FLASHOVER AND FIRE ANALYSIS
- A Discussion of The Practical Use of Flashover Analysis In Fire Investigations

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Abstract

Properly understanding the phenomenon of flashover and applying that understanding to fire investigation and analysis can be very valuable tools in unraveling the mysteries of a fire's origin, cause, and development. Nevertheless, many current practitioners in the fire investigation and analysis community misunderstand, or fail to fully understand, flashover. This lack of understanding being the case, the effective use of the analysis of a flashover event in a fire investigation is seldom done, or not done properly. Thereby the potential value of flashover analysis to an effective fire investigation is frequently lost.

There are several considerations associated with flashover and fire analysis for the modern fire investigator or fire analyst to understand in order to use the science effectively. These elements include proper working definitions of flashover and “full room involvement;” understanding the nature of the flashover phenomenon itself; methods for using flashover in investigations; and debunking commonly held misconceptions about flashover. The "problem" to be solved before a fire investigator or analyst can effectively use flashover in investigations is to reach a true understanding of each of these elements.

This paper endeavors to present historical research on the definitions and understanding of flashover; report current, peer-reviewed, practical definitions of flashover and “full room involvement;” give a basic applied-science understanding of the nature of flashover; discuss and debunk a number of commonly held misconceptions about flashover; provide some guidance in using flashover in fire investigations; list some areas of valuable information which can be gleaned from flashover analysis; and provide a basic scientific bibliography of published flashover research. It is also the intent of this discussion to present the topic in a format that reaches all the wide range of levels of education and experience in the fire investigation and analysis community.

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Introduction

With the original publication of the National Fire Protection Association's (NFPA) National Fire Code© NFPA 921 - *Guide for Fire and Explosion Investigations* in 1992, the practical use of science in fire investigations first became expressed in a widely read, peer-reviewed, fire investigation text.[1] Subsequent editions of NFPA 921 have expanded upon, further explained, and directed fire investigation professionals to these scientific principles and how these principles should be applied to fire investigations. Even before the publication of the first edition of NFPA 921, issues of the understanding and use of science in fire investigations were being taught in the National Association of Fire Investigator's (NAFI) National Fire, Arson, and Explosion Investigation Training Programs. While at the same time, other widely attended training seminars were missing the boat, teaching "old-wives'-tales" and pseudo-science. Some still are!

Among these scientific issues, the use of flashover in the analysis of a fire was widely recognized as both important and subject to controversy. The National Bureau of Standards – Center for Fire Research (now the National Institute of Standards and Technology – Building and Fire Research Laboratory) and other fire research facilities, worldwide were already reporting scientific research into the nature of flashover as early as the early 1970's.[2]

Transition to scientifically based fire investigation from anecdotally based fire investigation has been problematical. In a one-page article published by the Arizona Chapter of the International Association of Arson Investigators (IAAI) in 1991, the two fire investigator authors lamented the use of "this 'new theory of flashover'" to win the release of incarcerated individuals convicted of arson in two separate cases. In the article the authors questioned the validity of "laboratory" tests over "…what happens in the real world." [3]

The authors of the article wrote in part:

> "In the state of Arizona during the past year two landmark cases have won appeals on the 'New Flashover Theory' as put forward by some experts. In both cases the original investigations concluded that a liquid accelerant had been used in the fire. In both cases there was a loss of life, charges were brought and a jury found the responsible parties guilty as charged.
>
> "In this 'new theory of flashover' the 'experts' claim that flashover produces burn patterns on the floor which have all the characteristics of a liquid accelerant burn pattern.
>
> "We feel that it is time for the fire service and the fire investigators to help put this into perspective and let the industry know what happens in the real world, not in a laboratory." [4]

In 1992, Lentini reported on a 1990 landmark investigation, "The Lime Street Fire," in which he and DeHaan conducted a full-scale test fire investigation.[5] The result was the release of an improperly incarcerated defendant based upon the prosecutor's agreement with their conclusion that the reported "arson" patterns were caused by a natural, un-accelerated flashover. This proved to be both a landmark investigation and a conundrum for the IAAI. Many within the IAAI were appalled that two of their "fire science gurus" had used science to free an "arsonist."

This is the type of provincial thinking that the discussion here is intended to address.

"Fire Science Without Tears"

It is the intent of this discussion to present the topic in a format that reaches all levels of education and experience in the fire investigation and analysis community, a wide range since the use of proper fire science in fire investigations is unevenly applied. Well-known fire researcher and fire analyst Richard L. P. Custer once coined a phrase that aptly describes the tenor of this work: "*fire science without tears*." It is characterized by the use of non-dimensional, non-quantitative graphs, and simple formulae and equations with a limited use of fractional exponents (other than ½ to indicate square root). The more intricate details of the science and mathematics involved in understanding flashover can be found in various works cited in the bibliography. The reader is urged to go directly to these works for those details.

The "Problem"

Properly understanding the phenomenon of flashover and applying that understanding to fire investigation and analysis can be very valuable tools in unraveling the mysteries of a fire's origin, cause, and development. But even now, with the concept of flashover having been discussed and studied in the fire science profession for over forty years, flashover is not fully understood by the great majority of fire investigators. Misconceptions about flashover, its definition, nature, the time and conditions required for flashover to occur, and frequency of occurrence, abound in the fire investigation and analysis field. Many nationally prominent fire investigation-training venues are still today teaching inaccurate flashover pseudo-science, or worse, no fire science at all.

There are several considerations associated with flashover and fire analysis for the modern fire investigator or fire analyst to understand in order to use the science effectively. These elements include the proper definitions of flashover and "full room involvement;" understanding the flashover phenomenon itself; common misconceptions about flashover; and flashover's use in investigations. The "problem" to be solved before a fire investigator or analyst can effectively use flashover in investigations is to reach a true understanding of each of these elements.

Defining Flashover

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.[6] 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."

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.

