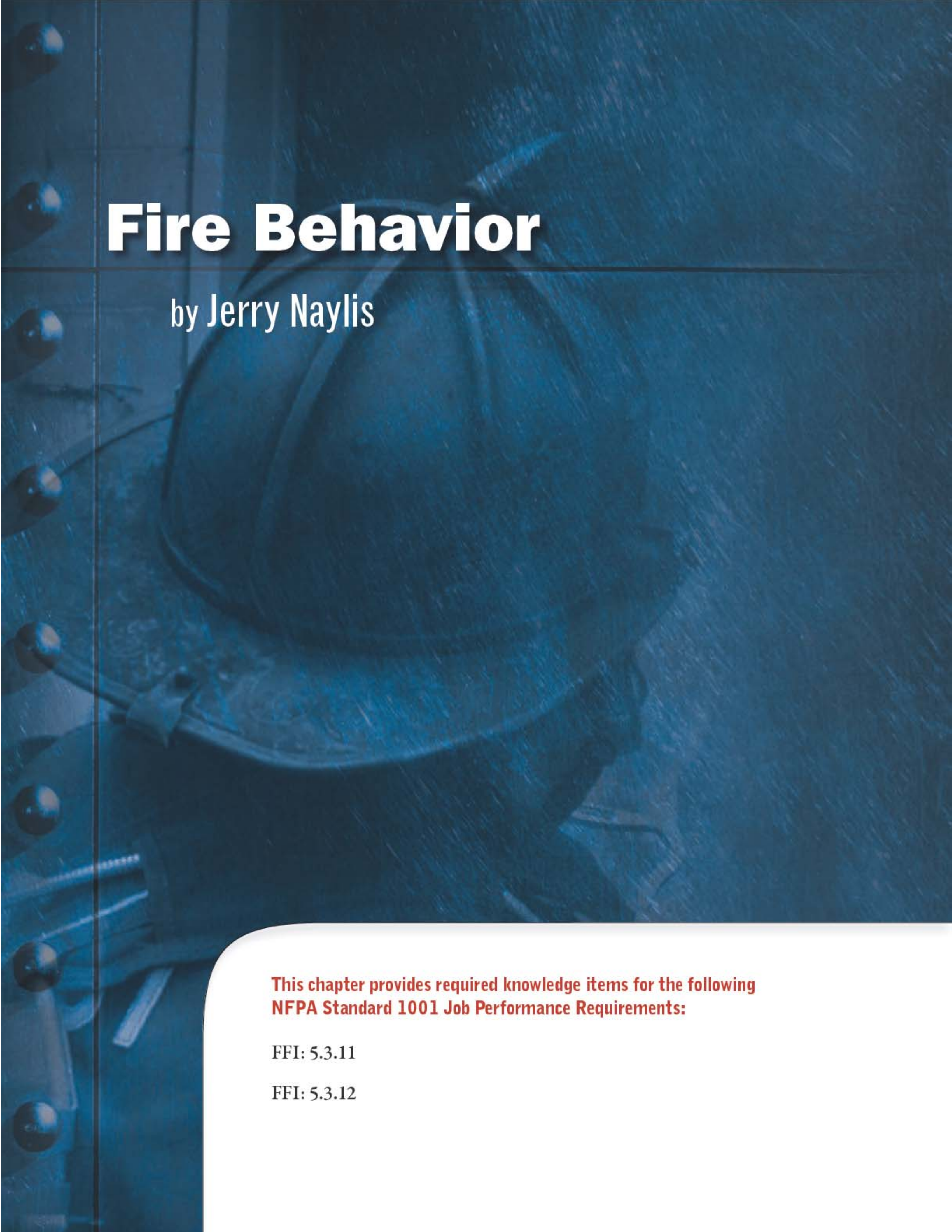
Fire Behavior

by Jerry Naylis



This chapter provides required knowledge items for the following NFPA Standard 1001 Job Performance Requirements:

FFI: 5.3.11

FFI: 5.3.12

OBJECTIVES

Upon completion of this chapter, you should be able to do the following:

- Describe the parts of the fire triangle and fire tetrahedron
- Identify basic measurements of heat and temperature
- Identify the characteristics of the three physical states of fuel
- Describe the combustion process
- Define the term *flammable* (or *explosive) limits*
- Identify four types of heat sources
- Describe three types of heat transfer
- Identify the three methods of heat transfer
- Describe heat release rate
- Define the term *thermal conductivity*
- Identify the three components of smoke
- Identify the four stages of fire development
- Define the terms *thermal layering* and *thermal balance*
- Describe the three phenomena of a fully-developed fire
- Describe the two general types of explosions

INTRODUCTION

Fire has sometimes been heralded as the most important discovery known to humankind. We have learned to harness the power and energy of fire to provide warmth to heat our homes and other buildings; to create power to move vehicles such as cars, trucks, and trains; and to cook food. We have also put fire to work for us in tasks like cutting metal with a torch, burning trash to boil water to turn a steam turbine in order to generate electricity, and melting metal so that it can be formed into products. The uses of fire are indeed plentiful and beneficial, so long as fire is controlled.

Unfortunately, fire can escape the confines created by its masters and unleash a fury that can leave a wake of death and destruction that is almost unimaginable. It is at these times that the fire service is called to control what some describe as a beast. To attack and control a fire, firefighters need to have an understanding of fire including how fire occurs, how a fire grows and spreads, and how a fire can be controlled and ultimately extinguished. For this to be accomplished, a firefighter needs to have a working knowledge of combustion dynamics, chemistry, physics, and basic engineering principles.

A good start would be to have a working definition of fire. We know that fire is a chemical reaction sometimes referred to as a process, and that fire creates heat and light in varying intensities, most of which can be seen by the naked eye. A fire requires oxygen to burn. The oxygen may come from the atmosphere or may come from an **oxidizer** (such as hydrogen peroxide), a material that readily gives off oxygen or, in some cases, another gas that takes the place of oxygen (such as chlorine or fluorine). For these reasons, we will use the definition of fire taken from **NFPA 921:** ***Guide for Fire and Explosion Investigations***, which defines fire as "a rapid oxidation process with the evolution of light and heat in varying intensities."

All matter exists in one of three states or categories: solids, liquids, or gases. Matter can also change from one state to another by heating or cooling, applying pressure, or releasing pressure. When matter changes phases directly from a solid to a gas, this process is called **sublimation**. Matter is further classified as organic or inorganic. Organic matter, by definition, consists of those substances that contain carbon. Inorganic matter refers to matter that does not contain carbon. Since all life on earth is based on carbon, generally speaking everything that was living or was once living will burn. Lumber in a house comes from what was once a living tree. The tree has been cut down and the wood has been shaped into varying dimensions. Even though the tree is no longer alive, the wood from the tree will still burn.

