# The Current Knowledge & Training Regarding Backdraft, Flashover, and Other Rapid Fire Progression Phenomena

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## Abstract

Rapid fire progression phenomena, such as backdraft and flashover, can result in danger to firefighters. This paper examines current research and divides these phenomena into categories based on fundamental physical and chemical processes. Implications include improved communication and technology transfer between fire scientists and fire service training personnel, training and education of firefighters, and firefighter safety during fire suppression activities.

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# Introduction

### *I. Background*

A recent review on the subject of flashover, backdraft, and smoke layer ignitions (i.e. rollover/flameover) has revealed that there are few papers on any one of these subjects and almost none discussing all three phenomena. In fact, many publications and articles on these phenomena are technically inaccurate or combine several phenomena into one. This review confirmed a fear that many in the fire safety profession (i.e. fire service personnel, fire investigators, fire protection engineers) do not fully understand these very important enclosure fire progression phenomena.

To effectively perform their duties, fire safety professionals must achieve a solid theoretical knowledge of fire behavior, more specifically enclosure fire behavior. In general terms, enclosure fire behavior is the study of the chemical and physical mechanisms controlling a fire that is within a compartment or building. Statistics prove that the enclosure fires are the most dangerous to human life. For example, in 2001, four out of every five fire deaths occurred in residential structure fires, excluding 9/11 (Cote, 10-11). While the public may hear more about wildfires and other conflagrations, the truth is that the most dangerous place to be is in our own homes. Thus, fire safety professionals must truly understand and grasp all the components of enclosure fire behavior to succeed at their mission of saving lives.

Various phenomena may arise during the development of a typical enclosure fire. Three distinct and commonly misunderstood phenomena – **flameover**, **backdraft**, and **flashover** – are the most dangerous because of the dramatic changes that rapidly occur throughout the compartment. The importance of properly understanding these phenomena cannot be over-emphasized. A review of the current statistics reveals that heart attacks and motor vehicle collisions are the major causes for firefighter deaths. However, there still remain a smaller percentage of firefighters dying in this country each year due to poor knowledge and training regarding enclosure fire behavior. According to Paul Grimwood, statistics recorded in the United States between 1985 and 1994 demonstrated that a total of 47 US firefighters lost their lives to "flashover" (57).

### *II. Purpose*

The purpose of this paper is to address the current lack of education and training regarding enclosure fire behavior throughout all fire safety professions. This article will specifically illustrate the inconsistencies of education and training regarding the rapid fire progression phenomena and provide a basis for the true meaning of each phenomenon.

### III. Literature Review

A literature review of the three most commonly misunderstood phenomena (e.g. flashover, backdraft, flameover) has been undertaken to attain a consenting analysis of each phenomenon. The discussion that follows illustrates a brief historical progression for each phenomenon as well as provides the most current scientific understanding. All references were found utilizing online and textbook sources. The primary means for the online sources were the University of Maryland's online library database, internet search engines, and government web sites. The textbook sources were mainly gathered from John A. Kennedy and Associates' private fire science library as well as the author's personal collection. In the Appendix there is a list of all the references that were reviewed for the literature review.

## A. Flashover Research

The British fire scientist Dr. Philip H. Thomas was the first to introduce serious scientific discussion of the term *flashover* in the 1960's. Thomas' initial understanding and definition of flashover was inaccurate, nevertheless it was the first time scientific thought was given to this deadly fire progression phenomenon. From that point forward there has been extensive scientific research and experimentation performed to better understand flashover. At present, it can be acknowledged that there is a solid understanding of the quantitative and qualitative mechanisms that make up this phenomenon due to the extensive research and studies performed by several premier fire scientists.

A recent study performed by a fire and explosion analyst Patrick M. Kennedy presents a solid basis for the qualitative and theoretical discussion of flashover. The research performed by Kennedy was largely targeted at the fire investigation community, however, it is useful to all fire safety professionals. James Quintiere and Bjorn Karlsson wrote the first text solely related to fire dynamics inside of an enclosure. In this text, *Enclosure Fire Dynamics,* Quintiere and Karlsson present a quantitative review of the mechanisms that contribute to the phenomenon of flashover. Dougal Drysdale has also done extensive research and studies into the qualitative and quantitative mechanisms, which can be found in his groundbreaking text, *Introduction to Fire Dynamics*. Both texts are largely targeted at fire protection engineering students and practicing fire protection engineers. Based upon these important studies, the quantitative and qualitative mechanisms that define flashover are well understood and identified.

### 1) Flashover Definitions

The earliest mention of flashover to be found in the NFPA literature is in the 10th Edition of the NFPA Handbook of Fire Protection (1948) in Chapter 30 on Interior Finishes – Insulation. This work describes the recognition of flashover by researchers into the design and development of World War II incendiary weapons. It defines "…a flashover point, at which all combustible surfaces in a room burst into flame." and discusses "…the time interval between the ignition of an incendiary bomb and the time when flashover occurred [as] a valuable criterion in evaluating the relative effectiveness of various incendiary bombs."

In discussing the lack of research into flashover at that time, the 10th Edition says:

> "It has long been recognized that fires, first spreading slowly, will eventually reach the stage where all the combustible material in the fire area will flash into flame. No attempts had been made to measure such time intervals under controlled fire test conditions prior to the wartime research on incendiary bomb performance. While the

> nature of the phenomenon had not been critically studied or defined, its occurrence in fires was clearly recognized" (Crosby, Fiske & Forester, p.561).

The 9th Edition (1941) and earlier editions of the FPH are mute on the issue.

This perception, based upon the theory that flashover was caused by the collection and ignition of pyrolysis gases from the interior finishes of the room, persisted in the NFPA Fire Protection Handbooks through the 13th edition (1969). It was not until the publication of the 14th Edition in 1976 that any mention of the major role of radiant ignition of the contents of the room was emphasized, citing research work by Thomas and the U. S. National Bureau of Standards. It was not until the 15th Edition (1981) and following editions that any scientific research on flashover was reported in any detail.

It has been popularly reported by Grimwood, that the British fire scientist Dr. Philip H. Thomas first introduced serious scientific discussion of the term flashover later in the 1960's.

> "[It] was used to describe the theory of a fire's growth up to the point where it became *fully developed*. Customarily, this period of growth was said to culminate in 'flashover', although Thomas admitted his original definition was imprecise and accepted that it could be used to mean different things in different contexts. Thomas then went on to inform us in UK Fire Research Note 663 (December 1967) that there can be more *than one kind of flashover* and described 'flashovers' resulting from both *ventilation* and fuel-*controlled* scenarios. Thomas also recognized the limitations of any precise definition of 'flashover' being linked with *total surface involvement of fuel* within a compartment (room) where, particularly in large compartments, it may be physically impossible for all the fuel to become involved at the same time" (2003, p.1)

Thomas' Original Definition

> "'In a compartment fire there can come a stage where the total thermal radiation from the fire plume, hot gases and hot compartment boundaries causes the generation of flammable products of pyrolysis from all exposed combustible surfaces within the compartment. Given a source of ignition, this will result in the sudden and sustained transition of a growing fire to a fully developed fire...This is called 'flashover'...'" (Grimwood, 2003, p.1).