The earliest discussion of flashover in a fire investigation text was in 1961 by pioneer fire investigator John Kennedy.[7,8] He wrote:

> "There is another factor mentioned previously which explains some of the rather mysterious, quick spreading fires that witnesses so often testify 'leaped across a room' or corridor. This is the 'flashover' characteristic which has been observed in numerous tests. It is closely related to room temperatures. Observations of test fires show that furniture ignites without direct flame contact between 400° F. and 500° F., but when the room temperature reaches the vicinity of 600° F. to 700° F. a 'flashover' occurs and the entire room appears to burst into flame at once. This is probably the explanation of eyewitnesses' stories of flames which seemingly leap across a room or down a corridor with express train speed."

It has been popularly reported by Grimwood, that the well-known and much respected British fire scientist Dr. Philip H. Thomas first introduced serious scientific discussion of the term flashover later in the 1960's.[9]

> "[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." [10]

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'...'" [11]

" British Standards (4422) of 1969 and 1987 further attempted to apply a more precise definition without success." [12]

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." [13]

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[14] provides some interesting exemplar results.

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 18th 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." [15]

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." [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°." [17]

> [Drysdale] "the transition from a localized fire to the general conflagration within the compartment when all fuel surfaces are burning" [18]

> [ISO] "…the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure." [19]

> [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." [20]

> [Babrauskas] "…the full involvement in flames of a room or other enclosed volume."[21]

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

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" [22]

> [Drysdale] "…the exposed surfaces of all combustibles will be burning…" [23]

> [NFPA FPH, 18th Ed.] "…fully involved compartment fire.." [24]

> [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." [25]

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." [26]

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.

A New Practical Definition of Flashover
For fire investigation professionals the current, peer-reviewed, practical definition of flashover is the result of an accepted public proposal to the 2004 Edition of NFPA 921 and contains all of the elements discussed above. The newly crafted NFPA 921-2004 definition of flashover 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." [27]

This is the working definition adopted for this discussion and should be used by the reader for the subsequent discussions herein.

Understanding Flashover

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.[28]

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.

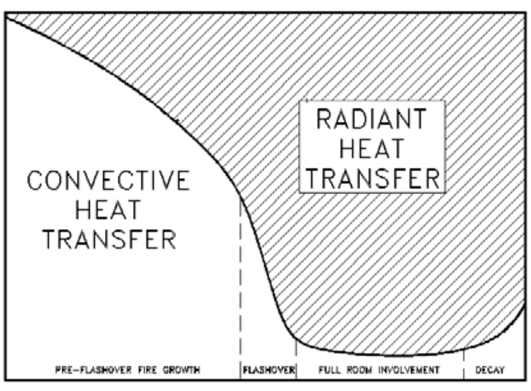

Figure 1 - Relationship of Heat Transfer Mechanisms within a Compartment Fire

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 contain more heat energy, 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 (see 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.

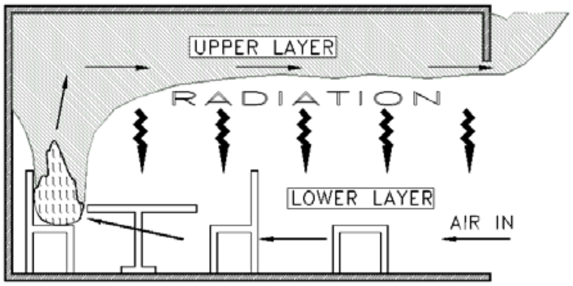

Figure 2 – Pre-flashover conditions in a compartment fire.

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.

The Flashover/Bathtub Analogy

Flashover has been analogously compared to the filling of a bathtub with the drain open. In this practical, though not perfect, analogy water represents the heat energy. The quantity of water available is the total heat of combustion of the available fuels (fuel load). The size of the spigot and the water pressure control the amount of water flow that is the heat release rate. The volume of the bathtub is analogous to the volume of the compartment and its ability to contain the heat energy. The size and location of the bathtub drain controlling the rate of water loss is the loss of heat energy through venting and conductance. In this analogy, if the bathtub becomes full and overflows, flashover occurs. (see Figure 3 below)

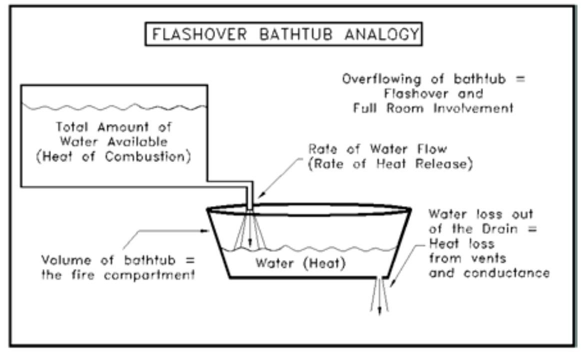

Figure 3 – The Flashover/Bathtub Analogy

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

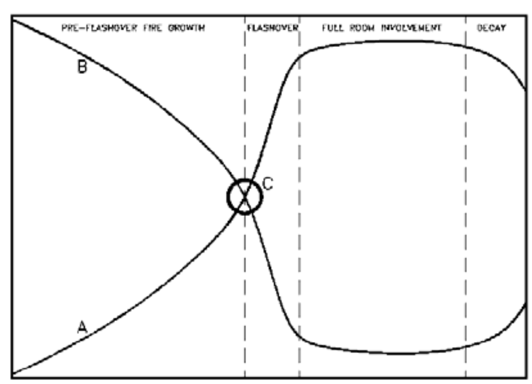

Figure 4 - Non-Dimensional Flashover Correlation Curves (Kennedy's Flashover Correlation Curves)

Non-Dimensional Flashover Correlation Curves
Figure 4 is a non-dimensional graph that displays a simplified correlation between various conditions in the fire compartment. The x-axis represents time. The y-axis represents properties that are variably increasing or decreasing during the course of the compartment fire.

