

NFPA 921

Guide for Fire and Explosion Investigations

2004 Edition



NFPA, 1 Batterymarch Park, Quincy, MA 02169-7471
An International Codes and Standards Organization

IMPORTANT NOTICES AND DISCLAIMERS CONCERNING NFPA DOCUMENTS

NOTICE AND DISCLAIMER OF LIABILITY CONCERNING THE USE OF NFPA DOCUMENTS

NFPA codes, standards, recommended practices, and guides, of which the document contained herein is one, are developed through a consensus standards development process approved by the American National Standards Institute. This process brings together volunteers representing varied viewpoints and interests to achieve consensus on fire and other safety issues. While the NFPA administers the process and establishes rules to promote fairness in the development of consensus, it does not independently test, evaluate, or verify the accuracy of any information or the soundness of any judgments contained in its codes and standards.

The NFPA disclaims liability for any personal injury, property or other damages of any nature whatsoever, whether special, indirect, consequential or compensatory, directly or indirectly resulting from the publication, use of, or reliance on this document. The NFPA also makes no guaranty or warranty as to the accuracy or completeness of any information published herein.

In issuing and making this document available, the NFPA is not undertaking to render professional or other services for or on behalf of any person or entity. Nor is the NFPA undertaking to perform any duty owed by any person or entity to someone else. Anyone using this document should rely on his or her own independent judgment or, as appropriate, seek the advice of a competent professional in determining the exercise of reasonable care in any given circumstances.

The NFPA has no power, nor does it undertake, to police or enforce compliance with the contents of this document. Nor does the NFPA list, certify, test or inspect products, designs, or installations for compliance with this document. Any certification or other statement of compliance with the requirements of this document shall not be attributable to the NFPA and is solely the responsibility of the certifier or maker of the statement.

ADDITIONAL NOTICES AND DISCLAIMERS

Updating of NFPA Documents

Users of NFPA codes, standards, recommended practices, and guides should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of Tentative Interim Amendments. An official NFPA document at any point in time consists of the current edition of the document together with any Tentative Interim Amendments and any Errata then in effect. In order to determine whether a given document is the current edition and whether it has been amended through the issuance of Tentative Interim Amendments or corrected through the issuance of Errata, consult appropriate NFPA publications such as the National Fire Codes® Subscription Service, visit the NFPA website at www.nfpa.org, or contact the NFPA at the address listed below.

Interpretations of NFPA Documents

A statement, written or oral, that is not processed in accordance with Section 6 of the Regulations Governing Committee Projects shall not be considered the official position of NFPA or any of its Committees and shall not be considered to be, nor be relied upon as, a Formal Interpretation.

Patents

The NFPA does not take any position with respect to the validity of any patent rights asserted in connection with any items which are mentioned in or are the subject of NFPA codes, standards, recommended practices, and guides, and the NFPA disclaims liability for the infringement of any patent resulting from the use of or reliance on these documents. Users of these documents are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

NFPA adheres to applicable policies of the American National Standards Institute with respect to patents. For further information contact the NFPA at the address listed below.

Law and Regulations

Users of these documents should consult applicable federal, state, and local laws and regulations. NFPA does not, by the publication of its codes, standards, recommended practices, and guides, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

This document is copyrighted by the NFPA. It is made available for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of safe practices and methods. By making this document available for use and adoption by public authorities and private users, the NFPA does not waive any rights in copyright to this document.

Use of NFPA documents for regulatory purposes should be accomplished through adoption by reference. The term “adoption by reference” means the citing of title, edition, and publishing information only. Any deletions, additions, and changes desired by the adopting authority should be noted separately in the adopting instrument. In order to assist NFPA in following the uses made of its documents, adopting authorities are requested to notify the NFPA (Attention: Secretary, Standards Council) in writing of such use. For technical assistance and questions concerning adoption of NFPA documents, contact NFPA at the address below.

For Further Information

All questions or other communications relating to NFPA codes, standards, recommended practices, and guides and all requests for information on NFPA procedures governing its codes and standards development process, including information on the procedures for requesting Formal Interpretations, for proposing Tentative Interim Amendments, and for proposing revisions to NFPA documents during regular revision cycles, should be sent to NFPA headquarters, addressed to the attention of the Secretary, Standards Council, NFPA, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101.

For more information about NFPA, visit the NFPA website at www.nfpa.org.

Copyright © 2004, National Fire Protection Association, All Rights Reserved

NFPA 921
Guide for
Fire and Explosion Investigations
2004 Edition

This edition of NFPA 921, *Guide for Fire and Explosion Investigations*, was prepared by the Technical Committee on Fire Investigations and acted on by NFPA at its November Association Technical Meeting held November 15–19, 2003, in Reno, NV. It was issued by the Standards Council on January 16, 2004, with an effective date of February 5, 2004, and supersedes all previous editions.

This edition of NFPA 921 was approved as an American National Standard on January 16, 2004.

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 the investigative process. The guide is intended for use by both public sector employees who have statutory responsibility for fire investigation and private sector persons conducting investigations for insurance companies or litigation purposes. The goal of the committee is to provide guidance to investigators that is based on accepted scientific principles or scientific research.

The first edition of the document, issued by NFPA in 1992, focused largely on the determination of origin and cause of fires and explosions involving structures. The second edition of the document included revised chapters on the collection and handling of physical evidence, safety, and explosions. NFPA 907M, *Manual for the Determination of Electrical Fire Causes*, was withdrawn as an individual document and was integrated with revisions into this document as a separate chapter. Elements of NFPA 907M that relate to other chapters of this document were relocated appropriately. New chapters dealing with the investigation of motor vehicle fires, management of major investigations, incendiary fires, and appliances were added.

The third 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. The chapter on electricity and fire was rewritten to improve organization, clarify terminology, and add references. In the chapter on fire patterns, several sections were revised. Other revisions were made in the chapter on physical evidence on the subject of preservation of the fire scene and of physical evidence. The edition also included new text regarding ignitable liquid detection canine/handler teams.

The fourth edition of this document included new chapters on building systems, fire-related human behavior, failure analysis and analytical tools, fire and explosion deaths and injuries, and wildfire investigations. An updated chapter on motor vehicle fires was written. The document was organized to group chapters into subjects that made it more usable.

The fifth edition of this document includes a revision of the document to comply with the new NFPA *Manual of Style* and a new chapter titled, “Analyzing the Incident for Cause and Responsibility,” a rewrite of the chapter on Legal Considerations, and a revision in the chapter on Recording the Scene.

Technical Committee on Fire Investigations

Daniel L. Churchward, *Chair*
Kodiak Enterprises, Inc., IN [SE]

Charles R. Watson, *Secretary*
S.E.A., Incorporated, MO [SE]

Michael Beasley, London Fire Brigade, England [U]

Craig L. Beyler, Hughes Associates, Inc., MD [SE]

Russell K. Chandler, Virginia Fire Marshal Academy,
VA [E]

John Comery, U.S. Department of Justice, OR [E]

Philip E. Crombie, Jr., Travelers Property & Casualty,
CT [I]

Richard L. P. Custer, Arup Fire, MA [SE]

Michael DiMascio, Solutions Engineering Inc., MA [SE]

Richard A. Dyer, Kansas City Fire Department, MO [E]

Rep. International Association of Fire Chiefs

Terry-Dawn Hewitt, McKenna Hewitt, CO [C]

Ronald L. Hopkins, Eastern Kentucky University, KY [U]

Rep. NFPA Fire Service Section

David J. Icove, Tennessee Valley Authority, TN [U]

Carolyn Kelly, Wisconsin Division of Criminal

Investigation, WI [E]

Rep. National Association of State Fire Marshals

Patrick M. Kennedy, John A. Kennedy & Associates, Inc.,

FL [U]

Rep. National Association of Fire Investigators

Michael E. Knowlton, State of New York, NY [E]

Hunter B. Lacy, Royal & SunAlliance, NC [I]

John J. Lentini, Applied Technical Services, Inc., GA [SE]

Jeffrey D. Long, Salt Lake City Fire Department, UT [U]

Hal C. Lyson, Robins, Kaplan, Miller & Ciresi, MN [C]

L. Jeffrey Mattern, FM Global, PA [I]

Rep. FM Global/FM Research

Ted B. Nixon, Ward & Whitmore Universal Fire

Consultants, FL [U]

Rep. International Assn. of Arson Investigators Inc.

Willard F. Preston, III, Delaware State Fire Marshal's
Office, DE [E]

Rep. International Fire Marshals Association

Anthony D. Putorti, Jr., National Institute of Standards
and Technology, MD [RT]

Richard J. Roby, Combustion Science & Engineering,
Inc., MD [SE]

Stuart A. Sklar, Fabian, Sklar & Davis, P.C., MI [C]

David M. Smith, Associated Fire Consultants, AZ [M]

Rep. International Fire Service Training Association

Michael E. Weyler, Engineering and Fire Investigations,
VA [SE]

Alternates

John G. Atherton, Burgoyne Incorporated, GA [U]
(Alt. to Michael Beasley)

Randall E. Bills, S.E.A., Incorporated, OH [SE]
(Alt. to Charles R. Watson)

Douglas Carpenter, Combustion Science & Engineering,
Inc., MD [SE]

(Alt. to Richard J. Roby)

Michael G. Chionchio, Delaware State Fire Marshal's
Office, DE [E]

(Alt. to Willard F. Preston, III)

Richard D. Dietzman, Engineering and Fire
Investigations, MA [SE]

(Alt. to Michael E. Weyler)

David S. Evinger, Robins, Kaplan, Miller & Ciresi, MN [C]
(Alt. to Hal C. Lyson)

Michael H. Fabian, Fabian, Sklar & Davis, P.C., MI [C]
(Alt. to Stuart A. Sklar)

Daniel T. Gottuk, Hughes Associates, Inc., MD [SE]
(Alt. to Craig L. Beyler)

Gerald Haynes, U.S. Department of the Treasury, DC [E]
(Alt. to John Comery)

Kathryn C. Kennedy, John A. Kennedy & Associates, Inc.,
FL [U]

(Alt. to Patrick M. Kennedy)

Jeffery T. Morrill, Applied Technical Services, Inc.,
GA [SE]

(Alt. to John J. Lentini)

Thomas P. Ruane, Fire Protection Publications, OK [M]
(Alt. to David M. Smith)

James H. Shanley, Jr., Travelers Property & Casualty,
IL [I]

(Alt. to Philip E. Crombie, Jr.)

Dennis W. Smith, Kodiak Enterprises, Inc., IN [SE]
(Alt. to Daniel L. Churchward)

Joseph P. Toscano, Fire Investigation Specialist, CT [U]
(Alt. to Ted B. Nixon)

Tony Walker, Louisiana State Fire Marshal, LA [E]
(Alt. to Carolyn Kelly)

William D. Walton, National Institute of Standards and
Technology, MD [RT]

(Alt. to Anthony D. Putorti, Jr.)

Russell M. Whitney, Salt Lake City Fire Department,
UT [U]

(Alt. to Jeffrey D. Long)

Christopher B. Wood, Arup Fire, MA [SE]

(Alt. to Richard L. P. Custer)

Nonvoting

Harold E. Nelson, Hughes Associates, Inc., VA [SE]
(Member Emeritus)

Frank E. Florence, NFPA Staff Liaison

This list represents the membership at the time the Committee was balloted on the final text of this edition. Since that time, changes in the membership may have occurred. A key to classifications is found at the back of the document.

Membership on a committee shall not in and of itself constitute an endorsement of the Association or any document developed by the committee on which the member serves.

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.

Contents

Chapter 1 Administration	921- 6	6.19 Area Patterns	921- 48
1.1 Scope	921- 6	6.20 Material Distortion	921- 49
1.2 Purpose	921- 6	Chapter 7 Building Systems	921- 49
1.3 Application	921- 6	7.1 Introduction	921- 49
1.4 Units of Measure	921- 6	7.2 Features of Design, Construction, and Structural Elements in Evaluating Fire Development	921- 50
Chapter 2 Referenced Publications	921- 7	7.3 Types of Construction	921- 52
2.1 General	921- 7	7.4 Construction Assemblies	921- 55
2.2 NFPA Publications	921- 7	Chapter 8 Electricity and Fire	921- 56
2.3 Other Publications	921- 7	8.1 Introduction	921- 56
Chapter 3 Definitions	921- 9	8.2 Basic Electricity	921- 56
3.1 General	921- 9	8.3 Building Electrical Systems	921- 61
3.2 NFPA Official Definitions	921- 9	8.4 Service Equipment	921- 62
3.3 General Definitions	921- 9	8.5 Grounding	921- 62
Chapter 4 Basic Methodology	921- 14	8.6 Overcurrent Protection	921- 63
4.1 Nature of Fire Investigations	921- 14	8.7 Branch Circuits	921- 67
4.2 Systematic Approach	921- 14	8.8 Outlets and Devices	921- 68
4.3 Relating Fire Investigation to the Scientific Method	921- 14	8.9 Ignition by Electrical Energy	921- 69
4.4 Basic Method of a Fire Investigation	921- 14	8.10 Interpreting Damage to Electrical Systems	921- 71
4.5 Reporting Procedure	921- 15	8.11 Identification of Arc Melting of Electrical Conductors	921- 75
Chapter 5 Basic Fire Science	921- 15	8.12 Static Electricity	921- 76
5.1 Chemistry of Combustion	921- 15	Chapter 9 Building Fuel Gas Systems	921- 80
5.2 Heat Transfer	921- 17	9.1 Introduction	921- 80
5.3 Ignition	921- 18	9.2 Fuel Gases	921- 80
5.4 Fuel Load	921- 22	9.3 Natural Gas Systems	921- 81
5.5 Fire Development	921- 23	9.4 LP-Gas Systems	921- 81
5.6 Products of Combustion	921- 29	9.5 Common Fuel Gas System Components	921- 82
5.7 The Spread of Fire in Buildings	921- 29	9.6 Common Piping in Buildings	921- 83
Chapter 6 Fire Patterns	921- 30	9.7 Common Appliance and Equipment Requirements	921- 83
6.1 Introduction	921- 30	9.8 Common Fuel Gas Utilization Equipment	921- 84
6.2 Dynamics of Pattern Production	921- 30	9.9 Investigating Fuel Gas Systems	921- 84
6.3 Fire Patterns Defined	921- 33	Chapter 10 Fire-Related Human Behavior	921- 87
6.4 Types of Fire Patterns	921- 34	10.1 Introduction	921- 87
6.5 Surface Effect of Char	921- 34	10.2 History of Research	921- 87
6.6 Spalling	921- 36	10.3 General Considerations of Human Responses to Fires	921- 87
6.7 Oxidation	921- 36	10.4 Factors Related to Fire Initiation	921- 89
6.8 Melting of Materials	921- 37	10.5 Children and Fire	921- 90
6.9 Thermal Expansion and Deformation of Materials	921- 38	10.6 Incendiary Fires	921- 90
6.10 Smoke and Soot	921- 38	10.7 Human Factors Related to Fire Spread ...	921- 90
6.11 Clean Burn	921- 38	10.8 Recognition and Response to Fires	921- 90
6.12 Calcination	921- 39	Chapter 11 Legal Considerations	921- 91
6.13 Window Glass	921- 40	11.1 Introduction	921- 91
6.14 Collapsed Furniture Springs	921- 40	11.2 Constitutional Considerations	921- 91
6.15 Location of Objects	921- 41		
6.16 Locations of Patterns	921- 41		
6.17 Pattern Geometry	921- 43		
6.18 Linear Patterns	921- 47		

11.3	Legal Considerations During the Investigation	921- 91	Chapter 17 Origin Determination	921-131
11.4	Pretrial Legal Considerations	921- 93	17.1	Introduction
11.5	Trials	921- 94	17.2	Fire Damage Assessment
Chapter 12 Safety	921- 98	17.3	Preliminary Scene Assessment	921-133
12.1	General	921- 98	17.4	Preliminary Scenario Development
12.2	Factors Influencing Scene Safety	921- 99	17.5	Detailed Exterior Surface Examination
12.3	Criminal Acts or Acts of Terrorism	921-101	17.6	Detailed Interior Surface Examination ...
12.4	Safety in Off-Scene Investigation Activities	921-101	17.7	Fire Scene Reconstruction
Chapter 13 Sources of Information	921-101	17.8	Fire-Spread Scenario.	921-136
13.1	General	921-101	17.9	Total Burns
13.2	Legal Considerations	921-101	Chapter 18 Fire Cause Determination	921-137
13.3	Forms of Information	921-102	18.1	General
13.4	Interviews	921-102	18.2	Process of Elimination
13.5	Governmental Sources of Information ...	921-102	18.3	Source and Form of Heat of Ignition ...
13.6	Private Sources of Information	921-105	18.4	First Material Ignited
13.7	Conclusion	921-106	18.5	Ignition Sequence
Chapter 14 Planning the Investigation	921-106	18.6	Opinions	921-139
14.1	Introduction	921-106	Chapter 19 Analyzing the Incident for Cause and Responsibility	921-139
14.2	Basic Incident Information	921-107	19.1	General
14.3	Organizing the Investigation Functions	921-107	19.2	The Cause of the Fire or Explosion
14.4	Pre-Investigation Team Meeting	921-107	19.3	The Cause of Damage to Property Resulting from the Incident
14.5	Specialized Personnel and Technical Consultants	921-108	19.4	The Cause of Bodily Injury or Loss of Life
14.6	Case Management	921-109	19.5	Determining Responsibility
Chapter 15 Documentation of the Investigation .	921-109	Chapter 20 Failure Analysis and Analytical Tools	921-141	
15.1	Introduction	921-109	20.1	Introduction
15.2	Photography	921-109	20.2	Time Lines
15.3	Note Taking	921-115	20.3	Systems Analysis
15.4	Diagrams and Drawings.	921-116	20.4	Mathematical Modeling
15.5	Architectural and Engineering Schedules	921-121	20.5	Fire Testing
15.6	Specifications	921-121	20.6	Data Required for Modeling and Testing
15.7	Reports	921-121	Chapter 21 Explosions	921-149
Chapter 16 Physical Evidence	921-122	21.1	General	921-149
16.1	General	921-122	21.2	Types of Explosions
16.2	Physical Evidence	921-122	21.3	Characterization of Explosion Damage ...
16.3	Preservation of the Fire Scene and Physical Evidence	921-122	21.4	Effects of Explosions
16.4	Contamination of Physical Evidence	921-123	21.5	Factors Controlling Explosion Effects ...
16.5	Methods of Collection	921-124	21.6	Seated Explosions
16.6	Evidence Containers	921-126	21.7	Nonseated Explosions
16.7	Identification of Physical Evidence	921-127	21.8	Gas/Vapor Explosions
16.8	Transportation and Storage of Physical Evidence	921-128	21.9	Dust Explosions
16.9	Chain of Custody of Physical Evidence	921-128	21.10	Backdraft or Smoke Explosions
16.10	Examination and Testing of Physical Evidence	921-128	21.11	Outdoor Vapor Cloud Explosions
16.11	Evidence Disposition	921-131	21.12	Explosives
			21.13	Investigating the Explosion Scene
			21.14	Analyze Origin (Epicenter)

21.15	Analyze Fuel Source	921-164	Chapter 26 Wildfire Investigations	921-200
21.16	Analyze Ignition Source	921-164	26.1	Introduction
21.17	Analyze to Establish Cause	921-164	26.2	Wildfire Fuels
Chapter 22 Incendiary Fires	921-165	26.3	Factors Affecting Fire Spread	921-202
22.1	Introduction	921-165	26.4	Indicators
22.2	Incendiary Fire Indicators	921-165	26.5	Origin Investigation
22.3	Potential Indicators Not Directly Related to Combustion	921-167	26.6	Security of the Area or Point of Origin
22.4	Other Evidentiary Factors	921-168	26.7	Fire Cause Determination
Chapter 23 Fire and Explosion Deaths and Injuries	921-171	26.8	Evidence	921-210
23.1	General	921-171	26.9	Special Safety Considerations
23.2	Death Scene Considerations	921-171	26.10	Sources of Information
23.3	Death-Related Pathological and Toxicological Examination	921-173	Chapter 27 Management of Major Investigations	921-211
23.4	Fundamental Issues of Death Investigations	921-174	27.1	Introduction
23.5	Mechanism of Death.	921-175	27.2	Understanding between the Parties
23.6	Postmortem Tests and Documentation	921-176	27.3	Agreement between Parties
23.7	Fire and Explosion Injuries	921-177	27.4	Organization of the Investigation
23.8	Mechanism of Inhalation Injuries	921-179	27.5	Team Leader Committee
Chapter 24 Appliances	921-180	27.6	Planning	921-213
24.1	Scope	921-180	27.7	Occupant Access
24.2	Appliance Scene Recording	921-180	27.8	Organization of an Investigation Team
24.3	Origin Analysis Involving Appliances	921-181	27.9	Regular Meetings
24.4	Cause Analysis Involving Appliances	921-181	27.10	Resources
24.5	Appliance Components	921-182	27.11	Preliminary Information
24.6	Common Residential Appliances	921-187	27.12	Safety
Chapter 25 Motor Vehicle Fires	921-189	27.13	Lighting	921-214
25.1	Introduction	921-189	27.14	Access for Investigator
25.2	Vehicle Investigation Safety	921-189	27.15	Securing the Scene
25.3	Fuels in Vehicle Fires	921-189	27.16	Sanitary and Comfort Needs
25.4	Ignition Sources	921-191	27.17	Communications
25.5	System Identification and Function	921-193	27.18	Interviews
25.6	Body Systems	921-196	27.19	Plans and Drawings
25.7	Recording Motor Vehicle Fire Scenes	921-196	27.20	Recording the Scene
25.8	Motor Vehicle Examinations	921-198	27.21	Search Patterns
25.9	Total Burns	921-199	27.22	Evidence
25.10	Stolen Vehicles	921-199	27.23	Release of Information
25.11	Vehicles in Structures	921-199	27.24	Conducting the Scene Examination
25.12	Recreational Vehicles	921-200	27.25	Preplan for Major Fire Investigations
25.13	Heavy Equipment	921-200	Annex A Explanatory Material	921-215
			Annex B Bibliography	921-236
			Annex C Informational References	921-238
			Index	921-241

NFPA 921

Guide for

Fire and Explosion Investigations

2004 Edition

IMPORTANT NOTE: This NFPA document is made available for use subject to important notices and legal disclaimers. These notices and disclaimers appear in all publications containing this document and may be found under the heading "Important Notices and Disclaimers Concerning NFPA Documents." They can also be obtained on request from NFPA or viewed at www.nfpa.org/disclaimers.

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

Changes other than editorial are indicated by a vertical rule beside the paragraph, table, or figure in which the change occurred. These rules are included as an aid to the user in identifying changes from the previous edition. Where one or more complete paragraphs have been deleted, the deletion is indicated by a bullet (•) between the paragraphs 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, Annex C lists the complete title and edition of the source documents for both mandatory and nonmandatory extracts. Editorial changes to extracted material consist of revising references to an appropriate division in this document or the inclusion of the document number with the division number when the reference is to the original document. 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.

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 is 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 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 different and unique from any other, this document is not designed to encompass all the necessary components of a complete investigation or analysis of any one case.

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 time and resource limitations or existing policies may limit the degree to which the recommendations in this document will be applied in a given investigation. This document has been developed as a model for the advancement and practice of fire and explosion investigation, fire science, technology, and methodology.

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.
2.54 cm	1 in.
0.3048 m	1 ft
0.09290 m ²	1 ft ²
28.32 L	1 ft ³
0.02832 m ³	1 ft ³
3.785 L	1 U.S. gal
0.4536 kg	1 lb
28.35 g	1 oz (weight)
0.3048 m/s	1 ft/s
16.02 kg/m ³	1 lb/ft ³
0.06308 L/s	1 gpm
Pressure exerted by 760 millimeters of mercury of standard density at 0°C, 14.7 lb/in. ² (101.3 kPa).	1 atmosphere
1.055 kW	1 Btu/s
1055 J	1 Btu
0.949 Btu/s	1 kW
248.8 Pa = 0.036 psi	1 in. w.c.
1 atmosphere	27.7 in. w.c.

Chapter 2 Referenced Publications

2.1 General. The documents or portions thereof listed in this chapter are referenced within this guide and should be considered part of the recommendations of this document.

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

NFPA 30, *Flammable and Combustible Liquids Code*, 2003 edition.

NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*, 2003 edition.

