Extreme Fire Behavior:
Understanding the Hazard

Introduction

Firefighting is dangerous work! Responding to a compartment fire, we are faced with dynamic and rapidly changing conditions, limited information, and often, a significant threat to human life and property. Firefighters frequently base their expectations of how a fire will behave on their experience. Gisborne's (1948) observations about wildland firefighters experienced judgment can be paraphrased to apply to structural firefighters as well:

> For what is experienced judgment except opinion based on knowledge acquired by experience? If you have fought fires in every type of building with every different configuration and fuel load, under all types of conditions, and if you have remembered exactly what happened in each of these combinations your experienced judgment is probably very good.

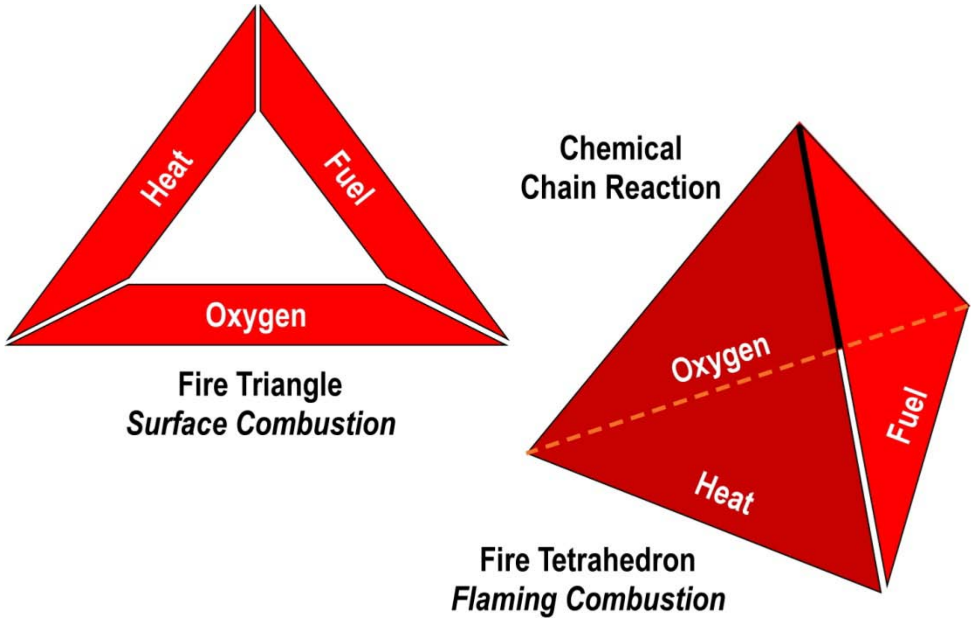
In most communities, the majority of fires occur in residential structures (e.g., single family homes, duplexes, apartment buildings). Far fewer fires happen in commercial and industrial buildings. Further, unlike the carpenter, electrician, lawyer, or physician, the firefighter spends little time actually performing the work of his or her craft. While having a small number of fires is a desirable situation for the community, there is limited opportunity for firefighters to gain the experience necessary to develop a sound understanding of fire behavior through experience alone. Study of fire behavior theory and the experience of others (e.g., case studies) provides a valuable supplement to (but cannot entirely replace) personal experience.

Combustion

If you examine common fire service texts there are a variety of definitions of combustion, but all describe the same phenomenon: A heat producing (exothermic) chemical reaction (oxidation) in which a fuel combines with oxygen. In its simplest form, hydrogen and oxygen combine, resulting in the production of heat and water vapor. However, most of the time this process is considerably more complex. In a typical structure fire complex, toxic, and flammable mixture of solid, gas, and vapor products of combustion are produced as complex fuels burn with limited ventilation.

Modes of combustion are differentiated based on where the reaction is occurring. In flaming combustion, oxidation involves fuel in the gas phase. This requires that liquid or solid fuels be heated to convert them to the gas phase. Some solid fuels, particularly those that are porous and can char can undergo oxidation at the surface of the fuel. This is non-flaming or smoldering combustion. The fire triangle and tetrahedron are simple models used to explain the basic process of non-flaming and flaming combustion as illustrated in Figure 1.

