THE APPLICATION OF FIRE DYNAMICS TO FIRE FORENSICS

by

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Abstract

Fire investigative methodologies were researched and analyzed resulting in the development of an organizational tool to be used for conducting fire investigations. The tool, or field-guide, was designed to aid the investigator in processing structural fire scenes. The tool accomplishes this by providing, 1) thirteen forms for properly documenting the scene, 2) flowcharts which can enhance the investigator's intuition for the fire's growth rate and spread, and 3) basic engineering correlations which can be used to help validate hypotheses the investigator may develop. By employing these methods, the field-guide can be effectively used to lead an investigator through the entire investigation process - from data collection, to the formulation of hypotheses, and ultimately, to quantitative validation.

Preface/Disclaimer

The following thesis was written as part of the author's requirements for the Degree of Master of Science in Fire Protection Engineering at Worcester Polytechnic Institute. Neither the author nor Worcester Polytechnic Institute can guarantee that the concepts expressed within the analysis will be relevant and appropriate for all investigations. The investigator must use professional judgement as to the applicability and accuracy of the methods presented in this thesis.

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Nomenclature/Abbreviations

a	Width of parallel rectangle (m)
α	Fire growth factor (kW/s^2)
A_f	Horizontal burning area of the fuel (m^2)
A_{fl}	Area of flame shape (m^2)
A_o	Area of the ventilation opening (m^2)
A_T	Total area of the compartment enclosing surfaces (m^2)
A_w	Effective area of ventilation (m^2)
ASTM	American Society for Testing and Materials
ATF	Bureau of Alcohol, Tobacco and Firearms
b	Length of parallel rectangle (m)
BFRL	Building and Fire Research Laboratory (NIST)
β	Mean-beam-length corrector
c	Perpendicular distance between parallel element and target (m)
c_c	Specific heat of the compartment surface material (kJ/kg K)
c_p	Specific heat of air (kJ/kg K)
CFEI	Certified Fire and Explosion Investigator
CFI	Certified Fire Investigator
δ	Thickness of compartment surface (m)
D_f	Diameter of the flame (m)
D	$0.188 + 0.313\, r/H$
dA	Differential receiver element
DOB	Date of birth
Eq.	Equation
F	Configuration factor from target to flame
FBI	Federal Bureau of Investigation

FEMA	Federal Emergency Management Agency
FF	Firefighter
FM	Factory Mutual Corporation
g	Acceleration due to gravity (9.81 m/s^2)
h_k	Effective heat transfer coefficient (kW/m^2 K)
ΔH_c	Heat of combustion (kJ/kg)
H	Height (m)
H_o	Height of the ventilation opening (m)
HRR	Heat Release Rate (kW)
IAAI	International Association of Arson Investigators
k	Extinction-absorption coefficient of the flame (-)
k_c	Thermal conductivity of the compartment surface (kW/m K)
K_m	Absorption coefficient (m^{-1})
L	Mean flame height (m)
$\dot{m}_{air}$	Mass flow rate of air into the compartment (kg/s)
$\dot{m}_b$	Mass loss rate, burning rate (kg/s)
$\dot{m}_g$	Mass loss rate out of the compartment (kg/s)
$\dot{m}_i$	Mass entrainment rate into the compartment (kg/s)
$\dot{m}''$	Mass loss rate per unit area (kg/m^2s)
$\dot{m}''_\infty$	Mass loss rate per unit area for very large pool fires (kg/m^2s)
M	Percent moisture content (%)
NAFI	National Association of Fire Investigators
NIST	National Institute of Standards and Technology
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
σ	Stefan-Boltzmann constant (5.6696×10^{-8} W/m^2K^4)
S_g	Dry specific gravity (-)
ρ_c	Density of the compartment surface (kg/m^3)

ρ_a	Density of air (kg/m^3)
$\dot{q}''$	Radiative heat flux received by the target (kW/m^2)
$\dot{Q}$	Instantaneous heat release rate (kW)
$\dot{Q}_{FO}$	Heat release rate necessary for flashover (kW)
$\dot{Q}_{VL}$	Ventilation-limited heat release rate (kW)
$\dot{Q}''$	Fire load density (kJ/m^2)
r_p	Protection radius of smoke/heat detectors or sprinklers (m)
r	Radial distance from the plume centerline to the target (m)
R	Charring rate (in/min)
R_o	Distance from radiation source centerline to the target (m)
Rec'd.	Received
Rev.	Revision
RTI	Response time index ($m^{1/2}s^{1/2}$)
S	Pathlength (m)
S_c	Floor area of the compartment (m^2)
S_p	Spacing of smoke/heat detectors or sprinklers (m)
Susp.	Suspected
t	Time (s)
t_0	Start time (s)
t_p	Thermal penetration time (s)
t^*_{2f},	Nondimensional transport time (-)
t^*_2.	Reduced time (-)
ΔT	Change in temperature (K)
ΔT_g	Upper layer gas temperature rise above ambient (K)
ΔT^*_2	Change in reduced gas temperature (-)
T	Temperature (K)
T_a	Ambient temperature (K)
T_d	Temperature of the detector (K)

T_f	Temperature of the flame or fuel burning (K)
T_g	Upper layer gas temperature (K)
T_{MAX}	Ceiling jet maximum temperature (K)
u	Instantaneous velocity of the fire gases (m/s)
u_{MAX}	Maximum ceiling jet velocity (m/s)
u^*_2	Reduced gas velocity (-)
UL	Underwriters Laboratories
USFA	United States Fire Administration
Vent.	Ventilation
χ_r	Radiative fraction of total energy released (-)
X_c	Combustion efficiency (typically 0.7 - 0.8)
X	*a/c*
y	z/H, dimensionless height
Y	Defined by Equation 5.17 for calculating sprinkler activation
z	Height of the lower gas layer (m)

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Chapter 1: Introduction

1.1 Problem Statement

The objective of this thesis is to illustrate the roles that both fire science and fire protection engineering can play in the investigation of fires. The link between fire investigation and fire science is strengthening due to recent attention by fire investigators and scientists, although it is still weak[1]. One illustrative example can be found by examining texts on the subject of fire investigation and noting the near absence of scientific tools[2]. Another example, perhaps more difficult to perceive, is the failure of the investigative community in general to properly document specific, detailed technical information relating to the fire building and the fire's growth, development, and spread[1]. An important aspect of this work is to not only evaluate the present state of fire investigative procedures with respect to the application of new technologies and scientifically substantiated fire dynamics principles, but also to present a new tool to ensure the proper documentation of relevant technical information.

First and foremost, the author identifies many deficiencies commonly used in fire investigations and suggests ways to minimize or eliminate them. Deficiencies such as the proliferation of scientifically unsubstantiated myths regarding fire patterns and behavior, the lack of a systematic and organized approach to investigation reporting, and the lack of communication and technology transfer between the fields of fire investigation and fire science will be addressed [1,2,3,4].

Second, the thesis includes a new three part investigative reporting tool or field-guide. The guide was developed to aid an investigator in the recording of as much relevant, site-specific information as possible early-on in the investigation, before critical observations and/or evidence are further damaged or lost. It is believed that such a tool, if implemented, could establish a new cooperative relationship between fire investigators and fire scientists. The tool will aid the on-site data collection efforts routinely done by fire investigators and the specialized post-incident fire reconstruction work being more and more frequently performed by fire scientists and fire protection engineers.

This approach is a step towards introducing fire investigators to the basic computational engineering tools used by engineers and scientists for simulating rates of fire growth, flashover, smoke spread, time to detection/alarm, tenability limits, etc. More importantly, the approach also points out the limitations of these engineering tools. This is needed to ensure their proper use and interpretation

1.2 Scope

In part, this thesis will evaluate the present state of fire investigation technology in the United States and the methods of practice currently being used by fire investigators. This was done by examining the following:

a) *Fire Investigation Reports* - fifty fire investigation reports from various agencies, government associations, fire departments, insurance companies, and/or private organizations was compiled. These reports were examined for thoroughness of details, clarity of conclusions, and to ascertain whether fire dynamics principles had been applied during the investigation and their role in determining relevant circumstances that may have contributed in some way to the development or consequences of the fire. [see References for list of reports]

b) *Fire Investigation Methodologies* - Guidelines, standards, texts and/or educational methodologies available to fire investigators were researched for the purpose of understanding the role that both fire science and fire dynamics play in the fire investigator's knowledge base[5,6,7,8,9,10,11,12,13,14,15]. In addition, agencies and individuals responsible for conducting fire investigations were contacted by the author.

c) *Fire Science Technologies* – In much the same way that fire investigation methodologies were assessed, texts and educational opportunities available to fire scientists and engineers were researched for the purpose of understanding the role that fire investigation has in the fire scientist's technical knowledge base[13,16,17,18]. The stylistic differences between investigations conducted by fire investigators and those conducted by fire protection engineers were also explored.

d) *Fire Dynamics Principles* - Fire dynamics principles and simple mathematical and graphical methods were identified for relevancy to fire investigation procedures[18,19,20,21,22,23,24]. Principles to be presented include methods for estimating heat release and growth rates of the fire, heat release rates required to produce flashover within a compartment, radiant heat flux to a target, flame height, smoke layer depth with respect to time, temperatures within an enclosure fire, and detector response times.

Two areas for improvement have been identified:

1. The denunciation of common, unsubstantiated fire investigative myths that have in the past plagued the credibility of the fire investigative community[3,25], and
2. An improved fire science education for fire investigators based on "investigation-related" fire dynamics.

Lastly, a new investigative tool, or field-guide, will be presented. The conceptual tool was designed for use with structural fire scenes and does require a basic knowledge of both fire investigative and fire dynamics principles.

Chapter 2: Fire Investigative Methodology

The following chapter will provide background information relevant to the fire problem in the United States, as well as provide the reader with a sense of what a fire investigation encompasses, who conducts fire investigations, when, and why they are conducted. The shortcomings of the discipline will also be presented.

2.1 The Fire Problem and Fire Investigation

Although the technical knowledge base of the fire protection engineering community has grown tremendously over the last century, U.S. fire loss statistics exhibit the need to continue expanding and applying this knowledge to the everyday world we live in. In 1995, public fire departments responded to 1,965,500 fires that caused $8.918 billion in property damage, claimed the lives of 4,585 civilians, and injured 25,775[26]. As a cause of accidental death in the home, fire is second only to falls and is the number one cause for children and young adults[27]. Of the 573,500 structure fires during 1995, 15.8 percent, or approximately 90,500 fires, were deliberately set or are suspected of having been deliberately set. These incendiary fires contributed to the deaths of 740 civilians and caused $1.647 billion in property damage[26].

It is not difficult to understand the tragedy and devastating effects that often result from a fire. However, understanding and accurately determining the events which ultimately lead up to a fire is quite difficult and requires a substantial amount of investigative work as well as the mastery of numerous facets of the science behind the behavior of fire, fuels, and human beings. This is the task faced by the fire investigator.

The complexities and uncertainties encountered by the fire investigator during an investigation can, at times, seem insurmountable. Every investigation must originate as an objective collection of facts, observations, photographs, interviews, evidence, and analyses. From these elements, unbiased hypotheses are conceived (see Figure 2.1). However, before any one hypothesis can be presented as the conclusion of the investigation, it must be tested through the consideration and elimination of all other reasonable areas of origin and possible causes.

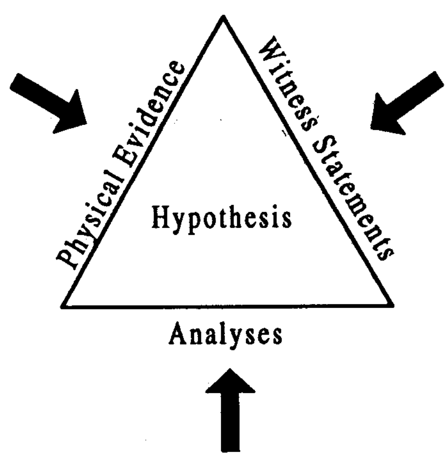

Figure 2.1 – Elements contributing to a hypothesis

As if this were not enough to manage, investigators can also be faced with additional complications such as handling several cases at one time, limited levels of staffing or investigative assistance, time constraints for conducting both an on-scene examination and for producing a final report, budgetary limits, and political influences. These are but a few of the additional obstacles that an investigator may need to overcome in the process of conducting an investigation.

2.2 What Does Fire Investigation Involve?

The term "fire investigation" has become quite generic term in the twentieth century, taking on several different definitions. Fire investigations of today are often built upon varying foundations in different disciplines, including:

- origin and cause determination – investigating for the purpose of concluding where and what caused the fire
- arson investigation – investigating incendiary fires for the purpose of prosecuting arsonists for their crimes
- failure analysis – investigating for the purpose of determining why something failed in a particular manner
- fire reconstruction simulation – investigating for the purpose of recreating the fire scenario based on data, observations, and information from the scene using various modeling techniques, including the use of computer models

2.3 Who Conducts Fire Investigations?

Municipal police and fire departments, fire marshal's offices, state police forces, private investigators, including the National Fire Protection Association[28](NFPA), consulting firms, and insurance companies conduct fire investigations. Fire investigations are also done by government agencies such as:

- The Federal Bureau of Investigation (FBI) – The FBI is a part of the United States Department of Justice, a division of the Executive Branch of the United States Government[29].
- The Bureau of Alcohol Tobacco and Firearms (ATF) – The ATF is a part of the United States Department of the Treasury, also a division of the Executive Branch of the United States Government. The ATF maintains the Certified Fire Investigator training program and along with members of the FBI, constitutes part of a National and International Response Team to assist federal, state, and local investigators at significant arson and explosive incidents[30,31].
- The United States Fire Administration (USFA) – The USFA is a part of the Federal Emergency Management Association (FEMA). The mission of the organization is to provide leadership, coordination, and support for the nation's fire prevention and control, fire training and education programs, and emergency medical services activities[32]. The USFA manages both the National Fire Academy and the National Fire Data Center, which maintains the National Fire

Incident Reporting System (NFIRS), the single largest annual collection of fire data in the world[33,32].

From analyzing the collected population of investigation reports (see References for list of reports), Table 2.1 presents the elements on which each agency tends to focus and the relative level of technical analysis conducted with respect to the incident being investigated.

Table 2.1 – Investigation types and levels of analysis by organization

Organization or Agency	**Investigation Type**	**Level of Analysis**
Municipal Police and Fire Departments	Origin and cause	Low
Fire Marshal's Offices	Origin and cause	Low to Moderate
State Police	Origin and cause	Low
Government Agencies (FBI, ATF, USFA)	Origin and cause Effects – Failure analysis	Moderate
Private Investigators (including NFPA)	Origin and cause Effects – Failure analysis (depends on individual client needs/desires)	Moderate
Insurance Companies	Failure analysis	Low

2.4 When Are Fire Investigations Conducted?

Fire investigations are conducted by different organizations for different reasons[6]. In most cases whether a fire is investigated or not will depend on the investigating agency and the type of incident. Incident types which are often investigated include, but are not limited to:

- suspicious fires or those suspected of being deliberately set
- large life loss/injury fires
- fires where large monetary or property losses are incurred
- fires involving the failure of a fire protection system or device
- fires where there are liability issues pertaining to the cause and/or property lost

Table 2.2 presents, by incident type, the organizations that are most likely to get involved in a subsequent investigation of the incident.

Table 2.2 – Investigating agencies by incident type

Incident type	Investigating agency
Suspected arson	Municipal Fire and Police Departments State Police Fire Marshal's Office FBI (large-scale incident)
Life loss	Municipal Fire and Police Departments State Police Fire Marshal's Office NFPA (technically significant incident) USFA
Property loss	Municipal Fire and Police Departments State Police Fire Marshal's Office NFPA (technically significant incident) Insurance companies Private investigators
Failure of protection system	NFPA (technically significant incident) USFA Insurance companies
Liability issues	Private investigators Insurance companies

2.5 Why Are Fire Investigations Conducted?

There are three primary reasons for investigating a fire incident. These reasons focus around 1) criminal suspicion, 2) financial restitution, and 3) educational purposes.

2.5.1 Criminal Suspicion

Fires suspected to involve criminal activities are investigated in order to fix or rule out criminal responsibility for the fire. The role of the fire investigator in this type of investigation is to arrest and prosecute individuals responsible for committing the crime of arson. Investigations of this sort must only be handled by organizations empowered with the necessary legal authority. Common motives for arson fires are profit or insurance fraud, vandalism, protest, revenge, vanity or excitement, and the concealment of another crime[6,8,11].

2.5.2 Financial Restitution

Fires are often investigated in order to fix financial responsibility, usually related to the filing of civil charges, against a building owner, contractor, product manufacturer, or other individual for losses incurred as a result of the fire. The role of the fire investigator in this type of investigation is to determine what failed, why, and who may be responsible for the failure[6,8,11].

2.5.3 Educational Purposes

Often overlooked are the educational opportunities that can stem from investigating fires. Through investigation, one can learn more about fire phenomena, human reactions to fire, and the behavior of materials under fire conditions. It is only by investigating fires that one can acquire knowledge about the underlying problems that may have caused the incident. As a result of discovering these problems, one can learn more about human behavior and reaction to fire for the purpose of improving firesafety education. Likewise, building code officials can propose changes to firesafety requirements and codes, and engineers, architects, and manufacturers can potentially design better materials, products, and buildings for increased performance under fire conditions resulting in greater safety afforded to society as a whole[34,35,36].

2.6 How Does One Assess the State of Fire Investigative Methodology?

Assessing the present state of any discipline is no easy task, fire investigation being no exception. Rather than assess highly developed techniques that can potentially be used by the more technologically adept investigator, gas chromatography and computer modeling for example, the author focused on the field as a whole, assessing the techniques and analytical methods that are typically employed by the "average" fire investigator[37]. In order to obtain such an assessment, several different types of media were examined, including informational texts on the subject, instructional course materials, investigative field guides, and numerous fire investigation reports[5-15,38]. Interviews were conducted with private investigators from the NFPA and other private agencies, investigators from the FBI and the ATF, attorneys, fire protection engineers, law officers and insurance agents. Topics discussed ranged from where the field of fire investigation has been in the past with respect to technology and education, where the field is currently, where it is headed in the future, where it should be headed, and how to get it there.

2.6.1 Problems with the Assessment

There were significant problems collecting appropriate data. Such problems included the lack of accessibility to fire investigation reports, the lack of detail in the fire investigation reports accessed, and the author's lack of practical experience.

2.6.1.1 Accessibility to Fire Investigation Reports

Gathering data is a fundamental part of any experimental analysis. Commonly, data is gathered by executing a scientific experiment of some kind and recording the results. However, in this case, the data collection process was somewhat different. The author attempted to gather as many fire investigation reports from as many different sources possible. The largest problem encountered during the data collection phase was the obstacle of trying to obtain such confidential information. Many fire investigation reports are prepared for individual clients and are considered proprietary information, such as those prepared by private investigators and insurance companies. These reports are paid for by the client and are not public record, unlike most of those conducted by state and government agencies. Investigation reports may not be released to the public due to their role in litigation. For this reason, several agencies, both private and public, were unable to provide investigation reports for the purposes of this analysis. Despite this, some information was gathered.

Despite these problems, the author was successful in obtaining what is believed to be a population of fire investigation reports representative of the quality of work being done in today's society. Some of the sources included the National Fire Protection Association, the Massachusetts State Fire Marshal's Offices, the National Institute of Standards and Technology, and a few private investigation agencies and insurance companies who prefer not to be named specifically.

2.6.1.2 Lack of Detail in Fire Investigation Reports

Fire investigation reports that are made available to the public seldom, if ever, present all facets of the entire investigative effort that have gone into the case. This conglomeration of evidence may be retained for a specified period of time as a part of a case file for the investigation. In most circumstances, case files are unavailable for review by the public.

Ordinarily the final report available to the public only presents the conclusion, if one has been determined, to the investigation. This type of report is what is referred to as a summary report. The evidence in support of the conclusion, such as witness statements, physical evidence, calculations, or photographs, may or may not be included, depending on the investigative agency and the reason for producing the report. Often, fire investigation reports will not state whether the final report is a summary report containing and explaining just the evidence relevant to the conclusion or a complete report containing all evidence collected. Without supporting evidence to evaluate, it is difficult to ascertain the merit of the investigator's conclusions. For the purpose of the analysis, the author has based his conclusions as to the thoroughness of the investigation on the findings written by the investigator in the fire investigation report only.

2.6.1.3 Author's Lack of Practical Fire Investigative Experience

Lastly, the author feels it is appropriate at this time to cite his lack of 'hands-on' experience in the field of fire investigation. Though the author has experience in fire suppression tactics and strategies, salvage, overhaul, and scene preservation, the author feels that the comparatively short amount of time spent studying and researching fire investigation methodologies does not make him an expert on the subject. However, the author does feel that he has obtained enough knowledge and experience to make an effective and objective assessment of the discipline and to offer ways upon which it can be improved.

2.7 Fire Investigation Shortcomings

The shortcomings within the field of fire investigation center on educational issues and a lack of standards pertaining to fire investigation practice. Included with educational issues are the weak foundation in fire science and the problem of few universally accepted textbooks on the subject[2,4].

2.7.1 Educational Issues – Training

Formal training received by fire investigators varies greatly, from minimal to a four-year Bachelor's degree program[4]. However, the majority of private fire cause investigators come directly from the fire service, their experience being gained through on-the-job training with a Fire Marshal's Office, or serving as a member of an arson squad after some years experience as a firefighter[37].

Investigators may be self-taught by studying one of the available textbooks[3,6,7,8,9,10,11,12], and since the quality of information contained in these texts is not equal, their level of technical expertise and scientific understanding is quite diverse. One flaw in the self-taught instructional system is that a student investigator cannot know which texts have merit and which do not. Another problem is the difficulty determining the level of knowledge gained through self-study. Additionally, the self-taught student may potentially lack the sufficient background knowledge in mathematics, chemistry, physics, materials, etc., to understand certain principles related to fire investigation. And lastly, the self-taught student lacks the interpersonal interaction that a student can achieve from an experienced instructor.

Seminars, typically lasting from one to five days and taking on a classroom lecture format, are also available to fire investigators and are a common form of training. Most fire investigators' training involves a combination of seminar instruction and hands-on, on-the-job training[4].

The National Fire Academy in Emmitsburg, MD along with several other state fire academies offers several short courses in fire investigation[14,15,39]. The duration and content of these courses vary greatly. Though their focus is more technologically oriented than that of the seminars, most courses do not provide advanced investigative training, but rather basic training in the aspects of fire investigation. These courses are typically offered only to fire service personnel whose duties pertain to the determination of the origin and cause of fires.

On a higher level, very few schools in the United States offer a Bachelor's degree program specifically in the discipline of fire and/or arson investigation. Among these are the University of Cincinnati, the University of New Haven, and Eastern Kentucky University[40,41,42]. Once again, these programs are tailored for the fire service investigator, to the inclusion of more fire service topics and the exclusion of more scientific fundamentals and fire research subjects.

The quality of fire investigation training and education can only be as good as that of the teacher, instructor, or author of the text. Herein lies another problem. Many instructors' and authors' qualifications are suspect. Instructors often do not have sufficient backgrounds in fire science or the technical aspects of fire investigation, not to mention the lack of formalized training in educational methodology. The culmination of these circumstances can result in a serious problem. Not only may the course content be technically invalid, but the instructional methodology may also be poor. Such a situation could potentially explain the proliferation of non-substantiated fire investigation theories and false-beliefs[2,4].

2.7.2 Texts

Compared to other disciplines, there are relatively few texts available for those interested in acquiring knowledge about fire investigation practice. Texts such as the fourth edition of Kirk's Fire Investigation, written by John D. DeHaan[6], and Practical Fire and Arson Investigation, Second Edition written by John J. O'Connor and David R. Redsicker[7], present theories which form the basic foundations upon which fire investigators build their expertise. However, with recent developments in the field of fire protection, fire scientists and researchers are beginning to question some of these theories considered to be basic truths by fire investigators.

Uncertainties about fire investigation texts concern the expertise and qualifications of the author(s), the lack of uniformity in subject matter and focus from textbook to textbook, the lack of quantitative fire dynamics, and the absence or failure to cite scientific or experimental research validating or supporting the theories pertaining to traditional observations made by fire investigators at fire scenes[2]. Recent scientific developments have shown that interpreting observations such as char depths and patterns, explosive limits, spalling of concrete, the color of smoke and flames, the annealing of springs in bedding and furniture, melting temperatures of metals, and localized burn patterns as exclusive indicators of a certain type of fire can be erroneous[2,25,43,44,45]. Such unsubstantiated theories, or myths, preceded the development of fire models, advanced analytical and experimental methods, and structured fire research. The perpetuation of such unsubstantiated theories in the literature and the application of these myths by uninformed investigators threatens not only the credibility of the individual investigator, but also that of the fire investigation community as a whole[3]. Every fire investigator must be familiar with the principles of fire dynamics in order to be able to ascertain when observed fire patterns can be explained by the presence of an accelerant, and when they cannot. Fire patterns can also be a result of different factors such as the nature and arrangement of the fuels, ventilation, or other variables. It is imperative that investigators are kept informed of advancements in the fields of fire science and fire protection engineering in order to maintain their competency in the disciplines[3].

2.7.3 Certifications

To date there exist two national certification programs specifically for fire investigators. The International Association of Arson Investigators' (IAAI) Certified Fire Investigator (CFI) Program and the National Association of Fire Investigators (NAFI) Certified Fire and Explosion Investigator (CFEI) Program both aim to recognize qualified fire investigators, and promote excellence in the training, education, and conduct of investigators [39,46]. Both programs require minimum qualifications associated with education, training, and experience, as well as a passing grade on a written examination in order to be officially certified. The NAFI also offers a one day Certified Fire Investigation Instructor Program that is open to all NAFI CFEI's. As part of this program individuals receive valuable schooling regarding the art and science of fire investigation and teaching methods.

2.7.4 Standards

Currently there exists but one document that could serve as an authoritative standard or guideline for fire investigation practice. The document, NFPA 921 - Guide for Fire and Explosion Investigations, was developed in 1986 by the National Fire Protection

Association's Technical Committee on Fire Investigations in an effort to establish guidelines and a recommended practice for the systematic investigation of fires and explosions[13]. The manual was also intended to be a reference work for the application of fire science principles to fire investigation. Another purpose of the guide was to debunk some of the proliferated, yet unsubstantiated myths of the fire investigation community.

2.7.5 Standardized reporting

Due to the lack of standards for fire investigation procedures and reporting, there is great variety in the documentation styles and resulting level of detail contained within fire investigation reports. NFPA 921 presents and explains certain investigative procedures relative to recording and preserving the fire scene and physical evidence, evidence collection, photography, and note taking[13]. However, no reference is made as to how all of the information gathered from an investigation of the scene is to be assembled into an effective resource for analyzing the incident. This is the purpose of the documentation tool introduced in Chapter 5.