Curve "A" is used to represent those conditions that increase during the life of the fire:

- Average upper layer temperature
- Average room temperature
- Radiant flux at floor level
- CO and other toxic gas concentrations
- Ratio of CO to O_2
- Upper layer depth
- Ratio of upper layer depth to lower layer height
- Ratio of amounts of radiant heat transfer to convected heat transfer
- Total heat release rate in the compartment
- Rate of fire growth (HRR/time)

The shape of curve "A," is based upon an approximation of the temperature curve of a compartment fire from ignition through pre-flashover fire growth, flashover, "full room involvement," and into the initial portion of the decay stage.

The shape of curve "B" is the reciprocal of curve "A." It represents those conditions that decrease during the life of the fire;

- Ratio of O_2 to CO
- Lower layer height
- Ratio of lower level height to upper layer depth
- Ratio of the amounts of convected heat transfer to radiant heat transfer
- Height of the "neutral plane" between upper layer outflow and air inflow at vents
- Survivability before flashover

Point "C" represents the initial point of non-survivability in the fire event at the onset of flashover indicated by an average upper layer temperature of ∞600°C (1112° F.) and radiant flux at floor level of ∞20 kW/m^2, the dramatic increase in environmental temperature, increase in CO and other toxic gases, and corresponding reduction of available O_2.

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.

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. [29] Some texts refer to these technical indicators as "triggering conditions."[30, 31]

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.

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.[32]

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[33] and by Skelly (NIST) in 1990[34] 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.[35] The commonly accepted minimum failure pressure of residential windowpanes is 0.689 kPa – 3.447 kPa (0.1 psi. – 0.5 psi.),[36] well above the pressures reported in the NIST tests. It is the rapid increase of the heating of the windowpanes that causes this effect to occur at or near flashover.

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.

Scientific Mendacity

Even for those who should understand all the scientific nuances of flashover, intellectual discipline in applying and developing hypotheses by analyzing a flashover, and ultimately drawing logical conclusions therefrom is often sadly lacking. Merely running a popular mathematical computer fire model and then adopting the numerical results, as "infallible truth" may not always be accurate. Careful attention to the basic computer model input data, understanding the limitations of the model or sub-routine utilized, and a comparison of those data to the reported or observed fire-scenario facts often requires a level of intellectual discipline and scientific objectivity beyond some investigators' capability. Despite the unquestionable value of modern mathematical computer fire modeling, they are only tools. Fire investigation cannot be accomplished only by sitting at a computer screen.

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.

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 investigator is cautioned not to make this fundamental mistake of defining "the disease as the symptoms" or "the symptoms as the disease."

Misconception – "Time To 'Full Room Involvement' (Too Fast = Incendiary)"

One of the most common and dangerous misconceptions about flashover is misunderstanding about how long it takes for flashover and the transition to "full room involvement" to occur. Many investigators over the years, and right on up to today, have opined that because a room fire went to "full room involvement" in what they consider a "short" period of time, the fire must have been accelerated and therefore incendiary.

NFPA 921 has directly addressed this common error in its sections:

> 3.5.3.2 Compartment Fires and Flashover. "Research has shown that time to flashover from open flame can be as short as 1½ minutes in residential fire tests with contemporary furnishings, or it may never occur. The heat release rate from a fully developed room flashover can be on the order of 10,000 kW (10 MW) or more."

and

> 19.2.8 Assessment of Fire Growth and Fire Damage.
> "Investigators may form an opinion that the speed of fire growth or the extent of damage was greater than would be expected for the "normal" fuels believed to be present and for the building configuration. However these opinions are subjective. Fire growth and damage are related to a large number of variables, and the assumptions made by the investigator are based on that investigator's individual training and experience. If subjective language is used, the investigator should be able to explain specifically why the fire was 'excessive,' 'unnatural,' or 'abnormal.'
>
> "What an investigator may consider as 'excessive' 'unnatural,' or 'abnormal' can actually occur in an accidental fire, depending on the geometry of the space, the fuel characteristics, and the ventilation of the compartment (see 3.5.4). Some plastic fuels that are difficult to burn in the open may burn vigorously when subjected to thermal radiation from other burning materials in the area. This might occur in the conditions during or after flashover.
>
> "The investigator is strongly cautioned against using subjective opinions to support an incendiary cause determination in the absence of physical evidence." [emphasis added]

It is an unfortunate fact that many innocent people have been accused of arson simply because the opining investigator does not understand flashover and thinks the fire was "too big too fast."[37]

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.

Misconception – "Fire Patterns Can Indicate That Flashover Occurred"

It is frequently opined that the occurrence of flashover can be determined by an examination of the post-fire patterns. The fire patterns cited in such an analysis are almost always patterns resultant from "full room involvement" (e.g., floor burning, relatively even charring on vertical or horizontal surfaces, or contents and furnishings, flaming out of doorways and windows, etc.). There are simply no recognizable patterns that describe the rapid transition to "full room involvement," only the ultimate "full room involvement" itself. The only viable evidence that flashover occurred in a compartment comes from accurate eyewitness descriptions, or as a result of competent mathematical or computer fire modeling analysis.

It should be a clear indicator of the incompetence of the investigator if he or she opines that flashover occurred and the sole basis for that opinion is an examination of the physical fire pattern evidence. No such opinion on that basis alone can be reasonably drawn. In such cases the investigator's expertise on both flashover and fire pattern analysis must be suspect.