Figure 1. Simple Combustion Models



While simple, these models provide a framework for understanding combustion and are useful in understanding the variables in compartment fire development and causes of extreme fire behavior phenomena.

Fire Development

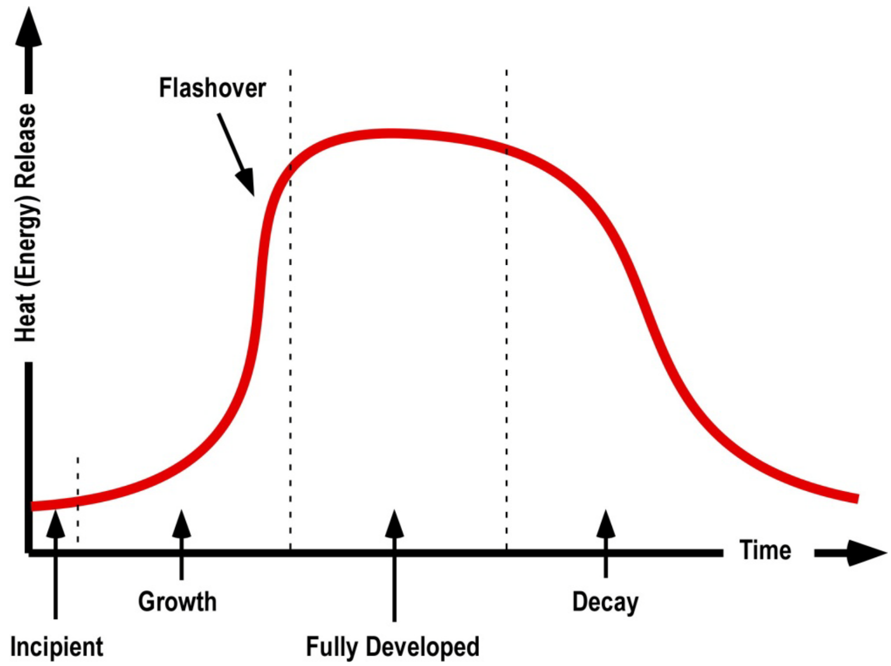
When a fire is unconfined, much of the heat produced by the burning fuel escapes through radiation and convection. What changes when the fire occurs in a compartment? Other materials in the compartment as well as the walls, ceiling and floor absorb some of the radiant heat produced by the fire. Radiant heat energy that is not absorbed is reflected back, continuing to increase the temperature of the fuel and rate of combustion.

Hot smoke and air heated by the fire become more buoyant and rise, on contact with cooler materials such as the ceiling and walls of the compartment; heat is conducted to the cooler materials, raising their temperature. This heat transfer process raises the temperature of all materials in the compartment. As nearby fuel is heated, it begins to pyrolize. Eventually the rate of pyrolysis can reach a point where flaming combustion can be supported and the fire extends.

In addition to containing heat energy, fires in compartments are influenced by the ventilation profile. The size of the compartment and the number and size of the openings that can provide a source of oxygen for continued combustion also influence fire development.

While the "stages of fire" have been described differently in fire service textbooks the phenomenon of fire development is the same. For our purposes, the stages of fire development in a compartment will be described as incipient, growth, fully developed and decay (see Figure 2). Despite dividing fire development into four "stages" the actual process is continuous with "stages" flowing from one to the next. While it may be possible to clearly define these transitions in the laboratory, in the field it is often difficult to tell when one ends and the next begins.

Figure 2. Fire Development in a Compartment



Note: This curve illustrates the *rate of heat release*. The shape of this curve will vary considerably based on the type of fuel involved and ventilation profile of the compartment. While temperature generally follows heat release, the shape of the time/temperature curve is likely to be a bit different.

