PHOENIX REGIONAL STANDARD OPERATING PROCEDURES	
Policy Name: **FIRE BEHAVIOR GLOSSARY & REFERENCE**	Policy Number: **M.P. 201.01D**
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Related Policies:	
Other Reference:	
Date Implemented: 1/2022-N	Review Date: 1/2028

The purpose of the procedures is to ensure the fundamental knowledge and understanding of fire behavior and fire dynamics. This knowledge is pivotal to professional fire suppression and life safety protection services to our community. It is also a critical element in the safety and longevity of firefighters working to protect our community. Phoenix Firefighters, not only need to know the dangers of fire, but need to truly understand what fire is, how it develops, and how it reacts with our tactics. To carry out our mission of saving lives and property, we must have an in depth understanding of fire behavior and fire dynamics.

This procedure is meant to be a glossary of fire science and fire behavior terms as well as reference tool for fire suppression fundamentals and tactics.

UL-FSRI: *Your Workplace Has Changed: You Need to Evolve*

UL-FSRI: *There is No Substitute for Knowledge*

CHEMISTRY OF FIRE

Fire: The term "fire" refers to how something burns. Fire is a rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities.

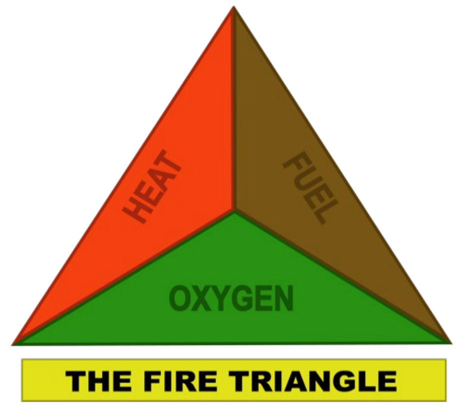
Combustion: Combustion is a chemical process of oxidation that occurs at a rate fast enough to produce heat and *usually* light in the form of either a glow or flame.

Modes of Combustion: Fire and combustion are similar conditions; however, combustion can occur without fire.
There are two modes of combustion, non-flaming and flaming.

Non-Flaming Combustion: Non-flaming combustion occurs more slowly and at a lower temperature producing a smoldering glow in the material's surface without flames.

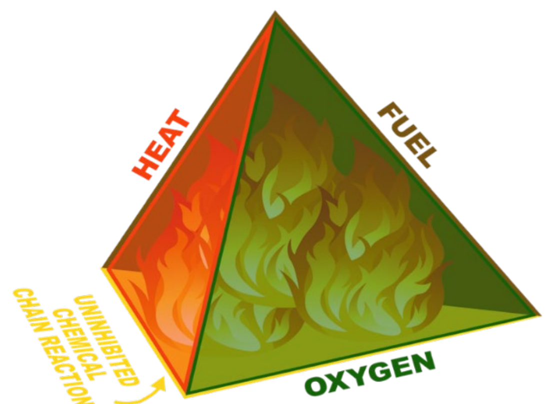
Flaming Combustion: Flaming combustion is commonly referred to as fire because it produces a visible flame above the material's surface.

Fire Models: Two models, the fire triangle and fire tetrahedron are used to explain the elements of fire and how fires can be extinguished.



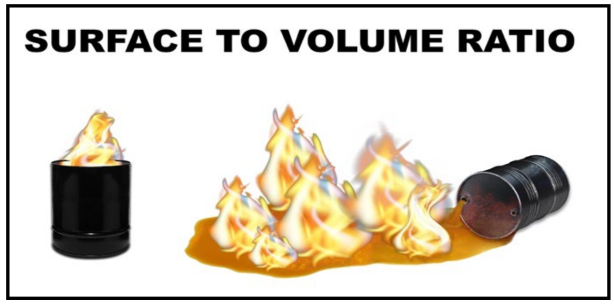
Fire Triangle: The oldest and simplest model, the fire triangle, illustrates the three elements necessary for combustion to occur: fuel, oxygen and heat. Remove any one of these elements and combustion will cease. The fire triangle best illustrates the elements required for ***non-flaming*** combustion; when burning is localized on or near the fuel's surface where it is in contact with oxygen. Examples of non-flaming combustion include burning charcoal briquettes or smoldering wood or fabric.