2.7.6 Quantity versus Quality

Lastly, and no fault of the investigator, is the lack of fires being thoroughly investigated. Unfortunately, municipal and state investigators neither have the resources, money, nor time to spend extensively investigating every fire within their jurisdiction. Trying to conduct as many investigations as possible, investigators working in the public sector often spread themselves too thin, consequently reducing the overall quality of their investigations.

2.8 The Role of Fire Investigation in Fire Science

As will be explained in Chapter 3, the “ends to the means” of fire science research is ultimately the application of the technology to lessen or remedy some societal malady or problem relating to fire. What better place to discover such fire problems than at a fire scene? It is here where the observant fire investigator can notice and document certain inexplicable phenomena and/or trends, spawning further research and understanding.

Before any fire can be analyzed or simulated, facts about the scene must be known. These facts are what need to be recorded in a thorough investigation. A properly executed investigation provides all of the raw data needed, or at least as much as is practically obtainable, for future analyses by scientists and engineers.

Chapter 3: Fire Science and Fire Protection Engineering

In a similar fashion to that of Chapter 2, the following chapter will provide analogous information relating to the disciplines of fire science and fire protection engineering, as well as present the shortcomings of these disciplines.

3.1 What Does Fire Science Involve?

Fire can be defined as a rapid oxidation process with the evolution of light and heat in varying intensities[13]. Like fire investigation, fire science has come to encompass more than just the study of fire alone. Combustion, heat transfer, energy release rates, fire plume dynamics, pressure gradients and vent flows, ignition, growth, and spread of flame, smoke production, toxicity, and propagation, enclosure dynamics, and fire modeling are all different aspects of fire science[18,47]. These aspects are studied in order to learn more about fire phenomena, so as to increase the accuracy by which scientists and engineers can simulate building performance, assess and combat hazards, and reconstruct fire scenarios.

3.2 Who Studies Fire Science?

Fire protection engineers and consultants, risk managers, fire investigators and the research community encompassing students, professors, and fire scientists are all involved, to some extent, in either the process of increasing of the scientific knowledge base or the application of fire science to solve problems. Some organizations engaged in fire research and testing are:

- The Building and Fire Research Laboratory of the National Institute of Standards and Technology (BFRL/NIST) – Under the direction of the Department of Commerce of the Executive branch of the U.S. government, the BFRL is dedicated to enhancing public safety through fire performance prediction and measurement technologies[48,49].
- Factory Mutual Corporation (FM) – Factory Mutual is a corporation that provides engineered solutions to risk management and firesafety problems, develops testing standards, and conducts approvals. Factory Mutual also carries out full-scale fire and explosion testing, physical/reduced-scale modeling, laboratory-scale product testing, and mathematical modeling/computer simulation[50]. Other large property insurance organizations are involved in similar research.
- Underwriters' Laboratories (UL) – Underwriter's Laboratories is a provider of product safety and quality registration services, also conducting laboratory-scale and reduced-scale product testing relating to fire[51].

- Universities – Mechanical engineering and fire protection engineering academic departments are some, but not all of the academic organizations involved[52,53].

In addition, private laboratories and fire protection consulting firms perform fire modeling for clients relating to building design and for litigation purposes. Risk managers, in order to asses and combat risks, use fire modeling to model the hazard that they are planning to prevent[54].

3.3 When is Fire Science Research Conducted?

Pure scientific research furthering the technical knowledge base of the field is often the work of government or privately funded projects and grants, or the work of academia. It is the application of these developments by fire protection engineers to a specific case that is commonly paid for by a client. In cases such as a suspected arson fire, a large property loss, or where liability is an issue, consulting firms and investigators may apply fire science to aid in the defense or prosecution of an individual, or to validate their expert opinion. In some circumstances, such as a technically significant or inexplicable incident, fire science may be applied by organizations such as the NFPA for analyzing an incident[28].

3.4 Fire Science Shortcomings

Fire science shortcomings relate to the newness of the discipline, the failure to communicate new findings effectively, technology transfer, educational issues, and the court's perception of fire investigation and fire reconstruction modeling[55,56].

3.4.1 Fire Science – A Young Discipline

Unlike traditional, multi-subject disciplines such as mechanical and civil engineering which are grounded in the time-tested, tried and true principles of engineering mechanics, fire protection engineering, being a comparatively new field, possesses a weaker foundation of scientifically proven and agreed upon engineering principles, tools, and equations[27]. As a discipline, fire protection engineering is still attempting to build its solid foundation of engineering principles. In short, the discipline is still developing.

3.4.2 Failure to Communicate New Findings

The development of new fire science knowledge is so rapid that it is virtually impossible for any one textbook to remain technologically up to date. Much of this new research is written for the scientific and engineering communities and published in technical journals prior to it appearing in books relating to fire investigation. *"Fire Safety Journal"*,

"Journal of Fire Protection Engineering", "Fire Technology", "Fire Science and Technology", "Combustion and Flame", "Symposium (International) on Combustion", and "Combustion Science and Technology" are but a few examples of these journals. The typical member of the fire investigative community is unable to effectively use much of the information published in such journals due to a lack of technical knowledge - a direct result of an inadequate education in the scientific principles of fire dynamics. Edward Comeau, the Chief Fire Investigator for the National Fire Protection Association, said:

> *There is a significant failure upon the part of academia to communicate and develop the technical information learned in a format and manner that can be understood by the average fire investigator...It is wonderful to learn all this information, but it does absolutely no good if it cannot be put into practical use*[55].

3.4.3 Educational issues - Practical "Face-to Face" Experience with Fire

Most fire protection engineers receive education up to and including the Bachelor's degree level.[57]. There are some exceptions. The Center for Firesafety Studies at Worcester Polytechnic Institute offers Masters degree and Doctoral degree programs in fire protection engineering[52,52,53].

A problem relating to the formal education of fire scientists and fire protection engineers is the lack of "face-to-face" experience with real fires. The author strongly believes that wearing the proper protective equipment and being in a compartment about to experience flashover, not being able to see, stand, or breathe, and feeling the heat being radiated from a fire should be an important part of any fire science and fire protection engineering curriculum. Witnessing first-hand an unchecked fire outside of controlled laboratory conditions not only puts the individual's perspective of fire and its potential in a whole new light, but also helps the individual relate to the work environment of fire service professionals.

3.4.4 The Court's Perception of Fire Investigation and Fire Modeling

On June 28, 1993 in William Daubert et al. Petitioners v. Merrell Dow Pharmaceuticals, Inc., the Supreme Court was called upon to determine the standard for admitting expert scientific testimony in a federal trial[58]. The Supreme Court ruled that in order for an expert's opinion to be admissible in a court of law, the mathematical model or technique upon which the expert opinion is based must be deemed to be based on scientifically valid principles and of generally accepted practice. What this means is that the technique or methodology must be scientifically proven to be valid, relevant to the task at hand, and be a recognized practice of the profession[58].

With respect to fire science and fire investigation, the problem with such a ruling is that the disciplines have few generally accepted practices upon which fire investigators may base their expert opinions with respect to fire investigation, origin and cause determination, and analysis. For this reason, the International Association of Arson Investigators (IAAI) objects to having the Daubert decision applied to fire investigation[46].

Another problem relates to the court's perception of computer modeling and "junk science". "Junk science" is what is referred to as using a model or technique beyond its limitations, or using said model or technique to tailor the result to that which is desired. This is where the expressions "garbage in, garbage out" and "black box engineering" are derived from. A study was conducted in 1994 at Worcester Polytechnic Institute by David Jacoby and Nathan Wittasek to gain knowledge into how the nation's courts perceive computer fire modeling. The authors concluded that judges and juries cannot always ascertain the difference between valid analyses that make use of accepted practices, and those that make use of "black box engineering", or "garbage in garbage out" science[59]. The end result is that juries end up awarding the case to the side that presents its case in the most understandable, believable manner, regardless of the validity of the analyses utilized.

3.5 The Role of Fire Science in Fire Investigation

Although fire science may seem to play a limited role in the determination of the origin and cause of a fire, the process of determining where and how a fire started actually has a part of its foundation in the basic principles of heat transfer, fluid flow, ignition, and flame spread theory. However, origin and cause determination will always be more about patience and carefully securing, preserving, and properly examining the fire scene than simply doing a heat transfer calculation.

Nevertheless, the importance of fire science comes into focus when fire reconstruction analysis is needed or desired. Fire analysis, i.e. reconstructing the fire's ignition, growth, and development, and simulating the production, propagation and toxicity of smoke, has its very foundation in enclosure fire dynamics.

Chapter 4: Fire Investigation and Fire Science – Bridging the Communication Gap

There appears to be a fundamental problem between the scientific research being conducted by fire scientists and engineers and the practical duties being performed by fire investigators. It is the author's belief that the problem stems from the fact that there does not exist a free exchange of knowledge and information from one field to the other. There is what is commonly referred to as a communication gap. The two fields are, for whatever reason, isolated from each other. The average fire scientist and the average engineer lack a sufficient amount of hands-on training with respect to the practical aspects of fire protection issues dealt with by the fire service and fire investigators. At the same time, average fire service and investigative personnel lack the scientific understanding obtained through a fire dynamics education which is necessary to fully comprehend the technical research being conducted in laboratories around the world. It is time the two fields work together to bring fire investigation literature out of the past, into the present, and ahead into the future by utilizing the information obtained through advanced scientific research. The following are two ways fire science and fire investigation can be brought into closer communication.

1. A stronger focus on scientific education
2. An organized approach to on-site investigation

4.1 A Stronger Focus on Scientific Education

On one hand, it is not necessary for all fire investigators to be proficient fire scientists or fire protection engineers. On the other hand, all fire investigators do need to posses the knowledge of what it is that fire scientists and engineers do, and what information fire scientists and engineers need from a fire investigation in order to do it accurately. Such an awareness level can be successfully achieved by,

a) debunking unsubstantiated fire investigative myths, and
b) studying fire dynamics basics, combined with "investigation-related" fire science.

4.1.1 Debunking Unsubstantiated Myths

The following section will discuss several of the scientifically unsubstantiated myths that have plagued the credibility of the fire investigative community for some time. Myths relating to heat transfer, fires "searching for oxygen", char depth and burn patterns, the crazing of glass and spalling of concrete, the melting of metals, along with some electrical fire misconceptions will be discussed.

4.1.1.1 Heat Transfer

Myth: *There are four modes of heat transfer. They are convection, conduction, radiation, and direct flame contact*[3].

From a technical standpoint, there are only three established modes of heat transfer[60]. Direct flame contact is not a separate mode of heat transfer, as will be explained. Conductive heat transfer, the type of heat transfer associated with solids, is the transfer of heat energy through a material by contact between its moving molecules[60]. Burning oneself by touching a hot object is a good example of conductive heat transfer. Radiative heat transfer is heat transfer by way of electromagnetic energy[61]. Feeling the heat from the sun's rays is a direct result of radiative heat transfer. Convective heat transfer, actually a special case of conduction, is heat transfer to, or from, a solid involving the movement of a surrounding fluid, such as a liquid or gas[61]. The heating of a building by a furnace or heater is a familiar example of convection. The heated air from the heat source, a controlled fire, is circulated throughout the building by convective heat transfer[61]. Direct flame contact is not a separate mode of heat transfer because it is actually a combination of both convective and radiative heat transfer. The fraction of heat transfer via convection versus radiation is a function of the optical thickness of the flame. When one touches an optically "thick" flame, the luminous portion of burning gases or vapors, one is experiencing both radiative heat transfer from being in close proximity to the luminous burning gases, and convective heat transfer from the heated, burning gases themselves. For optically "thin" flames, conductive heat transfer dominates.

4.1.1.2 Fires "Searching for Oxygen"

Myth: *Fires spread "in search of oxygen"*[3].

The belief that a fire propagates upwards because it is searching for oxygen is untrue. This belief was commonly used to justify the upward and outward spread of flame in compartment fires. However, fires actually spread, both upward and downward, as a result of an advancing ignition front. The length of the flame from the tip down to the ignition front is involved in the "forward" heating of the un-ignited fuel to the fuel's firepoint, releasing the pyrolyzing gases, or volatiles, necessary for combustion. The leading edge of the flame, acting as the source of piloted ignition for the volatiles, ignites the volatiles, thereby spreading the flames[62]. The pyrolyzing gases, the burning gases, and the products of combustion are heated to temperatures greater than that of the ambient air, and therefore, rise and burn. Other hot gases generated, such as carbon dioxide and carbon monoxide, along with any unburned volatiles accumulate at the upper levels of an enclosure as depicted in Figure 4.1[63]. Excess pyrolyzates and any unburned fuel will travel under the influence of buoyancy until they encounter oxygen, where they can readily burn. This phenomenon explains why a flame plume exists outside a doorway or window of a fully involved room fire. Firefighters stay low during interior fire attack to avoid the heat and low visibility created by the gases and combustion products contained in the upper layer. If the fire were indeed spreading in search of oxygen, it would propagate down towards the lower levels of an enclosure, where the oxygen level is higher, being that of the cool, ambient air (see Figure 4.1).

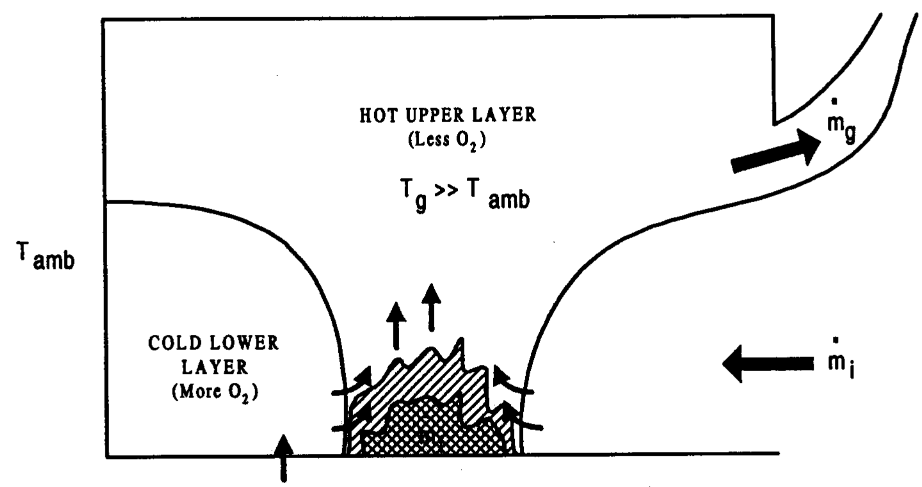

Figure 4.1 –The two layer assumption for enclosure fires[63]

4.1.1.3 Char Depth and Pattern

Myth: *The duration of burning can be determined by measuring the depth of wood char*[3].

The length of time that a fire has burned cannot be determined by measuring the depth of char. Char rate, though proportional to heat flux, is not linear with time. A common misconception is that wood chars at a constant rate. Initially, wood chars very quickly, then at a much slower rate due to an insulating effect created by the presence of the char itself[64].

Several parameters affect the development of wood char, the most significant of these being the intensity of the flames, or heat flux to the wood surface[3]. The higher the intensity, the faster the charring, and the deeper the resulting char. Therefore, any parameter that may affect the intensity of the flames, such as the type of fuel or ventilation effects, will affect the rate of char. Table 4.1 summarizes the parameters affecting the rate of char in wood[13]. Different species of wood char at different rates due to differing chemical and physical properties such as density or specific gravity, and permeability. A table listing some available data pertaining to the different properties of selected wood species is shown in Table 4.2. The geometry and orientation of the burning piece of wood with respect to the flames play an important role in the heat capacity and conductivity of the specimen and, therefore, also affect the rate of char formation. Another parameter affecting char rate is the velocity of the hot gases passing over the burning wood. Fast moving gases, increasing the rate of convective heat transfer, can lead to rapid charring. This is commonly seen in structure fires around windows and other ventilation openings in heavily involved fire rooms. Other properties affecting the rate of char include the orientation of the grain, moisture content of the wood, and of course, ambient conditions such as humidity and temperature. Testing has shown that the charring rate parallel to the grain of wood is roughly twice that of the rate transverse to the grain[65].

Table 4.1 – Parameters affecting the rate of char in wood listed in decreasing order of importance[13]

Intensity of the flames (heat flux to the wood surface)
Heat source or type of fuel burning
Ventilation effects
Species Density Permeability Thermal conductivity Latent heat of gasification
Dimensions Size Shape Surface area to mass ratio
Orientation With the grain Across the grain
Moisture content
Nature of surface coating
Velocity of hot gases
Ambient conditions

Table 4.2 – Properties of selected wood species[66].

Species	Density (kg/m^3)	Permeability (cm/s(atm/cm))	Latent heat of gasification (J/g)	Thermal conductivity (W/m °C)
Douglas fir	450	2	1820	0.11
Maple	540	---	2020	0.166
White oak	540	---	1410	0.166
Cedar	360	2	2260	---
Ponderosa pine	640	---	2790	.147
Western hemlock	340	10	---	---
Balsa	140	---	---	0.055
Cypress	460	---	---	0.097
Mahogany	---	---	2790	---

The depth to which the pyrolysis action of fire has converted an organic material to its volatile fractions and charcoal is referred to as the char depth[5]. As was stated earlier, heat applied to cellulosic materials, such as wood, causes progressive destruction of the cellulose and other constituents of the material. The same factors listed in Table 4.1 can affect the depth of char. In addition to these factors, from a fire investigation standpoint, the application of water by automatic suppression systems and/or fire department hose streams when applied selectively can inhibit charring in a particular area, while areas where water was not applied will exhibit a greater depth of char.

Measuring char can be used effectively to assess the relative fire duration throughout a structure. It should not be used to establish precise times of fire exposure. However, the most reliable use for measured char depth is to evaluate fire spread[6]. By accurately and consistently measuring the relative extent and depth of charring, a fire investigator can reasonably determine what portions of a structure or material were exposed the longest to a heat source or higher flux, accounting for the application of water, etc. The direction of flame spread may then be deduced, with decreasing char depths being farther away from the heat source. A depth of char grid diagram showing isochars, points of equal char depth, can prove to be extremely valuable when attempting to identify lines of demarcation[13].

Certain factors affect the validity of analyses making use of char depth[13]. These include:

1. Single versus multiple heat sources - Accurate char depth measurements may be useful in determining more that one heat source.
2. Char depth measurements only apply to identical materials with identical properties and dimensions.
3. Ventilation factors influencing the rate of burning - The measured depth of char may be larger near a ventilation source or other opening where hot fire gases can escape.
4. Consistency of measurement technique - The methodology used to measure char depth should be consistent for the reasons mentioned above.

Empirical Correlations for Determining the Rate of Char

Establishing a rate of char, though difficult, is critical to evaluating the fire resistance of structural members because char has virtually no load bearing capacity[65]. Although somewhat abstract, under "standard fire exposure"[67] (a specific fire condition produced in a test furnace - see Figure 4.2), charring rates tend to be fairly constant after the higher initial charring rate. The "standard fire exposure" of Figure 4.2 is that which structural members are exposed to in ASTM E 119, *Method for Fire Tests of Building Construction and Materials*[67]. The test involves subjecting the structural component to a heated furnace environment for a specified duration. Typically, gas burners are used to heat the furnace in such a manner that the temperature inside the furnace follows the time-temperature curve illustrated in Figure 4.2.

Expressions for charring rate are determined using both empirical models based on experimental data and theoretical models based on chemical and physical principles[65]. ASTM E 119 presents expressions for charring rate that are the result of many experimental studies. The empirical model that is most generally used assumes a constant transverse-to-grain char rate of 0.6 mm/min for all woods when exposed to the "standard fire exposure". The same empirical model assumes that the member is thick enough to be treated as a semi-infinite slab[67]. However, this rate is only applicable for the test conditions and for comparing the charring rate of different materials under the same fire conditions and is not applicable for practical fire investigation purposes.

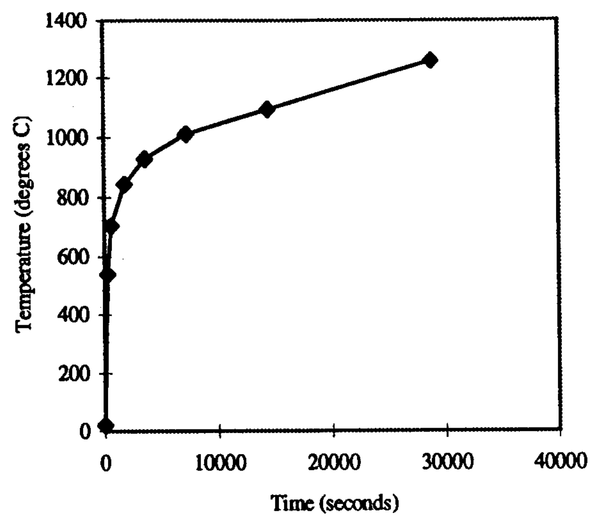

Figure 4.2 – ASTM E 119 Standard Fire Exposure Time/Temperature Curve[67]

Schaffer developed correlations for the transverse-to-grain charring rates of white oak, douglas fir, and southern pine as a function of density and moisture content when exposed to the "standard fire exposure" of ASTM E 119[65]. Contributing to the difficulties in predicting the rate of char in wood, moisture contents are not consistent from one species of wood to another. Moisture contents are also affected by local climates. Table 4.3 lists the moisture content of interior woodwork for specific cities during summer and winter[25].

Table 4.3 – Moisture content of interior woodwork for specific cities[25]

City	% Moisture Content	
	July	January
Boston, MA	13.0	7.0
Atlanta, GA	11.5	8.5
New Orleans, LA	13.5	12.5
Madison, WI	10.0	6.0
Salt Lake City, UT	4.5	7.0
San Francisco, CA	10.5	10.5
Seattle, WA	11.0	8.5

With that in mind, the correlations developed by Schaffer are as follows:

white oak: $$R = \frac{1}{2[(20.036 + 0.403M)S_g + 7.519]}$$ [Eq. 4.1]

douglas fir: $$R = \frac{1}{2[(28.726 + 0.578M)S_g + 4.187]}$$ [Eq. 4.2]

southern pine: $$R = \frac{1}{2[(5.832 + 0.120M)S_g + 12.862]}$$ [Eq. 4.3]

where R = charring rate in in./min.

M = percent moisture content

S_g = dry specific gravity

Once again, the correlations mentioned apply only for the standard ASTM E 119 fire exposure. At this period in time, data on charring rates for other fire exposures is limited. However, Hadvig in a report entitled *Charring of Wood in Building Fires*, developed a rather complex methodology, far too involved to be presented here, for the determination of charring depth as a function of time[68]. The methodology is briefly explained in The SFPE Handbook of Fire Protection Engineering, Second Edition, Section 4 Chapter 10[65].

Some theoretical models for wood charring based on conservation of energy have been and continue to be developed. Models of this kind, such as an early model by Bamford et al.[69] and later modified by Thomas[70], attempt to allow for the calculation of the charring rate for geometries other than a semi-infinite slab as well as for nonstandard fire exposures. Unfortunately, at this point in time no satisfactory model has yet been developed and universally agreed upon by the scientific community[65].

Myth: *Alligator char signifies a "fast-burning" fire while a "baked" appearance signifies a "slow-burning" fire*[72].

Alligator char, surprisingly enough, refers to char resembling that of the skin of an alligator. Alligator char consists of large, blocky blisters. An example of alligator char is depicted in Figure 4.3. There is no significant evidence of such a correlation, therefore one cannot use this as an exclusive indicator of the growth rate of a fire. In the past, fire investigators have given the appearance of char meanings beyond that which have been substantiated through controlled experiments and research. Under test conditions, single fires have been able to produce char of several different appearances[5].

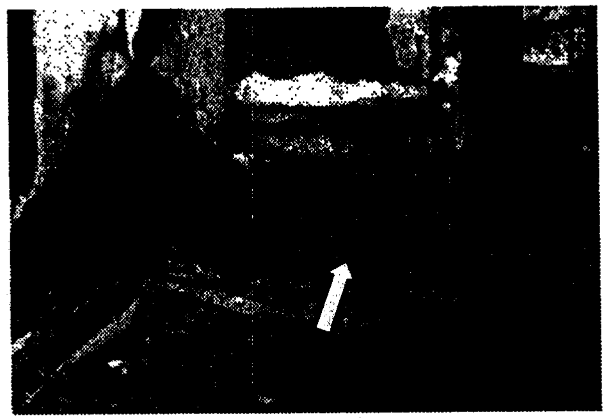

Figure 4.3 – Alligator char showing large blisters (courtesy of Auburn Fire Department)[71]

A better way to ascertain whether the fire was slow or fast burning is to examine the cross-section of a burned specimen. There is evidence supporting that a slow-burning fire will produce a gradual decrease from charred to unburned wood into the specimen while a fast-burning fire will produce a sharp line of demarcation between burned and unburned areas[5].

Myth: *Localized burn patterns signify the fact that flammable liquids were used to accelerate the fire*[43].

Localized burning patterns are sometimes referred to as "ghost patterns" because of their irregularly shaped and stained-looking appearance. These patterns are not conclusive proof that a flammable liquid was used to accelerate a fire. Several phenomena occurring during the normal growth stages of an unaccelerated enclosure fire can produce localized burn patterns[43]. Such phenomena include "drop down" effects from materials such as plastics that melt, drip, and/or pool then burn. This can be the case with burning and falling draperies and valences near windows, or polystyrene window panels themselves[64]. Materials normally located on the floor such as carpeting, linoleum floor tiles, and indoor/outdoor artificial grass mats can create burn patterns as well. Localized burn patterns can also be created on floors, thresholds, and windowsills as a result of convective heat transfer caused by heated gases exiting a compartment during a ventilation limited burning condition, a condition that occurs during any fire about to reach flashover. In addition, radiant heat transfer from the hot upper gas layer of a compartment fire and the undersides of freestanding furniture items can produce heat and smoke patterns on the enclosing surfaces of a room[44]. Figure 4.4 illustrates this principle.

