continues, but the role of radiation increases rapidly and becomes the dominant heat transfer mechanism.

5.5.3.3 Convection heat transfer occurs by two mechanisms, natural and forced convection. In forced convection, the velocity of the gas flowing over the material is externally imposed (e.g., by a fan). In natural convection, the velocity of the gas flowing over the material is the result of buoyancy-induced flows associated with the temperature difference between the surface and the gas. Heat transfer from a hot surface in a quiescent environment is by natural convection. The hot gas plume above the hot surface results from the high temperature of the hot surface relative to the environment.

5.5.4 Radiation. Radiation is the transfer of heat energy from a hot surface or gas, the radiator, to a cooler material, the target, by electromagnetic waves without the need of an intervening medium. For example, the heat energy from the sun is radiated to earth through the vacuum of space. Radiant energy can be transferred only by line of sight and will be reduced or blocked by intervening materials. Intervening materials do not necessarily block all radiant heat. For example, radiant heat is reduced by about 50 percent by some glazing materials. Radiators and targets are not limited to solids but can be liquids and gases, as well. For example, the smoke and hot gases that collect at ceiling level in a compartment fire are the source of radiant heat that may lead to ignition of materials.

5.5.4.1 The rate of heat transfer from a radiating material is proportional to that material's absolute temperature raised to the fourth power. For example, doubling the absolute temperature of a radiating material will result in a 16-fold increase in radiation from that material. Figure 5.5.4.1 illustrates this relation. Since all materials emit radiant energy proportional to the fourth power of their absolute temperatures, then the net heat radiation between two materials separated in space is proportional to the difference in the fourth powers of the absolute temperatures. Absolute temperatures are measured in Kelvins (°C + 273).

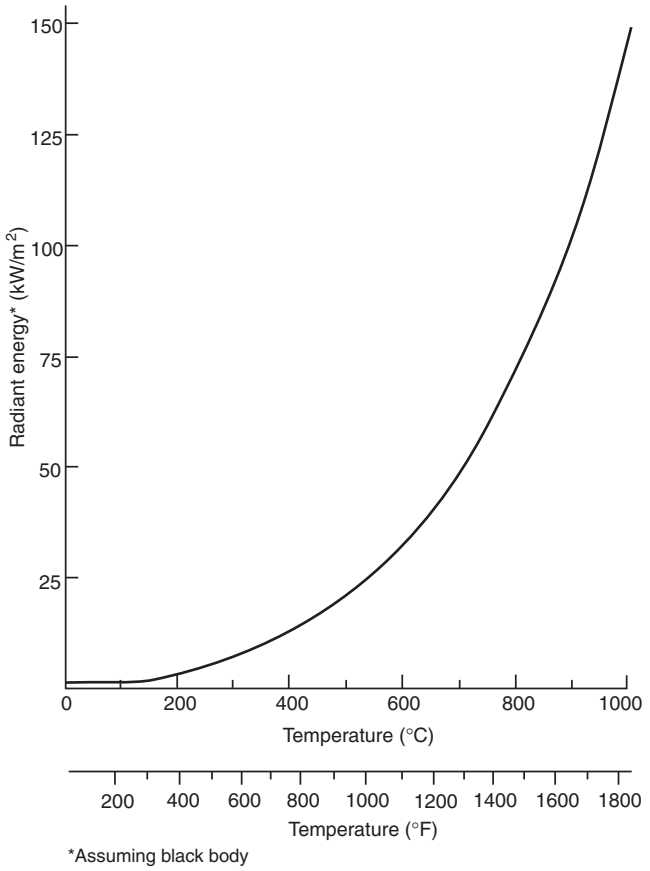


FIGURE 5.5.4.1 Relation of Radiation to Temperature.

5.5.4.2 The rate of radiant heat transfer is also strongly affected by the distance between the radiator and the target. As the distance increases, the amount of energy falling on a unit of area falls off in a manner that is related to both the size of the radiating source and the distance to the target. For example, when the distance between the radiator and the target doubles, the amount of net radiant heat transfer may not change significantly or may drop to as little as one fourth of its original value,

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depending on the size of the radiator relative to the distance involved. Table 5.5.4.2 provides general information on the effects of radiant heat fluxes.

5.5.5* Thermometry. Thermometry is the study of the science, methodology, and practice of temperature measurement. Though thermometry is seldom, if ever, needed at the fire scene, it is frequently used during the analysis or in cases of fire safety or code compliance in which the various physics or thermodynamic formulae present themselves.

5.5.5.1 There are several systems for measuring degrees of temperature and the relative hotness and coldness of a substance. These systems can be described in two general categories: empirical temperature scales and thermodynamic temperature scales.

5.5.5.2 Empirical Temperature Scales. The Fahrenheit and Celsius (Centigrade) scales are the most familiar empirical temperature scales. The size of a degree of temperature in each empirical system is based upon the relative temperatures at which water boils and freezes and other empirical comparisons.

5.5.5.2.1 Fahrenheit. The Fahrenheit scale is based on a 180-degree difference between the freezing and boiling temperatures of pure water. In the Fahrenheit scale, water freezes at 32 degrees Fahrenheit and boils at 212 degrees Fahrenheit. Absolute zero is –459.67 degrees Fahrenheit.

5.5.5.2.2 Celsius (Centigrade). The Celsius or Centigrade scale is based on the freezing point of pure water being 0 degrees Celsius and the boiling point 100 degrees Celsius. Absolute zero is –273.15 degrees Celsius.

5.5.5.2.2.1 The Celsius and Kelvin scales are SI units.

5.5.5.3 Thermodynamic (Absolute) Temperature Scales. The thermodynamic temperature scales are based on the lowest possible temperature of absolute zero, and therefore are called the absolute temperature scales. The simplest definition of *absolute zero* is: a theoretical lowest feasible temperature characterized by the absence of heat and molecular motion. Thermodynamic temperature scales differ from empirical scales in that they are based on the fundamental laws of thermodynamics or statistical mechanics instead of the scaling of properties of water. Where measurements are made in SI units, thermody-

Table 5.5.4.2 Effect of Radiant Heat Flux

Approximate Radiant Heat Flux (kW/m^2)	Comment or Observed Effect
170	Maximum heat flux as currently measured in a postflashover fire compartment.
80	Heat flux for protective clothing Thermal Protective Performance (TPP) Test.[a]
52	Fiberboard ignites spontaneously after 5 seconds.[b]
29	Wood ignites spontaneously after prolonged exposure.[b]
20	Heat flux on a residential family room floor at the beginning of flashover.[c]
20	Human skin experiences pain with a 2-second exposure and blisters in 4 seconds with second-degree burn injury.[d]
15	Human skin experiences pain with a 3-second exposure and blisters in 6 seconds with second-degree burn injury.[d]
12.5	Wood volatiles ignite with extended exposure[e] and piloted ignition.
10	Human skin experiences pain with a 5-second exposure and blisters in 10 seconds with second-degree burn injury.[d]
5	Human skin experiences pain with a 13-second exposure and blisters in 29 seconds with second-degree burn injury.[d]
2.5	Human skin experiences pain with a 33-second exposure and blisters in 79 seconds with second-degree burn injury.[d]
2.5	Common thermal radiation exposure while fire fighting.[f] This energy level may cause burn injuries with prolonged exposure.
1.0	Nominal solar constant on a clear summer day.[g]

Note: The unit kW/m^2 defines the amount of heat energy or flux that strikes a known surface area of an object. The unit kW represents 1000 watts of energy and the unit m^2 represents the surface area of a square measuring 1 m long and 1 m wide. For example, 1.4 kW/m^2 represents 1.4 multiplied by 1000 and equals 1400 watts of energy. This surface area may be that of the human skin or any other material.

[a]From NFPA 1971.

[b]From Lawson, "Fire and Atomic Bomb."

[c]From Fang and Breese, "Fire Development in Residential Basement Rooms."

[d]From Society of Fire Protection Engineering Guide: "Predicting 1st and 2nd Degree Skin Burns from Thermal Radiation," March 2000.

[e]From Lawson and Simms, "The Ignition of Wood by Radiation," pp. 288–292.

[f]From U.S. Fire Administration, "Minimum Standards on Structural Fire Fighting Protective Clothing and Equipment," 1997.

[g] *SFPE Handbook of Fire Protection Engineering*, 2nd edition.

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namic temperature is measured in Kelvins (symbol: K). Many engineering fields in the U.S., however, measure thermodynamic temperature using the Rankine scale (symbol: R).

5.5.5.3.1 ***Kelvin.*** A Kelvin of temperature is the same size as a degree Celsius, but the scale begins at absolute zero (0 Kelvin) and water freezes at 273.15 Kelvin.

5.5.5.3.2 ***Rankine.*** The Rankine scale uses increments of the same relative size as the Fahrenheit degrees scale, but the scale begins at absolute zero (0 Rankine), and water freezes at 491.67 Rankine.

5.5.5.3.3 The size of a degree Fahrenheit or Rankine is smaller than that of a degree Celsius or Kelvin. Formulae for converting between temperature scales are presented in Table 5.5.5.3.3.

5.5.5.3.4* Most fire science calculations involving temperature require that specific units of temperature be used — typically Kelvins or degrees Celsius. It is important to understand the particular equation and know what units are required to ensure accurate results.

5.6* Fuel Load, Fuel Packages, and Properties of Flames. This section deals with the combustion properties of fuels and collections of fuels.

5.6.1 Fuel Load.

5.6.1.1 The term *fuel load* is used to describe the amount of fuel present, usually within a compartment. For instance, a room that is filled with shelving units containing records stored in cardboard boxes is said to be a high fuel load compartment. It is commonly expressed in terms of wood-fuel equivalent mass (kg or lb) or the potential combustion energy (MJ) associated with that fuel mass.

5.6.1.2 The potential combustion energy is determined by multiplying the mass of fuel by the heat of combustion of the fuels. Heats of combustion typically range from 10 to 45 MJ/kg. While the total fuel load for a compartment is a measure of the total heat available if all the fuel burns, it does not determine how fast the fire will develop once the fire starts. Fuel load can be used in conjunction with the size of vent openings to estimate the duration of fully developed burning in a compartment.

5.6.1.3 The term *fuel load density* is the potential combustion energy output per unit floor area [MJ/m^2 (Btu/ft^2)] or the mass of fuel per unit floor area [kg/m^2 (lb/ft^2)]. Fuel load densities are most often associated with particular occupancies or used as a means to characterize the fire load characteristics of the room contents. The fuel load of a compartment is determined by multiplying the fuel load density by the compartment floor area.

5.6.2 Fuel Items and Fuel Package.

5.6.2.1 A fuel item is any article that is capable of burning. A fuel package is a collection or array of fuel items in close proximity to one another such that flames can spread throughout the array. Single-item fuel packages are possible when the fuel item is located away from other fuel items. A chair that is located away from other fuels is an example of a single-item fuel package. Fuel packages are generally identifiable by the separation of the array of fuel items from other fuel items. Typical fuel packages include the following:

(1) A group of abutting office workstations separated from other fuel arrays by aisles
(2) A collection of living room furniture in close proximity to one another, separated from other fuel arrays by space
(3) A double-row rack in a warehouse, separated from other shelves by aisles
(4) A forklift truck with a pallet of goods located away from other combustibles

5.6.2.2 Fire spread from one fuel package to another is generally by radiative ignition of the target fuel package.

Table 5.5.5.3.3 Conversions Between the Various Temperature Scales

To convert between the Fahrenheit, Celsius, Rankine, and Kelvin temperature scales, the following formulae are used:	
To convert from Fahrenheit to Celsius:	$°C = \frac{5}{9}\ (°F - 32)$
To convert from Celsius to Fahrenheit:	$°F = (\frac{9}{5}\ °C) + 32$
To convert from Fahrenheit to Rankine:	$R = °F + 460$
To convert from Rankine to Fahrenheit:	$°F = R - 460$
To convert from Fahrenheit to Kelvin:	$K = \frac{5}{9}\ (°F - 32) - 273$
To convert from Kelvin to Fahrenheit:	$°F = \frac{9}{5}\ (K - 273) + 32$
To convert from Celsius to Kelvin:	$K = °C - 273$
To convert from Kelvin to Celsius:	$°C = K + 273$
To convert from Celsius to Rankine:	$R = \frac{9}{5}\ °C + 492$
To convert from Rankine to Celsius:	$°C = \frac{5}{9}\ (R - 492)$
To convert from Rankine to Kelvin:	$K = \frac{5}{9}\ R$
To convert from Kelvin to Rankine:	$R = \frac{9}{5}\ K$

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5.6.3 Heat Release Rate.

5.6.3.1 General. Total fuel load in the room has no bearing on the rate of growth of a given fire in its preflashover phase. During this period of development, the rate of fire growth is determined by the heat release rate (HRR) from the burning of individual fuel arrays. The HRR describes how the available energy in a given material or group of materials is released. This quantity characterizes the power or energy release rate [watts (joules/sec) or kilowatts] of a fire and is a quantitative measure of the size of the fire. A generalized HRR curve can be characterized by an initial growth stage, a period of steady-state burning, and a decay stage as shown in Figure 5.6.3.1(a) through Figure 5.6.3.1(c). Equation 5.6.3.1 can be used to calculate the HRR of a burning item. The heat of combustion is generally considered a material property and therefore a constant for a specific fuel. Values for specific fuels can generally be obtained from the literature. The mass burning rate of a fuel is dependent on several factors, including surface area, fuel type, and fuel configuration. Steady-state burning rate values for many fuels have been studied and are available in the sources following Table 5.6.3.1. The largest value of the HRR measured is defined as the peak HRR. Representative peak HRRs for a number of fuel items are listed in Table 5.6.3.1. These values should only be considered as representative values for comparative purposes. Fuel items with the same function (e.g., sofas) can have significantly different HRRs. The actual peak HRR for a particular fuel item is best determined by test. The HRR during the growth phase generally increases as a result of increasing flame spread rates over the fuel package. The peak or steady period of heat release is characterized by full involvement of the fuel surface of the package in flames. The decay phase reflects the reduction in remaining fuel and fuel area available to burn or some other interruption of the uninhibited chain reaction, including consumption of available oxygen or suppression activities. The onset, duration, and severity of these stages depend on a variety of factors, including the incident heat flux to the burning item, the chemical and physical properties of the fuel, the surface area of the fuel, the substrate on which the fuel is burning, and whether or not it is burning in an enclosed environment.

