Fire Development in a Compartment Part 1: Review of Basic Fire Behavior

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Knowledge of basic fire behavior provides foundation for understanding fire development in a compartment, fire spread throughout a structure, and firefighting strategy and tactics. While for most readers, this information is a review, there are also likely to be a few new concepts or ways of looking at fire behavior phenomenon that will be useful in extending your understanding. A series of study and discussion questions are located at the end of this article. These questions are not a "quiz" on the content, but provide a way for you connect this look at basic fire behavior to structural firefighting. Use the questions as a starting point for a discussion at the kitchen table or informal company drill.

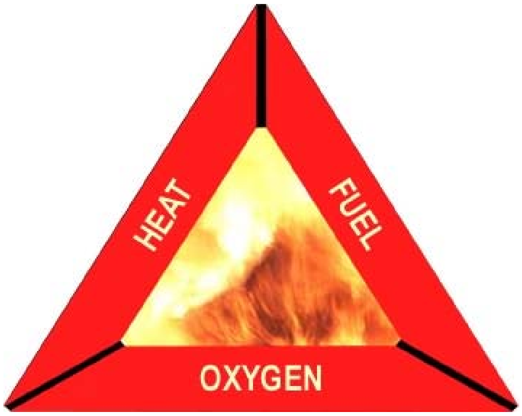
The Basics

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 the wide variety of fuels and limited ventilation produce a complex, toxic, and flammable mixture of solid, gas, and vapor products of combustion are produced by the oxidation reaction (more on this in a bit).

One familiar way of representing the key components of combustion is using the fire triangle. The fire triangle does not provide a complete explanation of the physical and chemical processes involved in the combustion process. However, it will work for the problem at hand, developing a good working knowledge of compartment fire behavior.

Combustion requires fuel and oxygen in the correct proportion as well as sufficient heat energy to start the reaction. Fuel must be in the gas (or vapor) phase in order for combustion to occur. This is simple when the fuel is already in the gaseous state (i.e. methane) as the fuel is already in this state. Liquids must be vaporized before combustion can occur. Some liquids vaporize sufficiently to burn at normal temperatures (i.e. gasoline), others require additional heat in order to release sufficient vapor to support combustion (i.e. fuel oil). However, when dealing with a compartment fire, the fuel is commonly a solid fuel such as wood, paper, or plastic.