> " British Standards (4422) of 1969 and 1987 further attempted to apply a more precise definition without success" (Grimwood, 2003, p.2)

Years later in the SFPE Handbook (1995), Walton and Thomas reported that "Flashover is not a precise term, and several variations in definition can be found in the literature" (Walton & Thomas, 1995, p.3/134).

**a) Other Varying Definitions**

It is quite true that the very definitions of flashover and such associated phrases as "full-room involvement" varies, often widely, from reference source to reference source. A search for the definition of the word flashover in the 2002 National Fire Codes provides some interesting exemplar results (NFPA, 2002).

> NFPA 101
> Life Safety Code
> 3.3.79* Flashover.
> “A stage in the development of a contained fire in which all exposed surfaces reach ignition temperatures more or less simultaneously and fire spreads rapidly throughout the space.”

> NFPA 402
> Guide for Aircraft Rescue and Fire Fighting Operations
> 1996 Edition
> “Flashover. All combustibles in a room or confined space have been heated to the point that they are giving off vapors that will support combustion, and all combustibles ignite simultaneously.”

> NFPA 555
> Guide on Methods for Evaluating Potential for Room Flashover
> 2000 Edition
> “1.4.2* Flashover. A stage in the development of a contained fire in which all exposed surfaces reach ignition temperatures more or less simultaneously and fire spreads rapidly throughout the space.”

> NFPA 921-2001
> Guide for Fire and Explosions Investigations
> “1.3.60 Flashover. A transition phase in the development of a contained fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space.”

Even this unusual definition, not dealing at all with fire growth within a compartment, was found.

> NFPA 230
> Standard for the Fire Protection of Storage
> 1999 Edition
> “Flashover. See definition of Flameover.”
>
> “Flameover. A fire that spreads rapidly over the exposed linty surface of the cotton bales. In the cotton industry, the common term is flashover and has the same meaning.”

The NFPA Fire Protection Handbook 18$^{th}$ edition (1997) provides an additional, more updated form of a definition:

"... a transition … from a fire that is dominated by the first materials ignited to a fire that is dominated by the burning materials throughout all of the room" (Custer, p.1-7).

Additional definitions found in the literature include:

[Karlsson and Quintiere] "The transition from the fire growth period to the fully developed stage in the enclosure fire development" (1999, p.16)

[Quintiere] "A dramatic event in a room fire that rapidly leads to full room involvement; an event that can occur at a smoke temperature of 500 to 600 C°" (1998, p.252)

[Drysdale] "the transition from a localized fire to the general conflagration within the compartment when all fuel surfaces are burning" (1985, p.283)

[ISO] "…the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure" (1996).

[Walton and Thomas] "Flashover is generally defined as the transition from a growing fire to a fully developed fire in which all combustible items in the compartment are involved in fire" (1995, p.3/134).

[Babrauskas] "…the full involvement in flames of a room or other enclosed volume" (2003, p.16).

Confusion with such terms as flash point, flash fire, flameover, and backdraft further complicates the issue (see the glossary).

**b) Defining "Full Room Involvement"**

With the exception of the "cotton bale" definition, all of the previous flashover definitions involve the terminal condition of "full room involvement" or some other reference to the "full fire involvement" of the confining room, compartment, or enclosure as the ultimate conclusion of the flashover event. But again a search of the literature failed to disclose an agreed upon definition of "full room involvement."

Such definitions as those listed below were typical:

[Quintiere] "…state of a compartment fire during which the flames fill the room involving all the combustibles" (1998, p.172).

[Drysdale] "…the exposed surfaces of all combustibles will be burning…" (1999, p.294).

[NFPA FPH, 18th Ed.] "…fully involved compartment fire.." (Cote, 1997)

> [Karlsson and Quintiere] “At the fully developed stage, flames extend out through the opening and all the combustible material in the enclosure is involved in the fire” (1999, p.16).

As a direct result of this definition research a proposal to add a definition of "Full Room Involvement" was submitted and approved for addition into the 2004 Edition of NFPA 921:

> “Full Room Involvement – condition in a compartment fire in which the entire volume is involved in fire” (p.11).

**c) Elements of a Practical Definition of Flashover**

All of the various aforementioned definitions of flashover contain one or more of the following elements:

*Flashover represents a transition in fire development* - Flashover is not a discrete event occurring at a single point in time, but a transition in the growth and spread of a fire.

*Rapidity* - Though not an instantaneous event, flashover happens rapidly, in a matter of seconds, to spread full fire involvement within the compartment.

*Confined space or contained fire* - There must be an enclosed space or compartment such as single room or enclosure.

*All exposed surfaces ignite* - Virtually all combustible surfaces existing in the lower layer of the enclosed space and exposed to the upper layer radiant flux become ignited.

*Fire spreads throughout compartment* - The rapid ignition of combustibles within the lower layer of the compartment spreads the fire.

*Resulting in “full room involvement”*- The result of the flashover is that every combustible surface within the room, compartment, or enclosure becomes ignited, the entire volume is involved in fire and this fire can no longer be contained within the room of origin.

**2) A New Practical Definition of Flashover**

For fire investigation professionals the current, peer-reviewed, practical definition of flashover is found in the 2004 Edition of NFPA 921 and contains all of the elements discussed above. The definition found in NFPA 921 and has been accepted by NFPA as the preferred definition is:

> “A transitional phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space resulting in full room involvement or total involvement of the compartment or enclosed area” (p.11).

Flashover is a rapidly occurring transitional event in the development of a compartment fire. It represents a significant increase in fire growth from a distinct source of burning or single fuel package to the ignition and burning of virtually every other exposed combustible fuel surface in the compartment.

Flashover is characterized by the spread of flaming combustion without any actual flame contact (flame impingement) between the original fuel(s) and the subsequent fuels. While the initial heat transfer mechanism in the early fire stages of a compartment fire is largely by convection, the heat transfer mechanism at and beyond flashover is primarily by radiation (NFPA 921, 2004, p.25).

In Figure 1 (below) based upon the reciprocal of the typical compartment fire time/temperature curve, is used to illustrate the dynamically changing relationship between convected and radiated heat transfer mechanisms during the course of compartment fire growth.