Misconception – "Flashover 'Destroys' Fire Patterns – Pattern Persistence"

Whether common fire patterns are destroyed by the occurrence of flashover has long been an issue argued by fire investigators. The survival of common fire patterns beyond flashover is termed "pattern persistence." The evolution of a fire in a compartment is a dynamic and ever-changing process. Fire and flame plumes, layer depths and temperatures, rates of heat release, ventilation, and radiant fluxes, all grow, peak, and decay throughout the life of a fire event. The fire patterns, both movement patterns and intensity patterns, change continuously during the life of the fire as well. It is the very nature of fire patterns to be changing and evolving in this manner. The fire patterns that an investigator identifies in a pre-flashover fire will necessarily be different than those that have evolved or been newly created during the flashover and "full room involvement" stages. One cannot say that a child was destroyed because he or she naturally grew into an adult. Similarly one cannot say that an "inverted cone pattern" was destroyed because it naturally evolved and grew into a truncated cone "V" pattern.

Full-scale room fire research sponsored by the United States Fire Administration addressed this issue of "patterns persistence" directly. In its 1997 report, "USFA Fire Burn Pattern Tests," the USFA's Fire Pattern Research Committee reported that, "various confirmed fire patterns concepts include…Pattern persistence through flashover…"[38] Identifiable traditional truncated cone patterns usually survive flashover. Patterns such as "pointers" and "arrows" on vertical wooden wall studs and circular "cleanburn" patterns on room ceilings are almost always post-flashover and "patterns persistent."

Using Flashover in Fire Investigations

The extremely high temperatures and heat release rates experienced in flashover and the "full room involvement" that follows make flashover essentially non-survivable. It is this non-survivability and flashover's position in the evolution of fire spread beyond the originating compartment that first made it of particular interest to fire safety researchers. It is also for this reason that fire safety experts have endeavored to study flashover in such detail. In 1998, Peacock et al wrote:

> "The occurrence of flashover within a room is of considerable interest since it is perhaps the ultimate signal of untenable conditions within the room of fire origin and a sign of greatly increased risk to other rooms within the building. Many experimental studies of full-scale fires have been performed that quantify the onset of flashover in terms of measurable physical properties."[39]

While fire safety engineering considerations were the original driving force for flashover research, use of the scientific, mathematical, and engineering principles derived from the research is now being applied in the post-fire investigations and analyses of the fire investigation profession.

Computer Modeling and Flashover Analysis

The use of fire safety studies, particularly with regard to modern mathematical computer fire models, for fire investigation and analysis purposes is really just a spin-off of this fire safety research work.

Because a frequent component of these various computer fire models deals with flashover, competent fire investigation analysts can quite readily avail themselves of the fire safety researchers' valuable efforts.

Some of the models most commonly applied to fire investigation issues are: ASET[40] (Available Safe Egress Time) and ASET-B;[41] CFAST (Fire and Smoke Transport);[42] FPEtool (Fire Protection Engineering Tools, including Fireform and the zone model Fire Simulator);[43] and the field model FDS (Fire Dynamics Simulator)[44] and its companion graphics program, SMOKEVIEW.[45]

ASET-B (Available Safe Egress Time - BASIC) is a program for calculating the temperature and position of the hot smoke layer in a single room with closed doors and windows. ASET-B is a compact easy to run program that solves the same equations as ASET. The required program inputs are a heat loss fraction, the height (elevation of the base) of the fire, the room ceiling height, the room floor area, the maximum time for the simulation, and the heat release rate of the fire. The program outputs are the temperature and thickness of the hot smoke layer as a function of time.

CFAST is a zone model that predicts the effect of a specified fire on temperatures, various gas concentrations and smoke layer heights in a multi-compartment structure. It is a subsequent generation program to FPEtool.

FPEtool is a collection of computer simulated procedures providing numerical engineering calculations of fire phenomena to the building designer, code enforcer, fire protection engineer and fire-safety related practitioner. Version 3.2 incorporates an estimate of smoke conditions developing within a room receiving steady-state smoke leakage from an adjacent space. Estimates of human viability resulting from exposure to developing conditions within the room are calculated based upon the smoke temperature and toxicity. There is no modeling of human behavior. Also new to this release is the estimation (in the FIRE SIMULATOR procedure) of the reduction in fire heat release rate due to sprinkler suppression. FPEtool also contains FIREFORM.[46]

FIREFORM is a collection of routines designed to give fast response to specific questions. While some routines require slightly more detail than a couple of input variables, the standard routine requires relatively little effort to generate a solution.[47] Included in FIREFORM are Thomas' Flashover Correlation, ASET-B, and Upper Layer Temperature.

UPPER LAYER TEMPERATURE is a fast, rugged method for predicting pre-flashover upper-layer gas temperatures in a compartment fire with a door and/or window.

FDS (NIST Fire Dynamics Simulator) is a computational fluid dynamics (CFD) field model of fire-driven fluid flow.

SMOKEVIEW is a visualization program that is used to display the results of an FDS or a later version of CFAST simulation.

Most of these programs are set to pause and report the onset of flashover when the average upper layer temperature reaches 600°C (1112° F.) or the requisite critical heat release rate for the defined compartment is reached.

Computer modeling of flashover can give the fire investigator or analyst several types of information that could ultimately be of great value: time to flashover; fire dynamics analysis, including minimum necessary heat release rate for flashover to occur; timing of fire growth; sufficiency of available fuel for flashover to occur; sufficiency of ventilation to prevent vitiation of the fire (smothering of the fire by the low O_2 content of the descending upper smoke layer); temperature profiles in the compartment; layer depth; and egress/escape analysis. All of these can also be used in conjunction with the "scientific method" for testing of the fire investigator's or analyst's hypotheses.[48]

However there is a necessary *caveat* for the use of fire modeling. The user must know what he or she is doing. NFPA 921 Section 15.7.4 - Models on Reconstruction, initially authored by Harold Nelson, the original creator of FPEtool, directly addresses this issue:

> "As emerging tools, these fire models require varying degrees of expertise by the user. In general, the user of a fire model is responsible for ascertaining that the method used is appropriate, that the data input is proper, and that the output is properly interpreted. Those who are not sufficiently informed to have an adequate level of confidence so that they can support the use of the fire models and their validity, if challenged, should not unilaterally use such methods. Users who do not have that competence should not use these analytical tools without the guidance and assistance of a person who can take that responsibility. Because of the value of these tools, however, practitioners are urged to become aware of them and to study, understand, and use those most appropriate to their needs and capabilities."[49]

It is also important for the fire investigator to keep in mind that the results of computer fire modeling should only be used as "reliable estimates." Every fire is in some way different from any other and the vagaries of ventilation, fire spread, and other fire dynamics issues affectively prevent the output data of models from being properly used as precisely exact.

