UNIT 2:
FIRE DYNAMICS AND THE BUILT ENVIRONMENT

OBJECTIVES

The students will be able to:

1. *Explain basic fire behavior chemistry and physics using the following terms as they relate to the built environment:*

   a. *Flashpoint.*
   b. *Boiling point.*
   c. *Flammable limits.*
   d. *Conduction.*
   e. *Convection.*
   f. *Radiation.*
   g. *Oxidizer.*
   h. *Triple point.*
   i. *Basic research.*
   j. *Applied research.*
   k. *Closed system.*

2. *Explain the progression of fire, from start to extinguishment using the following terms as they relate to the built environment:*

   a. *Heat flux/transfer.*
   b. *Heat of combustion.*
   c. *Heat Release Rate (HRR).*
   d. T^2 *fire.*
   e. *Flashover.*
   f. *Backdraft.*
   g. *Fire plume.*
   h. *Ceiling jet.*
   i. *Homeostasis.*

3. *Recognize the factors in building design that contribute to fire ignition, growth, and extinguishment.*

FIRE DYNAMICS

Before one can be fully competent in fire protection and code enforcement, he or she must be able to articulate how and why fires behave the way that they do. This unit provides the student a basis for the science that justifies much of what he/she does.

While mankind is believed to have discovered the use of fire 500,000 years ago, it only has been in recent years that research has been conducted into the scientific complexities of the fire environment. This research has given us a limited understanding of the chemical and physical properties that affect fire growth and spread, methods of heat transfer, and smoke and toxic gas production. Research also has continued in the areas of active and passive fire protection systems, such as fire sprinklers and fire resistant barriers, respectively. Together, this knowledge is known as "fire dynamics".

Fire behavior research is a challenging and exciting field. "Basic research" occurs at a number of State and private universities, research laboratories, and Federal facilities. Scientists and engineers try to explain the phenomenon of ignition and the sequence of events that occurs during combustion and fire growth. Different fuels, ignition sources, and scenarios are evaluated to study fire behavior. "Applied research" involves applying and translating the scientific data into day-to-day uses (i.e., better fire sprinkler designs, fire retardant fabrics and packaging, and materials handling and storage techniques).

Many requirements in the building and fire codes are intended to protect life and minimize property damage from unwanted and hostile fires. It is important to understand the fundamentals of fire behavior in structures so functional, aesthetic, and efficient building designs can be matched to the need to protect people and operations within the built environment.

Fire behavior in structures is complicated. Fuels, oxygen, ventilation, compartmentalization, fire protection systems, interior and exterior design, weather conditions, and human activities affect the outcome of a fire. Those in the fire protection field know that even when given the same set of identical circumstances, it is unlikely that two fires will behave the same or have the same result. Although building codes tend to treat structures within the same occupancy classifications as similar, the fire characteristics between and among structures is widely different.

The chemical reaction with physical effects that is called "fire" is a complex and dynamic event, even in controlled laboratory conditions. Thus, code officials must apply their knowledge of fire dynamics with reasoned and experienced judgment to achieve the highest level of fire protection success under destructive and life-threatening conditions.

It is important for the code official to understand the features of architecture and building components that influence fire growth and behavior and to understand how building and fire codes treat these factors.

MEASURING FIRE DEVELOPMENT

Both basic and applied research rely on "quantifying" values, that is, measuring them in a way that can be compared from one test to another.

In the United States we still prefer the United States System of Measurement that relies on the familiar feet, inches, pounds, watts, degrees Fahrenheit, and British thermal units (Btus). However, most of the test data are recorded in the metric-based International System (SI) units including meters, kilograms, Pascals, degrees Celsius, and Joules.

(Many of the Figures and Tables in your Student Manual (SM) reference both United States System of Measurement and International Standards (SI) units. A conversion table for these values is found on Job Aid 2.1.)

With the exception of the kilogram (kg), the conversions listed in the following chart are to base units such as Joule (J) and Watt (W). When considering a building fire, these units are so small that the values must be reported as kiloJoules (kJ) or kilowatts (kW). The "kilo" prefix means to multiply the base unit by 1,000. Another prefix that may be used is mega (M). This prefix means to multiply the base unit by 1,000,000.

Figure 2-1 provides examples of unit conversions.

Property	To Convert From	To	Multiply by
Length	Foot (ft)	Meter (m)	0.3048
	Meter (m)	Foot (ft)	3.281
Mass	Pound (lb)	Kilogram (kg)	0.4536
	Kilogram (kg)	Pound (lb)	2.205
Time	Second(s)	Second(s)	1.0
Area	Square foot (ft^2)	Square meter (m^2)	0.0929
	Square meter (m^2)	Square foot (ft^2)	10.76
Volume	Cubic foot (ft^3)	Cubic meter (m^3)	0.0283
	Cubic meter (m^3)	Cubic foot (ft^3)	35.3147
Energy, work, quantity of heat	British thermal unit (Btu)	Joule (J)	1054.8
	Joule (J)	British thermal unit (Btu)	0.000948
Power, heat release rate	British thermal unit per minute (Btu/min)	Watt (W) =J/s	17.573
	Watt (W) =J/s	British thermal unit per minute (Btu/min)	0.05688
	Watt (W)	British thermal unit per minute (Btu/sec)	0.000947
	Btu/lb	Joule/Kilogram	2326
Heat flux	British thermal unit per square foot second ($Btu/ft^2/sec$)	Watts per square meter (W/m^2), or, Joules/m^2/second ($J/m^2/sec$)	11364
	Watts per square meter (W/m^2), or, Joules/m^2/second ($J/m^2/sec$)	British thermal unit per square foot second (Btu/ft^2 /sec)	0.000088

*Reference: NIST Special Publication 811, *Guide for the Use of the International System of Units (SI)*, National Institute of Standards and Technology, Gaithersburg, MD, April 1995. See also the Web site www.convertme.com/en

Figure 2-1
SI Conversions

Note: There is a variety of free online unit conversion services. Use your Web browser and type in "conversion," or the specific units you want (i.e., heat flux conversions) to find them. The National Fire Protection Association (NFPA) *Fire Protection Handbook* includes a table of conversion factors in its appendices.

CANDLES AS AN EXAMPLE OF FIRE BEHAVIOR

Fire research has a long and storied history. As long as man has observed his environment, he has tried to explain how it works.

In 1826, Michael Faraday began a series of lectures during Christmas Holiday at the Royal Institute in England. The lectures were presented to young adults and focused on science. In 1860, he presented one of his more famous lecture series, *The Chemical History of a Candle.* The lecture described the working phenomenon of candles with a level of understanding of the properties of heat transfer that is comparable to our knowledge of the subject today.

To open our study of the principles of fire dynamics; we will use Faraday's evaluation of the burning process of a candle, which is an excellent model of a laminar diffusion flame.[1] As you read this, think about the times you have looked closely at a burning candle.

Lighting the candle wick results in a sustained flame on the wick. Radiated heat from the flame begins to soften and melt the paraffin wax [a hydrocarbon ($C_{20}H_{42}$)]. The melted wax is drawn-up the wick by capillary action (Faraday called this "capillary attraction"). When the liquid wax is exposed to the high temperatures of the flame, it is vaporized into a combustible fuel. Vaporizing the paraffin wax (the process of pyrolysis) occurs in the lower portion of the flame, where the liquid wax meets the flame. The rising vapors of paraffin wax are then consumed in the combustion process of the flame. The candle flame rises upward as a result of the principle of buoyancy, since the combustion gases and heat given to the flame are warmer and lighter than the surrounding (room air) atmosphere. The process continues and is accentuated by the fresh incoming air drawn into the flame region to fill in for the rising products of flame combustion. This process permits a continual supply of oxygen into the diffusion flame of the candle.

The candle flame has several distinct areas which are distinguishable by the change in color within the flame plume. As the paraffin is vaporized, it rises up into the flame region and is premixed with the fresh oxygen coming in from the sides and below the flame. This results in the bottom section of the flame appearing blue in color. The proper fuel-air ratio in this area results in clean combustion, with little soot. This fuel-rich vapor has not begun the process of being broken down by the heat of the flame.

The darker luminous zone, which comprises the inner bottom half of the candle flames, is the region where the chemical bonds of the paraffin fuel are broken down by the actions of heat. This permits the pyrolized paraffin fuel to mix with atmospheric air as the pyrolized fuel migrates toward the oxygen and forms a mixture. The mixing action of the fuel and oxygen, seeking to equalize themselves (diffuse) with their surrounding environment, follows the principles of Fick's Law.

Fick's Law states, "*…a given species (e.g., in connection with fire, oxygen, fuel, CO_2) will move from a high to low concentration in the mixture.*" For example, a drop of blue ink in a glass of water eventually will diffuse into the water to give a blue tinge. Oxygen in air will move to the flame where it has a concentration of zero percent as it is consumed in the reaction. Fuel is

[1] "Laminar diffusion flame" describes a smoothly burning candle flame in a well-ventilated environment.

transported into the opposite side of the flame by the same process. The combustion products diffuse away from the flame in both directions.

The yellow to white luminous zone of the candle is the region where soot (carbon atoms) is present and produces luminosity as the combustion with oxygen. Unburned carbon atoms eventually will escape the high temperature of the flame zone and combine with oxygen (O_2) to form carbon dioxide. A lighter halo exists around the majority of the flame, almost translucent in appearance. This area is the outermost region of combustion, where oxygen and pyrolized paraffin mixes efficiently with very little soot present.

LAWS OF CONSERVATION

The laws of conservation are fundamental principles of mechanics that serve as the guiding basis for all branches of science. We will discuss briefly these principles so that you will have a better understanding of the foundations that support the complex relationships developed by scientists and engineers and how they apply to the built environment.

Scientists use certain terms as a means of communicating their ideas about universal theories, and we will review a few of these prior to examination of the laws of conservation and thermodynamics. A **system** is defined as the portion of our universe that we are interested in studying. The **system** generally will have prescribed confines (boundaries) and matter (objects or mass) within it.

In order to isolate a particular phenomenon that is being studied, the **system** most often is considered "closed." A **closed system** is isolated from the effects of the outside world, with matter and energy remaining constant within it, and the effects of gravity and other energy and matter are shut out. A hypothetical room with no windows or doors and containing a known amount of combustible items and air volume would represent a closed system. An **open system** permits exchange of matter and energy between it and the outside **surroundings**, so the system can gain and lose energy and/or matter over time. A room with an open window and door that entrains fresh air from outside, and ventilates products of combustion and heat to the outside would be considered an **open system**. When the **system** and its **surroundings** are combined together, they form the **thermodynamic universe** for the particular process under review.

Conservation of Momentum

A system's total momentum ($m_{ass} \bullet v_{elocity}$) is said to be constant or "conserved." At any time, the sum of the momentum of all objects within a system will remain constant. (Total momentum = $mv_1 + mv_2 + mv_n$). If we observe momentum in one direction of the system, then there must be an equaling force in the opposite direction. Conservation of momentum accounts for the symmetry that is observed in our world. Sir Isaac Newton developed his Laws of Momentum that explain much of what we know about in the study of physics:

Newton's First Law: An object will remain at rest, or in motion in a straight line, unless it is acted upon by an external force. Set a small rubber ball on a table and it won't move. Tilt one end of the table (the external force) and the ball will start to move. As long as the table surface is smooth, the ball will travel in a straight line.

Newton's Second Law: A change in an objects motion will result in an increase in acceleration. As the ball described above rolls across the table surface, it will pick up speed at a steadily increasing rate.

Newton's Third Law: All internal forces of a system are generated in opposite pairs, so the acceleration of the center of mass of an isolated system is zero. This is the law of "equal and opposite" actions. The amount of energy needed to lift the table is equal to the energy created by the rolling ball (less the influence of friction caused by the table and the air.)

PRINCIPLES OF THERMODYNAMICS

Energy

Energy is defined as the capacity to do work, or extract heat. Energy is expended in order move an object from one point to another, or raise the temperature of a system. Energy may appear in various forms and is either stored (potential energy), or in motion (kinetic energy), or the potential energy between molecules of a substance (internal energy). The law of conservation of energy states that at any moment in time, the sum of the potential and kinetic energy of any object remains the same. Examples of potential and kinetic energy:

Potential Energy	Kinetic Energy
Electric battery (electric energy)	Electron transfer to power electric windows
Water stored in a water tower	Running water from shower
Diesel fuel in vehicle tank (chemical)	Powers internal combustion engine
Steam (thermal)	Powers steam turbine

Conservation of Energy

The energy (or capacity to do work) within a system remains constant. Energy is neither created nor destroyed but can be transformed from one form to another and the total energy of the system remains unchanged. The process of combustion decomposes a substance with the energy of the chemical bonds of the substance released as heat energy and products of combustion.

Think about the candle observation: potential energy (paraffin wax) is converted to heat energy in the flame. The heat energy excites the air molecules in the atmosphere causing buoyancy. The energy is transferred from the paraffin to the moving air.