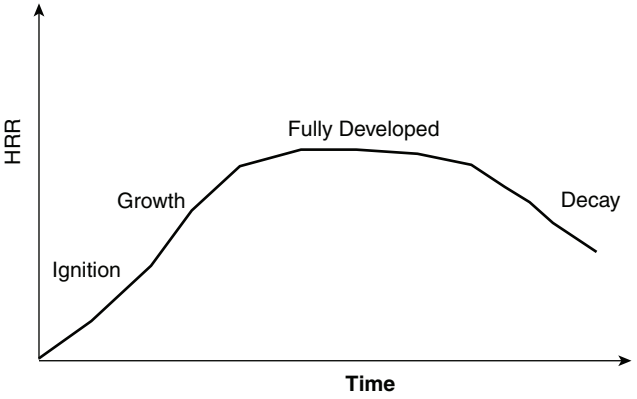


FIGURE 5.6.3.1(a) Idealized HRR Curve for a Fuel-Controlled Fire.

[5.6.3.1]

$$\dot{Q} = \dot{m}'' A \Delta H_c$$

where:

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

$\dot{m}''$ = mass loss per unit area per second (kg/m^2 • s)

A = area in m^2

ΔH_c = heat of the combustion of the fuel (kJ/kg)

Table 5.6.3.1 Representative Peak HRRs (Unconfined Burning)

Fuel	Mass		Peak HRR
	kg	lb	(kW)
Wastebasket, small	0.7–1.4	1.5–3	4–50
Trash bags, 42 L (11 gal) with mixed plastic and paper trash	2.5	7.5	140–350
Cotton mattress	12–13	26–29	40–970
TV sets	31–33	69–72	120 to over 1500
Plastic trash bags/paper trash	1.2–14	2.6–31	120–350
PVC waiting room chair, metal frame	15	34	270
Cotton easy chair	18–32	39–70	290–370
Gasoline or kerosene in 0.2 m^2 (2 ft^2) pool	19	42	400
Christmas trees, dry	6–20	13–44	3000–5000
Polyurethane mattress	3–14	7–31	810–2630
Polyurethane easy chair	12–28	27–61	1350–1990
Polyurethane sofa	51	113	3120
Wardrobe, wood construction	70–121	154–267	1900–6400

Sources: Values are from the following publications:

Babrauskas, V. and Krasny, J., *Fire Behavior of Upholstered Furniture*, NBS Monograph 173 Fire Behavior of Upholstered Furniture.

Babrauskas, V., "Heat Release Rates," in *SFPE Handbook of Fire Protection Engineering*, 3rd ed., National Fire Protection Association.

Lee, B.T., *Heat Release Rate Characteristics of Some Combustible Fuel Sources in Nuclear Power Plants*, NBSIR 85-3195.

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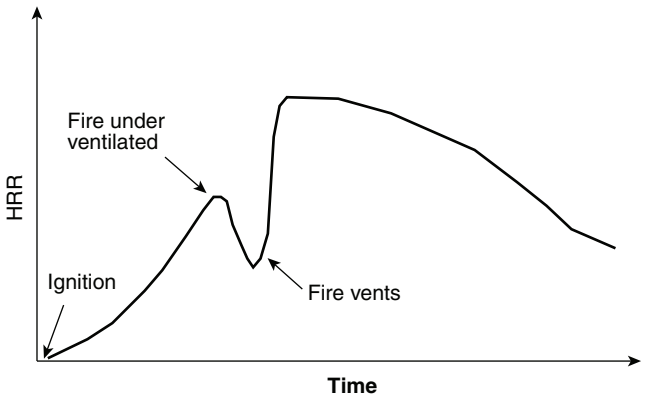


FIGURE 5.6.3.1(b) Idealized HRR Curve for a Ventilation-Controlled Fire.

5.6.3.1.1 Data from experiments conducted by NIST in acquired structures demonstrate the impact of ventilation on the temperatures in the structure fire. As the oxygen contained within the structure is reduced, the HRR of the fire decreases, and as a result, the gas temperatures within compartments in the structure decrease. As additional oxygen is made available to the fire due to a change in ventilation, such as the opening of a door or window, the HRR and temperature begin to increase again. This idealized ventilation-controlled model needs to be understood as a potential fire growth curve in structure fires by both firefighters and fire investigators.

5.6.3.1.2 While the rate of fire growth in a compartment is determined by the HRR of the fuel array, the rate of growth of a particular fuel item and its maximum HRR is a function of its properties, including the area of the fuel, the rate of mass loss, and the effective heat of combustion. The orientation of a particular fuel item may also affect the rate at which it reaches its maximum HRR. For example, a mattress in a horizontal configuration typically takes longer to reach maximum HRR than a similar mattress in a vertical configuration.

5.6.3.2* Compartment Fires. The total fuel load in a compartment has no bearing on the rate of growth of a given fire in its pre-flashover phase. During this period of development, the rate of fire growth is determined by the HRR from the burning of individual fuel arrays. In a compartment fire, as additional items ignite their individual HRRs combine and become the HRR for the compartment. Tests for measuring the HRR of fuel items or packages are usually performed in the "open," where radiant effects of a compartment are not present. When a fuel package is exposed to radiant heating, however, such as from the hot upper layer of a room, this can significantly increase the HRR for that fuel package compared to burning in the open. The two primary factors impacting the HRR of objects burning, in an enclosed space are the radiant feedback from the surrounding boundaries and hot upper gas layer, and the availability of combustion air (i.e., ventilation to the enclosed space). With sufficient air flow available, the former can produce enhanced burning conditions and higher overall HRRs. Restricted air flow can produce under-ventilated conditions within the enclosed space and reduce the HRR of the objects burning within compared to open burning.

5.6.3.2.1 In addition to these factors, experimental data show that while the incipient stages of fires can vary dramatically, the growth rates leading up to flashover are generally similar for a given fuel regardless of the presence of an accelerant. HRR curves for upholstered sofa fires are shown in Figure 5.6.3.2.1(a) and Figure 5.6.3.2.1(b) for a sofa burning; in the open, within an unventilated apartment structure, and within a ventilated apartment using two different ignition scenarios (small 10 kW fire and gasoline poured on the sofa). These figures illustrate the time differences associated with the

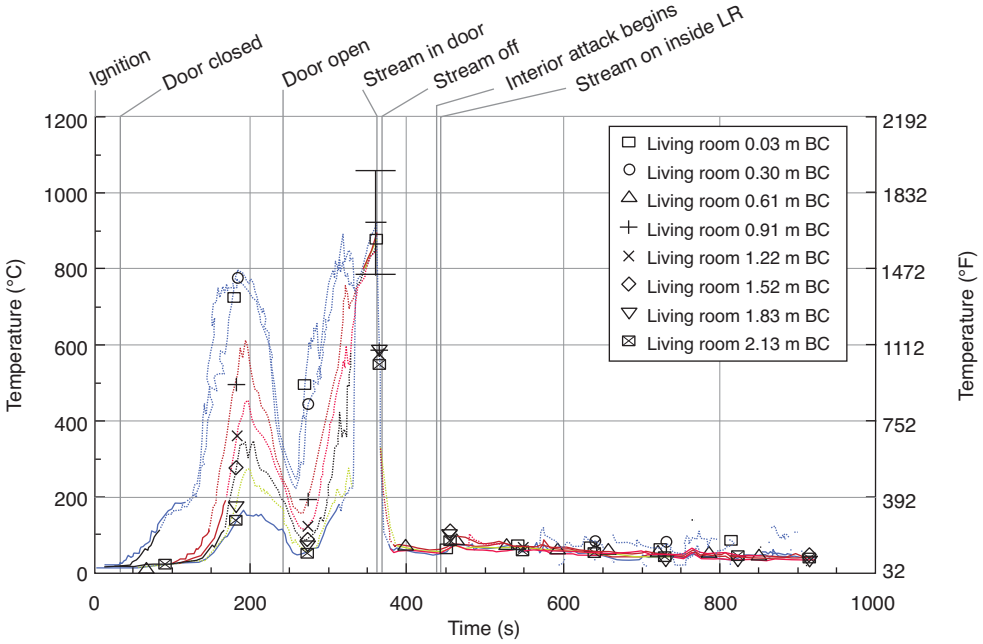


FIGURE 5.6.3.1(c) Actual Temperature Measurements from a Test Fire That Became Underventilated and Then Became Ventilated by the Opening of the Door.

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incipient stages of fire development in various scenarios [Figure 5.6.3.2.1(a)] and also show the similarity in the fire growth stage for all four scenarios when compared on a common timeframe [Figure 5.6.3.2.1(b)].

5.6.3.3 Liquid Fuel Fires. The HRR of a liquid fuel fire is dependent on two primary factors: the physical characteristics of the release (i.e., surface area and depth), and the combustion properties of the fuel. The physical characteristics of a liquid fuel fire will depend on the volume of liquid released, the extent of confinement, and the substrate on which the fuel is released.

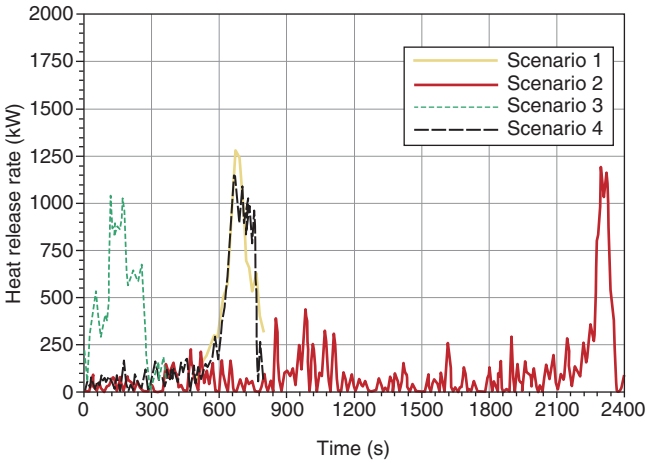


FIGURE 5.6.3.2.1(a) Comparison of Heat Release Rates Measured in Four Different Test Scenarios Involving the Same Model Upholstered Sofa. Scenario 1 was an open-burn, Scenario 2 was an initially unventilated compartment fire that was eventually ventilated, Scenario 3 was an unventilated compartment fire started using gasoline, and Scenario 4 was a ventilated compartment fire. [*Adopted from Mealy (2007)*]

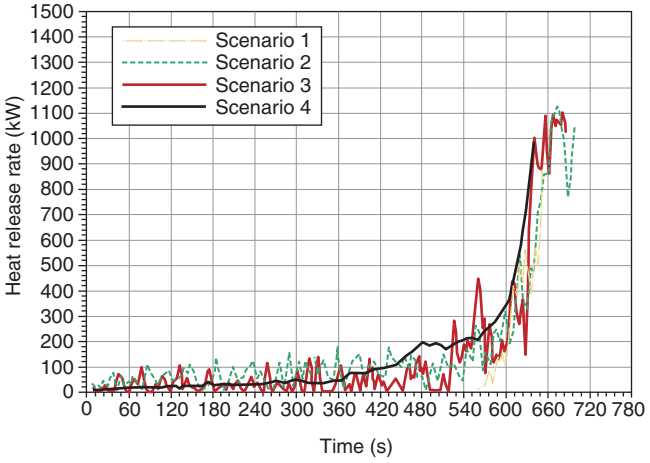


FIGURE 5.6.3.2.1(b) Time-Shifted Comparisons of the Exponential Fire Growth Stage Measured in the Four Different Test Scenarios Involving the Same Model Upholstered Sofa as Shown in Figure 5.6.3.2. Scenario 1 was an open-burn, Scenario 2 was an initially unventilated compartment fire that was eventually ventilated, Scenario 3 was an unventilated compartment fire started using gasoline, and Scenario 4 was a ventilated compartment fire. [*Adopted from Mealy (2007)*]

5.6.3.3.1* Confined Liquid Fuel Fires. In confined scenarios where the liquid fills the available area, the volume of liquid released correlates directly to the depth of the fuel layer. For depths greater than 5 mm (0.2 in.), the maximum steady-state mass burning rate for the fuel should be used. For depths less than 5 mm (0.2 in.), the mass burning rate will be substantially less because the fire will not have sufficient time to reach the maximum steady-state value.

5.6.3.3.2* Unconfined Liquid Fuel Fires. In unconfined scenarios, the area of the spill is primarily dictated by the volume of fuel spilled and secondarily by the characteristics of the liquid and substrate on which it is spilled. The depth of the fuel layer will be approximately 0.7 mm, but can vary by as much as 30 percent based on the substrate and fuel type. As described in 5.6.3.3.1, at depths less than 5 mm, mass burning rates are significantly smaller than the maximum steady-state value. Reductions on the order of 50 to 80 percent have been reported depending upon the fuel type and release scenario. When considering these types of scenarios, available data sets describing the impact of shallow fuel depths should be consulted. Fuel spill fires will typically only burn 90 seconds or less before the fuel is consumed due to the shallow depth.

5.6.3.3.3* Unconfined Liquid Fuel Fires on Carpet. For unconfined liquid fuel fires on carpet, the fire will behave like a confined fuel fire (i.e., deep fuel layer scenario) due to the porosity and complex structure of the carpet surface. Experimental data has shown that unconfined liquid fuel spills on carpet behave similar to confined pools in both fire size and burning duration.

5.6.4 Properties of Flames. The objective of this section is to provide information about the relationship between heat release rate and visible fire size, about the temperatures and velocities achieved within the visible flame, and about heat fluxes from fires to adjacent surfaces.

5.6.4.1 Color of Flame. The color of flame is not necessarily an accurate indicator of what is burning, or of the temperature of the flame.

5.6.4.2 The visible size of a flame is normally expressed as the flame height and the fire dimensions (length and width diameter of the involved fuel package). Observing a fire over time reveals that the height of the flame fluctuates over time. The following three visual measures of flame height are often employed:

(1) Continuous flame height — the height over which flames are visible at all instances
(2) Average flame height — the height over which flames are visible 50 percent of the time
(3) Flame tip height — the greatest height over which flames are visible at any time

5.6.4.3 The following flame height definitions define the three regions of a fire:

(1) Continuously flaming region (lower portion of visible flame)
(2) Intermittently flaming region (upper portion of the visible flame)
(3) Plume region (above the visible flame)

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5.6.4.4 These heights are best determined from frame-by-frame analysis of a videotape of the fire. Casually observed flame height determinations tend to be most consistent with the flame tip height, as our eyes seem to focus on the tip of the flame. The most widely reported flame height in the fire science literature is the average flame height.

5.6.4.5 Flame Height. Figure 5.6.4.5 shows the flame height of a circular fire source with heat release rates per unit area of 250, 500, and 1000 kW/m^2. Flame heights were calculated from the widely used Heskestad correlation. The figure illustrates that flame height is not strictly a function of the heat release rate. In addition, it is clear from the figure that even for a given heat release rate per unit area, small variations in observed flame height yield much larger variations in estimated heat release rate.