This chapter focuses on what fire is, what causes fire to start, how fires grow and spread, and, using that knowledge, what methods can be used to control and extinguish fires.

THE FIRE TRIANGLE AND THE FIRE TETRAHEDRON

Early texts used a simple three-sided **fire triangle** to shape a person's understanding of fire. Each side of the triangle represented what was needed for a fire to start. The three sides were identified as fuel, heat, and oxygen. These would be better stated as fuel, heat of ignition, and oxygen in sufficient quantity to support combustion (fig. 5–1). Once a fire was burning, the belief was that by removing one of the three sides, the fire would go out. If you removed the fuel, there would be nothing to burn, and the fire would be extinguished. If you cut off the supply of oxygen by smothering the fire, burning would stop. And if we removed the heat by cooling and quenching a fire with water, combustion would cease.

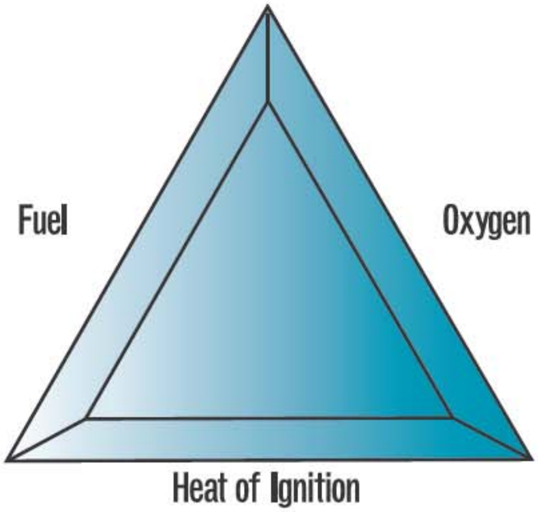


Fig. 5–1. The fire triangle

In the early 1960s, Walter M. Haessler conducted a series of tests to better explain how fires burned and how fire could be put out. His concepts were published in his seminal work, *Extinguishment of Fire*. Haessler put a new look on the old fire triangle by explaining that the fire triangle was in fact three-dimensional. The added dimension was the concept of free **radicals** being given off during a fire, which allowed a continuous chemical chain reaction to occur allowing the fire to continue to burn. Haessler used dry chemical fire-extinguishing agents to demonstrate that by arresting the fire radicals, the fire would be extinguished. After the fire was out, Haessler collected the dry chemical extinguishing agent and found that none of the agent had been consumed. With that, the three-dimensional fire triangle, known as the **fire tetrahedron**, was born (fig. 5–2).

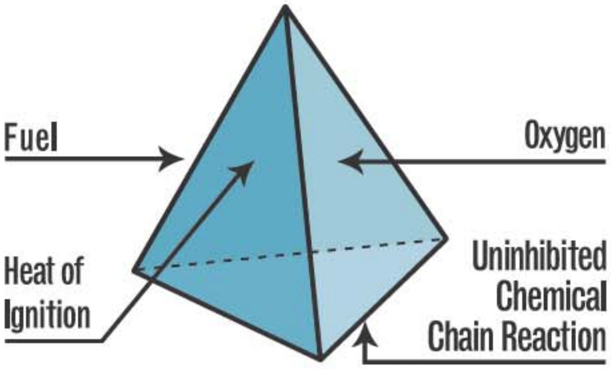


Fig. 5–2. A four-sided tetrahedron, the three-dimensional fire triangle illustrating the interrelationship of the chemical chain reaction in the combustion process

Measurements

Throughout any discussion of firefighting, firefighters will find it necessary to use a variety of terms alluding to a measurement. Therefore, every firefighter needs to be acquainted with the basic methods of measurements that relate to firefighting.

Not unlike what a person learns in elementary and secondary school, firefighting uses either the English system or metric system of measurements. While we use a number of measurement terms in our everyday lives, it is important to recognize that there are some measurement terms that are extremely important to firefighters because of the part these terms play in firefighting.

One example is temperature. Temperature is most commonly expressed in degrees. Different scales that have been developed over time to identify the measure of heat. These include **Rankine**, **Kelvin**, and the two most common scales, **Fahrenheit** and **Celsius** (fig. 5–3).

Heat is yet another measurement that firefighters need to be keenly aware of. Heat is a form of energy characterized by the vibration of molecules and is capable of starting and supporting chemical changes and changes of state (for example, changing a liquid to a gas). Heat is measured in BTUs in the English system and Joules in the metric system.

Firefighters need to know how much heat is being generated over time, known as **heat release rate (HRR)** so they can apply the correct volume of extinguishing agent to combat and extinguish the fire. The heat generation of a fuel is usually discussed in BTU/s, or joules/second (usually called watts). Heat release rates are established through laboratory tests where the heat release rate is measured over a period of time.

It is important for firefighters to realize that, while related, heat and temperature are two different things.

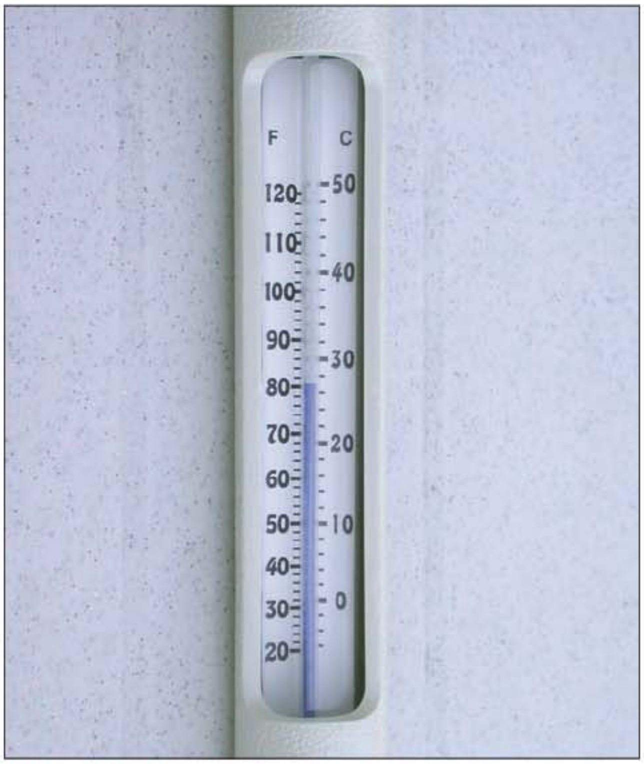


Fig. 5–3. The Fahrenheit scale and the Celsius scale

FUEL CHARACTERISTICS

FFI 5.3.10 All matter exists in one of three physical states: solids, liquids, and gases. Most matter can exist in any of the three states, with some only known to exist in two states, such as oxygen and helium. Additionally, matter can also be divided into things that burn (organic) and things that typically don't burn (inorganic). Those items that burn are usually organic, and those that will not burn are usually inorganic.