NFPA 45, *Standard on Fire Protection for Laboratories Using Chemicals*, 2000 edition.

NFPA 54, *National Fuel Gas Code*, 2002 edition.

NFPA 58, *Liquefied Petroleum Gas Code*, 2004 edition.

NFPA 68, *Guide for Venting of Deflagrations*, 2002 edition.

NFPA 70, *National Electrical Code®*, 2002 edition.

NFPA 72®, *National Fire Alarm Code®*, 1999 edition.

NFPA 77, *Recommended Practice on Static Electricity*, 2000 edition.

NFPA 121, *Standard on Fire Protection for Self-Propelled and Mobile Surface Mining Equipment*, 2001 edition.

NFPA 170, *Standard for Fire Safety Symbols*, 2002 edition.

NFPA 220, *Standard on Types of Building Construction*, 1999 edition.

NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers*, 2000 edition.

NFPA 471, *Recommended Practice for Responding to Hazardous Materials Incidents*, 2002 edition.

NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*, 2000 edition.

NFPA 1144, *Standard for Protection of Life and Property from Wildfire*, 2002 edition.

NFPA 1403, *Standard on Live Fire Training Evolutions*, 2002 edition.

NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*, 2002 edition.

NFPA 1971, *Standard on Protective Ensemble for Structural Fire Fighting*, 2000 edition.

NFPA 1977, *Standard on Protective Clothing and Equipment for Wildland Fire Fighting*, 1998 edition.

Fire Protection Handbook, 15th (1981), 16th (1986), 17th (1991), 18th (1997), and 19th (2003) editions.

Fire Protection Guide to Hazardous Material, 12th (1997) edition.

National Fuel Gas Code Handbook, 1996 edition.

The SFPE Handbook of Fire Protection Engineering, Society of Fire Protection Engineers, Quincy, MA, 1988, 1995, and 2000 editions.

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

2.3 Other Publications.

2.3.1 ANSI Publications. American National Standards Institute, Inc., 25 West 43rd Street, 14th Floor, New York, NY 10036.

ANSI Z129.1, *Precautionary Labeling of Hazardous Industrial Chemicals*, 2000.

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

ANSI Z535.1, *Safety Color Code*, 1998.

ANSI Z535.2, *Environmental and Facility Safety Signs*, 1998.

ANSI Z535.3, *Criteria for Safety Symbols*, 1998.

ANSI Z535.4, *Product Safety Signs and Labels*, 1998.

ANSI Z535.5, *Accident Prevention Tags*, 1998.

2.3.2 API Publication. American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005-4070.

RP 2003, *Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents*, 1991.

2.3.3 ASTM Publications. American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM D 56, *Standard Test Method for Flash Point by Tag Closed Tester*, 2002.

ASTM D 92, *Standard Test Method for Flash and Fire Points by Cleveland Open Cup*, 2002.

ASTM D 93, *Standard Test Method for Flash Point by Pensky-Martens Closed Cup Tester*, 2002.

ASTM D 1230, *Standard Test Method for Flammability of Apparel Textiles*, 2001.

ASTM D 1265, *Standard Practice for Sampling Liquefied Petroleum (LP) Gases (Manual Method)*, 2002.

ASTM D 1310, *Standard Test Method for Flash Point and Fire Point of Liquids by Tag Open-Cup Apparatus*, 2001.

ASTM D 1929, *Standard Test Method for Determining Ignition Temperature of Plastics*, 2001.

ASTM D 2859, *Standard Test Method for Flammability of Finished Textile Floor Covering Materials*, 1993.

ASTM D 3065, *Standard Test Methods for Flammability of Aerosol Products*, 2001.

ASTM D 3828, *Standard Test Methods for Flash Point by Small Scale Closed Tester*, 2002.

ASTM D 4809, *Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)*, 2000.

ASTM D 5305, *Standard Test Method for Determination of Ethyl Mercaptan in LP-Gas Vapor*, 1997.

ASTM E 84, *Standard Test Method for Surface Burning Characteristics of Building Materials*, 2003.

ASTM E 108, *Standard Test Method for Fire Tests of Roof Coverings*, 2000.

ASTM E 119, *Standard Methods of Tests of Fire Endurance of Building Construction and Materials*, 2000.

ASTM E 603, *Standard Guide for Room Fire Experiments*, 2001.

ASTM E 648, *Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source*, 2000.

ASTM E 659, *Standard Test Method for Autoignition Temperature of Liquid Chemicals*, 2000.

ASTM E 681, *Standard Test Method for Concentration Limits of Flammability of Chemicals*, 2001.

ASTM E 800, *Standard Guide for Measurement of Gases Present or Generated During Fires*, 2001.

ASTM E 860, *Standard Practice for Examining and Testing Items That Are or May Become Involved in Litigation*, 1982.

ASTM E 906, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products*, 1999.

ASTM E 1188, *Standard Practice for Collection and Preservation of Information and Physical Items by a Technical Investigator*, 1995.

ASTM E 1226, *Test Method for Pressure and Rate of Pressure Rise for Combustible Dusts*, 2000.

ASTM E 1352, *Standard Test Method for Cigarette Ignition Resistance of Mock-up Upholstered Furniture Assemblies*, 2002.

ASTM E 1353, *Standard Test Methods for Cigarette Ignition Resistance of Components of Upholstered Furniture*, 2002.

ASTM E 1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, 2003.

ASTM E 1387, *Standard Test Method for Ignitable Liquid Residues in Extracts from Fire Debris Samples by Gas Chromatography*, 2001.

ASTM E 1459, *Standard Guide for Physical Evidence Labeling and Related Documentation*, 1998.

ASTM E 1618, *Standard Guide for Ignitable Liquid Residues in Extracts from Fire Debris Samples by Gas Chromatography–Mass Spectrometry*, 2001.

2.3.4 IAAI Publication. International Association of Arson Investigators, 12770 Boenker Road, Bridgeton, MO 63044.

Fire and Arson Investigator (quarterly journal).

2.3.5 UL Publications. Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062.

UL 263, *Standard for Safety Fire Tests of Building Construction and Materials*, 2003.

UL 969, *Standard for Marking and Labeling Systems*, 1995.

2.3.6 USEA Publication. U.S. Fire Administration, 16825 S. Seton Ave., Emmitsburg, MD 21727.

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

2.3.7 U.S. Government Publications. U.S. Government Printing Office, Washington, DC 20402.

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

Title 49, Code of Federal Regulations, Part 129.625, “Fire Related Human Behavior,” U.S. Fire Administration, 257, 1994.

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

Hazardous Substances Act (15 USC, Section 1261 et seq., and Title 16, Code of Federal Regulations, Part 1500).

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

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

“Federal Food, Drug and Cosmetic Act” [15 USC, Section 321 (m), and Title 21, Code of Federal Regulations, Part 600].

United States Federal Rules of Evidence as amended through 2002.

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

U.S. Air Force, 1983

U.S. Senate Committee on Government Operations. *Chart of the Organization of Federal Executive Departments and Agencies*.

2.3.8 Other References.

Babrauskas, V., and J. Krasny. *Fire Behavior of Upholstered Furniture*, NBS Monograph 173. Washington, DC: National Bureau of Standards, November 2000.

Baumeister, T., E. A. Avallone, and T. Baumeister III. *Mark's Standard Handbook for Mechanical Engineers*, 10th edition. New York: McGraw-Hill, 1996.

Bennett, C. O., and J. E. Myers. *Momentum, Heat, and Mass Transfer*, 2nd edition, New York: McGraw-Hill Book Co., 1974.

Black, H.C., *Black's Law Dictionary*, 7th edition, West Pub. Co., 1999.

Bull, J. P., and J. C. Lawrence. “Thermal Conditions to Produce Skin Burns.” *Fire and Materials* 3(2) (June 1979): 100–105.

Bustin, W. M., and W. G. Duket. *Electrostatic Hazards in Petroleum Industry*. Research Studio Press, July 1983.

Derksen, W. L., Monohan, T. I., and deLhery, G. P., “The Temperature Associated with Radiant Energy Skin Burns,” *Temperature — its measurement and control in science and industry*, 3(3), pp. 171–175, 1963.

Douglas, J. E., A. W. Burgess, A. G. Burgess, and R. K. Kessler. *Crime Classification Manual*. New York: Lexington Books, 1997.

Drysdale, D. *An Introduction to Fire Dynamics*. New York: John Wiley and Sons, 1998.

Fang, J. B., and J. N. Breese. “Fire Development in Residential Basement Rooms.” National Bureau of Standards (currently NISTJ), NBSIR 80-2120, Gaithersburg, MD, 1980.

Fletcher, Richmond, and Yelverton, 1980.

Flick, E. W. *Industrial Solvents Handbook*, 5th edition. Park Ridge, NJ: Noyes Data Corp., 1998.

FMC Corporation, *FMC Product Safety Sign and Label System Manual*.

Gieck, K., and R. Gieck. *Engineering Formulas*. 7th edition. McGraw-Hill, 1997.

Guide to Plastics. New York: McGraw-Hill, 1989.

Hagglund and Persson. *An Experimental Study of the Radiation from Wood Flames*, FOA Report C 4589-D6(A3). Stockholm: Forsvarerets Forskningsanstalt.

Hagglund and Persson. *The Heat Radiation from Petroleum Fires*, FOA Report C 20126-D6(A3). Stockholm: Forsvarerets Forskningsanstalt.

Hilado, C. J. *Flammability Handbook for Plastics*, 4th edition, Lancaster, PA: Technomic Publishing, 1990.

Kennedy, P., and J. Shanley. “USFA Fire Burn Pattern Tests — Program for the Study of Fire Patterns.” FA 178, 7/97 (Federal Emergency Management Agency, United States Fire Administration, Emmitsburg, MD, 1997).

Krasny, J. *Cigarette Ignition of Soft Furnishings — A Literature Review with Commentary*. Center for Fire Research. Washington, DC: National Bureau of Standards, June 1987.

Lawson, D. I. "Fire and the Atomic Bomb." *Fire Research Bulletin*, No. 1, HMSO, London, 1954.

Lawson, D. I., and D. L. Simms, "The Ignition of Wood by Radiation." *British Journal of Applied Physics*, 3, 1952, 288–292.

Lee, B. T. *Heat Release Rate Characteristics of Some Combustible Fuel Sources in Nuclear Power Plants*, NBSIR 85-3195. Washington, DC: National Bureau of Standards, 1985.

Lees, F. *Loss Prevention in the Process Industries*, 1996.

Lide, D. R., ed. *Handbook of Chemistry and Physics*, 71st edition, Boca Raton, FL: CRC Press, 1990–1991.

McRae, 1984.

Mil-Std-202F, *Test Method for Electronic and Electrical Components*. "Method 301, Dielectric Withstand Voltage." U.S. Department of Defense Military Test Standard, 1998.

Mil-Std-202F, *Test Method for Electronic and Electrical Components*. "Method 302, Insulation Resistance."

Model Penal Code, Section 220.1(1), American Law Institute, Philadelphia, PA.

Plastics Handbook. New York: McGraw-Hill, 1986–1987.

Restatement of the Law, Second Torts, 402A, American Law Institute, Philadelphia, PA.

Severy, D. M., D. M. Blaisdell, and J. F. Kerkhoff. *Automobile Collision Fires*, SAE, 741180. Society of Automotive Engineers, 1974.

SFPE, "Predicting 1st and 2nd Degree Skin Burns from Thermal Radiation," *Engineering Guide, Society of Fire Protection Engineers*, 2000.

Stoll, A. M. and Chianta, M. A., "Method and rating system for evaluation of thermal protection," *Aerospace Medicine* 40, pp. 1232–1238, 1969.

Stoll, A. and Green, L. C., "Relationship between Pain and Tissue Damage due to Thermal Radiation," *Journal of Applied Physiology* 14, pp. 373–383, 1959.

Tan, S. H. "Flare System Design Simplified," *Hydrocarbon Processing*, 172–176, 1967.

Wood, P. G. Fire Research Note #953, Building Research Establishment, Borehamwood, UK, 1973.

Chapter 3 Definitions

3.1 General. The definitions contained in this chapter apply to the terms used in this guide. Where terms are not included, common usage of the terms applies.

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. A document, the main text of which contains only mandatory provisions using the word "shall" to indicate requirements and which is in a form generally suitable for mandatory reference by another standard or code or for adoption into law. Nonmandatory provisions shall be located in an appendix or annex, footnote, or fine-print note and are not to be considered a part of the requirements of a standard.

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 ignitable liquid, 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.

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

3.3.5 Ampacity. The current, in amperes (A), that a conductor can carry continuously under the conditions of use without exceeding its temperature rating.

3.3.6 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.

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

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

3.3.9 Area of Origin. The room or area where a fire began. (See also *Point of Origin*.)

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

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

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

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

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

3.3.15 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.

3.3.16 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.

3.3.17 BLEVE. Boiling liquid expanding vapor explosion.

3.3.18 Bonding. The process of connecting two or more conductive objects together by means of a conductor so that they are at the same electrical potential, but not necessarily at the same potential as the earth.

3.3.19 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.

3.3.20 Burning Rate. See 3.3.87, Heat Release Rate (HRR).

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

3.3.22 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.

3.3.23 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.

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

3.3.25 Char. Carbonaceous material that has been burned and has a blackened appearance.

3.3.26 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.

3.3.27 Clean Burn. A fire pattern on surfaces where soot has been burned away.

3.3.28 Combustible. Capable of burning, generally in air under normal conditions of ambient temperature and pressure, unless otherwise specified; combustion can occur in cases where an oxidizer other than the oxygen in air is present (e.g., chlorine, fluorine, or chemicals containing oxygen in their structure).

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

3.3.30 Combustible Liquid. A liquid having a flash point at or above 37.8°C (100°F). (See also *Flammable Liquid*.)

3.3.31 Combustion Products. Heat, gases, solid particulates, and liquid aerosols produced by burning.

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

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

3.3.34 Current. A flow of electric charge.

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

3.3.36 Deflagration. Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium. [68:3.3]

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

3.3.38 Detonation. Propagation of a combustion zone at a velocity that is greater than the speed of sound in the unreacted medium. [68:3.3]

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

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

3.3.41 Effective Fire Temperatures. Temperatures reached in fires that identify physical effects that can be defined by specific temperature ranges.

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

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

3.3.44 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.

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

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

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

3.3.48 Extinguish. To cause to cease burning.

3.3.49 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.

3.3.50 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.

3.3.51 Fall Down. See 3.3.40, Drop Down.

3.3.52 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.

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

3.3.54 Fire Analysis. The process of determining the origin, cause, development, and responsibility as well as the failure analysis of a fire or explosion.

3.3.55 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.

3.3.56* 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.

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

3.3.58 Fire Patterns. The visible or measurable physical effects that remain after a fire.

3.3.59 Fire Propagation. See 3.3.62, Fire Spread.

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

3.3.61* 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.

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

3.3.63 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. [72:3.3]

3.3.64 Flame Front. The leading edge of burning gases of a combustion reaction.

3.3.65 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 and prior to the ignition of other fuels separate from the origin.

3.3.66 Flammable. Capable of burning with a flame.

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

3.3.68 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 *Combustible Liquid*.)

3.3.69 Flammable Range. The range of concentrations between the lower and upper flammable limits. [68:3.3]

3.3.70 Flash Fire. A fire that spreads rapidly through a diffuse fuel, such as dust, gas, or the vapors of an ignitable liquid, without the production of damaging pressure.

3.3.71 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.

3.3.72 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.

3.3.73 Forensic. Legal; pertaining to courts of law.

3.3.74 Fuel. A material that will maintain combustion under specified environmental conditions. [53:3.3]

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

3.3.76 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.

3.3.77 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.

3.3.78 Full Room Involvement. Condition in a compartment fire in which the entire volume is involved in fire.

3.3.79 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.

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

3.3.81 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.), (c) through a combination of these ground return paths.

3.3.82 Hazard. Any arrangement of materials and heat sources that presents the potential for harm, such as personal injury or ignition of combustibles.

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

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

3.3.85 Heat Flux. The measure of the rate of heat transfer to a surface, expressed in kilowatts/m², kilojoules/m² · s, or Btu/ft² · s.

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

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

3.3.88 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/s (3000 ft/sec)]; a material capable of sustaining a detonation. (*See also Detonation.*)

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

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

3.3.91 Ignitable 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.

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

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

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

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

3.3.96 Inductive Reasoning. The process by which a person starts from a particular experience and proceeds to generalizations.

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

3.3.98 Joule. The preferred SI unit of heat, energy or work; 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 3.3.19, British Thermal Unit, and 3.3.21, Calorie.*)

3.3.99 Kilowatt. A measurement of energy release rate.

3.3.100 Kindling Temperature. See 3.3.94, Ignition Temperature.

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

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

3.3.103 Low-Order Explosion. 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.

3.3.104 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.

3.3.105 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. Also called *incombustible material* (not preferred).

3.3.106 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*.

3.3.107 Ohm. The unit of electrical resistance (R) that measures the resistance between two points of a conductor when a constant difference of potential of one volt between these two points produces in this conductor a current of one ampere.

3.3.108 Origin. See 3.3.115, Point of Origin, or 3.3.9, Area of Origin.

3.3.109 Overcurrent. Any current in excess of the rated current of equipment or the ampacity of a conductor; it may result from an overload (*see 3.3.110*), short circuit, or ground fault.

3.3.110* Overload. Operation of equipment in excess of normal, full-load rating or of a conductor in excess of rated ampacity, which, when it persists for a sufficient length of time, would cause damage or dangerous overheating.

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

3.3.112 Piloted Ignition Temperature. See 3.3.94, Ignition Temperature.

3.3.113* 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.

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

3.3.115 Point of Origin. The exact physical location where a heat source and a fuel come in contact with each other and a fire begins.

3.3.116 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.

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

3.3.118 Products of Combustion. See 3.3.31, Combustion Products.

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

3.3.120 Pyrolysis. The chemical decomposition of a compound into one or more other substances by heat alone; pyrolysis often precedes combustion.

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

3.3.122 Radiant Heat. Heat energy carried by electromagnetic waves that are longer than 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.

3.3.123 Radiation. Heat transfer by way of electromagnetic energy.

3.3.124 Rate of Heat Release. See 3.3.87, Heat Release Rate.

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

3.3.126 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.

3.3.127 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.

3.3.128 Rollover. See 3.3.65, Flameover.

3.3.129 Scientific Method. The systematic pursuit of knowledge involving the recognition and formulation of a problem, the collection of data through observation and experiment, and the formulation and testing of a hypothesis.

3.3.130 Seat of Explosion. A craterlike indentation created at the point of origin of an explosion.

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

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

3.3.133 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.

3.3.134 Self-Ignition. Ignition resulting from self-heating. Synonymous with spontaneous ignition.

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

3.3.136 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.

3.3.137 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. [318:3.3]

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

3.3.139 Smoke Explosion. See 3.3.14, Backdraft.

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

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

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

3.3.143 Spark. A moving particle of solid material that emits radiant energy due either to its temperature or the process of combustion on its surface. [654:15]

3.3.144 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.

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

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

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

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

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

3.3.150 Thermal Column. See 3.3.114, Plume.

3.3.151* Thermal Expansion. The proportional increase in length, volume, or superficial area of a body with rise in temperature.

3.3.152 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).

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

3.3.154 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.

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

3.3.156 Upper Layer. See 3.3.24, Ceiling Layer.

3.3.157 Vapor. The gas phase of a substance, particularly of those that are normally liquids or solids at ordinary temperatures. (See also 3.3.79, Gas.)

3.3.158 Vapor Density. The ratio of the average molecular weight of a given volume of gas or vapor to the average molecular weight of an equal volume of air at the same temperature and pressure.

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

3.3.160 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.

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

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

3.3.163 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.

3.3.164 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.

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 and truthfully. 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 that of the scientific method, which is used in the physical sciences. This method provides for the organizational and analytical process 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.

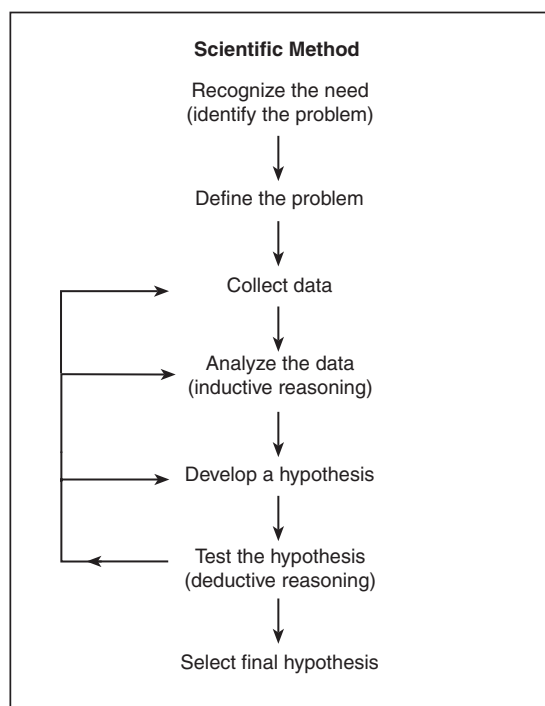


FIGURE 4.3 Use of the Scientific Method.

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 in what manner the problem can be solved. In this case, a proper origin

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.

4.3.4* Analyze the Data (Inductive Reasoning). All of the collected and observed information is analyzed by inductive reasoning: the process in which the total body of empirical data collected is carefully examined in the light of the investigator's knowledge, training, experience, and expertise. Subjective or speculative information cannot be included in the analysis, only facts that can be proven clearly by observation or experiment.

4.3.5 Develop a Hypothesis. Based on the data analysis, the investigator should now produce a hypothesis or group of hypotheses to explain the origin and cause of the fire or explosion incident. This hypothesis should be based solely on the empirical data that the investigator has collected.

4.3.6* Test the Hypothesis (Deductive Reasoning). The investigator does not have a truly provable hypothesis unless it 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 his or her hypothesis to all known facts. (See 3.3.35, *Deductive Reasoning*.) This testing of the hypothesis may be either cognitive or experimental. If the hypothesis cannot withstand an examination by deductive reasoning, it should be discarded as not provable and a new hypothesis should be tested. This test may include the collection of new data or the reanalysis of existing data. This process needs to be continued until all feasible hypotheses have been tested. Otherwise the fire cause should be listed as "undetermined."

4.3.7 Avoid Presumption of Cause. Until data have been collected, no specific hypothesis can be reasonably formed or treated. All fires, however, should be approached by the investigator without presumption.

4.4 Basic Method of a Fire Investigation. Using the scientific method in most fire or explosion incidents should involve the following five major steps from inception through final analysis.

4.4.1 Receiving the Assignment. The investigator should be notified of the incident, what his or her role will be, and 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 The investigator should conduct an examination of the scene if it is available and collect data necessary to the analysis. The actual investigation may take and include different steps and procedures, and these will be determined by the purpose of the investigation assignment. These steps and procedures are described in detail elsewhere in the document. A typical fire or explosion investigation may include all or some of the following: 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 or information from other appropriate sources.

4.4.3.2 It is during this phase of the investigation that the data necessary for the analysis of the incident will be collected.

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. An incident scenario or failure analysis should be described, explaining the origin, cause, fire spread, and responsibility for the incident.

4.4.6 Conclusions. Conclusions should be drawn according to the principles expressed in this guide and reported appropriately.

4.5 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 Chemistry of Combustion.

5.1.1 General. The fire investigator should have a basic understanding of ignition and combustion principles and should be able to use them to help in interpretation of evidence at the fire scene and in the development of conclusions regarding the origin and causes of the fire. The body of knowledge associated with combustion and fire would easily fill several textbooks. The discussion presented in this section should be considered introductory. The user of this guide is urged to consult the reference material listed Chapter 2, Annex B, and Annex C for additional details.

5.1.2 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 Figure 5.1.2). Fires can be prevented or suppressed by controlling or removing one or more of the sides of the tetrahedron.