5.6.4.6* Fuel Package Location.

5.6.4.6.1 Air Entrainment. When a burning fuel package is positioned away from a wall, air is free to flow into the plume from all directions and mix with the fuel gases. If the fuel package is placed against a wall or in a corner (formed by the intersection of two walls), air entrainment into the plume can be restricted, creating an imbalance in the airflow. As a result of the imbalance in airflow, the flame and thermal plumes will bend toward the restricting surface(s).

5.6.4.6.2 Flame and Plume Attachment. In cases where the flame or thermal plume bends sufficiently to become attached to the wall(s), the air entrainment is reduced. The fuel package must be sufficiently close to the wall(s) to cause the flame or thermal plume to attach to the wall(s) in order for the effects of restricted air entrainment to occur. The extent of the bending of the flame toward and the attachment to the wall(s) is dependent on the geometry of the fuel and the position of the fuel package relative to the wall(s).

5.6.4.6.3 Effect of Reduced Air Entrainment. A decrease in air entrainment has an effect on plume and upper layer temperatures as well as on the height of the flame.

5.6.4.6.3.1 Plume and Upper Layer Temperatures. A reduction in ambient air being entrained into the thermal plume lessens the amount of mixing of cooler ambient air with the thermal plume, resulting in less dilution and higher temperatures. Since the plume transports thermal energy to the upper layer, an increase in temperature in the plume will also produce an increase in the upper layer temperature.

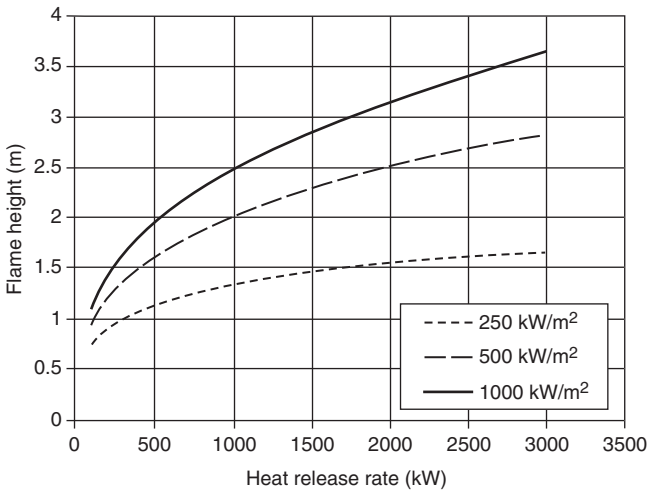


FIGURE 5.6.4.5 Average Flame Height (50 Percent Intermittency) as a Function of Heat Release Rate for a Range of Heat Release Rates per Unit Area of Fuel Package.

5.6.4.6.3.2 Flame Height. For diffusion flames, the mixing of fuel vapor and air controls the location where flaming combustion occurs; thus, the flame height at any given time represents the vertical distance (i.e., the mixing length) over which the fuel and air must be transported to complete the combustion process. Therefore, a reduction in air entrainment can result in greater flame heights, since the fuel vapor must be transported over a longer mixing length in order to completely mix with the reduced amount of air.

5.6.4.6.4 Effect of Walls. If the fuel package is positioned adjacent to one wall in a manner sufficient to reduce the air entrainment, there will be an increase in the absolute temperature of the upper layer when compared with the same fire positioned away from the wall. In contrast, experimental results have shown no significant increase in flame length for fire against a wall. Figure 5.6.4.6.4(a) and Figure 5.6.4.6.4(b) provide an example of this finding for a fire away from and against a wall.

5.6.4.6.5 Effect of Corners. When the same fuel package is placed in a corner sufficient to further reduce the air entrainment, there will also be an increase in the absolute temperature of the upper layer when compared with the same fire positioned away from corners. Similarly, a significant increase in the flame height is observed when the flames are attached to the walls in a corner configuration. Figure 5.6.4.6.5 provides an example of the increase in flame height for a fire in a corner configuration.

5.6.4.6.6 Analysis of Wall Effects. The possible effect of the location of wall(s) relative to the fire should be considered in the analysis of the fire and/or the interpretation of damage patterns produced by the fire.

5.6.4.6.7 Outdoor Fires. It should be noted that similar effects to those described above for indoor fires will also be observed for outdoor fires.

5.6.4.7* Flames that have flame heights in excess of the ceiling height result in flame extensions along the ceiling. If the free flame height is much greater than the ceiling height, the flame extension generally results in longer flames than would exist in the absence of a ceiling *(see Figure 5.6.4.7)*. The total length of a flame becomes longer $(H + h_r)$ when cut off by a ceiling, compared to its free height (h_f).

5.6.4.8 Factors such as ceiling height and distance from the plume can have significant effects on the response time of fire protection devices, such as heat and smoke detectors and automatic sprinklers. For a given device and fire size (as determined by HRR), the response time of the device will increase with higher ceilings and with increasing distance from the plume. Stated another way, the higher the ceiling or the farther away the device, the larger the heat output from the fire will be at the time the device responds. These factors should be considered when attempting to understand why a fire appears to be larger than expected at the time of alarm or sprinkler operation.

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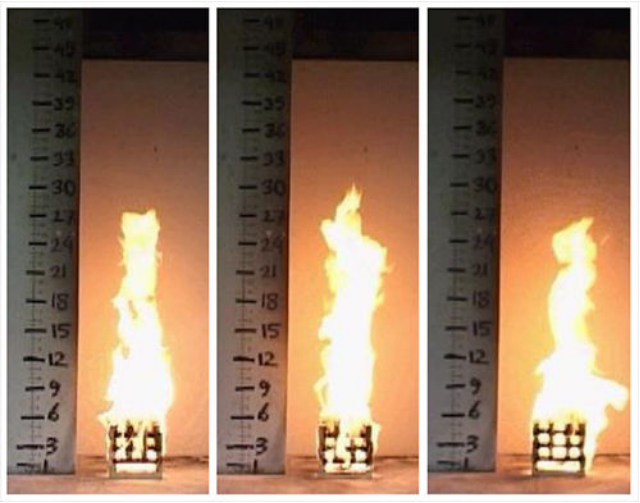


FIGURE 5.6.4.6.4(a) Average Flame Heights for Replicate Wood Crib Fires in the Open. The range of measured heat release rates and estimated average flame heights were 24 kW to 26 kW and 27 in. to 30 in., respectively.

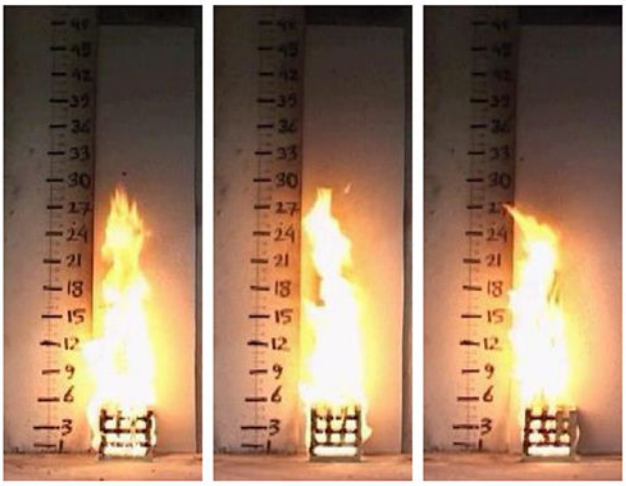


FIGURE 5.6.4.6.4(b) Average Flame Heights for Replicate Wood Crib Fires Against the Wall. The range of measured HRRs and estimated average flame heights were 21 kW to 25 kW and 27 in. to 30 in., respectively.

5.6.5 Thermal Structure of a Flame.

5.6.5.1 Continuous Flaming Region. Maximum time-averaged flame temperatures at a height occur at the centerline of the fire. In the continuously flaming region, centerline temperatures are approximately constant around 1000°C (1832°F). As indicated by data in Table 5.6.5.1, there is little variation in this temperature with the fuel. Methanol flames have higher temperatures due to the low radiant output of the flame, while sootier, more radiative flames are somewhat lower in temperature. In very large pool fires, the sootier flames can reach temperatures of 1200°C (2192°F) because radiative losses are relatively smaller. Flame temperatures for accelerants are not higher than for ordinary fuels, like wood or plastics.

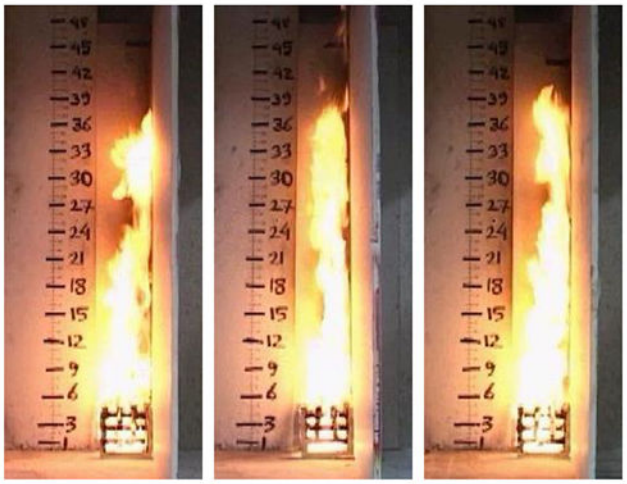


FIGURE 5.6.4.6.5 Average Flame Heights for Replicate Wood Crib Fires in a Corner Configuration. The range of measured heat release rates and estimated average flame heights were 25 kW to 26 kW and 37 in. to 40 in., respectively.

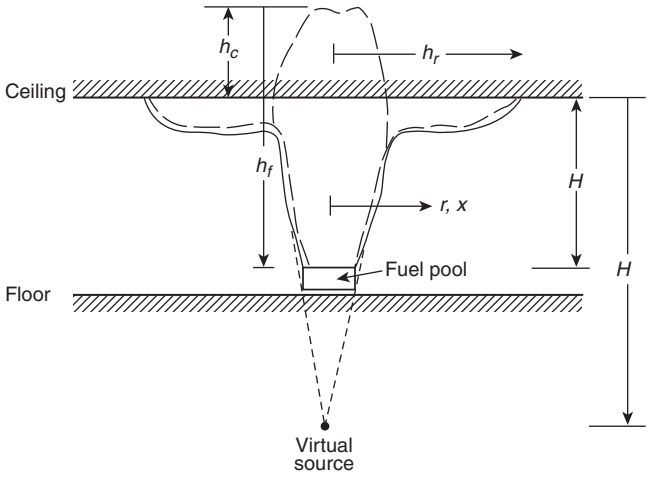


FIGURE 5.6.4.7 Representation of Theoretical Flame Heights in a Room with a Ceiling.

5.6.5.2 Intermittent Flame Region. Centerline time-averaged temperatures in the intermittent region fall from about 1000°C (1832°F) at the continuous flame region to about 300°C (572°F) at the plume region. The time-averaged temperature at the average flame height (50 percent intermittency) is about 500°C (932°F).

5.6.5.3 Plume Region. Centerline time-averaged temperatures in the plume region fall from about 300°C (572°F) at the intermittent flame region to ambient temperatures well above the visible flame.

5.6.6 Heat Fluxes from Flames. The thermal impact of a flame on nearby materials (combustibles or noncombustibles) and surfaces is measured in terms of the heat flux history to those surfaces. For example, the thermal decomposition and ignition of combustibles and the calcination of gypsum are governed by the incident heat flux history. As such, fire spread

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Table 5.6.5.1 Maximum Time-Averaged Flame Temperatures Measured on the Centerline of Fires Involving a Range of Fuels

Source	Temperature °C	Temperature °F
Flames		
Benzene[a]	920	1690
Gasoline[a]	1026	1879
JP-4[b]	927	1700
Kerosene[a]	990	1814
Methanol[a]	1200	2190
Wood[c]	1027	1880

[a]From Drysdale, *An Introduction to Fire Dynamics.*
[b]From Hagglund, B., Persson, L. E. (1976), Heat Radiation From Petroleum Fires, National Defence Research Inst., Stockholm, Sweden, FOA Report C20126-D6(A3).
[c]From Hagglund, B., Persson, L. E (1974), Experimental Study of the Radiation From Wood Flames, National Defence Research Inst., Stockholm, Sweden, FOA Report C4589-D6(A3).

and fire-generated patterns are directly governed by the distribution of heat flux from flames to adjacent surfaces.

5.6.6.1 Heat Fluxes from Flames to Contacted Surfaces.

5.6.6.1.1 Walls. Figure 5.6.6.1.1(a) shows the distribution of heat flux from a fire in a room corner to the wall surface. The fire source had a heat release rate of 300 kW and the flames reached the ceiling. Figure 5.6.6.1.1(b) shows the same condition, but in the absence of a ceiling. The shapes of the heat flux contours are clearly different, with the ceiling case showing a more pronounced V-pattern nature than the no ceiling case.

5.6.6.1.2 Ceilings. Figure 5.6.6.1.2 shows the heat flux contours on a ceiling. The maximum heat flux occurs at the area of flame impact, and the fluxes are reduced with increasing distance from the impact area.

5.6.6.2* Heat Fluxes from Flames to Remote Surfaces. Heat fluxes from flames to a remote surface decrease rapidly with distance. Figure 5.6.6.2(a) shows the maximum heat flux as a function of distance from a chair or couch fire to targets at a number of heights. fire. Figure 5.6.6.2(b) shows the heat flux histories for a number of target distances with the target 0.4 m above the floor. Figure 5.6.6.2(c) shows the heat flux as a function of L/D, the distance of the ground level target from a pool fire at the center of a circular pool fire divided by the pool diameter (e.g., $L/D = 0.5$ is the edge of the pool). Both these figures illustrate that heat fluxes are markedly reduced at target distances comparable to the fire diameter.

5.7* Ignition. Forms and mechanisms of ignition vary with the form of the material (gas, liquid, solid), the chemical properties of the material, and the form and intensity of heating. Classifications of ignition include smoldering vs. flaming ignition, and piloted vs. autoignition. Piloted ignition occurs when an external ignition source acts to ignite flammable vapors. Pilot sources include small flames, sparks, and hot surfaces. The following is a general introduction.