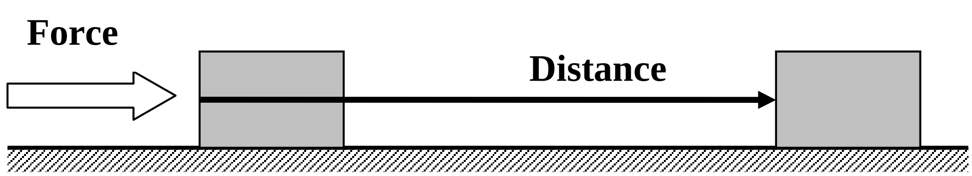
Think about holding the rubber ball in your hand and dropping it onto a ceramic floor. The ball will bounce off of the floor and continue to bounce, the height of each bounce somewhat less than the last, until all motion ceases and the ball rests on the floor.

The ball held in your hand has stored potential energy, due to its height and the pull of gravity. Once the ball is dropped, the stored potential energy is converted to kinetic energy of the fall. After striking the floor the ball begins to rise the gradually, losing its kinetic energy and having potential energy (pull of gravity) to fall again. At any point in time, the total sum of the potential and kinetic energy, and friction of compression, sound energy, and floor resistance are theoretically equal.

When the ball ceases to move, the energy that provided the initial movement has been converted to thermal energy as a result of the processes of compression of the ball as it bounces, and friction from the interaction with the floor. The ball's original kinetic energy has been converted into thermal energy stored within the ball and in the floor.

Work

Work is defined as the product of the external force on a body (mass) and the distance that the force acts. The diagram is true for constant applications of force. If a body does not move when a force is applied, then we cannot say that work has occurred. If the object moves in a direction that is not consistent with the applied force, then work is still accomplished, but only in the length and direction of the result. The work can be measured by multiplying that force times the distance: A block that is moved 5 meters by an applied force of 8 Newtons is the equivalent of 40 joules (mN) of work



Work = Force (pounds or Newtons) • **Distance** (feet or meters)

Figure 2-2
Visualization of Work Performed

Power is a term that describes **a rate of doing work** or using energy. Velocity is a dimension involving time and distance. In cases of where the force is constant and inline with the direction of the velocity, the formulas for power are

SI: P_{ower}=Newtons • meters/second = Joules/second = Watts

U.S.: P_{ower} = pounds • feet/second = ft lb/s = horsepower (hp)

If the force is not inline with the direction of the velocity then the formula for instantaneous power is the product of the force and velocity times the cosine of the angle between the two:

$$P_{instantaneous} = F_{orce} \bullet \cos\theta \, v$$

Why is the study of work important to the fire protection professional? Many fire protection systems, such as fire pump drivers, measure their output performance using work-based units.

Heat

Heat is expressed or defined as the **process** of transfer of energy from systems or objects of higher temperature to ones of lower temperature. The term **heat** describes an energy transfer resulting from a difference in temperatures of various objects. Objects do not contain heat, rather they possess internal energy. It is incorrect to state that objects or systems possess "heat." Objects having higher energy transfer the energy to objects of lower energy. The process of "sharing" or losing some of an object's internal energy is perceived as thermal heat, or a process of **heating**.

Temperature is a measure of the heat generated from the kinetic energy within a system or object. Depending upon the application, temperature is measured in degrees Fahrenheit, Celsius, Rankin, or Kelvin. Temperature is not a measure of the object's total energy. Two objects with the same temperature, coal and water for example, will not have the same internal energies, or specific heat values (ability of substance to store energy).

Work, Heat, and Energy

The **calorie** is the unit of heat energy in the metric system (SI). Heat measurement is called **calorimetry**. A calorie (or gram calorie) is the amount of heat required to raise the temperature of one gram of pure water one degree Celsius (°C). One kilocalorie will raise the temperature of one kilogram of water one °C.[2]

Heat and **work** are both capable of transferring energy to systems. If we heat and compress two equal volumes of air, our measurement of the final state of internal energy cannot distinguish which process (or combination of processes) created the increased internal energy. In 1843, James Joule performed an experiment which showed that one calorie of heat equaled 4.186 joules of mechanical energy, proving that there was a relationship between work and heat energy. Refer to the diagram on the following page.

[2] In U.S. measurements, a Btu is the amount of energy needed to raise the temperature of one pound of water one degree Fahrenheit.

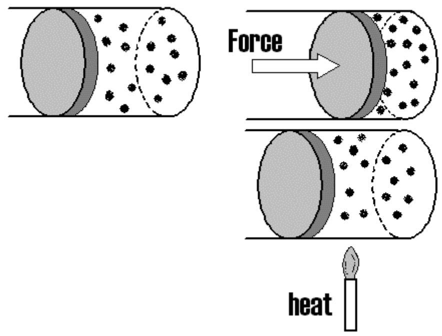


Figure 2-3
Increased Internal Energy Results from Work or Heat

Automobile engines are good examples of how heat and work transfer energy: a diesel-fueled engine relies on the compression of the fuel to create combustion, a gasoline engine employs heat in the form of a spark to ignite the fuel.

THERMODYNAMIC LAWS

The **First Law of Thermodynamics** is the application of the conservation of energy principle applied to heat and the thermodynamic process. The change in internal energy in a system is equal to the heat that is added, minus the work performed. When work is performed, the internal energy of a system usually is decreased.

As one liter of fuel is consumed to run a motor vehicle (work being performed in an open system), the total stored energy of the fuel is reduced (amount of fuel being burned).

The **Second Law of Thermodynamics** addresses the efficiency of heat engines and constraints on the direction of heat transfer. According to this law, it is impossible to extract heat from a warmer body and perform work without having some of the energy lost to a colder body. Otherwise, it is impossible to have a heat engine that is 100-percent efficient.

Thermal equilibrium is reached when a higher temperature object of system is in contact with a lower temperature system or object. Heat will flow from the warmer system to the colder one, resulting in **thermal equilibrium**. We see this principle at work when a fire-resistive barrier such as a masonry fire wall heats up when exposed to a fire.

Stoichiometric Reactions

The study that examines the relationships between the masses of the reaction substances, and the resulting products is called **stoichiometry.** The term is derived from the Greek words **stoicheion**, meaning "element, and **metron** meaning, "measure." Every fuel-air mixture has an optimum ratio at which point the combustion of the fuel will be complete. This occurs at or near the mixture known as the stoichiometric ratio. It is at this point the amount of air is in balance with the amount of fuel. Except for certain types of gas fires, this condition rarely occurs in fires outside a controlled environment like a laboratory.

The Ideal Gas Law

The Ideal Gas Law may be described as the condition where all collisions between gas molecules or atoms of identical particles of zero volume are elastic and there are not any internal molecular forces or attractions. The gas molecules of this hypothetical **ideal gas** are a group of spheres that can collide, but do not react with each other in any other way.

All internal energy is in the form of kinetic energy (motion) and changing the kinetic energy of the gas results in a change in temperature. As the gas molecules collide with the sides of the container, a kinetic pressure is created. The Ideal Gas Law infers that the measurement of this pressure, which results from the kinetic activity, is therefore proportional to the temperature.

Real gases such as methane, carbon dioxide, hydrogen, or argon do not behave exactly this way, but the principle is the similar. The behavioral connection between ideal and real gases breaks down at high pressures and low temperatures, where the intermolecular forces play a greater role in determining the properties of the gas.

The three variables that express the state of an ideal gas are all measurable properties. It is inconsequential as to how the gas molecules reach the measured "state." The state of change may be due to either the application of work or heat, as noted in the above example.

Scientists have established a standard reference point called Standard Temperature and Pressure (STP) relative to expressing and comparing properties and values of ideal gases. STP is 0 °C at 1 atmosphere (760 mmHg). One atmosphere is the weight of atmospheric air at sea level. In U.S. units, it is 32 °F at 14.7 psia. An atmosphere is abbreviated as "atm."

What is psia? It is scientific shorthand for "pounds per square inch absolute." Absolute pressure is the sum of atmospheric pressure and gauge pressure. Typically we measure tire pressure with an air gauge. The air pressure gauge measures pressure in excess of what the atmosphere provides and is translated as "psig," or pounds per square inch gauge. If we attempt to measure the pressure of a flat tire, the tire pressure gauge would read "zero." This measurement doesn't account for the pressure exerted by the earth's atmosphere. Pressure on a tire gauge equals the **absolute pressure** minus the **atmospheric pressure**. Fire protection system gauges (fire pumps, standpipes, sprinklers, water mist, etc.) generally read in psig values.

Another scientific reference point may be found in the codes when reviewing requirements for gaseous hazardous material use, storage, and handling: Normal Temperature and Pressure (NTP). Normal Temperature and Pressure is 21 °C (70 °F) at 1 atmosphere. NTP is used for comparing characteristics of hazardous materials because they seldom occur in the built environment at Standard Temperature and Pressure.

Boyle's and Charles's Laws

Two other important scientific rules are Boyle's Law and Charles's Law. If the gas temperature remains constant, then the relationship between pressure and volume is described using Boyle's Law. Boyle's Law states that at a **constant temperature**, the volume of a fixed amount of gas is inversely proportional to pressure. Therefore, if the temperature remains constant, as the pressure goes up, the volume goes down and vice versa.

Boyle's Law is used commonly to predict the result of introducing a change, in volume and pressure only, to the initial state of a fixed quantity of gas. The "before" and "after" volumes and pressures of the fixed amount of gas, where the "before" and "after" temperatures are the same (heating or cooling will be required to meet this condition), are related by the equation:

$$P_{after}\ V_{after} = P_{before}\ V_{before}$$

Where,
P = Pressure
V = Volume

On the other hand, if the gas **pressure** remains constant, then the derivation may be referred to as **Charles's Law**. At constant pressure, the volume of a given mass of an ideal gas increases or decreases by the same factor as its temperature (in degrees Kelvin) increases or decreases. The mathematical formula for Charles's Law is

$$V_{after}\ /T_{after\ (K)} = V_{before}\ T_{before(K)}$$

Where,
T = Temperature
V = Volume

The **Bernoulli Principle** also is a consideration when examining gas flows from a fire. Daniel Bernoulli (1700-1782), a Swiss mathematician, theorized that as the velocity of a fluid increased, the pressure decreased. Bernoulli's Principle proves that gas velocity and pressure are proportional to their product. When gases reach a point of obstruction, a velocity increase is required to maintain the flow. If the velocity of the gas increases, then the pressure will decrease accordingly.

If the Bernoulli Principle is applied to fire gases exiting at a ventilation opening, we should expect an increase in velocity. An increase in temperature inside of a closed structure will result normally in an increase in pressure. When the fire gases exit the structure through an opening (such as a window) lower pressure is encountered, therefore, according to Bernoulli's Principle, the velocity of the gas should increase. This accounts for observations of fire gases "shooting" out of openings, and helps us understand how to design fire protection features to deal with the velocities. These laws are used in fire behavior studies as well as understanding how hazardous materials behave in the environment.

Triple Point

In physics and chemistry, the **triple point** of a substance is the **temperature** and **pressure** at which three **phases** (**gas**, **liquid**, and **solid**) of that substance may coexist in **thermodynamic** equilibrium.

The triple point of carbon dioxide--a common gaseous fire suppression agent--occurs at a pressure of 5.2 atm (3952 mmHg) and 216.6 K (-56.4 ^{o}C). At temperature of 197.5 K (-78.5 ^{o}C), the vapor pressure of solid carbon dioxide is 1 atm (760 mmHg). This information is useful for designing carbon dioxide systems for special hazards.

WHAT IS FIRE?

The Fire Triangle and Tetrahedron

Fire is a chemical reaction that produces physical effects: heat, light, and material decomposition. In the simplest of terms, the components of "fire" can be illustrated by the fire triangle. The sides of the triangle represent heat, fuel, and oxygen. In addition to the heat, fuel, and oxygen, there is also the uninhibited chemical chain reaction. Some authors describe these conditions as a four-sided object, the fire tetrahedron.

- **Heat**: the energy needed to ignite a combustible fuel. It may be natural or manmade.
- **Oxygen**: the gas needed to sustain combustion. It may occur freely in nature (the atmosphere is about 21-percent oxygen) or introduced from some other chemical (an oxidizer).
- **Fuel**: a material that will convert from a solid, liquid, or gas and release energy during the process.
- **Uninhibited chain reaction**: the chemical process that sustains combustion without interruption.

While these elementary depictions are sufficient for many situations, a more detailed understanding of the chemistry and physics of fire is necessary to explain how fire and smoke behave in a building. Understanding these phenomena enable design professionals and code officials to properly apply both prescriptive and performance-based designs, codes, and fire protection systems and equipment.

Fire may be an essential part of an industrial process or residential heating appliance, but once there is a failure a fire may become hostile rather than beneficial. Unwanted fires pose a serious threat to life and property if they are not confined or extinguished.