In most cases, a fuel must be in a gaseous or vaporous state in order for it to burn. As stated in the introduction, fires almost always involve reactions between various combustibles and oxygen in the air. These reactions release heat, and reactions that release heat are called **exothermic** reactions. When liquids or solids are involved in a fire, the liquids vaporize first. However, the solids usually decompose or **pyrolyze** first. This produces vapors (pyrolysates) that will react with oxygen. The vaporization and pyrolysis actually absorb some heat, and reactions that absorb heat are called **endothermic reactions**.

Solid

When matter exists in a solid physical state, the molecules of the substance are thought to be closely or tightly arranged. The tighter arrangement and greater quantity of molecules relates to the density and the mass of a substance. For a solid fuel to ignite and burn, the solid must go through a transformation into a gaseous state. This transformation requires the solid substance to be heated to its **ignition temperature.** Ignition temperature is the minimum temperature at which combustion can be initiated under specified test condition. The ability of a solid to absorb heat is often dependent on the physical arrangement of the substance.

An issue that has a direct impact on the time to ignition of a solid is whether the substance is considered **thermally thin** or **thermally thick**. Thermally thick means that when a material is exposed to a heat flux on its front face, appreciable temperature rise has not yet occurred on its back face. On the other hand, thermally thin means that at a given instant the material's back face is at a temperature close to that of the front face.[1]

The greater the **surface-area-to-mass ratio**, the easier it is for the solid to absorb the heat, reach its ignition temperature and ignite. As an example, take a block of wood. If a heat source such as a candle is applied to the block of wood, a considerable period of time will pass before the block absorbs enough heat to ignite. If the same block of wood is converted to wood shavings, the substance is still a solid but has a greater surface area to mass ratio, allowing the wood shavings to reach the wood's ignition temperature and ignite. Finally, if the block of wood is converted into wood dust, the substance now has an even greater surface-to-mass ratio, and the ability of the dust to absorb heat has increased dramatically (fig. 5–4). And if the dust becomes suspended in air, the ignition process can occur so quickly that an explosion takes place. Yet in all three cases, the substance was a solid at the beginning of the process. From this we learn that not only is knowing the physical state important, but knowing the physical arrangement of the substance is equally important with respect to ignition.

Fig. 5–4. Each of these items is wood: the block, the shavings, and the sawdust. But they each have a different physical configuration and a different surface-area-to-mass ratio that will make ignition easier or more difficult.

Liquid

Some liquids are capable of burning under normal temperatures and pressures while others are not. The liquids that will not burn can absorb heat, boil, and evaporate but never burn. Sometimes, these liquids can be used as extinguishing agents, such as water. The liquids that burn are referred to as **flammable** and/or **combustible** depending on the flash point of the liquid and the naming convention followed by certain entities. The NFPA uses a break point of 100°F (38°C) to differentiate between flammable liquids (liquids with a flash point below 100°F [38°C]) and **combustible liquids** (liquids with a flash point at or above 100°F [38°C]). NFPA further breaks liquids into classes and sub-classes. In Europe, the differentiation point is 140°F (60°C). To avoid confusion, the more commonly accepted term for all liquids that burn is **ignitable liquids**. Flash point is the minimum temperature at which an ignitable liquid gives off sufficient vapor to form an ignitable mixture with air near the surface of the liquid or within a test vessel.

For an ignitable liquid to burn, the liquid must be at its flash point so that when fuel vapors are mixed with it, air will burn. There is a mistaken belief that an ignitable liquid must be suspended in air, or atomized, to burn. **Atomization** is a process that breaks a liquid into a mist; yet its physical state is still a liquid even though the liquid is in finely divided particles. However, when an ignitable liquid is atomized, there is maximum surface-to-mass ratio that permits rapid vaporization as the liquid is heated. All that is now needed is for an ignition source to be introduced to the ignitable liquids (fig. 5–5).

Fig. 5–5. When an ignitable liquid is atomized it becomes easier to vaporize and ignite.

The fire point of an ignitable liquid is that temperature at which sufficient vapors are present to ignite and have sustained combustion.

Gas

Just as there are liquids that burn or don't burn, the same holds true for gases. When subjected to cooling and pressurizing, many gases become liquids. What is key to remember is that by their nature flammable gases in most ambient temperatures and pressures have already vaporized and only need the introduction of an ignition source to burn if they are within their flammable limits. If there is too little gas, the mixture is too lean and ignition will not occur. If there is too much gas, the mixture will be too rich and will not ignite.

Flammable and explosive limits

FFI 5.3.11 In order for ignition of a vaporized fuel to occur, the mixture of oxygen and fuel vapor must fall into a range commonly called the **flammable or explosive limits**. While some texts refer to an air/fuel vapor mixture, firefighters need to remember that if the ambient atmosphere is oxygen-depleted, no ignition can occur. Generally speaking, the air at sea level has approximately 20.8% oxygen, which is more than enough to support ignition and combustion.

The flammable or explosive limits have a lower point and an upper point that represent the percentage of fuel vapor. If the amount of fuel vapor is below the lower explosive limit (LEL), the mixture is classified as too lean and will not ignite. If the amount of fuel vapor is above the upper explosive limit (UEL), the mixture is classified as too rich and will not ignite. When the fuel vapor percentage is between the lower and upper flammable or explosive limits, ignition will occur. And if the volume of fuel is significant (as in a house filled with natural gas) the ensuing ignition will have explosive consequences.

The difficulty in dealing with flammable limits is that each fuel gas has a distinctly different range. Additionally, while some gases have a narrow range, such as gasoline (LEL = 1.5%, UEL = 7.6%), others have a very wide range, such as carbon monoxide (LEL = 12.4%, UEL = 74%).

When a flammable mixture is present but below the lower explosive limit, the easiest way to prevent ignition is to ventilate and supply large quantities of fresh air to further dilute the mixture and keep it from reaching the lower explosive limit threshold point. However, if a mixture is encountered where the mixture is fuel rich, then the introduction of fresh air with adequate oxygen may dilute the mixture enough to cause it to fall into the mixture's flammable range. If this occurs, the slightest spark may be enough of an ignition source to wreak catastrophic results. In such cases, ventilation and ignition source suppression must occur simultaneously to avoid endangering firefighters.