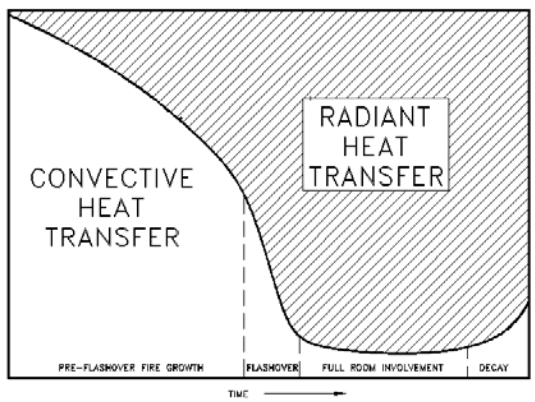


**Figure 1 – Relationship of Heat Transfer Mechanisms within a Compartment Fire**

Typically as a compartment fire begins there is a single fuel package burning. This produces a buoyant fire plume that begins spreading heat energy primarily by convected gases rising in the plume. At this point in the fire the effect of convective and radiant heat transfer to other fuel packages and the walls, floor and ceiling of the compartment are relatively minimal. As the buoyant plume's gases, and other heated products of combustion begin to collect below the ceiling and spread laterally, the upper layer begins to form. From this point on in the fire, radiant heating is occurring both from the original fuel package's fire plume and the now ever-deepening upper layer as well. As the upper layer continues to become deeper and increases in temperature, the radiant portion of the total heat transfer within the compartment increases and the ratio of the convected heat to radiant heat within the compartment decreases. At about the time of flashover, radiant heating becomes the dominant heat transfer mechanism. Outside the compartment in other adjacent spaces, convection remains the predominant heat transfer mechanism until the same process moving towards "full room involvement" of the next space.

In the simplest terms, fire scientists see the growth of a compartment fire by dividing the compartment into two stacked "zones," an upper layer defined by the accumulation of buoyant heated gases, smoke, particulates, and aerosols from the original burning item(s) accumulating, forming a layer, and banking down from the ceiling; and a cooler lower layer. The production of the upper layer, in turn, heats the ceiling and upper portions of the confining walls mostly by convection and conduction, creating additional fuel and products of combustion. The bottom of this ever-deepening upper layer represents the horizontal border or interface between the two layers. The lower layer remains relatively cool with the addition of entrained unheated air into the originating fire plume (Figure 2).

Radiated heat energy from the bottom interface of this hot upper layer heats the surfaces of the various fuels in the lower layer throughout the compartment. These various fuels typically include the compartment furnishings, contents, wall and floor coverings, and the lower walls. As the fire continues to grow, the heat release rate of the original fire plume and temperature of the upper layer increase. As the heat energy of the increasingly deeper and lowering upper layer increases, and the distance between the bottom of the upper layer and the fuels in the lower layer decreases, the radiant flux upon the unburned but now pyrolizing fuels present in the lower layer, grows exponentially. Thus fire growth and the rate of radiant flux increase until nearly simultaneous ignition of the target combustibles in the lower layer of the compartment occurs. This is flashover.

In Figure 2 the heavy arrows represent radiant heat energy from the bottom of the upper layer. The narrow arrows in the lower layer represent air entering the room at the bottom of the doorway and being entrained into the chair fire. The narrow arrows in the upper layer represent heat and smoke movement from the burning chair at the left.

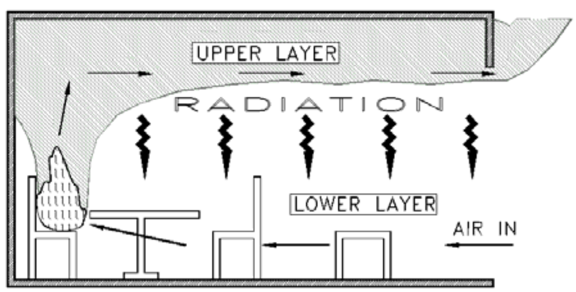

Figure 2 – Pre-flashover conditions in a compartment fire.

The dynamics of flashover requires a positive imbalance between the heat energy being input into the compartment and the energy leaving the compartment through vents and conduction through the room lining materials. When, or whether flashover occurs at all, is dependent upon the excess of heat energy input and the ability of the compartment to retain the heat. Energy input is comprised of the total available heat of combustion of the fuel load, the heat release rate (HRR) of the burning fuel(s), available ventilation to keep the fire growing, and the location of the fire within the compartment. The loss of the energy is through available vents (openings in doors, windows, walls and ceiling; and active HVAC), and thermal conduction through the compartment’s walls and ceiling.

Figure 3 illustrates a typical enclosure fire that begins with a single fuel burning and the eventual transition into full-room involvement indicating that flashover has occurred. The “t” stands for time and the measurements are made in seconds.

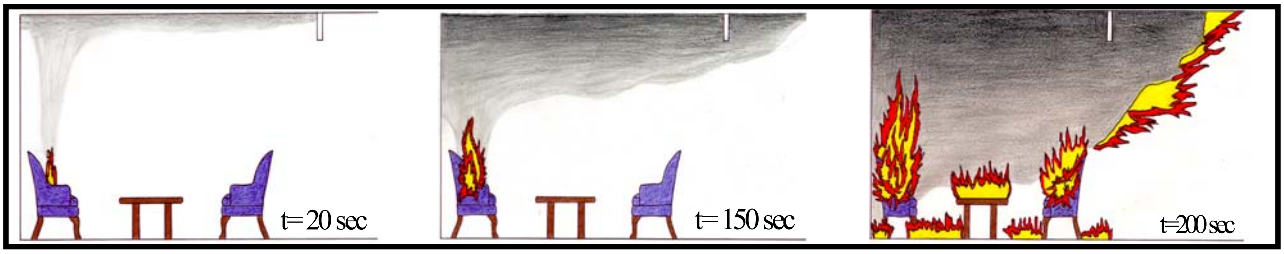


**Figure 3: Illustration of a typical enclosure fire transitioning through flashover**

### 3) Components That Control Flashover

Many varied components of the fire and the compartment themselves control whether and when flashover will occur. Thusly the components of various flashover prediction equations and computer fire models include:

- Ambient temperature at the beginning of the fire
- Size, shape, area, and volume of the compartment
- Area, height, width, and soffit (header) height of open doors and windows, or other vents
- Surface areas, materials, thickness, thermal inertia, and thus the conductance of surface lining materials
- Heat loss fraction
- Heat release rate (kW)
- Fire growth rate (kW/sec)
- Location of the fire within the compartment
- Active HVAC

### 4) Indicators of Flashover

Through years of actual full-scale and scaled model compartment fire testing and the subsequent production and testing of mathematical algorithms, fire researchers have developed sets of physical indicators that suggest that flashover has probably occurred within a given compartment.