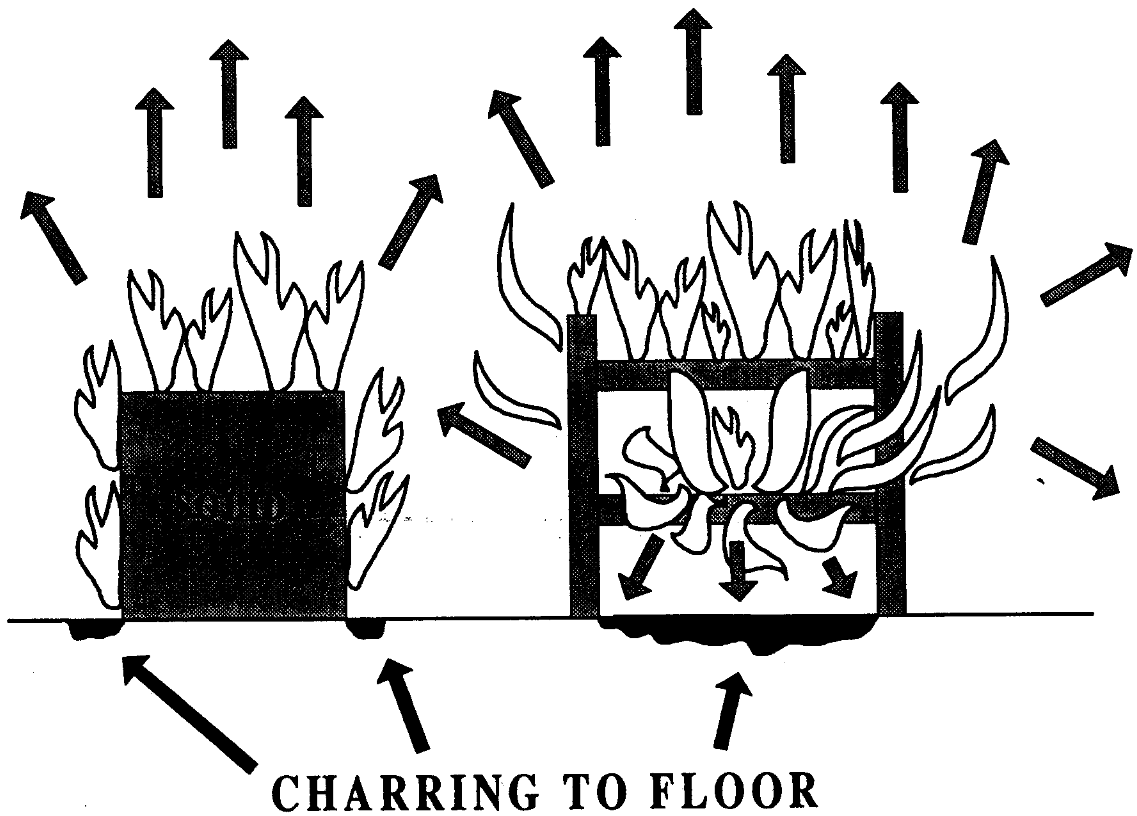

Figure 4.4 – Char patterns to floor caused by radiation from burning objects

Tests have shown that when a flammable liquid is used to intentionally start a fire in a room, it will most likely produce patterns on the floor or surfaces where it burned. The liquid pool of accelerant acts as an insulator for the floor area that it covers or protects. The pool itself is not burning, but rather the vapors being volatilized from the liquid pool are. The burning at the outer edges of the pool creates a char pattern, or "ghost mark" in the shape of the perimeter of the of liquid accelerant pool (see Figure 4.5). As the accelerant volatilizes and burns, the surface area of the protected area decreases, creating an entire "ghost mark" (see Figure 4.6).

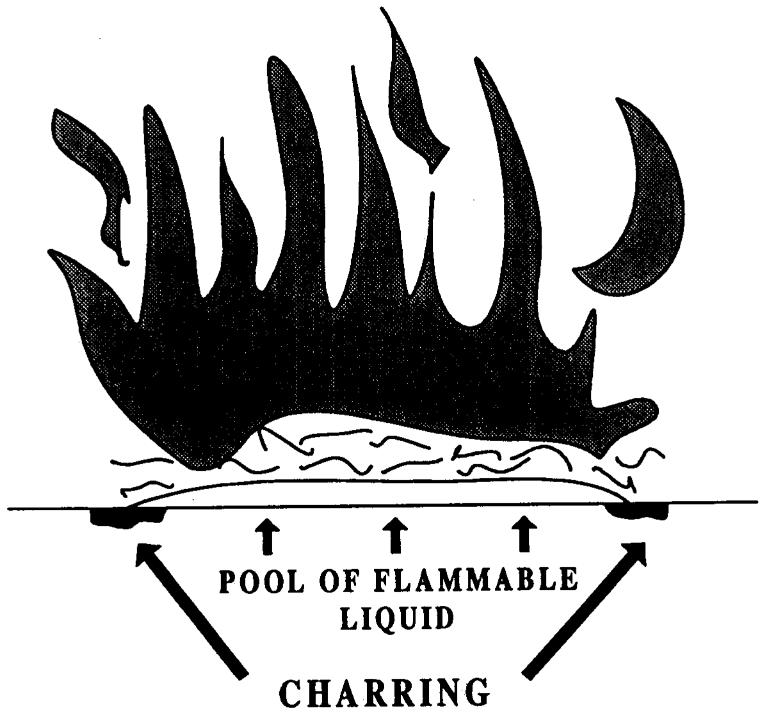

Figure 4.5 – Charring at outer edges of a pool fire.

However, if the room subsequently reaches flashover, or full room involvement, where all ignitable items within the compartment begin to burn, the liquid patterns may be obscured by those produced from the flashover phenomena itself[44]. Therefore, it is erroneous for the investigator to determine the cause of a fire merely by the observation of such patterns.

If it is suspected that an accelerant was used to start a fire, the investigator should collect a debris sample to be chemically analyzed for the presence of the suspected accelerant. The collection of any sample for chemical analysis should also include a control sample of the same material as the evidence sample but from an area that could not have come in contact with the suspected accelerant. The purpose for obtaining a control sample is so that the chemical analyst can determine what materials may have been present in the debris as a result of, or prior to, the fire and which are not related to the use of the suspected accelerant.

Figure 4.6 – "Ghost patterns" from a self-extinguished carpet pad on the left (A) and artificial grass-type indoor/outdoor carpeting on the right (B)[43]

Myth: *The lowest point of burning signifies the point of origin of a fire*[3].

The lowest point of burning is not by definition the point of origin. After a fire enters the established burning phase, the fire and its combustion products do spread upward and outward. However, fire also spreads downward, though at a much slower rate than it burns upward under natural conditions[3]. Unusual conditions such as the influence of ventilation, melting plastics, and ignitable liquids such as gasoline can make it easier for fires to burn downward[44]. When a room reaches flashover, it is not uncommon for the room to exhibit char from floor to ceiling. Any circumstances that would enhance or contribute to low burning must be considered and eliminated by the investigator before the lowest burning is declared the point of origin.

4.1.1.4 Accelerants

Myth: *Crazed glass is the result of a "fast" growing, accelerated fire*[72].

It was thought that the crazing of glass (the generation of minute stress cracks) was a direct result of a rapid build-up of heat from a "fast" growing, accelerated fire. However, recent scientific investigation into the topic has proven that the crazing of glass is caused by the opposite phenomenon – rapid cooling[73]. Such rapid cooling can occur when water droplets from automatic sprinkler systems and/or from fire department suppression efforts come in contact with heated glass. An examination of 50 structures destroyed in the October 1991 fire in the hills east of Oakland, CA conducted by John Lentini, David Smith, and Dr. Richard Henderson (all Certified Fire Investigators) revealed melted glass in 74% of the structures. Crazed glass was found in 24% of the structures. The investigators concluded that the crazed glass was more likely to be found in the houses near the periphery of the fire, where some suppression efforts may have taken place[74].

Myth: The s*palling of concrete is a result of abnormally high temperatures and therefore signifies the presence of flammable liquids*[3].

Spalling refers to the separation of a portion of concrete slab or assembly (see Figure 4.7)[13]. In the past, investigators thought that unusually high local temperatures were required for spalling to occur, and therefore an accelerant must have burned above a spalled portion of concrete. At best, this theory is doubtful for the reasons explained earlier with regards to the creation of ghost patterns. To reiterate, concrete below a pool of liquid accelerant remains at temperatures below the boiling point of the accelerant. The liquid cannot be present above its boiling point, and the liquid, not the volatilizing gases, is what is in contact with the surface of the concrete. The area directly around the base of the fire will be heated by the flames. However, the heat will be dissipated throughout the cool concrete[6].

Currently, several theories exist that could explain spalling phenomena[3]. One is the application of mechanical pressure to the surface of the concrete. Another theory is that with the application of heat, trapped water within the concrete is converted to steam which creates internal forces resulting in the separation of a portion of the concrete. Yet another theory is that differential expansion rates of the various materials constituting the concrete account for the internal stresses generated, causing the separation of the heated portion. And lastly, it has been suggested that the rapid cooling of concrete due to the application of water from extinguishment efforts can also result in the spalling of concrete.

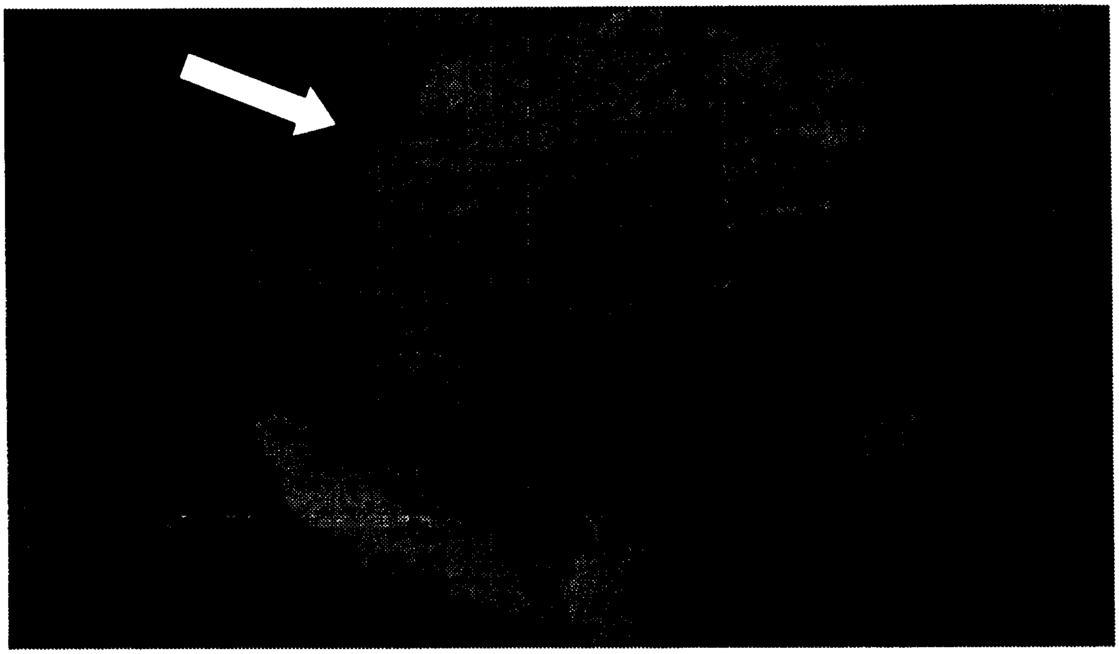

Figure 4.7 – Spalling of concrete on a ceiling[13]

Myth: *The melting of metals is a result of abnormally high temperatures and therefore signifies the presence of flammable liquids*[72].

In actuality, the melting of metals does not necessarily signify the occurrence of abnormally high temperatures. Alloys, metal products containing two or more elements typically as a solid solution, possess a melting point lower than that of their individual constituent metals. A well-ventilated compartment fire involving ordinary combustibles can produce temperatures in the 800°C to 1300°C range in the vicinity of the seat of the fire, thereby producing conditions capable of melting most structural materials, even cast iron[64].

4.1.1.5 Electrical Misconceptions

Myth: *Damaged conductors and damaged bus bars often overheat and ignite wooden structural members, resulting in a fire*[25].

Conductors can be defined as wires, cables, or other bodies or mediums suitable for carrying electric current. Bus bars can be defined as rigid metallic conductors, usually uninsulated, used to carry a large current or to make a common connection between several circuits[25]. The critical surface temperatures for the piloted and spontaneous ignition of wood range from 250 to 350° C and 450 to 600°C, respectively[13,75,76]. While it is true that a damaged conductor has relatively high thermal losses at the point of damage, experiments conducted by Professor Bernard Beland of the University of Sherbrooke England have shown that conductors and bus bars can be cut almost entirely through at one point without any appreciable heating capable of causing the ignition of wood[25]. Table 4.4 shows temperatures in 14, 10, and 6 AWG conductors carrying various currents when completely in tact versus temperatures when 3, 5, and 6 of the 7 strands comprising the braided wire conductor are severed.

Table 4.4 – Heating of damaged conductors[25].

Conductor Size (AWG)	Current (amp)	T (°C) Wire in tact (0 strands cut)	T (°C) 3 strands cut	T (°C) 5 strands cut	T (°C) 6 strands cut
14	20	38	45	51	73
14	40	87	116	126	287
10	40	41	52	70	98
10	80	85	131	157	194
6	100	57	68	106	150
6	200	150	242	390	---

One can see that, with the exception of the 14 AWG wire carrying a current of 40 amps that had 6 of seven strands cut, and the 6 AWG wire carrying a current of 200 amps, the temperatures in the area of the cuts on the wires are all below that of the piloted ignition temperature of wood.

A similar experiment was conducted with bus bars[77]. A 1/8" x 1" aluminum bus bar was purposely "damaged" and thermocouples were used to measure local temperature increases at the points of damage. Using a hacksaw, three cuts were made in the bus bar as shown in Figure 4.8.

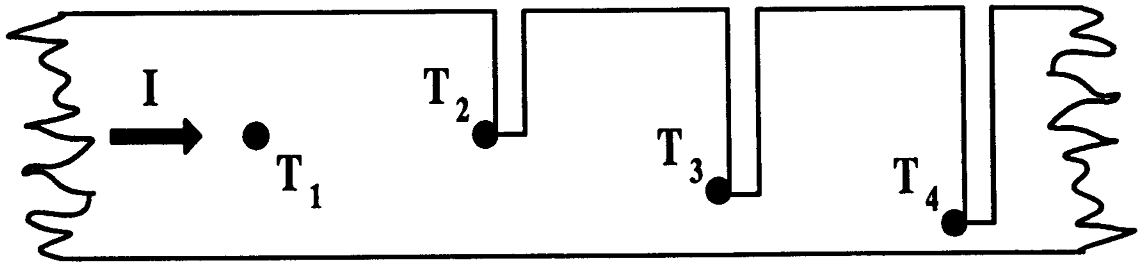

Figure 4.8 – Damaged bus bar showing locations of thermocouples T_1 through T_4[25]

Each cut was separated sufficiently from adjacent cuts so as not to incur interference heating to adjacent thermocouples. Table 4.5 shows the results of Professor Beland's experiment.

Table 4.5 – Temperatures in the damaged bus bar of Figure 4.8[25].

Current (amp)	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)
200	38	42	46	48
400	152	163	178	187
600	354	370	---	---

From Table 4.5 one can see that differences in the temperatures measured at the undamaged section to those at the damaged points are relatively small. Again, with the exception of when the bus bar was carrying a current of 600 amps, the resulting temperatures at the point of damage on the bus bars are all less than the 250 to 350°C temperature required for the piloted ignition of wood. Beland concluded that a cut to remove 87.5% of the bus bar's cross-section resulted in a temperature increase of only 25% above that of the undisturbed section[25].

Myth: *Stretching and the extreme bending of wires creates overheating, resulting in an electrical fire*[25].

Heating in stretched wires is a result of the Joule effect. When wires are stretched, the cross-sectional area of the conductor is decreased, the resistance (measured in ohms) increases, and thus more heat is generated. However, copper wires, common in residential and industrial applications, will experience only a 20% reduction in cross-sectional area before breaking occurs. The reduction in cross-sectional area before breaking in aluminum wires is even less, aluminum being a less malleable metal than copper. Beland concluded that stretched wires that have experienced 20% reductions in their cross-sectional area only result in 25% more than normal heating in the circuit. Beland also concluded that the extreme bending of wires does not produce any measurable effect on heating[25].

Myth: *Arcing wires are a common cause of residential structure fires*[25].

An arc is the flow of current between two conductors not within physical contact. Arcs are very difficult to start under household conditions. Common residential and commercial electrical systems in the United States are 120/240 Volts. Because air is a poor conductor, air cannot be "punctured" at normal conditions (20°C, and 1 atm). Only if the voltage is greater than 300 Volts and the electrodes are preheated through contact will an arc be started. Such an arc will most likely ignite paper and/or wood shavings, but would be unlikely to ignite a solid piece of wood[25].

4.1.2 Conclusions

In summary, one can see that no one indicator should be taken as sole conclusive proof of any observation, fact, or hypothesis. All indicators and all reasonable scenarios must be considered in a proper and thorough investigation.

4.2 Studying Fire Dynamics Basics and "Investigation-Related" Fire Science

The development of a structured fire dynamics curriculum for the fire investigator is beyond the scope of this thesis. However, at this time the author feels that it is appropriate to suggest topics that could be more emphasized in the formal training of any fire investigator. Such topics include fuel properties and their role in the combustion process. This would encompass the ignition and spread of flame with respect to both solid and liquid fuel types. Additional topics include basic equations of heat transfer and enclosure fire dynamics. Enclosure fire dynamics is what is alluded to with the term "investigation-related" fire science for the reason that investigations focus around the relationship that a fire has with a structure or compartment. The topic of enclosure fire dynamics would encompass a qualitative description of fire growth in an enclosure and the fire-induced environment, including the pre- and post-flashover states. Factors controlling the energy release rates in enclosure fires, the temperatures and velocities of ceiling jets, the production and propagation of smoke, and the response of heat and smoke detectors should also be studied.

4.3 An Organized Approach to On-site Investigation

The end result of an organized approach to on-site investigation is the full documentation of all relevant details. The problem with this axiom is that it is not possible for the investigator to know what details are relevant and what details are not under all circumstances at the time of the on-site data collection process. For this reason, it is important for the investigator to adhere to a consistent procedure for the documentation of all details. This can be accomplished successfully through analytical thinking and by following a uniform investigative methodology consistent with the investigative procedures and techniques suggested in NFPA 921[13].

The Scientific Method and Analytical Thinking

The scientific method is defined as the systematic collection and classification of data and the subsequent formation and testing of hypotheses based on the data. In effect, what this thesis is attempting to do is apply the scientific method to the fire investigative on-site data collection process. By doing so, investigators will have the appropriate information necessary to form better hypotheses and the necessary documentation to test them more accurately.

The field guide of Chapter 5 is based upon analytical thinking. The forms of the field guide were designed to be completed in sequence. The order is important. Completing the forms in their intended order enables the investigator to record information as a consistent routine in an efficient manner. Perhaps the easiest way to conceptualize this is to think of the field guide as a template. In using this template, the investigator is able to document each investigation according to the same method set forth within the template.

Chapter 5: The Field Guide Explained

The Field Guide is a three-part system. Part One consists of on-site data collection forms for properly documenting the scene. Part Two consists of flowcharts that can enhance investigators' intuition about the fire's growth rate and spread, aiding in the development of hypotheses. Lastly, Part Three consists of the models or tools necessary to quantitatively simulate certain fire phenomena referenced in the flowcharts of Part Two for the purpose of validating hypotheses that the investigator may develop. In the sections to follow, shaded areas and figures represent the forms, or pages, of the Field Guide that the investigator should have at the scene of the investigation.

5.1 Part One – On-Site Data Collection

Part One consists of thirteen separate forms. Each form has a different title and purpose, containing different information to be collected and recorded by the investigator. The order and titles of the forms are as follows:

- The General information Form
- The Witness Information Form
- The Photograph Information/Checklist Form
- The Site Plan Sketch Pad
- The Front Elevation Sketch Pad

- The Right Elevation Sketch Pad
- The Rear Elevation Sketch Pad
- The Left Elevation Sketch Pad
- The Floorplan Sketch Pad
- The Exploded Room Diagram Sketch Pad – Contents Form
- The Exploded Room Diagram Sketch Pad – Damage/Victims Form
- The Evidence Information Form
- The Victim Information Form

The chosen order of the forms comprising Part One is such that the methodology takes the investigator through the scene from general, basic information to more detailed, specific information. Concurrently, the methodology encourages the investigator to record all relevant exterior parameters before venturing into the documentation of specifics concerning the interior of the structure. Exterior parameters include recording the site plan and elevation sketches/drawings for the incident, obtaining exterior photographs, securing any relevant exterior physical evidence such as incendiary devices and/or evidence supporting their presence, and the recording of any witness' personal information. Once exterior parameters have been collected, interior data collection can begin. Interior parameters include information relevant to the configuration of spaces within the structure, such as floorplan sketches and photographs, information relevant to the specific damage and location of any victims within the structure, and documenting the collection of physical evidence.

5.1.1 The General Information Form

The General Information Form is reproduced in Figure 5.1. In the paragraphs to follow, the different sections incorporated on each of the forms are explained. The sections of the forms are discussed in the same order as they are intended to be completed, starting at the upper left-hand corner of each form and working from left to right across the form and downward.

Investigator Name

Enter the name of the investigator completing the individual form. The Investigator Name box appears on every form in order to provide accountability for the information documented on the individual forms. The organization of the Field Guide is such that for large incidents requiring an incident management system for the investigative effort, the forms may be separated and distributed to the different sectors to be completed individually, providing for a more timely and manageable investigative effort.

Date/Time

Enter the date and time of the incident, the date and time that the investigating agency was notified to respond, and the date and time that the investigative effort began. By documenting these three times, one is able to get a sense of how "old" the scene has become before investigative efforts have begun. A Date/Time box appears on all forms and is intended to be filled out by the documenting investigator when he/she begins recording the specific information requested on the form.

Incident Location

Enter the street address, city or town, state, and zip code of the incident location.

Incident Description

Enter a brief description of the incident that is to be investigated. A concise, one phrase incident description will suffice. Examples include: "structure fire in an occupied three story wood-frame apartment building", "structure fire in a one story ranch with attached garage", or "structure fire in an abandoned two story brick commercial building."

Responding Agencies

Enter the local, county, state, government, or private agencies and/or companies that are on-scene, or a responding to the scene. This would include local and state police agencies, local and state and mutual/automatic aid fire departments, government agencies such as the FBI/ATF, utility companies, the Red Cross, other investigative agencies, etc.

By recording this information, these agencies can be contacted for further information should it be needed.

Weather Conditions

Enter the weather conditions including the wind direction and velocity, the air temperature, the relative humidity, and note any precipitation events at both the time of the incident and the time of the investigation. A change in weather conditions from the time of the incident to the time of the investigation may provide the investigator with insight as to why the condition of the scene has been altered in some way.

Structure Information

Enter the following basic information regarding the structure involved:

- Construction type (i.e. wood-frame, masonry, steel, etc.)
- Exterior dimensions (length, width, and height)
- Occupancy type (i.e. residential, commercial, industrial, etc.)
- Utilities present within the structure and the service providers (electricity, gas, water, sewer, telephone)

Affiliated Persons

Enter the name(s), address(es), and phone number(s) of the following persons pertaining to the structure and/or incident:

- Property owner and whether consent to search the property was required and granted
- Landlord
- Maintenance Personnel
- Occupants

The intent of placing this information on the first form is so that the investigator can obtain these individuals' information promptly should he/she need to contact, question, or interview them in the future.

GENERAL INFORMATION

Investigator Name:

Date/Time of:
Incident: / / :
Notification: / / :
Investigation: / / :

Incident Location:
Street Address:
Town:
State/ZIP:

Incident Description:

Responding Agencies:

Weather Conditions:

Time of Incident:	**Time of Investigation:**
Wind Direction/Speed:	Wind Direction/Speed
Temperature:	Temperature:
Relative Humidity:	Relative Humidity:
Precipitation:	Precipitation:

Structure Information:
Construction Type:
Exterior Dimensions: **Length=** **Width=** **Height=**
Occupancy Type:
Utilities: **Power/Electricity:** **Water:**
Gas: **Sewer:**
Telephone:

Affiliated Persons:

Owner Name(s): **Consent to Search** ☐ Yes ☐ No **Address(es):** **Phone No.(s):**

Landlord Name(s): **Address(es):** **Phone No.(s):**

Maintenance Personnel: **Address(es):** **Phone No.(s):**

Occupant(s) Name(s): **Address(es):** **Phone No.(s):**

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Figure 5.1 – The General Information Form

5.1.2 The Witness Information Form

Statements and observations made by witnesses to an investigator play a crucial role in the formulation of the investigator's hypotheses as to what may have happened. For this reason, and for the simple reason that information obtained from witnesses shortly thereafter the incident tends to be more accurate than that obtained after some time has elapsed, the author has placed a high priority on the documentation of witness information. Hence, the Witness Information Form is second in the thirteen form series. The Witness Information Form is reproduced in Figure 5.2.

Discoverer(s) of Fire Name(s)

Enter the name(s) of the person(s) who first discovered the fire, whether or not a recorded statement was taken from the individual(s) and if so, the date(s) and time(s) of the statement(s). In addition, record the discoverer's of fire address(es) and phone number(s) so as to have this information should the individual need to be questioned further.

Notes

Notes text fields will appear throughout the forms. These sections are included frequently on all of the forms and are intentionally located where specific information is likely to be noted. Because every investigation is different, to have forms with only "rigid", fill-in-the-blanks would limit the amount of incident specific information that could be documented by the observant investigator. An abundance of open-ended Notes boxes is an attempt at a solution to this problem.

#1, #2, and #3 Witness Name(s)

Similar to the Discoverer of Fire section described above, enter the name(s) of any witness(es) along with whether or not a recorded statement was taken from the individual(s) and if so the date(s) and time(s) of the statement(s). The witness(es) personal information, including address(es) and phone number(s) should also be recorded. For the sake of simplicity and consistency, it is recommended that witnesses be referred to by their number designation if noted elsewhere in the forms or sketches of the Field Guide.

Occupant Name(s)

This section provides for the documentation of the occupant's personal information in a manner similar to that presented in the Discoverer of Fire and Witness sections described previously. A check box is provided for noting whether the occupant has granted the investigating agency the consent to search his/her private space should such consent be required by law.

Firefighter/Police Officer Name(s)

Enter the name(s) of firefighter(s) and/or law enforcement officer(s) who may have important information to contribute to the investigation and whether or not a recorded statement was taken from these individuals. Often, police officers arrive on the scene before the first fire companies and can observe the fire from its early stages, or perceive suspicious persons and/or activities. Likewise, firefighters advancing the first lines of the initial attack on the fire may have some important observations to share with an investigator relative to the fire encountered on arrival. The investigator should not overlook this type of information.