5.7.1 General. In order for most materials to be ignited, they generally must be in a gaseous or vapor state. A few materials may burn directly in a solid state or glowing form of combustion, including some forms of carbon (such as charcoal) and

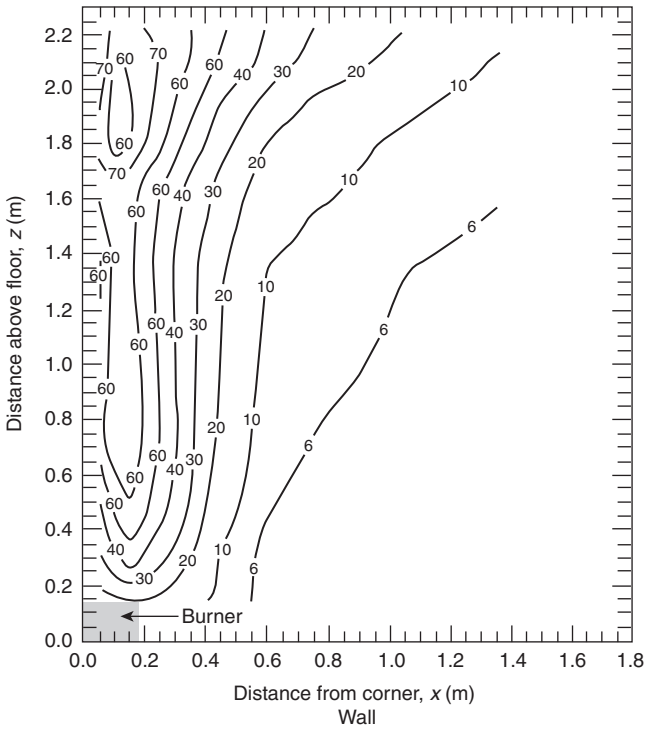


FIGURE 5.6.6.1.1(a) Wall Heat Flux (kW/m^2) Contours from a 300 kW Fire in a Corner Configuration. A ceiling is present at 2.3 m above the floor and the fuel burned was propane. ***[Adopted from Lattimer (2002).]***

magnesium. Gases or vapors from ordinary fuels must be present in the atmosphere in sufficient quantity to form a flammable mixture. Liquids with flash points below ambient temperature do not require additional heat to produce a flammable mixture. The temperature of the fuel vapors produced must then be raised to their ignition temperature. The time and energy required for ignition to occur is a function of the energy of the ignition source, the thermal inertia (k, ρ, c) of the fuel, the minimum ignition energy, and the geometry of the fuel. If the fuel is to increase in temperature, the rate of heat transfer to the fuel must be greater than the sum of the conduction losses, convection losses, radiation losses, energy associated with phase changes (such as the heat of vaporization), and energy associated with chemical changes (such as pyrolysis). In some cases, chemical changes in the fuel during heating may also produce heat prior to combustion (exothermic reaction). If the fuel is to reach its ignition temperature, the heat source itself must have a temperature higher than the fuel's ignition temperature. Spontaneous ignition is an exception.

5.7.1.1 Table 5.7.1.1 shows the temperature of selected ignition sources. A few materials, such as cigarettes, upholstered furniture, sawdust, and cellulosic insulation, are permeable and readily allow air infiltration. These materials can undergo solid phase combustion, known as smoldering. This is a flameless form of combustion whose principal heat source is char oxidation. Smoldering produces more toxic compounds than flaming combustion per unit mass burned, and it provides a chance for flaming combustion from a heat source too weak to produce flame directly.

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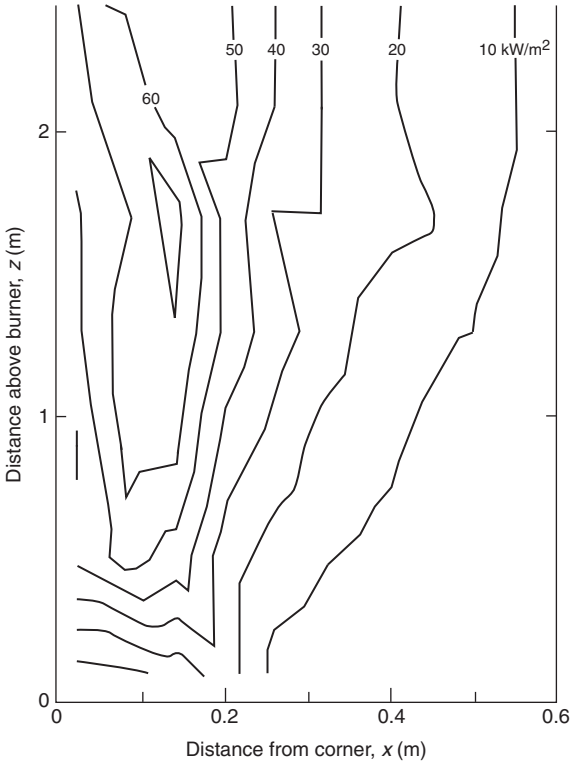


FIGURE 5.6.6.1.1(b) Wall Heat Flux (kW/m^2) Contours from a 300 kW Fire in a Corner Configuration. No ceiling is present and the fuel burned was propane. [*Adopted from Lattimer (2002)*.]

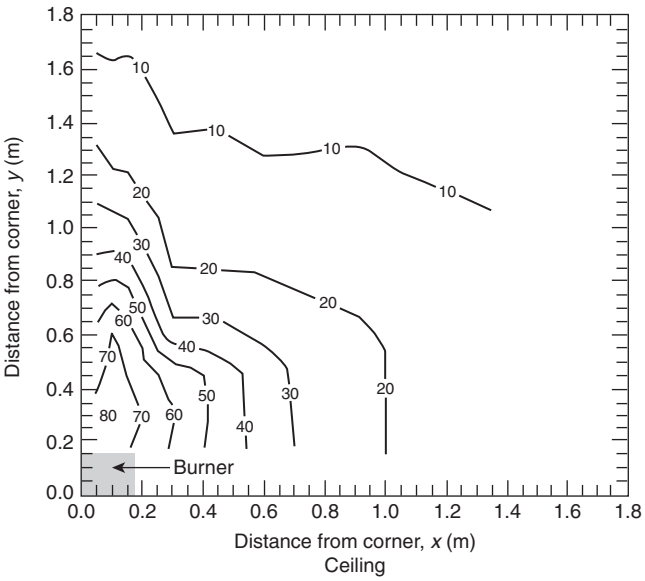


FIGURE 5.6.6.1.2 Ceiling Heat Flux (kW/m^2) Contours from a 300 kW Fire in a Corner Configuration. A Ceiling is Present at 2.3 m Above the Floor and the Fuel Burned was Propane. [*Adopted from Lattimer (2002)*.]

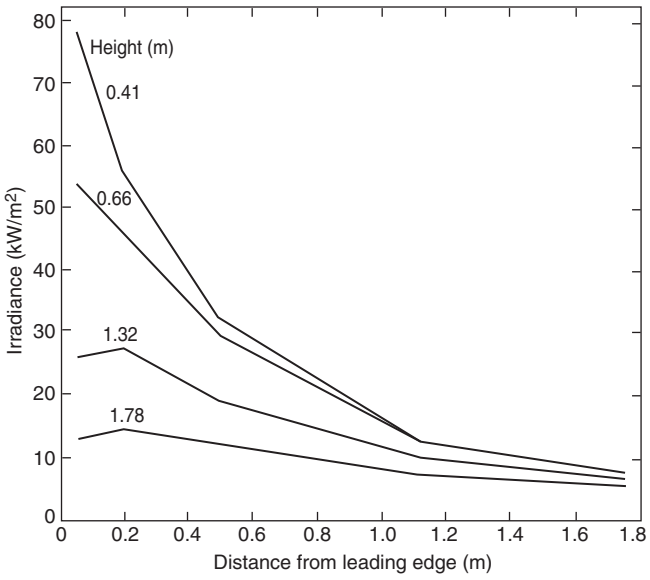


FIGURE 5.6.6.2(a) Maximum Radiant Heat Flux to Targets Facing a Wicker Couch Fire. [*Adopted from Krasny, Parker, and Babrauskas (2001)*.]

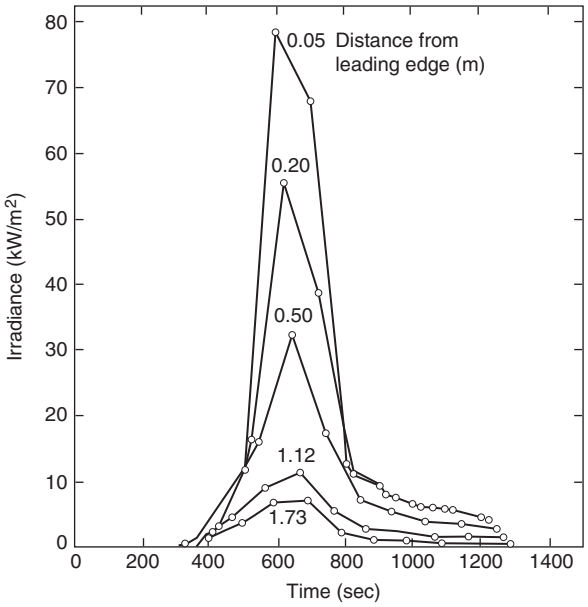


FIGURE 5.6.6.2(b) Radiant Heat Flux Histories to Targets at a Height of 0.41 m Facing a Wicker Couch Fire. [*Adopted from Krasny, Parker, and Babrauskas (2001)*.]

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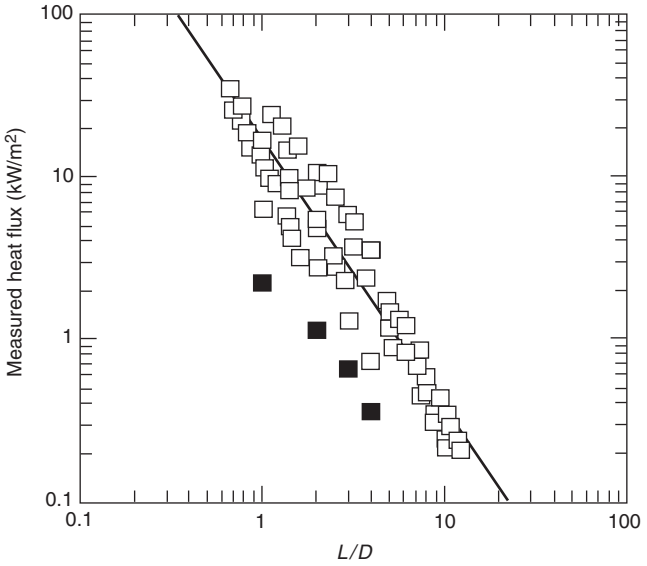


FIGURE 5.6.6.2(c) Radiant Heat Flux to a Target at Ground Level Facing Pool Fires. Data from 1 m to 30 m diameter pool fire tests are shown; data from larger diameter pool fire tests do not follow the correlation and are omitted here.

Table 5.7.1.1 Reported Burning and Sparking Temperatures of Selected Ignition Sources

Source	Temperature °C	Temperature °F
Flames		
Benzene[a]	920	1690
Gasoline[a]	1026	1879
JP-4[b]	927	1700
Kerosene[a]	990	1814
Methanol[a]	1200	2190
Wood[c]	1027	1880
Embers [d]		
Cigarette (puffing)	830–910	1520–1670
Cigarette (free burn)	500–700	930–1300
Mechanical sparks [e]		
Steel tool	1400	2550
Copper–nickel alloy	300	570

[a]From Drysdale, *An Introduction to Fire Dynamics.*
[b]From Hagglund, B., Persson, L. E. (1976), Heat Radiation From Petroleum Fires, National Defence Research Inst., Stockholm, Sweden, FOA Report C20126-D6(A3).
[c]From Hagglund, B., Persson, L. E (1974), Experimental Study of the Radiation From Wood Flames, National Defence Research Inst., Stockholm, Sweden, FOA Report C4589-D6(A3).
[d]From Krasny, J. (1987) *Cigarette Ignition of Soft Furnishings — A Literature Review with Commentary,* NBSIR 87-3509; National Bureau of Standards, Gaithersburg MD.
[e]From NFPA *Fire Protection Handbook*, 15th ed., Section 4, p. 167.

5.7.2 Ignition of Flammable Gases.

5.7.2.1 Flammable gases can only be ignited by a spark or pilot flame over specific ranges of gas concentration. These limits are normally expressed as the lower flammable/explosive limit (LFL/LEL), the lowest concentration by volume of flammable gas in air that will support flame propagation, and the upper flammable/explosive limit (UFL/UEL), the highest concentration of flammable gas in air that will support flame propagation. These limit concentrations fluctuate with temperature and pressure changes, and with changes in oxygen concentration.

5.7.2.2 In the absence of a spark or pilot flame, a flammable gas–air mixture can autoignite if the temperature of the mixture is sufficiently high. The lowest temperature at which a flammable gas–air mixture can be ignited without a pilot is termed the autoignition temperature (AIT). The AIT is strongly dependent upon the size and geometry of the gas volume and the flammable gas concentration. Typically, large volumes and stoichiometric flammable gas–air mixtures favor ignition at lower temperatures. Because the AIT is dependent upon the conditions, a handbook AIT determined using standard test methods is primarily of value in comparing different gases. Comparisons of different gases must be made in the same apparatus and conditions to be meaningful. Open clouds of flammable gas–air mixtures can ignite on hot surfaces, with ignition occurring at lower temperatures for larger hot surface areas.

5.7.3 Ignition of Liquids.

5.7.3.1 Flashpoint. The ignition of a liquid in a flashpoint test occurs when a sufficient vapor concentration is generated above the liquid surface to allow ignition of the flammable vapors above the liquid surface by a pilot source. The flammable vapor concentration at the surface must reach the lower flammability limit *(see 5.7.2, Ignition of Flammable Gases).* The liquid temperature above which an ignitible concentration of flammable vapors is generated is known as the flash point. At the flash point temperature, the vapors above the liquid can be ignited, but typically sustained burning of the liquid does not occur. The liquid must be heated to a slightly higher temperature, known as the fire point, at which burning of the vaporizing liquid fuel can be sustained as a pool fire. For some liquids, the flash point and fire point temperatures are the same.

5.7.3.2 Liquids at bulk temperatures below the fire point temperature cannot be ignited by a pilot flame or spark. However, liquids can be heated locally to achieve ignition and the fire can then spread to involve the pool. Local heating mechanisms can include flame impingement on the liquid surface or burning of the pooled liquid at a wick formed by material wetted by the liquid. Local application and ignition of a liquid above its flash point to a liquid below its flash point is another method that can cause ignition of a liquid that is otherwise below its flash point temperature.

5.7.3.3 Atomized liquids or mists (those having a high surface area to mass ratio) can be more easily ignited than the same liquid in the bulk form. In the case of sprays or mists, piloted ignition can occur at temperatures below the published flash point of the bulk liquid, and even very high flash-point liquids (several hundred degrees °C) have been shown to be ignitible when in the form of a spray.