Fire Tetrahedron: Research into fire behavior has determined that an uninhibited chemical chain reaction must also be present in addition to the other elements of the fire triangle (fuel, oxygen & heat) in order for flames to occur. Therefore, the fire tetrahedron was created to explain ***flaming*** combustion. Each element of the fire tetrahedron; fuel, oxygen, heat & uninhibited chemical chain reaction must be present for flaming combustion. Removing any element of the tetrahedron interrupts the chemical chain reaction and stops flaming combustion.



Fuel: Fuel may be found in any of three states of matter: solid, liquid, or gas. Only gases burn. For a solid or liquid to burn, they must be converted into a gas. Solids are converted into gas by **pyrolysis** and Liquids are converted to a gas by **vaporization.**

Pyrolysis: Pyrolysis is the chemical decomposition of a solid material that is caused by the absorption of heat. When pyrolysis of a material occurs, gas is released from the solid material. Pyrolysis often precedes combustion.



Surface to Mass Ratio: significantly affects the ease of ignition of solid fuels.

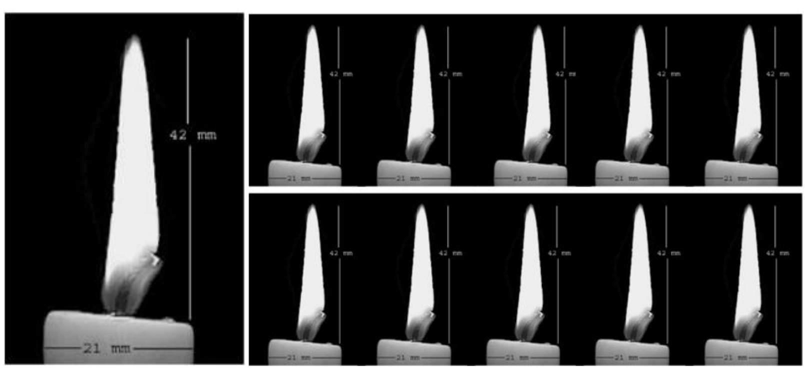
V**aporization**: Liquids are converted into gas by vaporization. Examples of vaporization include boiling water or water in a container evaporating in sunlight. In both cases, heat causes the liquid to vaporize.

Heat Energy: The transfer or flow due to the difference in temperature between two objects is called heat. Heat energy is a form of energy characterized by vibration of molecules and capable of initiating and supporting chemical changes and changes of state. In other words, it is the energy needed to change temperature of an object(s) – add heat, temperature increases; remove heat, temperature decreases.

Temperature: Temperature is a measure of the degree of molecular activity of a material compared to a reference point. Temperature is measured in degrees Fahrenheit or degrees Celsius.

Heat Release Rate: Heat release rate (HRR) is the rate at which fire releases energy – this is also known as power. HRR is measured in units of Watts (W), which is an International System unit equal to one Joule per second.

Temperature vs Heat Release Rate: One candle vs ten candles – same flame temperature but 10 times the heat release rate (see below). Both examples are producing 930° F - 2500° F in temperature. The single candle is producing ~ 80 W HRR. The ten candles are producing ~800 W HRR.



UL-FSRI: *Understanding the Basics: Heat Release Rate vs Temperature*

Surface to Volume Ratio: Surface to volume ration significantly affects the ease of ignition of liquid fuels. The greater the surface area compared to volume, the faster the liquid will vaporize. An example of this is a gallon of gasoline within a small steel container sitting on the floor in the middle of a room (smaller surface area) or a gallon of gasoline spilled out on a floor all over the room (larger surface area). The fire in the container will not produce the same volume of fire as the floor that is covered in gasoline.

Gaseous fuels can be the most dangerous because they are already in the natural state required for ignition. No pyrolysis or vaporization will be needed to ready the fuel. These fuels are also the most difficult to contain.