Collection of Input Data

In order to effectively use mathematical or computer fire modeling it is necessary for the analyst to collect the appropriate input data. This data must include detailed structural dimensions including not only the floor plan of the incident and adjoining compartments, but such details as ceiling heights; the size, shape, location, sill and soffit heights of doors, windows and other vents; and nature and thickness of room lining materials (walls, ceiling, floor, windows, and doors).

Analysis of a flashover also requires understanding of the heat release rate, fire growth rate, and total heat released. To do this it is required to know the types, quantities, location, aspect, and configuration of fuels. The composition, thickness, condition and layers of the materials comprising the walls, floors, windows, doors, and ceiling as well as the type, configuration, and condition of contents and furnishings, should be known. These last are the fuels for the flashover event.

NFPA 921-2001 contains Figure A.17.5.2 that gives useful examples of forms that can be used in data collection for compartment fire modeling.[50]

Understanding ventilation conditions is imperative to the soundness of the analysis. The position and condition (e.g. open or closed) of doors, windows, skylights, HVAC and other sources of ventilation, and venting must be known. Determining when ventilation sources were present or how and when they may have changed during the fire, are also aspects that can influence the output data.

Also of great importance is the identification of the first fuel package ignited and any additional secondary or tertiary fuels that would have fueled the primary fire growth in the compartment.

Fire growth rate represents the heat release rate of the fire over time (kW/s). Input of a fire growth rate into the computer fire model program tells the computer how much heat is being pumped into the system and at what rate. Standard fire growth rate curves are available within most of the computer fire models, or specific growth rates can be input for individually defined fuel packages. These standard curves are based upon the time needed for the fire to grow to an arbitrarily selected heat release rate.

The timing of the standard fire growth curves is based upon a "t-squared" fire approximation. A "t-squared" fire is one where the burning rate varies proportionally to the square of time that the fire burns. In the standard fire growth rate curves the fires are classified by speed of growth. The fire growth rates are classified as ultra fast, fast, medium or moderate, and slow. The fire growth curves classifications are defined on the basis of the time required for the fire to grow to a heat release rate of 1050 kW (1000 Btu/sec). (see Table 1 and Figure 5)

Classification of Growth Rate	Time to Reach 1050 kW (1000 Btu/sec) (Seconds)
Ultra Fast	75
Fast	150
Medium (Moderate)	300
Slow	600

Table 1 – "t-squared" Fire Growth Rates

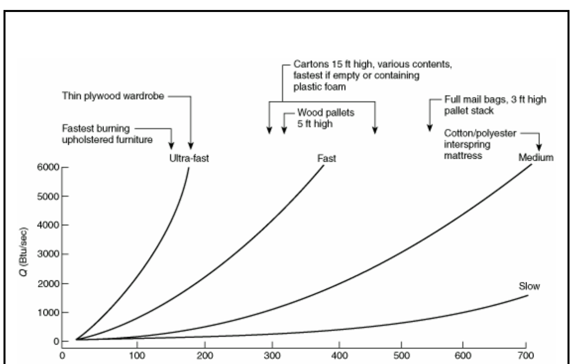

Figure 5 - Standard Fire Growth Rate Curves. (with some examples of fire test fuels)[51]

Technology Transfer and Training

A properly trained and disciplined fire investigator can gain much from the application of basic fire science principles dealing with fire growth within a compartment and the occurrence, development, or even absence of the flashover phenomenon in a fire event.

But proper training, education, and discipline in the assessment of flashover's role in a fire event are paramount.

In the fire investigation and analysis community the technology transfer from pure fire science research, through fire protection engineering, and fire engineering technology training really first became popular with the inception of NFPA's 921 document. An analysis of the practical system by which this technology transfer takes place was first published to the fire engineering community at Interflam '93, the Sixth International Fire Conference, held at the University of Oxford, England in 1993.[52] Thereafter, discussion of the nature of this technology transfer became a staple curriculum item at the annual NAFI/NFPA cosponsored National Fire, Arson, and Explosion Investigation Training Programs.[53]

It is through the application of this fire science technology transfer system that today's professional fire investigator is gaining the proper training, education, and discipline mentioned above at such programs as the three annual National Fire, Arson, and Explosion Investigation Training Programs cosponsored by NAFI and NFPA.

Valuable Information From Flashover Analysis

The use of the analysis of flashover in fire investigations can provide much valuable information or provide validation of preliminary theories or fire-spread scenarios. In many circumstances properly applied flashover analysis techniques can tell the investigator such information as: probability of flashover, time to flashover, survivability analysis, timeline event analysis, appropriateness of expected fire load, appropriateness of actual fire severity, and corroboration of witness information.

Probability of Flashover

A key and primary use of flashover analysis is to give the fire analyst a good idea of whether flashover will occur at all, given the circumstances of the compartment, its fuel, and ventilation. The various mathematical formulae and computer fire models can give the analyst a confirmation on whether his or her hypotheses that flashover is likely or even possible.

It can be a key element in applying the "scientific method" to the investigation at hand. For example, vitiation of a fire in a given compartment and ventilation scenario, thereby preventing or greatly delaying the advent of flashover, is a component-designed-in pause and report of many of the popular model programs.