WITNESS INFORMATION

Investigator Name: **Date/Time:**

Witness Information:

Discoverer of Fire Name(s):

Address(es): Phone No.(s):

Recorded Statement ☐ Yes ☐ No Date/Time: / / :

Notes:

#1 Witness Name:

Address(es): Phone No.(s):

Recorded Statement ☐ Yes ☐ No Date/Time: / / :

Notes:

#2 Witness Name:

Address(es): Phone No.(s):

Recorded Statement ☐ Yes ☐ No Date/Time: / / :

Notes:

#3 Witness Name:

Address(es): Phone No.(s):

Recorded Statement ☐ Yes ☐ No Date/Time: / / :

Notes:

Occupant Name(s):	**Consent to Search**	**Statement**	**Date/Time:**
	☐ Yes ☐ No	☐ Yes ☐ No	/ / :
Notes:			
	☐ Yes ☐ No	☐ Yes ☐ No	/ / :
Notes:			
	☐ Yes ☐ No	☐ Yes ☐ No	/ / :
Notes:			
	☐ Yes ☐ No	☐ Yes ☐ No	/ / :
Notes:			

Firefighter/Police Officer Name(s):	**Recorded Statement**	**Date/Time:**
	☐ Yes ☐ No	/ / :
Notes:		
	☐ Yes ☐ No	/ / :
Notes:		

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Figure 5.2 – The Witness Information Form

5.1.3 The Photograph Information/Checklist Form

The Photographic Information/Checklist Form, reproduced in Figure 5.3, serves two purposes. First, the form acts as an organized way to keep track of photographs that have been taken. Second, the form acts as a checklist to remind the investigator as to what photos should be taken of the scene, its surroundings, the structures involved, evidence items, etc. The author uses the term "photographs" loosely, meaning any type of visual images of the scene secured by the investigator, be they photographs from an ordinary 35mm camera or from a video camera.

The experienced investigator has a camera ready to take photographs at any time during the investigation. Although placed third in the thirteen form series, the Photographic Information/Checklist Form should start to be completed by the investigator as early as possible in the investigation. The Photographic Information/Checklist Form is also intended to be continually referred to and completed throughout the investigation, namely at the points in time when it is appropriate for an investigator to take the suggested photographs.

Columns on the Photographic Information/Checklist Form

The first column of the Photographic Information/Checklist Form is divided into two major sections: 1) the fire building, and 2) the exposures. Under each section are two sub-sections: a) interior photographs, and b) exterior photographs. The exterior photographs precede the interior photographs in each section due to their likelihood of being taken earlier in the investigation.

Roll Designation

Enter the designation for the roll of film on which the photographs were taken. A number or letter designation is sufficient, though a letter designation will be less likely to be confused with the photograph numbers.

Photograph Number(s)

Enter the individual or range of exposure numbers for the appropriate photographs taken.

Description(s)

Enter a brief description of the photograph. This may include what the item is, when the photograph was taken, where the photograph was taken from, or an important observation that can be seen in the photograph. Whenever possible, photographs should incorporate items of known size, length, or dimensions in the photograph. Such items can be added by the investigator (i.e. a coin placed next to a burn pattern, or a pole of a specified length) or can be dimensions taken off of the building. This type of information is very important for digital processing of the photograph, which can be done knowing the lens used and the distance to the item(s). Space being at a premium, it is important that extraneous information not be included in the description column. Location and direction of photograph can, and should, be added on the appropriate sketch pads.

PHOTOGRAPH INFORMATION/CHECKLIST

Investigator Name: **Date/Time:**

Photograph Information/Checklist:

Fire Building - Exterior:	**Roll Designation:**	**Photo No.(s):**	**Description(s):**
☐Front Elevation			
☐Right Elevation			
☐ Left Elevation			
☐ Rear Elevation			
☐ Aerial			
☐ Exterior Damage			
☐ Fire Dept. Operations			
Exposures - Exterior: ☐ Elevation			
☐ Orientation to Fire Building			
☐ Exterior Damage			
Fire Building - Interior: ☐ Non-Damaged Areas			
☐ Smoke Damaged Areas			
☐ Susp. Floor of Origin Damage			
☐ Susp. Area(s) of Origin Damage			
☐ Susp. Space(s) of Origin Damage			
☐ Susp. Point(s) of Origin Damage			
☐ Damage to Any Potential Causes			
☐ Detectors			
☐ Audible/Visual Alarms			
☐ Sprinklers			
☐ Items of Special Concern			
Exposures - Interior: ☐ Non-Damaged Areas			
☐ Damaged Areas			

Notes:

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Figure 5.3 – The Photograph Information/Checklist Form

5.1.4 The Site Plan Sketch Pad

The Site Plan Sketch Pad is designed for the investigator to be able to sketch an approximate overview of the entire incident scene. In addition to the Site Plan Sketch Pad reproduced in Figure 5.4A, a completed example of the Site Plan Sketch Pad is shown as Figure 5.4B.

Site Plan

One should sketch an overview of the incident scene using as much detail as practically possible. Included in the sketch should be the relative location of the fire building to any exposures, walkways, driveways, automobiles, trees, power lines, fire hydrants, fire apparatus, etc. Symbols designating the locations and perspectives from which exterior photographs were taken, such as those shown in Figure 5.4B, should also be indicated on the sketch of the site plan. A grid is provided in the drawing area to aid in the proportioning of the sketch as well as a box in the lower right hand corner for the purpose of placing a compass indicating North.

Details

Because it will most likely be impossible for the sketch of the site plan to be drawn to any specific scale, a Details section has been added to the lower third of the Site Plan Sketch Pad. It is suggested that distances from the fire building to exposures, roadways, water sources, power, and gas lines be measured and noted. Space is provided for recording important fire department response information such as the distance to the responding fire stations, the name of the incident commander or commanding officer(s), and the fire companies working at the scene. Spaces are also provided in the Notes box for noting any special hazards, circumstances, and/or observations unique to the incident at hand.

SITE PLAN SKETCH PAD

Investigator Name: **Date/Time:**

Site Plan:

Details:

Distance(s) to Exposure(s):

Distance(s) to Roadway(s):

Distance(s) to Water Source(s):

Distance(s) to Power Line(s):

Distance(s) to Gas Line(s):

Special Hazards:

Distance(s) to Fire Station(s):

Incident Commander:

Companies On-Scene:

Notes:

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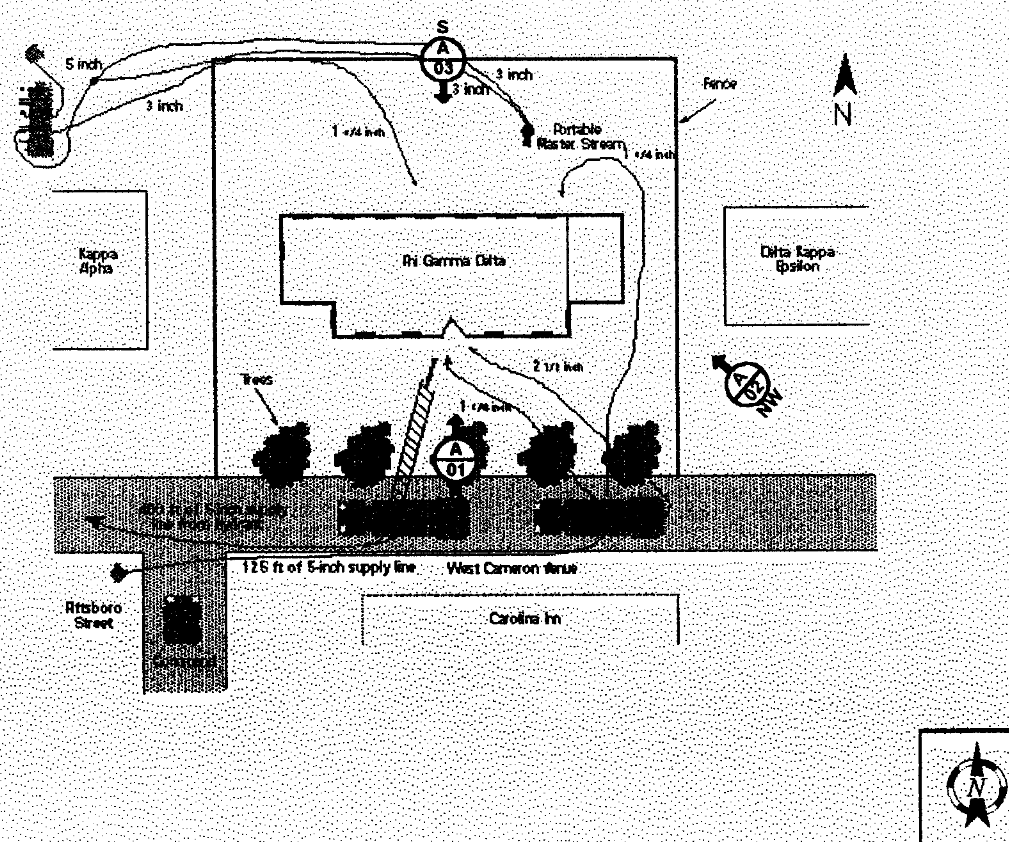
Figure 5.4A – Site Plan Sketch Pad

SITE PLAN SKETCH PAD

Investigator Name: John Doe **Date/Time:** 05/12/96

Site Plan: Phi Gamma Delta Fraternity House



Details:

Distance(s) to Exposure(s):

Distance(s) to Roadway(s):

Distance(s) to Water Source(s): 125 ft (Pittsboro St.), 400 ft (E34)

Distance(s) to Power Line(s):

Distance(s) to Gas Line(s):

Special Hazards:

Distance(s) to Fire Station(s): E31 - approx. 5 blocks

Incident Commander: CH C-1

Companies On-Scene: CH — E31, E32, E34, T71
NHVFD
Orange County EMS

Notes:

Exposures of no major concern due to separation and wind speed/direction

Possible occupants trapped

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Figure 5.4B – Completed example Site Plan Sketch Pad (Photo ©NFPA Fire Investigations Department. Used with permission.[78])

5.1.5 Elevation Sketch Pads

Elevation Sketch Pads are provided for the investigator to sketch the elevation views and record important exterior dimensions of the structure under investigation. The forms are ordered to follow a counter-clockwise path of travel around the structure starting with the front elevation, right elevation, rear elevation, and ending with the left elevation. The Elevation Sketch Pads are reproduced in Figures 5.5A, 5.5C, 5.5E, and 5.5G, with completed example front, right, and rear elevation sketch pads, shown in Figures 5.5B, 5.5D, and 5.5F.

Front, Right, Rear, and Left Elevation

Sketch the respective elevation of the structure under investigation. As is with the Site Plan Sketch Pad, a grid is provided in the drawing area to aid in the proportioning of the sketch.

Important exterior dimensions, such as those of the structure, vent openings, doors, windows, and areas of fire damage can be noted either on the sketch itself, in the lower Details box, or in the Notes box on the form. In the completed example front, right, and rear elevation sketch pads of Figures 5.5B, 5.5D, and 5.5F, the reader will notice that photographs are substituted for actual sketches. Although it is unlikely that good quality photographs of the fire building will be available for use this early on in the investigation process, if such photographs exist they should be obtained and may be used for this purpose. Good quality photographs will illustrate the building in its true scale more effectively than will the average sketch.

Details

Enter the exterior dimensions of the structure including the width (or length when appropriate), the height and number of stories of the structure, the exterior wall and roofing materials, and the dimensions of doors and windows. Incidentally, in his research the author has observed that details such as the dimensions of doors and windows are consistently overlooked in the majority of fire investigation reports. However, these measurements are critical to scientists and engineers who require them for analyzing ventilation effects and their role in the fire's growth and spread.

FRONT ELEVATION SKETCH PAD	
Investigator Name:	**Date/Time:**
Front Elevation:	
Details: Width: Height/No. of Stories: Exterior Wall Material(s): Roofing Material(s) Important Dimensions: Door(s): Window(s):	**Notes:**
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Figure 5.5A – Front Elevation Sketch Pad

FRONT ELEVATION SKETCH PAD	
Investigator Name: John Doe	**Date/Time:** 05/12/96

Front Elevation:

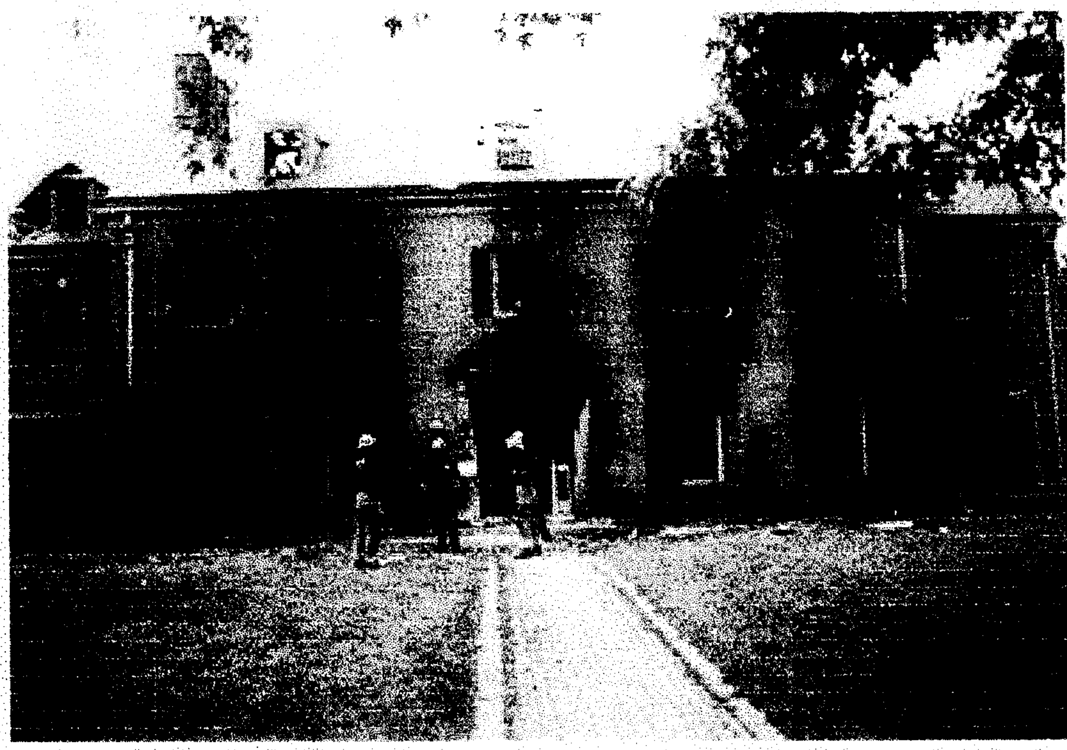

Photo Designation A-01 N

Details:	**Notes:**
Width: 88 ft.	Attic used for storage
Height/No. of Stories: 3.5 above grade	Exterior burn patterns
Exterior Wall Material(s): Masonry, approx 1.5 ft thick	
Roofing Material(s):	
Important Dimensions:	
Door(s):	
Window(s):	

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Figure 5.5B – Completed example Front Elevation Sketch Pad (Photo ©NFPA Fire Investigations Department. Used with permission.[78])

RIGHT ELEVATION SKETCH PAD	
Investigator Name:	**Date/Time:**
Right Elevation:	
Details: Length: Height/No. of Stories: Exterior Wall Material(s): Roofing Material(s): Important Dimensions: Door(s): Window(s):	**Notes:**
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Figure 5.5C – Right Elevation Sketch Pad

RIGHT ELEVATION SKETCH PAD

Investigator Name: John Doe **Date/Time:** 05/12/96

Right Elevation:

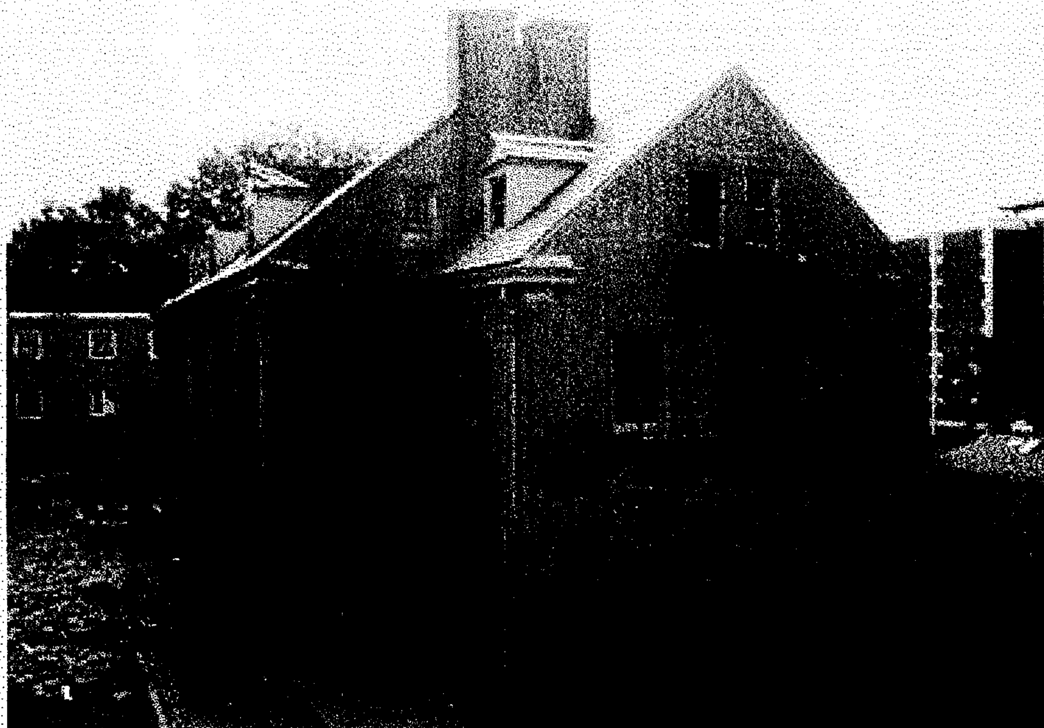

Photo Designation A-02 NW

Details:	**Notes:**
Length: 34 ft	Exterior burn patterns
Height/No. of Stories: 3.5 above grade	Fire escape
Exterior Wall Material(s): Masonry, 1.5 ft thick	Masonry wall separating E end from Main Bldg
Roofing Material(s)	
Important Dimensions:	
Door(s):	
Window(s):	

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Figure 5.5D – Completed example Right Elevation Sketch Pad (Photo ©NFPA Fire Investigations Department. Used with permission.[78])

REAR ELEVATION SKETCH PAD

Investigator Name:	**Date/Time:**

Rear Elevation:

Details:

Width:

Height/No. of Stories:

Exterior Wall Material(s):

Roofing Material(s)

Important Dimensions:

Door(s):

Window(s):

Notes:

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Figure 5.5E – Rear Elevation Sketch Pad

REAR ELEVATION SKETCH PAD	
Investigator Name: John Doe	**Date/Time:** 05/12/96

Rear Elevation:

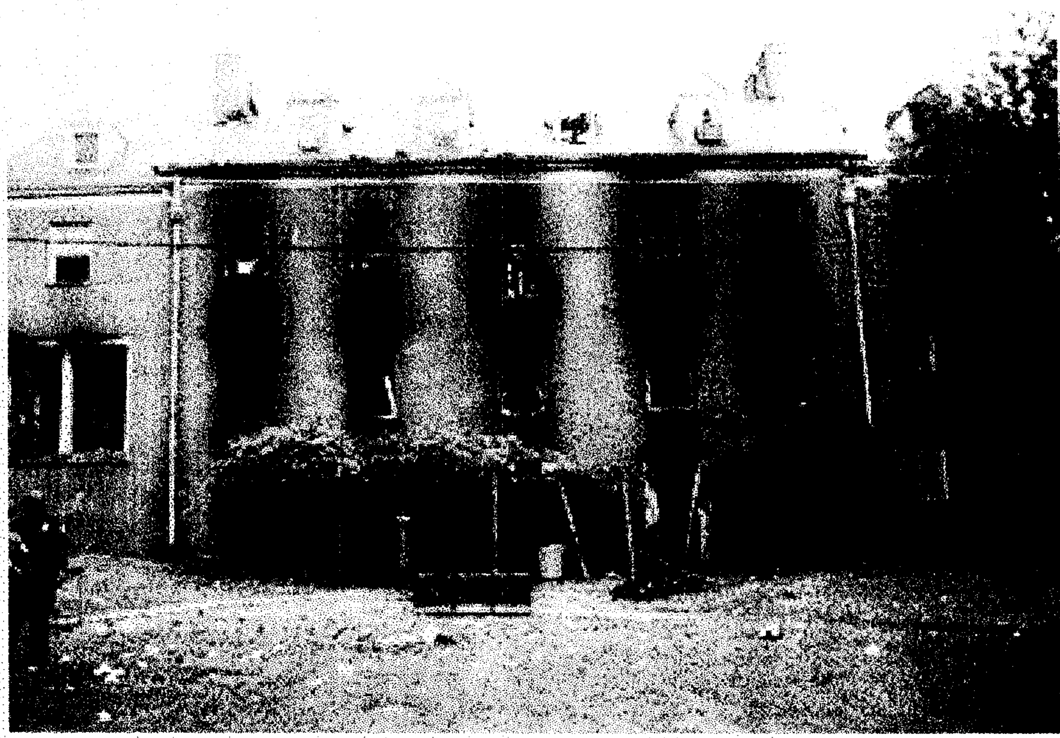

Photo Designation A-03 S

Details:	**Notes:**
Width: 88 ft	Basement exits to ground level in rear
Height/No. of Stories: 4.5 above grade	Exterior burn patterns
Exterior Wall Material(s): Masonry, 1.5 ft thick	
Roofing Material(s)	
Important Dimensions:	
Door(s):	
Window(s):	

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Figure 5.5.F – Completed example Rear Elevation Sketch Pad (Photo ©NFPA Fire Investigations Department. Used with permission.[78])

LEFT ELEVATION SKETCH PAD

Investigator Name: **Date/Time:**

Left Elevation:

Details:

Length:

Height/No. of Stories:

Exterior Wall Material(s):

Roofing Material(s)

Important Dimensions:

Door(s):

Window(s):

Notes:

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Figure 5.5G – Left Elevation Sketch Pad

5.1.6 Floorplan Sketch Pad

With the exterior documentation of the scene completed, it is time to begin acquiring knowledge about the interior of the structure. Conventional fire investigative methodology suggests documenting the interior of the structure from those areas that are least damaged to those which are most damaged. When using Floorplan Sketch Pads, the author suggests a more simplistic approach. Simply document the configuration of interior spaces from the lowermost to the uppermost floor. Doing so will create a routine to be followed consistently at every investigation. Every investigation being different, there will surely be cases where this routine will not be possible. However, at this stage of the investigation, walking through the structure in a systematic way while at the same time sketching the configurations of the spaces on each floor will enable the investigator to become more familiar with the layout of the building. Further along in the investigation, this familiarity with the structure will enable the investigator to more efficiently analyze and document the damage within the structure. Although noting generally where fire damage has occurred on each floorplan sketch is recommended, documenting the specific damage within the structure from least to most damaged areas will occur later on in the investigation, namely when completing the Exploded Room Sketch Pads – Damage/Victims Forms. The Floorplan Sketch Pad is reproduced in Figure 5.5A. A Completed example Floorplan Sketch Pad is shown in Figure 5.6B.

Floor Designation/Number

Enter a text descriptor of the floor, if appropriate (Basement, for example), and the floor number for the floorplan being sketched. The number of stories within the building will dictate the number of Floorplan Sketch Pads required to be completed by the investigator. It is recommended that a different Floorplan Sketch Pad be completed for every individual floor within the building. Sketch the floorplan of the floor in the gridded sketch area, noting space descriptors (Bedroom #1, Dining Room, Living Room, for example) and important dimensions in the sketch.

Details

Fields have been provided for noting specific information for up to five individual spaces on the floor being sketched. Important information to be recorded includes the space designation, the ceiling height and material(s), the wall materials and any interior finishes present, the floor material and finishes, and the dimensions of any vent openings, doors, and windows within the space.

Fire Protection Systems

Included in the Details section are fields to record the types of fire protection systems encountered within the structure, the particular spaces within the structure in which fire protection systems are present, and whether the systems did or did not actuate. Fire protection measures include fire detection systems, fire alarm systems, and fire suppression systems. Fields are also included for nothing the presence of egress signage and emergency lighting as well as a Notes box for recording other relevant observations.

FLOORPLAN SKETCH PAD

Investigator Name: **Date/Time:**

Floor Designation/No.:

Details:

Space Designation	Ceiling Height/Material	Wall Material/Interior Finish	Floor Finish(es)	Vent. Openings

	System Type	Spaces Present	Actuation	Notes:
Detection:			☐ Yes ☐ No	
Alarm:			☐ Yes ☐ No	
Suppression:			☐ Yes ☐ No	
Other:			☐ Yes ☐ No	

Egress Signage: ☐ Yes ☐ No
Lighting: ☐ Yes ☐ No

Notes:

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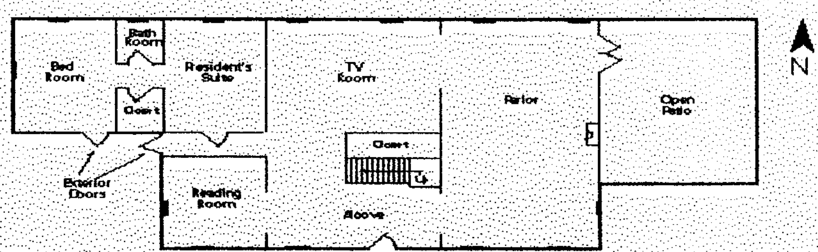
Figure 5.6A – Floorplan Sketch Pad

FLOORPLAN SKETCH PAD

Investigator Name: John Doe **Date/Time:** 05/12/96

Floor Designation/No.: First Floor



Details:

Space Designation	Ceiling Height/Material	Wall Material/Interior Finish	Floor Finish(es)	Vent. Openings
Alcove		painted plaster over gypsum with wood trim	1"x3" T&G Oak	
TV Room		painted plaster over gypsum with wood trim	1"x3" T&G Oak some carpeting	
Parlor		painted plaster over gypsum with wood trim	1"x3" T&G Oak some carpeting	
President's Suite		painted plaster over gypsum	1"x3" T&G Oak some carpeting	
Bedroom		painted plaster over gypsum	1"x3" T&G Oak some carpeting	
Reading Room		vert. 1"x8" rough sawn, heart pine nailed to horz. 1"x4" furring strips	1"x3" T&G Oak	
Open Patio				

	System Type	Spaces Present	Actuation	Notes:
Detection:			☐ Yes ☐ No	
Alarm:			☐ Yes ☐ No	
Suppression:			☐ Yes ☐ No	
Other:			☐ Yes ☐ No	

Egress Signage: ☐ Yes ☐ No

Lighting: ☐ Yes ☐ No

Notes:
Parlor - 2 upholstered couches, 1 upholstered chair
TV room - 2 upholstered couches, 1 upholstered chair, TV/entertainment center
Reading room - upholstered chair, small upholstered couch, wood lamp tables, sev. bookcases
President's suite - (sparsely furnished) 1 bed, 1 upholstered couch, misc furnishings

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Figure 5.6B – Completed example Floorplan Sketch Pad (Sketch ©NFPA Fire Investigations Department. Used with permission.[78])

5.1.7 The Exploded Room Sketch Pad – Damage/Victims Form

Following the documentation of the configuration of spaces within the structure is the documentation of the specific damage within the spaces of the structure. This can be accomplished by completing the Exploded Room Sketch Pad – Damage/Victims Form, reproduced in Figure 5.7A.