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5.7.3.4 Some liquids are capable of being oxidized in the liquid phase. Most often this only leads to ignition when the liquid is supported on a porous substrate (e.g., linseed oil on rags) This subject is treated in the solid fuels section on self-heating below. However, in some industrial situations contact between two liquid phases can result in an exothermic reaction (not necessarily oxidation) sufficient to cause an explosion.

5.7.3.5 Autoignition of a liquid can occur if the flammable vapors produced above the liquid surface are sufficiently hot so as to support gas phase autoignition as discussed above in the Ignition of Gases section. AITs for a given liquid vary with the scale and configuration, as they do for gases. Quantitative AIT determinations in the same apparatus are useful for comparing the behavior of different liquids.

5.7.4 Ignition of Solids. There are three forms of ignition that occur with solid fuels: smoldering ignition or, more generally, initiation of solid phase burning; piloted flaming ignition; and flaming autoignition.

5.7.4.1 Smoldering Ignition and Initiation of Solid Phase Burning.

5.7.4.1.1 General. Smoldering is a solid phase burning process, which normally includes a thermal decomposition step to create a char, followed by solid phase burning of the char produced.

5.7.4.1.1.1 The thermal decomposition process, often called pyrolysis, may be a purely thermal process or may involve interaction with oxygen. When oxygen is known to be involved, this is often referred to as oxidative pyrolysis. The initial thermal decomposition process is normally endothermic [i.e., it requires or uses energy rather than producing heat or energy (which would be exothermic)].

5.7.4.1.1.2 While some virgin materials are capable of solid phase oxidation (e.g., carbon or magnesium), most materials that smolder must be pyrolyzed to form a carbonaceous char, which subsequently oxidizes in the solid phase. The most common class of materials that smolder in this manner includes wood, paper, and other lignocellulosic products.

5.7.4.1.1.3 Materials that are neither capable of solid phase burning as a virgin fuel, nor capable of being pyrolyzed to form a char that can burn cannot smolder. As such, most thermoplastic materials are not capable of smoldering. Some thermosetting polymers (e.g., polyurethane foam), often decompose to form a liquid product when vigorously heated, but do form a char under more modest heating conditions.

5.7.4.1.1.4 The term *smoldering* is sometimes inappropriately used to describe a nonflaming response of a solid fuel to an external heat flux. Solid fuels, such as thermoplastics, when subjected to a sufficient heat flux, will degrade, gasify, and release vapors. There usually is little or no oxidation involved in this gasification process, and thus it is endothermic. This process is pyrolysis, and not smoldering. Smoldering must involve a solid phase exothermic process (i.e., it must be self-sustained).

5.7.4.1.1.5 Spontaneous combustion due to self-heating is a special form of smoldering ignition that does not involve an external heating process. An exothermic reaction within the material is the source of the energy that leads to ignition and burning. The key concept in ignition by self-heating is the ability of the material to dissipate the heat generated by the internal exothermic reactions. If the heat generated by the reaction cannot be dissipated to the surroundings, the material will rise in temperature to an extent that the reaction rates accelerate (i.e., runaway), and a smolder front is formed. Key variables in self-heating include the ambient temperature, the pile size, and the reaction kinetics of the exothermic process. As the ambient temperature rises, the baseline reaction rate increases, and as the pile size increases, the ability to dissipate heat to the surroundings decreases. Both high ambient temperatures and large pile sizes favor self-heating processes. See the following section for more detailed information concerning self-heating in piles.

5.7.4.1.1.6 While self-heating is most often associated with ignition processes in piles due to the inability of the material to dissipate the heat from internal exothermic reactions, all smoldering ignition mechanisms can be understood in the context of the fundamentals of self-heating theory. Smolder initiation by radiative heating, smolder initiation by contact with a hot surface, smoldering ignition by contact with hot objects (e.g., contact with hot welding slag, burning embers, or a cigarette), smoldering ignition of layers or other accumulations of dust in a dryer are all governed by the fundamental laws of self-heating theory. If heat from oxidizing the material cannot be adequately dissipated, a thermal runaway, resulting in smoldering, will occur.

5.7.4.1.1.7 Because all smoldering ignition mechanisms are governed by self-heating laws, there is no generally or widely applicable "standard" ignition temperature that can be assigned. For a specific pile size of a specific material, there is a critical ambient temperature (CAT) above which ignition is expected to occur. For a wood surface heated by radiation, there is a specific surface temperature above which smoldering will occur. However, these ignition temperatures are only applicable to the conditions under which they were experimentally determined. They are not generally or broadly applicable.

5.7.4.1.2 Self-Heating and Self-Ignition.

5.7.4.1.2.1 Self-heating is a process whereby a material undergoes a chemical reaction and increases in temperature solely due to exothermic reactions between the material (normally a solid) and the surrounding atmosphere (normally air).

5.7.4.1.2.2 Most organic materials and metals capable of reacting with oxygen will oxidize at some critical temperature with the evolution of heat. The evolution of heat is not restricted to oxidation reactions, but can also be due to various other chemical reactions, for example, polymerization, where liquids react to form solids. Generally, self-heating and spontaneous combustion (self-ignition) are commonly encountered in organic materials, such as animal and vegetable fats and oils, because these materials contain polyunsaturated fatty acids. Such fatty acids react with oxygen to generate heat. Unsaturated molecules contain carbon-to-carbon double bonds, which are reactive.

5.7.4.1.2.3 Self-heating and spontaneous combustion (self-ignition) of oils containing mostly saturated hydrocarbons, such as motor oil or lubricating oil, occur only under elevated temperature conditions (e.g., an oil-soaked rag wrapped around a steam pipe) or in very large piles at lower temperatures. Saturated hydrocarbons contain carbon-to-carbon single bonds, which are far less reactive than unsaturated oils. Unlike highly unsaturated oils such as linseed oil, consumer quantities

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of motor oil or lubricating oil on rags are not expected to self-heat to ignition.

5.7.4.1.2.4 Certain inorganic materials, such as metal powders, may undergo rapid oxidation, self-heating, and self-ignition to form metal oxides, given appropriate conditions.

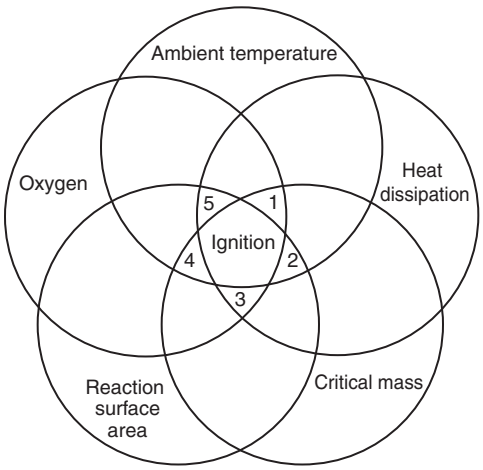
5.7.4.1.3 Mechanism of Self-Heating to Ignition. Spontaneous combustion requires certain steps for it to occur. First, the material must be capable of self-heating and must be subjected to conditions where self-heating is elicited. Next, the self-heating must proceed to thermal runaway (i.e., the heat generated exceeds the heat losses to the environment). Thermal runaway, in theory, means a temperature rise so large that stable conditions can no longer exist. In practice, it means that the material will undergo an internal temperature rise (often at or near its middle) on the order of several hundred degrees Celsius. Next, thermal runaway must result in self-sustained smoldering. The opposite of this is a condition where the material chars locally, but fails to establish a propagating smolder front.

5.7.4.1.3.1 Thermal runaway is an instability that occurs when heat generation exceeds heat loss within the material. It is a contest between exothermic chemistry and heat loss to the surroundings. Heat generation has its best chance of winning at the most insulated parts of the fuel package, that is, at the center, and this is usually where the highest temperatures are found. How well-insulated the interior of the fuel package is depends on the distance to the boundary and the temperature there. During self-heating, the center temperature is typically higher than the surrounding temperatures.

5.7.4.1.3.2 Self-heating to ignition requires a porous, permeable, and oxidizable material — the material must have all three properties. When smoldering, the fuel must char without melting, otherwise the porous and permeable qualities will be lost and self-heating will be inhibited. The solid may initially serve primarily as an inert substrate, as in the case of linseed-oiled rags, or the substrate also may act as the fuel. The most common self-heating substrates are organic solids derived from plant materials, such as cotton fabrics, wood and wood products, agricultural products, and coal. Self-heating may occur when the surroundings are at ordinary ambient conditions, for example, a pile of linseed-oiled rags, or it may require an elevated temperature.

5.7.4.1.3.3 The tendency to self-heat is dependent on the size and shape of the fuel package and its surrounding conditions. This tendency is not exclusively a material property. Therefore, evaluation of a material's self-ignition potential is incomplete (except for the elimination of non-self-heating fuel packages) without considering the particulars of the material's size, shape, and surroundings. For a given volume, low surface area shapes, such as spheres or cubes, promote self-heating more than high surface area shapes, such as thin sheets. The small external surface area reduces heat loss and the outer parts of the fuel package insulate the interior, promoting the rise in the interior temperature from self-heating. For example, linseed-oiled rags in a pile are more likely to self-heat than the same rags on a clothesline or laid flat. Figure 5.7.4.1.3.3 is a graphical representation of the conditions required for spontaneous ignition to occur.

5.7.4.1.3.4 The fuel package's initial temperature may be the crucial factor in whether ignition occurs. This is sometimes encountered in industrial drying of plant-derived materials



(1) Insufficient reaction surface area
(2) Insufficient oxygen concentration or diffusion
(3) Ambient temperature too low
(4) Insufficient insulation — heat dissipates
(5) Insufficient material

FIGURE 5.7.4.1.3.3 Conditions Required for Spontaneous Ignition to Occur in Materials Capable of Self-Heating.

such as wood products and agricultural products, and drying of oiled fabrics in clothes dryers. If fuel packages are assembled into sufficiently large symmetrical shapes while too hot, they may proceed to thermal runaway and ignition. If the material is dried to moisture content lower than equilibrium, part of the internal heat generation results from the latent heat of moisture absorption — the opposite of evaporative cooling.

5.7.4.1.3.5 Self-heating and the resulting smoldering within a pile may not be noticeable until the smoldering front reaches the surface. First visual indications of self-heating may be a wet spot on the surface of the pile resulting from condensation of water or from other products of the reactions. Redeposition of smoke within the pile often leads to little or no observable smoke above or around the pile. Musty odors may first be noticeable where piles are in enclosed areas.

5.7.4.1.3.6 Enclosure of the fuel in a sealed container or envelope may arrest self-heating because the enclosure eliminates one of the necessary conditions for self-heating-permeability, which allows oxygen diffusion into the solid. Without a supply of oxygen, oxidation and heat generation are inhibited unless the oxidizer is present within the material. For example, linseed-oiled rags in a closed paint can might not self-heat significantly before consuming the oxygen in the can. The use of containers or vapor barriers has been successfully employed to mitigate self-heating hazards, though depending on the amount of oxidizer present in the container and the physical properties and integrity of the container or barrier, self-heating to ignition may occur. Investigation of the particulars of the material storage container is required to assess the potential for self-heating within the container.

5.7.4.1.3.7 The minimum surroundings or exposure temperature necessary for ignition via self-heating is generally lower than the minimum ignition temperature for the same material without self-heating. For example, linseed oil on a cotton substrate can ignite when the surroundings are at ordinary ambient temperatures (20°C or 68°F), yet in the pure liquid

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form its flash point is reported as 222°C (428°F) and its AIT is 343°C (585°F).

5.7.4.1.3.8 Haystacks and other large packages of biomass that are assembled at ambient temperature may begin self-heating with biological activity. If the fuel's moisture content is appropriate, this biologically driven self-heating may be supplanted by oxidation, and thermal runaway followed by ignition may result.

5.7.4.1.3.9* Wood Ignition. Wood, like many other cellulosic materials, is subject to self-heating when exposed to elevated temperatures below its ignition temperature. However, the temperatures at which self-heating of wood will occur is not an intrinsic property of the material. Rather, it is dependent on factors such as the nature of the heat exposure, pile size, and geometry. For short-term heating (less than one day), wood requires a minimum temperature of approximately 250°C (482°F) to ignite, although this value rises as the heat flux increases. For wood subjected to long-term, low-temperature heating, exothermicity due to self-heating is increasingly important. Factors such as the nature of the heat exposure, the size of the wood specimen, and the geometry of the specimen play a deciding role. The scientific community has not reached consensus concerning the self-heating ignition of wood subjected to long-term heating.

5.7.4.1.3.10* Charcoal Briquettes. Charcoal briquettes have been suspected of self-heating to ignition even when packaged in household-sized bags [<9 kg (<20 lb)] at ordinary ambient temperatures. Of particular suspicion is the effect of wetting briquettes with water followed by evaporation. However, rigorous laboratory testing has shown that common-size bags of briquettes do not even approach self-ignition, even when placed in unusually high ambient temperatures, such as in a closed automobile in the sun. Charcoal briquettes have no greater tendency for self-heating than other common materials such as sawdust or hay, even after wetting. Spontaneous combustion of bagged charcoal briquettes in commercially available sizes is not possible under any normal ambient conditions. The effect of contaminants upon self-heating of charcoal briquettes has not been studied.

5.7.4.1.3.11* Contaminants. Contaminants in wood or other cellulosic materials are known to have an effect on thermal decomposition and oxidation. Contaminants that have been identified include fatty acids, vegetable oils, iron, iron oxide, iron sulphides, cobalt, copper, magnesium, lead carbonate, potassium carbonate, lead acetate, sodium acetate, and vanadium pentoxide. Quantitative work to deduce the effect of such contaminants on ignition behavior remains to be done.

5.7.4.1.4* Common Materials Subject to Self-Heating.

5.7.4.1.4.1 The most commonly encountered forms of self-heating and self-ignition by fire investigators are the following:

(1) Polymerization of fatty acids (animal fats, cooking oils, and drying oils) in cellulose materials (wood, cloth, and paper)
(2) Oxidation of carbonaceous materials (coal and charcoal)
(3) Biologically induced oxidation (hay bales and compost)
(4) Heat-induced oxidation of lingocellulose materials (usually wood fiber and cloth)
(5) Polymerization reactions (plastics, rubbers, adhesives, and paint overspray particles) *(See NFPA 33.)*

5.7.4.1.4.2 Because of the many possible combinations of these controlling or influencing factors, it is difficult to predict when the material will self-heat. Annex A of the NFPA *Fire Protection Handbook*, 19th edition, includes a list of materials susceptible to spontaneous ignition. Omission of any material does not necessarily indicate that it is not subject to self-heating.