Technology has advanced to the point where many departments now carry meters and instruments to take air samples to tell them if specific flammable gases are present and, if so, at what percentage. All firefighters would be well advised to learn how to use these devices to protect them from the inadvertent ignition of a flammable gas mixture.

The danger to firefighters is when additional air is introduced to a rich mixture that results in a mixture that falls within the flammable limits. It is also important to remember that even an arc from an electric switch opening or the striking of a match has sufficient temperature to ignite a fuel/air mixture within its flammable limits.

CHEMISTRY AND PHYSICS RELATED TO FIRE

A fire is a complex process with a combination of chemical and physical events. To understand how a fire burns requires knowing some basic principles of chemistry and physics. Firefighters need to understand these basic principles in the course of their careers in the fire service, so the following terms are defined to provide a knowledge baseline.

Specific heat. **Specific heat** is that amount of heat that a substance absorbs as the temperature of the substance increases. Specific heat is expressed as "the amount of thermal energy required to raise unit mass of a substance by one degree, and its units are J/kg·K"[2] (Joules per kilogram-Kelvin) in the metric system and BTU/lbm-°F in the English system.

Latent heat. The thermal energy absorbed when a substance is converted from a solid to a liquid or from a liquid to a gas is known as **latent heat**. The amount of heat absorbed by a liquid that passes to a gaseous form is called the *latent heat of vaporization*. Water has an extremely high heat of vaporization, which makes it an ideal extinguishing agent.

When heat is absorbed by water as it converts to steam it causes the surface of the burning solid object to cool. The word latent means "hidden," and in a way the heat of vaporization is hidden. Water absorbs a great deal of heat, but upon reaching its boiling point of 212°F (100 °C), it turns to vapor (steam). In reverse, when a gas changes to a liquid or a liquid changes to a solid, heat is released and the temperature drops. When its temperature reaches the freezing point of 32°F (0°C), water becomes ice.

More information on the latent heat of vaporized water when it is used to extinguish fire is provided in chapter 16, Fire Streams.

Density. The ratio of mass to volume of an object or substance is known as **density**. The greater the density of an object or substance, the more heat energy is needed to cause ignition.

Specific gravity and vapor density. The **specific gravity** of a substance is the ratio of the weight density of the substance to the weight density of another substance, usually water. All liquid substances have different specific gravities. Water is the benchmark that other liquids are measured against to determine if a liquid is heavier (which will sink) or lighter (which will rise), Assigning water a value of 1, all liquids with a specific gravity of less than 1 will float on water. All liquids with a value greater than 1 will sink below water. Table 5–1 provides the specific gravities of common liquids.

Vapor density is the term for comparing the weights of vapors and gases with the weight of air. The terms *vapor density* and *specific gravity* should not be used interchangeably, as one measures vapors and gases and the other measures liquids. Some substances will actually have different values for vapor density and specific gravity, depending upon the physical state of the substance (solid, liquid, or gas). Be careful to use the proper terminology when researching a substance.

Table 5–1. Specific gravities of common liquids

Liquid	Specific gravity
Acetone	0.787
Alcohol, ethyl (ethanol)	0.787
Alcohol, methyl (methanol)	0.789
Alcohol, propyl	0.802
Carbon disulfide	1.265
Carbon tetrachloride	1.589
Castor oil	0.959
Coconut oil	0.927
Cottonseed oil	0.929
Crude oil	0.876
Formaldehyde	0.815
Fuel oil	0.893
Gasoline	0.739
Hexane	0.657
Kerosene	0.820
Linseed oil	0.932
Mercury	13.633
Milk	1.035
Napthalene	0.963
Olive oil	0.703
Toluene	0.865
Turpentine	0.871

Air is the standard against which all other vapors and gases are compared and is assigned a vapor density value of 1. Vapors and gases with vapor densities greater than 1 will tend to drop to the ground. Gases and vapors with vapor densities less than 1 are lighter than air. There are only 13 gases known to be lighter than air. All other gases and vapors are heavier than air. The 13 gases lighter than air and their respective vapor densities are listed in table 5–2.

Table 5–2. Vapor densities of gases lighter than air

Gas	Vapor density
Hydrogen	0.070
Helium	0.140
Hydrogen cyanide	0.930
Hydrogen fluoride	0.901
Methane	0.550
Ethylene	0.968
Diborane	0.960
Natural gas (composed primarily of methane)	0.600
Carbon monoxide	0.970
Acetylene	0.900
Neon	0.967
Nitrogen	0.970
Ammonia	0.590

Types of heat

Heat energy comes in different forms, usually from a specific object or source. The heat of ignition is generally divided into the equipment involved in ignition and the form of the heat of ignition. It is important for firefighters to recognize and understand the sources or means of this heat generation. The four commonly accepted sources of heat are chemical, electrical, mechanical, and nuclear.

Chemical heat sources. As described earlier, fire itself is a chemical reaction, and one of the products of a fire is heat. So, the heat generated from a fire is often the heat of ignition that causes an uncontrolled fire to occur. As such, combustion is a form of chemical heat energy.

Spontaneous ignition is the initiation of combustion of a material by an internal chemical or biological reaction that has produced sufficient heat to ignite the material. This is observed by firefighters when rags and clothes made of natural fibers such as cotton become soaked with oils (such as linseed oil). The oil attacks the natural fibers breaking them down. As the fibers break down, a process takes place where heat is generated. The piles themselves allow the generated heat to be contained inside, sometimes causing them to ignite. This is the reason fire code regulations call for such oil-soaked rags to be stored in metal containers.

Electrical heat sources. Electricity is an extremely common energy source that is used by most people in everyday life. Electricity is used in residential, commercial, industrial, and institutional applications. A building or area without electricity is an anomaly.

Electricity is used to provide light, power appliances, cook food, and provide heat and air conditioning. Electric power flows from a generating facility, usually called a power plant, through transmission and distribution conductors, usually called power lines, to a service cable and into a distribution panel. This panel is generally equipped with a main or service disconnect and either fuses or circuit breakers that function as overcurrent protection devices.

From the distribution panel, electric current flows out to circuits where the electricity is used. Some circuits are **switch-controlled**, meaning that power will not flow to the outlet or electric device unless a switch is turned on. A common example is a switch-controlled light. Other circuits have electricity that is at the receptacle or outlet. As soon as a plug is inserted, electrical power flows into the appliance or device.