5.1.2.1 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, plas-

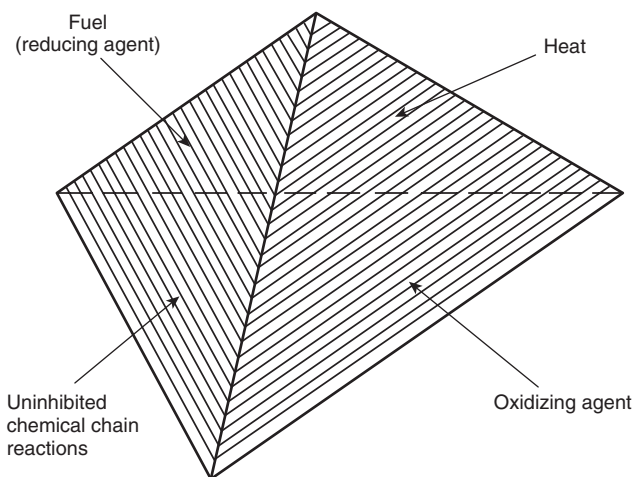


FIGURE 5.1.2 Fire Tetrahedron.

tics, 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 phases: solid, liquid, or gas. The phase 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 phase of a material is that which exists at standard conditions of temperature [21°C (70°F)] and pressure 101.6 kPa (14.7 psi) or 1 atmosphere at sea level].

5.1.2.1.1 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 5.3.

5.1.2.1.2 Some solid materials can undergo a smoldering reaction, where oxygen reacts directly with solid material. Smoldering can be the initial or the final stage of burning. Sometimes smoldering combustion breaks into flame; on other occasions smoldering continues through the total course of events.

5.1.2.1.3 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.

5.1.2.1.4 The form of a solid or liquid fuel is an important factor in its ignition and burning rate. For example, a fine wood dust ignites easier and burns faster than a block of wood. Some flammable liquids, such as diesel oil, are difficult to ignite in a pool but can ignite readily and burn rapidly when in the form of a fine spray or mist.

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

5.1.2.2 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.

5.1.2.2.1* Normal air contains 21 percent oxygen. In oxygen-enriched atmospheres, such as in areas where medical oxygen is in use or in high-pressure diving or medical chambers, combustion is greatly accelerated. Materials that resist ignition or burn slowly in air can burn vigorously when additional oxygen is present. Combustion can be initiated in atmospheres containing very low percentages of oxygen, depending on the fuel involved. As the temperature of the environment increases, the oxygen requirements are further reduced. While flaming combustion can occur at concentrations as low as 14 to 16 percent oxygen in air at room temperatures of 21°C (70°F), flaming combustion can continue at close to 0 percent oxygen under postflashover temperature conditions. Also, smoldering combustion, once initiated, can continue in a low-oxygen environment even when the surrounding environment is at a relatively low temperature. The hotter the environment, the less oxygen is required. This latter condition is why wood and other materials can continue to be consumed, even though the fire is in a closed compartment with low oxygen content. Fuels that are enveloped in a layer of hot, oxygen-depleted combustion products in the upper portion of a room can also be consumed.

5.1.2.2.2 It should be noted that certain gases can form flammable mixtures in atmospheres other than air or oxygen. One example is a mixture of hydrogen and chlorine gas.

5.1.2.2.3 For combustion to take place, the fuel vapor or gas and the oxidizer should be mixed in the correct ratio. In the case of solids and liquids, the pyrolysis products or vapors disperse from the fuel surface and mix with the air. As the distance from the fuel source increases, the concentration of the vapors and pyrolysis products decreases. The same process acts to reduce the concentration of a gas as the distance from the source increases.

5.1.2.2.4 Fuel burns only when the fuel/air ratio is within certain limits known as the flammable (explosive) limits. In cases where fuels can form flammable mixtures with air, there is a minimum concentration of vapor in air, below which propagation of flame does not occur. This is called the *lower flammable limit*. There is also a maximum concentration, called the *upper flammable limit*, above which flame will not propagate. These limits are generally expressed in terms of percentage by volume of vapor or gas in air.

5.1.2.2.5 The flammable limits reported are usually corrected to a temperature of 0°C (32°F) and 1 atmosphere. Increases in temperature and pressure result in reduced lower flammable limits, possibly below 1 percent, and increased upper flammable limits. Upper limits for some fuels can approach 100 percent at high temperatures. A decrease in temperature and pressure will have the opposite effect. Caution should be exercised when using the values for flammability limits found in the literature. The reported values are often based on a single experimental apparatus that does not necessarily account for conditions found in practice.

5.1.2.2.6 The range of mixtures between the lower and upper limits is called the flammable (explosive) range. For example,

the lower limit of flammability of gasoline at ordinary temperatures and pressures is 1.4 percent, and the upper limit is 7.6 percent. All concentrations by volume falling between 1.4 and 7.6 percent will be in the flammable (explosive) range. All other factors being equal, the wider the flammable range, the greater the likelihood of the mixture coming in contact with an ignition source and thus the greater the hazard of the fuel. Acetylene, with a flammable range between 2.5 and 100 percent, and hydrogen, with a range from 4 to 75 percent, are considered very dangerous and very likely to be ignited when released.

5.1.2.2.7 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 21.8.2.1.)

5.1.2.2.8 Fires usually have either an excess of air or an excess of fuel. When there is an excess of air, the fire is considered to be fuel controlled. When there is more fuel present than air, a condition that occurs frequently in well-developed room or compartment fires, the fire is considered to be ventilation controlled.

5.1.2.2.9 In a fuel-controlled compartment fire, all the burning will take place within the compartment, and the products of combustion will be much the same as burning the same material in the open. In a ventilation-controlled compartment fire, the combustion inside the compartment will be incomplete. The burning rate will be limited by the amount of air entering the compartment. This condition will result in unburned fuel and other products of incomplete combustion leaving the compartment and spreading to adjacent spaces. Ventilation-controlled fires can produce massive amounts of carbon monoxide.

5.1.2.2.10 If the gases immediately vent out a window or into an area where sufficient oxygen is present, they will ignite and burn when the gases are above their ignition temperatures. If the venting is into an area where the fire has caused the atmosphere to be deficient in oxygen, such as a thick layer of smoke in an adjacent room, it is likely that flame extension in that direction will cease, although the gases can be hot enough to cause charring and extensive heat damage.

5.1.2.3 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 (Btu/sec or kilowatts) or as the total heat energy received over time (Btu or 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.

5.1.2.4 Uninhibited Chemical Chain Reaction.

5.1.2.4.1 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 5.3.

5.1.2.4.2 Combustion of solids can occur by two mechanisms: flaming and smoldering. Flaming combustion takes place in the gas or vapor phase of a fuel. With solid and liquid fuels, this combustion is above the surface. Smoldering is a surface-burning phenomenon with solid fuels and involves a lower rate of heat release and no visible flame. Smoldering fires frequently make a transition to flaming after sufficient total energy has been produced, or when airflow is present to speed up the combustion rate.

5.2 Heat Transfer.

5.2.1 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 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.

5.2.1.1 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 maintain or change the temperature of an object. When heat energy is transferred to an object, the temperature increases. When heat is transferred away, the temperature decreases.

5.2.1.2 Heat is always transferred from the high-temperature mass to the low-temperature mass. Heat transfer is measured in terms of energy flow per unit of time (Btu/sec or kilowatts). The greater the temperature difference between the objects, the more energy is transferred per unit of time and the higher the heat transfer rate is. Temperature can be compared to the pressure in a fire hose and heat or energy transfer to the waterflow in gallons per minute.

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

5.2.2 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 physical properties of the material. The properties are the thermal conductivity (k), the density (ρ), and the heat capacity (c). 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).

5.2.2.1 If thermal conductivity (k) is high, the rate of heat transfer through the material is high. Metals have high thermal conductivities (k), while plastics or glass have low thermal conductivity (k) values. Other properties (k and c) being equal, high-density (ρ) materials conduct heat faster than low-density materials. Therefore, low-density materials make good insulators. Similarly, materials with a high heat capacity (c) require more energy to raise the temperature than materials with low heat capacity values.

5.2.2.2 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. When solids are exposed to temperatures that are continuously changing, a more common condition, the result is changing rates of heat transfer. During this period, all three properties — thermal conductivity (k), density (ρ), and heat capacity (c) — play a role. Taken together, these properties are commonly called the *thermal inertia* of a material and are expressed in terms of k , ρ , and c . Table 5.2.2.2 provides data for some common materials.

Table 5.2.2.2 Thermal Properties of Selected Materials

Material	Thermal Conductivity (k) (W/m-K)	Density (ρ) (kg/m ³)	Heat Capacity (c_p) (J/kg-K)
Copper	387	8940	380
Concrete	0.8–1.4	1900–2300	880
Gypsum plaster	0.48	1440	840
Oak	0.17	800	2380
Pine (yellow)	0.14	640	2850
Polyethylene	0.35	940	1900
Polystyrene (rigid)	0.11	1100	1200
Polyvinylchloride	0.16	1400	1050
Polyurethane*	0.034	20	1400

*Typical values, properties vary.

Source: Drysdale, *An Introduction to Fire Dynamics*, 2nd ed., p. 33.

5.2.2.3 The impact of the thermal inertia on the rise in temperature in a space or on the material in it is not constant through the duration of a fire. Eventually, as the materials involved reach a constant 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 (preflashover).

5.2.2.4 Conduction of heat into a material as it affects its surface temperature is an important aspect of ignition. Thermal inertia is an important factor in how fast the surface temperature will rise. The lower the thermal inertia of the material, the faster the surface temperature will rise.

5.2.2.5 Conduction is also a mechanism of fire spread. Heat conducted through a metal wall or along a pipe or metal beam can cause ignition of combustibles in contact with the heated metals. Conduction through metal fasteners such as nails, nail plates, or bolts can result in fire spread or structural failure.

5.2.3 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.

5.2.3.1 Heat is transferred by convection to a solid when hot gases pass over cooler surfaces. The rate of heat transfer to the solid is a function of the temperature difference between the hot gas and the surface, 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. Since a flame itself is a hot gas, flame contact involves heat transfer by convection.

5.2.3.2 In the early history of a fire, convection plays a major role in moving the hot gases from the fire to the upper portions of the room of origin and throughout the building. As the room temperatures rise with the approach of flashover, convection continues, but the role of radiation increases rapidly and becomes the dominant heat transfer mechanism. See 5.5.4.2 for a discussion of the development of flashover. Even after flashover, convection can be an important mechanism in the spread of smoke, hot gases, and unburned fuels throughout a building. Convection then spread the fire or toxic or damaging products of combustion to remote areas.

5.2.4 Radiation. Radiation is the transfer of heat energy from a hot surface material, 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 on the order of 50 percent by some glazing materials. Radiators and targets are not limited to solids but can be liquids and gases. 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 flashover. Flashover is discussed in Section 5.5.4.2.

5.2.4.1 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 5.2.4.1 illustrates this relation. Since all materials emit radiant energy proportional to the fourth power of their 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.

5.2.4.2 The rate of radiation 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, depending on the size of the radiator relative to the distance involved.

5.3 Ignition.

5.3.1* General. In order for most materials to be ignited, they should 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 and magnesium. These gases or vapors should then be present in the atmosphere in sufficient quantity to form a flammable mixture. Liquids with flash

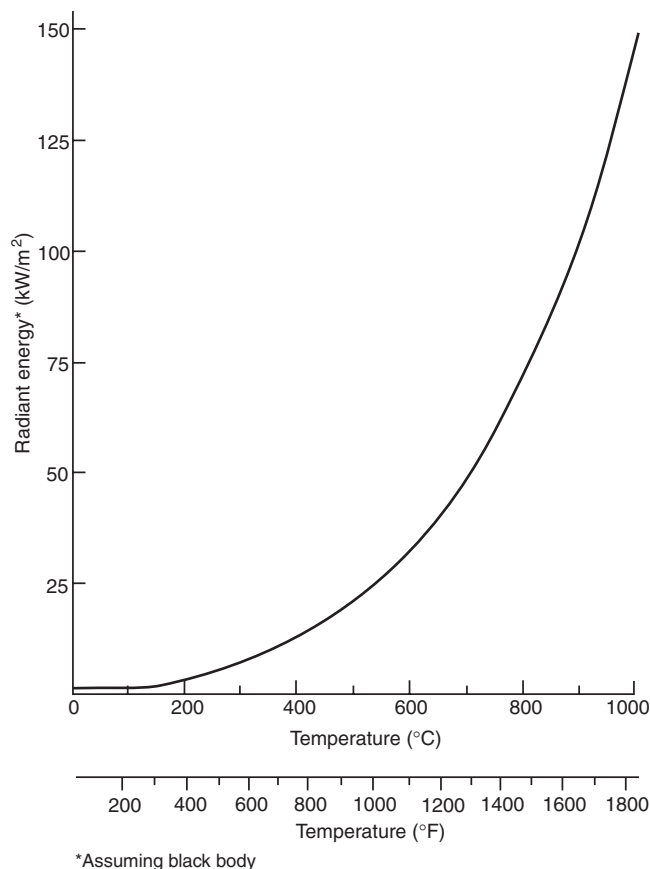


FIGURE 5.2.4.1 Relation of Radiation to Temperature.

points below ambient temperatures do not require additional heat to produce a flammable mixture. The fuel vapors produced should 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 required by the fuel, 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.

5.3.1.1 Table 5.3.1.1 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 burn as solid phase combustion, known as smoldering. This is a flameless form of combustion whose principal heat source is char oxidation. Smoldering is hazardous, as it 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.

Table 5.3.1.1 Reported Burning and Sparking Temperatures of Selected Ignition Sources

Source	Temperature	
	°C	°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

^aFrom Drysdale, *An Introduction to Fire Dynamics*.

^bFrom Hagglund and Persson, *The Heat Radiation from Petroleum Fires*.

^cFrom Hagglund and Persson, *An Experimental Study of the Radiation from Wood Flames*.

^dFrom Krasny, *Cigarette Ignition of Soft Furnishings — A Literature Review with Commentary*.

^eFrom NFPA *Fire Protection Handbook*, 15th ed., Section 4, p. 167.

5.3.1.2 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 wood, 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 more appropriately referred to as forced pyrolysis, and not smoldering.

5.3.2 Ignition of Solid Fuels. For solid fuels to burn with a flame, the substance should either be melted and vaporized (like thermoplastics) or be pyrolyzed into gases or vapors (i.e., wood or thermoset plastic). In both examples, heat must be supplied to the fuel to generate the vapors.

5.3.2.1 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 a low-density foam plastic ignites more quickly than high-density plastic.

5.3.2.2 The amount of surface area for a given mass (surface area to mass ratio) also affects the quantity of energy necessary for ignition. It is relatively easy to ignite one pound of thin pine shavings with a match, while ignition of a one-pound solid block of wood with the same match is very unlikely.

5.3.2.3 Because of the higher surface area to mass ratio, corners of combustible materials are more easily burned than flat surfaces. Table 5.3.2.3 shows the time for pilot ignition of wood exposed to varying temperatures.

5.3.2.4 Caution is needed in using Table 5.3.2.3, as the times and temperatures given are for ignition with a pilot flame. These are good estimates for ignition of wood by an existing fire. These temperatures are not to be used to estimate the temperature necessary for the first item to ignite. The absence of the pilot flame requires that the fuel vapors of the first item ignited be heated to their autoignition temperature. In *An Introduction to Fire Dynamics*, Douglas Drysdale reports two temperatures for wood to autoignite or spontaneously ignite. These are heating by radiation, 600°C (1112°F), and heating by conduction, 490°C (914°F).

5.3.2.5 For spontaneous ignition to occur as a result of radiative heat transfer, the volatiles released from the surface should 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.

5.3.2.6 Figure 5.3.2.6(a) illustrates the relationship between ignition energy and time to ignition for thin and thick materials. When exposed to their ignition temperature, thin materials ignite faster than thick materials (e.g., paper vs. plywood) as shown in Figure 5.3.2.6(b).

Table 5.3.2.3 Time Required to Ignite Wood Specimens

Wood 32 mm × 32 mm × 102 mm (1¼ in. × 1¼ in. × 4 in.)	No Ignition in 40 Min		Exposure Before Ignition, by Pilot Flame, Minutes						
	°C	°F	180°C (356°F)	200°C (392°F)	225°C (437°F)	250°C (482°F)	300°C (572°F)	350°C (662°F)	400°C (752°F)
Long leaf pine	157	315	14.3	11.8	8.7	6.0	2.3	1.4	0.5
Red oak	157	315	20.0	13.3	8.1	4.7	1.6	1.2	0.5
Tamarack	167	334	29.9	14.5	9.0	6.0	2.3	0.8	0.5
Western larch	157	315	30.8	25.0	17.0	9.5	3.5	1.5	0.5
Noble fir	187	369	—	—	15.8	9.3	2.3	1.2	0.3
Eastern hemlock	180	356	—	13.3	7.2	4.0	2.2	1.2	0.3
Redwood	157	315	28.5	18.5	10.4	6.0	1.9	0.8	0.3
Sitka spruce	157	315	40.0	19.6	8.3	5.3	2.1	1.0	0.3
Basswood	167	334	—	14.5	9.6	6.0	1.6	1.2	0.3

Source: NFPA *Fire Protection Handbook*, 19th ed., Section 3, p. 37.

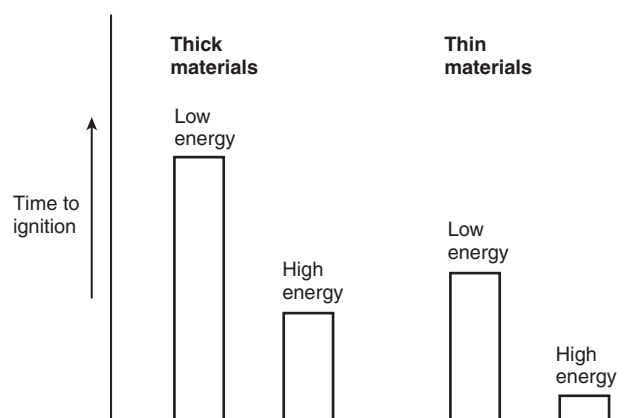


FIGURE 5.3.2.6(a) Relationship of Energy Source to Ignition Time for Thick and Thin Materials.

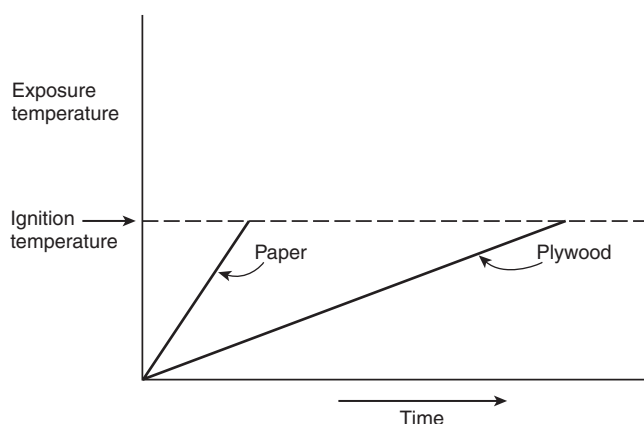


FIGURE 5.3.2.6(b) Relationship of Material Thickness to Ignition Time When Exposed to Ignition Temperature.

5.3.3 Ignition of Liquids.

5.3.3.1 In order for the vapors of a liquid to form an ignitable mixture, the liquid should be at or above its flash point. The flash point of a liquid is the lowest temperature at which it gives off sufficient vapor to support a momentary flame across its surface based on an appropriate ASTM test method. The value of the flash point may vary depending on the type of test used. Even though most of a liquid may be slightly below its flash point, an ignition source can create a locally heated area sufficient to result in ignition.

5.3.3.2 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 spray or mists, ignition can occur at ambient temperatures below the published flash point of the bulk liquid.

5.3.4 Ignition of Gases. Combustible substances in the gaseous state have extremely low mass and require the least amount of energy for ignition.

5.3.5 Ignition Properties of Materials. Table 5.3.5 provides ignition property data for selected solids, liquids, and gases.

5.3.6* Self-Heating and Self-Ignition.

5.3.6.1 Self-heating is a process whereby a material undergoes an exothermic chemical reaction and increases in temperature without drawing heat from its surroundings. In this type of reaction, self-heating of a material to its ignition temperature will result in self-ignition.

5.3.6.1.1 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 also a result of organic materials capable of polymerization reactions, where liquids react to form solids. Generally, self-heating and self-ignition are most 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.

5.3.6.1.2 Self-heating and self-ignition of oils containing mostly saturated hydrocarbons, such as motor oil or lubricating oil, occurs 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 of motor oil or lubricating oil on rags are not expected to self-heat to ignition.

5.3.6.1.3 Certain inorganic materials, such as metal powders, may undergo rapid oxidation, self-heating, and self-ignition to form metal oxides under isolated conditions.

5.3.6.2 Mechanism of Self-Heating to Ignition. The process of self-heating to ignition begins with heating and proceeds to thermal runaway. Self-heating is a rise in temperature above its surrounding temperature within a body due to internal heat generation. With this increase in temperature comes an increase in reaction rate and in turn an increase in heat generation. 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.

5.3.6.2.1 Self-heating to ignition can occur in porous, permeable, and oxidizable materials — 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 occur at elevated temperatures.

Table 5.3.5 Ignition Properties of Selected Materials

Material	Ignition Temperature		Minimum Radiant Flux (kW/m²)	Energy Required (kJ/m²)	Minimum Ignition Energy (mJ)
	°C	°F			
Solids					
Polyethylene ^a	488	910	19	1500–5100	—
Polystyrene ^a	573	1063	29	1300–6400	—
Polyurethane (flexible) ^a	456–579	852–1074	16–30	150–770	—
PVC ^a	507	945	21	3320	—
Softwood ^b	320–350	608–660	—	—	—
Hardwood ^b	313–393	595–740	—	—	—
Dusts (cloud) ^c					
Aluminum	610	1130	—	—	10
Coal	730	1346	—	—	100
Grain	430	805	—	—	30
Liquids ^d					
Acetone	465	869	—	—	1.15 ^e
Benzene	498	928	—	—	0.22 ^e
Ethanol	363	685	—	—	—
Gasoline	456	853	—	—	—
(100 octane)					
Kerosene	210	410	—	—	—
Methanol	464	867	—	—	0.14 ^e
Methyl ethyl ketone	404	759	—	—	0.53 ^e
Toluene	480	896	—	—	2.5 ^f
Gases ^d					
Acetylene	305	581	—	—	0.02 ^e
Methane	537	999	—	—	0.28 ^e
Natural gas	482–632	900–1170	—	—	0.30 ^f
Propane	450	842	—	—	0.25 ^e

^aFrom NFPA *Fire Protection Handbook*, 19th ed., Table A.6, Section 3, p. 25.

^bFrom NFPA *Fire Protection Handbook*, 17th ed., pp. 3–25.

^cFrom NFPA *Fire Protection Handbook*, 16th ed., Table 5.9A.

^dIgnition temperatures from NFPA *Fire Protection Guide to Hazardous Materials*.

^eFrom *The SFPE Handbook of Fire Protection Engineering*, Table 2-5.2.

^fFrom NFPA *Fire Protection Handbook*, 15th ed., Section 2, Table 11.3B.

5.3.6.2.2 The tendency to self-heat is dependent on the size and shape of the fuel package, and its surroundings. This tendency is not exclusively a material property, as flash-point is, and therefore evaluation of a material's self-ignition hazard is incomplete (except for the elimination of non-self-heating fuel packages) without taking into account the particulars of the material's size, shape, and surroundings. For a given volume, symmetrical shapes, such as spheres or cubes, promote self-heating more than thinner shapes because the interior is better insulated by the outer parts of the fuel package itself. For example, linseed-oiled rags in a pile are more likely to self-heat than the same rags hung on a clothesline or laid flat.

5.3.6.2.3 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 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 genera-

tion results from the latent heat of moisture absorption — the opposite of evaporative cooling.

5.3.6.2.4 Enclosure of the fuel in a sealed container will likely 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. For example, linseed-oiled rags in a closed paint can will not self-heat significantly before consuming the oxygen in the can.

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

5.3.6.2.6 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.

5.3.6.2.7* 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. Exposure temperatures needed for wood self-heating to ignition are significantly lower than those shown in Table 5.3.5 for flaming ignition of fresh wood.

5.3.6.2.8* Charcoal Briquettes. Charcoal briquettes have been suspected of self-heating to ignition even when packaged in household-sized bags (<9 kg or <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 proven that common sizes of briquettes do not come close to self-ignition even when placed in unusually high ambient temperatures, such as in a closed automobile in the sun. Charcoal briquettes have no more 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 impossible under any normal ambient conditions.

5.3.6.3 Common Materials Subject to Self-Heating.

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

- (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) Enzyme induced oxidation (hay bales and compost).
- (4) Heat induced oxidation of cellulose materials (usually wood fiber and cloth).
- (5) Polymerization reactions (plastics, rubbers, adhesives, and paint overspray particles) See NFPA 33, *Standard for Spray Application Using Flammable or Combustible Materials*.