5.7.4.1.5 Oxidizer Fires. An oxidizing agent is a chemical substance that, while not necessarily combustible by itself, can rapidly increase the rate of burning of other substances, or result in spontaneous combustion when combined with other substances. Many of these oxidizers are only found in industrial situations, but swimming pool sanitizers, such as calcium hypochlorite and the salts of dichloroisocyanuric or trichloroisocyanuric acid (stabilized chlorine) will undergo spontaneous heating or spontaneous combustion when contaminated with certain organic materials, particularly hypergolic substances, or with other oxidizers. Once an oxidizer fire starts, a decomposition reaction may take place within the mass of oxidizer, which, while not technically combustion, evolves large quantities of heat and light. These reactions may be quite violent. For a list of oxidizing substances, and the regulations governing their classification and storage requirements, see NFPA 400.

5.7.4.1.6 Pyrophoric Materials. Certain elements, particularly white phosphorus, sodium, potassium, and some finely divided metals, such as zirconium, spontaneously ignite when exposed to air. Materials that undergo spontaneous combustion upon exposure to air are known as *pyrophoric*.

5.7.4.1.7 Transition to Flaming Combustion.

5.7.4.1.7.1 Smoldering can transition to flaming if the smoldering creates sufficient flammable vapors for piloted flaming ignition. This normally occurs when the smoldering becomes vigorous as a result of enhanced airflow to the smolder region. This can occur as a result of the spread of smoldering to generate additional airflows, the creation of a hole or channel by smoldering that then acts as a chimney, or by external imposition of an airflow. When a flammable concentration of vapors is developed, the glowing char can act as the ignition source for ignition of the vapors.

5.7.4.1.7.2* The time required from smolder initiation to transition to flaming is not predictable. Transitions to flaming in upholstered furniture have been observed in times ranging from 20 minutes to many hours. Times for transitions to flaming in large piles can be measured in days or months. Because transition to flaming is governed by changes in airflow and the creation of holes or channels, the time to transition to flaming combustion, if it happens at all, appears to be largely random.

5.7.4.1.7.3 When flaming combustion is initiated by a smoldering source such as a cigarette, or by self-heating, the process leading up to the appearance of the first flame may be quite slow. Once flaming combustion begins, however, the development of the fire may be faster than if the original ignition source were a flame, due to preheating of the fuel.

5.7.4.2 Piloted Flaming Ignition of Solid Fuels. For solid fuels to burn with a flame, the substance must either be melted and vaporized (e.g., thermoplastics) or pyrolyzed into gases or vapors (e.g., wood or thermoset plastics). In both cases, heat must be supplied to the fuel to generate the flammable vapors. In piloted ignition, these flammable vapors are ignited by a

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pilot source, in the form of a small flame, a spark, an ember, or a hot surface.

5.7.4.2.1 While the concept of a piloted ignition temperature for solids is an engineering approximation rather than a reproducibly measurable property, the principle is sufficiently robust to allow general application of experimentally determined ignition temperatures. The range of ignition temperatures for solids ranges from about 270°C to 450°C (518°F to 842°F). Ignition temperatures for non-fire retardant plastics tend to range from 270°C to 360°C (518°F to 680°F), wood based products tend to range from 330°C to 375°C (626°F to 707°F). Ignition temperatures above 400°C (752°F) are generally observed only in inherently fire-retardant materials or materials significantly loaded with fire retardants.

5.7.4.2.2 Associated with the ignition temperature concept is the concept of a minimum radiant flux for piloted ignition. Based upon a thick, well-insulated rear (unexposed) surface, the ignition temperature, along with simple steady state heat transfer concepts, can be applied to deduce the minimum radiant heat flux that can cause ignition. For most materials, the critical radiant heat flux is in the range of 10 to 15 kW/m^2 with some materials exhibiting higher values. This is in contrast with minimum heat fluxes for smoldering ignition of 7 to 8 kW/m^2.

5.7.4.2.3 The experimentally determined value of the minimum heat flux depends upon the duration of the test, with shorter test periods resulting in higher minimum heat flux values. Piloted ignitions have been observed up to about one hour of radiant heating. Most minimum heat flux testing uses a test duration of 15 to 20 minutes. This could increase the minimum heat flux from 10 to 12 kW/m^2.

5.7.4.2.4 As discussed in the Conduction Heat Transfer section, the transient surface temperature rise in a thick material during exposure to a specific heat flux is governed by the thermal inertia of the material. Because thermal inertias vary widely and ignition temperatures range narrowly, variations in material behavior result largely from variations in the thermal inertia. Generally, conductivity and thermal inertia are proportional to the material density. High-density materials of the same generic type (woods, plastics) conduct energy away from the area of the ignition source more rapidly than low-density materials, which act as insulators and allow the energy to remain at the surface. For example, given the same ignition source, oak takes longer to ignite than a soft pine, and low-density foam plastic ignites more quickly than high-density plastic. It is relatively easy to ignite a pile of thin pine shavings, while ignition of a one-pound solid block of wood is more difficult.

5.7.4.2.5 The thickness of the material also markedly affects the ignitibility of a sample. For instance, a piece of paper or wood shaving is much easier to ignite than a thick block of wood. As the thickness increases, the time to ignition increases until thermally thick behavior dominates and increasing the thickness has little additional impact. Thin materials are also easier to ignite because two-sided heating at an edge is also possible. It is easier to ignite the edge of a piece of paper than the center of the sheet.

5.7.4.3 Flaming Autoignition of Solids. Where no pilot sources are available, ignition of solids relies upon auto-ignition of the flammable gases generated by heating. While autoignition temperatures are not well defined in that they are highly dependent upon environmental conditions, it is common to find reported AITs in the 400°C to 600°C (752°F to 1112°F) range. Drysdale (1999) reports two temperatures for wood to autoignite. These are heating by radiation, 600°C (1112°F), and heating by convection, 490°C (914°F). For autoignition to occur as a result of radiative heat transfer, the volatiles released from the surface need to be hot enough to produce a flammable mixture above its autoignition temperature when it mixes with unheated air. With convective heating, on the other hand, the air is already at a high temperature and the volatiles need not be as hot.

5.8* Flame Spread.

5.8.1 General. The growth of a fire normally includes the spread of flame over involved fuel surfaces. The rapidity of the fire growth depends upon the fuel properties and the orientation of the fuel surfaces. Broadly speaking, flame spread can be classified as concurrent flame spread or counterflow flame spread. These terms relate the direction of flame spread compared to the direction of gas flow. Examples of these types of flame spread are shown in Figure 5.8.1.

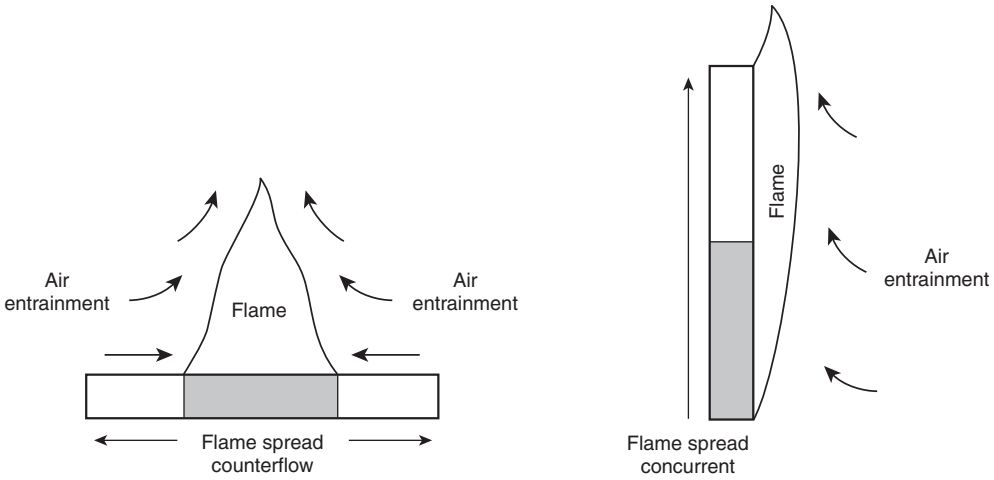


FIGURE 5.8.1 Examples of Counterflow and Concurrent Flame Spread. [*Adopted from Beyler and DiNenno (1994).*]

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5.8.1.1 Counterflow Flame Spread. Counterflow flame spread, also known as opposed flow flame spread, occurs where the flame spread direction is counter to or opposed to the gas flow. Notable examples of this are lateral spread on a horizontal surface (Figure 5.8.1) or downward flame spread on a vertical surface. Counterflow flame spread is generally slow as a result of the limited ability of the flame to heat the fuel ahead of the flame front.

5.8.1.2 Concurrent Flame Spread. Concurrent flame spread, also known as wind-aided flame spread, occurs where the flame spread direction is the same as the gas flow or wind direction. Notable examples of concurrent flow flame spread include upward flame spread on a wall. Concurrent flame spread is generally quite rapid as a result of the direct contact of the flame with the fuel ahead of the flame front.

5.8.1.3 Fire Spread on Sloped Surfaces. Figure 5.8.1.3 illustrates the counterflow and concurrent flow on surfaces at varying slopes. Fires on sloped surfaces, such as sloping combustible walls, ramps, or stairs, display the effects of concurrent flow fire spreads *(see Figure 5.8.1.3)*. Most such ramp or stair constructions in structures are sloped at 30 degrees to 50 degrees from the horizontal. The sloped fire spread is a combined effect of the preheating of the combustible surface above the flame by conductive, convective, and radiant heat transfer mechanisms and the exponentially increased radiant effect on the surface above the flame by the concurrent air entrainment from the side facing the slope "bending" the flame down toward the surface.

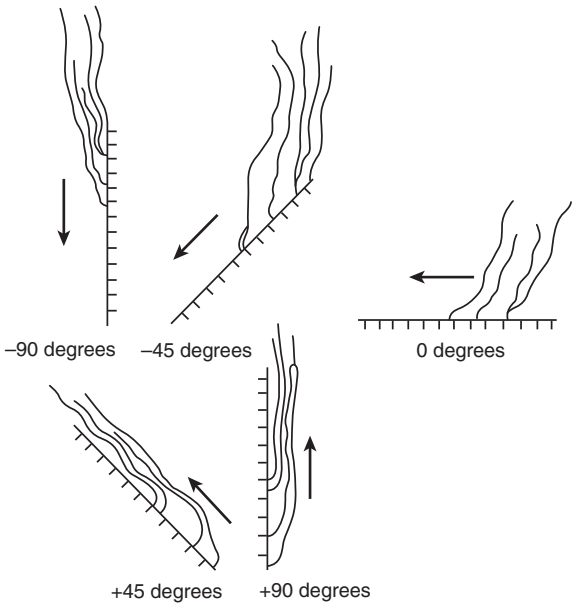


FIGURE 5.8.1.3 Interaction Between the Flame and the Fuel for Flame Spread at Different Angles of Inclination. Counterflow: –90 degrees, –45 degrees, 0 degrees; concurrent flow: +45 degrees +90 degrees.

5.8.1.3.1* Fire Spread in an Inclined Trench. The 1987 King's Cross Underground ("tube") (subway) Station escalator fire in London drew attention to a previously unrecognized mechanism (at least for fires in buildings), the "Inclined Trench." An "Inclined Trench" is a sloped combustible surface that is laterally bounded by vertical side walls. The best example is an enclosed stairway, with walls on either side. Upward flame spread (concurrent flow) on vertical surfaces is rapid, but this can be enhanced by the local geometry. If there are two inward facing combustible surfaces, such as in a corner or within the side walls of an enclosed combustible stairway, upward spread is enhanced by cross-radiation (feedback radiation) between the burning surfaces. Cross-radiation between the surfaces can greatly enhance the rate of spread and the rate of burning. A relatively simple change to the way in which air could gain access to the flames has an enormous effect on the rate of heat transfer from the flame to the surface, which can result in extremely rapid upward flame spread. It is important to understand the mechanism in order to appreciate its behavior. For upward spread, the physical configurations around the spreading flame can have a dramatic effect. The fire at the King's Cross Underground Station in London in November 1987 involved a wooden escalator inclined at an angle of 30 degrees. A fire became established across the full width of the escalator and flames spread up the escalator "trench" also at an angle of 30 degrees, rather than rising vertically. This was caused by the confinement provided by the sides of the escalator. The rate of upward spread was totally unexpected and was probably equal to the rate that would have been experienced if the escalator had been vertical. The effect is illustrated in Figure 5.8.1.3.1, which shows how the rate of (upward) flame spread on the slabs of polymethylmethacrylate (PMMA) changes as the angle of the slab is increased from 0 degrees (horizontal) to 60 degrees. Without sidewalls, the rate of spread remained unchanged until about 20 degrees, and thereafter increased slowly. However, with sidewalls in place (mimicking the escalator side walls), the rate of spread increased dramatically at slopes above 15 degrees.

5.8.2 Flame Spread on Liquids.

5.8.2.1 Flame spread on liquid fuels depends upon the liquid temperature relative to the flash point. Below the flash point,

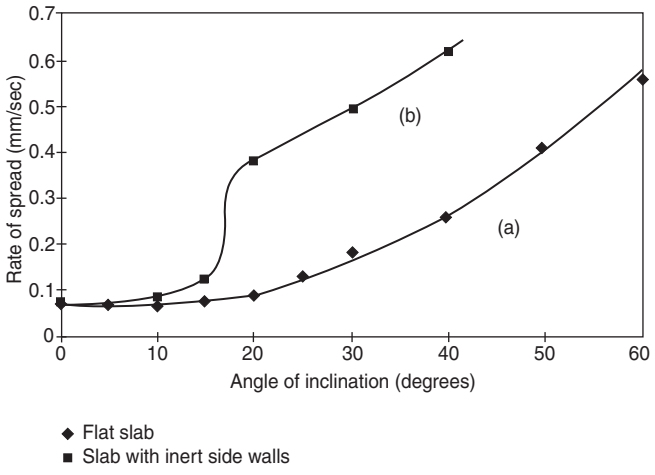


FIGURE 5.8.1.3.1 Variation of the Rate of Upward Flame Spread Over 60 mm Wide Slabs of PMMA at Different Angles. [*From "Fire Dynamics," ISFI (2006)*.]

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flame spread is via liquid flow, and above the flash point, the flame spread is via gas phase spread mechanisms.

5.8.2.2 Liquid Phase Flame Spread. Most liquid phase flame spread is counterflow flame spread, though downwind flame spread in a pool fire or upward flame spread on fuel cascading down a wall are examples of concurrent flame spread. Counterflow flame spread on liquids is aided by surface tension–driven liquid flows within the pool, which accelerate flame heated fuel ahead of the flame front. For very thin fuel layer thicknesses, the surface tension–driven flows are retarded. Several investigators have observed that liquid phase flame spread does not occur at fuel thicknesses of less than 2 mm. Free spills of fuel on flat, horizontal surfaces are typically about 1 mm deep, though deeper spills are expected on realistically leveled floor surfaces. Liquid-driven flame spread rates are generally in the 1 to 10 cm/sec range. See Figure 5.8.2.2 for data on JP-8, a military jet fuel very similar to Jet A used in commercial jet aircraft.