The flow of electrical current can generate heat. In the simplest of terms, electricity is a flow of electrons from a negatively charged location where electrons are abundant to a location where electrons are less abundant, known as a positively charged location. This flow of electrons usually occurs along a **conductor**. The flow of electrons occurs as these electrons move from one atom to another along the conductor. As this occurs, electrons collide with molecules, causing the molecules to break apart, which then results in the liberation of heat energy. The quantity of heat generated depends on a number of variables, including the amount of electricity moving along the conductor and the density of the conductor. Typically, the denser a substance is, the better conductor it is. For example, **metals** are generally good conductors of electricity. Aluminum conducts electrical current (a good reason to be very careful with aluminum ground ladders around any wires), and copper is a better conductor. This is why copper is preferred for household wiring. However, silver is even better than copper as a conductor of electricity. But the cost of wiring a house using silver wire would be prohibitive! Other, less dense substances are not good conductors. Two examples are wood and cotton. Both of these are extremely poor conductors.

As the quantity or volume of electrical current (measured in amperes, or amps) flowing along a conductor increases, the potential for molecular collisions increase. This difficulty is sometimes referred to as **resistance** and is expressed in **ohms**. As resistance and quantity of electrical flow increase, the amount of heat generated increases. This is why electrically powered appliances that require large amounts of electricity to run need to have larger wires for the circuits. Specific wire diameters (wire gauges) are rated for maximum number of amps it can carry safely; the smaller the diameter, the smaller the amps it can carry without overheating. Toasters with very small diameter wires inside that glow when energized are a good example of this phenomenon.

Electrical heat energy can also be generated when a flow of electricity is suddenly interrupted by the separation of the conductor. A common example is when a switch that is closed (in the on position) is opened up (put in the off position) as current flows. The resulting arc is a release of electrical heat energy. Although these arcs are typically small in size, as is the amount of heat generated, the temperature that is generated can be substantial. Some arcs have been recorded at 2,000°F (1,093°C). Obviously, a sustained arc from a downed overhead wire can generate a continuous high-temperature, high-heat release event capable of igniting a building on fire.

Lightning is another example of electrical heat energy release. Clouds in the sky may be at differing levels of electron charging. As these clouds connect, allowing electrons to flow, one can observe what some people term **cloud-to-cloud lightning**. When a cloud and the earth have differing charges, we witness a discharge between the earth and the cloud.

Static electricity exists as the name implies, statically. Electric charges collect on the surface of an object. They are not flowing. There are a number of situations or conditions that will cause a static electricity discharge. The more common are the following:

1. Contact and separation between dissimilar solids
2. Flowing powders
3. Flowing liquids or gases

An example that many people can relate to is sliding a foot across a carpet and then touching a metal object. The resulting shock that is received is a static electricity discharge. Another example is the electric charge created when certain flammable liquids or gases flow, particularly at an elevated pressure. The static electric charge can become the ignition source, such as when acetylene gas escapes rapidly from a pressurized gas cylinder. The gas can be ignited as it flows forth from the cylinder without the introduction of any other ignition source.

Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction, where currents are generated within the metal and resistance leads to heating of the metal.

A microwave oven appliance cooks or heat food by dielectric heating, a method of heating non-conductive materials. A microwave is a radio wave that is between one millimeter and one meter in wave length. Microwave radiation is used to heat water and other polarized molecules within the food.

Mechanical heat sources. Heat of ignition can also come from mechanical actions that, developed at a sufficient temperature, will ignite flammables or combustibles. Mechanical heat is usually developed by friction when two items are rubbed together. The easiest example that demonstrates this is to rub your hands together. The faster you rub, the greater the heat produced. In that same vein, metals that rub together will also generate heat. Often, some form of lubricant is used to absorb the heat, particularly if the two metals rubbing together are part of a piece of machinery or a process. If the lubricant is insufficient or breaks down, the potential exists for enough heat to be generated to ignite surrounding combustibles, including the residual lubricant.

Friction can also create sparks where there is a lack of any lubricant. Visualize the metal edge of an axe coming in contact with a grinding wheel used to sharpen the axe head. As the edge of the metal touches the wheel, a shower of sparks flies out. Although seemingly small and insignificant, these sparks carry enough heat to ignite flammable vapors, finely divided dust particles, or wood shavings.

Compression can also generate heat, particularly if the compression is done under pressure and at a rapid pace. If a compressed gas cylinder, such as a self-contained breathing apparatus, bottle is filled too rapidly, the bottle itself will heat up as the bottle absorbs the mechanical heat energy created by the rapid compression of the breathing air. As the bottle cools off, the compressed gas, in this case air, will be subject to a lowering of the available pressure and thus the volume of air in the bottle. This is why all compressed gas cylinders should be filled slowly.

Nuclear heat sources. The two forms of nuclear heat energy are **fusion** and **fission**. Nuclear heat energy is generated when atoms are either split apart, which is called fission, or combined, which is called fusion.

Nuclear material is radioactive and unstable. These materials are constantly breaking down during a molecular process where they seek to become stable. During this process, energetic particles are spontaneously emitted by the disintegration of the radioactive material's atomic nuclei. As this fission process occurs, heat energy is released. In a controlled setting, fission is used to heat water to drive turbines and produce electricity. It should be noted that at the current time nuclear fusion cannot be controlled and has no commercial use, although its use is being explored in some experimental environments.

Regardless of how or why radioactive material is released, fires involving radiation emitting elements should only be fought by individuals specially trained and properly protected against radiation exposure. Regular firefighting personal protective equipment (PPE) offers absolutely no protection to the firefighter from any radiation that may be released. Under no circumstance should firefighters in structural PPE attempt to fight a fire involving radioactive material, no matter how small the quantity, until the radiation exposure hazard has been abated.

Heat release rate

The previous section discussed common sources of heat: chemical, electrical, mechanical, and nuclear. When we are discussing a fire's heat release rates (HRR), we are referring to the amount of energy or heat released *over a period of time*. We commonly discuss a 100 watt (100 joules-per-second) light bulb, a 100 megawatt nuclear reactor, or a 10,000 BTU/hr air conditioner. All are examples of energy being released or used over time (fig. 5–6).

When we discuss the heat release rate of a fire, we commonly use units of BTU/second in English units or watts in metric units. For example, a 1 meter by 1 meter (about a square yard) diesel fuel fire will have about a 2 megawatt heat release rate. As long as diesel fuel keeps pouring into that one square meter area, the fire will keep burning at a steady heat release rate (the fire would burn out in a short time if only a thin layer of oil was ignited and the fuel was not replenished).