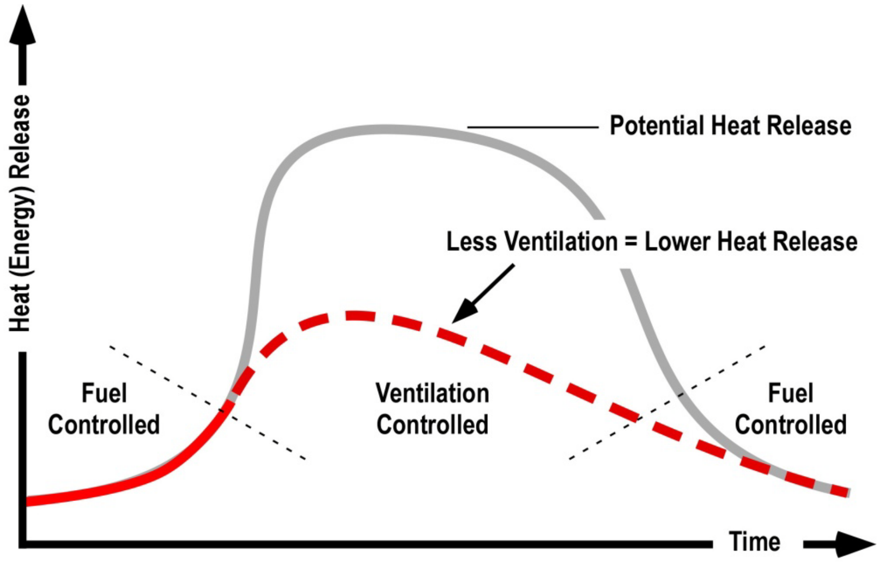
Flashover is not one of the "stages", but simply a rapid transition from the growth to fully developed stage. Flashover will not always occur (the fire may decay before reaching flashover or this transition may take place slowly). Two interrelated factors have a major influence on fire development within a compartment.

First, the fuel must have sufficient heat energy to develop flashover conditions. For example, ignition of several sheets of newspaper in a small metal wastebasket is unlikely to have sufficient heat energy to develop flashover conditions in a room lined with sheetrock. On the other hand, ignition of a couch with polyurethane foam cushions placed in the same room is quite likely to result in flashover.

The second factor is ventilation. A developing fire must have sufficient oxygen to reach flashover. In modeling fire development in a hotel room, Birk (as cited in Grimwood, Hartin, McDonough, and Raffel, 2005) determined that closing the door prevented the room from reaching flashover (provided that other openings such as windows remained intact). If insufficient ventilation exists, the fire may enter the growth stage and not reach the peak heat release of a fully developed fire.

The distinction between fuel controlled and ventilation controlled is critical to understanding compartment fire behavior. As previously outlined, compartment fires are generally fuel controlled while in the incipient and early growth stage and again as the fire decays and the demand for oxygen is reduced (see Figure 3).

Figure 3. Fire Development with Limited Ventilation



While a fire is fuel controlled, the rate of heat release and speed of development is limited by fuel characteristics as air within the compartment and the existing ventilation profile provide sufficient oxygen for fire development. However, as the fire grows the demand for oxygen increases, and at some point (based on the vent profile) will exceed what is available. At this point the fire transitions to ventilation control.

When fire development is limited by the ventilation profile of the compartment, changes in ventilation will directly influence fire behavior. Reducing ventilation (i.e. by closing a door) will reduce the rate of heat release and slow fire development. Increasing ventilation (i.e. by opening a door or window) will increase the rate of heat release and speed fire development. Changes in ventilation profile may be fire caused (failure of glass in a window), occupants (leaving a door open), or tactical action by firefighters.

Extreme Fire Behavior

The term extreme fire behavior is originated in the wildland firefighting community. The National Wildfire Coordinating Group Glossary of Wildland Fire Terminology (NWCG, 2006) states: “Extreme ‘implies a level of fire behavior characteristics that ordinarily precludes methods of direct control action…’” (p. 68). This term has equal applicability when dealing with compartment fires. Flashover, backdraft, and smoke explosion, while different, can all be classified as extreme fire behavior phenomena.

Rapid fire progress presents a significant threat to firefighters during structural firefighting. If firefighters do not have a high level of situational awareness this hazard is increased. It is difficult to develop proficiency in recognizing fire behavior indictors and developing an understanding of fire dynamics from fireground experience or classroom study alone.

Extreme fire behavior phenomena may be classified on the basis of duration of increased heat release rate. Step events result in rapid fire development and sustained increase in heat release rate. Transient events result in an extremely rapid, but generally brief increase in heat release rate (i.e., deflagration).