COMBUSTION PROCESSES

In the precombustion phase of fire, fuels may be heated to their ignition temperature from a variety of sources. Ignition temperature is the minimum temperature a substance must attain in order to ignite under specific test (laboratory) conditions. Heat is the energy that is needed to maintain a change in temperature. Temperature is the measurement that expresses the degree of molecular activity of a material compared to a reference point such as the freezing point of pure water.

Pyrolysis

During the precombustion phase, vapors and solid particulate matter are being released from the fuel. These materials commonly are called pyrolysis products or pyrolyzate. Pyrolysis is the transformation of a material into one or more other substances by heat alone. Glowing combustion or smoldering may or may not be related to the oxygen level. Such glowing can occur during both the initial and final stages of a fire. While a limited oxygen level may result in smoldering, such conditions also can be created by the amount of fuel vapor production or temperature.

Flaming combustion occurs when there is sufficient energy (heat), fuel vapors in the flammable range, and adequate oxygen. The chemical reaction must be unimpeded if the fire is to continue. These phases may exist individually or simultaneously in any given fire.

Diffusion Flame Process

During flaming combustion, the flames are either **diffused** or **premixed**. In most structural fires the pure fuel vapors are released and diffused or mixed with the surrounding air (oxygen). This mixing process is known as diffusion. If the fuel vapors and air mixture fall with the flammable range and an ignition source is present, ignition will occur. Flames, which are the result of this mixing of fuel vapors and air, are known as diffusion flames.

Premixed Flame Process

Premixed combustion occurs when the fuel vapors/gases are mixed in advance with an appropriate quantity of air or oxygen to form a mixture prior to ignition. Premixed combustion occurs during an explosion, but most commonly occurs with gas-fired appliances or industrial processes. Premixed combustion is typically more efficient and produces less smoke than diffusion flames.

THE IGNITION PROCESS

The traditional approach to fire and life safety is based on the assumption that a single episode of unwanted ignition will occur, and the building and fire protection features will minimize the impact of the result. Fire-resistive construction, compartmentalization, fire detection, and fire sprinkler systems "react" to the fire and--if all work properly--confine, report, and control the fire to some manageable level. If the fire is not suppressed by the fire protection system or timely occupant action, the local fire authorities may be called to intervene. Fire protection codes and protective inspections are intended to prevent fires from occurring, but if they do, the built environment is called upon to perform.

Ignition Types

Ignition is that sequence of events that brings environmental fuels, oxygen, and a heat source together in adequate proportion to start a fire. Much of the content of fire prevention codes is based on ignition prevention: keeping flammable or combustible fuels away from heat sources.

When evaluating a building or facility, design professionals and code officials must examine closely the potential types of ignition that might occur based on the operations, processes, and storage that will exist. They are

- **Autoignition** that occurs when the fuel is heated sufficiently for the vapors to ignite without the presence of any outside arc, spark, ember, or open flame. Compressive and percussive forces often are adequate to ignite fuels.

- **Piloted ignition** that occurs when an arc, spark, ember, or open flame ignites fuel vapors. The amount of energy (heat) required for piloted ignition is less than that necessary for auto-ignition. This is because the "pilot" is igniting vapors, rather than heating the solid fuel.

- **Spontaneous heating to ignition**--often called "spontaneous combustion"--is a form of autoignition. Certain fuels are or can become "self-heating." This process commonly is known as spontaneous heating. This is a process whereby a material increases in temperature without drawing or absorbing heat from its surroundings. The incubation process results from oxidation, often aided by bacterial action when agricultural products are involved. Under the right conditions, the self-heating can generate sufficient temperatures for ignition to occur. When ignition occurs as a result of spontaneous heating, it is known as "spontaneous ignition." The following figure shows some of the materials that are subject to spontaneous heating and ignition.

Alfalfa meal	Used burlap bags
Castor oil	Charcoal
Coal	Cocoanut oil
Cod liver oil	Corn meal feeds
Cottonseed	Fish meal
Foam rubber	Linseed Oil
Metal powders	Peanuts/oil
Powdered eggs	Powdered milk
Powdered latex gloves	

Figure 2-4
Partial List of Materials Subject to Spontaneous Heating and Ignition

Ignition Temperatures

Different fuels have different ignition temperatures: the temperature to which they must be heated to sustain combustion. Unfortunately, laboratory established ignition temperatures might not be replicable outside of scientifically-controlled conditions in the "real" world. Due to the wide range of variables that can exist outside the lab, ignition temperatures should be regarded solely as approximations.

Variables affecting ignition temperature include the rate and duration of fuel heating, the shape and volume of the test container, the kind and temperature of the ignition source, airflow, and the variables of contaminants in the fuels. Fuels found in the environment seldom are as pure as those tested in a laboratory.

Some products will self-ignite if they are heated to their autoignition temperature.

Figure 2-5 provides examples of common products and their autoignition temperatures.

Material	Autoignition Temperature	
	°F	°C
Acetone	869	465
Ammonia	928	498
Butane	550	288
Ethane	882	472
Ethanol	685	363
Gasoline (varies based on octane rating)	536 to 880	280 to 475
Methane	999	537
Methanol	725	385
Octane	403	206
Propane	842	450
Toluene	896	480

Source: NFPA *Fire Protection Handbook, 18th edition,* p. 3-34.

Figure 2-5
Autoignition Temperature of Common Fuels

For piloted ignition to occur, a "competent" ignition source must be present. A competent ignition source is one that has both sufficient temperature and energy to raise a fuel to its ignition temperature during the contact period. While the temperatures of many potential ignition sources exceed the ignition temperature of common fuels, the ignition source must last long enough, and be in contact with the fuel long enough, to raise the fuel to its ignition temperature.

For example, a 110/220-volt electrical arc results in temperatures in the 6,000 to 10,000 °F (3,343 to 5582 °C) range; however, in most instances, the event is extremely short lived and the contact period is limited. Unless the arc occurs in the presence of flammable vapors or other volatile material, ignition most likely will not occur.

This is a key principle of fire protection in many industrial occupancies: keeping electrical arcs away from flammable vapors or dusts to prevent fires or explosions. National Fire Protection Association (NFPA) 70, *National Electrical Code*® and the model fire codes "classify" hazardous areas based on the fire or explosion potential. Once the boundaries of the hazardous area are defined--for example the interior of a spray booth--the electrical code specifies "explosion proof" or "enclosed" wiring and devices must be used. The size and shape of the classified areas varies depending upon factors like fuel volatility and ventilation.

Figure 2-6 provides examples of fuels and their range of ignition temperatures.

Material	**Ignition Temperature**	
	°F	**°C**
Ammonia (refrigerant)	1,210	660
Asphalt	905	485
Cotton	750	400
Cotton seed oil	650	343
Ethanol	798	425
Gasoline (100 octane)	824	440
Kerosene (Fuel Oil No. 1)	410	210
Natural Gas	900 to 1,170	482 to 632
Paper newsprint (cuts)	450	232
Polyester fiberglass composite wall panel	830	447
Polyethylene construction material (rigid)	824	444
Polypropylene siding, rigid	651	363
Polystyrene concrete forming unit	698	370
Polyvinyl chloride soffit material (rigid)	752	403
Recycled plastic/wood waste lumber substitute	698	370
Refrigerant, home air conditioner (hydro-fluorine)	386	198
Refrigerant, home air conditioner (hydro-carbon)	1,585	887
Urethane foam	852 to 1,074	456 to 759
Wood (fir, oak, pine, etc.)	378 to 507	192 to 265

Source: NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids*; various product Web sites.

Figure 2-6
Ignition Temperatures of Some Materials

FUELS

Fuels may be materials used for the construction of the structural frame of the building, its interior finishes, and its contents. Fire behavior is affected by both the available fuel and air or oxygen. Fuels may exist in the solid, liquid, or gaseous state, but only the vapors actually burn. For flammable liquids and gases, adequate concentrations of vapor may exist in their natural state that would enable piloted or autoignition to occur. For solids, pyrolysis releases vapors from the solid surface where they can mix with adequate quantities of air or oxidizers to sustain combustion.

Fuels that normally exist in a gaseous state and those that produce sufficient vapors at normal ambient temperatures ((flammable liquids, e.g., gasoline) or (liquefied petroleum gases, e.g., propane or butane)) present a higher hazard since no preheating is necessary for combustion to occur in the presence of a competent ignition source. The development of a fire depends on the fuel and its state, the location and geometry of the fuel, and the ventilation.

Fuel or Fire Loading

Traditionally, fuel's potential energy has been expressed in pounds or kilograms, such as a value of 8,000 Btus per pound (18,608 J per g). This method does not reflect the **rate** at which the fuel will burn, but is limited to the **amount of potential energy** available. Nowadays, though, many building components and furnishings employ hydrocarbon-based constituents. Studies show the potential heat energy of these products may be as high as 16,000 to 24,000 Btus per pound (37,216 to 55,824 J per g).

"Fire load" is the amount of fuel per square foot (or m^2) generally within a structure. This is an important value because the design principle of most fire suppression systems is to provide enough heat absorbing agent--such as water from a sprinkler system--to control the heat output. If the heat output exceeds the cooling capacity, the fire will destroy property. If the fire suppression system--including water from firefighter's hoselines--can control the heat output, the fire will be extinguished.

As an example, a fire sprinkler system designed to protect a warehouse full of metal equipment in wooden crates needs less water than one protecting a similar building full of upholstered furniture wrapped in plastic because the heat output in the latter scenario would be greater than the former.

Flammable or Explosive Limits

For any ignition to take place, the fuel must be heated sufficiently to produce enough vapors that, when mixed with air, fall within the flammable or explosive range/limit. Flammable limits are the upper and lower concentration limits of a vapor or gas in air that can be ignited. Flammable limits also may be known as "explosive limits," "explosive range," or "flammable range." Several factors, working together, affect whether or not sufficient vapors will be produced in quantities needed to create a flammable range. These factors include the temperature and energy of the heat source and the thermal properties, density, and heat absorbing capacity of the material (fuel).

Flammable ranges are important considerations in those occupancies where flammable or combustible liquids or gases are used, processed, dispensed, or stored. One recognized mitigation strategy to prevent fires in these environments is to provide natural or mechanical ventilation adequate to prevent vapor air concentrations within their flammable range.

Figure 2-7 provides a sample of common products and their laboratory-established flammable limits.

Material	Lower Flammable Limit (%)	Upper Flammable Limit (%)
Acetone	2.5	12.8
Acetylene	2.5	100
Benzene	1.2	7.8
Carbon monoxide	12.5	74
Ethylene	2.7	36
Gasoline	1.4	7.6
Isobutane	1.8	8.4
Propylene glycol	2.6	12.5
Toluene	1.1	7.1

Source: NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids.*

Figure 2-7
Common Product Flammable Limits

Flashpoint and Boiling Point

Unit 6: Hazardous Materials Recognition and Control, addresses hazardous materials in greater detail. Two of the important concepts that the code enforcement official must understand to apply hazardous materials regulations correctly are "flashpoint" and "boiling point" or "boiling temperature." Both of these physical characteristics must be assessed when the code official deals with flammable and combustible liquids.

Flashpoint is the temperature at which a liquid fuel emits adequate vapors that a spark will ignite the vapors, but not sustain combustion. Like other products, flashpoint temperatures are established by tightly controlled laboratory tests and their application in the "real" world should be evaluated carefully.

Boiling point, or temperature, is the temperature at 1 atm where the liquid's vapor pressure equals the atmospheric pressure. Once a liquid's vapor pressure **exceeds** atmospheric, the liquid will begin to boil.

Flashpoint and boiling point are used in conjunction to classify flammable and combustible liquids for correct fire code regulations. This will be discussed in Unit 6.

> Note: As with any hazardous materials analysis, the code official should consult at least three sources of information, including product Material Safety Data Sheets (MSDSs), independent consultants and chemists, product manufacturers, the local hazardous materials response team, or other reliable sources, before evaluating mitigation plans.

Heat of Combustion

Fuel or fuel loading essentially is a description of a material's "heat of combustion." The "heat of combustion" should not be confused with the heat release rate discussed next. Heat of combustion is the total Btu (caloric) value that can be extracted from a fuel under perfect conditions. Heat release rate pertains to the speed at which combustibles will burn.

The heat of combustion is influenced both by the physical form of the fuel and its chemical composition, also known as fuel chemistry. This simply represents how much energy the fuel would release if completely consumed. It does not reflect the release over any specific time period.

Consider a cut Christmas tree as an example. A typical tree weighs about 12 pounds (5.472 kg). Given an average value of 8,000 Btu per pound (18,608 kJ/kg), one would expect this tree to possess about 96,000 Btus (223,296 kJ/kg) of heat energy if fully consumed.