Heat Release Rates (HRRs) for Common Items

	Weight, lbs (kg)	kW
Chairs		
Upholstered, polyurethane foam	62.3 (28.3)	2,100
PVC waiting room with metal frame	34 (15.4)	270
Metal frame with polyurethane foam padding	16.5 (7.5)	40
Cotton easy chair	39.70 (18)	290–370
Mattress		
Cotton	26–29 (12–13)	40–970
Polyurethane foam	7–31 (3.2–14.1)	810–2,630
Mattress and box spring (cotton and Polyurethane foam)	137.45 (62.3)	660
Sofa, upholstered polyurethane	113 (51.3)	3,120
Christmas tree	14–16 (6.4–7.3)	500–650
Gasoline – 2 sq ft (0.2 sq m) pool		400

Sources: NFPA 921, *Guide for Fire and Explosion Investigations*; Quincy, MA, 2001; *Fire Investigation*, IFSTA, Stillwater, OK, 2000

Fig. 5–6. An example of the heat release rates of different types of common objects

Heat transfer

FFI 5.3.12 When anything burns, there are several by-products that are released. As discussed in the previous section, one of those by-products is heat. The heat that is generated is transferred to other objects. Depending on a number of factors, the heat that is transferred can cause the fire to spread and grow. These factors include the amount of heat being generated over a particular period of time, the item or substance being heated (combustibility and physical state), the distance between the fire and the item being heated, and the ability of the item being heated to retain the heat and reach its ignition temperature.

There are three modes by which heat is transferred from one substance to another. They are **conduction**, **convection**, and **radiation**.

Conduction. Conduction occurs when heat is transferred by direct contact between solid objects. One example is a steam pipe from a building's heating system that comes into contact with wooden structural members. The heat from the steam is transferred to the metal pipe that carries the steam to the heating system, providing heat for the building. The metal pipe absorbs this heat and transfers it to the wooden structural member, such as a ceiling joist in a basement that the steam pipe is in contact with. The constant heat being applied to the wood does several things. The heat dries the wood and causes the cellulose in the wood to break down. When the wood has been subject to enough heat and the wood has reached its ignition temperature, the wood will ignite and begin to smolder. This decomposition—breaking down of the wood under heat—is also known as **pyrolysis**.

There are several important points to remember regarding conduction. The heavier and denser a material is, the better conductor of heat it is. So metals are excellent conductors of heat. The second point is that ability to transfer heat by conduction is directly related to the mass of the object and the quantity of heat being released. A single candle burning will not generate the same amount of heat as a large bonfire. If you put the end of a six-inch deep metal I-beam into both fires, the I-beam exposed to the candle would barely warm up whereas the I-beam exposed to the bonfire would quickly heat up and could—through conduction from the end immersed in the fire to the other end—ignite combustibles away from the initial source of the fire, in this example the bonfire. This happens in real building fires when a steel beam passing through a wall between two rooms is heated by a fire in one room and ignites objects in the other room through conduction (fig. 5–7).

All matter is thermally conductive and will absorb, hold, and transmit heat. This ability is generally dependant on the density of a substance, which is the ratio of its mass to volume. If the substance is very dense, its thermal conductivity is high, whereas if the substance has low density, its thermal conductivity is low. Substances that have low thermal conductivity are good insulators since they inhibit the transfer of heat. Examples would include fiberglass and mineral wool. Substances that have high thermal conductivity are thought of as poor insulators and will allow the transfer of heat, such as metals.

Fig. 5–7. A steel beam exposed to fire in one room can ignite materials in an adjacent room.

Convection. Convection is the transfer of heat via a fluid medium, either liquid or air. Flames and heated gases/smoke passing over a material's surface will transfer heat through convection. Many objects are ignited in this way (fig. 5–8).

Fig. 5–8. As flame passes over the surface of a material, it can ignite the material.

An accepted principle of physics is that warm air will rise and cooler air will fall. This is because, as air is warmed, the density of the air is reduced making the air lighter and allowing it to rise. As the air rises in the atmosphere, heat is given off to the surrounding air. When the heated air reaches the same temperature and density as the surrounding air, upward movement stops since equilibrium has been achieved. As the air's density begins to increase, it now begins to fall back down to the surface. This can sometimes be seen when smoke rises out of a smoke stack. It may eventually stop rising at a certain level, when it reaches the temperature of the surrounding air.

The same principle applies to liquids. When a liquid absorbs heat, the volume of the space occupied by the liquid expands. When the liquid reaches its boiling point, vapor is given off. Since the density of this vapor is lower than that of the surrounding air, the vapor rises just as heated air rises. If the heated liquid is in a closed container, then pressure will build up inside of the closed container until that pressure is released. Sometimes this pressure release is planned and regulated, such as when boiling water in a tea pot is poured out and the external heat source is removed. However, sometimes the release is not planned or regulated and the release is violent. An example would be a fire impinging on a cylinder or container containing liquefied flammable gases such as propane. A failure of any portion of the cylinder/container would be followed by a violent rupture and along with it the release and ignition of the now-boiling liquefied flammable gas. This type of event is commonly known as a **boiling liquid expanding vapor explosion** or **BLEVE**.

Radiation. Radiation is the transfer of heat through space by light waves. These light waves range from ultraviolet to infrared and contain electromagnetic energy that travels outward in all directions. This energy is absorbed by objects that are remote from and in a direct line with a fire.

Radiation is able to travel through space, including vacuums, as well as through transparent items such as clear glass and water curtains. As the target objects absorb the radiated heat, they in turn begin to give off radiated heat. This is why radiation is now viewed as even more of a hazard than conduction or convection with respect to fire spread (fig. 5–9).

The most common example of radiation heat transfer is the sun warming the earth's surface. Another example would be the warmth felt on a person's face while looking at a fire in a fireplace. If you turn and look away, your face feels cooler immediately because it is no longer exposed to the direct electromagnetic energy being given off by the fire.

When there is a fire in a building, radiated heat energy is emitted from the fire in a direct line to all objects surrounding the fire. As the items heat up, they in turn re-radiate to other objects. The heat release of the original fire and the ability of the target object to absorb and retain this heat will dictate how quickly or how slowly the fire may spread. One thing is certain: this mode of heat transfer will facilitate flashover more than the other two.

Fig. 5–9. Vinyl siding melted by radiant heat

Smoke

As identified earlier in the chapter, smoke is a product of combustion. According to NFPA 921, smoke is defined as "the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass." Carbon particles ("soot," which gives smoke its distinctive range of colors) are the predominant solid particulate. Liquid particulates include condensed tars and even water vapor. A multitude of gases are produced including carbon monoxide and hydrogen cyanide (the predominant substances that cause the most deaths in a fire).

While the specific health hazards of smoke are discussed in greater detail in chapter 10, Self-Contained Breathing Apparatus, and chapter 14, Ventilation, it is important to understand the role that smoke plays in the development of a fire in a compartment. As will be seen later in this chapter, the hot smoke at the ceiling of a room will play a crucial role in the development of flashover. Smoke may also become explosive under the right conditions, resulting in a backdraft (smoke explosion).