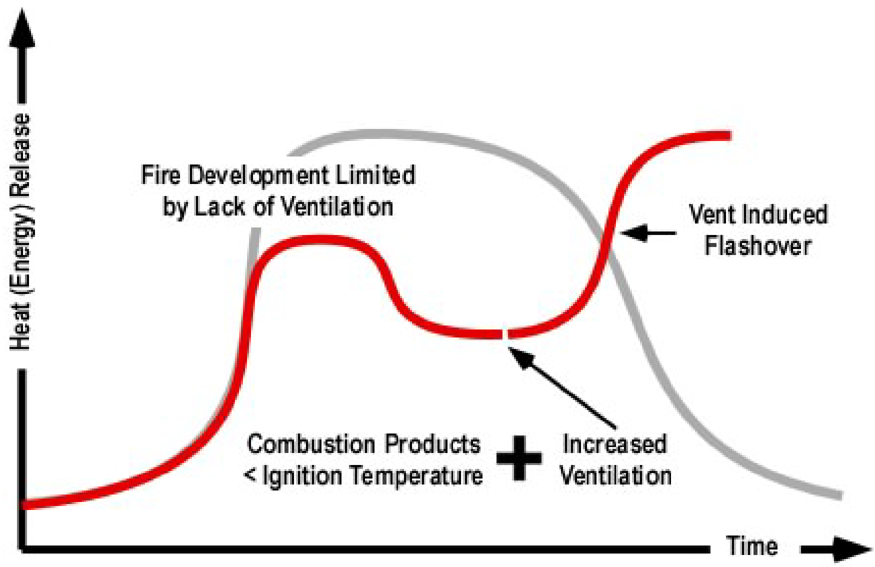
Flashover

Flashover is the sudden transition from a developing to fully developed fire. This phenomenon involves a rapid transition to a state of total surface involvement of all combustible material within the compartment. If flashover occurs, the rate of heat release in the compartment as well as the temperature in the compartment increases rapidly. Flashover may occur as the fire develops in a compartment or additional air is provided to a ventilation-controlled fire (that has insufficient fuel in the gas phase and/or temperature to backdraft).

Indicators of flashover include a radiant heat flux at the floor of 15-20 kW/m^2 and average upper layer temperature of 500°-600° C (932°-1112° F) (Drysdale, 1998). More observable indicators include rapid flame spread and extension of flames out of compartment openings. Compartment windows may also fail due to rapid temperature increases on the inner surface of window glazing (Gorbett & Hopkins (2007).

Given adequate ventilation flashover occurs as part of normal fire development as previously illustrated in Figure 2. If ventilation is limited, the fire may become ventilation controlled prior to flashover. A subsequent increase in ventilation may result in flashover (as illustrated in Figure 4).

Figure 4. Ventilation Induced Flashover



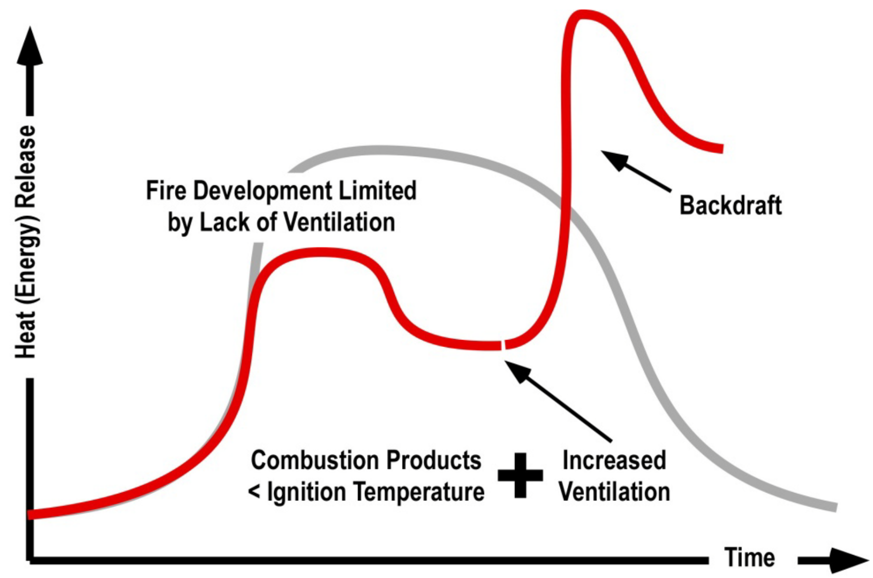
Flashover is driven by heat release rate. If heat release rate is sufficient radiation will become the dominant heat transfer method within the compartment and rapidly raise the temperature of combustible surfaces to their auto ignition temperature. When ventilation is adequate, the initiating event is simply involvement of sufficient fuel to generate the necessary heat release rate. When the fire is burning in a ventilation controlled regime, the increase in heat release rate may result from increased ventilation.