Construction Materials and Contents

Many of the materials used in the building construction and contents are synthetics or are hydrocarbon based, e.g., plastics. These materials have a much greater energy potential than traditional building materials such as wood. As the chart in Figure 2-8 shows, hydrocarbon-based fuels have approximately twice the energy potential as ordinary combustibles.

Material	Heat of Combustion (Btu/lb)	Heat of Combustion (kJ/kg)
Asphalt	17,150	39,890
Corrugated fiber carton	5,970	13,886
Cotton batting	7,000	16,282
Gasoline	19,250	44,775
Oil, cotton seed	17,100	39,774
Paper newsprint (cuts)	7,883	18,336
Paraffin oil	17,640	41,030
Polystyrene	18,000	41,868
Polyvinyl chloride (rigid)	7,500 to 9,500	17,445 to 22,097
Wood (sawdust shavings)	7,500 to 9,500	17,445 to 22,097
Wood--oak	8,493	19,754
Wood--pine	9,676	22,506
Wrapping paper	7,106	16,770

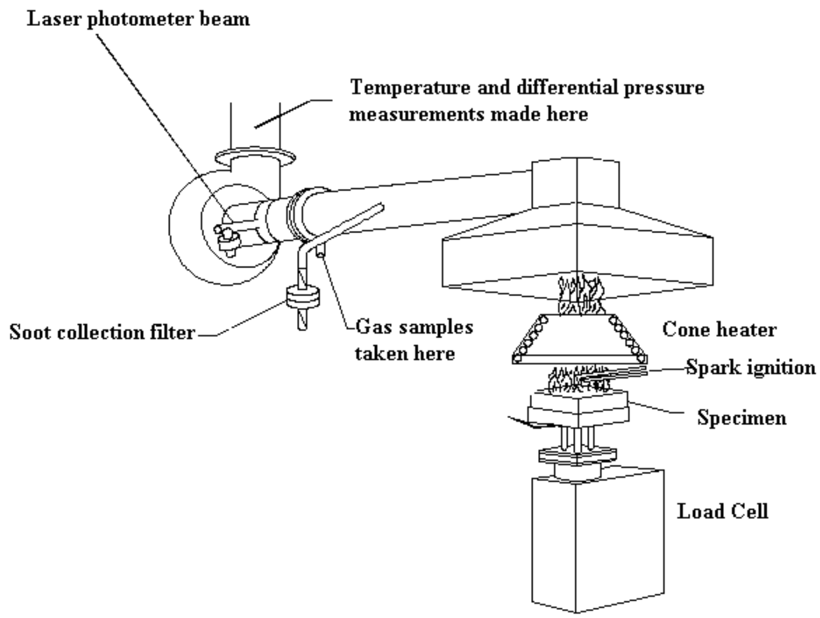
Note: SI values are converted to kilojoules. One kilojoule equals 1,000 joules.

Figure 2-8
Energy Potential (Heat of Combustion): Common Combustibles

Cone Calorimeter

Heat of combustion values come from controlled experiments with a laboratory device known as a cone calorimeter. The calorimeter measures the oxygen consumed during a fire to establish the heat of combustion. The test procedures also presume 100 percent fuel consumption. While total fuel consumption in the built environment may be feasible for flammable gases or liquids, it is uncommon for solid fuels. Also, remember the fuel samples are controlled for moisture, density, weight, and purity, which seldom, if ever, occurs outside the laboratory.

Figure 2-9 represents a typical cone calorimeter test apparatus.



(Image courtesy of National Institute of Standards and Technology, Building and Fire Research Laboratory.)

Figure 2-9
Cone Calorimeter Test Apparatus

Heat Release Rate or Rate of Heat Release

The rate at which a fuel burns and releases its energy is known as the heat release rate (HRR). Some fire protection texts refer to this as the Rate of Heat Release (RHR). The HRR is determined by multiplying the mass loss rate (mass/time) by the heat of combustion (energy/mass) and the combustion efficiency (the portion of the mass actually converted to energy).

The HRR is a relative measure of a fire's "ferocity." HRR is influenced by the fuel's physical form and its chemical composition, also known as "fuel chemistry." HRR is quantified using the kilowatt (kW).

Remember, HRR is not the same as heat of combustion since HRR describes release over a specific time period. For example, while a lumber yard fire may appear spectacular with leaping flames and lots of radiant heat, the HRR from a fire in shredded wastepaper like that found at a recycling center is much greater.

A fire that is increasing in energy output is classified as a "growing fire" and the HRR may increase over time. Normally, this type of fire will be fuel controlled. When the HRR becomes relatively constant over time, with neither a rapid increase nor decrease, the fire is considered to be in a "steady state."

Figure 2-10 graphically depicts a fire transitioning from a "growing state" to "steady state."

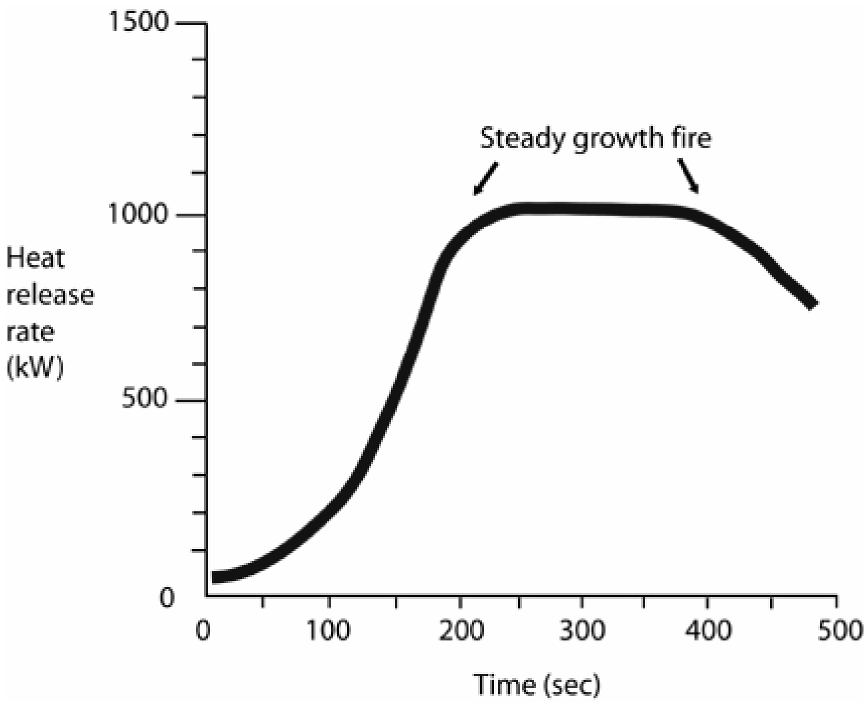
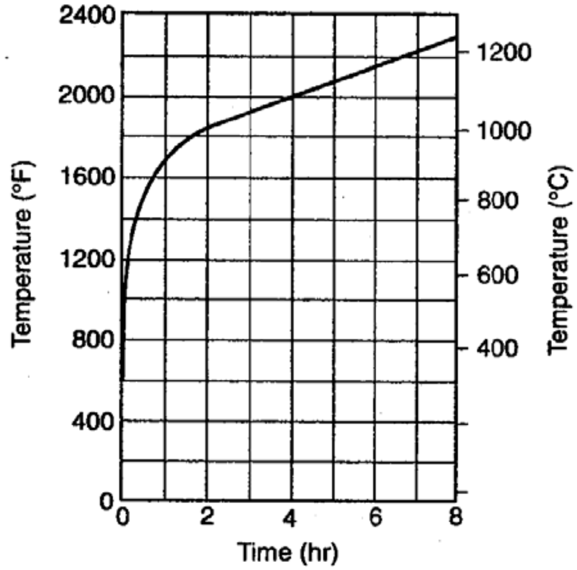


Figure 2-10
Graph of a Growing and Steady State Fire

Steady state fires are the basis for the Standard-Time Temperature Curve (STTC) used for evaluating the fire-resistance performance of common building materials. The STTC was adopted by the American Society of Testing and Materials (ASTM) in 1918, and is the basis for several fire test standards.



Note: The following are the points that determine the curve.

1000°F (538°C)............................at 5 minutes
1300°F (704°C)..........................at 10 minutes
1550°F (843°C)..........................at 30 minutes
1700°F (927°C)..................................at 1 hour
1850°F (1010°C)..............................at 2 hours
2000°F (1093°C)..............................at 4 hours
2300°F (1260°C)..............................at 8 hours or over

Source: NFPA 251, *Standard Methods of Tests of Fire Resistance of Building Construction and Materials, 2007 Edition.*

Figure 2-11
Standard Time/Temperature Curve

The Standard Time/Temperature Curve

It is important for the code official to understand the STTC's significance. Though dated and of questionable validity in today's built environment, it remains the primary method for evaluating building construction fire-resistance ratings.

The selection of building materials and the design of construction details play an important role in building fire safety. Two considerations are

- structural frame to avoid collapse; and
- ability of barriers to prevent ignition and flame spread to adjacent spaces.

Structural collapse potential and fire endurance of beams, girders, and columns that comprise the structure's frame were determined by the American Society for Testing and Materials (ASTM) in 1907 using the Standard Time/Temperature Curve, by fire-resistance tests established in 1918 by the NFPA, and by fire-resistance ratings which are commonly referred to as:

- 15 minutes;
- 30 minutes;
- 45 minutes;
- 1 hour;
- 1-1/2 hours;
- 2 hours;
- 3 hours; and
- 4 hours.

Combinations of building materials are put together into an "assembly" and tested in a laboratory to establish fire-resistance ratings. A mockup wall constructed of No. 25 gage carbon sheet steel studs spaced 16 inches apart and covered **on both sides** with a layer of 5/8-inch Type X gypsum wallboard properly attached and having taped joints is just one example of an "assembly."

This assembly is installed in a test furnace and subjected to increasing heat using the Standard Time/Temperature Curve. A 1-hour rating indicates that the assembly survived the standard test for 1 hour or longer, 2-hour rating indicates the assembly withstood a 2 hour or longer test without failure of a critical element. Acceptance criteria are specific and **may** include

- failure to support load;
- temperature increase on the unexposed surface (the side opposite the heat source) 250 °F (121.1 °C) above ambient;
- passage of heat or flame sufficient to ignite cotton waste;
- excess temperature on steel members; and/or
- failure under hose stream applications (walls and partitions).

It is also important to note there is no guarantee that an assembly given a particular fire-resistance rating in the lab will perform the same way in the built environment because of differences in quality of materials, construction, maintenance, fuel, and ventilation, etc. Fire-resistance rating should be looked at as comparisons, a 3-hour assembly likely will survive longer than a 2-hour, a 2-hour longer than a 1-hour, and so on.

T^2 Fires

Fires also can be defined by the time it takes to reach a given HRR. While we base current fire protection decisions on a test procedure almost a century old, current research shows that most fires grow exponentially, that is, the HRR increases to the square of the burning time. These fires are referred to commonly as "T squared fires." The HRR of the growth phase can be expressed as:

$\bar{Q} = \alpha t^2$
α = fire growth constant usually expressed in kJ/sec $^{(n-1)}$
t = time after ignition beginning with open flaming, normally expressed in seconds

By comparing the T^2 fires to the Standard Time/Temperature Curve, it is evident more research needs to be accomplished to assess the performance of fire-resistive construction when exposed to the fuel arrays more commonly seen today.

Heat Release Rate for Different Types of Fuel

Research also has established fire growth constants (α) for four standardized T^2 fires as follows:

Category	Fire Growth Constant kJ/sec $^{(n-1)}$	Time to Reach 1 mW Heat Release Rate
Ultrafast	α = 0.1876 kJ/sec$^{(n-1)}$	75 sec. or 1.25 min.
Fast	α = 0.0469 kJ/sec$^{(n-1)}$	150 sec. or 2.5 min.
Medium	α = 0.01172 kJ/sec$^{(n-1)}$	300 sec. or 5 min.
Slow	α = 0.00293 kJ/sec$^{(n-1)}$	600 sec. or 10 min.

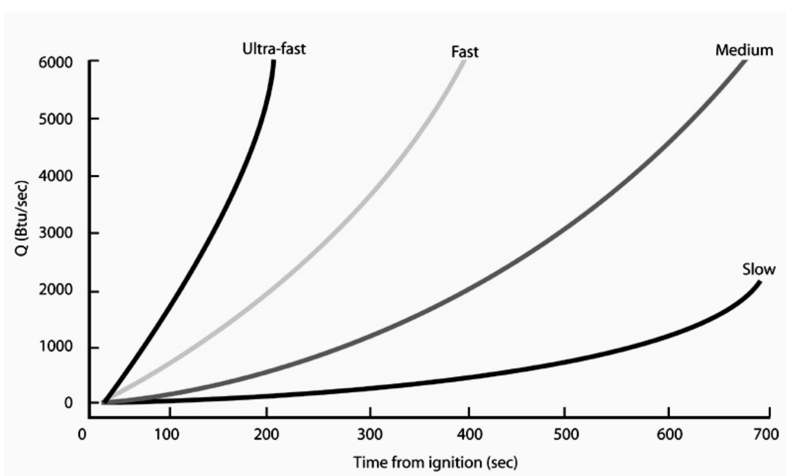


Figure 2-12
Fire Growth Rates for T^2 Fires (Btu/sec)

Examples of these fires shown in Figure 2-12 are as follows.