#### a) Technical Indicators

Scientists and engineers must have quantitative data to do their studies with anything approximating certitude. To do such when researching flashover, technical indicators that flashover has occurred must be measurable (quantitative). The actual definitive elements of flashover, rapidity, transition to "full room involvement," ignition of exposed surfaces, and fire spread, are too subjective and qualitative to be used in any mathematical or purely scientific or engineering analysis. The two commonly accepted technical indicators of flashover involve temperature and radiant heat flux, respectively. The technical indicators of flashover include the observations of an average upper layer temperature of ~ 600°C (1112° F.) or radiant flux at floor level of ~20 kW/$m^2$. Some texts refer to these technical indicators as "triggering conditions" (Custer, 1997, p.1-7).

In many early testing scenarios and research burns where expensive water-cooled radiometers were unavailable, “telltales” of crumpled newsprint pages were used by placing then on the floor of the test room and physically observing when they became ignited by radiant heat, thereby indicating that flashover had occurred. The critical radiant flux of these “telltales” was approximate to the 20 $kW/m^2$ now considered the critical radiant flux for flashover to occur.

Other non-technical indicators, particularly when they represent more subjective observations such as are frequently reported by eyewitnesses, while still of analytical value to the fire analyst, are also impossibly difficult to quantify for scientists.

**b) Non-Technical Indicators**

At or near flashover several other physical observations are frequently reported. Witnesses commonly report that the fire "exploded" within the compartment or very rapid flame extension moving laterally throughout the compartment, general floor level burning, the breaking of external windows, flame extension escaping the compartment doors or windows, or the culminating “full room involvement” itself (Kennedy & Kennedy, 1985, p.120).

The breaking of external windows is commonly associated with flashover or reported as frequently occurring just after transition to “full room involvement.” Thus this window-breaking phenomenon is a commonly reported observation by eyewitness and can, with judicious caution, be used as an indicator of when flashover has occurred. It had been widely believed that the rapid increase of pressure within the flashed-over compartment was the cause of this window breakage. But testing conducted by Fang and Breese (NBS) in 1980 and by Skelly (NIST) in 1990 indicate that it is not the relatively small overpressure that results from flashover of 0.014 kPa to 0.028 kPa (0.002 psi to 0.004 psi), but rather the temperature differential of ~70°C (158° F.) between the exposed and unexposed surfaces of the glass (beneath the glazing) which creates the window breakage. The commonly accepted minimum failure pressure of residential windowpanes is 0.689 kPa – 3.447 kPa (0.1 psi. – 0.5 psi.), well above the pressures reported in the NIST tests (NFPA 921, 2004). It is the rapid increase of the heating of the windowpanes that causes this effect to occur at or near flashover.

**5) Misconceptions about Flashover**

Unfortunately, the phenomenon of flashover and its proper evaluation in fire investigations and analyses is currently much misunderstood in the professional fire investigation community. Some of the most commonly encountered misconceptions about flashover are listed below.

**a) Misconception –“‘Full Room Involvement’ Means Flashover Occurred”**

The fact that a compartment fire ultimately resulted in "full room involvement" does not, in and of itself, indicate that flashover had to have occurred. Flashover, though quite common, is not a requisite phase of compartment fire growth and does not necessarily occur in every compartment fire that progresses to "full room involvement." Many fully involved compartment fires have never experienced flashover. The transition to full involvement need not always be rapid, as in flashover. It may also be slower, representing different fire spread and heat transfer mechanisms. Issues of the compartment shape, area, ceiling heights, fuel heat release and fire growth rates, and particularly venting and ventilation, can affect whether flashover (the rapidity portion of transition to full room involvement) ever actually occurs.

For example, high rates of ventilation within the compartment with attendant reduction in heat accumulation can prevent the effective production of a hot upper layer and flashover. Continued normal fire spread under those conditions can ultimately bring the compartment to full involvement, only more slowly.

Conversely, particularly in ignitable liquid fueled fires or flash fires from diffuse gaseous or particulate fuels, "full room involvement" can occur nearly from the beginning of the fire event without any initial hot upper layer accumulation.

**b) Misconception – "Flashover Is Defined By Its Indicators"**

The indicators of flashover do not define flashover. Rather, flashover is defined by its nature (rapid transition to a "full room involvement"). The presence of one or more indicators of flashover "does not a flashover make." The technical indicators of flashover (i.e. ~600°C (1112° F.) upper layer temperature, or ~20 $kW/m^2$ radiant flux), and even the other non-technical indicators, can commonly occur in fires that have never experienced actual flashover. The mere presence of one or more of the indicators does not define flashover. The definition of flashover, as reported above, does not even contain in its defining elements any of the listed indicators other than the ultimate outcome of flashover, "full room involvement." This is a misconception commonly held, even by some well-respected fire researchers. The fire safety professional is cautioned not to make this fundamental mistake of defining "the disease as the symptoms" or "the symptoms as the disease."

**c) Misconception – "'Full Room Involvement' is Flashover"**

Though "full room involvement" is the culminating condition when a flashover occurs, they are separate and distinct fire dynamics phenomena. They are not the same, and though they are frequently closely related, neither is the singular defining element of the other. This problem is generally brought about by the indiscriminant interchanging of the word "flashover" with the phrase "full room involvement" in some texts and lectures. Flashover and "full room involvement" are not synonymous concepts and care should be taken to use the terms exactly.

## B. Backdraft Research

The backdraft phenomenon has not been studied as extensively as that of flashover. Nevertheless, there have been studies that aid in the better understanding of the theoretical nature of backdraft. The team of Fleischmann and Pagni from the University of California, Berkeley were the first to explore backdraft with experimentation. In this study, Fleischmann and Pagni created a small-scale compartment and were able to reliably reproduce the phenomenon. These tests have been and continue to be the foundation for all research of this phenomenon.

In 1994 and again in 2001, the Fire Research and Development Group from England performed a survey of backdraft (Chitty). Richard Chitty, the author of this survey, states, "that the ultimate finding was that research on backdraught (backdraft) is sparse, and had identified only one active group at the University of California, Berkeley studying this phenomenon" (2001, p.12). Since the time of the Chitty survey there have been three other entities that have taken an active role in the study of the backdraft phenomenon, including Essex County Fire and Rescue Services in England, Lund University in Sweden, and Hughes and Associates in the United States. Direct contact has been made with all entities to obtain any recent publication and details of their studies. At present these studies have presented similar results as those of Pagni and Fleischmann. Therefore, it has been validated that the theoretical basis and general understanding of the backdraft phenomenon is understood. However, the quantitative mechanisms of the backdraft phenomenon are still largely absent.