5.3.6.3.2 Because of the many possible combinations of these controlling or influencing factors, it is difficult to predict when the material will self-heat. Table 5.3.6.3.2 lists a few materials subject to self-heating. A more complete list is found in Table A.10 of the NFPA *Fire Protection Handbook*, 19th edition. Omission of any material does not necessarily indicate that it is not subject to self-heating.

5.3.6.4 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

Table 5.3.6.3.2 Some Materials Subject to Spontaneous Ignition

Material	Tendency
Charcoal	High
Fish meal	High
Linseed oiled rags	High
Brewing grains	Moderate
Latex foam rubber	Moderate
Hay	Moderate
Manure	Moderate
Wool wastes	Moderate
Baled rags	Variable (low to moderate)
Sawdust	Possible
Grain	Low

Source: NFPA *Fire Protection Handbook*, 19th ed., Table A.10.

governing their classification and storage requirements, see NFPA 430, *Code for the Storage of Liquid and Solid Oxidizers*.

5.3.6.5 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.

5.3.7 Transition to Flaming Combustion. 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.

5.4 Fuel Load.

5.4.1 General. The term *fuel load* has been used to indicate the potential severity of a fire and has been expressed in terms of Btu (British thermal unit) or pounds of fuel per square foot of floor area. An example is provided in 5.4.1.1.

5.4.1.1 The Btus were expressed in wood equivalent based on 8000 Btu per pound. The fuel load was determined by weighing the fuel in a room and converting the weight of plastic to pounds of wood using 16,000 Btu per pound as the value for plastic (one pound of plastic equals two pounds of wood). The total Btus (or pounds of fuel) were divided by the area of the room floor. While this approach can be a measure of the total heat available if all the fuel burns, it does not depict how fast the fire will develop once the fire starts.

5.4.1.2 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, to include fuel configuration, compartment size, compartment properties, ventilation, ignition source, and first fuel ignited. The rate of fire growth as reported by witnesses is not reliable or supported independent evidence of an incendiary fire.

5.4.2 Heat Release Rate.

5.4.2.1 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 burning of individual fuel arrays. The HRR describes how the available energy is released. This quantity characterizes the power — energy released per unit time (Btu/second or kilowatts) — 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 5.4.2.1. The largest value of the HRR measured is defined as the peak heat release rate. Representative peak HRRs are listed in Table 5.4.2.1. These values should only be considered as representative values for comparison purposes. Fuel items with the same function (e.g., sofas) can have significantly different HRRs. The actual peak heat release rate for a particular fuel item is best determined by test.

5.4.2.2 In a compartment fire, as additional items ignite, their individual HRRs are additive to obtain an HRR for the compartment. Tests for measuring the HRR of fuel arrays are usually performed in the “open” where the effects of compartmentation are not realized. When a fuel package is exposed to

thermal radiant energy, such as the hot upper layer of a room, it can increase the HRR for that fuel package. This rate is controlled by the chemical and physical properties of the fuel and the surface area of the fuel array.

5.4.3 Heat Release Rate Factors. One important physical property that relates to the form of the material is the surface area to mass ratio. Pine shavings, for example, burn faster than a block of wood of the same weight. Finely ground wood flour dispersed in air burns very rapidly and can result in an explosion. Plastics can have heat release rates significantly greater than the same item made of cellulose due to significant differences in values for the heat of combustion, which is a chemical property of the material. Compare a cotton mattress to one of the same size but made of polyurethane foam (*see Table 5.4.2.1*). The difference between these materials relates not only to the chemical composition of the fuel but also to the physical properties, including those that determine the thermal inertia (*see 5.2.2*). Low-density materials burn faster than high-density materials of similar chemistry. Soft pine, for example, burns faster than oak, and lightweight foam plastics burn faster than more dense, rigid plastics. After flashover, the heat release rate in the fire is controlled by the preceding factors and the availability of air and the exposed combustible surface.

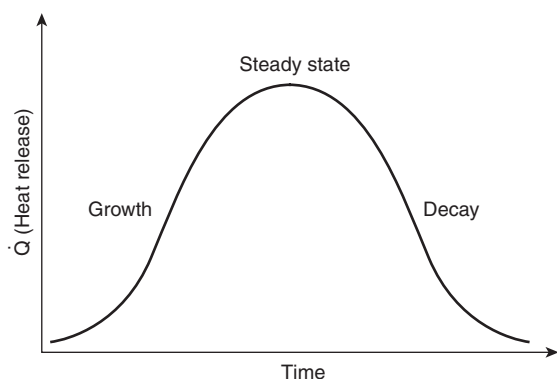


FIGURE 5.4.2.1 Idealized Heat Release Rate Curve.

5.5 Fire Development.

5.5.1 General. The rate and pattern of fire development depend on a complex relationship between the burning fuel and the surrounding environment. In confined burning, the collection of heat at the top of the room can raise the temperature of the ceiling and produce a large body of high-temperature smoke. The radiation from this upper portion of the space can significantly enhance the rate of heat release from a burning item. In such cases, the values given in Table 5.4.2.1 would be inappropriately low.

Table 5.4.2.1 Representative Peak Heat Release Rates (Unconfined Burning)

Fuel	(kg)	(lb)	Peak HRR (kW)
Wastebasket, small	0.7–6.1	1.5–3	4–18
Trash bags, 11 gal with mixed plastic and paper trash	1.1–3.4	2½–7½	140–350
Cotton mattress	11.8–13.2	26–29	40–970
TV sets	31.3–32.7	69–72	120–290
Plastic trash bags/paper trash	1.2–14.1	2.6–31	120–350
PVC waiting room chair, metal frame	15.4	34	270
Cotton easy chair	17.7–31.8	39–70	290–370
Gasoline/kerosene in 0.61 m ² (2 ft ²) pool	19	—	400
Christmas trees, dry	6.4–7.3	14–16	500–650
Polyurethane mattress	3.2–14.1	7–31	810–2630
Polyurethane easy chair	12.2–27.7	27–61	1350–1990
Polyurethane sofa	51.3	113	3120

Sources: Values are from the following publications:

Babrauskas and Krasny, *Fire Behavior of Upholstered Furniture*.

Lee, *Heat Release Rate Characteristics of Some Combustible Fuel Sources in Nuclear Power Plants*.

NFPA 72, *National Fire Alarm Code*®, 1999 ed., Annex B.

5.5.2 Plumes. Heat from a fire in the open rises as a column of hot gas called a *plume*. The resulting airflow draws cool air into the base of the fire from all directions. Cool air is also drawn into the plume above ground level by the moving mass of hot air, as shown in Figure 5.5.2(a). This inflow of cool air into the plume is called *entrainment* and results in decreased temperatures with increasing height in the plume, as shown in Figure 5.5.2(b). Fire spread will be primarily by radiant ignition of nearby fuels. Spread rate over solids will generally be slow unless aided by air movement (wind) or sloping surfaces.

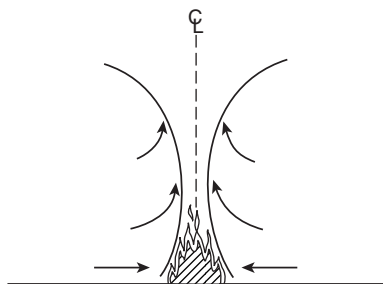


FIGURE 5.5.2(a) Fire Plume in the Open.

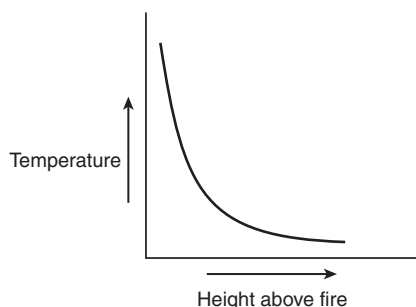


FIGURE 5.5.2(b) Temperature in a Fire Plume.

5.5.3 Unconfined Fires. When no ceiling exists over a fire, and the fire is far from walls, the hot gases and smoke of the plume continue to rise vertically until they cool to the ambient air temperature. At that point, the smoke will stratify and diffuse in the air. Such conditions would exist for a fire outdoors. The same conditions can exist with a fire in a building at the fire's very early stages, when the plume is small or if the fire is in a very large-volume space with a high ceiling such as an atrium. Fire spread from an unconfined fire will be primarily by radiant ignition of nearby fuels. The spread rate across solid materials will generally be slow unless aided by air movement (wind in the case of outdoor fires) or sloping surfaces that allow preheating of the fuel.

5.5.4 Confined Fires. When plumes interact with the ceiling or walls of a compartment, the flow of smoke and hot gases and the growth of the fire will be affected. Low heat release rate fires that are remote from walls or other bounding surfaces, such as the back of a couch, will behave as if they were in the open.

5.5.4.1* Fires Confined by a Ceiling. When a horizontal surface, such as a ceiling, exists over a fire plume, the hot gases and smoke in the rising plume impinge on the horizontal surface. This causes the plume to move horizontally under the

ceiling. This horizontal flow spreads in all directions until stopped by any intervening walls. As the hot gases flow away from the centerline of the plume under the ceiling, a relatively thin layer develops that is driven by the buoyancy of the hot products of combustion. This relatively rapid flow in the form of a shallow layer is referred to as a *ceiling jet*. The ceiling jet is an important feature in the development of a compartment fire since it is the principal means of heat and mass transfer to smoke and heat detectors and sprinklers that are generally located under ceilings. See Figure 5.5.4.1(a).

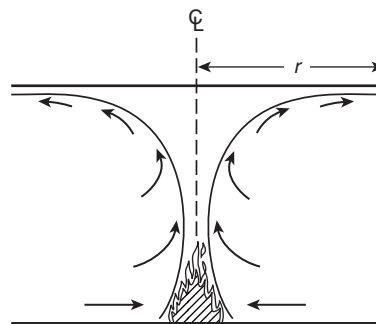


FIGURE 5.5.4.1(a) Fire Confined by a Ceiling in a Large Room.

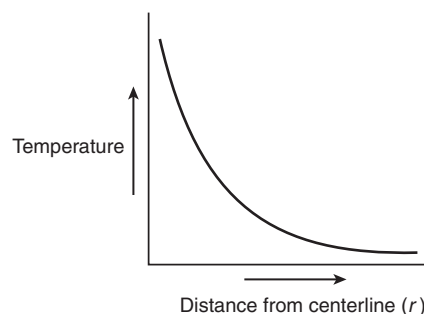


FIGURE 5.5.4.1(b) Ceiling Layer Temperature Away from the Plume.

5.5.4.1.1 Heat is convected from the hot ceiling jet into the relatively cooler ceiling above. The ceiling jet is hottest near the plume centerline and becomes cooler as the distance (r) from the centerline of the plume increases due to the cooling by heat losses to the ceiling. See Figure 5.5.4.1(b).

5.5.4.1.2 Fire spread with a plume confined by a ceiling will be by ignition of combustible ceiling or wall material, ignition of nearby combustibles such as room contents or warehouse stock, or a combination of these mechanisms. The gases in the upper (smoke) layer may transfer heat to materials in this upper layer by convection and radiation. Transfer of heat below the smoke layer is dominated by radiation. Fire growth, when the plume is confined by a ceiling, will be faster than when the plume is unconfined.

5.5.4.1.3 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 (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.

5.5.4.2 Compartment Fires and Flashover. The heat output from a fire in a compartment is confined by walls as well as the ceiling. The closer proximity of the walls results in a more rapid development of the hot gas layer at the ceiling and the creation of a much deeper layer. Figure 5.5.4.2 depicts a room with a door opening. There are two fuel packages in the room; one is the item first ignited, and the other is the “target” fuel or second item ignited. Initially, the ceiling layer will be thin, resembling the no-wall situation. However, as the gases reach the walls and can no longer spread horizontally, the bottom of the layer will descend and become uniform in depth. Smoke detectors in the compartment of origin will generally respond early in this stage of fire development.

5.5.4.2.1 When the smoke level reaches the top of the door opening, as illustrated in Figure 5.5.4.2.1, it will begin to flow out of the compartment. If the rate of smoke production does not exceed the rate of smoke flow out of the compartment, the ceiling layer will not descend further.

5.5.4.2.2 If the fire grows in size, the bottom of the ceiling layer 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 5.5.4.2.2. 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.

5.5.4.2.3 At the start of this 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 to be sufficient and the fire may continue to have sufficient oxygen even as it grows. Normally, this would be a location that had a large door or window opening as compared to fuel surface burning. In such cases, the gases collected at the upper portion of the room, while hot, will contain significant oxygen and relatively small amounts of unburned fuel.

5.5.4.2.4 If the amount of air resident in the room, plus that transported to the room through the HVAC system or drawn in through openings, is not sufficient to burn all of the combustibles being pyrolyzed by the fire, the fire will shift from fuel control to ventilation control. In that situation, the ceiling layer will contain unburned products of combustion such as hydrocarbon vapors, carbon monoxide, and soot. In general, there will be insufficient oxygen for flaming in the ceiling layer. In both cases, the gases can be well above the temperatures necessary to char or pyrolyze combustible finished materials in the hot layer.

5.5.4.2.5 Automatic sprinklers will normally operate early during this phase or even during the prior phase of burning. Quick-response sprinklers will operate much sooner than standard sprinklers. Detectors located outside the compartment may operate, depending on their location and the ability of smoke to travel from the fire to the point of the detector.

5.5.4.2.6 As the fire continues to grow, the ceiling layer gas temperatures approach 480°C (900°F), increasing the intensity of the radiation on the exposed combustible contents in the room. The surface temperature of these combustible contents rises, and pyrolysis gases are produced and become heated to their ignition temperature. When the upper layer temperature reaches approximately 590°C (1100°F), pyrolysis gases from the combustible contents ignite along with the bottom of the ceiling layer. This phenomenon, known as flashover, is illustrated in Figure 5.5.4.2.6. 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.

5.5.4.2.7 Postflashover burning conditions in a compartment are turbulent and dynamic. During postflashover burning, the position of the ceiling layer bottom and the existence and size of flaming on target fuels within the layer can vary between the conditions shown in Figure 5.5.4.2.6 and Figure 5.5.4.2.7. While the burning of floors or floor coverings is common, such burning may not always extend under target fuels or other shielding surfaces.

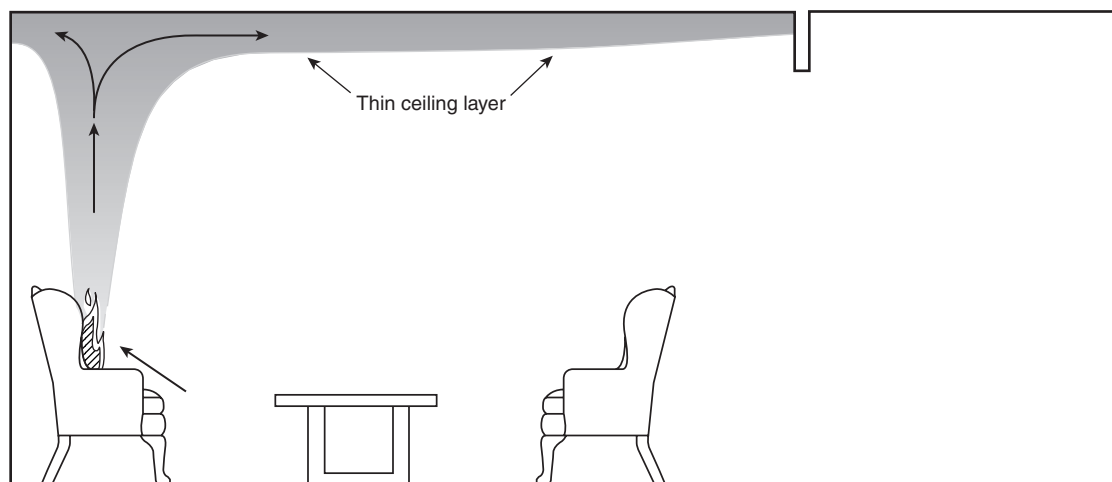


FIGURE 5.5.4.2 Early Compartment Fire Development.

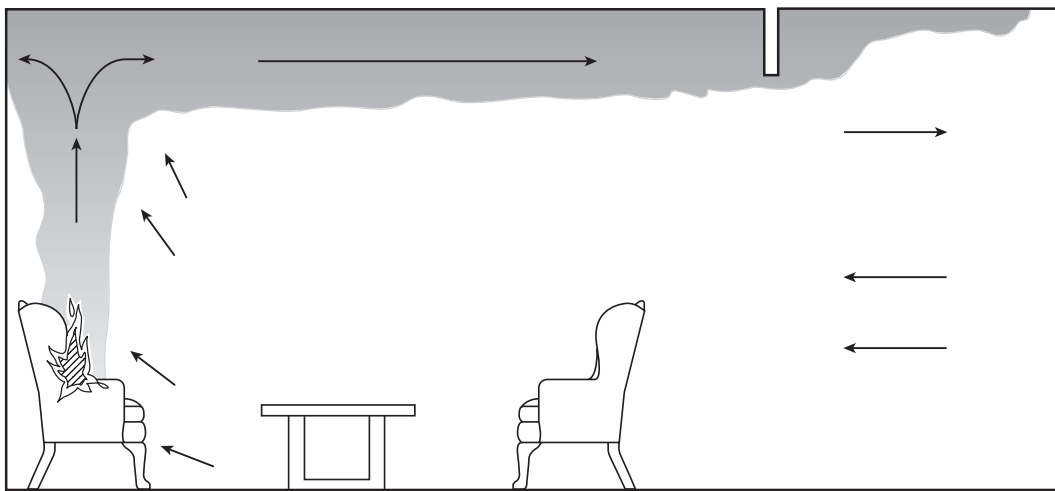


FIGURE 5.5.4.2.1 Ceiling Layer Development in Compartment Fire.

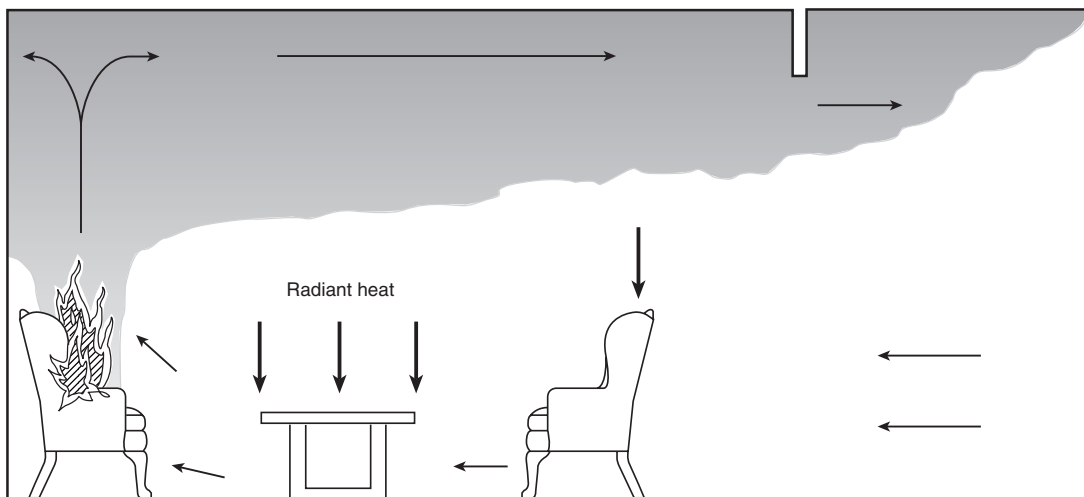


FIGURE 5.5.4.2.2 Preflashover Conditions in Compartment Fire.

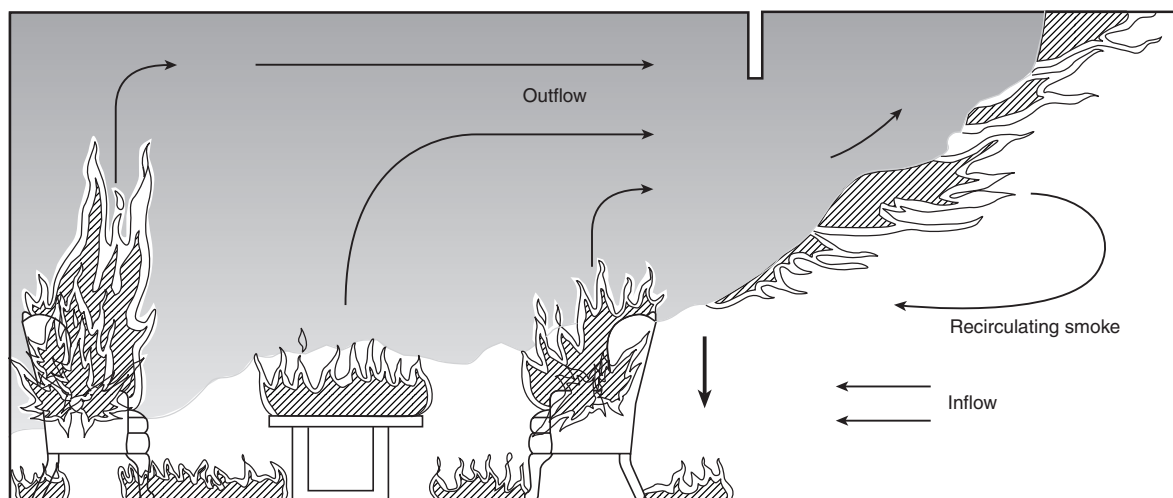


FIGURE 5.5.4.2.6 Flashover Conditions in Compartment Fire.

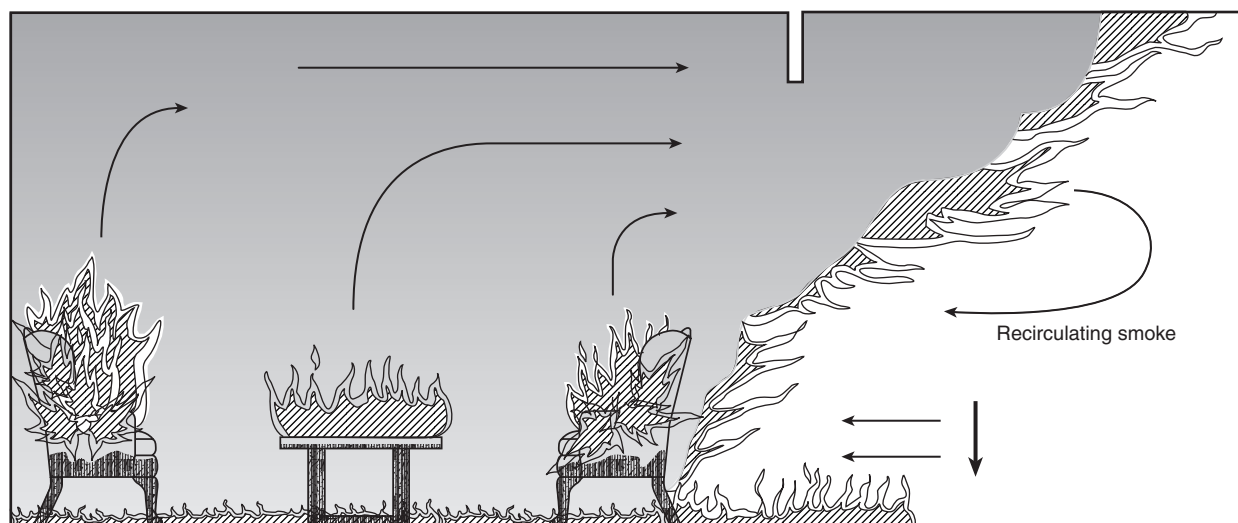


FIGURE 5.5.4.2.7 Postflashover or Full Room Involvement in Compartment Fire.

5.5.4.2.8 Flashover represents a transition from a condition where the fire is dominated by burning of the first item ignited (and nearby items subject to direct ignition) to a condition where the fire is dominated by burning of all items in the compartment. It is important for investigators to be aware of the fact that flashover is a triggering condition, not a closed-ended event. The postflashover condition is called *full room involvement*. The onset of flashover occurs when the hot gas layer imposes radiant energy levels (flux) on unignited fuels of approximately 20 kW/m^2 . This flux level is usually sufficient to ignite ordinary combustible materials. Flux levels in full room involvement are considerably higher than at the beginning of flashover. Levels at the floor of 170 kW/m^2 have been recorded. See Table 5.5.4.2.8 for the effects of various heat fluxes.