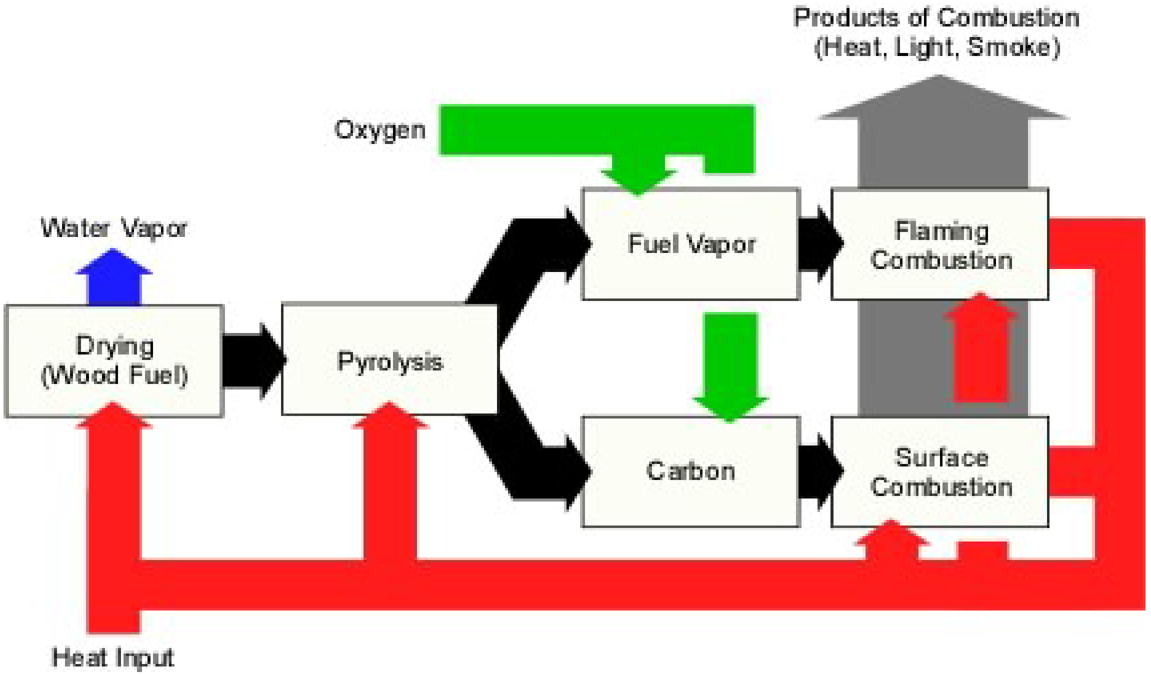
Figure 1. Fire Triangle



Take this a step further and consider how wood fuel burns. As illustrated in Figure 2 when wood is first heated water vapor is driven off as the wood dries. As heating continues, the wood begins to pyrolyse and is decomposed into its volatile components and carbon.

Ignition requires that fuel vapor and oxygen in adequate concentration be heated to their ignition temperature. Note that this does not require the solid wood fuel to be heated to its ignition temperature. If adequate fuel vapor is being released and mixed with air it can be ignited. Fuel vapor and carbon burn separately. Visible flames involve combustion of fuel vapor. On the other hand, oxidation of carbon may take place at the surface of this solid material (such as with glowing coals).

Figure 2. Wood Combustion Process



Pyrolysis begins at a considerably lower temperature (below 400^{o} F) than is required for ignition of volatile pyrolysis products (which ranges roughly from 1000^{o} F – 1300^{o} F). Table 1 outlines the pyrolysis effects within different temperature zones (Browne as cited in Pitts, Johnsson, & Bryner) and ignition temperatures of carbon and common volatile components evolved from pyrolysis of wood.

Table 1. Pyrolysis Zones and Ignition Temperatures

Pyrolysis Zones
Zone A: Up to 392° F (200° C) Wood is dried and small amounts of decomposition take place
Zone B: 392° – 536° F (200° – 280° C) A large number of complex chemical compounds are generated through decomposition and charring begins
Zone C: 536° – 932° F (280° – 500° C) Rapid pyrolysis takes place, releasing and/or generating a wide range of complex chemical compounds. Secondary reactions between these products can take place and charcoal is formed.
Zone D: > 932° F (500° C) Surface temperature of charcoal is sufficient to induces secondary reactions such as combination of free carbon and carbon dioxide (simple asphixiant) to produce large amounts of carbon monoxide (toxic and flammable)

Ignition Temperatures	
Fixed Carbon:	765° F – 1094° F (407° – 590° C)
Hydrogen:	1076° – 1094° F (580° – 590° C)
Methane:	1202° – 1382° F (650° – 750° C)
Ethylene:	1008° – 1018° F (542° – 548° C)
Ethan e:	968° – 1166° F (520° – 630° C)
Benzene:	1097° – 1364° F (740° C)
Carbon Monoxide:	1191° – 1216° F (644° – 658° C)

Listed ignition temperatures are based on the range of temperatures (low to high) listed in multiple reference sources. Ignition temperature is also influenced by the oxygen concentration in the atmosphere.

Pyrolysis of wood results in production of a far greater number of complex chemical compounds. The materials listed are simply a representative sample of the more common of these substances.

Products of Combustion

Like the basic model of combustion provided by the fire triangle, description products of combustion as heat, smoke and sometimes light is deceptively simple. Of these three general types of products, heat and smoke are generally of the most interest to firefighters.

Heat refers to the total amount of energy in a substance. Temperature on the other hand refers to average kinetic energy (energy of movement). A critical aspect of temperature is that heat will flow from substances having higher temperature to those having lower temperature. This is particularly important in understanding both fire spread and fire control tactics.