COMPARTMENT FIRE DEVELOPMENT

FFI 5.3.11 All fires follow a distinct pattern in their development. The four stages of fire development are ignition, growth, full development, and decay (fig. 5–10). And before any fuel can be ignited, the fuel must be heated to a point where the fuel emits ignitable vapors. Obviously these vapors exist if the fuel's state is gaseous, and in some cases, ignitable liquids vaporize at low temperatures (gasoline's flash point is –45°F [–43°C]) while others have to be heated, such as fuel oil, motor oil, or vegetable oil. Solids must also be heated to point where ignitable vapors (pyrolysates) are emitted.

Ignition

Ignition occurs at the instant when an ignition source unites with an ignitable vapor in an oxygen-sufficient environment, resulting in a chemical chain reaction, and a fire begins to burn. If the ignitable vapor is already present, ignition occurs almost instantaneously. If the fuel is a solid, it may take a few seconds or longer to produce the ignitable vapor. But once the vapor starts to burn, ignition has taken place. In most cases, the fire is small and limited, sometimes called an **incipient fire**. The exception, of course, is where there are massive amounts of flammable gas capable of being ignited simultaneously.

Growth

Once ignition occurs, the fire must grow or it will die. The heat generated from the ignition now begins to cause heat transfer to spread to surrounding combustibles. Once these surrounding combustibles emit sufficient ignitable vapors, they in turn ignite, causing the fire to grow in size and spread. There are several factors that will affect the fire's ability to grow and spread.

The first factor is the amount of available oxygen. Once a fire begins to burn, available oxygen is consumed in the combustion process. If the amount of available oxygen falls below 16% of the atmosphere, the fire has a more difficult time burning. The fire will create even more carbon monoxide when the oxygen level is below 16%. If the oxygen level drops below 8%, the fire will not be able to sustain itself. Air (oxygen) is drawn into a fire through a process called **entrainment** (fig. 5–11).

Fig. 5–10. The four stages of fire development: ignition, growth (pre-flashover), fully developed (flashover), and decay (post-flashover)

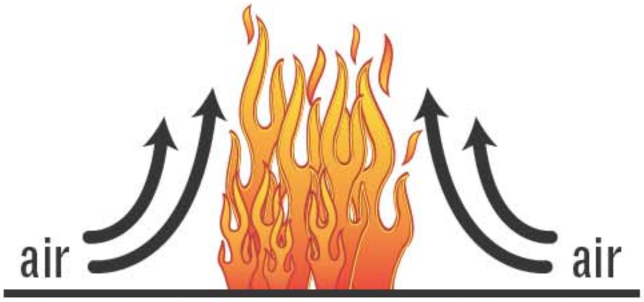


Fig. 5–11. Fire development showing air entrainment

The second factor is the amount of fuel that is available to burn. A good example is a fire in a fireplace. Once the logs are consumed, the fire goes out for lack of fuel. Conversely, if there is an ample volume of fuel such as a structure full of combustibles, the fire will grow substantially. The physical state of the fuel package and its HRR will determine how fast the fire will grow and spread.

The third factor is the relative size of the space where the fire is to the involved fuel and its distance from other surrounding combustibles. If the space is large and high, the heat generated by the fire will be distributed throughout the space and make it difficult for other combustibles to be preheated. On the other hand, if the space to the ceiling and walls is small, the heat that is absorbed by the ceiling and walls can be radiated back to the fire, allowing it to intensify, which means that the fire can grow larger and faster.

The fourth factor is the insulating value of the ceiling and walls. The better the insulating value, the less heat will pass through. This heat will be radiated back to the fire and the surrounding combustibles. If the insulating value is low and allows heat to pass through easily, that heat will not help the fire to grow.

Thermal layering and thermal balance. **FFI 5.3.12**

As a fire grows, the hot gases generated by the fire rise until they become obstructed, usually at first by the ceiling. The hot gases will spread out in all directions seeking a new path to rise. Once the hot gases reach this path, they will continue to rise. Conversely, if the gases meet a vertical obstruction such as a wall, the hot gases will begin to bank down until the hot gases find an opening that will allow them to rise again, such as a doorway, open window, or stairway. Some of the heat energy from the heated gases is transferred to the ceiling and walls in a room fire, allowing some of the heated gases to cool slightly. These cooler gases are pushed down in the room's atmosphere as the hot gases that continue to generate rise above the cooler gases. This phenomenon is known as **thermal layering**, because each portion of heated gases stratifies as equilibrium is achieved. The hottest point will be at the ceiling, while the coolest layer will be near the floor. The temperatures between the ceiling and floor will be layered. Firefighters sometimes refer to this as **thermal balance**.

The heated gases at the ceiling will be distributed throughout the room or compartment causing the temperature at the floor level to rise quickly. Any firefighters or trapped occupants will be rapidly exposed to excessively high temperatures. This is why it is critical for ventilation to be closely coordinated with fire attack and the application of fire streams.

Fully developed compartment fire

Once the fire has involved an entire compartment or space, the fire is considered to be fully developed. If this is an outside fire, all of the combustibles in a given area would be on fire. The fire would be free burning and has plenty of oxygen to continue burning. A compartment or space fire could be a room, an apartment, a floor, or an entire building. One of the hallmarks of a fully developed compartment fire is that the rate of burning inside the compartment is limited by the amount of ventilation that the room is receiving. This type of fully developed fire is sometimes called a **ventilation-controlled fire** (fig. 5–12a). Fires that have plenty of oxygen (ventilation) but have limited access to fuel are termed **fuel-controlled** fires (fig. 5–12b).

Fig. 5–12. a) Ventilation-controlled fire and b) fuel-controlled fire. (Courtesy of Dustin Hughes)

Rollover. As a fire burns and consumes a room's contents, the heated fire gases rise up to the ceiling. These heated gases and smoke are fuel and under the right circumstances will ignite. Flames will appear at the ceiling level and will travel over the heads of anyone in the room who is staying low. This is known as **rollover** (also sometimes called **flameover**[4]). The danger associated with a rollover is that a fire can travel overhead and get behind firefighters, blocking their egress path, allowing the fire to spread, and making subsequent investigation into a fire's origin more difficult by making it appear that there is more than one point of origin. In large rooms with large fuel loads this can be a particularly difficult issue.

As stated before, once a room has flashed over, a fire changes from a fuel-controlled fire to a ventilation-controlled fire. In this case pyrolysates that are hot enough to ignite will not be able to burn until they "find" enough oxygen. Usually this occurs when the gases exit (roll) through a window or a door.