Category	Fuel Array
Ultrafast	Thin plywood wardrobe cabinet, upholstered furniture
Fast	5-ft. high stack of empty wood pallets, 15 ft. high stack of cartons of various contents
Medium	3-ft. high pallet stack of full mailbags, cotton/polyester innerspring mattress
Slow	Solid wood cabinetry, wood table, bedroom dresser

Figure 2-13
T^2 Fire Fuel Arrays

Other examples can be found in NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*.

Figure 2-14 shows the heat release rate for a sofa.

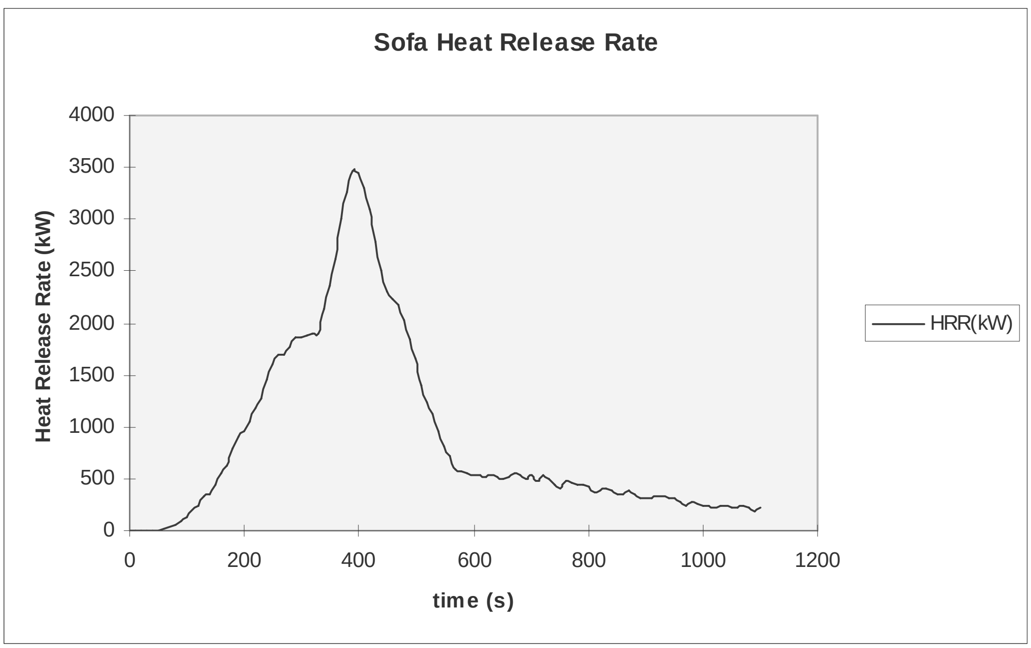


Figure 2-14
Heat Release Rate for a Sofa

These "standardized" fires should be interpreted with caution. In certain circumstances or conditions, the use of this data would be inappropriate, such as where flammable liquid pool fires are anticipated or for occupancies such as warehouses or "big box stores."

There still is a lot of research to be done in this field. The complex interrelationships of fuel, ventilation and geometry mean every fire will be different.

While it is important to study a materials' HRR, another term occurs in fire studies: **peak** heat release rate. This is the point in the fire where the burning material is releasing its maximum heat output. For example, a fire in a pile of waste paper releases a relatively small amount of heat until optimum fuel--oxygen ratios are reached causing the fire to burn its hottest.

Figure 2-15 provides a list of common materials and their **peak** HRRs under laboratory conditions.

Item	Weight (lbs)	Peak HRR (Btu/sec)	Peak HRR (kW)
Burning cigarette		0.004739	0.005
Burning match		0.75828	0.08
Small trash can fire	1.5 to 3	47.355 to 284.13	50 to 300
Trash bags, 11 gallon with mixed plastic and paper trash	2.5 to 7.5	132.7 to 331.7	140 to 350
Cotton mattress	26 to 29	37.9 to 919.4	40 to 970
Televisions sets	69 to 72	113.7 to 274.8	120 to 290
Plastic trash bags with paper trash	2.6 to 1	113.7 to 331.7	120 to 350
PVC waiting room chair, metal frame	34	255.9	270
Cotton easy chair	39 to 70	274.8 to 350.7	290 to 370
Gasoline/Kerosene in 2 ft^2 pool		379.1	400
Christmas trees, dry	14 to 16	473.9 to 616.1	500 to 650
Polyurethane mattress	7 to 31	767.7 to 2492.8	810 to 2630
Polyurethane easy chair	27 to 61	1279.6 to 1886.2	1350 to 1990
Burning upholstered chair		75.68 to 2369.6	80 to 2500
Polyurethane sofa		2957.3	3120
Burning Christmas tree	12 to 14	1516.5 to 4928.8	1600 to 5200
Base Design Fire*		4995.7	5275

Source: NFPA 921, *Guide for Fire and Explosion Investigations.*

* Minimum HRR design fire for smoke management system design required of the International Building Code (IBC).

Figure 2-15
Sample Peak Heat Release Rates

Ventilation

Atmospheric Oxygen

The third leg of the fire triangle is oxygen. When combined with adequate fuel and a viable ignition source, the introduction of oxygen enables combustion to occur.

In the typical fire, the oxygen source is atmospheric air. The air we breathe consists of about 18-percent oxygen, 72-percent nitrogen, and trace amounts of other gases. The oxygen in air combines readily with fuels to sustain combustion. As long as the oxygen concentration remains above 14 to 15 percent, free burning combustion can occur. As the amount of oxygen decreases, the quality of combustion decreases with greater production of toxic gases (especially carbon monoxide), soot particles, and smoke.

As the environment in an enclosure deteriorates due to consumption of the available oxygen, dangerous backdraft conditions can develop. A backdraft may occur when oxygen is introduced into a heated, confined space that is oxygen-deficient. The in-rush of oxygen enables the heated combustibles to ignite nearly simultaneously with almost explosive results. In fact, some fire suppression personnel use the term "smoke explosion" to describe a backdraft. During fire operations, firefighters work hard to open windows, doors, and other barriers to relieve smoke buildup before it reaches backdraft conditions.

Generally, in the early stages of fire development, the behavior of the fire is "fuel controlled," that is, there is a sufficient, if not excess, amount of air but a limited fuel supply. In a compartment with little or no ventilation, the fire will continue to grow and may reach a point where the amount of fuel vapors being produced exceeds the amount that can be consumed with the available air or oxygen. A fire that is controlled or limited by the amount of available air or oxygen is "ventilation controlled."

Oxidizing Agents

In some circumstances, the oxygen portion of the fire triangle may be provided by an "oxidizer," a material that yields oxygen or other oxidizing gas, or that reacts to promote or initiate combustion of combustible materials. These materials support combustion in the absence of atmospheric oxygen. A list of oxidizers may include organic (with molecular carbon) or inorganic chemicals.

These materials have excess oxygen which may be liberated, especially at higher temperatures. This capacity to provide oxygen makes these chemicals a fire and explosion hazard when they come in contact with all forms of combustibles (wood, paper, textiles, plastics, etc.). In addition, mixtures of oxidizers and combustibles can be ignited by a heat energy originating from a weak ignition source such as friction, physical impact, or static electricity. Some of these compounds are capable of reacting with combustibles at room temperature with the result of a fire and/or explosion. Figure 2-16 provides the classifications and a description of the potential hazards.

Class Rating	Hazard Description
Class 1	An oxidizing material whose primary hazard is that it may increase the burning rate of combustible material with which it comes in contact.
Class 2	An oxidizing material that will moderately increase the burning rate or which may cause spontaneous ignition of combustible material with which it comes in contact.
Class 3	An oxidizing material that will cause a severe increase in the burning rate of combustible material with which it comes in contact or which will undergo vigorous self-sustained decomposition when catalyzed or exposed to heat.
Class 4	An oxidizing material that can undergo an **explosive reaction** when catalyzed or exposed to heat, shock, or friction.

Figure 2-16
Oxidizer Hazard Classes

Other materials without oxygen in their chemical formula may be classified as oxidizers. To be defined as an oxidizer, the chemical substance simply must be capable of accepting electrons. Chemicals in the class of compounds known as the halogens materials that can act as halogenating agents fall into this category. Examples include fluorine and chlorine in the gaseous state, and bromine in the liquid state. Figure 2-17 provides a sample of some oxidizing chemicals by hazard class.

Hazard Class	Sample Oxidizers
Class 1	Aluminum nitrate, potassium dichromate, ammonium persulfate, potassium nitrate, barium chlorate, potassium persulfate, barium nitrate, silver nitrate, barium peroxide, sodium carbonate peroxide, calcium chlorate, sodium dichloro-s-triazinetrione, calcium nitrate, sodium dichromate, calcium peroxide, sodium nitrate, cupric nitrate, sodium nitrite, hydrogen peroxide (8 to 27.5%), sodium perborate, lead nitrate, sodium perborate tetrahydrate, lithium hypochlorite, sodium perchlorate monohydrate, lithium peroxide, sodium persulfate, magnesium nitrate, strontium chlorate, magnesium perchlorate, strontium nitrate, magnesium peroxide, strontium peroxide, nickel nitrate, zinc chlorate, nitric acid (<70% conc.), zinc peroxide, perchloric acid (<60% conc.)
Class 2	Calcium hypochlorite (<50% wgt.), potassium permanganate, chromium trioxide (chromic acid), sodium chlorite (<40% wgt.), halane, sodium peroxide, hydrogen peroxide (27.5 to 52% conc.), sodium permanganate, nitric acid (>70% conc.), trichloro-s-triazinetrione
Class 3	Ammonium dichromate, potassium chlorate, hydrogen peroxide (52 to 91% conc.), potassium dichloroisocyanurate calcium hypochlorite (>50% wgt.), sodium chlorate, perchloric acid (60 to 72.5% conc.), sodium chlorite (>40% wgt.), potassium bromate, sodium dichloro-s-triazinetrione
Class 4	Ammonium perchlorate, ammonium permanganate, guanidine nitrate, hydrogen peroxide (>91% conc.), perchloric acid (>72.5%), potassium superoxide

Source: NFPA 325, *Guide to Fire Hazard Properties of Flammable Liquids, Gases and Volatile Solids.*

Figure 2-17
Sample Oxidizers

Fire Development

Traditional Fire Stages

Traditionally, fires have been categorized in three basic stages: incipient, free burning, and smoldering. Incipient stage is when there is no active or open flaming. In this stage, glowing or smoldering combustion may be present for a considerable period of time. In the free burning stage, open flaming is present, with increased fuel consumption and heat production. The last stage, smoldering, occurs when the oxygen level decreases below 14 to 15 percent. If an additional oxygen supply is introduced, the fire may return to the free burning stage. These descriptions, while helpful in certain circumstances, are not definitive enough for use in performance-based design.

Fire Realms

Some fire protection texts have established different realms of the fire process. These realms are shown in the chart in Figure 2-18 and graphically in Figure 2-19.