**1) Backdraft Definitions**

Steward 1914:

> "These 'smoke explosions' frequently occur in burning buildings and are commonly termed 'back draughts' or 'hot air explosions'. Fire in the lower portion of a building will often fill the entire structure with dense smoke before it is discovered issuing from crevices around the windows. Upon arrival of the firemen openings are made in the building which admit free air, and the mixture of air and heated gases of combustion are ignited with a flash on every floor, sometimes with sufficient force to blow out all the windows, doors of closed rooms where smoke has penetrated, ceilings under attics etc" (Steward, 1914).

The Institution of Fire Engineers (IFE) defines backdraft as:

> "An explosion of greater or lesser degree, caused by the inrush of fresh air from any source or cause, into a burning building, where combustion has been taking place in a shortage of air."

The NFPA definition is:

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

Fleischmann, C. and Pagni, P. defines backdraft as:

> "If the compartment is closed, the excess pyrolyzates accumulate, ready to burn when a vent is suddenly opened, for example, as may happen when a window breaks due to the fire-induced thermal stress or a firefighter enters the compartment. Upon venting, a gravity current carries fresh air into the compartment. This air mixes with the excess pyrolyzates to produce a flammable, premised gas, which can be ignited in many ways."

Enclosure Fire Dynamics – Quintiere and Karlsson

> *Backdraft* Limited ventilation during an enclosure fire can lead to the production of large amounts of unburnt gases. When an opening is suddenly introduced, the inflowing air may mix with these, creating a combustible mixture of gases in some part of the enclosure. Any ignition sources, such as a glowing ember, can ignite this flammable

mixture, resulting in extremely rapid burning gases out through the opening and cause a fireball outside the enclosure. (Quintiere, 1999)

**a) Elements of a Practical Definition**

All of the various aforementioned definitions of backdraft contain one or more of the following elements:

*Ventilation Controlled Fire* – Combustion cannot sustain itself without adequate oxygen. This oxygen typically comes in the form of atmospheric air. When a compartment does not have any open ventilation to re-supply the air/oxygen, the fire will begin to decay.

*Unburned Pyrolysis Products* – Incomplete combustion of the fuel(s) produce heavy volumes of unburned pyrolyzates, which are suspended in the compartment.

*Confined space or contained fire* - There must be an enclosed space or compartment such as single room or enclosure.

*Sudden Introduction of Air/Oygen* – An opening is suddenly introduced into the compartment and allows fresh air to enter into the compartment.

*Rapid Burning of Pyrolysis Products* – Ignition occurs of the suspended pyrolyzates and a flame front begins to progress through the compartment.

*Fire spreads out of the compartment* - The flame front will exit the compartment via an open vent and result in a fireball and overpressure.

**b) A New Practical Definition of Backdraft**

The most fitting current definition for backdraft is modified from Quintiere and the Pagni/Fleischmann study.

> Limited ventilation during an enclosure fire can lead to the production of large amounts of unburnt pyrolysis products. When an opening is suddenly introduced, the inflowing air forms a gravity current and begins to mix with the unburned pyrolysis products, creating a combustible mixture of gases in some part of the enclosure. Any ignition sources, such as a glowing ember, can ignite this combustible mixture. Resulting in an extremely rapid burning of gases/pyrolysis products forced out through the opening and causes a fireball outside the enclosure.

## 2) Understanding Backdraft

Similar to the fire described during a flashover event, a fire that may result in a backdraft usually originates from a single item burning. This fire will grow and may spread to other combustibles within the room from direct flame impingement or flaming combustible items dropping down from the upper layer, similar to a typical enclosure fire. Sometime during the growth of the fire, the fire becomes under-ventilated due to a lack of ventilation and begins to decay. An under-ventilated compartment fire produces excess pyrolyzates (unburned fuel) because of inefficient combustion. In a backdraft situation, temperatures are typically still high enough to sustain pyrolysis of the combustibles located within the compartment, regardless of the lack of oxygen for combustion, which further adds pyrolysis products to the compartment's atmosphere. Thus causing the upper layer to descend and nearly fill the entire volume of the compartment. This under-ventilated fire can occur in two different ways. First, the fire can become under-ventilated by utilizing most of the available oxygen within the enclosure and not have any additional sources of ventilation to sustain combustion. Secondly, the fire can begin having enough ventilation for the fire to transition through flashover to occur, but because of the rapid increase in fuels and combustion, the excess oxygen is consumed forcing the fire to become ventilation controlled. (Step 1-Figure 4)

*A gravity current is created when a vent is suddenly opened*. A gravity current, consisting of air, is formed when a door or window is suddenly opened either by an occupant or fire service personnel. A gravity current is a current formed when two fluids of differing densities interact in such a way that a vertical interface exists between the fluids, the resulting motion consists of the heavier fluid flowing horizontally beneath the lighter fluid. In other words, when the opening is made, the hot fuel-rich gases flow out the upper portion of the opening, while the cooler exterior air is being drawn into the compartment at the lower portion of the opening. (Step 2-Figure 4)

*An ignitable mixture is formed*. An ignitable mixture is formed at the shear interface between the smoke layer and this influx of air created by the gravity current. *An ignition source must be present at the interface for ignition.* This ignitable mixture at the shear interface will ignite if presented with a suitable ignition source (i.e. smoldering combustion, hot surfaces, flaming combustion). (Steps 3 & 4-Figure 4)

*A flame front propagates through the compartment.* Once this initial ignition takes place, more mixing of air and the smoke layer will commence, thereby creating a greater concentration of an ignitable mixture. A flame front will form from this chain reaction of ignitions and will propagate through the compartment. An increase in temperature and increase in pressure will commence due to the flame front propagation. The increase of pressure inside the compartment forces excess fuel-rich gases through the opened vent. These excess fuel-rich gases suddenly begin mixing with the available oxygen exterior of the compartment and ignite causing a tremendous fire ball upon exit from the compartment. (Steps 5 & 6-Figure 4)