Smoke is an aerosol comprised of gases, vapor, and solid particulates. Fire gases such as carbon monoxide are generally colorless, while vapor and particulates provide smoke its varied colors. Most components of smoke are toxic present a significant threat to human life. Often smoke is perceived as less of a threat than visible flames. This is not always a correct perception. Leaking fuel gases such as methane and propane are generally treated with a great deal of respect. However, carbon monoxide, likely the most common fire gas has both a lower ignition temperature and considerably wider flammable range than either of the two most common fuel gases (methane and propane). Figure 3 illustrates the combustibility of smoke from a burning "dolls house". This often unrecognized hazard presents a significant threat to firefighters if not mitigated by effective fire control and ventilation tactics.

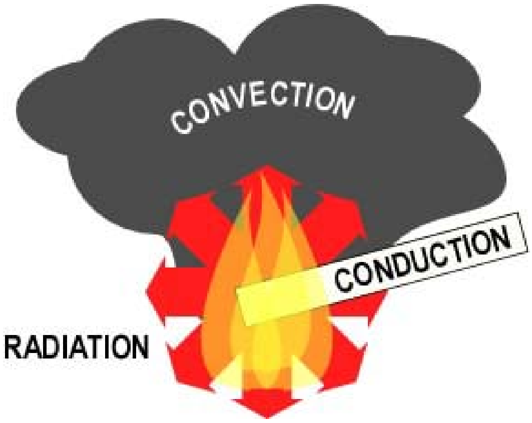
Figure 3. Dolls House

Photo by John McDonough

Heat Transfer

In a way, our discussion has jumped ahead of itself. In order for pyrolysis to begin and ignition to occur, heat must be transferred to the fuel. Heat transfer is also important to understanding both fire spread and fire control tactics. Heat is transferred from materials having a higher temperature to those having lower temperature through three principle mechanisms: Radiation, convection, and conduction.

Figure 3. Heat Transfer



Conduction: Heat transfer through conduction requires direct contact between a hot object and objects of lower temperature. This is the predominant method of heat transfer in the initial stages of fire development. In addition, direct contact between hot gases and cooler fuel results in heat transfer through conduction.

Convection: When a fluid medium (such as air) is heated it becomes less dense, expands, and rises. Hot products of combustion and pyrolysis products spread through convection and heat other materials on contact (as well as through radiation).

Radiation: Heat energy in the form of electromagnetic radiation moves away from a hot object in all directions. Radiant heat is particularly important to fire development in a compartment in that it serves as one of the primary mechanisms for fire spread within the compartment. While normally we think of radiation from flames, any hot object radiates heat energy. Hot gases and in particular particulates (such as carbon) in smoke can radiate significant heat.

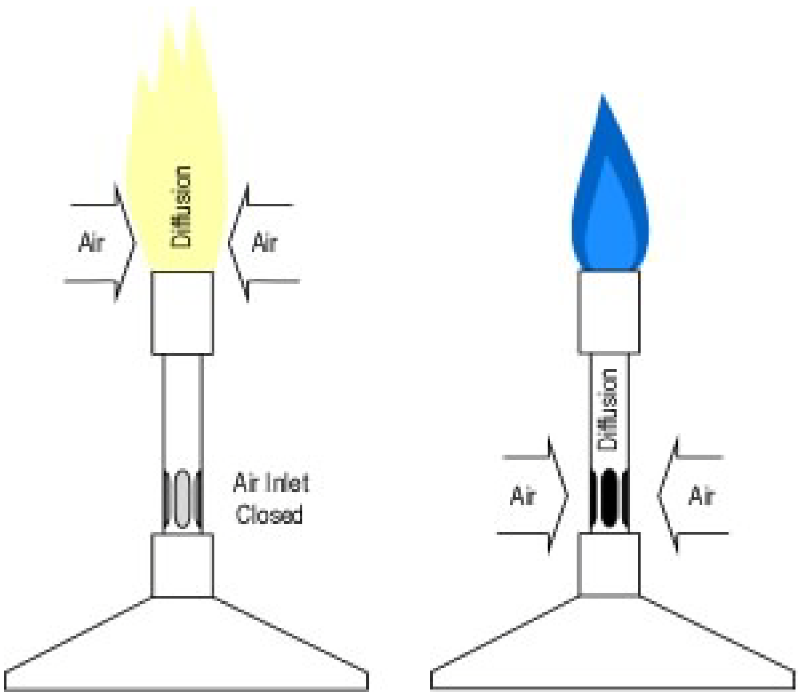
Knowledge of heat transfer is essential in understanding fire development. It is also important to effective use of water as an extinguishing agent!