Thomas's Flashover Correlation[54] is a sub-routine contained in FIREFORM in FPETool and in CFAST. This procedure contains an equation for estimating the amount of energy needed in a room or similar confined space to raise the level of temperature to a point likely to produce flashover. Though there are some limitations on its usefulness, the correlation can give the investigator a quick overview of the minimum heat release rate necessary for flashover to occur in a moderate size compartment. Its input data consist only of the size and height of the room and the size and heights of the vents (e.g., open doors and windows).

The theory behind Thomas' Flashover Correlation results from simplifications applied to a hot upper layer energy balance in a room. These simplifications resulted in the equation below. The term, A_{room}, within the equation represents heat losses to the total internal surface area of the compartment, and the term, (A_{vent} $H_{vent}^{½}$), represents energy flow out of the vent opening. The two constants, 7.8 for A_{vent} and 378 for $H_{vent}^{½}$, represent values correlated to experimentally tested flashover conditions.[55]

Solving Thomas's Flashover Correlation equation for heat release rate will provide the minimum heat release rate needed for flashover to occur in the defined compartment.

$$\dot{Q}_{fo} = 7.8\, A_{room} + 378\, (A_{vent}\, H_{vent}^{½})$$

Where:

$\dot{Q}_{fo}$ =	Heat release rate necessary for flashover (kW)
A_{room} =	Area of all surfaces within the room, exclusive of the vent area (m^2)
A_{vent} =	Area of the total of all vents (m^2)
H_{vent} =	The difference between the elevation of the highest point of all the vents and the lowest point of all the vents (m)

The equation does not know where the vent is located or whether the vent is a window or a door, though the equation was developed from tests that included window venting. The equation does not consider whether or not the walls are insulated. Use of the equation for compartments with high thermal inertia, high conductance lining materials, such as thin metal walls, would be inappropriate. The experiments were conducted with compartments, not greater that 16 m^2 (172 $ft.^2$), with thermally thick walls and fueled by fires in wooden cribs. Babrauskas later verified the equation in gypsum wallboard lined rooms with furniture-fueled fires.[56]

Building on Thomas and others, Babrauskas gives us a formula for determining the minimum heat release rate of a fire that can cause a flashover in a given room as a function of the ventilation provided through an opening. Known as the "ventilation factor," and colloquially referred to within the fire science community as "*A root H*," it is calculated as the area of the opening (A_{vent}) times the square root of the height of the opening (H_{vent}).[57]

An approximation of the heat release rate required for flashover to occur from Babrauskas can be found from the following equation:

$$\dot{Q}_{fo} = (750\, A_{vent})\, (H_{vent})^{½}$$

Where:

$\dot{Q}_{fo}$ =	Heat release rate necessary for flashover (kW)
A_{vent} =	Area of vent opening (m^2)
H_{vent} =	Height of vent opening (m)

Heat release rates at flashover from 33 actual full-scale tests with a variety of fuels is reported by Barauskas et al as high as 5.9 MW and as low as just over 1 MW, with the median average at 1.7 MW, which they denote as "probably more characteristic of the data." The majority of these reported heat release rates was between 1 MW and 2 MW.[58]

Upper Layer Temperature (U-Temp) is a fast, mathematical sub-routine for predicting pre-flashover upper-layer gas temperatures in a compartment fire with a door and/or window also contained in the original FPEtool FIREFORM routines. It was developed from a regressional fit to a large number of experimentally measured fire data. This large database is, in large part, a reason for the procedure's robustness. The authors of this method are McCaffrey, Quintiere and Harkelroad.[59]

The prediction of upper layer temperature begins with an energy balance about a control volume. This control volume includes the hot pyrolysates and entrained air that together rise and form the gaseous upper layer within the room. The control volume does not include the barrier surfaces (ceiling and walls); the control volume extends to, but not beyond the openings from the vents. By applying conservation of energy to this control volume, a general expression for the temperature of the upper layer in the room becomes available, thereby predicting flashover when the technical indicator of ∞600°C (1112° F.) upper layer temperature ($T - T_\infty$) is reached.

$$\dot{Q}_{fire} = m_{out}\, c_p\, (T - T_\infty) + \dot{Q}_{surface}$$

Where:

$\dot{Q}_{fire}$ =	Fire heat release rate into the control volume (kW)
$\dot{Q}_{surface}$ =	Heat lost from the control volume to the room surfaces (except floor) (kW)
m_{out} =	Mass flow rate of hot gas out of the room (kg/s)
c_p =	Heat capacity of slab denoted by subscript (kJ/kg/ K)
T =	Temperature of the control volume (smoke) gases (K)
T_∞ =	Temperature of the ambient room air at simulation start (K)

Time to Flashover

By giving an estimate of the time needed for flashover to begin at a specific fire growth rate, flashover analysis can be used to give an approximation of the time of fire inception. Time of inception of the fire and time of flashover would certainly be of interest in examining the possibility of victims' escape, the presence or absence of witnesses or perpetrators at the time of ignition, ability of fire rescue units to have mitigated the injuries by prompt fire suppression or rescue, and any number of related timing issues.

It must be kept in mind that the popular computer fire models report this time to flashover, not from the expected time of ignition, but from the time that the initiating flame is self-sustaining. This usually means that the data is reported from the time that the originating flame is ~25 cm (10") high. The time that the fire takes to reach this self-sustaining flame height is referred to as the "virtual time." The virtual time can be relative long as in a smoldering ignition scenario, or short as in a direct open flame impingement ignition scenario. Many of the heat release rate and burning time data used in the construction of the models come from tests conducted by various fire research on actual or simulated initial fuel packages. Many of these tests are reported in NFPA 72-2002 - The National Fire Alarm Code© Table B.2.3.2.6.2(e) Furniture Heat Release Rates[60] and NFPA 92B –2002 Guide for Smoke Management Systems in Malls, Atria, and Large Areas Table B.5.2(a) Unit Heat Release Rate for Commodities, Table B.5.2(b) Maximum Heat Release Rates, and Table B.5.3(d) Heat Release Rates of Chairs in Recent NBS Tests.[61]

Survivability Analysis

Because flashover is generally considered to be non-survivable, having a reliable estimate of when flashover occurred the investigator can make a reasonable estimate of the last possible time that a fire fatality victim could have been alive in a flashed-over compartment. This is particularly true if the victim's cause of death was directly related to thermal burns. Comparison of victims' injuries can also be made to the pre- and post-flashover data that is commonly produced in typical flashover analyses (e.g. how the location and severity of injuries correlate to the victims actions in relation to the temporal aspects of the flashover and the upper and lower layer temperatures). Escape and egress time estimates may also be made from some of this reported data. In such analyses it can generally be assumed that escape from or through a fully involved room is impossible.