Space Designation/Number

Enter the numeric or text descriptor of the space (Room 1, Dining Room, Living Room, Parlor, for example) and the floor number or descriptor on which the space is located. Sketch an exploded room diagram of the space illustrating the observed damage. An example of such a diagram, along with a completed example Exploded Room Sketch Pad – Damage/Victims Form is depicted in Figure 5.7B.

Damage Details/Notes

Enter as many details as possible about the observed damage. Record what items are damaged, and in what way they are damaged. Provide a key or legend for symbols used in the sketch. Record and make special note of the photograph designations for all photographs taken illustrating any damage, or victims, discovered within the space.

Potential Areas of Origin

List any and all potential areas of origin within the space. For an investigation to be credible in a court of law, it is important that all potential heat sources be considered and eliminated before the origin and cause of a fire is determined.

Evidence Secured

List any and all evidence items secured with their respective evidence item numbers. Symbols representing the locations where samples were collected can be depicted in the exploded room diagram as is shown in Figure 5.7B.

Victim Details/Notes

If victims are discovered within the space, indicate the victim's designation number, the location and position in which the victim was found, and any relevant evidence items found around him or her. More specific victim information will be documented when completing the Victim Information Form.

EXPLODED ROOM DIAGRAM SKETCH PAD - DAMAGE/VICTIMS

Investigator Name: **Date/Time:**

Space Designation/No.:

Damage Details/Notes:

Potential Areas of Origin:

Evidence Secured:

Victim Details/Notes:

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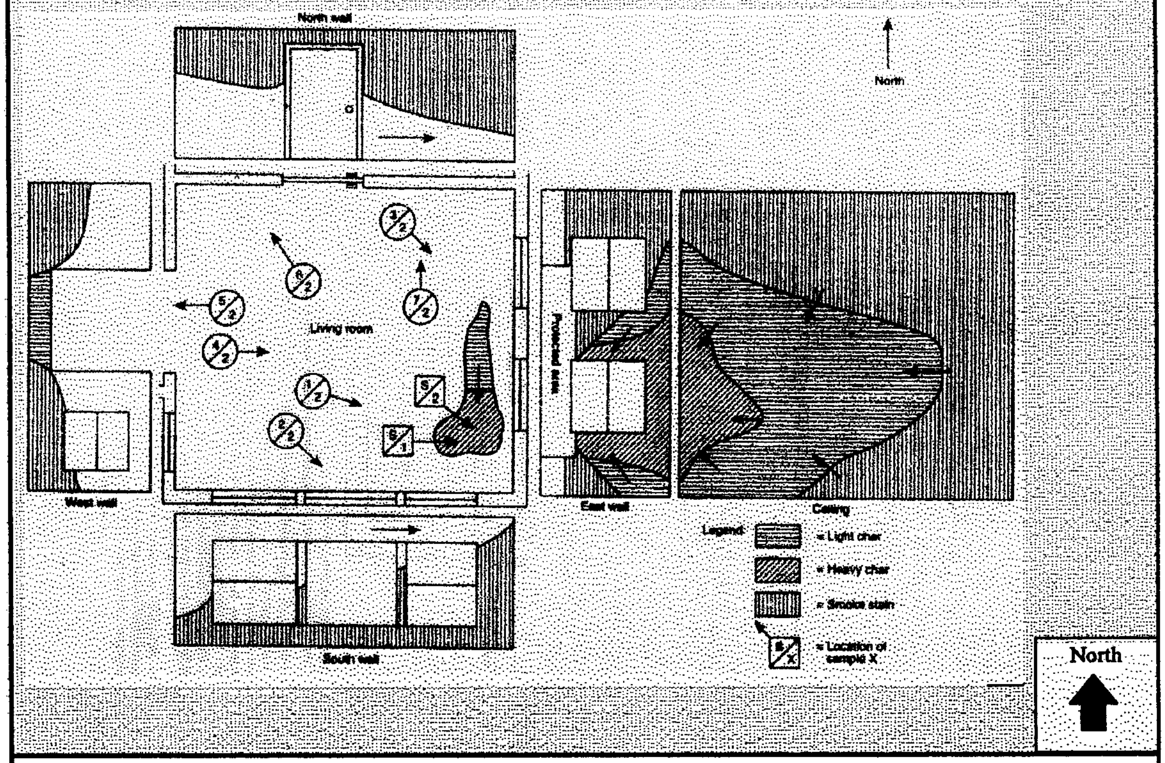
Figure 5.7A – The Exploded Room Sketch Pad – Damage/Victims Form

EXPLODED ROOM DIAGRAM SKETCH PAD - DAMAGE/VICTIMS

Investigator Name: John Doe **Date/Time:** 5/2/98 02:36

Space Designation/No.: Living Room, First Floor



Damage Details/Notes:
Arrows point to suspected area of heat source
Heaviest damage in southeast corner of room
Circles indicate locations of photographs - exposure numbers and roll designation

Potential Areas of Origin:
Southeast corner sofa

Evidence Secured:
Boxes indicate evidence items secured - number refers to evidence item number
Samples are of charred flooring material - to be tested for accelerants

Victim Details/Notes:
No victims

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Figure 5.7B – Completed example Exploded Room Sketch Pad – Damage/Victims (Sketch from NFPA 921[13])

5.1.8 The Exploded Room Sketch Pad – Contents Form

A picture or sketch of a room or space illustrating the orientation of its contents before the fire incident can be very useful. Constructing such a sketch is often difficult for an investigator to do due to the extent to which fire service personnel overhaul the structure after extinguishment efforts have concluded. However, interviewing building occupants or even having them complete the illustration can both be effective methods of gaining insight into the original configuration of the room contents. The Exploded Room Sketch Pad – Contents Form, reproduced in Figure 5.8, is intended to be used for this purpose.

Space Designation/Number

Enter the numeric or text descriptor of the space and the floor number, or text descriptor, on which the space is located. Sketch an exploded room diagram of the space illustrating the contents and their orientation within the space. As stated earlier, interviewing and/or using occupants to aid in the completion of the sketch can be very effective.

Contents Details/Notes

Being as specific as possible, list the items believed to be present within the space at the time of the fire, their brand names, model numbers, physical properties including size and dimensions, as well as their constituent materials, if known. Documenting this information will facilitate the most accurate reconstruction possible of the fire's growth rate and development within the space. Record and make special note of the photograph designations for all relevant photographs obtained which may illustrate the pre-fire contents contained within the space and/or their arrangement within the space.

Detection, Alarm and Suppression Systems

Document the detection, alarm, and suppression system type in the respective field when present within the space. Be as descriptive as possible. Indicate the symbol(s) used in the sketch to represent detectors, alarm signaling devices, manual pull-stations, and sprinklers. Document whether the system activated by checking the appropriate 'yes' or 'no' box adjacent to the 'Activation' field. Lastly, document any unique observations in the Notes fields for each system type.

EXPLODED ROOM DIAGRAM SKETCH PAD - CONTENTS

Investigator Name: **Date/Time:**

Space Designation/No.:

Contents Details/Notes:

Detection:	**Alarm:**	**Suppression:**
Type:	Type:	Type:
Symbol:	Symbol:	Symbol:
Activation: ☐ Yes ☐ No	Activation: ☐ Yes ☐ No	Activation: ☐ Yes ☐ No
Notes:	Notes:	Notes:

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Figure 5.8 – The Exploded Room Sketch Pad – Contents Form

5.1.9 Evidence Information Form

The Evidence Information Form, reproduced in Figure 5.9, is included in order to provide accountability for evidence secured from the scene. The form contains fields to document what the item is, where it was discovered and by whom, how it was packaged, where it is being stored, and who has had the item in his or her possession since the time of collection.

Evidence Item/Label

Enter the identification number or text descriptor assigned to the evidence item. Every evidence item collected at the scene should have a unique label assigned to it. For the duration of the investigation, these labels shall be used when referring to the individual evidence items. A separate Evidence Information Form shall be completed for each individual evidence item. It is on this more specific form where photographs taken of the evidence item can be noted.

Location Discovered

Enter the location, room, or space in which the evidence item was first discovered. Remain consistent with the location designations assigned earlier in the Site Plan, Elevation, Floorplan, and Exploded Room Sketch Pads.

Consent to Search

When consent to search is required by law, indicate by checking the appropriate box whether consent to search the premises was granted.

Search Warrant Required and Obtained

Indicate by checking the appropriate boxes whether a search warrant was required and obtained in order to conduct the search of the premises.

Collection Date/Time and Person(s) Collecting

Enter the exact date and time that the evidence item was collected and the person(s) responsible for securing the evidence.

State at time of Collection

Enter the state or condition of the evidence item at the time of collection. Documenting this information will help the investigator to track the condition of the evidence item should any changes take place to the item from either natural causes, such as "aging", or from unnatural causes, such as tampering.

Control Sample

Enter whether or not a control sample was collected for the evidence item. If so, indicate the control sample's evidence item/label. A separate Evidence Information Form should be completed for all control samples collected.

Packaging Method

Indicate how the evidence item was packaged at the scene to reduce the risk of persons tampering with the evidence item. Metal cans, glass jars, special liquid and solid accelerant evidence bags, and common plastic bags are all examples of basic packaging methods[13].

Storage Location

Enter the location at which the evidence item will be, or is being, stored.

Chain of Possession

This section is included in order to track the possession of the evidence item. Person's receiving the evidence item shall document the name of the person from whom they received the item, the name of the person who is receiving the item, and the date and time at which possession of the item was transferred.

Analyses to be Conducted

This section is included for the investigator to note what analyses, if any, will be conducted on or using the evidence item.

Notes

Lastly, a Notes field is included to document any unique observations and/or specific information not included in the upper portions of the Evidence Information Form.

EVIDENCE INFORMATION

Investigator Name: **Date/Time:**

Evidence Item/Label:

Location Discovered:

Consent to Search: ☐Yes ☐No

Search Warrant Required: ☐Yes ☐No **Obtained:** ☐Yes ☐No

Collection Date/Time: / / : **Person(s) Collecting:**

State at time of Collection:

Control Sample Collected: ☐Yes ☐No **Evidence Item/Label:**

Packaging Method:

Storage Location:

Chain of Possession:

Rec'd. From:

By:

Date/Time: / / :

Rec'd. From:

By:

Date/Time: / / :

Rec'd. From:

By:

Date/Time: / / :

Analyses to be Conducted Using Evidence Item:

Notes:

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Figure 5.9 – The Evidence Information Form

5.1.10 The Victim Information Form

The last of the thirteen form series, a Victim Information Form is included in order to document important information surrounding the victim's discovery, identification, and subsequent laboratory analysis, when required. The Victim Information Form is reproduced in Figure 5.10. The Victim Information Form should be completed in as much detail as possible at the scene. However, in some situations only limited information will be available, at which times the remainder of the form is to be completed following the necessary laboratory analyses.

Victim Designation

Enter the identification number or text descriptor assigned to the victim. Each victim should have a unique label. Assigning numbers to victims in the order in which they were discovered is perhaps the most common and least confusing practice. A separate Victim Information Form shall be completed for each individual victim.

If ascertainable, enter the gender of the victim, the exact date and time of discovery, by whom the victim was discovered, the location at which the victim was found, and a description of the body position at time of discovery in the appropriate fields.

Related Photographs

List any photographs taken relating to the victim. Enter the Roll Designation(s), Photo or Exposure Number(s), and a brief description of what is depicted in the photograph. The location and perspective at which the photographs were taken should be marked with symbols on the Exploded Room Sketch Pad – Damage/Victims Form.

Related Evidence Secured

List any Evidence Items secured at the scene that may be related to the victim's association with the incident. Briefly describe what the evidence item is and why it may be related to the victim.

Laboratory Analysis

Indicate whether laboratory analyses will be required to further identify the victim by checking the appropriate check box. If analyses are required, enter the types of analyses to be conducted and the agencies responsible.

Personal Information

Once positive identification of the victim has been established, enter the victim's name, date of birth, social security number, address, and association with the incident.

VICTIM INFORMATION

Investigator Name: **Date/Time:**

Victim Designation:

Gender:

Date/Time discovered:

Discovered by:

Location discovered:

Description of body position:

Related Photographs:

Roll Designation: Photo No.(s): Description(s):

Related Evidence Secured:

Evidence Item/Label(s): Description(s):

Laboratory analysis required for identification ☐ Yes ☐ No

Analyses Conducted: By:

Personal Information:

Name: DOB:

Social security number:

Street address:

Town/State/Zip:

Association to incident:

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Figure 5.10 – The Victim Information Form

5.2 Part Two – Intuition-Enhancing Flowcharts

After documenting the scene, the investigator develops, and subsequently tries to substantiate, hypotheses about the fire. Four flowcharts have been developed in order to provide the investigator with a better sense for the fire's growth rate and spread. However, before delving into the explanations of the flowcharts, it may be helpful to provide a brief explanation of the stages of fire development within a compartment.

5.2.1 Stages of Fire Development

A compartment fire is defined as a fire that is confined to a room or enclosure within a building or structure. Compartment fires have definite stages of fire development. The typical stages of compartment fire development, as shown in Figure 5.11, are[79]:

1. Ignition
2. Growth
3. Flashover and post-flashover
4. Decay

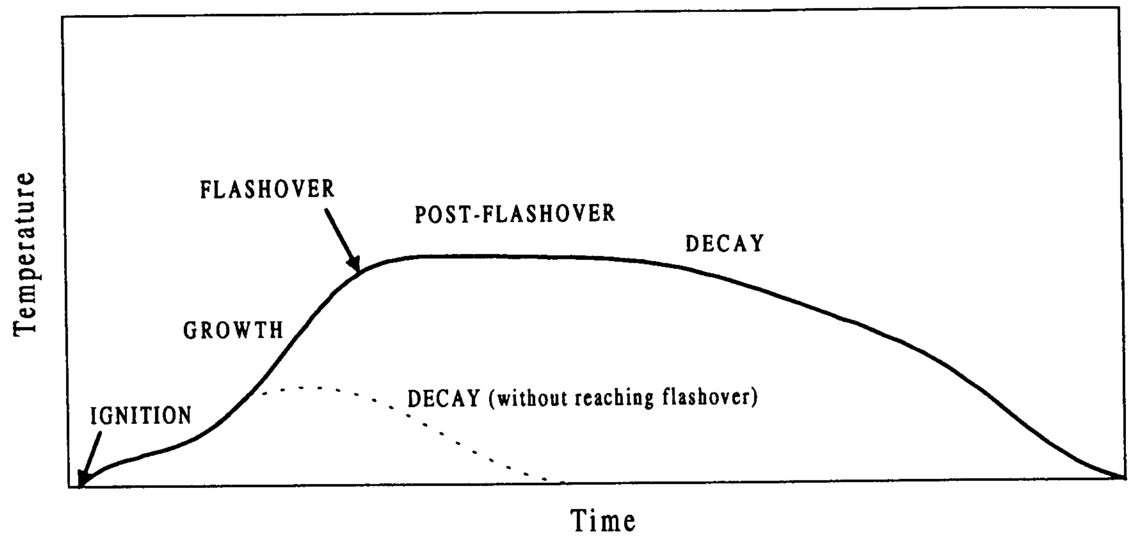


Figure 5.11 – Temperature/time curve showing the stages of fire development[79]

Every compartment fire must undergo ignition and decay stages, however whether a fire undergoes a full growth, flashover, and corresponding post-flashover stage depends on several variables. The quantity, type, and arrangement of the fuels, the size and ventilation capabilities of the compartment, the amount of oxygen available to be entrained by the fire, and the efficiency of any automatic or manual fire suppression efforts all play a role in a fire's development.

Ignition

The ignition stage occurs when a heat source of sufficient energy necessary to commence sustained combustion comes in contact with one or more fuel packages[79]. The ignition stage may consist of smoldering or flaming combustion depending on the type of fuel package and ignition source exposure. During the ignition stage, the fire will behave as though it is in the open, unaffected by the confinement of the compartment in which it is located. Little, if any, changes in the environment within the compartment will be noticed[79].

Growth

The growth stage occurs when the fire begins to spread over the item first ignited and to other fuel packages. The fire consequently develops in size, height of flame, and heat release rate[79]. It is during this stage that as the fire continues to grow, the influence of confinement by the compartment will begin to be evident. The buoyant products of combustion will begin to rise, forming a ceiling jet as a result of confinement caused by walls and ceilings. The heated gases will accumulate in the upper region of the compartment and the beginnings of a hot, upper gas layer will develop. Walls, corners, and the ceiling will influence entrainment and flame height[80]. If present, detection and suppression equipment will usually activate during the growth phase. Unless either the amount of fuel or oxygen available to the fire becomes limited, the exothermic combustion reaction is inhibited, or the flames are cooled sufficiently, conditions within the compartment will begin to deteriorate rapidly and will eventually lead to the onset of flashover, or full room involvement. Occupants within the fire compartment who have not escaped prior to flashover are unlikely to survive. However, if either the fuel or oxygen available becomes sufficiently limited, or the flames are adequately cooled, the fire may cease to develop or begin to recede. When this occurs, the fire is said to have entered the decay stage.

Flashover and Post-Flashover

Flashover and post-flashover have been grouped together to form one stage in a fire's development. Flashover is the brief transition period from the growth stage to the fully developed or post-flashover fire, in which all combustible items in the compartment become involved in the fire[79]. Early experiments conducted in 1968 by T. E. Waterman revealed that a minimal heat flux of approximately 20 kW/m^2 at floor level was required for flashover. Waterman also observed that flashover was not attained until the burning rate within the compartment surpassed 40 g/s. Presently, the most widely used criteria for flashover are upper gas layer temperatures in the neighborhood of 500 to 600°C as observed in experiments conducted by Hagglund and Fang in the mid 1970's[80].

The post-flashover stage occurs when the heat release rate of the fire is at its largest. The hot gas layer during this stage may be as low as the floor of the compartment. Often, under post-flashover conditions, the fire will become ventilation controlled, meaning that the fire will be pyrolyzing more fuel than can be burned with the available amount of oxygen within the compartment. The compartment fire environment, specifically the increased radiation to the floor from the presence of the hot and smoky gas layer, plays a significant role in increasing the pyrolysis rate of the burning objects. Under such circumstances, the unburned fuel leaves the compartment through any ventilation openings present. Cracks around the perimeters of doors and windows, doors and windows themselves, HVAC vents, and pipe chases can all act as ventilation openings to hot fire gases. Once the hot gases escape, they will burn outside the compartment where adequate oxygen levels can be found. Hagglund originally used this observation as his criterion for determining the occurrence of flashover[80].

Decay

The decay stage occurs as the fire begins to burn out. Only a fuel-limited condition, a ventilation-limited condition, fire suppression efforts, or any combination of the latter will bring about the decay stage. During the decay stage, the heat release rate begins to decrease and approach zero as time increases[80].

5.2.2 The Flowcharts

Four flowcharts have been developed for the purpose of enhancing the investigator's intuition for the fire's growth rate and spread. The flowcharts deal with the following fire phenomena:

1. The time to detector and/or sprinkler operation
2. The height of the flames
3. The height of the smoke or hot gas layer within the compartment over time

4. The occurrence of flashover

Each flowchart expands upon information obtained from an investigation making use of the on-site data collection methodology and forms described earlier in Section 5.1, On-Site Data Collection. The purpose of the flowcharts is to help the investigator gain insight into the fire's behavior. Why the fire behaved in a certain way, why it developed at a certain rate, why occupants weren't able to escape, and why detectors or sprinklers did not operate are just a few of the questions that can potentially be answered by following the logic presented in the following flowcharts.

Format of the Flowcharts

Each flowchart begins with a text box containing a question posed to the investigator. Under each question are potential resources, including important observations for which the investigator should look, for finding an answer to the question. Once an answer or opinion is obtained, a 'YES' or 'NO' decision must be made. Depending on the specific flowchart and answer, more information may or may not be required to proceed. If more information is needed, a text box will follow the 'YES' or 'NO' decision. Within this text box will be fire phenomena to examine either qualitatively or quantitatively. Quantitative methods will be in italicized print and refer to the Calculation Methods of the Field Guide to be presented in Section 5.3. By using the Calculation Methods, the investigator should be able to quantitatively model some of the more relevant fire phenomena. The flowcharts are depicted in Figures 5.12 through 5.15.

5.2.2.1 The Detector Response Flowchart

The purpose of the Detector Response Flowchart is to aid the investigator in determining the times at which smoke, heat, or automatic sprinklers actuated, or should have actuated during the fire. Calculation methods associated with estimating detector response deal with determining the conditions, or environment, within the compartment at an estimated point in time. Besides those specifically developed for estimating heat and smoke detector response time, calculation methods associated with estimating time to detection include those for estimating pre-flashover compartment fire temperatures, and the temperature and velocity of ceiling jets. Determining how rapidly the fire might have spread from one fuel package to another by calculating the radiant heat transfer to the various fuel packages, or targets, of concern also can play a role in estimating the time to detection.

5.2.2.2 The Flame Height Flowchart

The purpose of the Flame Height Flowchart is to help the investigator determine whether witness statements of fire size and growth concur with the facts and physical evidence observed and collected during the investigation. By quantitatively comparing the observed flame heights from witness statements with those calculated for the fuel packages present within the compartment using the calculation method to be described in Section 5.3, the investigator can gain insight into whether the fire's growth was unusual and/or accelerated in some way.

5.2.2.3 The Smoke Layer Level Flowchart

The purpose of the Smoke Layer Level Flowchart is to help the investigator determine the rate at which the products of combustion filled the compartment(s) of concern. Also making use of occupant and witness statements, the Smoke Layer Level Flowchart enables the investigator to compare information from the witness statements relating to the presence of smoke to quantified values determined by using the calculation methods suggested in Figure 5.14.

5.2.2.4 The Flashover Flowchart

The purpose of the Flashover Flowchart is to determine whether flashover or full room involvement occurred, whether it occurred as a natural result of the fire or as a result of an accelerant being used, and lastly when and why it occurred given the compartment and fuels under investigation.