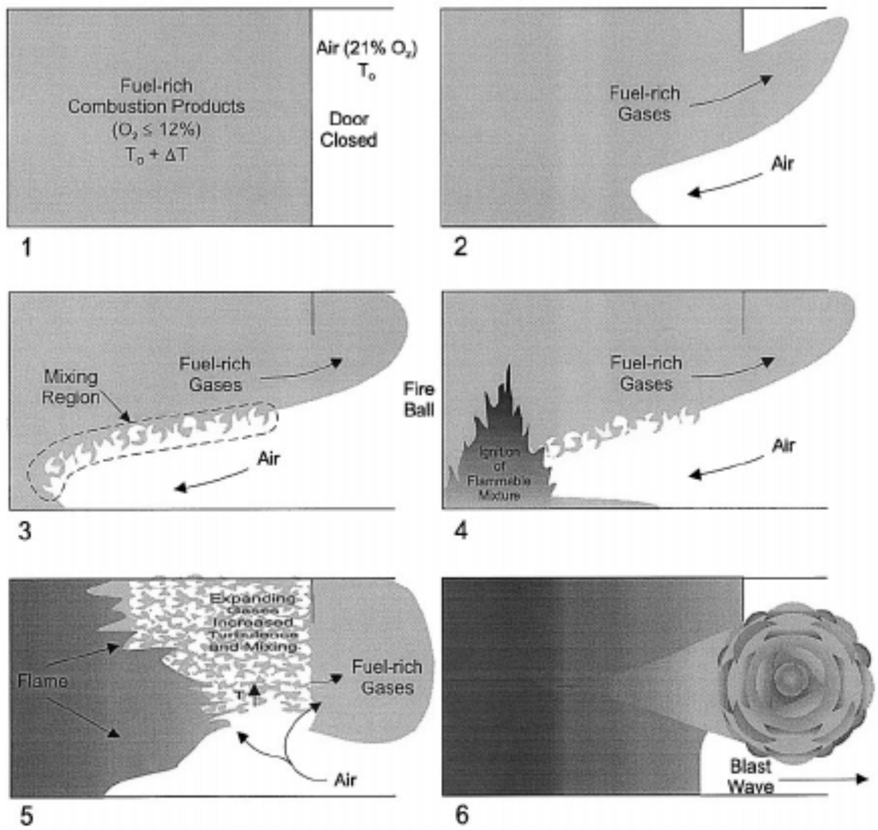


**Figure 4: Progression of a typical Backdraft (Source: Gottuk, D.)**

The study by Fleischmann and Pagni more succinctly found:

- An underventilated compartment fire produces excess pyrolyzates (unburned fuel) because of inefficient combustion due to the lack of oxygen.
- A gravity current, consisting of air, is formed when a door or window is suddenly opened. A gravity current is a current formed when two fluids of differing densities interact in such a way that a vertical interface exists between the fluids, the resulting motion consists of the heavier fluid flowing horizontally beneath the lighter fluid.
- A flammable mixture is formed at the shear interface between the smoke layer and this influx of air.
- This flammable mixture at the shear interface will ignite if presented with a suitable ignition source.
- Once this initial ignition takes place, more mixing of air and the smoke layer will commence, thereby creating a flame front that will propagate through the compartment. Excess fuel (pyrolysis products) is forced through the opening due to a pressure build-up from the propagating flame front, thus causing a tremendous fire ball upon exit from the compartment. (Figure 4)

**3) Components That Control Backdraft**

1. Underventilated Compartment Fire
2. Production of un-burnt, oxygen deficient pyrolysis products (excess pyrolyzates)
3. Sudden Introduction of Air (i.e. window or door)
4. A Gravity Current carries fresh air into compartment
5. Air Mixes with un-burnt oxygen deficient pyrolysis products creating a flammable/combustible mixture interface
6. If ignition source is present at this flammable/combustible mixture interface, then ignition will occur.
7. Turbulent mixing of air and un-burnt, oxygen deficient pyrolysis products results from the ignition of this interface, which results in further flame spread.
8. A deflagration occurs as the flame propagates through the compartment.
9. Excess un-burnt pyrolyzates are forced through the opening by the positive pressure build-up and heat created by the propagating flame front
10. The excess pyrolyzates outside the compartment ignite once presented with fresh air and ignited by the following flame front. Creating a fire ball and blast wave.

**4) Indicators of a Backdraft**

The following are indicators that a backdraft may occur.

1. The fire may be pulsating. Windows and doors are closed, but smoke is seeping out around them under pressure and being drawn back into the building.
2. No visible flames in the room.
3. Hot doors and windows.
4. Whistling sounds around doors and windows. If the fire had been burning for a long time in a concealed space, a lot of unburned gases may have accumulated.
5. Window glass is discolored and may be cracked from heat (Norman, 1991).

The key indicator that has been witnessed in the past is the in and out movement of the smoke, which gives the appearance that the 'building is breathing'.

**5) Misconceptions Regarding Backdraft**

Many misconceptions were found in the current literature, including many of the current traditional training documents. In this paper only one will be addressed.

**a) Misconception – "Backdraft is fueled by Carbon Monoxide"**

Many texts state that Carbon Monoxide is a major fuel that drives the backdraft phenomenon. However, there is no scientific backing for these statements; in fact numerous studies have been done to disprove this theory (Gottuk; Gojkovic; Sutherland; Fleischmann). These studies reveal that the major fuel constituent that drives the backdraft phenomenon is the incomplete solid pyrolysis products within the smoke layer. Many texts incorrectly use the fact that Carbon Monoxide has a flammability range as proof that CO is the fuel behind the backdraft phenomena. However, in reality the LEL of CO is the most important factor when investigating this issue. Carbon Monoxide requires a substantial mixture (12%) in air before it is flammable or explosive coupled with the fact that studies have shown typical enclosure fires rarely have CO mixtures above 5% (DeHaan; Babrauskas; Gottuk). Therefore, the misconception has no basis or scientific support.

## C. Flameover (Rollover) Research

No experimental research specifically related to flameover or rollover could be identified. Due to the insufficient stand-alone research regarding this phenomenon, a presentation of references removed from other texts will be established. A paper written by Chief Vincent Dunn, formerly of the New York fire department, erroneously defines and explains the phenomenon of flameover. He defines the phenomenon as, "the rapid spread of flame over the surface of walls and ceiling walls, and ceilings painted or covered with a combustible finish can exhibit flameover" (2002, p.2). Chief Dunn incorrectly applies a premise that the ceiling or walls must be of a combustible nature and that it is this combustible fuel that stimulates the flame spread. In fact, NFPA's preferred definition, in direct opposition to Chief Dunn, correctly defines flameover (rollover) as, "the condition where unburned fuel (pyrolysate) from the originating fire has accumulated in the ceiling layer to a sufficient concentration (i.e., at or above the lower flammable limit) that it ignites and burns; can occur without ignition and prior to the ignition of other fuels separate from the origin" (2002, p.7).