Timeline Event Analysis

Timeline analysis has become an important tool of the fire analyst. NFPA 921 cites timelines in its section 17.2 - Failure Analysis and Analytical Tools.[62] Both hard and soft times as well as benchmark times may be attributed to accurate flashover analysis, particularly when produced from judiciously run mathematical models and eyewitness observations. Issues of survivability, time of ignition, comparing injuries to fire development and activation of fire protection devices, and the presence or absence of witnesses or possible perpetrators, can all be utilized in a timeline based upon flashover analysis.

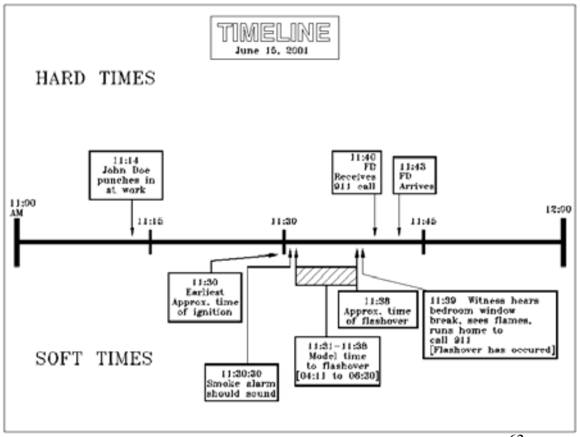

Figure 6 – Exemplar Timeline analysis[63]

Figure 6 is an exemplar timeline from an analysis of a fictional fire that is considered to have occurred on June 15, 2001 at about 11:30 AM. Note that hard times are reported above the timeline and soft times, including a computer modeling prediction of flashover, are reported below the timeline. The model "time to flashover" is reported as an estimate between 4 minutes 11 seconds, using the standard fast fire growth rate curve, and 6 minutes 30 seconds, using the standard moderate fire growth rate curve. This is because the modeler has chosen to be conservative in the estimate of the fire growth rate. The "approximate time of flashover" (11:38 AM) is a benchmark time drawn from an eyewitness' report of windows breaking and the appearance of flames outside the room of origin.

Hard times identify "a specific point in time that is directly or indirectly linked to a reliable clock or timing device of known accuracy."[64]

Soft times "can be either estimated or relative time. Relative time is the chronological order of events or activities that can be identified in relation to other events or activities. Estimated time is an approximation based on information or calculations that may or may not be relative to other events or activities."[65]

Benchmark events are events that are particularly valuable as a foundation for the time line or may have significant relation to the cause, spread, detection, or extinguishment of a fire.[66]

Appropriateness of Expected Fire Load

Does the expected or reported pre-fire fuel load agree with the presumption of the flashover analysis? The flashover analysis can determine if the expected or reported fuel load was sufficient to allow flashover to occur. If the expected fuel load is too little for flashover to occur and the other results of the analysis indicate that flashover did indeed occur, then this irregularity must be investigated and explained. It could well be that additional unreported fuels were present, either innocently or by someone's design. This clearly is an issue of major interest to the fire investigator.

Appropriateness of Actual Fire Severity

Conversely, if the actual fire severity (HRR and fire growth rate) revealed during the flashover analysis does not match with the expected or reported fuel present in the compartment, the fire investigator would want to clear up this apparent anomaly. If the incident fire growth or heat release rate produced flashover conditions, or produced flashover faster than the analysis would indicate based on the expected fuel, the investigator would certainly want to explain these inconsistencies.

Corroboration of Witness Information

The flashover analysis can provide information that would confirm or possibly disagree with witness provided information. Since it is most common for witness information to be faulty because of the frailty of human perception and memory, most competent fire investigators would acquiesce to the physical or computational data in the light of questionable witness statements. But the investigator is strongly cautioned not to take any such apparent disagreements too lightly. It is entirely possible that the computational input data is faulty or the physical evidence has been misinterpreted. The objective investigator must evaluate either possibility.

In a recent case, some of the mathematical modeling indicated that flashover and "full room involvement" had occurred in a structure prior to the fire department's arrival. Therefore it was opined that several children who had perished in the flashed-over compartment could not have possibly been alive, and therefore able to be rescued at the time of the fire department's appearance on the scene. But it later became apparent from the numerous reliable statements of the responding fire fighters and other witnesses that they had indeed heard the children screaming upon the fire department's arrival and for some noticeable time afterward.

Conclusion

Though the existence of flashover has been known since the 1940's and the basic scientific principles of the phenomenon of flashover have been understood by the fire science community since the 1960's, modern fire investigation and analysis has only recently embraced the occurrence of flashover as a valuable analytical tool. Many otherwise competent fire investigators still do not understand either flashover itself or its importance in modern fire analysis. This is changing. With the advent of NFPA 921 and the many training classes based upon its precepts, the fire investigation community is beginning to see that the use of flashover analysis can significantly aid in making better and more accurate conclusions about many of the aspects of the fires under its scrutiny.