Other Important Concepts

To a great extent, our interest in fire development in compartments involves flaming combustion; development from the incipient stage to the fully developed fire.

When fuel vapor must mix with air in the combustion zone, the resulting flame is called a diffusion flame (the fuel vapor must diffuse to reach the flammable range in air). In a diffusion flame, fuel defuses in the air to form a reaction zone containing fuel, air, and heat in the correct proportion to support combustion. When fuel vapor is mixed prior to combustion, this is called a pre-mixed flame. Lean and rich (as applied to the entire mixture of fuel gas or vapor and air) only apply to pre-mix flames. Diffusion and pre-mixed flames are illustrated in Figure 4.

Figure 4. Diffusion and Pre-Mixed Flames.



When the air inlet on the Bunsen burner is closed, fuel and air mix outside the burner producing a yellow flickering flame. When the air inlet is opened and air is mixed with the fuel in correct proportion prior to combustion, the flame changes appearance (becomes blue) and flame temperature increases.

In most cases, fire development in a compartment involves diffusion flames. Pyrolysis products released from heated solid fuel mix with air at the point of combustion. Sometimes this takes place at a considerable distance from the solid fuel (think about flames from a door or window). When fuel and air mix prior to combustion, ignition of the fuel-air mixture can release a tremendous amount of energy (as with a number of the concepts mentioned before, this will be important later).

While the fire triangle consists of fuel, heat, and oxygen; other materials can have a significant impact on how a fire develops. Non-combustible materials such as the non-combustible gases making up the other 79% of air, water vapor, and fuel moisture absorb heat energy and slow the process of ignition and combustion. A simple demonstration of this concept is to take two sheets of newspaper and spray one with a fine mist of water and then try and ignite each sheet. The moist sheet will be difficult if not impossible to burn due to the need for the match to heat up the water and drive if off the fuel. Materials that absorb heat, but do not participated actively in the combustion reaction are referred to as thermal ballast. While this concept is important in understanding fire development, it is also central to the effectiveness of fire control tactics used to prevent or reduce the probability of rapid fire progress.

Study and Discussion Questions

Reading about fire behavior is considerably different than experiencing it first hand. Resist the temptation to brush off basic concepts as too simple or elementary or more detailed explanations as too complex. Making a connection between theory and your own experience or the experiences of others is an effective way to learn. Use these questions to focus your thinking on how basic fire behavior theory connects with incidents that you or other members of your crew have responded to.

1. How do fire suppression operations and tactical ventilation influence the three sides of the fire triangle? Heat is likely to come to mind quickly. However, we actually have the potential to influence all three sides in more than one way.
2. How does hot smoke spreading through a structure contribute to pyrolysis of fuels located remote from the fire? How might this influence fire spread and the hazard presented to firefighters?
3. Which presents a greater threat to firefighters, flames or smoke? Think about why you think this is the case.
4. How is heat transferred from hot materials to water used for fire control and extinghishment? What factors might influence the effectiveness of this process?
5. As mentioned in this article, most of the flaming combustion in a structure fire involves diffusion flames, where might you encounter pre-mixed flames?
6. How does the concept of thermal ballast relate to fire control and suppression?

What's Next

In May we will continue our examination of fire development in a compartment by following the fire from ignition through the incipient and growth stages to a fully developed fire and into decay. In addition, specific emphasis will be placed on developing your understanding of the flashover, backdraft, and smoke explosion phenomenon.

References

Pitts, W.M., Johnsson, E.L., & Bryner, N.P. (1994). Carbon monoxide formation in fires by high-temperature anaerobic wood pyrolysis. Twenty-Fifth Symposium (International) on Combustion. Pittsburg, PA. The Combustion Institute. 1455-1462.