Backdraft

A backdraft involves deflagration (explosion) or rapid combustion of hot pyrolysis products and flammable products of combustion upon mixing with air. Several conditions are necessary in order for a backdraft to occur within a compartment. The fire must have progressed into a ventilation-controlled state with a high concentration of pyrolysis products and flammable products of combustion. Oxygen concentration in the compartment is low, generally to the point where flaming combustion is limited. In addition, there must be sufficient temperature to ignite the fuel when mixed with air (Grimwood, Hartin, McDonough, & Raffel, 2005; Karlsson & Quintiere, 2000).

As illustrated in Figure 5, the energy release from a backdraft is extremely rapid and is generally transient, lasting only a short time. Backdraft generally results in a brief, but quite substantial release of energy. However, depending on the volume of fuel and location of ignition, this phenomenon may result in an extended release of energy. For example a backdraft occurring in a New York apartment building resulted in a substantial increase in heat release rate for 5 ½ minutes (Bukowski, 1996).

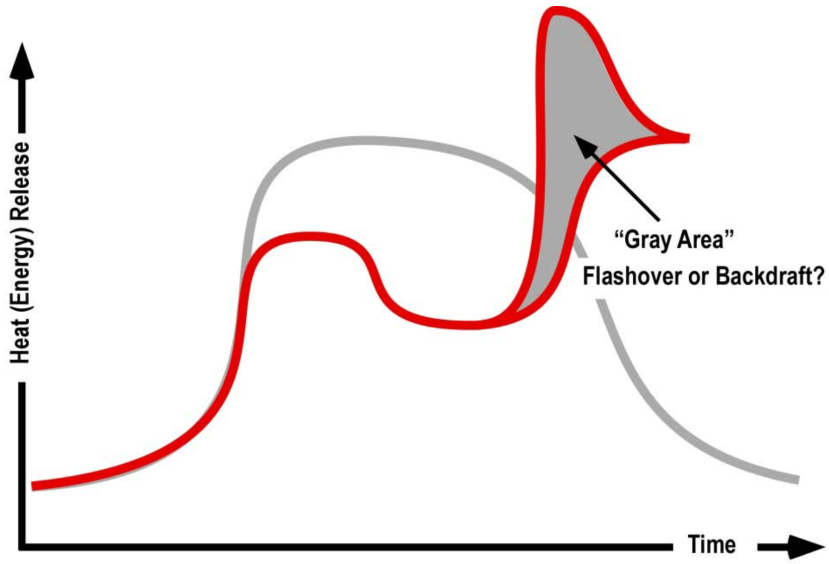
Figure 5. Backdraft



While the increase in heat release rate resulting from a backdraft is transient, changes in ventilation profile as a result of overpressure (e.g., failure of windows or other structural openings) the fire often transitions to a fully developed state (Karlsson & Quintiere).

Like a ventilation induced flashover, the initiating event for a backdraft is a change in ventilation profile providing additional oxygen. What then is the difference between these two events? The major difference is the speed with which the heat release rate increases (see Figures 4 and 5). Backdraft involves a deflagration while ventilation induced flashover does not. However, the distinction between these two phenomena is not completely clear with some events occurring in the field falling in the "gray area" illustrated in Figure 6.