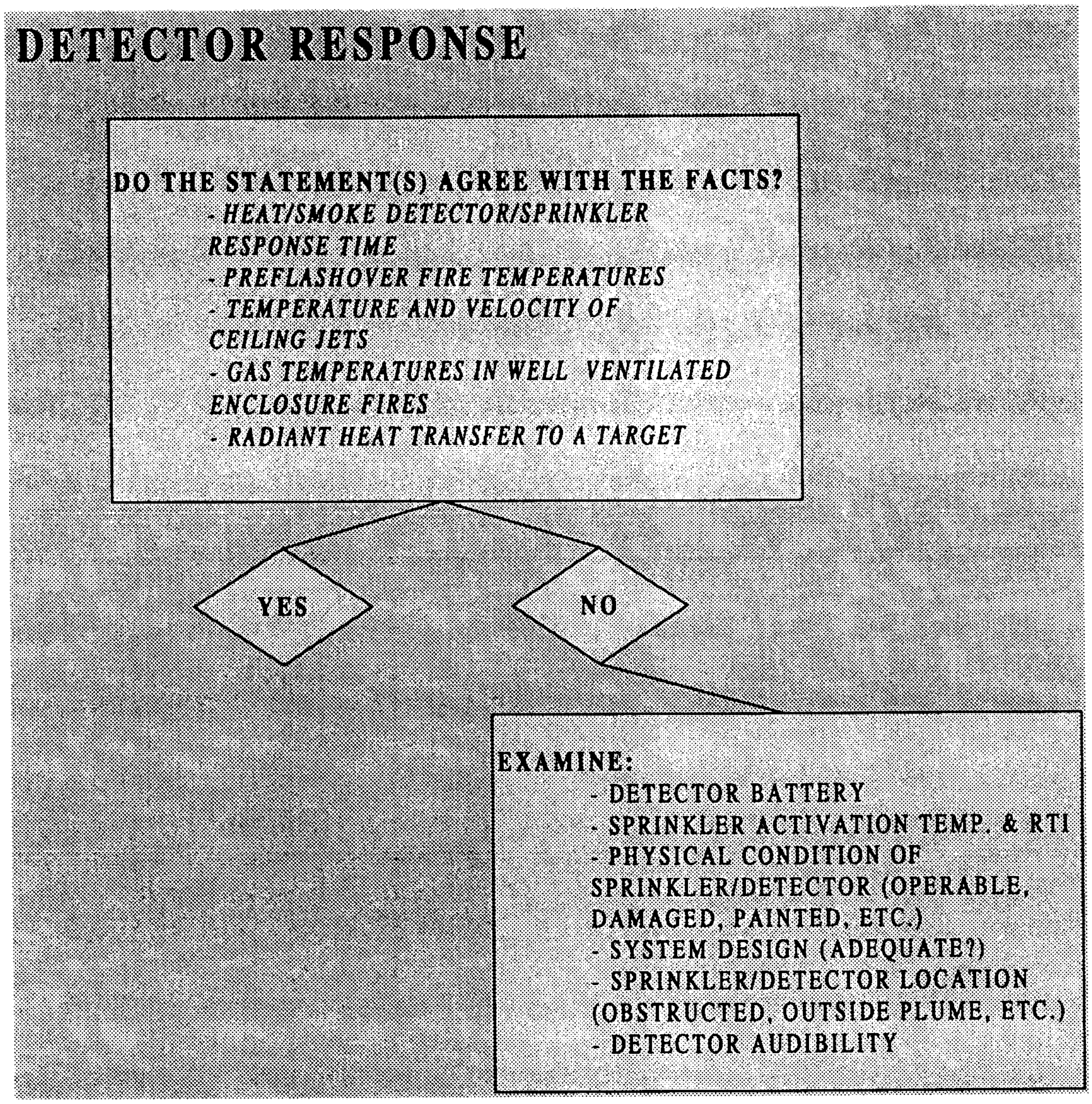


Figure 5.12 – The Detector Response Flowchart

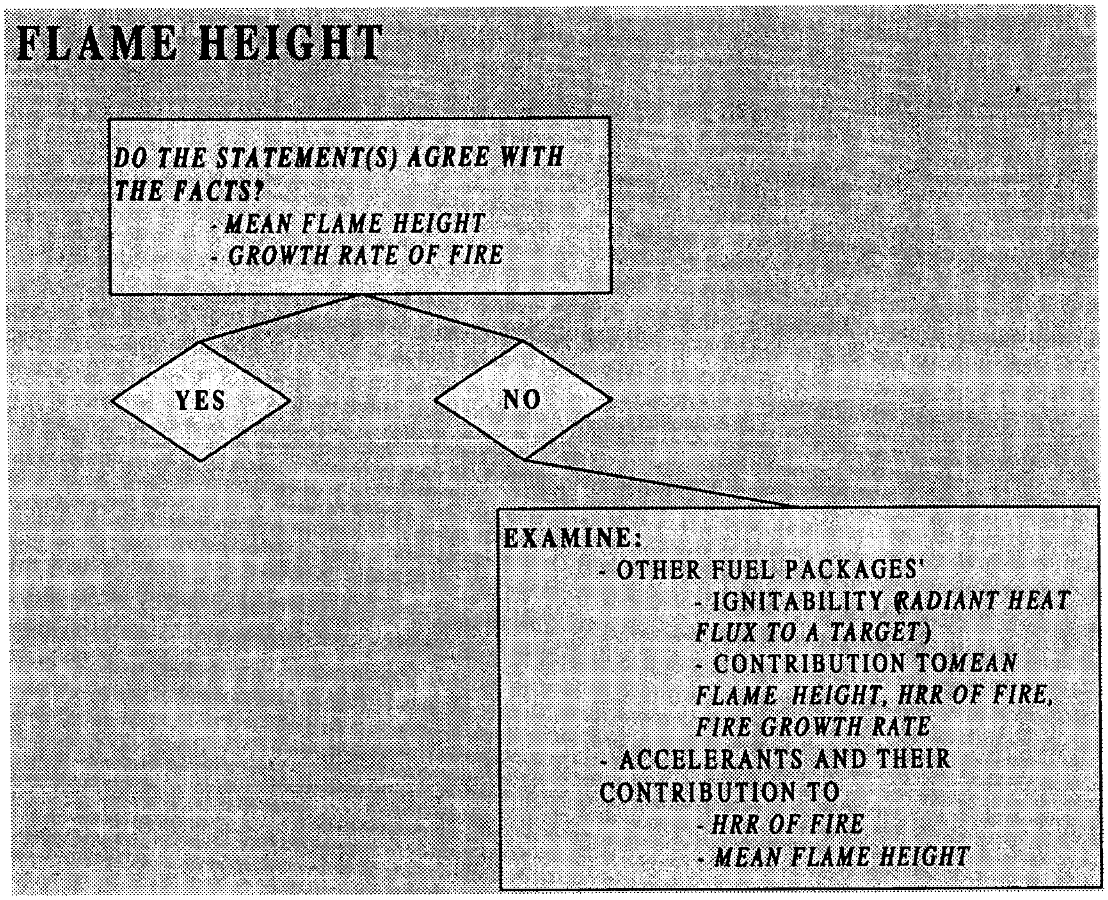


Figure 5.13 – The Flame Height Flowchart

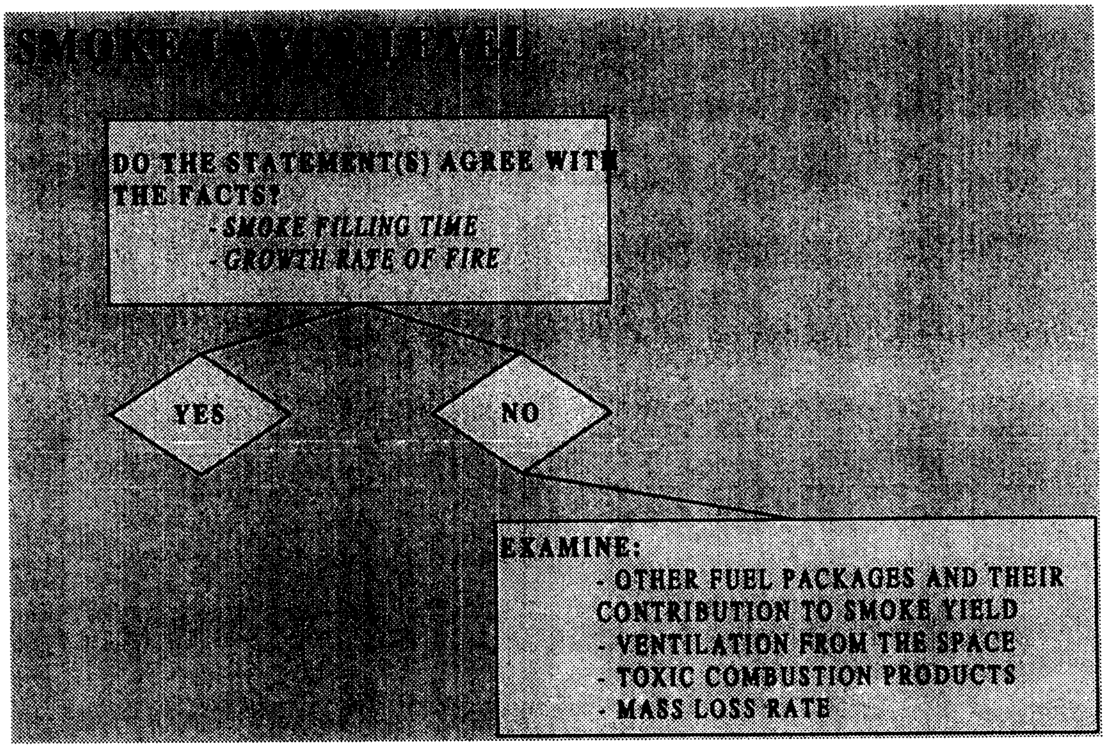


Figure 5.14 – The Smoke Layer Level Flowchart

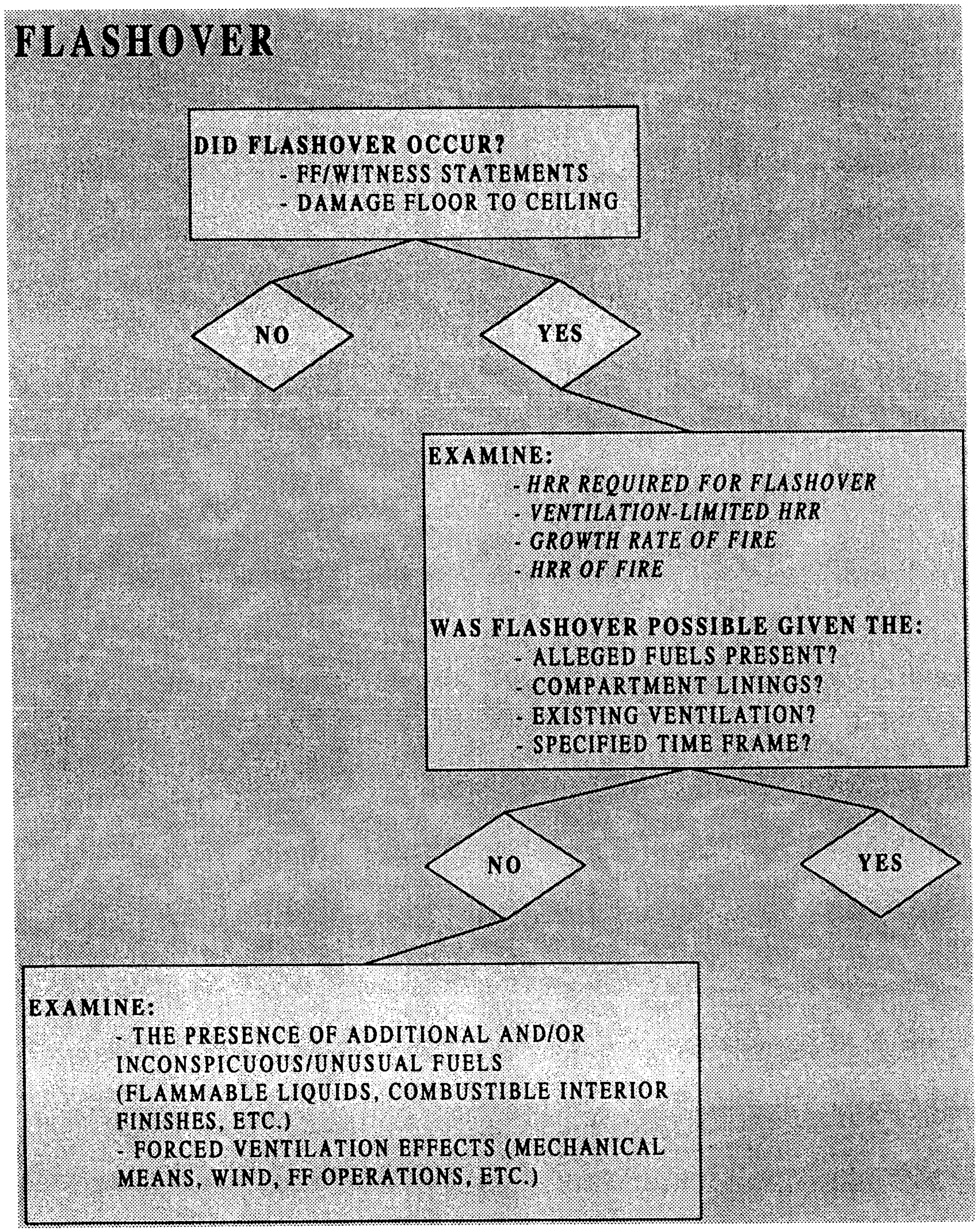


Figure 5.15 – The Flashover Flowchart

5.3 Part Three – Calculation Methods

Eleven basic calculation methods, or models, have been included for the purpose of enabling the investigator to simulate certain phenomena relating to the growth and development of fires. The calculation methods presented are:

1. Estimating the growth rate of the fire
2. Estimating the heat release rate of the fire
3. Estimating radiant heat transfer from a point source to a target
4. Estimating radiant heat transfer from a parallel planar source to a target
5. Estimating maximum temperature and velocity of ceiling jets
6. Estimating heat/smoke detector and sprinkler response time
7. Estimating mean flame height
8. Estimating pre-flashover compartment fire temperatures
9. Estimating smoke filling time
10. Estimating the heat release rate necessary for flashover
11. Estimating the ventilation limited heat release rate of the fire

Format of the Calculation Methods

Each calculation method is presented on a separate page, or series of pages where required. At the top of the page is a description of the method, followed by the equation or equations to be used in the method, and a brief definition of the dependant variable and its respective units for which the method will solve. The variables (along with their appropriate units) required to properly use the method, and the assumptions and limitations inherent to the method are also listed. Furthermore, guidance is given as to where, in the appropriate text fields of the on-site data collection forms and sketch pads presented in Section 5.1, to find values for the necessary variables. Whenever possible, generic data in the forms of graphs, tables, and figures, relating to the properties of fuels has been included with the methods to aid the investigator with their use. Where necessary, additional information pertaining to variables and/or the application of any specific data expressed within the generic data table or figure will be explained below the respective table or figure. Following each calculation method is a sample calculation, demonstrating how the method can be used in a manner relevant to an investigation.

Method for: Estimating the Growth Rate of the Fire[81]

$$\dot{Q} = \alpha t^2 \qquad \text{[Eq. 5.1]}$$

where $\dot{Q}$ is the estimated instantaneous heat release rate at established burning (kW) at time, t (s)

Required Variables:

α - the fire growth factor (kW/s^2) [refer to Tables 5.1 – 5.4 and Figures 5.16 – 5.21]
t - the time from established ignition (s)

Assumptions/Limitations:

- Assumes the fire growth factor, α, is constant over the growth period.
- Does not account for HRR from ignition to established burning.
- Only accounts for the HRR for the growth phase of the fire until the fire reaches its maximum HRR or combustion is limited due to insufficient oxygen. The method does not account for the time period from ignition to t_0, the time at which the burning item begins established burning.
- Does not apply to smoldering fires or fires with a steady HRR, such as flammable liquids
- Does not account for reduction in HRR due to suppression

Relevant Areas on Field-guide Forms:

1. Floorplan Sketch Pad (ceiling and wall materials, interior finishes)
2. Exploded Room Sketch Pad - Contents Form (contents details/notes)
3. Exploded Room Sketch Pad - Damage/Victims Form (damage details/notes)

Generic Data:

Table 5.1 - Values of α for different growth rates according to NFPA 204M[82]

Growth rate	α (kW/s^2)	Time (s) to reach 1055 kW
Slow	0.003	600
Medium	0.012	300
Fast	0.047	150
Ultra fast	0.190	75

Table 5.2 - Typical growth rates recommended for various types of occupancies[83]

Type of occupancy	Growth rate α (kW/s^2)
Dwellings without upholstered furniture	0.012, medium
Dwellings containing upholstered furniture	0.047;fast, to 0.190;ultra fast
hotels, nursing homes	0.047, fast
Shopping centers, entertainment centers	0.190, ultra fast
schools, offices	0.047, fast
Hazardous industries, high piled combustible storage	No typical value

Generic Data (continued):

Table 5.3 - Energy release rate data from Nelson[84]

Item Description	Growth rate, α, (kW/s^2)	Peak energy release rate⁺, (kW/m^2 of floor area)
fire retarded treated mattress	0.003, slow	17
Lightweight type C upholstered furniture**	0.012, medium	170*
moderate weight type C upholstered furniture**	0.003, slow	400*
mail bags, full, stored 5 feet high	0.047, fast	400
cotton/polyester innerspring mattress	0.012, medium	565*
Lightweight type B upholstered furniture**	0.012, medium	680*
medium weight type C upholstered furniture**	0.003, slow	680*
methyl alcohol pool fire	0.190, ultra-fast	740
heavy weight type C upholstered furniture**	0.003, slow	795*
Polyurethane innerspring mattress (including bedding)	0.047, fast	910*
moderate weight type B upholstered furniture**	0.012, medium	1020*
wooden pallets, 1 ½ feet high	0.012, medium	1420
medium weight type B upholstered furniture**	0.012, medium	1645*

⁺Peak energy release rates represent the peak energy released per unit floor area occupied by the individual test sample

* Peak rates of energy release were of short duration. These fuels typically showed a rapid rise to the peak and a corresponding rapid decline. In each case the fuel package tested consisted of a single item.

** The classification system used to describe upholstered furniture is as follows:

Lightweight - less than about $5lbs/ft^2$ of floor area. A typical 6ft long couch would weigh under 75lbs.
Moderate weight - about $5\text{-}10lbs/ft^2$ of floor area. A 6ft long couch would weigh between 75 and 150lbs.
Medium weight - about $10\text{-}15lbs/ft^2$ of floor area. A 6ft long couch would weigh between 150 and 300lbs.
Heavyweight - more than about 15lbs/ft of floor area. A typical 6ft long couch would weigh over 300lbs.
Type A - furniture with untreated or lightly treated foam plastic padding and nylon or other melting fabric.
Type B - furniture with lightly or untreated foam plastic padding or nylon or other melting fabric.
Type C - furniture with cotton or treated foam plastic padding, having cotton or other fabric that resists melting.

Generic Data (continued):

Table 5.3 continued - Energy release rate data from Nelson[8484]

Item Description	Growth rate, α, (kW/s²)	Peak energy release rate⁺, (KW/m² of floor area)
Lightweight type A upholstered furniture**	0.047, fast	1700*
empty cartons, 15 feet high	0.047, fast	1700
diesel oil pool fire (> about 3 feet in diameter)	0.047, fast	1985
cartons containing polyethylene bottles, 15 feet high	0.190, ultra-fast	1985
moderate weight type A upholstered furniture**	0.047, fast	2500*
Particleboard wardrobe/chest of drawers	0.047, fast	2550*
gasoline pool fire (> about 3 feet in diameter)	0.190, ultra-fast	3290
thin plywood wardrobe - fire retardant paint on all surfaces	0.190, ultra-fast	3855*
wooden pallets, 5 feet high	0.047, fast	3970
medium weight type A upholstered furniture**	0.047, fast	4080*
Heavyweight type A upholstered furniture**	0.047, fast	5100*
thin plywood wardrobe (50in. x 24in x 72in high)	0.190, ultra-fast	6800*
wooden pallets, 10 feet high	0.047, fast	6800
wooden pallets, 16 feet high	0.047, fast	10200

⁺Peak energy release rates represent the peak energy released per unit floor area occupied by the individual test sample

*Peak rates of energy release were of short duration. These fuels typically showed a rapid rise to the peak and a corresponding rapid decline. In each case the fuel package tested consisted of a single item.

** The classification system used to describe upholstered furniture is as follows:

Lightweight - less than about 5lbs/ft² of floor area. A typical 6ft long couch would weigh under 75lbs.
Moderate weight - about 5-10lbs/ft² of floor area. A 6ft long couch would weigh between 75 and 150lbs.
Medium weight - about 10-15lbs/ft² of floor area. A 6ft long couch would weigh between 150 and 300lbs.
Heavyweight - more than about 15lbs/ft of floor area. A typical 6ft long couch would weigh over 300lbs.
Type A - furniture with untreated or lightly treated foam plastic padding and nylon or other melting fabric.
Type B - furniture with lightly or untreated foam plastic padding or nylon or other melting fabric.
Type C - furniture with cotton or treated foam plastic padding, having cotton or other fabric that resists melting.

Generic Data (continued):

Table 5.4 - Fire growth rates for various commodities[20]

Commodity Description and mass (kg)	Test No.	α (kW/s²)	t_0^* (s)
metal wardrobe, 41.4kg (total)	15	0.4220	10
chair F33 (trial loveseat) 39.2kg	18	0.0066	140
chair F21, 28.15kg (initial stage of fire growth)	19	0.0344	110
chair F21, 28.15kg	19	0.04220	190
metal wardrobe, 40.8kg (total) (average growth)	21	0.0169	10
metal wardrobe, 40.8kg (total) (later growth)	21	0.0733	60
metal wardrobe, 40.8kg (total) (initial growth)	21	0.1055	30
chair F24, 28.3kg	22	0.0086	400
chair F23, 31.2kg	23	0.0066	100
chair F22, 31.9kg	24	0.0003	150
chair F26, 19.2kg	25	0.0264	90
chair F27, 29.9kg	26	0.0264	360
chair F29, 14.0kg	27	0.1055	70

* t_0 is defined as the start time, in seconds, of the test. It is after the amount of time t_0 has passed that the item has begun established burning. It is at this time when the heat release rate curve as a function of time begins can be approximated by the P=2 power law expression, $\dot{Q} = \alpha t^2$.

Generic Data (continued):

Table 5.4 (continued) - Fire growth rates for various commodities[20]

Commodity Description and mass (kg)	Test No.	α (kW/s^2)	t_0^+ (s)
chair F28, 29.2 kg	28	0.0058	90
chair F25, 27.8kg (later growth)	29	0.2931	175
chair F25, 27.8kg (initial growth)	29	0.1055	100
chair F30, 25.2kg	30	0.2931	70
chair F31, (loveseat) 39.6kg	31	0.2931	145
chair F31, (loveseat) 39.6kg	37	0.1648	100
chair F32, (sofa) 51.5kg	38	0.1055	50
½ inch plywood wardrobe with fabrics, 68.8kg	39	0.8612	20
½ inch plywood wardrobe with fabrics, 68.32kg	40	0.8612	40
1/8 inch plywood wardrobe with fabrics, 36.0kg	41	0.6594	40
1/8 inch plywood wardrobe with fire retardant (interior finish initial)	42	0.2153	50
1/8 inch plywood wardrobe with fire retardant (interior finish later)	42	1.1722	100
repeat of ½ inch plywood wardrobe, 67.62kg	43	1.1722	50
1/8 inch plywood wardrobe with fire retardant latex paint, 37.26kg	44	0.1302	30

$^+$ t_0 is defined as the start time, in seconds, of the test. It is after the amount of time t_0 has passed that the item has begun established burning. It is at this time when the heat release rate curve as a function of time begins can be approximated by the P=2 power law expression, $\dot{Q} = \alpha t^2$.

Generic Data (continued):

Table 5.4 continued - Fire growth rates for various commodities[20]

Commodity Description and mass (kg)	Test No.	α (kW/s^2)	t_0* (s)
chair F21, 28.34kg (large hood)	45	0.1055	120
chair F21, 28.34kg	46	0.5210	130
chair, adjustable back metal frame, foam cushion, 20.8kg	47	0.0365	30
Easychair CO7, 11.52kg	48	0.0344	90
Easychair, 15.68kg (F-34)	49	0.0264	50
chair, metal frame with cushion, 16.52kg	50	0.0264	120
chair, molded fiberglass, no cushion, 5.28kg	51	0.0733	20
molded plastic patient chair, 11.26kg	52	0.0140	2090
chair, metal frame with padded seat and back, 15.5kg	53	0.0086	50
loveseat, metal frame with foam cushions, 27.26kg	54	0.0042	210
group chair, metal frame with foam cushion, 6.08kg	55	Never exceeded 50kW	
chair, wood frame with latex foam cushions, 11.2kg	56	0.0042	50
loveseat, wood frame with foam cushions, 54.60kg	57	0.0086	500
Wardrobe, ¾ inch particle board, 120.33kg	61	0.0469	0
Bookcase, plywood with aluminum frame, 30.39kg	62	0.2497	40
Easychair, molded flexible urethane frame, 15.98kg	64	0.0011	750
Easychair, 23.02kg	66	0.1876	3700
Mattress and boxspring, 62.36kg (initial fire growth)	67	0.0086	400
Mattress and boxspring, 62.36kg (initial fire growth)	67	0.0009	90

* t_0 is defined as the start time, in seconds, of the test. It is after the amount of time t_0 has passed that the item has begun established burning. It is at this time when the heat release rate curve as a function of time begins can be approximated by the P=2 power law expression, $\dot{Q} = \alpha t^2$.

Generic Data (continued):

The following figures can be used to estimate the instantaneous heat release rate, in kW, at a specific time, in seconds, for the burning item of concern.

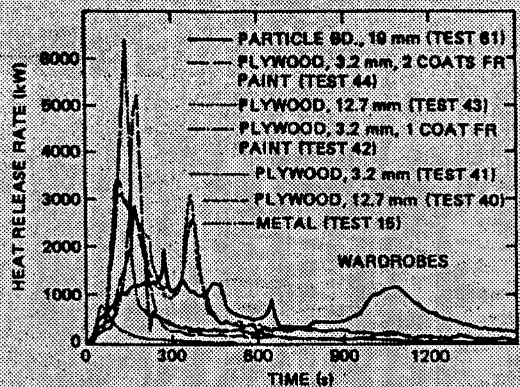


Fig 5.16 - HRR results for wardrobes[21]

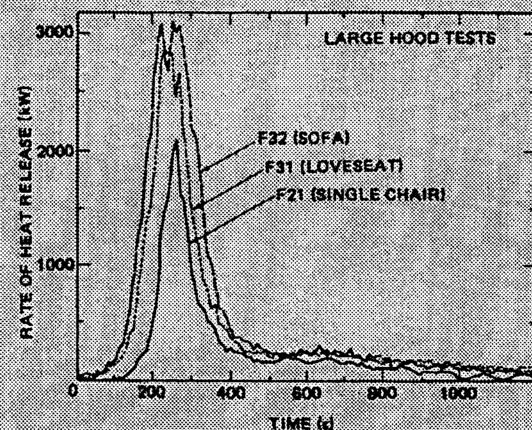


Fig. 5.17 - HRR results for upholstered furniture[21]

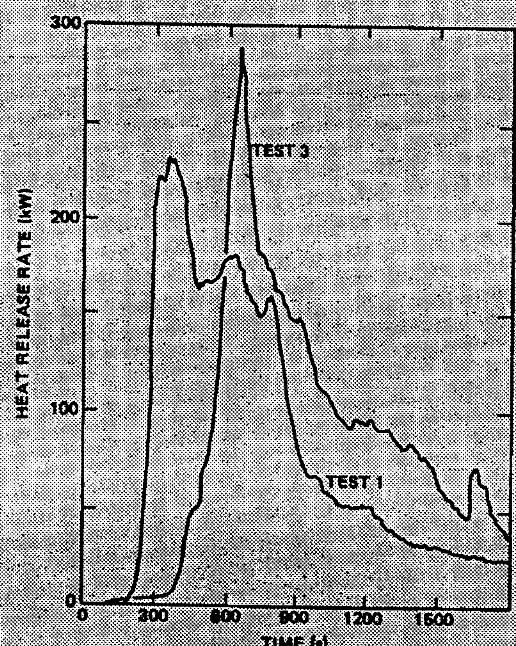


Fig. 5.18 - HRR results for television sets[21]

Generic Data (continued):

The following figures can be used to estimate the instantaneous heat release rate, in kW, at a specific time, in seconds, for the burning item of concern.