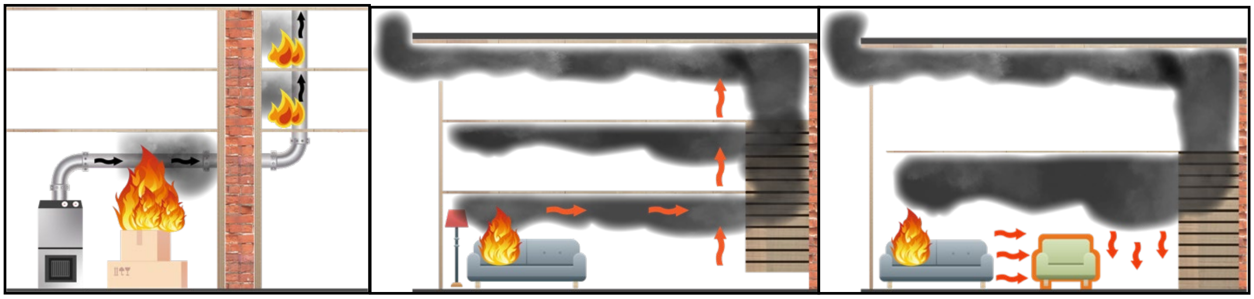
Oxygen: Oxygen in the air is the primary oxidizing agent in most fires. Normally, air consists of 20.8% oxygen. At normal ambient temperatures, materials can ignite and burn at oxygen concentrations as low as **15 percent**. When oxygen concentration is reduced below 15%, the flaming combustion will diminish, causing combustion to continue in the non-flaming mode. This means that below 15% there will not be visible flames, but because combustion continues in the non-flaming mode, heat and dense, fuel rich smoke will continue to be produced. If oxygen is introduced to this type of atmosphere, the fuel rich environment can ignite and be hazardous to firefighters.

Some fires involve fuels that contain chemical oxidizers (their own oxygen source) such as Ammonium Nitrate Fertilizer and Hydrogen Peroxide. These compounds can cause rapid burning rates, flame spread and explosions when they breakdown and do not depend on oxygen in the air to burn.

When oxygen concentration is higher than 20.8%, materials exhibit very different burning characteristics. Materials that burn at normal oxygen levels will burn more intensely in oxygen-enriched atmospheres. Many materials that do not burn at all in normal oxygen levels, may burn readily in oxygen-enriched atmospheres. Nomex, a fire-resistant fabric used in our PPE does not burn readily in normal oxygen concentrations. When placed in an oxygen enriched atmosphere, Nomex ignites and burns vigorously. Some petroleum-based materials may ignite spontaneously without an external heat source in oxygen-enriched atmospheres.

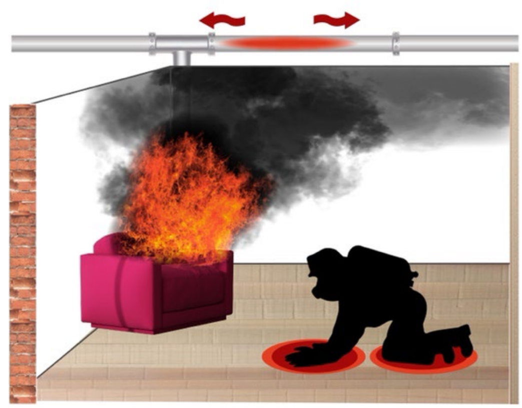
HEAT TRANSFER: A number of natural laws of physics are involved in the transmission of heat. One is called the **Law of Heat Flow**; it specifies that heat *always* flows from a hot substance to a cold substance. The colder of two objects in contact with each other will absorb heat until both objects are at the same temperature.

Heat can travel throughout a building by one or more of three methods: conduction, convection, and radiation. The following sections describe how this heat transfer takes place.