Realm	Approximate Range of Fire Sizes	Major Factors That Influence Growth
1. Preburning/ Precombustion	Overheat to ignition	• Amount and duration of heat flux • Surface area receiving heat from material ignitability • Pyrolyzation rate
2. Initial burning	Ignition to radiation point 10" (254 mm) high flame	• Fuel continuity • Material ignitability • Thickness • Surface roughness • Thermal inertia of fuel • Pyrolyzation rate
3. Vigorous burning	Radiation point to enclosure point 10" (254 mm) to 5' (1.5 m) flame	• Interior finish • Fuel continuity • Feedback • Material ignitability • Thermal inertia of the fuel • Proximity of flames to surfaces
4. Interactive burning	Enclosure point to ceiling point 5' (1.5 m) to flame touching ceiling	• Interior finish • Fuel arrangement • Feedback • Height of fuels • Proximity of flames to walls • Ceiling height • Room insulation • Size and location of openings • Heating, Ventilating, and Air Conditioning (HVAC) operation
5. Remote burning	Ceiling point to full room involvement Flame touching ceiling to flashover	• Fuel arrangement (amount and location) • Ceiling height • Length/Width ratio • Room insulation • Size and location of openings • HVAC
6. Full room involvement	Ceiling point to full room involvement Flame touching ceiling to flashover	• Fuel arrangement (amount and location) • Ceiling height • Length/Width ratio • Room insulation • Size and location of openings • HVAC • Fire protection and control features

Figure 2-18
Realms of the Fire Process

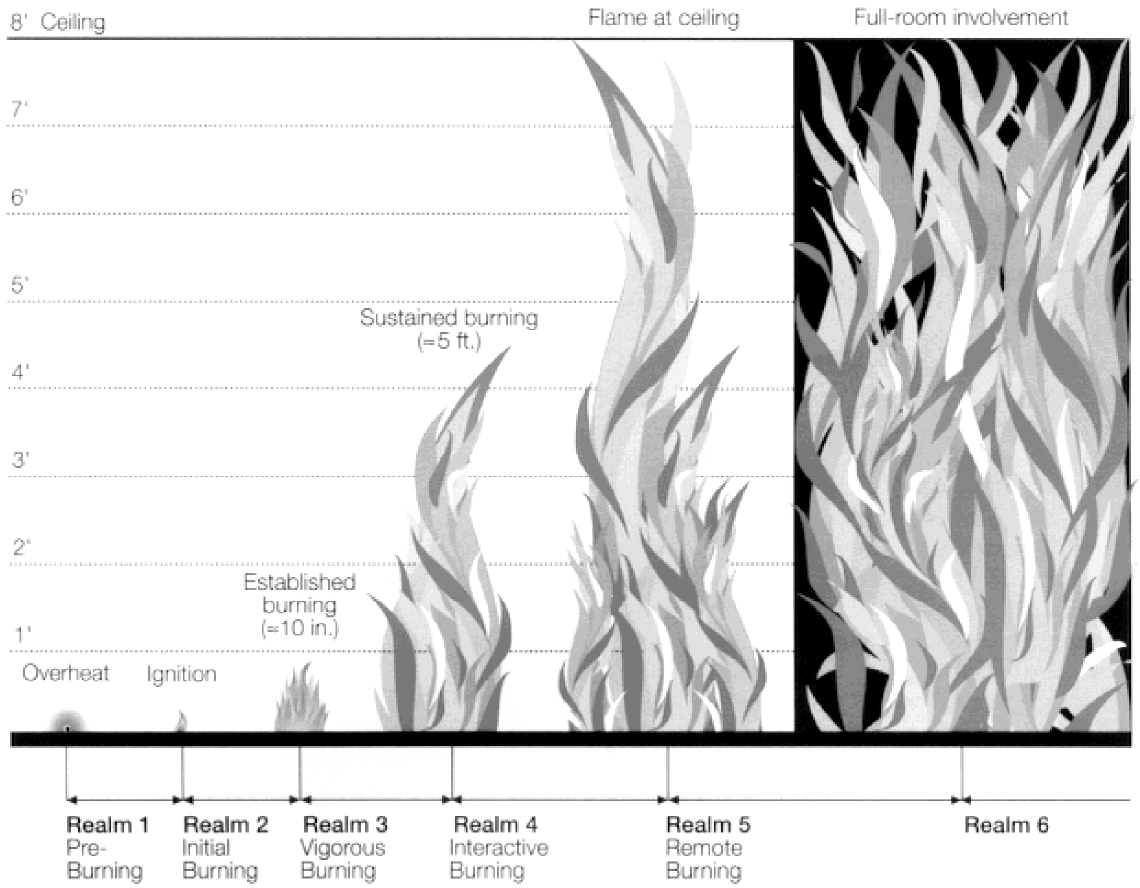


Figure 2-19
Graphic Depiction of the Fire Realms

Initial fire behavior within a compartment often will determine the extent of fire spread within and beyond the compartment of origin. While the fire prevention goals of preventing ignition from ever occurring are laudable, in code enforcement we must assume that an unwanted ignition will occur at some time. When a fire has reached a point where the size of the flame is sufficient to allow for continued flaming combustion without any additional, independent heat source, it is considered to be "established burning." The flame height during this phase is often considered to be at 10 inches (250 mm) from the fuel surface.

Fire Plumes

Directly above the fire, a column of hot gases and combustion products rises upward. This column is known as a "plume." As the hot gases rise, cooler air is drawn in or entrained into the plume; this is known as "entrainment." This cooler air is drawn from around the base of the fire and the boundaries between the plume and the surrounding air. (Remember Faraday's candle description.) The temperature of the plume decreases with the height above the fire, due to cooling effects of the entrained air.

As long as the environment around the fire plume is relatively stable and not influenced significantly by ventilation, the fire plume will rise in the shape of a cone. (When this pattern remains on a vertical surface after a fire, investigators often describe it as a V-pattern.) If doors or windows are opened, or a smoke management system operates, the path of the fire plume may vary dramatically. Likewise, if the fuel array within the space is irregular, the fire plume may follow it.

Once the plume temperature equals the surrounding air temperature, fire gases and smoke stop rising because they lose their buoyancy. Buoyancy is upward force due to the molecular activity of the heated gases near the fire plume. When this equalization occurs, the smoke begins to spread out horizontally, or stratify. In a tall compartment, such as an atrium or covered stadium, or with low energy fires, this loss of buoyancy may result in delayed activation of automatic fire detection devices, automatic fire sprinklers, rooftop smoke vents or smoke management systems. Prescriptive building codes for a long time have required horizontal separations to prevent vertical air currents from carrying heat and toxic gases throughout the upper stories of a building. Normally, except for atrium designs, the model prescriptive building codes prohibit more than two adjacent floors from sharing a common atmosphere. Furthermore, in some tall, one-story buildings, like warehouses, fire-resistive construction may be omitted at the ceiling because there may not be enough thermal energy to threaten the structure at the high elevations.

In day-to-day conditions, often we observe indoor air movement patterns that are influenced by the exterior weather conditions. The "stack effect" is the natural, vertical air movement in buildings caused by temperature differences and densities between indoor and outdoor air. Like fire plumes, when the buoyancy of the natural air currents diminish, the stack effect may cause normal air pollutants in the ambient environment to spread horizontally.

Ceiling Jets

When the flames reach a ceiling or other horizontal barrier, the smoke and combustion products will spread laterally from the plume centerline. If the ceiling is smooth and flat, the flow generally is equal in all directions. The movement of the smoke and combustion products across the ceiling is known as the "ceiling jet." Plumes and ceiling jets are the mechanisms by which the hot gases and combustion products reach automatic fire detection devices and sprinklers.

Obstructed construction (such as beam pockets, waffle-slab construction, or deep joists), sloped or arched ceilings, irregular shapes, and finish materials affect the speed and direction of ceiling jets.

Figure 2-20 illustrates a fire plume and ceiling jet.

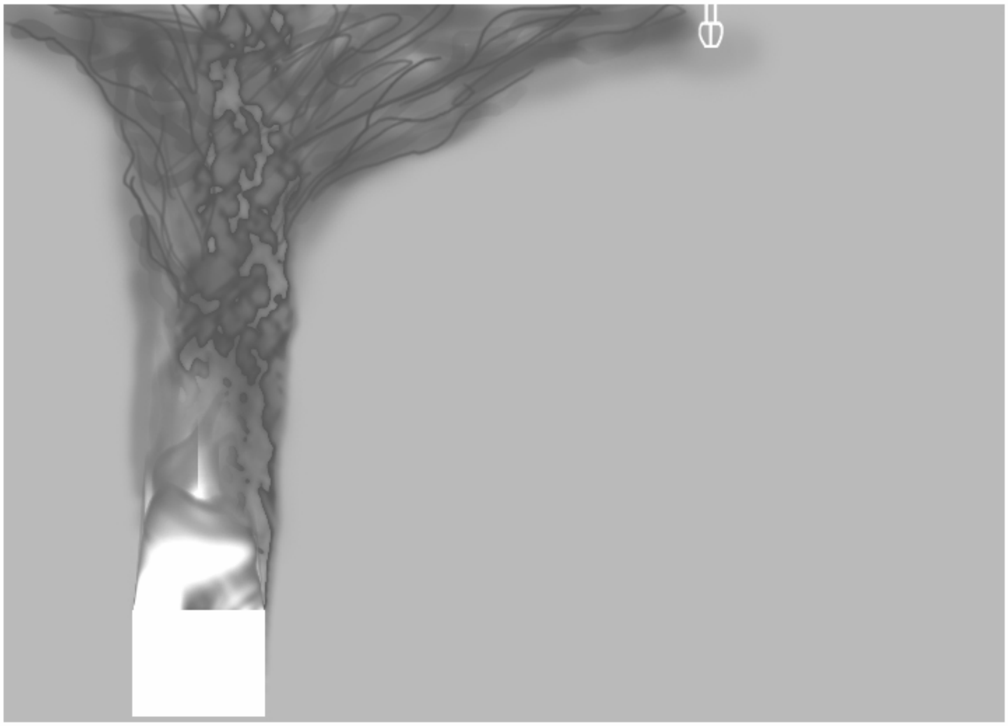


Figure 2-20
A Fire Plume and a Ceiling Jet

Flashover

As the fire in a compartment progresses, hot gases and combustion products rise, flames reach the ceiling, spread out (the ceiling jet), and begin to fill the upper portions of the room forming what is known commonly as the "upper layer." The upper layer is sometimes also referred to as the smoke layer or hot gas layer. As the fire continues, the upper layer thickens and will flow out into adjoining compartments through any openings. As the fire intensifies (increased HRR), the upper layer will descend closer to the floor. This results in what is known as "radiation feedback": the condition of electromagnetic waves reflected from one heated surface to another. In this case, the opaque surface of the upper layer is an excellent reflector to radiate the heat back toward the floor. The temperature in the upper layer also will increase, resulting in greater radiant heat levels on other objects in the compartment.

If sufficient radiant heat is projected on the other objects in the room, flashover will occur. Flashover is the transition phase in the development of a fire: the combustible surfaces exposed to thermal radiation reach ignition temperature nearly simultaneously and fire spreads rapidly throughout the space. Under flashover conditions, the fire is dominated by the burning of all items in the compartment. It is the final realm of a growing fire.

Flashover generally occurs when the upper layer temperature reaches approximately 1,100 °F (600 °C) and the radiant flux (heat flow) from the upper layer reaches approximately 20 kW/m^2 (0.00176 $Btu/ft^2/sec$). It has been shown that if the flame can be prevented from reaching the ceiling, the possibility of flashover occurring is reduced. Once flashover occurs, excess fuel vapors that cannot be consumed or combusted with the air available in the compartment will be produced and the fire will become ventilation controlled.

A ventilation-controlled fire may result in flame extension through vent openings into adjacent compartments and/or windows, if they fail or are open. Flashover will not occur in every fire scenario. If the fuel is limited or ventilation is insufficient, the ceiling layer may not develop sufficiently to make the transition to flashover.

Flameover or Rollover

It is possible for flameover to occur prior to flashover. Flameover is the condition where the underburned smoke and gases accumulated in the ceiling layer ignite. It is possible for flameover to occur without flashover. This condition also is known as "rollover."

Fully Developed Fire

A fully developed fire is a steady or post-flashover fire at peak HRR. Its peak burning will last for a short or extended time, depending on available fuel and oxygen. Some fully developed fires occur with total involvement of the fire enclosure, often leading to spread to other enclosures if adequate fuel and oxygen exist and there is no compartmentalization or active fire protection to slow or suppress the fire.

HEAT TRANSFER: HOW FIRES SPREAD IN THE ENVIRONMENT

In the environment, warm objects release their heat energy to cooler objects until a thermal balance is achieved. This balance is called "homeostasis." As heat is applied to a fuel in the early phases of combustion, some of the heat is absorbed or conducted into the interior of the material by molecular action. Conductivity is the ability of material to conduct heat, and materials with a higher density have a tendency to be more efficient heat conductors. Some construction materials--especially unprotected steel or metal products--are excellent heat conductors.

A material's conductivity can be demonstrated by the following examples:

- Grasp an empty expanded plastic foam coffee cup. Notice that your hand feels warmer. This is because your body heat, which previously had been lost to the atmosphere, now is retained by the insulation effect of the cup and sensed by the nerves in your skin.

- To compare, place your hand on a dense wooden surface like a tabletop. Notice that your hand feels cooler than before. This is because some of the heat from your hand is being absorbed into the table surface that generally is denser that the expanded foam cup.

Denser materials require more molecular energy to raise their temperature. The surface of such a material will heat slower and therefore delay ignition. Many building materials used in fire resistive construction (i.e., gypsum, concrete masonry units, monolithic concrete, spray-on fire proofing) are effective because of their high heat resistant values.

Heat Transfer Methods

A major factor affecting fire behavior is heat transfer. This affects ignition, growth, spread, decay, and extinction. Building and fire code requirements often are predicated on the goal of minimizing the influence of heat transfer. The three mechanisms of heat transfer are conduction, convection, and radiation.

Conduction

Conduction is the form of heat transfer that takes place within or between solids when one portion of an object is heated. For example, if you place your hand on your desk it will feel cold because you are transferring heat from your hand to the desk. Energy is transferred from the heated area to the unheated area. If the thermal conductivity of the material is high, the rate of heat transfer will be high.