5.5.4.2.9 Once flashover conditions have been reached, full room involvement will follow in the majority of fires unless the fuel is exhausted, the fire is oxygen deprived, or the fire is extinguished. In full room involvement, the hot layer can be at floor level, but tests and actual fires have shown the hot layer is not always at floor level (see Figure 5.5.4.2.7).

5.5.4.2.10 At the time of flashover, the compartment door becomes a restriction to the amount of air available for combustion inside the compartment, and the majority of the pyrolysis products will burn outside the compartment. Flameover or rollover generally occurs prior to flashover but may not always result in flashover conditions throughout a compartment, particularly where there is a large volume or high ceiling involved or there is limited fuel present.

5.5.4.2.11 Research has shown that time to flashover from open flame can be as short as $1\frac{1}{2}$ minutes in residential fire tests with contemporary furnishings, or it may never occur. The rate of heat release from a fully developed room flashover can be on the order of $10,000 \text{ kW}$ (10 MW) or more.

5.5.5 Effects of Enclosures on Fire Growth. For a fire in a given fuel package, the size of the ventilation opening, the volume of the enclosure, the ceiling height, and the location

of the fire with respect to the walls and corners will affect the overall fire growth rate in the enclosure.

5.5.5.1* Ventilation Opening. The minimum size fire that can cause a flashover in a given room is a function of the ventilation provided through an opening. This function is known as the *ventilation factor* and is calculated as the area of the opening (A_o) times the square root of the height of the opening (h_o).

5.5.5.1.1 An approximation of the heat release rate for flashover (HRR_{fo}) can be found from the following relationship:

$$HRR_{fo} (\text{kW}) = (750A_o)(h_o)^{0.5}$$

where:

HRR_{fo} = heat release rate for flashover

A_o = area of opening in m^2

h_o = height of opening in m

5.5.5.1.2 The same formula using English units is:

$$HRR_{fo} (\text{Btu/s}) = 36.5A_o(h_o)^{0.5}$$

where:

HRR_{fo} = heat release rate for flashover

A_o = area of opening in ft^2

h_o = height of opening in ft

5.5.5.1.3 A log versus log graph of the HRR for a range of ventilation factors is shown in Figure 5.5.5.1.3. If the room dimensions are known, a closer approximation can be found using the following relationship:

$$HRR_{fo} (\text{kW}) = (378A_o)(h_o)^{0.5} + 7.8A_w$$

where:

HRR_{fo} = heat release rate for flashover

A_o = area of ventilation opening in m^2

A_w = area of walls, ceiling, and floor in m^2

Table 5.5.4.2.8 Approximate Rate of Radiant 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
16	Human skin experiences sudden pain and blisters after 5-second exposure with second-degree burn injury. ^a
12.5	Wood volatiles ignite with intended exposure ^d and piloted ignition.
10.4	Human skin experiences pain with 3-second exposure and blisters in 9 seconds with second-degree burn injury. ^{a,b}
6.4	Human skin experiences pain with a second exposure and blisters in 18 seconds with second-degree burn injury. ^{a,c}
4.5	Human skin becomes blistered with a 30-second exposure, causing a second-degree burn injury. ^a
2.5	Common thermal radiation exposure while fire fighting. ^f This energy level may cause burn injuries with prolonged exposure.
1.4	Thermal radiation from the sun. Potential sunburn in 30 minutes or less. ^g

Note: The unit kW/m² 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 (m²) represents the surface area of a square measuring 1 m long and 1 m wide. For example, 1.4 kW/m² 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.

Sources:

^aFrom NFPA 1971, *Standard on Protective Ensemble for Structural Fire Fighting*.

^bFrom Lawson, "Fire and the Atomic Bomb."

^cFrom Fang and Breese, "Fire Development in Residential Basement Rooms."

^dFrom Lawson and Simms, "The Ignition of Wood by Radiation," pp. 288-292.

^eFrom Tan, "Flare System Design Simplified," pp. 172-176.

^fFrom U.S. Fire Administration, "Minimum Standards on Structural Fire Fighting Protective Clothing and Equipment."

^gFrom Bennett and Myers, *Momentum, Heat, and Mass Transfer*.

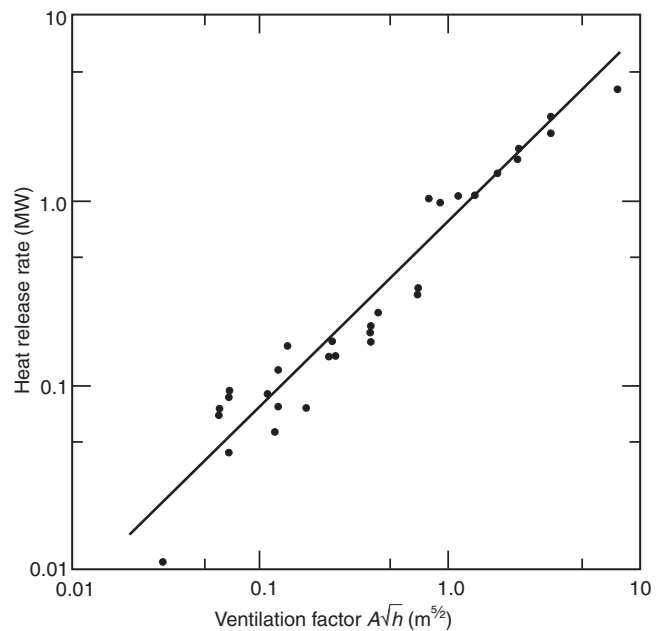


FIGURE 5.5.5.1.3 Minimum Heat Release Rate for Flashover.

5.5.5.1.4 This relationship accounts for heat losses to the bounding surfaces of the room (i.e., the walls, ceiling, and floor). If the losses to the floor are small, then the floor area can be deleted from the value of A_w . The same formula using English units is:

$$HRR_{fo} (\text{Btu/s}) = 18.4A_o(h_o)^{0.5} + 0.69A_w$$

where:

HRR_{fo} = heat release rate for flashover

A_o = area of ventilation opening in ft²

A_w = area of walls, ceiling, and floor in ft²

h_o = height of opening in ft

5.5.5.2 Room Volume and Ceiling Height. Development of a ceiling layer of sufficient temperature to cause radiant ignition of exposed combustible fuels and the layer gases is necessary for flashover. High ceilings or large compartment volumes will delay this buildup of temperature and therefore delay or possibly prevent flashover from occurring. The distance between the bottom of the hot layer and the combustible fuel is also a factor but of less importance.

5.5.5.3 Location of the Fire in the Compartment. When a burning fuel package is away from a wall, air is free to flow into the plume from all directions and mix with the fuel gases. This brings air for combustion into the flame zone and cools the upper part of the plume by entrainment. (See 5.5.2.)

5.5.5.3.1 If the fuel package or the fire plume is against a wall (not in a corner), air will be able to enter the plume from only about half of the theoretical circle around it. This will result in longer flames and a faster rise in the temperature of the gases in the ceiling layer. This, in turn, leads to flashover sooner than if the same fuel package had been in the center of the compartment.

5.5.5.3.2 When the same fuel package is placed in a corner, 75 percent of the airflow into the plume is restricted, resulting in even longer flames, higher plume and ceiling layer temperatures, and shorter times to flashover.

5.5.5.3.3 It should be noted that walls or other barriers to airflow will affect flame length and plume temperature outdoors as well.

5.5.5.3.4 The possible effect of the location of walls relative to the fire should be considered in interpreting the extent of damage as a clue to fire origin. In making the determination, the possibility that the fuel in the suspected area of origin was not the first material ignited and that the greater degree of damage was the result of wall or corner effects should be considered.

5.5.6* Flame Height.

5.5.6.1 The height of flames above the surface of burning fuels is directly related to the HRR of the fire. For a given fuel, the HRR is related to the amount of surface burning. If the flame height of a fire is known or can be estimated, the approximate HRR can be determined. The height of the flame is related to the heat output of a simple pool or single item fire by the relationship:

$$H_f = 0.174(k\dot{Q})^{0.4}$$

5.5.6.2 If the flame height is known, the heat release rate can be estimated by using the following formula:

$$\dot{Q} = \frac{79.18H_f^{5/2}}{k}$$

where:

H_f = flame height in meters

k = wall effect factor

$\dot{Q}$ = fuel heat release rate in kilowatts

5.5.6.2.1 The value of k to be used is as follows: $k = 1$ when there are no nearby walls; $k = 2$ when the fuel package is at a wall; $k = 4$ when the fuel package is in a corner.

5.5.6.2.2 For a typical wastebasket fire of 150 kW where there are no nearby walls ($k = 1$), this yields an estimated flame plume of 1.3 m (4.3 ft). For an upholstered chair, where the heat is $\dot{Q}$ on the order of 500 kW, the plume would be about 2.1 m (6.9 ft) in height.

5.6 Products of Combustion.

5.6.1 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, produce nitrogen oxides and possibly hydrogen cyanide as combustion products. Literally hundreds of compounds have been identified as products of incomplete combustion of wood.

5.6.2 When less air is available for combustion, as in ventilation-controlled fires, the production of carbon monoxide increases as does the production of soot and unburned fuels.

5.6.3 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 ex-

remely 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. Since 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.

5.6.4 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.

5.6.5 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.

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

5.6.7 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 the low-oxygen conditions, or ventilation-controlled conditions in a postflashover fire, can be quite dark or black. Black smoke also can be produced by the burning of other materials, including most plastics and ignitable liquids.

5.6.8 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.

5.6.9 Smoke production rates are generally less in the early phase of a fire but increase greatly with the onset of flashover, if flashover occurs.

5.7 The Spread of Fire in Buildings. 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. In the context of this discussion, flame spread is associated with 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.

5.7.1 Flame Spread.

5.7.1.1 For flame spread to occur on solid materials, heat transfer from the flame front to the material surface must first heat the solid surface ahead of the flame front. If the surface temperature is sufficient and a flammable mixture can be created above the surface through pyrolysis of the solid material, the flame front can propagate through burning in the vapor phase. The characteristics of a material can have a significant influence on the flame over a particular material. These factors include material properties, surface texture, thickness of the material, orientation

of the object (i.e., vertical or horizontal spread), and wind direction (i.e., wind-aided or opposed flow spread). Combinations of these factors can either aid or hinder the rate at which flame will spread over an object. Flames may spread differently on different portions of the same fuel package, slowly across the horizontal surface of a chair cushion with spread increasing rapidly as the back of the chair becomes involved. If a material is able to melt when exposed to direct flame impingement or convective or radiative heating from an adjacent flame or hot products of combustion such as a hot upper layer in a room, 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 is a good example of 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.

5.7.1.2 Flame spread over liquids can occur more rapidly than flame spread over solids. Flammable vapors are usually easier to form since the energy to volatilize the liquid is much less than the energy required to pyrolyze a solid. Convective flows within the liquid ahead of the flame front help to heat the liquid and enhance the spread rate of flame over the surface of a pool. The temperature of the surface of the pool relative to the flash point temperature is a determining factor in the rate of flame spread over combustible liquids.

5.7.2 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 remote ignition of adjacent fuel packages.

5.7.2.1 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.

5.7.2.2 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.

5.7.2.2.1 Thermal radiant heat transfer that results in ignition can occur as hot smoke flows to adjacent compartments. The dominant method of spreading fire from one 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. (*See NFPA 555, Guide on Methods for Evaluating Potential for Room Flashover.*)

5.7.2.2.2 In addition to thermal radiant transfer from the hot layer, the investigator should be aware of “drop down” (*see 6.16.5.2*). When a flame is burning an elevated structure or material within a compartment, the possibility exists that before the fuel is completely consumed, the structural elements will lose integrity and cause the fuel to fall to other areas within the compartment or on 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. The “drop down” fuel may provide enough conductive, convective, or radiant heat to ignite a lower fuel package, thus spreading fire.

5.7.3 Paths of Smoke Spread in Buildings. The flow of gases across an opening is the result of differences in pressure. Therefore, smoke can flow through doors, windows, and other opening within compartments. Since no compartment is hermetically sealed, there are leakage areas where smoke can flow between compartments. Plenum spaces above false ceilings are also a significant path for smoke travel. Smoke movement by temperature difference can result from the heat from the fire. In tall buildings smoke at a distance from the fire may be the same temperature as the ambient air but may be moving due to the building stack effect. Stack effect pressures result from differences between the temperatures inside and outside of the building. Pressure from HVAC systems can also transport smoke from one compartment to another.

Chapter 6 Fire Patterns

6.1 Introduction.

6.1.1 One of the major objectives of a fire scene examination is the recognition, identification, and analysis of fire patterns. The analysis of fire patterns is performed in an attempt to trace fire spread, identify areas and points of origin, and identify the fuels involved.

6.1.2 The circumstances of every fire are different from every other fire because of the differences in the structures, fuel loads, ignition factors, airflow, ventilation, and many other variable factors. This discussion, therefore, cannot cover every possible variation in fire patterns and how they come about. The basic principles are covered here, and the investigator should apply them to the particular fire incident under investigation.

6.2 Dynamics of Pattern Production.

6.2.1 General. The recognition, identification, and proper analysis of fire patterns by an investigator depends on an understanding of the dynamics of fire development and heat and flame spread. This recognition, identification, and proper analysis includes an understanding of the way that the three modes of heat transfer (conduction, convection, and radiation) produce the fire patterns and the nature of flame, heat, and smoke movement within a structure. (*See Chapter 5.*)

6.2.1.1 The damage created by flame, radiation, hot gases, and smoke creates patterns that investigators use to locate the area or point of fire origin.

6.2.1.2 The patterns seen by an investigator can represent much of the history of the fire. Each time another fuel package is ignited or the ventilation to the fire changes, the rate of energy production and heat distribution will change. Any burning item can produce a plume and thus a fire pattern. Determining which pattern was produced at the point of origin by the first material ignited usually becomes more difficult as the size and duration of the fire increase.

6.2.1.3 The means by which patterns can arise are discussed here. Guidance on the use and interpretation of patterns is found in Chapter 6 and Chapter 17.

6.2.2* Plume-Generated Patterns. Most fire patterns generated directly by fire plumes are truncated cone patterns. They represent the lines of demarcation created when the three-dimensional (cone) shapes of the fire plumes are truncated or cut by an intervening plane surface such as a wall, ceiling, or bottom of a table or shelf. These truncated cone fire patterns include the following:

- (1) V patterns on vertical surfaces
- (2) Inverted cone patterns
- (3) Hourglass patterns
- (4) U-shaped patterns
- (5) Pointer and arrow patterns
- (6) Circular-shaped patterns

6.2.2.1 As the buoyant column of hot gases, flames, and smoke rising above a fire in the plume are cooled by air entrainment the plume temperatures approach that of the surrounding air (decreased temperatures with increasing height in the plume). Therefore the production of fire patterns is most prominent when the surface displaying the patterns has been exposed to plume temperatures near or above its minimum pyrolysis temperature. The presence of a physical barrier, such as a ceiling, will contribute to the lateral extension of the plume boundary in a ceiling jet. Downward radiation from the ceiling jet below the horizontal obstructing plane or the bottom of the descending upper layer produces a widening of the top of the plume.

6.2.2.2 When no ceiling exists over a fire, and the fire is far from walls, the hot gases and smoke of the plume continue to rise vertically until they ultimately cool to the ambient air temperature. At that point, the smoke and hot gases will stratify and diffuse in the air. Such conditions would exist for an unconfined fire outdoors. The same conditions can exist with a fire in a building at the very early stages of a fire, low heat release rate when the plume is small, or if the fire is in a very large-volume space with a high ceiling such as an atrium.

6.2.2.3 The rate of heat release of the burning fuel also has a profound effect on the shape of the fire patterns produced. Lower heat release rate fuels may not produce flame heights sufficient for the flame zone of the plume to reach a ceiling or other horizontal barrier. These fires produce triangular-shaped fire patterns with the bases at the bottom and the vertices at the top, such as in inverted cone or hourglass patterns. As the rate of heat release increases and the flame zone begins to approach the horizontal barrier, the sides of the patterns produced become columnar (straight sided). As the heat release rates continue to increase, creating ceiling jets and/or descending upper smoke layers, direct flame impingement on surfaces and downward radiating heat energy begin to broaden the tops of the fire patterns, and "V" shaped, "U" shaped, pointer or arrow patterns are produced on the truncating vertical surfaces. Circular shaped patterns are produced on the bottoms of horizontal surfaces.

6.2.2.4 The plume width varies with the size of the base of the fire and will increase over time as the fire spreads. A narrow base pattern will develop from a small surface area fire, and a wide base pattern will develop from a fire with a large surface area. (See Figure 6.2.2.4.)

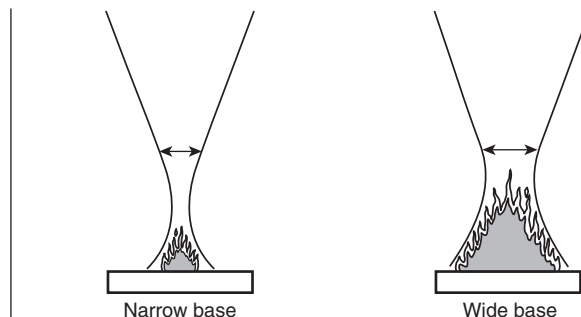


FIGURE 6.2.2.4 Effects of Fire Base on Fire Pattern Width.

6.2.2.5 A fire that develops and grows in a particular fuel will first produce patterns consistent with a small fire, that is, inverted cone, assuming there is a surface close enough on which to produce these patterns. As the heat release rate and flame height increase, this inverted cone pattern is often obscured by the formation of the subsequent pattern, that is, columnar. Likewise, the columnar pattern is often obscured by the V-pattern that forms if the fire continues to grow. The earlier patterns will be observable only if the fire goes out because of suppression, lack of oxygen, or fuel depletion. For this reason, observation of these patterns gives the investigator insight into the fire's stage of development, the rate of fire growth of a particular fuel, and the peak heat release rate of a particular fuel at the time it was suppressed. It must also be understood that the lack of an observable inverted cone, hourglass, or columnar pattern after a fire is suppressed does not mean that one was not present earlier in the fire's growth. If the fire achieves flashover and full room involvement, the patterns formed early in the growth of the fire are often changed by the intense convective and radiant heat transfer.

6.2.3 Ventilation-Generated Patterns. Blowing air over glowing embers will raise their temperatures and can generate enough heat to melt metals. More heat is transferred by convection as the velocity of the hot gas increases. These phenomena can explain the presence of numerous burn patterns.

6.2.3.1 Airflow over coals or embers can raise temperatures high enough to burn holes through floors. If a building burns extensively and collapses, embers buried in debris can produce holes in floors. Once a hole is made, air can flow up through the hole, and the burning rate can increase. Careful interpretation of these patterns should be exercised, since they may be mistaken for patterns originating from ignitable liquids. Holes in floors may be caused by glowing combustion, radiation, or an ignitable liquid. Because the surface below a liquid remains cool (or at least below the boiling point of the liquid) until the liquid is consumed, holes in the floor from burning ignitable liquids may result when the ignitable liquid has soaked into the floor or accumulated below the floor level. Evidence other than the hole or its shape is necessary to confirm the cause of a given pattern. (See 6.3.3, 6.16.2.4, and 6.17.8.2.)

6.2.3.2 When a door is closed on a fire, hot gases (being lighter) can escape through the space at the top of the closed door, resulting in charring. Cool air may enter the compartment at the bottom of the door, as in Figure 6.2.3.2(a). In a fully developed room fire where the hot gases extend to the floor, the hot gases may escape under the door and cause charring under the door and possibly through the threshold, as in Figure 6.2.3.2(b). Charring can also occur if glowing debris falls against the door either on the inside or the outside, as in Figure 6.2.3.2(c).

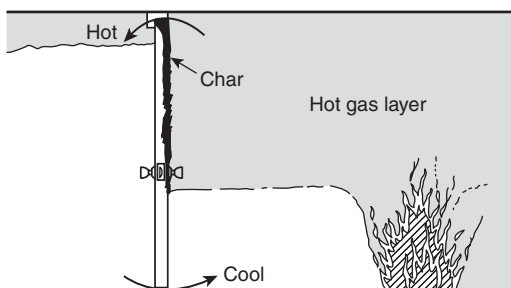


FIGURE 6.2.3.2(a) Airflow Around Door.

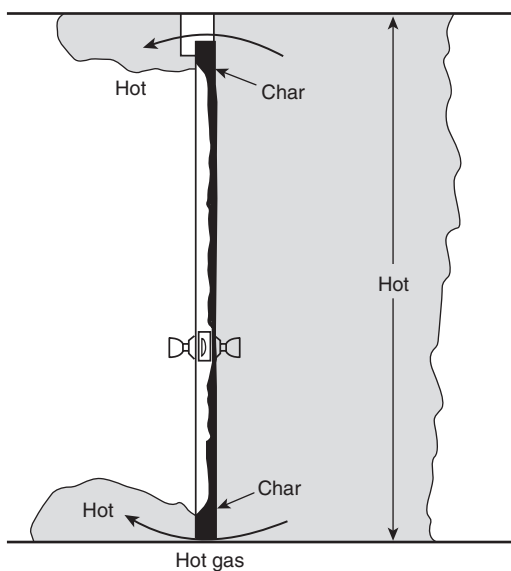


FIGURE 6.2.3.2(b) Hot Gases Under Door.

6.2.3.3 Ventilation of fires and hot gases through windows, doors, or other openings in a structure greatly increases the velocity of the flow over combustible materials. In addition, well-vented fires burn with higher heat release rates. These factors, combined with higher radiation temperatures, can act to burn wood at a higher rate and can spall concrete or deform metal components. Areas of great damage are indicators of a high heat release rate, ventilation effects, or long exposure. Such areas, however, are not always the point of fire origin. For example, fire could spread from slow-burning fuels to rapid-burning fuels with the latter producing most of the fire damage.

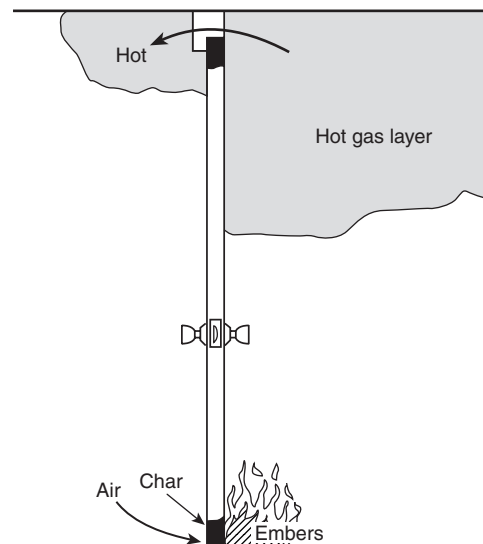


FIGURE 6.2.3.2(c) Glowing Embers at Base of Door.

6.2.3.4* Effects of Room Ventilation on Pattern Magnitude and Location.

6.2.3.4.1 The ventilation of the room of fire origin has a great effect on the growth and heat release rate of a fire, and for this reason greatly affects pattern formation. In limited, full-scale testing, it was found that patterns that indicated areas of intense burning remote from the point of origin were observed and appeared to be from ventilation effects only. This result was observed in rooms that had flashover conditions where clean burn areas were produced under a window that had been broken during the fire, away from the origin. It was observed as areas of intense burning on furniture items near a door opening as truncated cone patterns on walls opposite door openings.

6.2.3.4.2 The effect of ventilation on the intensity of the fire, as well as the location, shape, and damage magnitude of patterns being used to determine the origin of the fire should be considered. Where fresh air ventilation is available to a fire, it is not uncommon to find locally heavy damage patterns on combustible items close to the ventilation opening, patterns which may have no relevance to the point of origin.

6.2.4 Hot Gas Layer–Generated Patterns. The radiant flux from the overhead hot gas layer can produce damage to the upper surfaces of contents and floor covering materials. This process commonly begins as the environment within the room approaches flashover conditions. Similar damage to floor surfaces from radiant heat frequently occurs in adjacent spaces outside rooms that are fully involved in fire. Damage to hallway floors and porches are examples. If the fire does not progress to full room involvement (see 5.5.4.2 through 5.5.4.2.11), the damage may include blistering, charring, or melting. Protected surfaces may exhibit no damage. At this time in the fire development, a line of demarcation representing the lower extent of the hot gas layer may form on vertical surfaces. The degree of damage generally will be uniform except where there is drop down, burning of isolated items that are easily ignited, or protected areas. Damage to the undersides of furnishings below the bottom of the hot layer is unlikely.