Figure 6. The Gray Area

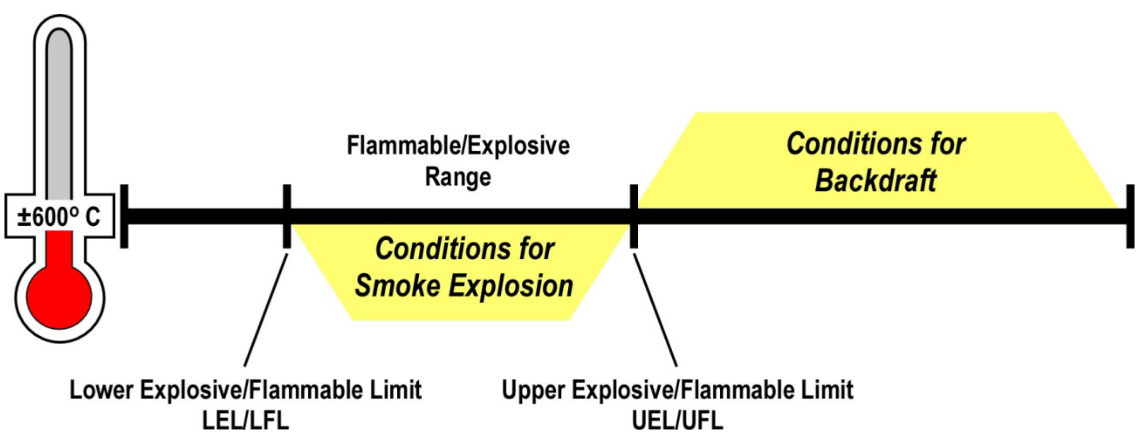


It is important for firefighters to remember that increasing the oxygen supplied to a ventilation controlled fire will result in increased fire growth and heat release rate. This may occur relatively slowly or it may be explosive, depending on conditions within the compartment.

Smoke Explosion

Many old texts dealing with basic fire behavior or ventilation used the terms smoke explosion and backdraft interchangeably. However, smoke explosion or fire gas explosion and backdraft are quite different phenomena. In the case of both backdraft and smoke explosion, smoke is the fuel. However, the other sides of the fire triangle are quite different. A backdraft requires a high concentration of fuel gas/vapor, low concentration of air, and temperature above the ignition temperature of flammable products of combustion and pyrolysis produces. On the other hand, a smoke explosion requires a mixture of fuel (smoke) and air within the flammable range but will be below the ignition temperature of flammable products of combustion and pyrolysis products (see Figure 7). If the fuel/air mixture had reached its ignition temperature, it would already have ignited. In many respects, a smoke explosion is similar to ignition of propane or natural gas inside a structure**.**

Figure 7. Explosive/Flammable Range



If a source of ignition is present, the fuel/air mixture will ignite explosively. Factors that influence the violence of a smoke explosion include the extent to which the structure confines the fuel/air mixture and how close the concentration of fuel and air is to a stoichiometric mixture (ideal for complete combustion). The more confined and closer the concentration is to stoichiometric, the greater the violence of the explosion.

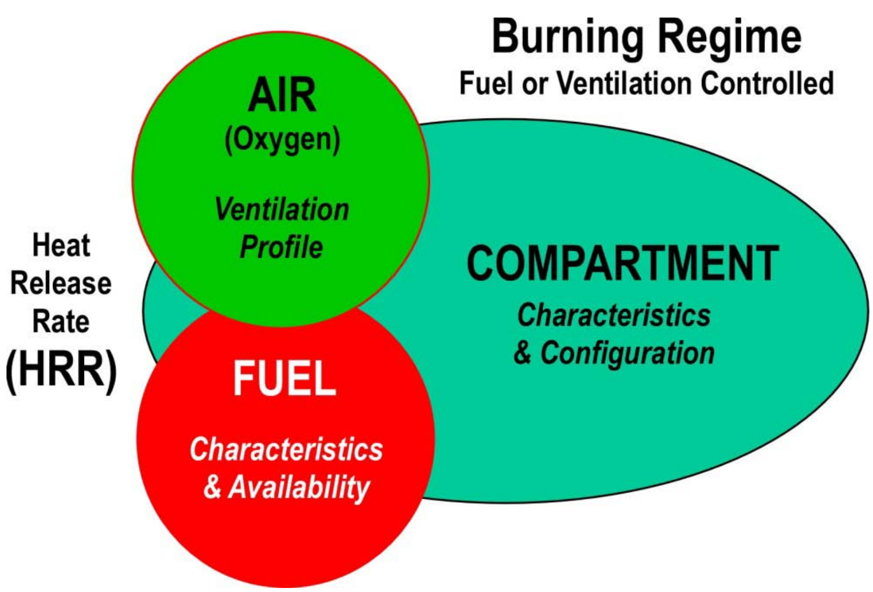
Smoke from an underventilated fire can flow through leakage in a structure to collect in concealed spaces or other compartments within the building. Remember, smoke is fuel! If smoke is present, even if cool and well away from involved compartments there is potential for a smoke explosion. Karlsson and Quintiere (2000) observe that this phenomenon is "seldom observed in enclosure fires". However, while infrequent, the conditions required for a smoke explosion can develop within a structure and present a significant threat to firefighters.