Flashover. During the development of a fire, heat is generated. Some of this heat is in heated gases and fills the atmosphere of the involved room or compartment, while heat is also transferred to the structural elements and contents. The temperature of the contents rises as the heat is transferred. If the contents are ignitable liquids, the liquid will change to vapor once the liquid's flashpoint is reached. If the contents are solids, ignitable vapors will be given off when the ignition temperature is reached.

Obviously, all contents have different ignition temperatures and different physical states, and their ability to absorb the transferred heat is determined by numerous factors. However, because a fire in a confined area such as a room or compartment can result in the generation of significant heat levels, it is possible for all of the contents to quickly reach their ignition temperature. At this point, all of the contents are giving off ignitable vapors (pyrolysates). As these vapors ignite, all of the contents of the entire room or compartment become involved. This is known as **flashover** (fig. 5–13).

There are a number of ways to define flashover, the most deadly of fire "events" (building occupants will not survive the effects of a flashover; firefighters wearing full protective equipment have a only a few seconds to reach safety outside the flashover environment before they will succumb—even then, they will likely suffer injuries). One is that flashover occurs when a fire changes from becoming a fuel-controlled fire to a ventilation-controlled fire. Another is that flashover occurs when the upper thermal layer reaches a temperature of about 500–600°C (about 900–1100°F). However you define it, this sudden change can take place in a matter of seconds and create a life-and-death situation for firefighters. It is critical that all firefighters learn to identify the warning signs of an impending flashover and take immediate measures to reduce or eliminate the potential for flashover.

FLASHOVER WARNING SIGNS

- Flames licking overhead (rollover)
- *Rapid* buildup of heat in a room or compartment
- Appearance of smoke or gases coming off all contents, including carpet
- Flames emerging from doors and windows as these are the places where gaseous fuel can find a lot of oxygen.

BACKDRAFT WARNING SIGNS

- Smoke puffing from the building; sometimes the building appears to be "breathing"
- Smoke churning in window glass
- Window glass appears as if it is being pulled in
- Lack of any visible flame
- Air rushes in when any opening or vent is created

FIREGROUND NOTE

When a stream of water is introduced into a room or compartment where thermal layering is taking place, the thermal balance will be upset.

Fig. 5–13. Flashover

Backdraft. **FFI 5.3.11** A fire needs oxygen (or an oxidizing agent) in order to burn. Normally, this is not a problem since the atmosphere contains sufficient oxygen to allow a fire to burn (approximately 20.8%). However, if the fire is burning in a closed or confined area or space, the fire will consume the available oxygen and generate large amounts of carbon monoxide along with an assortment of other fire gases.

As the oxygen level drops below 16%, visible flames start to diminish because the fire is being starved of oxygen. The danger is that the compartment is charged with super heated gases and smoke. The sudden reintroduction of oxygen to the compartment or space will literally breathe new life into the fire. There will be a rapid influx of outside air as if the fire is sucking the oxygen in. This will be followed by an even faster reappearance of flames in an *explosive manner* that has the power to blow out windows and doors and even push out walls.

This is known as **backdraft,** sometimes called a **smoke explosion** (fig. 5–14). The violent explosive force of a backdraft has been known to lift buildings off of their foundations and hurl people across streets.

Vertical ventilation at the highest point over the fire can reduce the buildup of superheated gases and minimize or prevent the possibility of backdraft.

Decay

Once the fuel package has been mostly consumed and the HRR drops significantly, the fire will diminish in size. This is the point at which the fire is in the decay stage. Small pockets of fire may still exist as the fuel

Fig. 5–14. Backdraft

slowly moves to the point of total consumption. Glowing embers will be the final indicator that the fire is about to cease because all of the available combustibles have been consumed by the fire.

During a fire, all four phases may be seen simultaneously, albeit in different locations. A unique example is a high-rise building fire, especially when the involved area is above the reach of fire department hose streams. As the fire burns a floor, the floor above is pre-heated. When sufficient ignitable vapors are emitted, ignition occurs on the floor above while the fire is burning. The fire in the floor above, grows until the entire floor becomes involved, which is now pre-heating the floor above. Concurrently, as the fire now consumes all available combustibles on the original floor of involvement, the fire in that floor enters the decay stage until the fire ultimately dies out from a total lack of fuel.

EXPLOSIONS

During your firefighting career, you will likely respond to the scene of an **explosion** after it has occurred. You may even be a witness to an explosion taking place. Explosions are not common events, but is important to understand the basics of these potentially deadly events. According to NFPA 921, an explosion is "the sudden conversion of **potential energy** (chemical or mechanical) into **kinetic energy** with the production and release of gases under pressure, or the release of gas under pressure. These high-pressure gases then do mechanical work such as moving, changing, or shattering nearby materials." Explosions occur very quickly and usually have devastating results. Explosions will be covered in some subsequent chapters.

There are two types of explosions: **deflagrations** and **detonations**. The difference is the speed in which they occur: the "combustion zone" (blast wave) moves slower than the speed of sound in a deflagration, while the combustion zone in a detonation moves faster than the speed of sound.

Natural gas explosions and many dust explosions are examples of a deflagration (fig. 5–15a). The use of an explosive such as TNT (trinitrotoluene) results in a detonation (fig. 5–15b). Generally speaking, deflagrations, while destructive and potentially deadly, do not have the same "shattering effect" of the more powerful detonation.

Fig. 5–15. Results of a) gas explosion and b) TNT explosion. (Courtesy of David Forward)

NOTES

1. Drysdale, Dougal. *An Introduction to Fire Dynamics*, 2nd ed. Chichester, UK: Wiley, 1999.
2. Babrauskas, Vytenis. *Ignition Handbook*. Issaquah, WA: Fire Science, 2003.
3. www.nafed.org/resources/library/UL300.cfm
4. NFPA 921: *Guide for Fire and Explosion Investigations* , 2004 Ed.

QUESTIONS

1. Describe two ways fire can obtain oxygen in order to support combustion.
2. What is the definition of fire?
3. What is the process of sublimation?
4. What is specific heat and its unit measurement?
5. Describe the process of latent heat of vaporization.
6. What effect does density play when it comes to ignition of an object or substance?
7. List the four common acceptable sources of heat and energy. Give examples of each.
8. Two types of reactions are ____________________ and ___________________.
9. List three physical states of a fuel.
10. Define ignition temperature.
11. Describe surface to mass ratio and its effects on fuel characteristics.
12. What is flash point?
13. What is fire point?
14. The four stages of fire development are ________________, __________________, _______________, and __________________.
15. List four factors that affect a fire's ability to grow.
16. Can all four stages of a fire be seen at once? If so, describe how this can occur.
17. List the warning signs of a potential backdraft.