6.2.5 Patterns Generated by Full Room Involvement. If a fire progresses to full room involvement (*see 5.5.4.2 through 5.5.4.2.11*), damage found at low levels in the room down to and including the floor can be more extensive due to the effects of high radiative flux and the convected heat from the descending hot gas layer. Damage can include charring of the undersides of furniture, burning of carpet under furniture, uniform burning around table legs, burning of baseboards and the undersides of doors, and burning on floor covering in corners. Holes can be burned through carpet and floors. The effects of protected areas and floor clutter on low burn patterns should be considered (*see 6.17.7.2 and 6.18.2*). Although the degree of damage will increase with time, the extreme conditions of the full room involvement can produce major damage in a few minutes, depending on ventilation and fuels present.

6.3 Fire Patterns Defined. Fire patterns are the visible or measurable physical effects that remain after a fire. These include thermal effects on materials, such as charring, oxidation, consumption of combustibles, smoke and soot deposits, distortion, melting, color changes, changes in the character of materials, structural collapse, and other effects.

6.3.1 Lines or Areas of Demarcation. Lines or areas of demarcation are the borders defining the differences in certain heat and smoke effects of the fire on various materials. They appear between the affected area and adjacent unaffected or less affected areas.

6.3.1.1 The production of lines and areas of demarcation, and the subsequent fire patterns that they define, depend on a combination of variables: the material itself, the rate of heat release of the fire, fire suppression activities, temperature of the heat source, ventilation, and the amount of time that the material is exposed to the heat.

6.3.1.2 For example, a particular material may display the same heat exposure patterns from exposure to a low-temperature heat source for a long period of time as to a high-temperature heat source for a shorter period of time. The investigator should keep this concept in mind while analyzing the nature of fire patterns.

6.3.2 Surface Effect. The nature and material of the surface that contains the fire pattern will have a bearing on the shape and nature of the pattern itself.

6.3.2.1 The shape and texture of the surface can affect the actual shape of the lines of demarcation displayed or increase or decrease the amount of pyrolysis and combustion by differing surface areas. If both a smooth and rough surface of the same material are exposed to the same source of heat, the rougher surface will sustain more damage. This effect is a result of the turbulence of the hot gases interacting with the surface as well as an increase in the surface-to-mass ratio. Differing surface coverings, such as paint, tiles, brick, wallpaper, plaster, and so forth, may increase or decrease the rate of heat degradation or burning.

6.3.2.2 Combustible surfaces will be darkened by the beginnings of pyrolysis, be burned, or be in various stages of charring, including the total loss of material. Noncombustible surfaces, such as mineral materials or metals, may exhibit color changes, oxidation, physical distortions, or melting.

6.3.3 Penetrations of Horizontal Surfaces. Penetration of horizontal surfaces, from above or below, can be caused by radiant heat, direct flame impingement, or localized smoldering with or without the effects of ventilation.

6.3.3.1 Penetrations in a downward direction are often considered unusual because the more natural direction of heat movement is upward through the action of buoyancy. In fully flashed-over compartments, however, hot gases may be forced through small, pre-existing openings in a floor, resulting in a penetration. Penetrations may also arise as the result of intense burning under furniture items such as polyurethane mattresses, couches, or chairs. Flaming or smoldering under collapsed floors or roofs can also lead to floor penetrations. Downward penetration, such as a hole burned into a floor or tabletop, should be noted and analyzed by the investigator.

6.3.3.2 Whether a hole burned into a horizontal surface was created from above or below may be identified by an examination of the sloping sides of the hole. Sides that slope downward from above toward the hole are indicators that the fire was from above. Sides that are wider at the bottom and slope upward toward the center of the hole indicate that the fire was from below. (*See Figure 6.3.3.2.*)

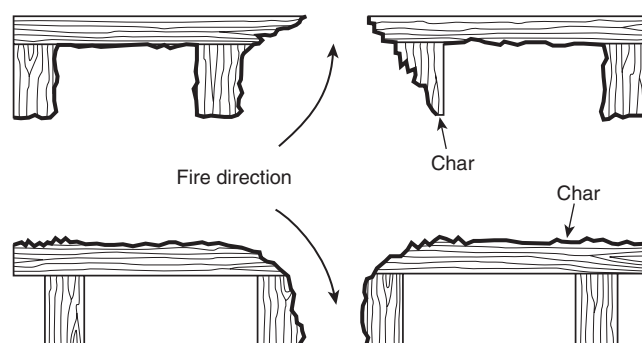


FIGURE 6.3.3.2 Burn Pattern with Fire from Above and Below.

6.3.3.3 Another reliable means of determining whether a fire moved up through or down through a surface is to compare the extent of destruction on the two levels separated by the surface. If fire moved up through the surface, the damage to the bottom side of the penetrated surface will be more extensive when compared to the top side. The converse is true where the fire moved downward.

6.3.3.4 It is, of course, possible for both upward and downward movement to occur through a hole during the course of a fire. The investigator should keep in mind that only the last movement through the hole may be evident.

6.3.4 Loss of Material. Typically, when wood or other combustible surfaces burn, they lose material and mass. The shapes and quantities of remaining combustibles can themselves produce lines of demarcation and, ultimately, fire patterns to be analyzed by the investigator. For example, the fact that the tops of wooden wall studs are burned away at progressively lower heights can be used in the "pointer and arrow" fire pattern analysis of fire spread.

6.3.5 Victim Injuries. The investigator should carefully note and document the position and condition of any fire victims and their relationship to other objects or victims. Autopsy reports and medical records may provide useful information regarding burn damage. For example, burn damage patterns and protected areas can be used in a similar way as damage to furniture and other items discussed in previous sections.

6.4 Types of Fire Patterns. There are two basic types of fire patterns: movement patterns and intensity patterns. These types of patterns are defined largely by the fire dynamics discussed in Section 5.5. Often a systematic use of more than one type of fire pattern at a fire scene can be used in combination to lead back to the heat source that produced them. Some patterns may display aspects defining both movement and intensity (heat/fuel).

6.4.1 Movement Patterns. Flame and heat movement patterns are produced by the growth and movement of fire and the products of combustion away from an initial heat source. If accurately identified and analyzed, these patterns can be traced back to the origin of the heat source that produced them.

6.4.2 Intensity (Heat) Patterns. Flame and heat intensity patterns are produced by the response of materials to the effects of various intensities of heat exposure. The various heat effects on a certain material can produce lines of demarcation. These lines of demarcation may be helpful to the investigator in determining the characteristics and quantities of fuel materials, as well as the direction of fire spread.

6.5 Surface Effect of Char. Many surfaces are decomposed in the heat of a fire. The binder in paint will char and darken the color of the painted surface. Wallpaper and the paper surface of gypsum wallboard will char when heated. Vinyl and other plastic surfaces on walls, floors, tables, or counters also will discolor, melt, or char. Wood surfaces will char, but, because of the greater significance of wood char, it is treated in greater detail in 6.5.1 through 6.5.5. The degree of discoloration and charring can be compared to adjacent areas to find the areas of greatest burning.

6.5.1 Wood Char. Charred wood is likely to be found in nearly all structural fires. When exposed to elevated temperatures, wood undergoes chemical decomposition that drives off gases, water vapor, and various pyrolysis products as smoke. The solid residue that remains is mainly carbon. Char shrinks as it forms, and develops cracks and blisters.

6.5.2* Rate of Charring. The depth of char measurements should not be relied on to determine the duration of the burning. The rule of 2.54 cm (1 in.) in 45 minutes for the rate of charring of pine is based on one set of laboratory conditions in a test furnace. Fires may burn with more or less intensity during the course of an uncontrolled fire than under a controlled laboratory fire. Actual laboratory char rates from exposure to heat from one side vary from 1 cm (0.4 in.) per hour at 390°C (750°F) to 25.4 cm (10 in.) per hour at temperatures approaching 1090°C (2000°F) in intense fires. Even these figures will vary with the species of the wood, orientation of the grain, moisture content, and other variables. Charring rate is also a function of the velocity of hot gases and the ventilation conditions. Fast-moving gases or ventilation can lead to rapid charring.

6.5.2.1 The rate of charring and burning of wood in general has no relation to its age once the wood has been dried. Wood tends to gain or lose moisture according to the ambient temperature and humidity. Thus, old dry wood is no more combustible than new kiln-dried wood if they have both been exposed to the same atmospheric conditions.

6.5.2.2 Overall, the use of the nature of char to make determinations about fuels involved in a fire should be done with careful consideration of all the possible variables that can affect the speed and severity of burning.

6.5.3 Depth of Char. Analysis of the depth of charring is most reliable for evaluating fire spread, rather than for the establishment of specific burn times or intensity of heat from adjacent burning materials. By measuring the relative depth and extent of charring, the investigator may be able to determine what portions of a material or construction were exposed the longest to a heat source. The relative depth of char from point to point is the key to appropriate use of charring — locating the places where the damage was most severe due to exposure, ventilation, or fuel placement. The investigator may then deduce the direction of fire spread, with decreasing char depths being farther away from the heat source.

6.5.3.1 Depth of Char Diagram. Lines of demarcation that may not be obvious can often be identified for analysis by a process of measuring and charting depths of char on a grid diagram. By drawing lines connecting points of equal char depth (isochars) on the grid diagram, lines of demarcation may be identified.

6.5.3.2 Depth of Char Analysis. Certain key variables affect the validity of depth of char pattern analysis. These factors include the following:

- (1) Single versus multiple heat or fuel sources creating the char patterns being measured. Depth of char measurements may be useful in determining more than one fire or heat source.
- (2) Comparison of char measurements, which should be done only for identical materials. It would not be valid to compare the depth of char from a wall stud to the depth of char of an adjacent wooden wall panel.
- (3) Ventilation factors influencing the rate of burning. Wood can exhibit deeper charring when adjacent to a ventilation source or an opening where hot fire gases can escape.
- (4) Consistency of measuring technique and method. Each comparable depth of char measurement should be made with the same tool and same technique. [See Figure 15.4.2(f).]

6.5.3.3 Measuring Depth of Char. Consistency in the method of measuring the depth of char is the key to accurate figures. Sharp pointed instruments, such as pocket knives, are not suitable for accurate measurements. The sharp end of the knife will have a tendency to cut into the noncharred wood beneath.

6.5.3.3.1 Thin, blunt-ended probes, such as certain types of calipers, tire tread depth gauges, or specifically modified metal rulers are best.

6.5.3.3.2 The same measuring tool should be used for any set of comparable measurements. Nearly equal pressure for each measurement while inserting the measuring device is also necessary for accurate results.

6.5.3.3.3 Char depth measurements, illustrated in Figure 6.5.3.3.3(a), should be made at the center of char blisters, rather than in or near the crevasses between blisters. Dial calipers with depth probes of round cross-section, shown in Figure 6.5.3.3.3(b), are excellent depth of char measurement tools. Figure 6.5.3.3.3(c) illustrates their use.

6.5.3.3.4 When determining the depth of charring, the investigator should take into consideration any burned wood that may have been completely destroyed by the fire and add that missing depth of wood to the overall depth measurement.

6.5.4 Depth of Char Patterns with Fuel Gases. When fugitive fuel gases are the initial fuel sources for fires, they produce relatively even depths of char over the often wide areas that they cover.

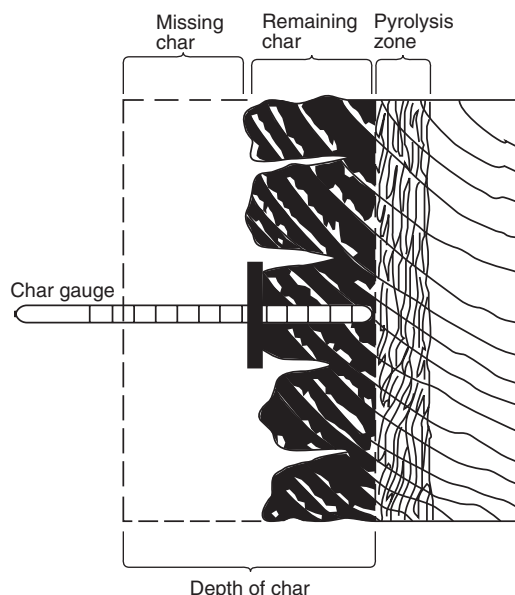


FIGURE 6.5.3.3.3(a) Measuring Depth of Char.

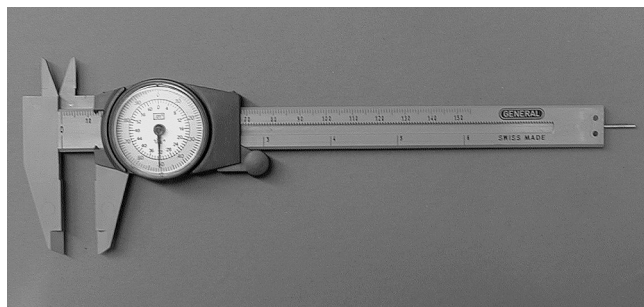


FIGURE 6.5.3.3.3(b) Dial Calipers with Depth Probes.

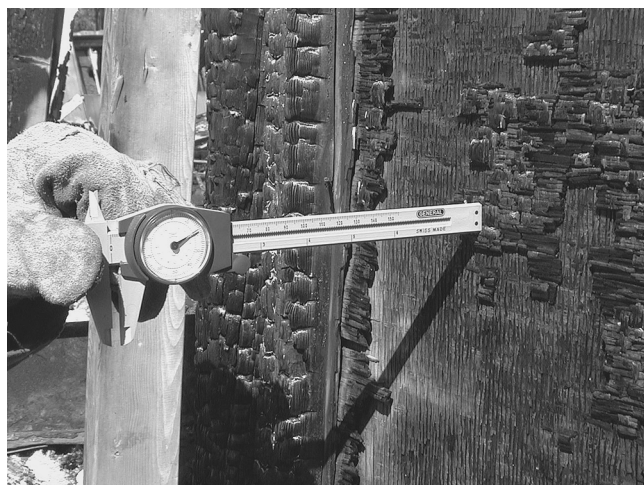


FIGURE 6.5.3.3.3(c) Using Dial Calipers to Measure Depth of Char.

6.5.4.1 Progressive changes in depth of char that are used by investigators to trace fire spread may exist only in those areas to which the fire spreads from the initial locations of the pocketed fuel gases.

6.5.4.2 Deeper charring may exist in close proximity to the point of gas leakage, as burning may continue there after the original quantity of gas is consumed. This charring may be highly localized because of the pressurized gas jets that can exist at the immediate point of leakage and may assist the investigator in locating the leak.

6.5.5 Interpretation of Char. The appearance of the char and cracks has been given meaning by the fire investigation community beyond what has been substantiated by controlled experimentation. It has been widely stated that the presence of large shiny blisters (alligator char) is proof that a liquid accelerant was present during the fire. This is a misconception. These types of blisters can be found in many different types of fires. There is no justification that the appearance of large, curved blisters is an exclusive indicator of an accelerated fire. Figure 6.5.5, showing boards exposed to the same fire, illustrates the variability of char blister.

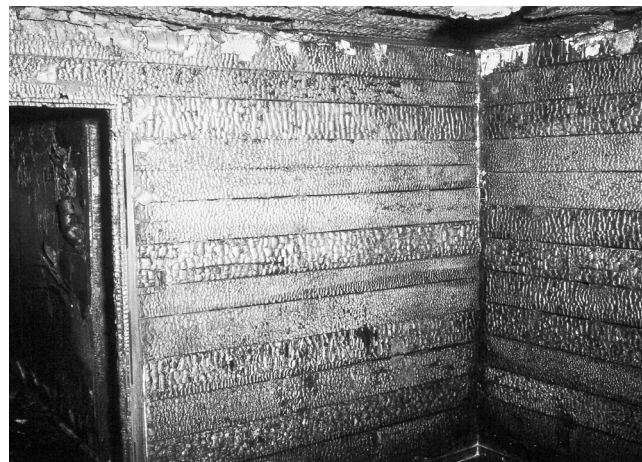


FIGURE 6.5.5 Variability of Char Blister.

6.5.5.1 It is sometimes claimed that the surface appearance of the char, such as dullness, shininess, or colors, has some relation to the use of a hydrocarbon accelerant or the rate of fire growth. There is no scientific evidence of such a correlation, and the investigator is advised not to claim indications of accelerant or fire growth rate on the basis of the appearance of the char alone.

6.5.5.2 Depth of char is often used to estimate the duration of a fire. The rate of charring of wood varies widely depending upon such variables as the following:

- (1) Rate and duration of heating
- (2) Ventilation effects
- (3) Surface area to mass ratio
- (4) Direction, orientation, and size of wood grain
- (5) Species of wood (pine, oak, fir, etc.)
- (6) Moisture content
- (7) Nature of surface coating

6.5.5.3 The investigator is cautioned that no specific time of burning can be determined based solely on depth of char.

6.6 Spalling.

6.6.1 General. Spalling is the breakdown in surface tensile strength of concrete, masonry, or brick caused by exposure to high temperatures and rates of heating resulting in mechanical forces within the material. These forces are believed to result from one or more of the following:

- (1) Moisture present in uncured or “green” concrete
- (2) Differential expansion between reinforcing rods or steel mesh and the surrounding concrete
- (3) Differential expansion between the concrete mix and the aggregate (This is most common with silicon aggregates.)
- (4) Differential expansion between the fine-grained surface finished layers and the coarser-grained interior layers
- (5) Differential expansion between the fire exposed surface and the interior of the slab

6.6.1.1 Spalling of concrete or masonry surfaces may be caused by heat, freezing chemicals, or abrasion. It may be induced more readily in poorly formulated or finished surfaces. Spalling is characterized by distinct lines of striation and the loss of surface material, resulting in cracking, breaking, and chipping or in the formation of craters on the surface.

6.6.1.2 Spalling of concrete, masonry, or brick has often been linked to unusually high temperatures caused by burning accelerant. While spalling can involve high rates of heat release or a rapid change in temperature, an accelerant need not be involved. The primary mechanism of spalling is the expansion or contraction of the surface while the rest of the mass expands or contracts at a different rate.

6.6.1.3 Spalled areas may appear lighter in color than adjacent areas. This lightening can be caused by exposure of clean subsurface material. Adjacent areas may also tend to be sooted.

6.6.1.4 Another factor in the spalling of concrete is the loading and stress in the material at the time of the fire. Since these high-stress or high-load areas may not be related to the fire location, spalling of concrete on the underside of ceilings or beams may not be directly over the origin of the fire. (See Figure 6.6.1.4.)



FIGURE 6.6.1.4 Spalling on Ceiling.

6.6.2* Interpretations of Spalling.

6.6.2.1 In the past, spalling of concrete at a fire scene has been thought to be a positive indicator of a liquid accelerant-involved fire.

6.6.2.2 The rapid cooling of a heated mass of concrete, brick, or masonry can also cause spalling. A common source of rapid cooling in a fire is extinguishment by water.

6.6.2.3 The presence or absence of spalling at a fire scene should not, in and of itself, be construed as an indicator of the presence or absence of liquid fuel accelerant. The presence of ignitable liquids will not normally cause spalling beneath the surface of the liquid. The ability of the surface to absorb or hold the liquid may be a factor in the production of spalling, especially on horizontal surfaces such as concrete floors. For example, a painted or sealed concrete floor is unlikely to spall. Rapid and intense heat development from an ignitable liquid fire may cause spalling on adjacent surfaces, or a resultant fire may cause spalling on the surface after the ignitable liquid burns away.

6.6.2.4 Since spalling can occur from sources other than fires, it is desirable to determine whether spalling was present prior to the fire.

6.6.2.5 Overall, it should be noted that the importance of spalling to the fire investigator lies in the documentation and analysis of a heat source.

6.7 Oxidation. Oxidation is the basic chemical process associated with combustion. Oxidation of some materials that do not burn can produce lines of demarcation and fire patterns of use to fire investigators. For these purposes, oxidation may be defined as a combination of oxygen with substances such as metals, rock, or soil that is brought about by high temperatures.

6.7.1 The effects of oxidation include change of color and change of texture. The higher the temperature and the longer the time of exposure, the more pronounced the effects of oxidation will be. Bare galvanized steel with mild heating will get a dull whitish surface from oxidation of the zinc coating. This oxidation also eliminates the protection that the zinc gave the steel. If the unprotected steel is wet for some time, it will then rust. Thus there can be a pattern of rusted compared to non-rusted galvanized steel.

6.7.2 When uncoated iron or steel is oxidized in a fire, the surface first gets a blue-gray dullness. Oxidation can proceed to thick layers of oxide that can flake off. After the fire, if the metal has been wet, the usual rust-colored oxide may appear.

6.7.3 On stainless steel surfaces, mild oxidation can give color fringes, and severe oxidation will give a dull gray color.

6.7.4 Copper forms a dark red or black oxide when exposed to heat. The color is not significant. What is significant is that the oxidation can form a line of demarcation. The thickness of the oxide depends upon the duration and intensity of the exposure (heat flux) to the fire or more heat. The more it is heated, the greater the oxidation. These color changes can form lines of demarcation. Burn patterns created on metal appliance cabinets may be helpful in determining fire origin and direction of travel.

6.7.5 Rocks and soil, when heated to very high temperatures, will often change colors that may range from yellowish to red.

6.7.6 Soot and char are also subject to oxidation. The dark char of the paper surface of gypsum wallboard, soot deposits, and paint can be oxidized by continued exposure to fire heat. The carbon will be oxidized to gases and disappear from whatever surface it was on. This will result in what is known as clean burn. (See Section 6.11.)

6.8 Melting of Materials.

6.8.1 General. The melting of a material is a physical change caused by heat. The border between the melted and non-melted portions of a fusible material can produce lines of heat and temperature demarcation that the investigator can use to define fire patterns.

6.8.1.1 Many solid materials soften or melt at elevated temperatures ranging from a little over room temperature to thousands of degrees. A specific melting temperature or range is characteristic for each material. (See Table 6.8.1.1.)

6.8.1.2 Melting temperatures of common metals range from as low as 170°C to 188°C (338°F to 370°F) for solder to as high as 1460°C (2660°F) for steel. When the metals or their residues are found in fire debris, some inferences concerning the temperatures in the fire can be drawn.

6.8.1.3 Thermoplastics melt at rather low temperatures, ranging from around 93°C (200°F) to near 400°C (750°F). They can also be consumed in a fire. Thus, the melting of plastics can give information on temperatures, but mainly where there have been hot gases and little or no flame in that immediate area.

6.8.1.4 Glass melts or softens over a range of temperatures. Nevertheless, glass can give useful information on temperatures during a fire.

6.8.2 Temperature Determination. If the investigator knows the approximate melting temperature of a material, an estimate can be made of the temperature to which the melted material was subjected. This knowledge may assist in evaluating the intensity and duration of the heating, the extent of heat movement, or the relative rates of heat release from fuels.

6.8.2.1 When using such variable materials as glass, plastics, and white pot metals for making temperature determinations, the investigator is cautioned that there is a wide variety of melting temperatures for these generic materials. The best method for utilizing such materials as temperature indicators is to take a sample of the material and have its melting temperature ascertained by a competent laboratory, materials scientist, or metallurgist.

6.8.2.2 Wood and gasoline burn at essentially the same flame temperature. The turbulent diffusion flame temperatures of all hydrocarbon fuels (plastics and ignitable liquids) and cellulosic fuels are approximately the same, although the fuels release heat at different rates.

6.8.2.3 The temperature achieved by an item at a given location within a structure or fire area depends on how much it is heated. The amount of heating depends on the temperature and velocity of the airflow, the geometry and physical properties of the heated item, its proximity to the source of heat, and the amount of heat energy present. Burning metals and highly exothermic chemical reactions can produce temperatures significantly higher than those created by hydrocarbon- or cellulosic-fueled fires.

6.8.2.4 Identifiable temperatures achieved in structural fires rarely remain above 1040°C (1900°F) for long periods of time. These identifiable temperatures are sometimes called *effective fire temperatures*, for they reflect physical effects that can be defined by specific temperature ranges. The investigator can use the analysis of the melting and fusion of materials to assist in establishing whether higher than expected heat energy was present.