### 1) Definition of Flameover

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

### 2) Understanding Flameover

Typically as a compartment fire begins there is a single fuel package burning. This produces a buoyant fire plume that begins spreading heat energy primarily by convected gases rising in the plume. At this point in the fire the effect of convective and radiant heat transfer to other fuel packages and the walls, floor and ceiling of the compartment are relatively minimal. As the buoyant plume's gases, and other heated products of combustion begin to collect below the ceiling and spread laterally, the upper layer begins to form. From this point on in the fire, radiant heating is occurring both from the original fuel package's fire plume and the now ever-deepening upper layer as well. As the temperature increases in the upper layer, the unburned fuel that has been accumulating may gradually reach its auto ignition temperature (AIT) and pockets of partially mixed fire gases will begin to ignite. For ignition to occur, those pockets of gases must have already mixed with fresh air to bring the mixture within its flammable limits. This fresh air is being entrained from the compartment into the bottom of the upper layer. As this process continues, the pockets of gases will merge into a flame front that will begin to propagate through the compartment. Typically this flame front is witnessed rolling across the ceiling. This is termed as a flameover or rollover. The radiation from the flameover will begin to increase the temperatures of those items in the lower layer. A flameover often times precedes a flashover, but is not a required event for flashover to occur.

The reason why the flameover rolls across the ceiling is simply the increase in buoyancy of the now ignited particulates displacing the now cooler smoke from the ceiling layer. This rolling effect is further influenced by the entraining of fresh air into the base of these detached flames.

**3) Components that Control Flameover/Rollover**

1. Underventilated Compartment Fire
2. Build-up of un-burnt oxygen deficient pyrolysis products forming an upper layer within the compartment.
3. One or more of the fuels present in the layer accumulates to within its flammability range.
4. Ignition occurs either due to direct flame contact from the flame or from the fuels coming within its auto-ignition temperature.
5. Presented with oxygen at the lower portion of the upper layer, forming a flammable region.
6. Ignition occurs at the location of the flammable mixture and the flame spreads until the local fuel and/or oxygen is exhausted.

**4) Indicators of a Flameover**

1. *Upper layer begins to Thicken (visibility decreases)*. The amount of incomplete combustion products are increasing in the upper layer.
2. *Upper Layer Temperature Increases*. The upper layer temperature begins to increase, gradually bringing those pyrolyzates to their auto ignition temperature. Firefighters may begin to feel the heat from the descending upper layer.
3. *Turbulent mixing in the upper layer.* If the upper layer begins to mix vigorously, the temperature distribution throughout the upper layer is increasing and is causing the mixing of fresh air at the underside of the upper layer to greatly increase.

**5) Misconceptions Regarding Flameover**

Many misconceptions were found in the current literature, including many of the current traditional training documents.

**a) Misconception – "Flameover is Flashover"**

Many textbooks and articles publish the accounts of firefighters who state that they have lived through a flashover. This is not possible! A flashover is the near simultaneous ignition of all combustibles within the compartment due to the radiation heat transfer from the upper layer. Flashover is a step event, meaning that once the transition is completed the compartment will continue to quickly increase in the amount of heat load imposed on materials within that compartment. Turnout gear is not manufactured nor can it withstand the heat flux that would be imposed on a firefighter in a flashover event. On the other hand, a flameover is more of a localized, transient event that occurs relatively quickly and subsides. The intensity may be near the same magnitude as that of the beginning stages of a flashover, but the duration of this exposure is low. The issue here is that a flameover, while dangerous and sometimes a sign of an impending flashover, is not nearly as dangerous as that of a flashover and should be characterized as such.

**b) Misconception – "Flashover Chamber "**

One of the newest training fads around the world is the use of portable shipping containers for training firefighters, typically known as a flashover chamber. These shipping containers are setup with a fire compartment and a viewing compartment (Figure 5). A fire is set in ordinary combustibles within the fire compartment and students sit and watch the fire behavior from the lower viewing compartment. An instructor demonstrates the cooling of the upper layer with the different types of hose streams as well as demonstrates the effect of ventilation. The instructor will allow the fire compartment to increase in heat to illustrate that flames will begin to form dissociated from the original flame plume. The instructor will then state that this is flashover and illustrate to the students several signs of an impending flashover. The training is top notch for the firefighter and should not cease. It is the incorrect terminology that should be changed. These unattached flames that are occurring in the upper layer are actually the beginning of a flameover. Therefore, the actual term for this training exercise is a flameover chamber.


**Figure 5: "Flashover" chamber (Photograph of Auburn, Indiana Fire Department Training Facility)**

## D. Standards and Textbooks

The other purpose of the paper was to review the current standard and most-widely used textbooks for firefighters. The two most prominent texts in this area were reviewed for this paper, including: the National Fire Protection Association's *Standard for Fire Fighter Professional Qualifications* and the International Fire Service Training Association's *Essentials of Fire Fighting.*

**1) NFPA 1001**

NFPA 1001 is split into two major sections over a total of 12 pages. The first section of the standard deals with Fire Fighter 1 requirements and the second section deals with Fire Fighter 2 requirements. These two sections are the different types of certifications that this standard addresses. These sections are cumulative, meaning that a person must possess all requisite knowledge required by the first certification to attempt the second certification.

The fire fighter 1 section details the requisite knowledge that a person must possess in order to be certified as a "Fire Fighter 1". This section separates the knowledge and skills required into six major sections. These sections include general knowledge requirements, general skill requirements, fire department communications, fire ground operations, rescue operations, and prevention, preparedness, and maintenance. The only section that directly relates to this report is the discussion regarding enclosure fire behavior training requirements found under 5.3.1.2 (A) of the 2004 NFPA 1001 edition (p.6). The only enclosure fire behavior training requirements in this section are contained in two short phrases, which read, “the methods of heat transfer, the principles of thermal layering within a structure on fire are to be met” (p.6).

The fire fighter 2 section details the requisite knowledge and skills that a person must possess in order to be certified as a “Fire Fighter 2”. This section separates the knowledge and skills required into the same six major sections as the fire fighter 1 section, except with different lists of required skills and knowledge to be met. The only reference to enclosure fire behavior requirements can be found under 6.3.2, which reads, “coordinate an interior attack line for team’s accomplishment of an assignment in a structure fire” (p.11).

This standard gives no detail of how these knowledge and skill sets are to be met. Nor does this standard detail the amount of time that should be spent on obtaining each requisite knowledge and skill. Essentially this standard only describes in a checklist format, the requisite knowledge and skill that should be held by a person to be certified as a fire fighter 1 and 2. The standard relies upon other organizations to produce training materials and methods to ensure that the requirements have been met.

**2) Essentials of Fire Fighting**
The International Fire Service Training Association (IFSTA) is one of the organizations that write a training manual specifically to accomplish the requirements set forth in NFPA 1001. They produce a 700-page textbook titled *Essentials of Fire Fighting* written by a group of volunteers that have specific expertise in the fire service. The scope of this textbook reads, “The Essentials of Fire Fighting manual is designed to provide the firefighter candidate with the information needed to meet the fire-related performance objectives in NFPA 1001, Levels 1 and 2” (p.2). This textbook has individual chapters and topics. However, every section that is related as accomplishing a requirement that has been discussed in NFPA 1001 has a subtitle that details which section of NFPA 1001 is covered. This textbook has a 27-page chapter devoted to fire behavior that covers the two NFPA 1001 requirements mentioned above.