5.8.2.3 Gas Phase Flame Spread. When the liquid is above its flash point, flammable concentrations of fuel vapors exist near the fuel surface. Flame spread occurs through the premixed fuel vapor/air layer at speeds typical of premixed flames, 1 to 2 m/sec *[see Figure 5.8.2.2 for data on JP-8, a military fuel similar to commercial jet fuel (Jet A).]*

5.8.3 Flame Spread on Solids.

5.8.3.1 Flame spread on solid fuels can be thought of in terms of a continuous ignition process. At each location, the fuel needs to be heated to conditions where it can ignite and burn. As such, all the factors that affect ignition of a solid fuel also affect flame spread rates. Flame spread rates on solids depend upon the flame spread mechanism (concurrent vs. counterflow) as well as the thickness and thermal properties of the fuel.

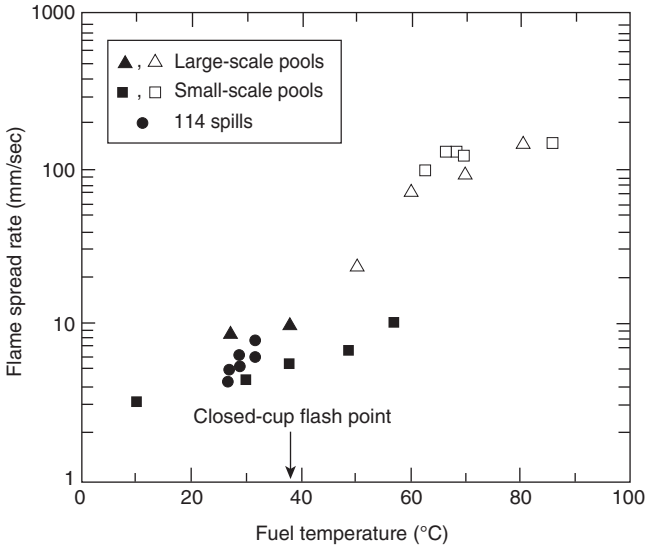


FIGURE 5.8.2.2 Counterflow Flame Spread Rates Over 5 mm (0.2 in.) Deep JP-8 as a Function of Fuel Temperature. JP-8 is a military fuel very similar to Jet A used in commercial jet aircraft. Large-scale data are from tests on a pool 5 ft by 40 ft while the small-scale data are from tests on a pool 8 in. by 5 ft. The transition to gas phase flame spread moves toward the flash point with increasing scale. [*Adopted from Gottuk and White (2002)*.]

5.8.3.2 Counterflow Flame Spread on Thin Fuels. Counterflow flame spread on thin fuels normally occurs for downward flame spread. The flame attaches to the surface of the fuel on both sides of the sheet and the active burning region of the fuel is usually fairly short. Flame spread down a match stick or flame spread down a piece of paper are typical examples of this type of behavior. Flame spread rates are generally in the range of 0.2 to 2 mm/sec with the highest rates occurring for the thinnest fuel.

5.8.3.3 Concurrent Flame Spread on Thin Fuels. Concurrent flame spread on thin fuels normally occurs for upward flame spread. The flame attaches to the surface of the fuel on both sides of the sheet. Because the flame spread rate is faster than counterflow flame spread, the active burning region of the fuel is longer. Flame spread up a curtain or drapery or flame spread up a piece of paper are typical examples of concurrent flame spread on thin fuels. Flame spread rates are generally in the range of tens of cm/sec with the highest rates occurring for the thinnest fuel. No general trends of flame spread rate with fuel thickness are possible because thinner fuels ignite faster, but also burn out faster (yielding shorter flame lengths).

5.8.3.4* Counterflow Flame Spread on Thick Fuels. Counterflow flame spread on thick fuels normally occurs for downward flame spread on a wall or horizontal spread on an upward facing horizontal surface (see Figure 5.8.3.4). Heat transfer from the flame foot (see Figure 5.8.3.4 insert), is via both the gas phase and the solid phase. Heating rates are limited by the very small region of heat transfer, normally a heating length measured in millimeters. Heat is also lost into the thick material. Unenhanced flame spread rates are generally on the order of 0.1 mm/sec. Polyurethane foam spread rates of 2 to 4 mm/sec result from the very low density. Many thick materials cannot support counterflow flame spread without external heating. A common example of this is thick wood. With preheating to 100–200°C, most wood products will support counterflow flame spread. Sources of such preheating include radiation from hot compartment gases or from a nearby flame. Flue space geometries are well suited to provide mutual radiative support for surface burning and flame spread. With external heating, flame spread rates on thick solid fuels can approach the gas phase flame spread rates of liquid fuels.

5.8.3.5* Concurrent Flame Spread on Thick Fuels. Concurrent flame spread on thick fuels normally occurs for upward flame spread on walls or on the underside of combustible ceilings. With a thick fuel, the flame length that heats the material ahead of the burning area is continuously increasing. This allows for the possibility of unlimited acceleratory flame spread rates. Measurement of flame spread rate on a 1.6 m PMMA walls yields flame spread rates up to 6 mm/sec and measurements on a 3.5 m wall yield rates up to 10 mm/sec [Orloff et al. (1974), Wu et al. (1996)]. Similar measurements on a 1.3 m tall corrugated cardboard wall yielded flame spread rates up to 6 to 9 mm/sec [Grant and Drysdale (1995)]. Faster flame spread rates are observed in the flue spaces of rack storage of commodities in cardboard boxes. From an igniter at floor level at time zero, flames can involve fuel at a height of 2 m in 30 seconds and involve cardboard at the 5 m height in 42 seconds [McGrattan et al. (1998)]. Increasing flame spread rates do not occur for all materials and all exposing flames. If the fire exposing a wall is not sufficiently large, upward flame spread may not occur at all or may grow to a limiting height before spread ceases [Saito et al. (1986)].

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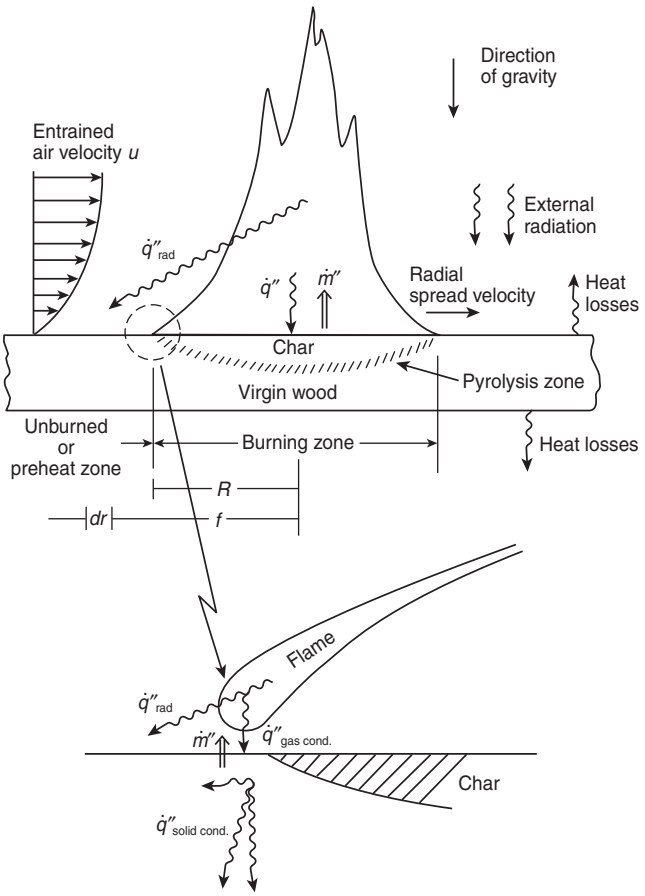


FIGURE 5.8.3.4 Flame Spread on a Horizontal Surface of Wood. [*Adopted from Atreya (1984).*]

5.8.3.6 Role of Melting and Dripping in Flame Spread. Flames may spread differently on different portions of the same fuel package, for example, a flame may spread slowly across the horizontal surface of a chair cushion with spread increasing rapidly as the back of the chair becomes involved. If a material melts, it is likely to drip and pool on horizontal surfaces. The dripping of liquefied polyurethane foam from furniture can form a pool fire under that furniture. The ignition of the underside of the furniture by the pool fire increases the rate of burning of the furniture and results in rapid flame spread. The melting and dripping of material can also result in the removal of fuel from the spreading flame front. This can significantly hinder the ability of the flame front to propagate across the surface of the material.

5.8.3.7 Role of External Heating on Flame Spread. External heating of a fuel surface by a nearby flame or by radiation from upper layer hot gases building up in a compartment can significantly enhance flame spread rates.

5.9* Fire Spread in a Compartment.

5.9.1 The heat release rate of a fire is generally a function of the amount and type of fuel that is involved at any given time and the ventilation conditions. An increase in the heat release rate can occur through flame spread on an individual fuel package, through the ignition of additional fuels, or by changes in ventilation. As the fire grows in size, it increases the potential for fire spread to other compartments or areas within the building. Flame spread is the movement of flames on an individual fuel package (e.g., sofa or combustible wall), and fire spread is described as the ignition of additional fuel packages that can spread the fire throughout a compartment or building.

5.9.2 Fire Spread. Fire spread, as opposed to flame spread, involves the ignition of more remote fuel packages. The fuel packages can be located within the same or in adjacent compartments. The fire can spread either by direct flame impingement or by remote ignition of adjacent fuel packages.

5.9.2.1 Fire Spread by Flame Impingement. As a fire grows, flame spread can be aided by the flow created by hot gases rising within the compartment. For example, the flames from a pool fire in the center of a compartment can be deflected by the flow of ambient air into the compartment through a doorway. The deflection of these flames from one fuel package can impinge on a second fuel package located adjacent to the first. In addition, due to lack of symmetry of airflow into a fire plume, flames from fuel packages located against a wall or in a corner can attach to vertical surfaces. If these surfaces are combustible, they can be ignited through direct flame contact.

5.9.2.2 Fire Spread by Remote Ignition. Remote ignition can occur through the three modes of heat transfer. A transfer of heat through conduction that results in ignition can occur through ceilings and walls. A common example would be the ignition of wood studs behind noncombustible masonry walls or partitions due to the heat from a compartment fire being conducted through the masonry to the combustible structural members.

5.9.2.2.1 Thermal radiant heat transfer that results in ignition can occur from flame radiation or hot gas layer radiation to remote fuel packages. The dominant method of spreading fire from one remote location to another remote location is through radiation. The hot smoke layer will transmit thermal radiation to other fuel packages, which may ignite. If the initial fire in a compartment grows large enough and involves enough fuel, the radiative output from the fire can become large enough to heat surfaces of other remote fuel packages up to the point when autoignition occurs and flame spread then begins on the remote fuel. This effect is observed at the point when a compartment transitions to flashover. Some of the factors that can affect this phenomenon are the size of the fire, the amount of energy radiated, the geometry between the two fuel objects (i.e., facing each other or at an angle, one large object exposing a small object), and the distance between the two objects.

5.9.2.2.2 Fire spread can also occur as a result of "drop down." This occurs when a flaming material drops down and ignites combustibles that it falls on or near. When a flame is burning on an elevated structure or material within a compartment, the possibility exists that before the fuel is completely consumed, the elements will lose integrity and cause the fuel to fall to other areas within the compartment or to a lower level or floor of a building. If this occurs, the still-burning fuel could be next to combustible material that has yet to ignite. Drop down also occurs with burning thermoplastic materials, curtains, draperies, or other thin fuel items.

5.10 Compartment Fire Development. The following is a list of references that pertain to compartment fire development:

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(1) Custer, R. (2003), "Dynamics of Compartment Fire Growth," NFPA Fire Protection Handbook, 19th ed., Section 2.4.
(2) Thomas, P. (1995), "The Growth of Fire-Ignition to Full Involvement," *Combustion Fundamentals of Fire*, ed. Cox, G., Academic Press, London.
(3) Quintiere, J. (2002), "Compartment Fire Modeling," *SFPE Handbook of Fire Protection Engineering*, ed. DiNenno, P., National Fire Protection Association, Quincy, MA.
(4) Walton, D., Thomas, P. (2002), "Estimating Temperatures in Compartment Fires," *SFPE Handbook of Fire Protection Engineering*, ed. DiNenno, P., National Fire Protection Association, Quincy, MA.
(5) Cooper, L. (2002), "Compartment Fire-Generated Environment and Smoke Filling," *SFPE Handbook of Fire Protection Engineering*, ed. DiNenno, P., National Fire Protection Association, Quincy, MA.

5.10.1 General.

5.10.1.1 The rate and pattern of fire development depend on a complex relationship between the burning fuel and the surrounding environment.

5.10.1.2 In a compartment fire, the collection of heat at the top of the room can raise the temperature at the ceiling and produce a large body of high-temperature smoke and hot gases. The radiation from this upper portion of the space can significantly enhance the rate of fire spread and heat release from a burning item. This can result in heat release rates significantly greater than are observed in open burning.

5.10.1.3 Compartments can also restrict the heat release rate by limiting the inflow of air to support combustion. This section summarizes the development of a fire in a compartment.

5.10.1.4 The rate of fire growth as determined by witness statements is highly subjective. Many times witnesses are reporting the fire growth from time of discovery, which cannot be directly correlated to ignition time. The rate of fire growth is dependent on many factors besides fuel load, including fuel configuration, compartment size, compartment properties, ventilation, ignition source, and first fuel ignited. Eyewitnesses reporting a rapid rate of fire growth should not be construed as data supporting an incendiary fire cause.

5.10.2 Compartment Fire Phenomena.

5.10.2.1 When a fire plume reaches the ceiling of a compartment, the flow of smoke and hot gases and the growth of the fire will be affected. Figure 5.10.2.1 depicts a room with a door opening. There are multiple fuel items in the room; one is the item first ignited, and the others are "target" fuels. The fire plume strikes the ceiling and the flow is diverted to flow under the ceiling as a ceiling jet. Ceiling jet gases flow in all directions until the gases strike the walls of the compartment. As the ceiling jet flow reaches the walls and can no longer spread horizontally, the gases turn downward and begin the creation of a layer of hot gases below the ceiling.

5.10.2.2 Smoke Filling. The fire acts as a "pump," adding mass (hot gases) and energy to the upper layer. This continued addition of hot gases to the layer causes the upper layer to grow in depth. The depth of the upper layer of hot gases will continue until the hot upper gas layer reaches the base of the fire or until the layer fills down to the top of an opening.