Table 6.8.1.1 Approximate Melting Temperatures of Common Materials

Material	°C	°F
Aluminum (alloys) ^b	566–650	1050–1200
Aluminum ^a	660	1220
Brass (yellow) ^b	932	1710
Brass (red) ^b	996	1825
Bronze (aluminum) ^b	982	1800
Cast iron (gray) ^a	1350–1400	2460–2550
Cast iron (white) ^a	1050–1100	1920–2010
Chromium ^a	1845	3350
Copper ^a	1082	1981
Fire brick (insulating) ^a	1638–1650	2980–3000
Glass ^a	593–1427	1100–2600
Gold ^a	1063	1945
Iron ^a	1540	2802
Lead ^a	327	621
Magnesium (AZ31B alloy) ^b	627	1160
Nickel ^a	1455	2651
Paraffin ^a	54	129
Plastics (thermo)		
ABS ^d	88–125	190–257
Acrylic ^d	90–105	194–221
Nylon ^d	176–265	349–509
Polyethylene ^d	122–135	251–275
Polystyrene ^d	120–160	248–320
Polyvinylchloride ^d	75–105	167–221
Platinum ^a	1773	3224
Porcelain ^a	1550	2820
Pot metal ^c	300–400	562–752
Quartz (SiO ₂) ^a	1682–1700	3060–3090
Silver ^a	960	1760
Solder (tin) ^a	135–177	275–350
Steel (stainless) ^b	1427	2600
Steel (carbon) ^b	1516	2760
Tin ^a	232	449
Wax (paraffin) ^c	49–75	120–167
White pot metal ^c	300–400	562–752
Zinc ^a	375	707

^aFrom Baumeister, Avallone, and Baumeister III, *Mark's Standard Handbook for Mechanical Engineers*.

^bFrom Lide, ed., *Handbook of Chemistry and Physics*.

^cFrom NFPA *Fire Protection Guide to Hazardous Materials*.

^dFrom McGraw-Hill, *Plastics Handbook*.

^eFrom Gieck and Gieck, *Engineering Formulas*.

6.8.3 Alloying of Metals. The melting of certain metals may not always be caused by fire temperatures higher than the metals' stated melting point. It may be caused by alloying.

6.8.3.1 During a fire, a metal with a relatively low melting point may drip onto other metals that do not often melt in fires. This phenomenon can also occur when component parts of a heated object are in contact with each other. If the lower-melting-temperature metal can mix with the higher-melting-temperature metal, that mixture (alloy) will melt at a temperature less than the melting temperature of the higher-melting-temperature metal and in some cases less than that of either metal. Examples of relatively low-melting-temperature metals are aluminum, zinc, and lead. (See Table 6.8.1.1.) Metals that can be affected by alloying include copper and iron (steel). Copper alloying is often found, but iron (steel) alloying might be found in only a few cases of sustained fire.

6.8.3.1.1 Copper wiring and tubing or piping are often affected by alloying. Drips of low-melting-temperature metal may simply stick to the surface if the heating has been brief. With further heating, the low-melting-temperature metal will wet the surface and begin to mix. Aluminum can mix through the wire or wall of the tubing to give a yellow alloy at about 10 percent aluminum, but that is not often found. More commonly, the aluminum will mix in higher proportions and give a brittle silvery alloy. The surface of the spot of aluminum on the surface of the copper may appear gray, and the surface may be fairly dark near the copper-aluminum interface. Copper that has been alloyed with aluminum will be very brittle. For example, bending copper wire at the point of alloying will likely cause it to break there.

6.8.3.1.2 When zinc alloys with copper, a yellowish brass will result. Because zinc is less common in buildings than is aluminum, zinc alloying is not often encountered.

6.8.3.1.3 Alloys do not form readily with steel in fires. However, if aluminum or zinc is heated for a long time with a steel object, that object may develop pits or holes from alloying.

6.8.3.1.4 If fire evidence containing aluminum-alloyed copper is exposed to weather, the alloy may corrode away, leaving neat holes in tubing or blunt ends on wires. Those edges will not have the appearance of melting.

6.8.3.2 Alloying may be confirmed by metallurgical analysis, and the alloy may be identified. When metals with high melting temperatures are found to have melted due to alloying, it is not an indication that accelerants or unusually high temperatures were present in the fire.

6.9 Thermal Expansion and Deformation of Materials. Many materials change shape temporarily or permanently during fires. Nearly all common materials expand when heated. That expansion can affect the integrity of solid structures when they are made from different materials. If one material expands more than another material in a structure, the difference in expansion can cause the structure to fail.

6.9.1 The bending of steel beams and columns in a fire above about 538°C (1000°F) is caused by the progressive loss of strength of the steel. The more the load on any unrestrained steel object, the more will be the deformation for a given time and temperature. Bending is not a matter of melting. Thermal expansion can also be a factor in the bending of the beam, if the ends of the beam are restrained.

6.9.2 Plastered surfaces are also subject to thermal expansion. Locally heated portions of plaster walls and ceilings may expand and separate from their support lath. This breaking away of the plaster can produce lines or areas of heat demarcation displaying V patterns, U patterns, and truncated cone patterns.

6.10 Smoke and Soot. Fuels that contain carbon can form soot in their flames. Petroleum products and most plastics form soot most readily. When flames touch walls and ceilings, soot will commonly deposit. A specific deposit shows where there has been a particular fuel load. Soot also deposits on surfaces by settling. Such general soot deposits show merely that soot formed nearby but do not indicate the specific source.

6.10.1 Smoke and soot can collect on cooler surfaces of a building or its contents, often on upper parts of walls in rooms adjacent to the fire. Smoke, especially from smoldering fires, tends to condense on walls, windows, and other cooler surfaces. Because

deposits of pyrolysis products tend to be widely distributed, they do not help locate the exact point of origin.

6.10.2 Smoke condensates are shades of brown, whereas soot is black. Smoke condensates can be wet and sticky, thin or thick, or dried and resinous. These deposits, after drying, are not easily wiped off. Where there has been open flame, the deposits will likely be a mixture of soot and smoke. When smoke deposits are subsequently heated in a fire, the brown deposit may be changed in color, texture, and composition and may become darker or charred.

6.10.3 Some fires might produce only dry soot deposits that wipe easily from windows or other surfaces. Floors and top surfaces of contents often get a coating of soot that settles on them during and after sooty fires.

6.10.4 Both the carbonized smoke deposit and soot deposits can be burned off of windows or other surfaces by prolonged exposure to fire.

6.11 Clean Burn. Clean burn is a phenomenon that appears on noncombustible surfaces when the soot and smoke condensate that would normally be found adhering to the surface is burned off. This produces a clean area adjacent to areas darkened by products of combustion, as shown in Figure 6.11. Clean burn is produced most commonly by direct flame contact or intense radiated heat.



FIGURE 6.11 Clean Burn on Wall Surface.

6.11.1 Although they can be indicative of intense heating in an area, clean burn areas by themselves do not necessarily indicate areas of origin. The lines of demarcation between the clean burn and sooted areas may be used by the investigator to determine direction of fire spread or differences in intensity or time of burning.

6.11.2 The investigator should be careful not to confuse the clean burn area with spalling. Clean burn does not show the loss of surface material that is a characteristic of spalling.

6.12* Calcination.

6.12.1 General. The term *calcination* is used by fire investigators to describe the numerous changes that occur in gypsum wallboard surfaces during a fire. Calcination of a gypsum wallboard involves driving the free and chemically bound water out of the gypsum as well as other chemical and physical changes to the gypsum component itself. Calcination involves a chemical change of the gypsum to another mineral anhydrite. Calcined gypsum wallboard becomes less dense from heat exposure than original, pre-fire, non-calcined wallboard. The deeper the calcination into the wallboard the greater the total amount of fire exposure (heat flux and duration).

6.12.1.1 The gypsum wallboard has a measurable response to heat. First the paper surface will char and might also burn off. The gypsum on the side exposed to fire changes color from pyrolysis of the organic binder and destiffener in it. With further heating, the color change may extend all the way through, and the paper surface on the backside will char. The face exposed to fire will become whiter as the surface carbon is burned away (clean burn). When the entire thickness of wallboard has turned whitish, there will be no paper left on either face, and the gypsum will be chemically dehydrated and converted to a more crumbly, less dense solid. Such a wallboard might stay on a vertical wall but will frequently drop off of an overhead surface, particularly if it has absorbed significant quantities of extinguishment water or post fire precipitation. Fire-rated gypsum wallboard has mineral fibers or vermiculite particles embedded in the gypsum to preserve the strength of the wallboard during fire exposure. The fibers add strength to the wallboard even after it has been thoroughly calcined.

6.12.1.2 Color changes other than shades of gray may occur after gypsum wall surfaces are exposed to heat. The color itself has no significance to the fire investigator. However, the difference between colors may show lines of demarcation.

6.12.1.3 The relationship between the calcined and no calcined areas on gypsum wallboard can also display visible lines of demarcation on the surface. Depth of calcination measurements can be plotted to display patterns not visible on the surface.

6.12.2* General Indications of Calcination. The calcination of gypsum board is an indicator demonstrating the heat exposure sustained by the material. The areas of greatest heat exposure may be indicated by both visual appearance and the depth of calcination. The relative differences in color and depth of calcination from point to point may be used as an indicator to establish the areas of greater or lesser heat exposure due to all fire condition variables, such as area of origin, ventilation, and fuel load.

6.12.3 Depth of Calcination Diagram. A depth of calcination diagram can be produced in the same manner as that for depth of char. (See 6.5.3.1.)

6.12.4 Depth of Calcination Analysis. Relative depth of calcination can indicate differences in total heating of the fire-exposed gypsum wallboard with greater calcination depths indicating more heating than lesser depths. Deeper calcination readings indicate longer or more intense heating (heat flux), and the higher temperatures that those areas of the wallboard achieved during the fire.

6.12.4.1 Certain key variables affect the validity of depth of calcination analysis. These factors include the following:

- (1) Single versus multiple heat or fuel sources, creating the calcination patterns being measured, should be considered. Depth of calcination patterns may be useful in determining multiple heat or fire sources.
- (2) Comparisons of depth of calcination measurements should be made only from the same material. It should be recognized that gypsum wallboard comes in different thicknesses, uses different materials of construction, and does change with time. The investigator must carefully consider sections of walls or ceilings that may have had new sections inserted as a repair.
- (3) The finish of the gypsum wallboard (e.g., paint, wallpaper, stucco) should be considered when evaluating depth of calcination. The investigator should recognize that some of these finishes are combustible and may affect the patterns if they are ignited.
- (4) Measurements should be made in a consistent fashion to eliminate errors in this data collection, as discussed in 6.12.5.
- (5) Gypsum wallboard can be damaged during suppression, overhaul and post-fire by hose streams and standing water. Wetting of the calcined wallboard can soften the gypsum to the point where little or no reliable measurements can be made.

6.12.5 Measuring Depth of Calcination. The technique for measuring and analyzing depth of calcination can use a visual observation of cross sections or a probe survey.

6.12.5.1 The visual method requires careful removal of small, full-thickness, sections [minimum approximately 50 mm (2 in.) diameter] of walls or ceilings to observe and measure the thickness of the calcined layer.

6.12.5.2 The probe method requires that a survey of the depth of calcination be undertaken by inserting a small cross-section probe device, such as illustrated in Figure 6.12.5.2(a) and Figure 6.12.5.2(b), and recording the depth at which a relative difference in resistance of the calcined gypsum is felt. When using the probe method the investigator should conduct the survey at regular lateral and vertical grid intervals along the surface of the involved wallboard, usually in increments of 0.3 m (1 ft) or less. Care should be taken to use approximately the same insertion pressure for each measurement. Such surveys can be made on either wall or ceiling installations of wallboard.

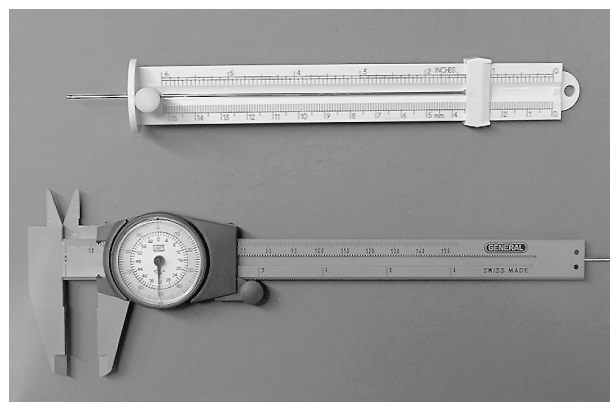


FIGURE 6.12.5.2(a) Two Instruments that Can be Used to Measure the Depth of Calcination.

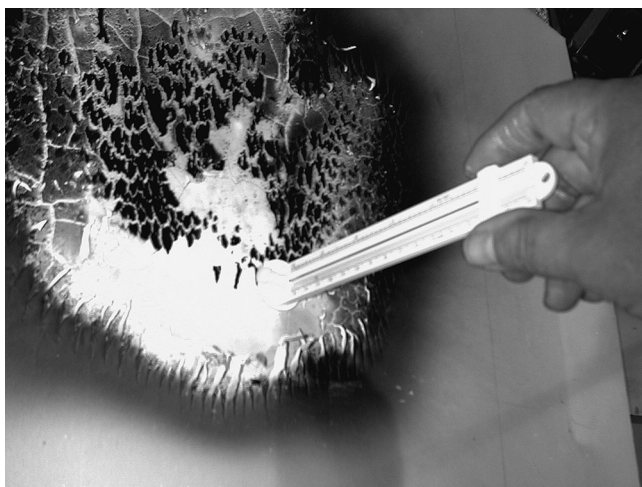


FIGURE 6.12.5.2(b) Measuring Depth of Calcination on a Piece of Gypsum Wallboard.

6.13 Window Glass. Many texts have related fire growth history or fuels present to the type of cracking and deposits that resulted on window glass. There are several variables that affect the condition of glass after fire, which include the type and thickness of glass, rate of heating, degree of insulation to the edges of the glass provided by the glazing method, degree of restraint provided by the window frame, history of the flame contact, and cooling history.

6.13.1* Breaking of Glass. If a pane of glass is mounted in a frame that protects the edges of the glass from radiated heat of fire, a temperature difference occurs between the unprotected portion of the glass and the protected edge. Experimental research estimates that a temperature difference of about 70°C (158°F) between the center of the pane of glass and the protected edge can cause cracks that start at the edge of the glass. The cracks appear as smooth, undulating lines that can spread and join together. Depending on the degree of cracking, the glass may or may not collapse from its frame.

6.13.1.1 If a pane of glass has no edge protection from radiated heat of fire, the glass will break at a higher temperature difference. Also, experimental research suggests that fewer cracks are formed, and the pane is more likely to stay whole.

6.13.1.2 Glass that has received an impact will have a characteristic “cobweb” pattern. The cracks will be in straight lines and numerous. The glass may have been broken before, after, or during the fire.

6.13.1.3 If flame suddenly contacts one side of a glass pane while the unexposed side is relatively cool, a stress can develop between the two faces and the glass can fracture between the faces.

6.13.1.4 *Crazing* is a term used in the fire investigation community to describe a complicated pattern of short cracks in glass. These cracks may be straight or crescent-shaped and may or may not extend through the thickness of the glass. Crazing has been theorized as being the result of very rapid heating of one side of the glass while the other side remains cool. There is no published research to confirm this theory. However, there is published research establishing that crazing can

be created by the rapid cooling of glass by the application of water spray in a hot environment.

6.13.1.5 Occasionally with small size panes, differential expansion between the exposed and unexposed faces may result in the pane popping out its frame.

6.13.1.6 The pressures alone developed by fires in buildings generally are not sufficient either to break glass windows or to force them from their frames. Pressures required to break ordinary window glass are in the order of 2.07 kPa to 6.90 kPa (0.3 psi to 1.0 psi), while pressures from fire are in the order of 0.014 kPa to 0.028 kPa (0.002 psi to 0.004 psi). If an overpressure has occurred — such as a deflagration, backdraft, or detonation — glass fragments from a window broken by the pressure will be found some distance from the window. For example, an overpressure of 10.3 kPa (1.5 psi) can cause fragments to travel as far as 30.3 m (100 ft).

6.13.1.7 The investigator is urged to be careful not to make conclusions from glass-breaking morphology alone. Both crazing and long, smooth, undulating cracks have been found in adjacent panes. The small craters or pits found in the surface of glass are believed to be the result of rapid cooling by water spray during fire suppression activities.

6.13.2* Tempered Glass.

6.13.2.1 Tempered glass, whether broken when heated by fire impact or when exploded, will break into many small cube-shaped pieces. Such glass fragments should not be confused with crazed glass. Tempered glass fragments are more regularly shaped than the complicated pattern of short cracks of crazing.

6.13.2.2 Tempered glass is commonly found in applications where safety from breakage is a factor, such as in shower stalls, patio doors, TV screens, motor vehicles, and in commercial and other public buildings.

6.13.3 Staining of Glass.

6.13.3.1 Glass fragments that are free of soot or condensates have likely been subjected to rapid heating, failure early in the fire, or flame contact. The proximity of the glass to the area of origin or heat source and ventilation are factors that can affect the degree of staining.

6.13.3.2 The presence of a thick, oily soot on glass, including hydrocarbon residues, has been interpreted as positive proof of the presence or use of liquid accelerant. Such staining can also result from the incomplete combustion of other fuels such as wood and plastics and cannot be exclusively interpreted as having come from an accelerant.

6.14* Collapsed Furniture Springs. The collapse of furniture springs may provide the investigator with various clues concerning the direction, duration, or intensity of the fire. However, the collapse of the springs cannot be used to indicate exposure to a specific type of heat source or ignition, such as smoldering ignition or the presence of an ignitable liquid. The results of laboratory testing indicate that the annealed springs, and the associated loss of tension (tensile strength), is a function of the application of heat. These tests reveal that short-term heating at high temperatures and long-term heating at moderate temperatures over 400°C (750°F) can result in the loss of tensile strength and in the collapse of the springs. Tests also reveal that the presence of a load or weight on the springs while they are being heated increases the loss of tension.

6.14.1 The value of analyzing the furniture springs is in comparing (comparative analysis) the differences in the springs to other areas of the mattress, cushion, frame, and so forth. Comparative analysis of the springs can assist the investigator in developing hypotheses concerning the relative exposure to a particular heat source. For example, if at one end of the cushion or mattress the springs have lost their tension and the other end has not, then hypotheses may be developed. The hypotheses should take into consideration other circumstances, effects (such as ventilation), and evidences at the scene concerning duration or intensity of the fire, area of origin, direction of heat travel, or relative proximity of the heat source. In any event, the portion with the loss of spring strength may indicate greater relative exposure to heat than those areas without the loss of strength.

6.14.2 Other circumstances and effects that may be considered along with analyzing the springs include the loss of mass and material or depth of char to the frame if constructed of wood. Similar analysis may also include color changes, possibly indicating intensity, in metal frames.

6.14.3 Still other effects for comparative analysis include consideration of the covering material of the springs. The absence of material may indicate a portion closer to the source of heat, while the presence of materials may indicate an area more remote from the heat source.

6.14.4 The investigator should also consider the condition of the springs prior to the fire.

6.15 Location of Objects. Certain types of patterns can be used to locate the positions of objects as they were during a fire.

6.15.1 Heat Shadowing. Heat shadowing results from an object blocking the travel of radiated heat, convected heat, or direct flame contact from its source to the material on which the pattern is produced. Conducted heat, however, does not produce heat shadowing.

6.15.1.1 The object blocking the travel of the heat energy may be a solid or liquid, combustible or noncombustible. Any object that absorbs or reflects the heat energy may cause the production of a pattern on the material it protects.

6.15.1.2 Heat shadowing can change, mask, or prohibit the production of identifiable lines of demarcation that may have appeared on that material. Patterns produced by the heat shadowing, may, however, assist the fire investigator in the process of reconstruction during origin determination.

6.15.2 Protected Areas. Closely related in appearance to the resulting pattern of heat shadowing is a protected area. A protected area results from an object preventing the products of combustion from depositing on the material that the object protects, or prevents the protected material from burning.

6.15.2.1 The object preventing the depositing of products of combustion may be a solid or liquid, combustible or noncombustible. Any object that prevents the settling of the products of combustion, or prevents the burning of the material, may prevent the development of a pattern on the material it protects. Figure 6.15.2.1 provides an example.

6.15.2.2 Patterns produced by protected areas may, however, assist the fire investigator in the process of fire scene reconstruction during the origin determination by indicating the location of objects in their pre-fire locations. (See Section 17.7.)

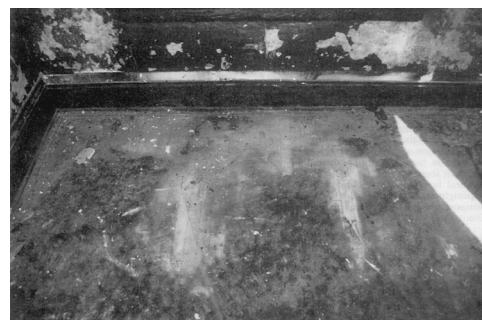


FIGURE 6.15.2.1 Photograph on Top, Showing Protected Area; Photograph at Bottom, Showing How the Chair Was Positioned During the Fire.

6.16 Locations of Patterns.

6.16.1 General. Fire patterns may be found on any surface that has been exposed to the effects of the fire or its by-products. These surfaces include interior surfaces, external surfaces and structural members, and outside exposures surrounding the fire scene.

6.16.1.1 Interior surfaces commonly include walls, floors, ceilings, doors, windows, furnishings, appliances, machinery, equipment, other contents, personal property, confined spaces, attics, closets, and the insides of walls.

6.16.1.2 Exterior surfaces commonly include walls, eaves, roofs, doors, windows, gutters and downspouts, utilities (e.g., meters, service drops), porches, and decks.

6.16.1.3 Outside exposures commonly include outbuildings, adjacent structures, trees and vegetation, utilities (e.g., poles, lines, meters, fuel storage tanks, and transformers), vehicles, and other objects.

6.16.2 Walls, Ceilings, and Floors. Fire patterns are often found on walls, ceilings, and floors. As the hot gas zone and the flame zone of the fire plume encounter these obstructions, patterns are produced that investigators may use to trace a fire's origin. (See Section 5.5 through Section 5.6.)

6.16.2.1 Walls. Patterns that are displayed on walls are the most noticeable. The patterns may appear as lines of demarcation on the surfaces of the walls or may be manifested as deeper burning. Once the actual surface coverings of the walls are destroyed by burning, the underlying support studs can also display various patterns. These patterns are most commonly V patterns, U patterns, clean burn, and spalling.

6.16.2.2 Ceilings. The investigator should not ignore patterns that occur on ceilings or the underside of such horizontal surfaces as tabletops or shelves. The buoyant nature of fire gases concentrate the heat energy at horizontal surfaces above the heat source. Therefore, the patterns that are created on the underside of such horizontal surfaces can be indicators of locations of heat sources. Although areas immediately over the source of heat and flame will generally experience heating before the other areas to which the fire spreads, circumstances can occur where fuel at the origin burns out quickly, but the resulting fire spreads to an area where a larger supply of fuel can ignite and burn for a longer period of time. This process can cause more damage to the ceiling in that area than in the area immediately over the origin.

6.16.2.2.1 These horizontal patterns are roughly circular. Portions of circular patterns are often found where walls meet ceilings or shelves and at the edges of tabletops and shelves.

6.16.2.2.2 The investigator should determine the approximate center of the circular pattern and investigate below this center point for a heat source.

6.16.2.3 Damaged Inside Walls and Ceilings. Fire damage to combustible construction elements behind walls and ceilings has sometimes been interpreted to mean that the fire started within the wall or ceiling. This interpretation may not always be correct.

6.16.2.3.1 It is possible for the heat of a fire to be conducted through a wall or ceiling surface and to ignite wooden structural members within the wall or ceiling. The ability of the surface to withstand the passage of heat over time is called its finish rating.

6.16.2.3.2 While the finish rating of a surface material only represents the performance of the material in a specific laboratory test (e.g., UL 263, *Standard for Safety Fire Tests of Building Construction and Materials*) and not necessarily the actual performance of the material in a real fire, knowledge of the finish ratings concept can be of value to an investigator's overall fire spread analysis.

6.16.2.3.3 This heat transfer process can be observed by the charring of the wooden structural element covered by the protective membrane, shown in Figure 6.16.2.3.3.