Compartment Fire Variables

The primary variables influencing fire development and extreme fire behavior in a compartment fire are fuel characteristics and availability, ventilation profile, and compartment characteristics and configuration (see Figure 8).

Chemical and physical fuel characteristics and availability determine total potential energy available (fire load) and potential heat release rate. However, release of thermal energy in a combustion reaction requires oxygen (often from air). When a fire occurs in a compartment, the area and height of the compartment along with ventilation influence the speed of fire development and heat release rate required to reach flashover.

Figure 8. Compartment Fire Variables



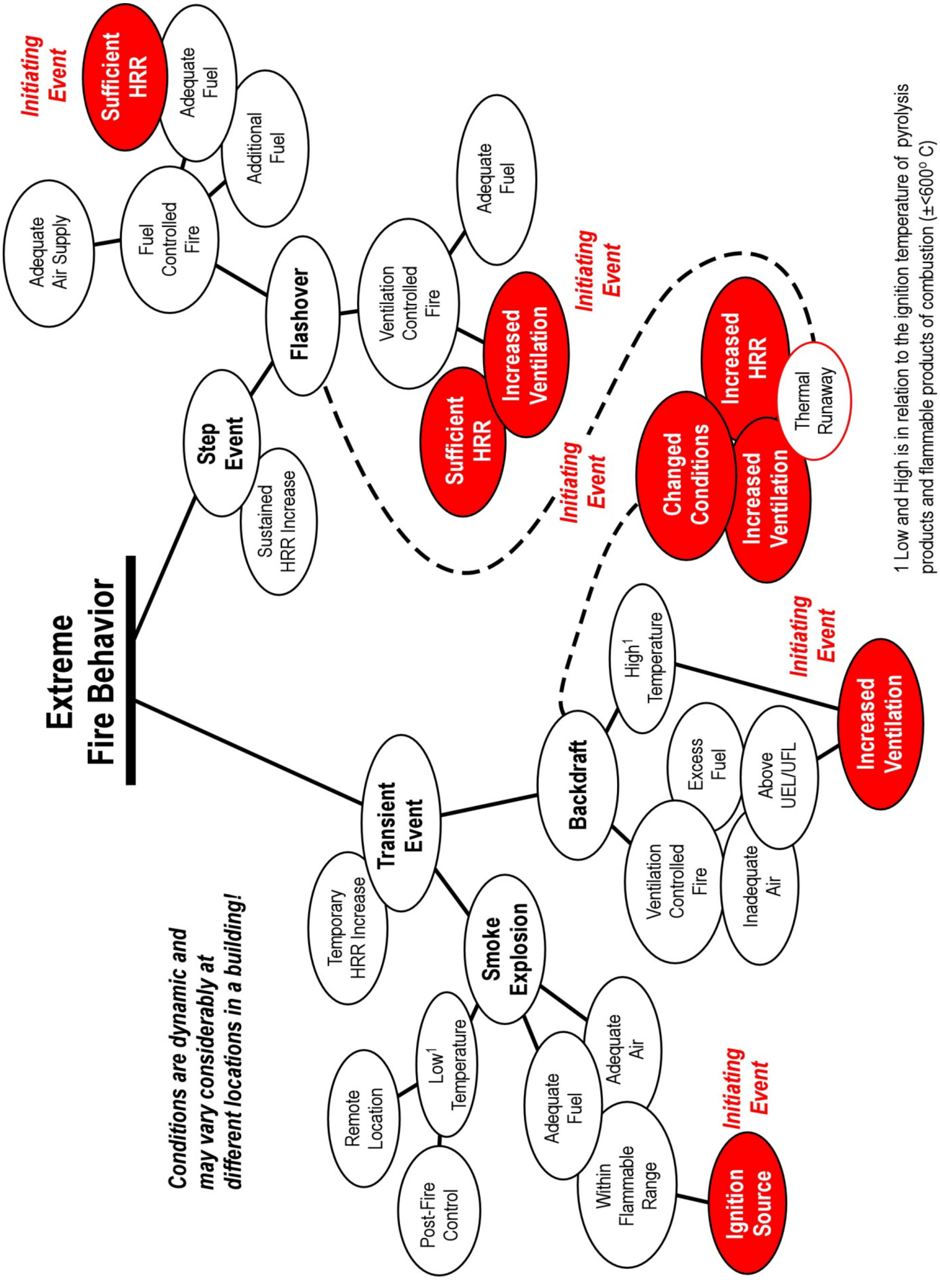
As a compartment fire develops, the ventilation profile often limits the air that is available to support combustion, bringing the fire into a ventilation controlled burning regime. As a fire becomes ventilation controlled, the percentage of pyrolysis products that are burned in the combustion process is reduced and the percentage of flammable products of combustion that are produced increases. The flammable components in smoke are a critical factor in extreme fire behavior such as ventilation induced flashover, backdraft, and smoke explosion. This is why it is important for firefighters to view smoke as fuel.