In the built environment, the use of steel for construction materials is very common. Steel has a high thermal conductivity and, when heated, may ignite objects far from where the initial fire started.

Convection

Convection is the transfer of heat energy by the movement of heated liquids or gases from the source of heat to a cooler part of the environment. For example, if you place your hand above a lighted candle, you will receive heat by convection.

Convection plays a major role in the spread of smoke and fire gases to the upper portions of the room of origin and throughout a building. Building codes do a lot to prevent or mitigate the impact of convective heat spread: stair enclosures, shaft protection, horizontal floor/ceiling assemblies, even roof-top smoke and heat vents are important code tools used to control vertical heat transfer.

Radiation

Radiation is the transfer of heat energy from a hot surface to a cooler surface by electromagnetic waves without an intervening medium. For example, if you put a lighted candle into a holder and hold your hands on either side of it, your hands will be heated by radiation. Radiant energy is transferred only by line of sight and will be reduced or blocked by intervening opaque materials.

Building codes addressed radiant heat risks in one of two ways: increasing the distance between buildings or increasing the fire-resistive construction requirements of exterior walls.

Measuring Heat Transfer

Heat Flux

Heat flux is simply the measurement of the amount of heat that is transferred to a surface or target fuel. Heat flux is expressed as the heat flow rate per unit area and is measured in Btu/ft^2/sec or kW/m^2. Heat flux measurement is important when evaluating the likelihood that a fire will migrate through a structure. It also is used in the Radiant Panel Test (see below) to evaluate the combustibility of floor covering products.

Figure 2-21 provides samples of representative heat fluxes.

Heat Flux Radiated From	Btu/ft^2/sec	kW/m^2
Human body on hot summer day (98 °F, 37 °C)	0	0
Interior through insulated wall (R19) on cold winter day (14 °F, -10 °C)	0.0008	0.009
Human body on cold winter day	0.22	0.025
Sun, on a clear day in the tropics	0.12	1.4
100-watt incandescent bulb at 3.9 inches (10 cm)	0.56	6.4
Source that burns human skin in 10 seconds	0.88	10
Source that burns human skin in 1 second	4.41	50
Propane torch at flame tip	8.81	100
Oxy-acetylene torch at flame tip	88	1,000
Surface of the sun (radiation only)	5,727	65,000

Source: Vatell Corporation.

Figure 2-21
Heat Flux Values for Common Conditions

Figure 2-22 provides samples of the minimum heat flux required to ignite these products.

Material	$Btu/ft^2/sec$	kW/m^2
Phenolic foams, rigid	0.616	7
Red oak	0.968	11
Polyethylene, rigid	1.672	19
Polyethylene, foam	1.672 to 1.936	19 to 22
Polypropylene	1.76	20
Polystyrene, foams or rigid	1.584 to 2.376	18 to 27
Polyvinyl chloride	1.848	21

Source: NFPA *Fire Protection Handbook, 18th edition.*

Figure 2-22
Minimum Heat Flux for Ignition

Fuel Geometry or Location

The geometry or location of the fuels also can affect overall fire behavior. Large volume compartments or compartments with high ceilings allow dilution of fire gases and provide a "reservoir" for smoke. A fuel package that is located in a corner will result in faster fire growth than one located against a flat wall or out in the compartment. The number and configuration of compartment walls also can affect overall fire behavior. These factors will influence heat transfer and thus affect overall fire behavior. In some building designs, this "reservoir" concept may be an effective method to consider for managing smoke migration throughout a structure.

Fuel geometry (the placement of fuel in the structure) also is important. Fuels that already are in a liquid or gaseous state are more hazardous than solid fuels because they are ignited more easily and may respond to environmental conditions such as wind or gravity; but even the configuration of solid fuels is important.

Due to radiation feedback, a fire that originates in a small or confined space typically will grow faster than one that originates in the center of a large room. Certain construction materials, such as concrete or masonry floors, walls and ceilings, are noncombustible and will act as heat "sinks," absorbing heat energy. Combustible materials that usually will ignite include paneling, wallboard, ceiling tiles, wood framing, manufactured wood and oriented strand board (OSB). The presence of heat sinks and combustible surfaces affects the rate at which a building contents fire becomes a structure fire, and the likelihood it will spread beyond the room of origin.

Fuel placement of such as furniture, storage, and finishes within a building influences the development of a fire. How fuel burns depends on ventilation, surface area, and radiation feedback between the combustible materials and the room, walls and ceiling surfaces. Some of the most dramatic examples of the impact of fuel placement come from applied research performed by FM Global Research (formerly Factory Mutual Research). Their warehouse fire protection study videos clearly show how materials stored on closely arrayed racks or pallets burn more ferociously than similar products separated by wide aisles and stored less than 12 feet (4.2 m) above the floor.

The size of the fuel also influences the fire development; as does the density--the thermal thickness or thinness--of the fuel. For example, a thick board will not burn so quickly as thin paneling; and a flat wall will burn less readily than a corner section (all things being equal, especially finishes).

All of these factors can influence the ignition potential, ventilation, available fuel, surface area, and heat transfer mechanisms during a fire event.

Interior Finish Flammability

Even if a building is constructed of noncombustible materials, human occupants still introduce combustible finishes to soften the environment. Many tragic fires have occurred from easily-ignited or fast-burning interior finishes on walls or ceilings.

Walls and Ceilings

To identify and categorize materials to their relative fire risk, building codes classify interior wall and ceiling materials by flame spread ratings in accordance with Steiner Tunnel Test requirements (ASTM E84 and NFPA 255 standards). Materials are classified to indicate their ability to support combustion and flame, as well as the amount of smoke generated by the burning sample. Finish materials are compared to the fire spread characteristics of red oak to express their relative risk.

Almost all building codes cite ASTM E84 as the basis for their applied standards. This test, widely known as the Steiner Tunnel Test, simulates a fire exposure of about 2400 °F in the area of the flame. In the test, a 36 sq. ft. (3.34 m^2) test sample is placed in the top of the Steiner Tunnel, and heated by gas flames for 10 minutes at a rate of about 5,000 Btu/min (88kW). This creates a temperature near the test sample of about 1,600 °F (900 °C).

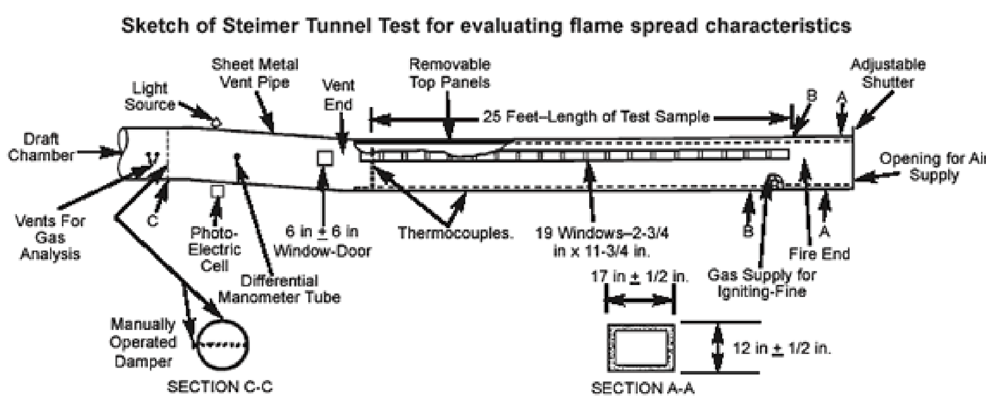


Figure 2-23
Steiner Tunnel Test Apparatus

The time is measured for the flame to travel down the tunnel for the length of the material, or until the flame ceases. That time is then imposed on a dimensionless scale developed by rating cement asbestos board time performance at "0," and the time performance of select grade red oak at "100." These ratings indicate the rate at which fire will spread across the surface of a material. For example, a wall decorated with paper will have a faster flame spread rating than a bare wall.

Figure 2-24 represents the classifications from the Steiner Tunnel Tests. The numbers in the Flame Spread Rating column are derived from mathematical formulas, and are **not** interpreted as feet/sec, inches/min, etc.

Class	Flame Spread Rating	Max. Smoke Development
1 or A	0 to 25	450
2 or B	26 to 75	450
3 or C	76 to 200	450

Figure 2-24
Flame Spread Classifications

Likewise, the maximum smoke development values are derived mathematically from a light absorption per minute relationship. NFPA 255, *Standard Method of Test of Surface Burning Characteristics of Building Materials*, provides a detailed explanation of the Steiner Tunnel Test procedures.

Floor Finishes

Floor surfaces, because of their orientation and radiation feedback from heated upper layers of a fire, respond differently from walls or ceiling finishes. Consequently, they must be tested under different conditions.

Floor covering samples are tested in accordance with ASTM E648 and NFPA 253, *Standard Method of Test for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source*, that measure "critical radiant flux," the amount of energy from an overhead test apparatus that will ignite the floor finish. The test is intended to simulate the conditions from a room flashover.

The building and fire codes establish floor finish "classes" based on the materials' ignition resistance. Class 1 indicates a higher amount of heat is required ($0.45 W/cm^2$). Class 2 indicates a lower amount of heat is required ($0.22 W/cm^2$). From a fire safety perspective, Class 1 is preferable to Class 2.

Fire officials must remember that before approving a product for installation, the test data must represent the conditions in which the material will be used. For example, carpeting that will be installed on a wall must be tested in accordance with the flame spread requirements established in the Steiner Tunnel Test rather than the critical radiant flux procedures.

Structures and Contents

The geometry of structures and contents has a significant effect on the outcome of a fire. Codes recognize this by establishing property line setbacks, minimizing vertical openings, separating or isolating hazardous processes or occupancies, and providing active fire protection to detect, confine, and control a fire.

Building Design Influences

We construct buildings to protect people and possessions from the elements: including rain, snow, sleet, floods, earthquakes, cold, heat, dust, and even outdoor fires. When we erect structures, we create spaces that define boundaries. The walls, floors and roofs of buildings provide an "envelope" in which myriad human activities occur. Unfortunately, one of these activities can be unwanted fires.

Students of fire protection history know how major fires and catastrophes influence changes in building and fire codes (see Unit 1: Fire in America). We anticipate these changes result in better structures that are able to resist these environmental influences. But what about the buildings' interiors? What designs, orientations, architectural statements, or materials influence fire behavior? Not every building shares the same geometric features of slab floor, plumb walls, flat ceilings, or limited openings. The wide variety of spatial designs affect fire plumes, ceiling jets, heat transfer, and smoke migration. These design considerations also include the location of the structure on the site and its proximity to other buildings or fire hazards, e.g., structures, fuel tanks, and the proximity of the fire to walls and corners, all of which also affect fire behavior.

In the prescriptive building codes, passive fire-rated separations (i.e., firewalls and floor/ceiling assemblies) and fire sprinklers systems are required to provide a means to slow a fire for occupant escape, or keep a fire small enough that the fire suppression forces should be capable of controlling it. In performance-based designs, these separations may not be employed when considering the other features that may be provided.

Some of the building design influences that affect fire behavior include

- **Compartment volume**. Small compartments generally will reach flashover conditions faster than large ones because of the reradiative effects of the smoke layer and the proximity to adjacent combustibles.

- **Ceiling height**. All things being equal, it seems obvious that the higher the ceiling is above the fire, the longer it takes for the fire plume to reach it. But what about conditions where the ceiling height is variable in the same compartment? How can fire behavior be predicted consistently in the variable environment?

- **Ceiling configuration**. There are almost unlimited challenges created by heavy timber or concrete waffle-deck construction where deep pockets affect air currents, creating eddy effects in fire plumes and ceiling jets.

- **Ceiling slope**. The design and geometrics of sloped ceilings are limited only by an architect's creativity and an engineer's ability to provide structural support. One must consider the differences in fire plumes and ceiling jets among arched, sloped, clerestory, or dome ceiling designs.

- **Atriums**. A popular design feature used to provide interior spaciousness, atriums penetrate more than two adjacent floors of a building, thus creating a chimney effect for hot smoke and toxic gases. Air flow through and from adjacent tenant spaces may affect air distribution currents. Many atriums are outfitted with sprinklers and smoke management systems that will affect fire behavior.

  In some circumstances, the height of the atrium is significant enough to observe stack effect in the atrium: the condition where heated fire gases lose their upward buoyancy and begin to settle out or travel horizontally.

- **Vertical and horizontal openings**. Prescriptive building and fire codes focus heavily on confining fires both vertically (floor/ceiling assemblies, stair enclosures, shaft construction) and horizontally (fire separations, fire walls) within the limits established by the codes.

  Furthermore, the prescriptive codes pay close attention to those spots where penetrations occur through fire-resistive barriers. Pipes, tubes, cables, and related features that are "punched through" fire-resistive walls and ceilings are a weak spot in the barrier, and must be protected to an equivalent level of fire resistance.