Valuable technology transfer is taking place. Fire science related fire investigation training programs are currently being taught by such groups as the National Association of Fire Investigators, the National Fire Protection Association, the National Institute of Standards and Technology, the Society of Fire Protection Engineers, the Fire Marshals Association of North America, and colleges and universities worldwide. Widely held misconceptions about flashover are being debunked. More and more, fire investigators are seeing the value of, and using contemporary fire science mathematical and computer fire modeling techniques to more fully evaluate a fire's origin, cause, and development.

The past may have been murky, but the future is clear. The use of science in the investigation of fires is of principal importance.

Acknowledgements

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END

Glossary

Backdraft - An explosion resulting from the sudden introduction of air (i.e., oxygen) into a confined space containing oxygen-deficient superheated products of incomplete combustion. [NFPA 921-2001]

Clean Burn - A fire pattern on surfaces where soot has been burned away. [NFPA 921-2001]

Entrainment - The process of air or gases being drawn into a fire, plume, or jet. [NFPA 921-2001]

Exposed Surface - The side of a structural assembly or object that is directly exposed to the fire. [NFPA 921-2001]

Fire Analysis - The process of determining the origin, cause, development, and responsibility as well as the failure analysis of a fire or explosion. [NFPA 921-2001]

Fire Growth Rate – The rate at which the heat release rate (HRR) increases or decreases as a function of time, usually expresses in kW per second (kW/s)

Fire Investigation - The process of determining the origin, cause, and development of a fire or explosion. [NFPA 921-2001]

Fire Load (fuel load) - The total quantity of combustible contents of a building, space, or fire area, including interior finish and trim, expressed in heat units or the equivalent weight in wood. [NFPA 921-2001]

Fire Science - The body of knowledge concerning the study of fire and related subjects (such as combustion, flame, products of combustion, heat release, heat transfer, fire and explosion chemistry, fire and explosion dynamics, thermodynamics, kinetics, fluid mechanics, fire safety) and their interaction with people, structures, and the environment. [NFPA 921-2001]

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 921-2001]

Flash Fire - A fire that spreads rapidly through a diffuse fuel, such as dust, gas, or the vapors of an ignitable liquid, without the production of damaging pressure. [NFPA 921-2001]

Flashover - 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. [NFPA 921-2004]

Flash Point - The lowest temperature of a liquid, as determined by specific laboratory tests, at which the liquid gives off vapors at a sufficient rate to support a momentary flame across its surface. [NFPA 921-2001]

FPH – The NFPA's Fire Protection Handbook

Fuel Load (fire load) - The total quantity of combustible contents of a building, space, or fire area, including interior finish and trim, expressed in heat units or the equivalent weight in wood. [NFPA 921-2001]

Fuel Package – an individual fuel or a group of fuels that form a singular burning item or target fuel for radiant ignition. For example, an upholstered chair may be made up of several differing combustible materials, but can be considered as a singular burning item when ignited.

Full Room Involvement - condition in a compartment fire in which the entire volume is involved in fire. [NFPA 921-2004]

Heat Flux - The measure of the rate of heat transfer to a surface, expressed in kilowatts/m^2, kilojoules/$m^2 \cdot s$, or Btu/$ft^2 \cdot s$. [NFPA 921-2001]

Heat Loss Fraction – The fractional amount of energy emitted as radiation from a flame. [Yang *et al*]

Heat Release Rate - (HRR) - The rate at which heat energy is generated by burning. [NFPA 921-2001]

HRR – (Heat Release Rate) - The rate at which heat energy is generated by burning. [NFPA 921-2001]

HVAC – Heating, Ventilation, and Air Conditioning

IAAI – The International Association of Arson Investigators

Interflam – an international conference on fire science and engineering usually held triennially at various sites in the UK, produced by Interscience Communications of London, and cosponsored by the NFPA, NIST, SFPE, the British Fire Research (FRS) Station, and the Swedish National Research and Testing Institute.

Lower Layer – the cooler layer below the buoyant upper layer of hot gases and smoke produced by a fire in a compartment

NAFI – The National Association of Fire Investigators

Non-Dimensional Graph – a graph that displays a principle without any specific dimensions or quantifications in the "x" or "y" axes.

"Neutral plane" - a boundary layer in a compartment fire between the out-flowing hotter gases (resulting from the positive pressure) and the in-flowing cooler gases (resulting from the negative pressure). This boundary layer or boundary zone is commonly referred to as the neutral plane, i.e., neutral or equal with respect to pressure inside and outside the room. [Fire Protection Handbook, 18^{th} Ed.]

NFPA – The National Fire Protection Association

NFPA 921 – National Fire Code 921, *Guide for Fire and Explosion Investigations*

NIST – The United States' National Institute of Standards and Technology

Pyrolysis - The chemical decomposition of a compound into one or more other substances by heat alone; pyrolysis often precedes combustion. [NFPA 921-2001]

Radiant Flux - The measure of the rate of radiant heat transfer to a surface, expressed in kilowatts/m^2, kilojoules/$m^2 \cdot s$, or Btu/$ft^2 \cdot s$. [NFPA 921-2001]

"t-squared" fire - A fire where the burning rate varies proportionally to the square of the time that the fire burns. [NFPA 92B]

Technology Transfer – The conveyance of technical knowledge to the education and training community and through the educators to the practitioners. [Interflam '93]

Upper Layer – (Ceiling Layer) A buoyant layer of hot gases and smoke produced by a fire in a compartment. [NFPA 921-2001]

Vent - An opening for the passage of, or dissipation of, fluids, such as gases, fumes, smoke, and the like. [NFPA 921-2001]

Ventilation - (1) Circulation of air in any space by natural wind or convection or by fans blowing air into or exhausting air out of a building. (2) A fire-fighting operation of removing smoke and heat from the structure by opening windows and doors or making holes in the roof. [NFPA 921-2001]

Venting - The escape of smoke and heat through openings in a building. [NFPA 921-2001]

Vitiation – severe reduction in the growth of a compartment fire by the initial fuel package being immersed in the descending, O_2-depleted, upper layer.

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