6.16.2.4* Floors. Floors should not be ignored by the investigator. Should flashover occur, the transition to flashover is associated with a radiant heat flux that exceeds approximately 20 kW/m^2 (2 W/cm^2) at a mean floor level, typical value for the radiant ignition of common combustible construction materials. Postflashover or full room involvement conditions can typically produce fluxes in excess of 170 kW/m^2 and may modify or obliterate pre-existing patterns.

6.16.2.4.1 Since 1970, carpeting and rugs manufactured or imported to be sold in the United States have been resistant to ignition or fire spread. Typically, cigarettes or matches dropped on carpets will not set them on fire. ASTM D 2859, *Standard Test Method for Flammability of Finished Textile Floor Covering Materials* (Methanamine Pill Test), describes the test used to measure the ignition characteristics of carpeting from a small ignition source. Carpeting and rugs passing the pill test will have very limited ability to spread flame or char in a horizontal direction when exposed to small ignition sources such as a cigarette or match.

6.16.2.4.2 Fire will not spread across a room on the surface of these carpets or rugs without external help, such as from a fire

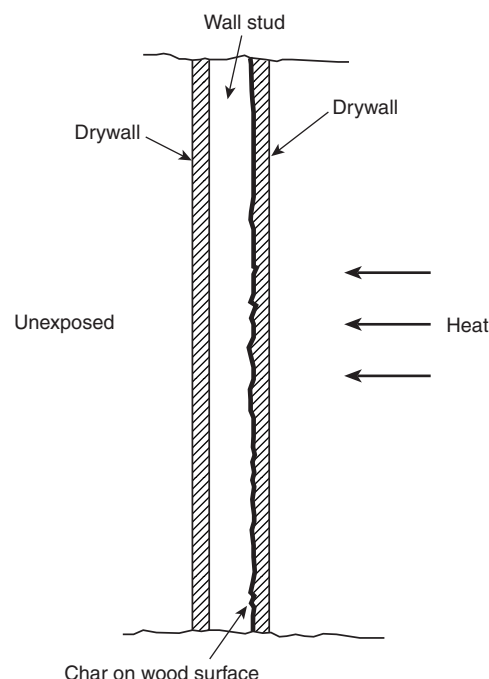


FIGURE 6.16.2.3.3 Charring of Wooden Structural Elements by Heat Conduction Through Wall Surface Material.

external to the carpet, in which case the fire spread on the carpet will terminate at a point where the radiant energy from the exposing fire is less than the minimum needed to support flame spread on the carpet (critical radiant flux). Carpet is expected to burn when exposed to flashover conditions since the radiant heat flux that produces flashover exceeds the carpet's critical radiant flux.

6.16.2.4.3 Burning between seams or cracks of floorboards or around door thresholds, sills, and baseboards may or may not indicate the presence of an ignitable liquid. If the presence of an ignitable liquid is suspected, samples should be collected and laboratory tests should be used to verify their presence. (See Section 16.5.)

6.16.2.4.4 Burning from full room involvement can also produce burning of floors or around door thresholds, sills, and baseboards due to radiation, the presence of hot combustible fire gases, or air sources (ventilation) provided by the gaps in construction. These gaps can provide sufficient air for combustion of, on, or near floors (see 6.2.3). If the investigator develops a hypothesis that charring in these areas resulted from these effects, samples can also be taken to indicate an ignitable liquid was not present.

6.16.2.4.5 Like other areas of low burning, holes burned in floors can be produced by the presence of ignitable liquids, glowing embers, or the effects of flashover or full room involvement (see 6.17.7.2). The collection of samples and laboratory verification of the presence or absence of ignitable liquid residues may assist the investigator in developing hypotheses and drawing conclusions concerning the development of the holes.

6.16.2.4.6 Fire-damaged vinyl floor tiles often exhibit curled tile edges exposing the floor beneath. The curling of tile edges can frequently be seen in nonfire situations and is due to natural shrinkage and curling of the tiles from loss of plasticizer. In

a fire, the presence of radiation from a hot gas layer will produce the same patterns. This pattern can also be caused by ignitable liquids. Analysis for their presence may be difficult due to the presence of hydrocarbons in tile adhesives.

6.16.2.4.7 Unburned areas present after a fire can reveal the location of content items that protected the floor or floor covering from radiation damage or smoke staining.

6.16.3 Outside Surfaces. External surfaces of structures can also display fire patterns. In addition to the regular patterns, both vertical and horizontal external surfaces can display burn-through. All other variables being equal, these burn-through areas can identify areas of intense or long-duration burning.

6.16.4 Building Contents. The sides and tops of building contents can form the bounding surfaces for fire patterns as well. Any patterns that can be produced on walls, ceilings, and floors can also be produced on the sides, tops, and undersides of chairs, tables, shelves, furniture, appliances, equipment, machinery, or any other contents. The patterns will be similar in shape but may only display portions of patterns because of their size.

6.16.5 Elevation. Patterns can also be used to determine the height at which burning may have begun within the structure.

6.16.5.1 Low Burn Patterns. It is common for the lowest portions of fire patterns to be closer to their heat sources. In general, fires tend to burn upward and outward from their origins. Fire plumes made up of the hot gases and airborne products of combustion are expanding and less dense than the surrounding air and are therefore buoyant. The growth in volume and buoyancy causes these heated products to rise and spread. The investigator should identify these areas of low burning and be cognizant of their possible proximity to a point of origin. The investigator should remember that in a compartment where the fire has transitioned through flashover to the fully developed stage, burning down to floor level is not necessarily indicative of an origin at the floor level.

6.16.5.2 Fall Down (Drop Down). The investigator should keep in mind that during the progress of a fire, burning debris often falls to lower levels and then burns upward from there. This occurrence is known as *fall down* or *drop down*. Fall down can ignite other combustible materials, producing low burn patterns that may be confused with the area of fire origin.

6.17* Pattern Geometry.

6.17.1 General.

6.17.1.1 Various patterns having distinctive geometry or shape are created by the effects of fire and smoke exposure on building materials and contents. In order to identify them for discussion and analysis, they have been described in the field by terms that are indicative of their shapes. While these terms generally do not relate to the manner in which the pattern was formed, the descriptive nature of the terminology makes the patterns easy to recognize. The discussion that follows will refer to patterns by their common names and provide some information about how they were formed and their interpretation. Additional information can be found in Section 6.2.

6.17.1.2 Since the interpretation of all possible fire patterns cannot be traced directly to scientific research, the user of this guide is cautioned that alternative interpretations of a given pattern are possible. In addition, patterns other than those described may be formed. Separate scientific research studies have begun to delve into the formation and interpretation of fire patterns. The two studies examined both pattern geometries and causal factors.

6.17.2 V Patterns on Vertical Surfaces. The appearance of the V-shaped pattern is created by flames, convective or radiated heat from hot fire gases, and smoke within the fire plume. (See 6.2.2.) The V pattern often appears as lines of demarcation (see 6.3.1) defining the borders of the fire plume and less heated areas outside the plume. An example is shown in Figure 6.17.2.



FIGURE 6.17.2 Typical V Pattern Showing Wall and Wood Stud Damage.

6.17.2.1 The angle of the V-shaped pattern is dependent on several variables (see 6.2.2), including the following:

- (1) The heat release rate (HRR) and geometry of the fuel
- (2) The effects of ventilation
- (3) The ignitability of the vertical surface on which the pattern appears and combustibility of the vertical surface on which it appears
- (4) The presence of interceding horizontal surfaces such as ceilings, shelves, table tops, or the overhanging construction on the exterior of a building (See 6.2.2.)

6.17.2.2 The angle of the borders of the V pattern does not indicate the speed of fire growth; that is, a wide V does not indicate a slowly growing fire, or a narrow V does not indicate a rapidly growing fire.

6.17.3 Inverted Cone Patterns. Inverted cones are commonly caused by the vertical flame plumes of the burning volatile fuels not reaching the ceiling.

6.17.3.1 Interpretation of Inverted Cone Patterns. Inverted cone patterns are manifestations of relatively short-lived fires that do not fully evolve into floor-to-ceiling flame plumes or flame plumes that are not vertically restricted by ceilings. Because they often appear on noncombustible surfaces, they do not always readily spread to nearby combustibles. For this reason, many investigators have taken to inferring from these patterns that the fires that caused them were fast burning.

6.17.3.1.1 The correct analysis of such patterns is that the burning was of relatively short duration rather than any relationship to the rate of heat release. That short duration occurred because additional fuel sources did not become involved before the initial fuel was consumed.

6.17.3.1.2 Inverted cone patterns have been interpreted as proof of ignitable liquid fires, but any fuel source (leaking fuel gas, Class A fuels, etc.) that produces flame zones that do not become vertically restricted by a horizontal surface, such as a ceiling or furniture, can produce inverted cone patterns.

6.17.3.2 Inverted Cone Patterns with Natural Gas. Leaking natural gas is prone to the production of inverted cone patterns. This is especially true in the case of natural gas if the leakage occurs from below floor level and escapes above at the intersection of the floor and a wall, as in Figure 6.17.3.2. The subsequent burning often does not reach the ceiling and is manifested in the production of the characteristic triangular inverted cone pattern shape.

6.17.4 Hourglass Patterns. The plume of hot gases above a fire is composed of a hot gas zone shaped like a V and a flame zone at its base. The flame zone is shaped like an inverted V. When the hot gas zone is truncated by a vertical plane surface, the typical V pattern is formed. If the fire itself is very close to or in contact with the vertical surface, the resulting pattern will show the effects of both the hot gas zone and the flame zone together as a large V above an inverted V. The inverted V is generally smaller and may exhibit more intense burning or clean burn. The overall pattern that results is called an *hourglass*. (See 6.2.2.)

6.17.5 U-Shaped Patterns. U patterns are similar to the more sharply angled V patterns but display gently curved lines of demarcation and curved rather than angled lower vertices. (See Figure 6.17.5.) U-shaped patterns are created by the effects of radiant heat energy on the vertical surfaces more distant from the same heat source than surfaces displaying sharp V patterns. The lowest lines of demarcation of the U patterns are generally higher than the lowest lines of demarcation of corresponding V patterns that are closer to the fire source.

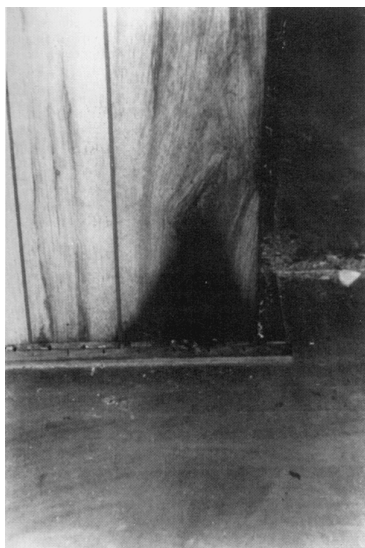


FIGURE 6.17.3.2 Inverted Cone Pattern Fueled by a Natural Gas Leak Below the Floor Level.

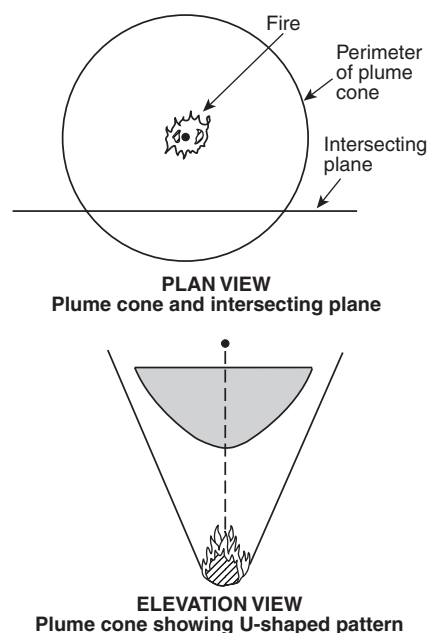


FIGURE 6.17.5 Development of U-Shaped Pattern.

6.17.5.1 U patterns are analyzed similarly to V patterns, with the additional aspect of noting the relationship between the height of the vertex of the U pattern as compared to the height of the vertex of the corresponding V patterns.

6.17.5.2 If there are two patterns from the same heat source, the one with the lower vertex will be closer to that heat source.

6.17.6 Truncated Cone Patterns. Truncated cone patterns, also called truncated plumes, are three-dimensional fire patterns displayed on both horizontal and vertical surfaces. (See Figure 6.17.6.) It is the interception or truncating of the natural cone-shaped or hourglass-shaped effects of the fire plume by these vertical and horizontal surfaces that causes the patterns to be displayed. Many fire movement patterns, such as V patterns, U patterns, circular patterns, and "pointer or arrow" patterns, are related directly to the three-dimensional "cone" effect of the heat energy created by a fire.

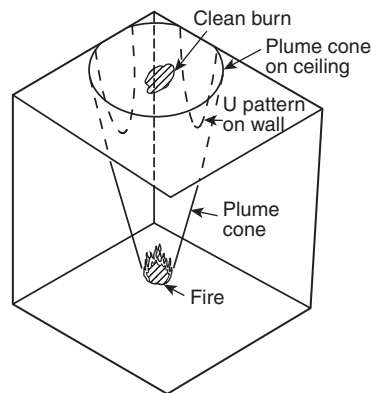


FIGURE 6.17.6 Truncated Cone Pattern.

6.17.6.1 The cone-shaped dispersion of heat is caused by the natural expansion of the fire plume as it rises and the horizontal spread of heat energy when the fire plume encounters an obstruction to its vertical movement, such as the ceiling of a room. Thermal damage to a ceiling will generally extend beyond the circular area attributed to a “truncated cone.” The truncated cone pattern combines two-dimensional patterns such as V-shaped patterns, pointers and arrows, and U-shaped patterns on vertical surfaces, with the circular patterns displayed on ceilings and other horizontal surfaces.

6.17.6.2 The combination of more than one two-dimensional pattern on perpendicular vertical and horizontal surfaces gives the truncated cone pattern its three-dimensional character.

6.17.6.3 A theoretical demonstration of the truncated cone pattern is when the four vertical walls of a room each display varied V or U patterns, as well as circular or portions of circular patterns appearing on the ceiling. Corresponding patterns may also be discernible on the furnishings in the room.

6.17.7 Pointer and Arrow Patterns. These fire patterns are commonly displayed on a series of combustible elements such as wooden studs or furring strips of walls whose surface sheathing has been destroyed by fire or was nonexistent. The progress and direction of fire spread along a wall can often be identified and traced back toward its source by an examination of the relative heights and burned-away shapes of the wall studs left standing after a fire. In general, shorter and more severely charred studs will be closer to a source of fire than taller studs. The heights of the remaining studs increase as distance from a source of fire increases. The difference in height and severity of charring will be noted on the studs, as shown in Figure 6.17.7.

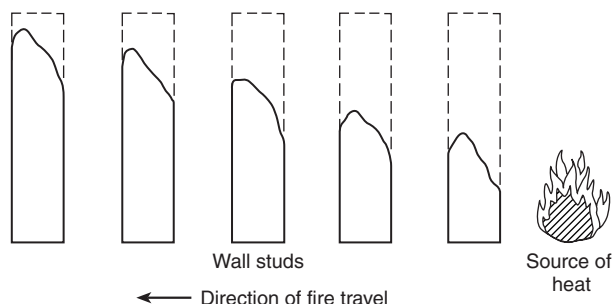


FIGURE 6.17.7 Wood Wall Studs Showing Decreasing Damage as Distance from Fire Increases.

6.17.7.1 The shape of the studs' cross section will tend to produce “arrows” pointing back toward the general area of the source of heat. This is caused by the burning off of the sharp angles of the edges of the studs on the sides toward the heat source that produces them, as shown in Figure 6.17.7.1.

6.17.7.2 More severe charring can be expected on the side of the stud closest to the heat source.

6.17.8 Circular-Shaped Patterns. Patterns that are generally circular in shape are common at fire scenes. These patterns are never truly circular unless they represent areas that have been protected from burning by circular items, such as wastebaskets or the bottoms of furniture items.

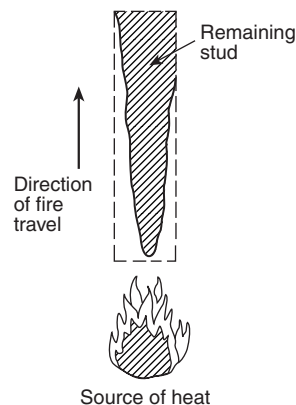


FIGURE 6.17.7.1 Cross Section of Wood Wall Stud Pointing Toward Fire.

6.17.8.1 Bottoms of Horizontal Surfaces. Patterns on the underside of horizontal surfaces, such as ceilings, tabletops, and shelves, can appear in roughly circular shapes. The more centralized the heat source, the more circular or nearly circular the patterns may appear.

6.17.8.1.1 Portions of circular patterns can appear on the underside of surfaces that partially block the heated gases or fire plumes. This appearance can occur when the edge of the surface receiving the pattern does not extend far enough to show the entire circular pattern or when the edge of the surface is adjacent to a wall.

6.17.8.1.2 Within the circular pattern, the center may show more heat degradation, such as deeper charring. By locating the center of the circular pattern, the investigator may find a valuable clue to the source of greatest heating, immediately below.

6.17.8.2 Irregular Patterns. Irregular, curved, or “pool-shaped” patterns on floors and floor coverings should not be identified as resulting from ignitable liquids on the basis of observation of the shape alone. In cases of full room involvement, patterns similar in appearance to ignitable liquid burn patterns can be produced when no ignitable liquid is present.

6.17.8.2.1 The lines of demarcation between the damaged and undamaged areas of irregular patterns range from sharp edges to smooth gradations depending on the properties of the material and the intensity of heat exposure. Denser materials like oak flooring will generally show sharper lines of demarcation than thermoplastic (e.g., nylon) carpet. The absence of a carpet pad often leads to sharper lines.

6.17.8.2.2 These patterns are common in situations of post-flashover conditions, long extinguishing times, or building collapse. These patterns may result from the effects of hot gases, flaming and smoldering debris, melted plastics, or ignitable liquids. If the presence of ignitable liquids is suspected, supporting evidence such as the use of a combustible gas indicator, chemical analysis of debris for residues, or the presence of liquid containers should be sought. It should be noted that many plastic materials release hydrocarbon fumes when they pyrolyze or burn. These fumes may have an odor similar to that of petroleum products and can be detected by combustible gas indicators when no ignitable liquid accelerant has been used. A “positive” reading should prompt further investigation

and the collection of samples for more detailed chemical analysis. It should be noted that pyrolysis products, including hydrocarbons, can be detected in gas chromatographic analysis of fire debris in the absence of the use of accelerants. It can be helpful for the laboratory, when analyzing carpet debris, to burn a portion of the comparison sample and run a gas chromatographic analysis on both. By comparing the results of the burned and unburned comparison samples with those from the fire debris sample, it may be possible to determine whether or not hydrocarbon residues in the debris sample were products of pyrolysis or residue of an accelerant. In any situation where the presence of ignitable liquids is suggested, the effects of flashover, airflow, hot gases, melted plastic, and building collapse should be considered.

6.17.8.2.3 When overall fire damage is limited, however, and small, or isolated irregular patterns are found, the presence of ignitable liquids may be more likely, although the use of supporting evidence is still recommended. [See Figure 6.17.8.2.3(a) and Figure 6.17.8.2.3(b).] Even in these cases, radiant heating may cause the production of patterns on some surfaces that can be misinterpreted as liquid burn patterns. [See Figure 6.17.8.2.3(c).]



FIGURE 6.17.8.2.3(a) Irregular Burn Patterns on a Floor of a Room Burned in a Test Fire in Which No Ignitable Liquids Were Used.



FIGURE 6.17.8.2.3(b) Irregularly Shaped Pattern on Floor Carpeting Resulting from Poured Ignitable Liquid; Burned Match Can be Seen at Lower Left.



FIGURE 6.17.8.2.3(c) “Pool-Shaped” Burn Pattern Produced by a Cardboard Box Burning on an Oak Parquet Floor.

6.17.8.2.4 Pooled ignitable liquids that soak into flooring or floor covering materials as well as melted plastic can produce irregular patterns. These patterns can also be produced by localized heating or fallen fire debris.

6.17.8.2.5 The term *pour pattern* implies that a liquid has been poured or otherwise distributed, and therefore, is demonstrative of an intentional act. Because fire patterns resulting from burning ignitable liquids are not visually unique, the use of the term *pour pattern* and reference to the nature of the pattern should be avoided. The correct term for this fire pattern is an *irregularly shaped fire pattern*. The presence of an ignitable liquid should be confirmed by laboratory analysis. The determination of the nature of an irregular pattern should not be made by visual interpretation of the pattern alone. See Figure 6.17.8.2.5(a) and Figure 6.17.8.2.5(b) for examples of fire patterns on floors.

6.17.8.3 Doughnut-Shaped Patterns. A distinct doughnut-shaped pattern, where a roughly ring-shaped burn area surrounds a less burned area, may result from an ignitable liquid. When a liquid causes this pattern, shown in Figure 6.17.8.3, it is due to the effects of the liquid cooling the center of the pool as it burns, while flames at the perimeter of the doughnut produce charring of the floor or floor covering. When this condition is found, further examination should be conducted as supporting evidence to the presence of ignitable liquids.



FIGURE 6.17.8.2.5(a) Fire Patterns on Floor Resulting from Fully Developed (Post-Flashover) Fire in Full Scale Test Burn of Residential Structure. Floor Was Carpeted and Room Had Typical Residential Furnishings; No Ignitable Liquids Were Present.



FIGURE 6.17.8.2.5(b) Fire Patterns on Linoleum Floor Resulting from Fully Developed (Post-Flashover) Fire in Full-scale Test Burn of Residential Structure; No Ignitable Liquids Were Present.

6.17.9 Liquids Versus Melted Solids. Many modern plastic materials will burn. They react to heating by first liquefying, and then, when they burn as liquids, they produce irregularly shaped or circular patterns. When found in unexpected places, such patterns can be erroneously identified as flammable or combustible liquid patterns and associated with an incendiary fire cause.

6.17.9.1 Often the association of an ignitable liquid with a particular irregular pattern has been ruled out on the presumption that ignitable liquid vapors will always cause explosions. This is not the case. The expansion of the products of combustion from flammable liquids will cause explosions only if they are sufficiently confined to damage the structure or confining vessel and have the proper fuel-air mixture. (See 5.1.2.2 and 21.8.2.1.) Whether an explosion occurs is a function of the quantity of vaporized fuel present at the time of ignition, the presence of venting openings in the structure, and the strength and construction of the confining structure.

6.17.9.2 The investigator should be careful to identify properly the initial fuel source for any irregularly shaped or circular patterns.



FIGURE 6.17.8.3 Doughnut-Shaped Fire Pattern on a Carpeted Floor.

6.17.10 Commercial Fuel Gas Patterns. The burning of the common commercial fuel gases, natural gas and liquefied petroleum (LP) gases, can provide distinctive fire patterns. Distinctive localized burning between ceiling joists, between interior vertical wall studs, and in the corners of ceilings of rooms is quite common and a good indicator of the presence of natural gas.

6.17.10.1 Natural gas has a vapor density of 0.65; therefore, it is lighter than air and will rise when released. This property of natural gas will create gas pockets in the upper areas of rooms and structures.

6.17.10.2 The LP-Gases, being heavier than air (with vapor densities of about 1.5 for propane and 2.0 for butane), also tend to pocket within a structure, though at low levels. However, the buoyant nature of their products of combustion when ignited prevents them from producing similar pocketing burn patterns as natural gas.

6.17.11 Saddle Burns. *Saddle burns* are distinctive U- or saddle-shaped patterns that are sometimes found on the top edges of floor joists. They are caused by fire burning downward through the floor above the affected joist. Saddle burns display deep charring, and the fire patterns are highly localized and gently curved. These patterns are often created by the burning of liquid fuels, (not necessarily ignitable liquids). They also may be created by radiant heat from a burning material in close proximity to the floor (e.g., sofa). Ventilation caused by floor openings may also contribute to the development of these patterns, shown in Figure 6.17.11.

6.18 Linear Patterns. Patterns that have overall linear or elongated shapes can be called linear patterns. They usually appear on horizontal surfaces.

6.18.1 Trailers. In many incendiary fires, when fuels are intentionally distributed or "trailed" from one area to another, the elongated patterns may be visible. Such fire patterns, known as *trailers*, can be found along floors to connect separate fire sets, or up stairways to move fires from one floor or level within a structure to another, as shown in Figure 6.18.1. Fuels used for trailers may be ignitable liquids, solids, or combinations of these.