- **Surface finishes**. The interior finish of the space must be evaluated carefully. Material flame spread ratings must be considered, especially if the proposed design incorporates a new material, or an old material applied in a new way.

- **Construction materials**. Different materials may behave differently under similar environmental conditions. A concrete masonry unit (CMU) wall may be constructed as a firewall and provide substantial fire resistance based on its hourly rating. A wood-framed, gypsum wallboard-covered wall may have a similar fire-resistance rating, but once compromised may not survive.

- **Active fire protection**. Sprinklers, water spray, smoke management, and special agent systems all play an important part in fire control. The code official must assure these items are considered when reviewing the potential fire behavior in a structure.

- **Ventilation**. Natural or mechanical ventilation, or both, dramatically affect fire behavior in buildings. How might "normal" air currents change when the HVAC system operates? Or, what will occur when the HVAC system--which may be an integral part of the smoke management system--fails to operate?

Influences of Contents

Building contents may change daily. One day, a structure may have a nominal amount of combustibles in it, and the next, it may be full of highly flammable materials.

Some of the contents influences that the code official must consider when assessing hazards include

- **Fuels**. For years, the fire service has referenced Class A combustibles: those products that leave an ash when they burn. The fire behavior of most Class A combustibles is compared to that of ordinary wood products having a heat of combustion of about 8,000 to 10,000 Btu/lb (18,608 to 23,260 kJ/kg), and usually easily extinguished with adequate quantities of water.

  Now, however, fuels come in a variety of materials: rigid and foamed plastics, flammable and combustible liquids, mixed plastics and ordinary combustibles, animal and vegetable products, metals and wood, plastics and wood, and polymers. Add to this the vast selection of packaging and shipping materials and the fire protection challenge is enormously complicated.

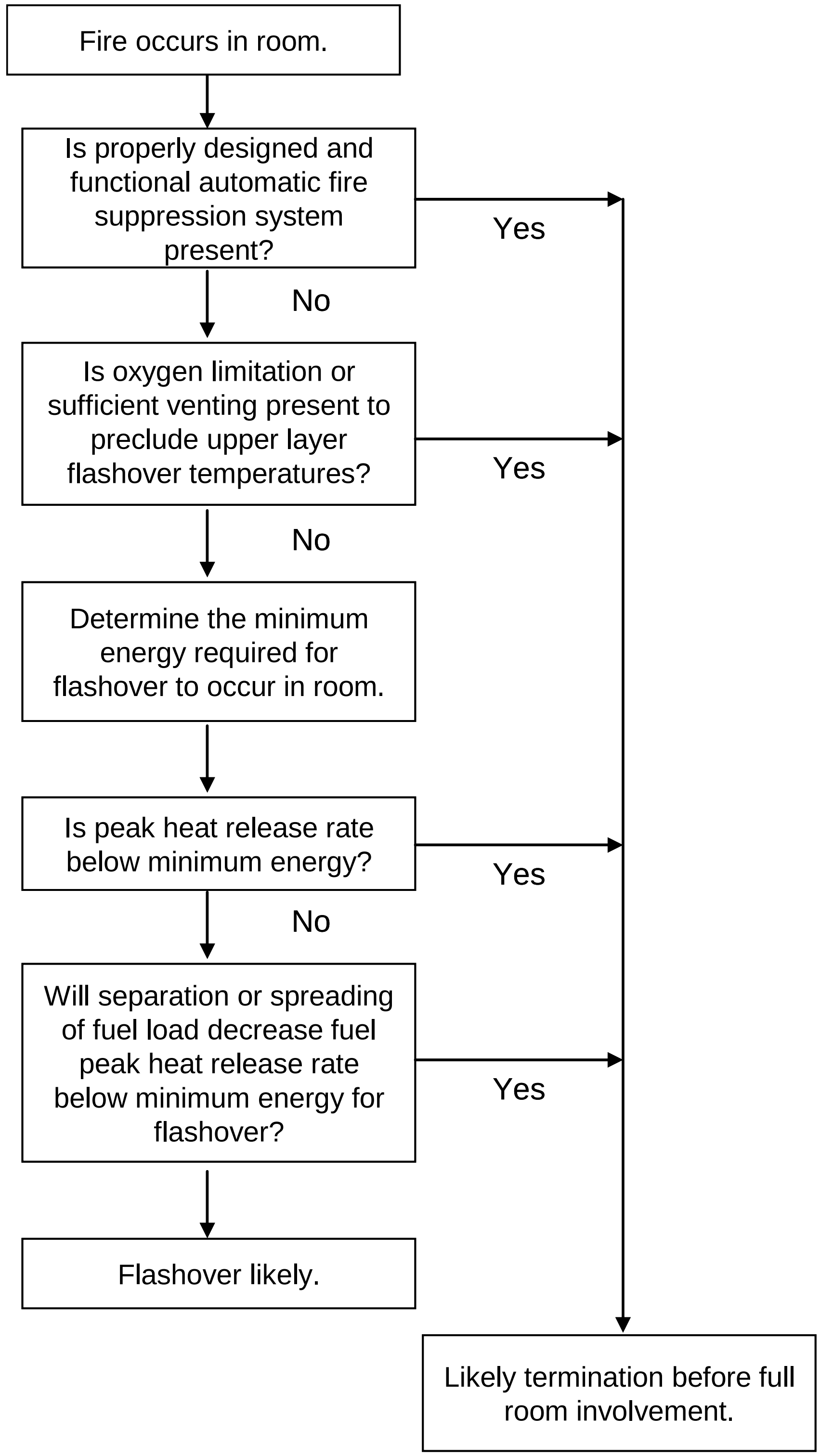
  As an example, under the prescriptive requirements of NFPA 13, *Standard for the Installation of Sprinkler Systems*, in storage occupancies contents are categorized into "commodity classes." The commodity class that is assigned (I to IV, with IV being the most hazardous of the list) establishes fire sprinkler system requirements for discharge density and area of application. Generally, it is most cost effective to install fire protection for the commodity class that most likely will occur in the facility. Thus, if a storage facility operator stores only books in cardboard boxes, the fire protection system likely would be designed to protect a Class III commodity. If the commodity were changed to Class IV, the fire sprinkler system may not be adequate to protect the new risk.

- **Storage arrays**. The location and method of contents and storage in a building also affects the successful outcome of a fire. Ordinarily, wide aisles with lots of space between displayed goods, furniture, or other contents are the best means of preventing fire from spreading from one storage area to another.

  When combustibles are stored on racks, shelves, pallets, or in other configurations, the fire protection challenge increases. FM Global Research has performed years of study on the issues of these so-called "high challenge" fires. The code official must know exactly how materials will be stored or handled in a building to evaluate the adequacy of the performance design.

NFPA 555

NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover*, provides designers and the code official a seven-step flowchart to assess the likelihood that flashover will occur within the room of fire origin. While much of the guide is based on sophisticated scientific principles and measurements, the flowchart focuses decisionmaking into those factors that may affect an incipient fire's outcome.



Source: NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover, 2000 edition.*

Figure 2-25
Flow Chart for Evaluating Potential Room Flashover Toxicity

Fire officials and health care practitioners have known for a long time that despite the public's perception about fires, smoke, and toxic gases really are the predominant killers.

During combustion, fuels may release toxic constituents, or chemical reactions that occur during the fire may create toxic materials. These materials may include gases or particulates, including carbon monoxide, carbon dioxide, hydrogen cyanide, formaldehyde, hydrogen fluoride, soot, nitric oxide, and nitrogen dioxide. Figure 2-26 below provides a list of some toxic materials that result from combustion of various products.

Material	Toxic Gas or Vapor
All combustible materials containing carbon	Carbon dioxide, carbon monoxide
Celluloid	Nitrogen oxides
Leather, plastics containing nitrogen, cellulose materials, cellulosic plastics, and rayon	Hydrogen cyanide
Rubber, thiokols	Acrolein
Fire-retardant plastics, fluorinated plastics	Sulphur dioxide
Melamine, nylon, urea formaldehyde resins	Halogen acids (hydrochloric hydrobromic, hydrofluoric acids, phosgene)
Phenol formaldehyde resin	Ammonia
Phenol formaldehydes, wood nylon, polyester resins	Aldehydes
Polystyrene	Benzene
Foamed plastics	Azo-bis-succino-nitrile
Some fire retardant plastics	Antimony compounds
Polyurethane foams	Isocyanates

Figure 2-26
Toxic Materials as a Result of Combustion

Toxic Fire Gases

Even incomplete combustion causes problems. Carbon monoxide is one of the leading causes of fire deaths because of its affinity for the oxygen-carrying red blood cells in humans. Carbon monoxide quickly attaches to the red blood cells, blocking out their oxygen carrying capacity and creating a potentially lethal condition where oxygen is unable to get to the brain and sustain life. Even if a person is not killed outright, the effects of carbon monoxide poisoning include disorientation and impairment.

Smoke, another constituent of incomplete combustion, reduces visibility and increases occupant anxiety. Increasing smoke conditions may prevent occupants from seeing exits or exit signs. Choking smoke may keep people from leaving to find clearer areas.

The subject of toxicity and smoke is a specialized and highly technical topic that will not be covered here. The important matter for the code official to remember is that any performance-based proposal must address the issues of smoke management, human behavior, and egress.

SUMMARY

While in a perfect world there would be unwanted fires and no need for building and fire codes, we do not live in a perfect world. An understanding of the dynamics of fire behavior will enable the code official and the designer to use building design strategies to control fire development and spread.

Design strategies that promote fire safety include

- limiting or removing sources of ignition;
- separation of fuel and ignition sources; and
- using materials with good fire performance.

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JOB AIDS

Job Aid 2.1
Conversion Table*

Most of the test data or model prediction results that may be generated as part of a performance-based fire safety design will be in International System (SI) units. Therefore it is important for the code official to have an understanding of the units that may be used.

With the exception of the kilogram (kg), the conversions given in the table below are to base units such as a Joule (J) or a Watt (W). In the scope of a fire within a building, these units are small, so the values would be reported as kiloJoules (kJ) or kiloWatts (kW). The kilo prefix means multiply the base unit by 1,000. Another prefix that may be used is **mega**. This prefix means multiply the base unit by 1,000,000.

For additional conversion information, you can go to www.convert-me.com/en

Property	To Convert from	To	Multiply by
Length	Foot (ft)	Meter (m)	0.3048
Mass	Pound (lb)	Kilogram (kg)	0.4536
Area	Square foot (ft^2)	Square meter (m^2)	0.0929
Volume	Cubic foot (ft^3)	Cubic meter (m^3)	0.0283
Energy, work, quantity of heat	British thermal unit (Btu)	Joule (J)	1055.0
	Btu/lb	Joule/Kilogram	2326
Power, heat release rate	British thermal unit per minute (Btu/min)	Watt (W) = J/s	17.573
Heat Flux	British thermal unit per square foot minute (Btu/(ft^2 min))	Watts per square meter (W/m^2)	189.15
Temperature	Celsius (°C)	Fahrenheit (°F)	(1.8 x °C) +32
	Celsius (°C)	Kelvin (K)	(°C) + 273.15

*NIST Special Publication 811, *Guide for the Use of the International System of Units (SI)*. Gaithersburg, MD: National Institute of Standards and Technology, MD, April 1995.

Job Aid 2.2
Sample Peak Heat Release Rates

Item	Weight (lbs)	Peak HRR (Btu)	Peak HRR (kW)
Burning cigarette		0.004739	0.005
Burning match		0.075828	0.08
Small trash can fire	1.5 to 3	47.3 to 284.3	50 to 300
Trash bags, 11 gallon with mixed plastic and paper trash	2.5 to 7.5	132.7 to 331.7	140 to 350
Cotton mattress	26 to 29	37.9 to 919.4	40 to 970
Televisions sets	69 to 72	113.7 to 274.8	120 to 290
Plastic trash bags with paper trash	2.6 to 31	113.7 to 331.7	120-350
PVC waiting room chair, metal frame	34	255.9	270
Cotton easy chair	39 to 70	274.8 to 350.7	290 to 370
Gasoline/Kerosene in 2 ft^2 pool		379.1	400
Christmas trees, dry	14 to 16	473.9 to 616.1	500 to 650
Polyurethane mattress	7 to 31	767.7 to 2492.8	810 to 2630
Polyurethane easy chair	27 to 61	1279.6 to 1886.2	1350 to 1990
Burning upholstered chair		2369.6	2500
Polyurethane sofa		2957.3	3120
Burning Christmas tree		1516.5 to 4928.8	1600 to 5200
Base Design Fire*		5000	5275

* Minimum HRR design fire for smoke management system design required by Section 909.9 of the International Building Code (IBC).

Source: NFPA 921, *Guide for Fire and Explosion Investigations.*