Increased air supply to a ventilation controlled fire will always result in an increased heat release rate. As discussed earlier, these changes can also result in extreme fire behavior such as ventilation induced flashover or backdraft.

Summary

Figure 9 provides a graphic representation of the three types of extreme fire behavior phenomena discussed in this paper and events that precipitate their occurrence. Understanding how extreme fire behavior phenomena occur is critical to safe and effective firefighting operations. Firefighters must be able to recognize the potential for extreme fire behavior and the potential for changing conditions and tactical operations to influence fire behavior. This understanding coupled with personal experience provides a basis for sound decision making and tactical action based on experienced judgment.

Figure 9. Extreme Fire Behavior Concept Map



References

Bukowski, R. and Richard, W. (1996, November). Modeling a backdraft incident: The 62 watts street (NY) fire. *Fire Engineers Journal* (1), 14-17.

Drysdale, D. (1998). *An introduction to fire dynamics.* New York: John Wiley & Sons.

Gisborne, H. (1948) Fundamentals of fire behavior. Fire Control Notes 9(1), 13-24.

Gorbet, G & Hopkins, R. (2007) The current knowledge & training regarding backdraft, flashover, and other rapid fire progression phenomena. Paper presented at the annual meeting of the National Fire Protection Association, Boston, MA.

Grimwood, P., Hartin, E., McDonough, J., & Raffel, S. (2005). *3D firefighting: training, techniques, and tactics*. Stillwater, OK: Fire Protection Publications.

Karlsson, B. & Quintiere, J.G. (2000). *Enclosure fire dynamics.* Boca Raton, FL: CRC Press.

National Wildfire Coordinating Group (NWCG). (2006). Glossary of wildland fire terminology. Retrieved March 16, 2008 from http://www.nwcg.gov/pms/pubs/glossary/pms205.pdf

Additional Reading

Hartin, E. (2005). *Extreme Fire Behavior - Backdraft.* Retrieved March 16, 2008 from www.firehouse.com

Hartin, E. (2005). *Extreme Fire Behavior - Flashover.* Retrieved March 16, 2008 from www.firehouse.com

Hartin, E. (2005). *Smoke Burns.* Retrieved Retrieved March 16, 2008 from www.firehouse.com

Hartin, E. (2006). *Extreme fire behavior: Smoke explosion*. Retrieved August 25, 2006 from www.firehouse.com