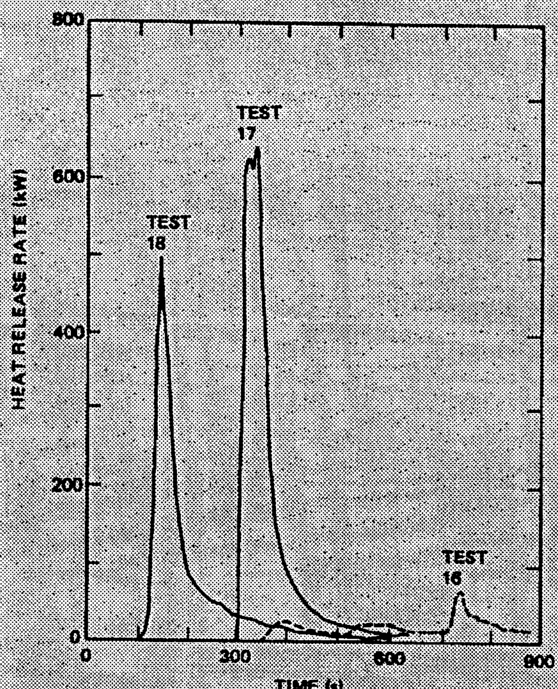


Fig 5.19 - HRR results for Christmas trees[21]

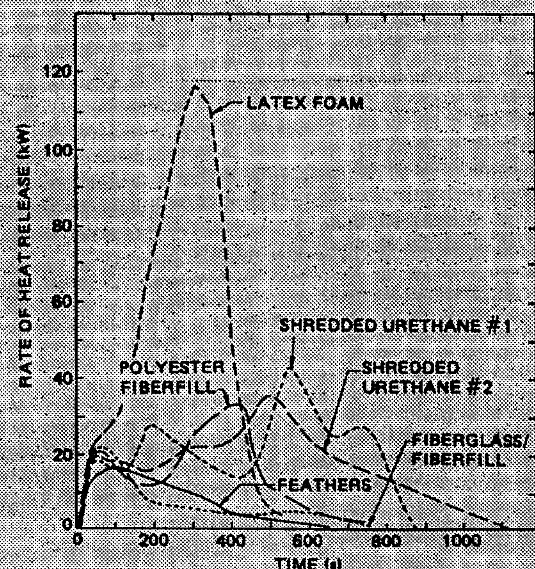
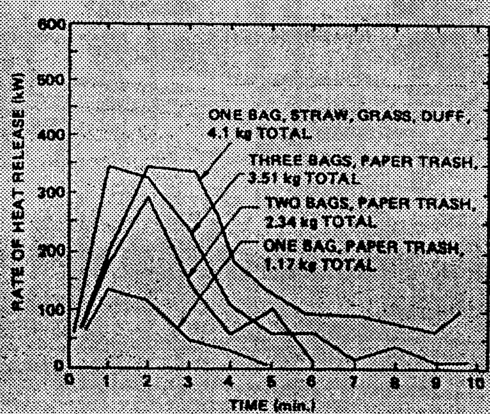


Fig. 5.20 - HRR results for pillows[21]



5.21 - HRR results for trash bags[21]

Sample Calculation for: Estimating the Growth Rate of the Fire

Problem: An investigator is examining a bedroom fire in which flashover took place. The heat release rate necessary to produce flashover within the compartment was calculated to be roughly 1200 kW. Statements from witnesses and firefighters set the time to flashover at some time between 5 and 10 minutes (300 and 600 seconds) after fire was reported to 911. Should the aforementioned information about the time to flashover by itself seem at all peculiar to the investigator?

Solution:

In order to answer the question, one can calculate the range of growth rates, α, for the fire using Equation 5.1 and compare the range of values to experimental data to ascertain whether the fire developed at an unusual rate.

[Eq. 5.1] $$\dot{Q} = \alpha t^2 \text{ kW}$$

Therefore, $$\alpha = \frac{\dot{Q}}{t^2} \text{ kW/s}^2$$

$\dot{Q} = 1200$ kW
$t^2 = (300)^2, (600)^2$

$$0.013\frac{kW}{s^2} \leq \alpha \leq 0.003\frac{kW}{s^2}$$

Comparing the calculated range of values for α to the values of α listed in Table 5.1 reveals that the fire developed at a '0.003, slow' to 'medium' rate. Further comparison with data contained in Tables 5.2, 5.4, and 5.5 reveals that the time period of 5 to 10 minutes for flashover within a bedroom is not unusual and should not alone evoke special concern from the investigator, especially since the initial start time, t_0, is not known.

Method for: Estimating the Heat Release Rate (HRR) of the Fire[21]

$$\dot{Q} = A_f \dot{m}'' X_c \Delta H_c \qquad \text{[Eq. 5.2]}$$

where $\dot{Q}$ is the estimated constant heat release rate (kW)

Required Variables:

A_f - the horizontal burning floor area of the fuel (m^2)
$\dot{m}''$ - the burning rate of the material per horizontal area ($kg/(m^2 s)$)
X_c - the combustion efficiency (typically 0.7 - 0.8)
ΔH_c - the complete heat of combustion (kJ/kg) [refer to data in Table 5.5]

Assumptions/Limitations:

- Burning rates determined experimentally may be smaller in an enclosure fire due to decreased oxygen levels
- The complete heat of combustion, determined in a bomb calorimeter, accounts for the combustion of the entire sample in pure oxygen, leaving almost no residue and releasing almost all of its potential energy - unrepresentative of real enclosure fires.
- For pool fires of diameter, D, greater than 0.2m (D>0.2m), the burning rate will be defined as:

$$\dot{m}'' = \dot{m}''_{\infty}\left(1 - e^{-k\beta D}\right) \qquad \text{[Eq. 5.3]}$$

where $\dot{m}''_{\infty}$, and $k\beta$ depend on the liquid type and are given in Table 5.6.

Relevant Areas on Field-guide Forms:

1. Floorplan Sketch Pad (ceiling and wall materials, interior finishes)
2. Exploded Room Sketch Pad - Contents Form (contents details/notes)
3. Exploded Room Sketch Pad - Damage/Victims Form (damage details/notes)

Generic Data:

Table 5.5 - Burning rates per unit area and complete heats of combustion for various materials[22]

Material (values in brackets indicate pool diameters tested)	$\dot{m}''$ (kg/m^{2}s)	ΔH_c (MJ/kg)
Polyethylene	0.026	43.6
Polypropylene	0.024	43.4
heavy fuel oil (2.6-23m)	0.036	
kerosene (30-80m)	0.065	44.1
crude oil (6.5-31m)	0.056	
n-dodecane (0.94m)	0.036	44.2
gasoline (1.5-223m)	0.062	
JP-4 (1-5.3m)	0.067	
JP-5 (0.6-1.7m)	0.055	
n-heptane (1.2-10m)	0.075	44.6
n-hexane (0.75-10m)	0.077	44.8
transformer fluids (2.37m)	0.025-0.30	
polystyrene (0.93m)	0.034	39.2
xylene (1.22m)	0.067	39.4
benzene (0.75-6.0m)	0.081	40.1
Polyoxymethylene	0.016	15.4
polymethylmethacrylate, PMMA (2.37m)	0.030	25.2
methanol (1.2-2.4m)	0.025	20
acetone (1.52m)	0.038	29.7
flexible polyurethane foams	0.021-0.027	23.2-27.2
rigid polyurethane foams	0.022-0.025	25.0-28.0
polyvinylchloride, PVC	0.016	16.4
tefzel™, ETFE	0.014	12.6
teflon™, FEP	0.007	4.8

Generic Data (continued):

Table 5.6 - Data for large pool (D>0.2m) burning rate estimates[21]

Material	Density (kg/m^3)	$\dot{m}''_\infty$ (kg/m^{2}s)	ΔH_c (MJ/kg)	kβ (m^{-1})
liquid H_2	70	0.017	120.0	6.1
LNG (mostly CH_4)	415	0.078	50.0	1.1
LPG (mostly C_3H_8)	585	0.099	46.0	1.4
methanol (CH_3OH)	796	0.017	20.0	*
ethanol (C_2H_5OH)	794	0.015	26.8	*
butane (C_4H_{10})	573	0.078	45.7	2.7
benzene (C_6H_6)	874	0.085	40.1	2.7
hexane (C_6H_{14})	650	0.074	44.7	1.9
heptane (C_7H_{16})	675	0.101	44.6	1.1
xylene (C_8H_{10})	870	0.090	40.8	1.4
acetone (C_3H_6O)	791	0.041	25.8	1.9
dioxane ($C_4H_8O_2$)	1035	0.018	26.2	5.4**
diethyl ether ($C_4H_{10}O$)	714	0.085	34.2	0.7
benzene	740	0.048	44.7	3.6
gasoline	740	0.055	43.7	2.1
kerosene	820	0.039	43.2	3.5
JP-4	760	0.051	43.5	3.6
JP-5	810	0.054	43.0	1.6
transformer oil, hydrocarbon	760	0.039**	46.4	0.7**
fuel oil, heavy	940-1000	0.035	39.7	1.7
crude oil	830-880	0.022-0.045	42.5-42.7	2.8
polymethylmethacrylate ($C_5H_8O_2$)$_n$	1184	0.020	24.9	3.3
polypropylene (C_3H_6)$_n$	905	0.018	43.2	
polystyrene (C_8H_8)$_n$	1050	0.034	39.7	

* Value independent in turbulent regime
** Estimate uncertain since only two points available

Sample Calculation for: Estimating the Heat Release Rate (HRR) of the Fire

Problem: A fuel spill involving approximately 10 gallons of gasoline is contained in a 2 m diameter retention basin. Rather than notify the proper authorities to clean up the spill, the foreman hastily decides to ignite the pool of gasoline. What will be the expected heat release rate of such a pool fire?

Solution:

Using Equations 5.2 and 5.3, coupled with data provided in Table 5.6 for gasoline, the heat release rate, $\dot{Q}$, can be calculated.

[Eq. 5.2] $$\dot{Q} = A_f \dot{m}'' X_c \Delta H_c \quad \text{(kW)}$$

$A_f = \pi(2/2)^2 \ \text{m}^2$

$X_c = 0.8$

From Table 5.6, for gasoline: $\Delta H_c = 43.7$ MJ/kg = 43700 kJ/kg

Because D>0.2 m, from Equation 5.3,

$$\dot{m}'' = \dot{m}''_\infty \left(1 - e^{-k\beta D}\right) \ \text{kg/m}^2\,\text{s}$$

From Table 5.6 for gasoline: $\dot{m}''_\infty = 0.055 \ \text{kg/m}^2\,\text{s}$
$k\beta = 2.1 \ \text{m}^{-1}$

Substituting into Equations 5.2 and 5.3,

$$\dot{m}'' = 0.055\left(1 - e^{-(2.1)(2)}\right) = 0.054 \ \text{kg/m}^2\,\text{s}$$

$$\dot{Q} = \pi(0.054)(0.8)(43700) = 5931 \ \text{kW}$$

A heat release rate of approximately 5900 kW, or 5.9 MW, can be expected from a 2 m diameter gasoline pool fire.

Method for: Estimating Radiant Heat Transfer from a Point Source to a Target[85]

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi \cdot R_o^2} \qquad \text{[Eq. 5.4]}$$

where $\dot{q}''$ is the radiative heat flux received by the target (kW/m^2)

Required Variables:

χ_r - the radiative fraction of total energy released (-)
$\dot{Q}$ - the estimated heat release rate (kW) at the time of concern
R_o - the distance from the centerline of the radiation source to the target (m)

Assumptions/Limitations:

- Radiation is assumed to be isotropic, or as emanating from a point source.
- Target is assumed to be normal to the radiation source.
- Flux reduces as the square of the distance

Relevant Areas on Field-guide Forms:

1. Floorplan Sketch Pad (ceiling and wall materials, interior finishes)
2. Exploded Room Sketch Pad - Contents Form (configuration/spacing of fuel packages, contents details/notes - fuel types)
3. Exploded Room Sketch Pad - Damage/Victims Form (damage details/notes)
4. Witness interviews/statements/information (Sketch Pads also if witness has been asked to illustrate observations as part of their statement)

Generic Data:

- The radiative fraction, χ_r, depends on the fuel, flame size, and configuration. Common values for χ_r range from 0.15 for low sooting fuels, such as alcohols, to 0.60 for high sooting fuels. For fires larger than several meters in diameter, cold soot enveloping the luminous flame can reduce χ_r considerably[86].

Sample Calculation for: Estimating Radiant Heat Transfer from a Point Source to a Target

Problem: Using the point source method of Equation 5.4, estimate the incident flux to a wooden shed located 10 m from the center of the burning 2 m gasoline pool fire mentioned in the **Sample Calculation for: Estimating the Heat Release Rate (HRR) of the Fire**. Compare this estimate to the critical heat flux for wood. (The critical heat flux is defined as the minimum heat flux at or below which a material cannot generate a combustible mixture, comprised of the pyrolyzates mixed with air, to support ignition[22].)

Solution:

The radiative heat flux at the shed, $\dot{q}''$, can be calculated using Equation 5.4,

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi \cdot R_o^2} \text{ kW/m}^2$$

$R_o = 10$ m

$\dot{Q} = 5931$ kW

$\chi_r = 0.3$ (approximation for gasoline)

Substituting into Equation 5.4,

$$\dot{q}'' = \frac{(0.3)(5931)}{4\pi(10^2)} = 1.41 \text{ kW/m}^2$$

The critical heat flux for wood is approximately 10 kW/m^2 [22]. Therefore, the flux at the shed being estimated at only 1.41 kW/m^2, it would seem that there is not enough incident energy at the shed to cause the ignition of the structure.

Method for: Estimating Radiant Heat Transfer from a Parallel Planar Source to a Target[23]

$$\dot{q}'' = F\left(\frac{\chi_r \dot{Q}}{A_{fl}}\right) \quad \text{[Eq. 5.5]}$$

where $\dot{q}''$ is the radiative heat flux received by the target (kW/m^2)

Required Variables:

F - configuration factor from target to flame (-) [refer to **Generic Data]**

χ_r - radiative fraction of total energy released (-)

$\dot{Q}$ - the estimated heat release rate (kW) at the time of concern

A_{fl} - area of flame shape (m^2)

Assumptions/Limitations:

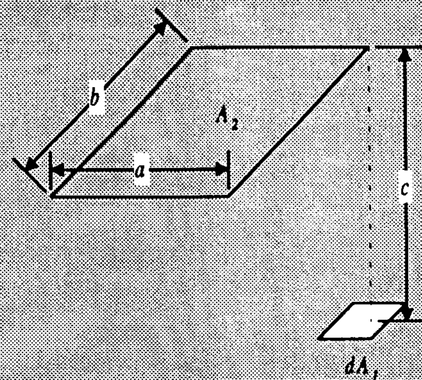
- Radiant source, or flame, is idealized as a simple rectangular plane of area A_{fl}.
- Soot particles are assumed to be perfectly spherical, and uniformly and randomly distributed.

Relevant Areas on Field-guide Forms:

1. Floorplan Sketch Pad (ceiling and wall materials, interior finishes)
2. Exploded Room Sketch Pad - Contents Form (configuration/spacing of fuel packages, contents details/notes - fuel types)
3. Exploded Room Sketch Pad - Damage/Victims Form (damage details/notes)
4. Witness interviews/statements/information (Sketch Pads also if witness has been asked to illustrate observations as part of their statement)

Generic Data:

Configuration factor, *F*, for a receiver element lying perpendicular to one corner of a parallel rectangle[23]:

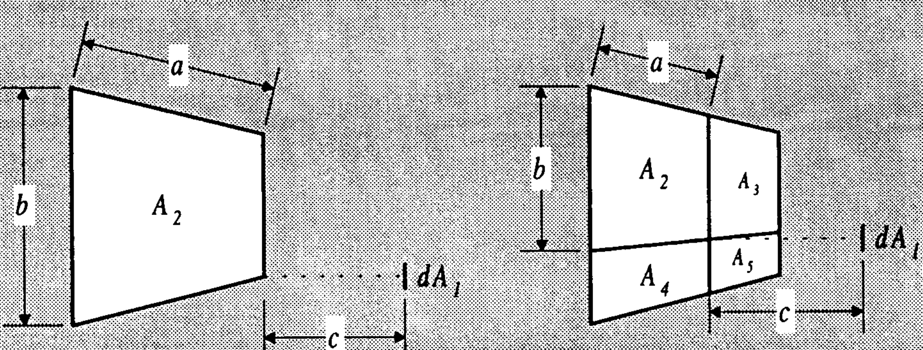


$X = a/c \qquad Y = b/c$

$$F_{d1-2} = \frac{1}{2\pi}\left\{\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left[\frac{Y}{\sqrt{1+X^2}}\right] + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left[\frac{X}{\sqrt{1+Y^2}}\right]\right\}$$

Where F_{d1-2} is the configuration factor for the receiver element dA_1 lying perpendicular to one corner of the parallel rectangle A_2. **Note:** The argument of $\tan^{-1}$ must be expressed in radians, not degrees.

Combining configuration factors for determining the configuration factor, *F*, for a receiver element lying perpendicular to a plane:



$$F_{d1-2,3,4,5} = F_{d1-2} + F_{d1-3} + F_{d1-4} + F_{d1-5}$$

Sample Calculation for: Estimating Radiant Heat Transfer from a Parallel Planar Source to a Target

Problem: A room and contents fire has reached flashover at approximately 2000 kW and is now emitting flames through two 1 m square windows spaced 1 m apart, effectively creating a 3 m by 1 m wall of flame. Estimate the heat flux to a neighboring structure, a perpendicular distance of 5 m away from the burning structure.

Solution:

The radiative heat flux at the shed, $\dot{q}''$, can be calculated using Equation 5.5,

$$\dot{q}'' = F\left(\frac{\chi_r \dot{Q}}{A_{fl}}\right) \text{ kW/m}^2$$

$\dot{Q} = 2000$ kW

$\chi_r = 0.6$ (conservative approximation for a sooty fire)

$A_{fl} = (3)(1) = 3$ m^2 (see **Sample Calculation for: Estimating Mean Flame Height)**

The fire is assumed to radiate as a rectangular plane with a length of 3 m and height of 1 m. Therefore, one quarter of the configuration factor for the flames, A_1, to the neighboring structure, dA_2 can be calculated by,

$$\frac{1}{4}F_{d1-2} = \frac{1}{2\pi}\left\{\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left[\frac{Y}{\sqrt{1+X^2}}\right] + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left[\frac{X}{\sqrt{1+Y^2}}\right]\right\}$$

where $X = \dfrac{3/2}{5}$ and $Y = \dfrac{1/2}{5}$

Substituting into the above equation, and solving for $F_{d1\text{-}2}$,

$F_{d1\text{-}2} = 0.036$

Substituting into Equation 5.5,

$$\dot{q}'' = (0.036)\left(\frac{(0.6)(2000)}{3}\right) = 14.4 \text{ kW/m}^2$$

The estimated flux to the neighboring building is 14.4 kW/m^2. The critical heat flux for wood being approximately 10 kW/m^2 [22], the neighboring structure is indeed an exposure problem and should be protected by hose streams in order to prevent ignition.

Method for: Estimating Maximum Temperature and Velocity of Ceiling Jets[81]

For $r/H \leq 0.18$:

$$T_{MAX} - T_{\infty} = \frac{16.9\dot{Q}^{2/3}}{H^{5/3}} \quad \text{[Eq. 5.6]}$$

For $r/H > 0.18$:

$$T_{MAX} - T_{\infty} = \frac{5.38\left(\frac{\dot{Q}}{r}\right)^{2/3}}{H} \quad \text{[Eq. 5.7]}$$

For $r/H \leq 0.15$:

$$u_{MAX} = 0.96\left(\frac{\dot{Q}}{H}\right)^{1/3} \quad \text{[Eq. 5.8]}$$

For $r/H > 0.15$:

$$u_{MAX} = \frac{0.195\dot{Q}^{1/3}H^{1/2}}{r^{5/6}} \quad \text{[Eq. 5.9]}$$

where T_{MAX} is the ceiling jet maximum temperature (K) and,
u_{MAX} is the maximum ceiling jet velocity (m/s)

Required Variables:

T_{∞}	- the ambient temperature (K)
$\dot{Q}$	- the estimated heat release rate (kW) at the time of concern
H	- the ceiling height of the compartment (m)
r	- the radial distance from the centerline of the fire plume to the point of concern (m)

Assumptions/Limitations:

- Correlations valid for steady fires only, where the heat release rate, $\dot{Q}$, is constant.
- Assumes that the properties of T_{MAX} for r/H • 0.18 and u_{MAX} for r/H • 0.15 are independent of the radial distance r from the plume centerline.
- The experimental data upon which the correlations were based were test burns of various types of solid and liquid fuels with energy release rates ranging from 500 kW to 100 MW under smooth ceilings with heights ranging from 4.6m to 15.5m.
- The correlations apply only during times after fire ignition when the ceiling flow can be considered unconfined.
- T_{MAX} and u_{MAX} occur very close to the ceiling, at around 1% of the distance from the fuel to the ceiling. Therefore, be advised that detection and suppression devices placed outside this range will experience cooler temperatures and lower velocities, lending to increased response/actuation times.

Relevant Areas on Field-guide Forms:

1. General Information (T_{∞})
2. Floorplan Sketch Pad (ceiling height, distance r)
3. Exploded Room Sketch Pad - Contents Form (ceiling height, distance r)
4. Exploded Room Sketch Pad - Damage/Victims Form (ceiling height, distance r)
5. Witness interviews/statements/information (Sketch Pads also if witness has been asked to illustrate observations as part of their statement)

Sample Calculation for: Estimating Maximum Temperature and Velocity of Ceiling Jets

Problem: A kerosene pool fire is ignited if an industrial building, releasing 200 kW, in an room with a floor area of 6 m by 6 m and a height of 5 m. Detection devices at ceiling level are positioned in such a manner that the maximum distance from the plume axis to the nearest device is 6 m. Estimate the maximum ceiling jet velocity and the maximum ceiling jet temperature at a detection device positioned 5 m from the plume centerline. Also estimate the ceiling jet temperature at or near the plume axis.

Solution:

Since $r/H > 0.15$, the maximum ceiling jet velocity at a position 5 m from the plume centerline is calculated using Equation 5.9,

$$u_{MAX} = \frac{0.195(200)^{1/3}(5)^{1/2}}{(5)^{5/6}} = 0.67 \text{ m/s}$$

Since $r/H > 0.18$, the maximum ceiling jet temperature at a position 5 m from the plume centerline is calculated using Equation 5.7,

Assuming an ambient temperature, T_∞, of 20°C,

$$T_{MAX} = \frac{5.38\left(\frac{200}{5}\right)^{2/3}}{5} + 20 = 32.6 \text{ °C}$$

The ceiling jet temperature at or near the plume axis, where $r/H \leq 0.18$, can be estimated using Equation 5.6,

Also assuming an ambient temperature, T_∞, of 20°C,

$$T_{MAX} = \frac{16.9(200)^{2/3}}{(5)^{5/3}} + 20 = 59.5 \text{ °C}$$

Method for: Estimating Heat/Smoke Detector and Sprinkler Response Time[20]

Step 1: Determine the height, H, of the detector above the fuel
Step 2: Estimate the fire growth characteristic, α, for the fuel expected to be burning
Step 3: Determine the spacing of the existing detectors or sprinklers, S_p. The protection radius, r_p, is then defined as $r_p = S_p/1.414$
Step 4: Determine the detector's rated response temperature and its RTI or τ_o and u_o. (RTI=$\tau_o u_o^{1/2}$)
Step 5: Make a first estimate of the response time of the detector or the fire size at detector response. They are related through the power-law fire growth equation $\dot{Q} = \alpha t^2$.
Step 6: Assume that the fire starts obeying the power-law model at time $t = 0$.
Step 7: Set the initial temperature of the detector and its surroundings at 293K (20°C)
Step 8: Using Equation 5.10, calculate the nondimensional time, t^*_{2f}, at which the initial heat front reaches the detector.

$$t^*_{2f} = 0.95\left(1 + {}^{r_p}\!/\!_H\right) \qquad \text{[Eq. 5.10]}$$

Step 9: Use the estimated response time along with Equation 5.11 to calculate the corresponding reduced time t^*_2. If t^*_2 is greater than t^*_{2f}, continue with **Step 10**. If not try a longer estimated response time, and return to **Step 8**.

$$t^*_2 = \frac{0.493t}{\alpha^{-1/5} H^{4/5}} \qquad \text{[Eq. 5.11]}$$

Step 10: Calculate the ratio u/u^*_2 using Equation 5.12.

$$u^*_2 = \frac{2.030u}{\alpha^{1/5} H^{2/5}} \qquad \text{[Eq. 5.12]}$$

Step 11: Calculate the ratio $\Delta T/\Delta T^*_2$ using Equation 5.13.

$$\Delta T^*_2 = \frac{0.017\Delta T}{\alpha^{2/5} H^{-3/5}} \qquad \text{[Eq. 5.13]}$$

Step 12: Use Equation 5.14 to calculate ΔT^*_2.

$$\Delta T^*_2 = \left[\frac{t^*_2 - t^*_{2f}}{0.188 + 0.313\,{}^{r_p}\!/\!_H}\right]^{4/3} \qquad \text{[Eq. 5.14]}$$

Step 13: Equation 5.15 is used to calculate the ratio $u^*_2/(\Delta T^*_2)^{1/2}$.

$$\frac{u^*_2}{(\Delta T^*_2)^{1/2}} = 0.59\left(\frac{r_p}{H}\right)^{-0.63} \qquad \text{[Eq. 5.15]}$$

Step 14: Use Equations 5.16 and 5.17 to calculate D and Y.

$$D = 0.188 + 0.313\frac{r_p}{H} \qquad \text{[Eq. 5.16]}$$

$$Y = \left(\frac{3}{4}\right)\left(\frac{u}{u^*_2}\right)^{1/2}\left[\frac{u^*_2}{(\Delta T^*_2)^{1/2}}\right]^{1/2}\left(\frac{\Delta T^*_2}{RTI}\right)\left(\frac{t}{t^*_2}\right)D \qquad \text{[Eq. 5.17]}$$

Step 15: Equation 5.18 can now be used to calculate the resulting temperature of the detector, $T_d(d)$ in K.

$$T_d(d) = \left(\frac{\Delta T}{\Delta T^*_2}\right)\Delta T^*_2\left[1 - \frac{(1-e^{-Y})}{Y}\right] + T_d(0) \qquad \text{[Eq. 5.18]}$$

Step 16: If the temperature of the detector is below its operating temperature, this procedure is repeated using a larger estimated response time. If the temperature of the detector exceeds its operating temperature, a smaller response time must be used. Repeat this procedure until the detector temperature is approximately equal to its operating temperature.

Required Variables:

H	- ceiling height or height above the fuel (m)
α	- fire growth characteristic for the fire (kW/s^2) [refer to Tables 5.1 – 5.4 and Figures 5.16 – 5.21]
S_p	- spacing of the existing detectors or sprinklers (m)
RTI	- detector's response time index (m$^{1/2}$s$^{1/2}$)
τ_o	- detector time constant measured at reference velocity u_o (s)
u_o	- reference velocity at which τ_o is measured (m/s)
t	- iterative estimate of detector/sprinkler response time (s)
$T_d(0)$	- the temperature of the detector at time t=0 seconds (K)

Assumptions/Limitations:

- Method assumes:
  - the density of air, ρ_a, is 1.1 kg/m^3
  - the specific heat of air, c_p, is 1.04 kJ/kg K
  - the ambient temperature, T_a, is 293°K (20°C)
  - the acceleration due to gravity, g, is 9.81 m/s^2
  - the fire exhibits a t^2 fire growth pattern
- Assumes a flat, unobstructed ceiling
- Errors in predicted temperatures and velocities will be greatest for fast fires and low ceilings.
- Stratification, which can occur with high ceilings, is not accounted for in the methodology.
- Method intended for predicting actuation times of heat detectors only. However, the method can be extended to roughly estimate actuation times of smoke detectors by assuming that a smoke detector usually responds when the temperature increase at the detector location is between 10C° and 15C° above ambient[20].
- This is an approximate method only for estimating detector response time, and should be used with great caution

Relevant Areas on Field-guide Forms:

1. Floorplan Sketch Pad (detection/alarm system type, spaces present, actuation, notes)
2. Exploded Room Sketch Pad - Contents Form (detection, alarm, suppression)
3. Witness interviews/statements/information

Sample Calculation for: Estimating Heat/Smoke Detector and Sprinkler Response Time

Problem: A medium growth rate fire, involving a moderate weight upholstered chair, estimated to develop according to $\dot{Q} = 0.01172t^2$, takes place in a room with a ceiling height of 2.66 m. A heat detector mounted on the ceiling, with an actuation temperature of 57°C and RTI of 16.56, is located 1.42 m away from the fire. Estimate how long it will take for the heat detector to actuate.