5.10.2.3 When the hot smoky layer reaches the top of the door opening, as illustrated in Figure 5.10.2.3, it will begin to flow out of the compartment. The descent of the hot gas layer will be stopped when the flow of hot gases out of the opening is equal to the rate of hot gas addition to the layer by the plume.

5.10.2.4 If the fire grows in size, the bottom of the ceiling layer, the layer interface, will continue to descend, the temperature of the hot smoke and gases will increase, and radiant heat from the layer will begin to heat the unignited target fuel, as shown in Figure 5.10.2.4. A well-defined flow pattern will be established at the opening, with the hot combustion products flowing out the top and cool air flowing into the compartment under the smoke layer.

5.10.2.5 In the early stage of burning, there is sufficient air to burn all of the materials being pyrolyzed. This is referred to as *fuel-controlled burning*. As the burning progresses, the availability of air may continue and the fire may have sufficient oxygen even as it grows. Normally, this would be a compartment that had a large door or window opening. In such cases, the gases collected at the upper portion of the room will contain significant oxygen and relatively small amounts of unburned fuel.

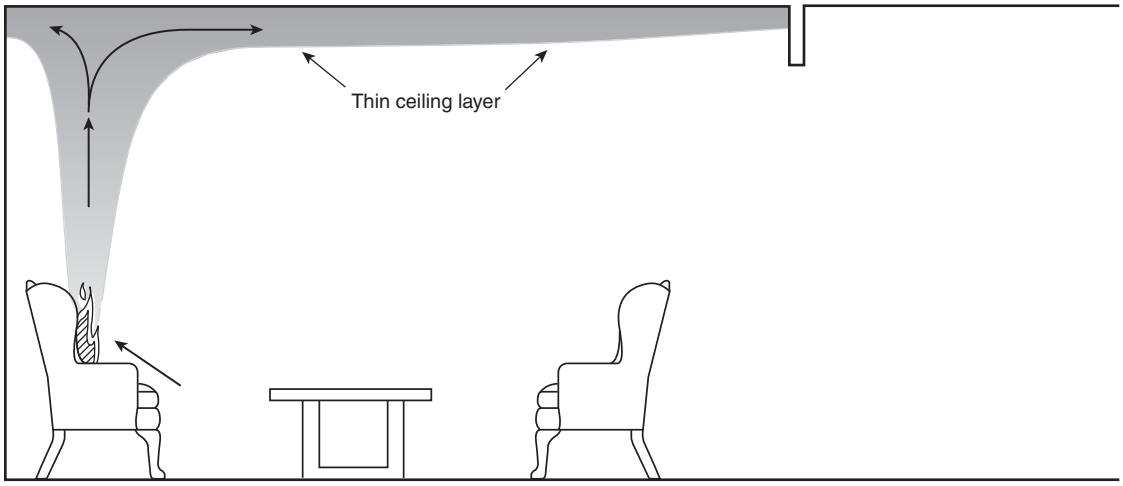


FIGURE 5.10.2.1 Early Compartment Fire Development.

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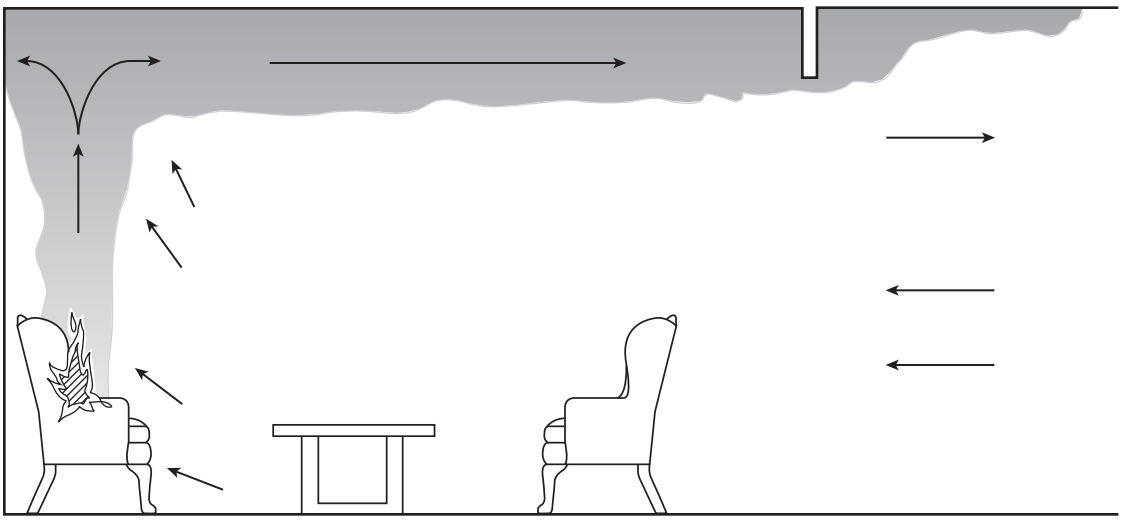


FIGURE 5.10.2.3 Upper Layer Development in Compartment Fire.

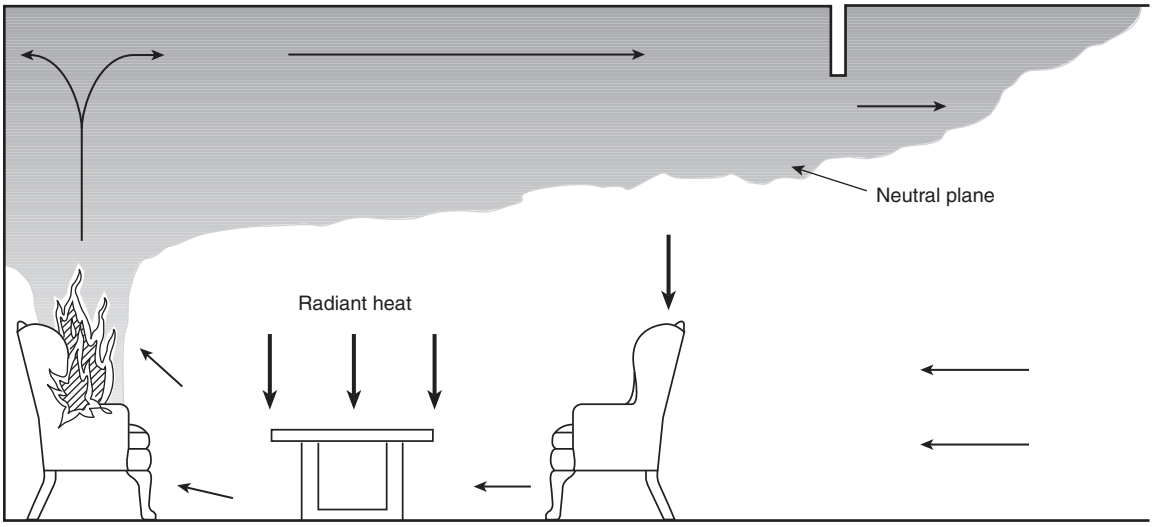


FIGURE 5.10.2.4 Preflashover Conditions in Compartment Fire.

5.10.2.6 As the fire continues to grow, the ceiling layer gas temperature and the intensity of the radiation on the exposed combustible contents in the room increase. Figure 5.10.2.6 shows the evolution in the relative importance of convection and radiation heat transfer. As the fire develops, both convective and radiative heat fluxes increase, but radiation comes to dominate the overall heat transfer. The surface temperature of these combustible contents rises, and pyrolysis gases are produced. When the upper layer temperature reaches approximately 590°C (1100°F), the combustible contents ignite, involving all of the combustible surfaces exposed to upper layer radiation. This phenomenon, known as flashover, is illustrated in Figure 5.10.2.6. The terms *flameover* and *rollover* are often used to describe the condition where flames propagate through or across the ceiling layer only and do not involve the surfaces of target fuels. Flameover or rollover generally precede flashover but may not always result in flashover. As the fire develops, the relative significance of radiation heat transfer comes to dominate over convection heat transfer.

5.10.2.7* If the air flow into the compartment is not sufficient to burn all of the combustibles being pyrolyzed by the fire, the fire will shift from fuel controlled (i.e., where the heat release rate of the fire depends on the amount of fuel involved) to ventilation controlled (i.e., where the heat release rate is controlled by the amount of oxygen available). In a ventilation-controlled fire, the hot gas layer will contain reduced oxygen levels. Fires that reach full room involvement can produce high levels of unburned pyrolysis products and carbon monoxide, and low levels of oxygen (e.g., 0–5 percent). *(See Figure 5.10.2.7 for an example of a ventilation-controlled fire.)*

5.10.2.8 During postflashover burning, the position of the bottom-of-the-ceiling layer and the existence and size of flaming on or associated with target fuels within the layer can vary between the conditions shown in Figure 5.10.2.6 and Figure 5.10.2.7. While the burning of floors or floor coverings is common, such burning may not always extend under target

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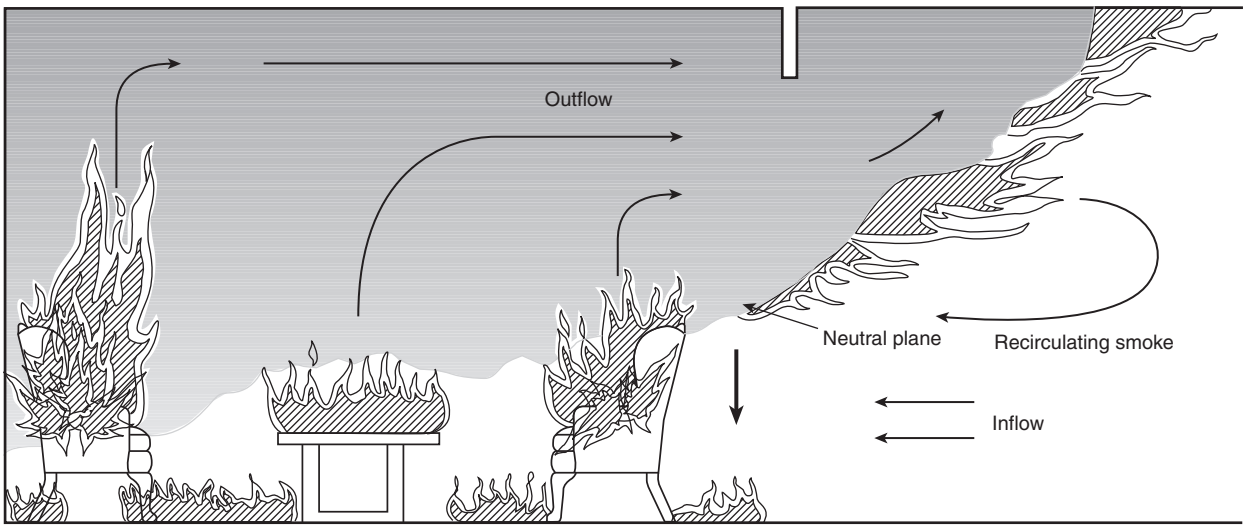


FIGURE 5.10.2.6 Flashover Conditions in Compartment Fire.

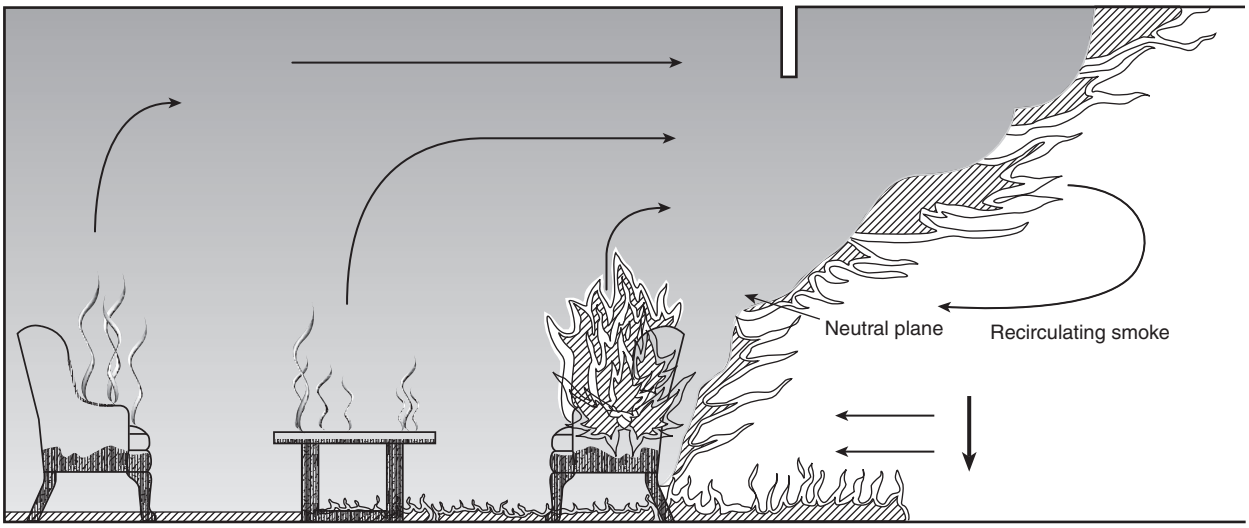


FIGURE 5.10.2.7 Postflashover or Full Room Involvement in a Typical Compartment Fire. Although pyrolysis can continue throughout the compartment, flaming combustion will only occur where there is sufficient oxygen present. Depending on the momentum of the entraining air, flaming combustion may occur within the ventilation stream at various depths into the compartment.

fuels or other shielding surfaces. This fully developed fire stage is typically ventilation-controlled burning.

5.10.3 Compartment Vent Flows.

5.10.3.1 Airflows required to support a compartment fire can be provided by mechanical ventilation (HVAC flows) or by natural ventilation via openings (vents). Except where natural ventilation openings are extremely limited, natural ventilation generally dominates over mechanical ventilation.

5.10.3.2 Natural ventilation via an existing open door or window occurs due to buoyancy associated with the fire and the hot gas layer in the fire compartment. The hot gases, having a much lower density than ambient air, flow out of the top of the opening and the air that replaces the lost gases flows into the lower portion of the opening. The height at which the flow changes direction is known as the "neutral plane." This demarcation is often visible in the fire patterns on the door frame. An upward sweeping region of thermal damage on an open door records the flow of hot gases.

5.10.3.3 Single Opening Flows.

5.10.3.3.1 When the upper hot layer interface is near the top of the opening, the outflow of gases through the opening occurs at and above the height of the interface. Under these conditions the layer interface and the neutral plane are at the same height.

5.10.3.3.2 When the hot layer interface moves down near the base of the opening, the neutral plane is no longer at the interface height. When the hot upper gas layer within the room

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