# Conclusions

## *Summary and Interpretation of Findings*

The literature review revealed that the accurate knowledge and accurate science regarding the rapid fire progression phenomena are available. In fact these phenomena have been studied a considerable amount by some of the great fire scientists and have been detailed in this report. While all the mechanisms are not fully understood for all aspects of each phenomenon, the fundamental mechanisms are understood. Qualitative analysis of these phenomena is understood and has been documented extensively. Fire service personnel to accurately perform their duties only need to understand these theoretical or qualitative mechanisms that make up these phenomena. Thus, the first major problem seems to lie in the transferring of this accurate knowledge from the fire scientists to other professionals within the fire service profession.

The literature review also revealed that there are several terms that are being defined and used interchangeably. The multiple definitions and usage of similar terminology for different phenomena add to the widespread confusion. It is important that the definitions be universal in their meanings and usage. Communication problems arise when the inaccurate term or definition is used. (See Glossary for accurate definitions)

Much of the current fire research knowledge gained by fire service personnel are based upon independent learning or from certification courses. The primary media for this independent learning and current research is trade periodicals and journals. Technical inaccuracies regarding these phenomena are still being presented in many of the major fire service publications (e.g. *Firehouse, Fire Engineering*), only adding to the confusion of the understanding of these phenomena. In fact, the literature review shows that technically inaccurate papers greatly outnumber the technically accurate papers.

The training officers and instructors that are currently teaching these important fire behavior mechanisms are not being held accountable for their qualifications nor the material that they are teaching.

NFPA 1001 is not thorough enough in its requirements. It only provides a list of minimum requirements that should be obtained by a firefighter candidate to obtain these certificates. Out of a 12-page document, only two sentences are devoted to requiring more enclosure fire behavior training, yet statistics demonstrate that the majority of lives are lost due to enclosure fires. Thus, the requirements are very disproportionate to the problem. Also, NFPA 1001 is very vague in its requirements and the establishment of those requirements. For instance, the Standard does not detail what specific knowledge should be obtained, how the material should be taught, what certifications the teacher or trainer should posses, and worst of all, the amount of time that should be allotted for each section.

The *Essentials of Fire Fighting* textbook covers all the minimum requirements established by NFPA 1001. Therefore, it accomplishes its goal of certifying individuals through NFPA 1001. However, out of a 700-page textbook only 27 pages are devoted to enclosure fire behavior. The chapter on fire behavior is very brief and limited in its discussion. In fact, much of the material is outdated. This is also a very inadequate solution to a large problem. Some responsibility should rest with the writers and editors of this textbook for its failure to adequately train firefighters. However, the main responsibility should rest with the Technical Committee for NFPA 1001, because the *Essentials of Fire Fighting* textbook is only designed to meet those requirements of NFPA 1001. Thus, if the Technical Committee made more detailed and stringent requirements for enclosure fire behavior the *Essentials of Fire Fighting* textbook would have to update and broaden its scope related to fire behavior.

One of the largest failures in the fire safety profession is technology transfer. Technology transfer is essentially the transferring of that knowledge held by few in our business and distributing it to the masses. Specifically, it is experimentation and studies completed by those scientists that publish their findings in trade periodicals that typically do not appeal to the everyday fire officer or fire fighter. Therefore, the information is not being transferred to those that may need it the most. Moreover, many of those scientific reports are so convoluted with technical jargon and mathematical expressions that the important qualitative information is lost and not comprehensible to many. The problem of technology transfer is further exacerbated by the continued publishing of incorrect information in those trade journals that are more influential to the fire officer and firefighter. This further propagates incorrect knowledge to another generation of fire fighters and training officers, because they cite those 'reputable' magazines as their basis for their opinions.

### *Recommendations*

On the basis of my conclusions, I recommend the following:

1. *Definitions must become universal*. It is important that the definitions be universal in their meanings and usage. Communication problems arise when the inaccurate term or definition is used.
2. *Technical Literature must be properly edited and reviewed before publication*. Technical editors need to be more aware of these incorrect terms and their usage within their publications. Putting a stop to these technical inaccuracies within trade journals and publications is a necessary step to abolish the usage of incorrect terms.
3. *Technology Transfer must become a priority for all fire safety professions*. The introduction of the internet should have increased the technology transfer between all fire safety professions, but it still not getting accomplished. All fire safety personnel need to be proactive in searching for articles that may assist with their duties. Training officers, especially, need to gather the information and disseminate it to the fire service personnel.
4. *Instructor qualifications must be upgraded.* Fire departments are going to have to require an upper-level degree in fire science and/or some other related science field for instructors. The fire service needs to be more proactive in eliminating the old myths.
5. *Instructors' material must be certified*. The materials that these instructors are teaching should be reviewed and certified as being scientifically accurate. Also, the use of only scientifically approved textbooks for training should be established.
6. *NFPA 1001 must become more descriptive*. NFPA 1001 must be more than just a checklist. It can still maintain a minimum status; however, it should become much more detailed in its meanings. Additional Job Performance Requirements (JPR's) need to be introduced that increase the minimum level of scientific knowledge required.
7. *Tougher requirements for fire behavior training governed by NFPA 1001-Standard for Fire Fighter Professional Qualifications.* NFPA 1001 must become more stringent in its fire behavior requirements. Two phrases out of a 12-page document are simply not enough of a requirement to prevent firefighter deaths.

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# Glossary

**Backdraft:** Limited ventilation during an enclosure fire can lead to the production of large amounts of unburnt gases. When an opening is suddenly introduced, the inflowing air may mix with these, creating a combustible mixture of gases in some part of the enclosure. Any ignition sources, such as a glowing ember, can ignite this combustible mixture, resulting in an extremely rapid burning gases out through the opening and cause a fireball outside the enclosure. The speed at which the flame progresses through the unburnt gases will determine if an explosion will occur and create structural damage. The phenomenon can be extremely hazardous (Quintiere 13).

**Flameover:** The condition where unburned fuel (pyrolysate) from the originating fire has accumulated in the ceiling layer to a sufficient concentration (i.e., at or above the lower flammable limit) that it ignites and burns; can occur without ignition and prior to the ignition of other fuels separate from the origin (NFPA 921 7).

**Flashover:** A transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full room involvement or total involvement of the compartment or enclosed space (NFPA 921 8).

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# Appendix B : About the Authors

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