Solution:

Step 1: Determine the height, H, of the detector above the fuel.
$H = 2.66$ m

Step 2: Estimate the fire growth characteristic, α, for the fuel expected to be burning.
α is estimated to be 0.01172, a medium growth rate fire

Step 3: Determine the spacing of the detectors, or the distance of the detector to the fire.
The distance from the detector to the fire is known to be 1.42 m.

Step 4: Determine the detector's RTI.
The RTI is given to be 16.56. (This information is detector-specific, and often may only be ascertained from correspondence with the manufacturer.)

Step 5: Make a first estimate of the response time of the detector.
First estimate of detector response time = 106 sec

Step 6: Assume that the fire starts obeying the power-law model at time t=0.

Step 7: Set the initial temperature of the detector and its surroundings at 293K (20°C)

Step 8: Using Equation 5.10, calculate the nondimensional time, t^*_{2f}, at which the initial heat front reaches the detector.

$$t^*_{2f} = 0.95\left(1 + {}^{1.42}\!/_{2.66}\right) = 1.46$$

Step 9: Use the estimated response time along with Equation 5.11 to calculate the corresponding reduced time t^*_2.

$$t^*_2 = \frac{0.493(106)}{(0.01172)^{-1/5}(2.66)^{4/5}} = 9.83$$

Since t^*_2 is greater than t^*_{2f},, the method continues with Step 10.

Step 10: Calculate the ratio u/u^*_2 using Equation 5.12.

$$\frac{u}{u^*_2} = \frac{1}{\dfrac{2.030}{(0.001172)^{1/5}(2.66)^{2/5}}} = 0.25$$

Step 11: Calculate the ratio $\Delta T/\Delta T^*_2$ using Equation 5.13.

$$\frac{\Delta T}{\Delta T^*_2} = \frac{1}{\dfrac{0.017}{(0.01172)^{2/5}(2.66)^{-3/5}}} = 0.68$$

Sample Calculation for: Estimating Heat/Smoke Detector and Sprinkler Response Time (cont'd)

Step 12: Use Equation 5.14 to calculate ΔT^*_2.

$$\Delta T^*_2 = \left[\frac{9.83 - 1.46}{0.188 + 0.313 \left(1.42\right)/2.66}\right]^{4/3} = 67.29$$

Step 13: Use Equation 5.15 to calculate the ratio $u^*_2/(\Delta T^*_2)^{1/2}$.

$$\frac{u^*_2}{\Delta T^*_2{}^{1/2}} = 0.59\left(1.42/2.66\right)^{-0.63} = 0.87$$

Step 14: Use Equations 5.16 and 5.17 to calculate D and Y.

$$D = 0.188 + 0.313\left(1.42\right)/\left(2.66\right) = 0.36$$

$$Y = \left(3/4\right)\left(0.25\right)^{1/2}\left[0.87\right]^{1/2}\left(67.29/16.56\right)\left(106/9.83\right)\left(0.36\right) = 5.43$$

Step 15: Equation 5.18 can now be used to calculate the resulting temperature of the detector.

$$T_d\left(106\right) = \left(0.68\right)\left(67.29\right)\left[1 - \left(1 - e^{-5.43}\right)/5.43\right] + 57 = 57.6$$

The temperature of the detector at time of detection, T_d(106 sec), is approximately 57.6°C. Had the temperature of the detector been below its actuation temperature, a larger estimate for the time to detection would have to be used and the method repeated until the temperature of the detector equals that of its operating temperature. Had the temperature of the detector been significantly above its actuation temperature, a smaller estimate for the time to detection would have to be chosen and the method repeated until the temperature of the detector equals that of its operating temperature. For such an iterative method, creating a spreadsheet is a one way to save time in performing the necessary calculations.

Method for: Estimating Mean Flame Height[85]

$$L = 0.235\dot{Q}^{2/5} - 1.02D_f \qquad \text{[Eq. 5.19]}$$

where L is the mean flame height (m)

Required Variables:

$\dot{Q}$ - the estimated instantaneous heat release rate (kW) at the time of concern
D_f - the diameter of the flame (m)

Assumptions/Limitations:

- Mean flame height is defined as the average height of the visible flame height over time
- Flame is assumed to be a cone with base diameter D_f.
- Use caution in estimating $\dot{Q}$ based on L because of the 2/5 power

Relevant Areas on Field-guide Forms:

1. Witness interviews/statements/information (Sketch Pads if witness has been asked to illustrate observations)

Sample Calculation for: Estimating Mean Flame Height

Problem: What mean flame height can be expected from the 2 m diameter gasoline pool fire mentioned in the **Sample Calculation for: Estimating the Heat Release Rate (HRR) of the Fire**?

Solution:

The mean flame height, L, can be calculated using Equation 5.19.

[Eq. 5.19] $$L = 0.235\,\dot{Q}^{2/5} - 1.02D_f \text{ m}$$

$$\dot{Q} = 5931 \text{ kW}$$

$$D_f = 2 \text{ m}$$

Substituting into Equation 5.19,

$$L = 0.235(5931^{2/5}) - 1.02(2) = 5.55 \text{ m}$$

A mean flame height of approximately 5 m can be expected from the 2 m diameter gasoline pool fire.

Method for: Estimating Pre-Flashover Compartment Fire Temperatures[24]

$$\Delta T_g = 6.85\left(\frac{\dot{Q}^2}{A_o\sqrt{H_o}\,h_k A_T}\right)^{1/3} \qquad \text{[Eq. 5.20]}$$

where ΔT_g is the upper gas temperature rise (K) above ambient (295K)

Required Variables:

$\dot{Q}$	- the estimated instantaneous heat release rate of the fire (kW)
A_o	- the area of the ventilation opening (m^2)
H_o	- the height of the ventilation opening (m)
h_k	- the effective heat transfer coefficient (kW/m^2K) [refer to **Assumptions/Limitations]**
A_T	- the total area of the compartment enclosing surfaces (m^2)

Assumptions/Limitations:

- Method assumes:
  - the density of air, ρ_a, is 1.2 kg/m^3
  - the specific heat of air, c_p, is 1.05 kJ/kg K
  - the ambient temperature, T_a, is 295K (20°C)
  - the acceleration due to gravity, g, is 9.8 m/s^2
- The characteristic fire growth time and thermal penetration time of the room-lining materials must be determined in order to evaluate the effective heat transfer coefficient. (see below, and **Generic Data**)
- The heat transfer coefficient, h_k, can be determined using a steady-state approximation when the time of exposure, t (s), is greater than the thermal penetration time of the compartment surfaces, t_p (s), by

$$h_k = k_c/\delta \qquad \text{for } t > t_p \qquad \text{[Eq. 5.21]}$$

$$h_k = (k_c \rho_c c_c / t)^{1/2} \qquad \text{for } t_p \geq t \qquad \text{[Eq. 5.22]}$$

where the thermal penetration time, t_p (s), is defined as

$$t_p = (\rho_c c_c / k_c)(\delta/2)^2 \qquad \text{[Eq. 5.23]}$$

ρ_c	- the density of the compartment surface (kg/m^3)
c_c	- the specific heat of the compartment surface material (kJ/kg K)
k_c	- the thermal conductivity of the compartment surface (kW/m K)
δ	- the thickness of the compartment surface (m)
t	- the exposure time (s)

- If there are several wall and/or ceiling materials in the compartment, it is suggested that an area-weighted average for the heat transfer coefficient, h_k, be used.
- The method holds true for compartment upper layer gas temperatures up to approximately 600°C (flashover).
- The method applies to steady state as well as time-dependent fires, provided the primary transient response is the wall conduction phenomenon.
- The energy release rate of the fire must be determined from data or other correlations. (see **Method for: Estimating the Heat Release Rate of the Fire**)
- The method is not applicable to rapidly developing fires in large enclosures in which significant fire growth has occurred before the combustion products have exited the compartment.
- The method is based on data from a limited number of experiments and does not contain extensive data on ventilation-controlled fires or data on combustible walls and ceilings. Most of the fuel in the test fires was located near the center of the room.

Relevant Areas on Field-guide Forms:

1. Elevation Sketch Pad (important dimensions – doors, windows)
2. Floorplan Sketch Pad (ventilation openings, ceiling and wall materials, interior finishes)
3. Exploded Room Sketch Pad - Contents Form (contents details/notes)
4. Exploded Room Sketch Pad - Damage/Victims Form (damage details/notes)

Generic Data:

Table 5.7 – Thermal properties of some common materials[60]

Material	k (W/m K)	c_p (J/kg K)	ρ (kg/m³)
Copper	387	380	8940
Steel (mild)	45.8	460	7850
Brick (common)	0.69	840	1600
Concrete	0.8-1.4	880	1900-2300
Light-weight concrete	0.15	1000	500
Glass (plate)	0.76	840	2700
Gypsum plaster	0.48	840	1440
PMMA[a]	0.19	1420	1190
Oak[b]	0.17	2380	800
Yellow pine[b]	0.14	2850	640
Asbestos	0.15	1050	577
Fibre insulating board	0.041	2090	229
Polyurethane foam[c]	0.034	1400	20
Air	0.026	1040	1.1

[a] Polymethylmethacrylate
[b] Properties measured perpendicular to the grain
[c] Typical values only.

Sample Calculation for: Estimating Pre-Flashover Compartment Fire Temperatures

Problem: A fire, developing according to the relationship $\dot{Q} = 0.01172t^2$, is burning in a compartment 3.6 m, by 2.4 m, by 2.4 m high. The compartment has an opening 0.8 m wide and 2.0 m high. The compartment boundaries are made of 0.15m thick light-weight concrete. Estimate the upper layer gas temperature at times t =180 seconds (3 minutes) and t =300 seconds (5 minutes).

Solution:

Step 1: The instantaneous heat release rates of the fire at t =180 sec and t =300 sec can be calculated by Equation 5.1, $\dot{Q} = 0.01172t^2$, as follows,

$$\dot{Q} = 0.01172\left(180^2\right) = 380 \text{ kW}$$
$$\dot{Q} = 0.01172\left(300^2\right) = 1055 \text{ kW}$$

Step 2: The penetration time, t_p, is calculated from Equation 5.23 as

$$t_p = (\rho_c c_c / k_c)(\delta/2)^2$$

where ρ_c = 500 kg/m^3 (from Table 5.7 for light-weight concrete)
c_c = 1000 J/kg K (from Table 5.7 for light-weight concrete)
k_c = 0.15 W/m K (from Table 5.7 for light-weight concrete)
δ = 0.15 m

$$t_p = \left[\frac{(500)(1000)}{0.15}\right]\left(\frac{0.15}{2}\right)^2 = 18750 \text{ seconds}$$

Step 3: Because $t_p \geq t$, conduction into the walls will be transient for a long time (5.2 hours), Equation 5.22 is used to calculate the heat transfer coefficients for times t =180 sec and t =300 sec,

For t = 180 sec, $$h_k = \left[\frac{(0.15)(500)(1000)}{180}\right]^{1/2} = 20.4 \text{ W/m}^2\text{ K} = 0.0204 \text{ kW/m}^2\text{ K}$$

For t = 300 sec, $$h_k = \left[\frac{(0.15)(500)(1000)}{300}\right]^{1/2} = 15.8 \text{ W/m}^2\text{ K} = 0.0158 \text{ kW/m}^2\text{ K}$$

Step 4: The upper gas temperature rise can now be determined for time t =180 sec and t =300 sec by substituting the appropriate variables into Equation 5.20,

Where, $$A_T = 4(3.6)(2.4) + 2(2.4)(2.4) - (0.8)(2) = 44.48 \text{ m}^2$$

For t = 180 sec, $$\Delta T = 6.85\left(\frac{380^2}{(0.8)(2)(\sqrt{2})(0.0204)(44.48)}\right)^{1/3} = 283 \text{ C}^\circ$$

Sample Calculation for: Estimating Pre-Flashover Compartment Fire Temperatures (cont'd)

$$\text{For t} = 300 \text{ sec,} \quad \Delta T = 6.85\left(\frac{1055^2}{(0.8)(2)(\sqrt{2})(0.0158)(44.48)}\right)^{1/3} = 608\,C^\circ$$

Assuming that the ambient temperature in the room was 20°C to begin with, the upper layer gas temperature at 180 seconds will be (20+283) = 303°C. At 300 seconds, the temperature rise was calculated to be approximately 608 C°, giving an upper layer gas temperature of (20+608) = 628°C. One of the limitations of this method, as stated in the **Assumptions/ Limitations** for the method, is that the procedure holds true for compartment upper layer gas temperatures up to approximately 600°C, the temperature of the upper gas layer associated with the onset of flashover. The estimated upper gas layer temperature being 628°C, it is likely that the compartment has reached the flashover stage by 300 seconds.

Method for: Estimating Smoke Filling Time[87]

Step 1: Calculate the dimensionless heat release rate, $\dot{Q}^*$

$$\dot{Q}^* = \frac{\dot{Q}}{1100H^{5/2}} \qquad \text{[Eq. 5.24]}$$

Step 2: Calculate the dimensionless height, y

$$y = \frac{z}{H} \qquad \text{[Eq. 5.25]}$$

Step 3: Read the value of the parameter $\dot{Q}^{*\,1/3}\tau$ from Figure 5.22 for a given y and $\dot{Q}^*$ and solve for τ

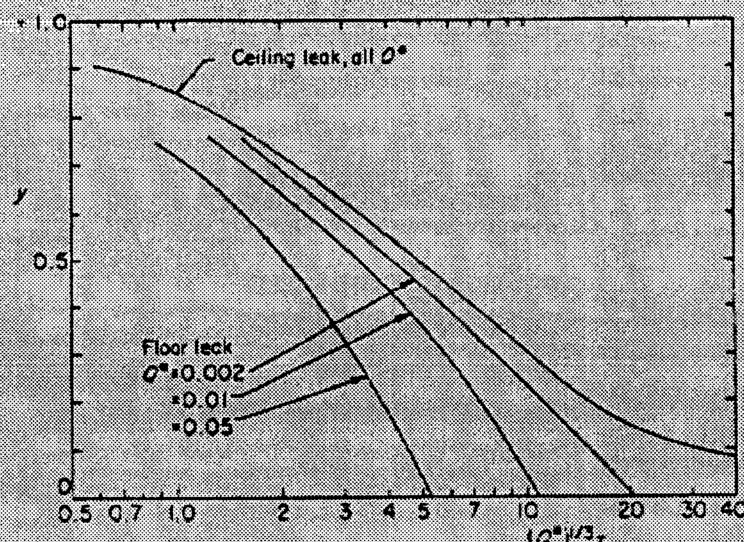


Figure 5.22 - y versus $\dot{Q}^{*\,1/3}\tau$

Step 4: Use the value of τ to calculate the time t when the layer is at height z using the definition of dimensionless time, τ

$$\tau = t\sqrt{\frac{g}{H}}\frac{H^2}{S_c} \qquad \text{[Eq. 5.26]}$$

Required Variables:

$\dot{Q}$	- the estimated heat release rate (kW) of the fire
H	- the height of the ceiling (m)
z	- the height of the lower layer (m)
t	- time (s)
S_c	- the floor area of the compartment (m^2)

Assumptions/Limitations:

- Method assumes:
  - the density of air, ρ_a, is 1.2 kg/m^3
  - the specific heat of air, c_p, is 1.0 kJ/kg K
  - the ambient temperature, T_a, is 293°K (20°C)
  - the acceleration due to gravity, g, is 9.81 m/s^2
- Assumes a 2-layer concept, with a horizontal interface between the uniform (isothermal) hot upper and cold lower gas layers.
- Assumes the fire is a steady state, constant output, point source within a single compartment.
- Mass burning rate of the fuel is ignored.
- No account is taken of heat losses to walls and ceilings.
- No account is taken of any hydrodynamic pressure differences with height. The pressure is assumed to have a single value within the whole compartment.

Relevant Areas on Field-guide Forms:

1. Elevation Sketch Pad (important dimensions - doors and windows)
2. Floorplan Sketch Pad (ceiling and wall materials, interior finishes, ventilation openings)
3. Exploded Room Sketch Pad - Contents Form (contents details/notes)
4. Exploded Room Sketch Pad - Damage/Victims Form (damage details/notes)
5. Witness interviews/statements/information

Sample Calculation for: Estimating Smoke Filling Time

Problem: A kerosene pool fire is ignited if an industrial building, releasing 200 kW, in an room with a floor area of 6 m by 6 m and a height of 5 m. Estimate the time until the smoke layer is at 2.5 m, or half of the room is filled.

Solution:

Step 1: Calculate the dimensionless heat release rate, $\dot{Q}^*$, using Equation 5.24,

$$\dot{Q}^* = \frac{200}{1100(5)^{5/2}} = 0.003$$

Step 2: Calculate the dimensionless height, y, using Equation 5.25,

$$y = \frac{2.5}{5} = 0.5$$

Step 3: Figure 5.22 gives a value $\dot{Q}^{*\,1/3}\tau = 4$, therefore, $\tau = \dfrac{4}{0.003^{1/3}} = 27.7$. Solving Equation 5.26 for time, t, gives

$$t = \frac{27.7}{\left(\sqrt{\frac{9.81}{5}}\right)\left(\frac{5^2}{36}\right)} = 28.47 \text{ sec}$$

Therefore, it would take approximately 29 seconds for the 6 m by 6 m by 5 m room to be half filled with smoke, assuming no ventilation openings. Additional calculations would be necessary to determine if sufficient oxygen was available in the compartment to allow a fire to grow this large.

Method for: Estimating the Heat Release Rate (HRR) Necessary for Flashover[24]

$$\dot{Q}_{FO} = 7.8A_T + 378A_o\sqrt{H_o} \qquad \text{[Eq. 5.27]}$$

Where $\dot{Q}_{FO}$ is the estimated heat release rate (kW) necessary for flashover

Required Variables:

A_T - the total surface area of the compartment enclosing surfaces (m^2)
A_o - the surface area of the ventilation opening (m^2)
H_o - the height of the ventilation opening (m)

Assumptions/Limitations:

- Assumes a 2-layer concept, with uniform hot upper and cold lower gas layers.
- Assumes the space is roughly cubical in geometry.
- Assumes the average net radiative and convective heat transfer from the upper gas layer to the compartment surfaces can be approximated by $7.8A_T$.
- Assumes an upper later temperature of 577°C is required for flashover.
- Assumes the specific heat of the gas is 1.26 kJ/kgK.

Relevant Areas on Field-guide Forms:

1. Elevation Sketch Pad (important dimensions - doors, windows)
2. Floorplan Sketch Pad (ventilation openings)
3. Exploded Room Sketch Pad - Contents Form
4. Exploded Room Sketch Pad - Damage/Victims Form

Sample Calculation for: Estimating the Heat Release Rate (HRR) Necessary for Flashover

Problem: A room and contents fire is being investigated to determine whether there were enough combustibles in the fire room for the room to reach the flashover stage. The room is 3.6 m by 2.4 m, with a ceiling height of 2.4 m. From observing burn patterns on the inside of the door in the vicinity of the hinges, it has been ascertained that the door to the fire room from the hallway was in the open position. The opening to the room measures 0.8 m wide by 2 m high. With the specified ventilation configuration, what is the heat release rate required to attain flashover within such a compartment?

Solution:

To answer the question, the heat release rate necessary for flashover, $\dot{Q}_{FO}$, can be determined using Equation 5.27.

[Eq. 5.27] $$\dot{Q}_{FO} = 7.8A_T + 378A_o\sqrt{H_o} \text{ kW}$$

$$A_T = 4(3.6 \times 2.4) + 2[(2.4)^2] - (0.8 \times 2) = 44.5m^2$$

$$A_o = 0.8 \times 2 = 1.6m^2$$

$$H_o = 2m$$

$$\dot{Q}_{FO} = 7.8(44.5) + 378(1.6)\sqrt{2} = 1202kW$$

The estimated heat release rate necessary for flashover is approximately 1200 kW.

Method for: Estimating the Ventilation-Limited Heat Release Rate (HRR) of the Fire[19]

$$\dot{Q}_{VL} = 1560 A_w H_O^{1/2} \qquad \text{[Eq. 5.28]}$$

Where $\dot{Q}_{VL}$ is the estimated ventilation-limited heat release rate (kW)

Required Variables:

A_w - effective area of ventilation (m^2)
H_O - height of ventilation opening (m)

Assumptions/Limitations:

- Assumes that the fire is ventilation controlled and that all the air that enters the compartment is burned therein .
- Method assumes:
  - the mass flow rate of air in to the compartment, $\dot{m}_{air}$, in kg/s can be represented by

$$\dot{m}_{air} = 0.52 A_w H^{1/2} \qquad \text{[Eq. 5.29]}$$

  - the heat of combustion per unit mass of air consumed, ΔH_c, is 3000 kJ/kg (approximate constant for most fuels)

Relevant Areas on Field-guide Forms:

1. Elevation Sketch Pad (important dimensions - doors, windows)
2. Floorplan Sketch Pad (ventilation openings)
3. Exploded Room Sketch Pad - Contents Form
4. Exploded Room Sketch Pad - Damage/Victims Form

Sample Calculation for: Estimating the Ventilation-Limited Heat Release Rate (HRR) of the Fire

Problem: Given a compartment 3.6m by 2.4 m, with a ceiling height of 2.4 m, calculate the ventilation limited heat release rate for the compartment provided there exists only one opening, 0.8 m wide and 2 m high, into the compartment. Is it possible that flashover could be attained in this compartment with this ventilation configuration?

Solution:

In order to answer the question, the ventilation limited heat release rate. $\dot{Q}_{VL}$, must be determined. $\dot{Q}_{VL}$ can be determined from Equation 5.28.

[Eq. 5.28] $$\dot{Q}_{VL} = 1560 A_w H_O{}^{1/2} \text{ kW}$$

$$A_w = (0.8 \times 2) = 1.6 m^2$$

$$H_O = 2m$$

$$\dot{Q}_{VL} = 1560(1.6)(2)^{1/2} = 3529 kW$$

The ventilation limited heat release rate for the compartment is 3529 kW. From the **Sample Calculation for: Estimating the Heat Release Rate (HRR) Necessary for Flashover**, it was determined that the heat release rate necessary for flashover within the compartment was approximately 1200 kW. The heat release rate necessary for flashover being less than the ventilation limited heat release rate, flashover can be reached within the compartment with this ventilation configuration.

Chapter 6: Conclusions

With this thesis, the author has explained the fundamental aspects of a fire investigation and has suggested a structured method to apply basic principles of fire science and fire protection engineering to the investigation of fires. Specific conclusions of the work include:

A. Investigating fires is a very difficult task, drawings from many complicated disciplines.

B. The present state of the field of fire investigation could use improvement, specifically by,

   1) "debunking" unsubstantiated fire investigative myths, such as those discussed in Section 4.1.1, with scientific proof,

   2) re-structuring the scientific education of fire investigators to include more "investigation-related" fire science topics. Such a re-structuring would include the studying of the proper ways to utilize basic calculation methods for the purpose of quantitatively estimating fire phenomena, such as those presented in Sections 5.3.

   3) receiving aid and support from the fire science and fire protection engineering communities. Scientific and engineering tools need to be introduced into the repertoire of the fire investigator. Furthermore, technological developments and new scientific discoveries in these disciplines, and how they can relate to

the investigation of fires, need to be communicated in an understandable manner to the fire investigative community. Through such technology transfer, the relationship between fire science and fire investigation can be strengthened to benefit both disciplines.

4) improving the fire investigative documentation process by developing a standard of practice for fire investigation procedures that would make more uniform the information recorded during an investigation.

C. The fire investigation documentation process can be improved by the implementation of the Field Guide presented in Chapter 5. The method of the Field Guide will improve the process by,

1) providing the investigator with an organized, consistent approach to recording and analyzing information about the fire scene from the beginning to the end of the investigation,

2) providing forms that work to guide the investigator through the documentation process, suggesting important information to look for, document, and examine,

3) providing intuition-enhancing flowcharts to aid the investigator in developing hypotheses about the incident being investigated, and

4) providing calculational tools that can be used to prove or disprove such hypotheses, by allowing investigator to quantitatively estimate certain fire phenomena.

D. An organized, systematical approach to the investigation of fires will facilitate more thorough documentation, thereby increasing the efficiency of an investigation and any future analyses to be performed.

The development of the Field Guide concept is only a small part in the process to improve the current state of fire investigation. There is much future work that needs to be done to bring all of the concepts and ideas explained within this thesis to fruition. The foremost action would be the implementation of the Field Guide into the investigation process by the fire investigative community. The author is not so naive as to believe that the Field Guide is without flaws. However, the author does believe that is could serve as a starting point and foundation upon which a better system can be built. It is only by using the Field Guide that its weaknesses can be discovered and improved upon.

Additional work to be done with respect to improving the current state of fire investigation technologies could involve:

- Developing a comprehensive fire science curriculum for fire investigators. Introducing such a field guide and how to effectively use it to process a fire scene could be a part of such a curriculum,
- Expanding the theory of the Field Guide so that it may be applied to other types of incident investigations such as wildland fires, vehicle fires, and hazardous material incidents,

- The testing of the Field Guide by different investigation units to evaluate its use.
- Once the Field Guide is shown to be a valuable tool to the investigator, and its format perfected, the concept of the Field Guide could be converted into an extensive software package. Such a software package, when coupled with a laptop computer on-scene, could enable the investigator to enter all relevant information onto electronic forms, incorporate digital photographs, and even use the information entered in the appropriate text fields of the electronic forms to automatically estimate certain fire phenomena using built-in algorithms for the calculation methods of Section 5.3.

It has been said that fire investigation is changing more now than ever before[3]. New and modern tools will inevitably help the investigator to do a better job. The consummate goal of investigating fires is the same as that of the other disciplines associated with fire protection. The goal is not merely to determine the origin and cause of a particular fire, but to reduce and eliminate the destruction of property, the injuries, and the hundreds of deaths caused each year by fire. It is only when the fire protection community fully understands how and why fires originate and develop that measures can be taken to prevent them from happening in the future.

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