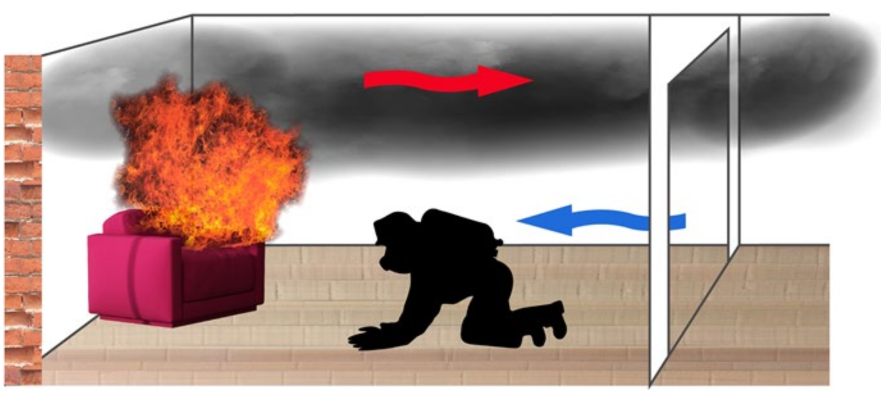
CONDUCTION **CONVECTION** **RADIATION**

Conduction: Heat may be conducted from one body to another by direct contact of two objects or by an intervening heat-conducting medium (material). An example of this type of heat transfer is a cellar fire that heats pipes enough that the pipes ignite the wood inside walls remote from the fire. Another example is firefighters crawling on a hot floor that burn their knees.



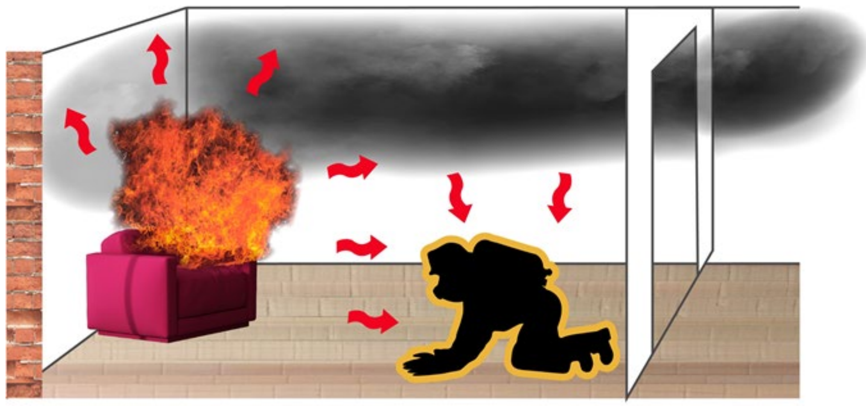
CONDUCTION

Convection: Convection is the transfer of heat by the movement of air or liquid. When water is heated in a container, it expands and grows lighter, hence, the upward movement. Heated air in a building will expand (**creating pressure**) and rise. For this reason, fire spread by convection is mostly in an upward direction; however, air currents can carry heat in any direction. Convection currents are generally the cause of heat movement, from room to room, from floor to floor and from area to area. The spread of fire through corridors, up stairwells, and elevator shafts; between walls, and through attics is caused mostly by the convection of heat currents.



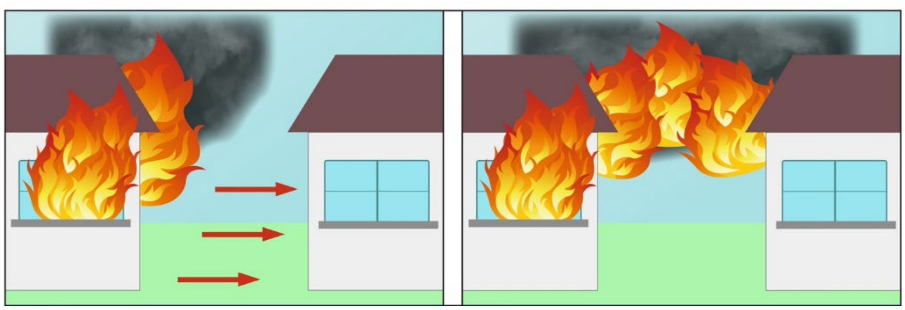
CONVECTION

Radiation: Radiation describes heat transfer through the movement of heat waves. Heat and light waves will cause radiated heat to travel through a space until it reaches an object.



RADIATION

As the object is exposed to heat radiation, it will in return radiate heat from its surface. Radiated heat is one of the major sources of fire spread to exposures. Radiated heat is also one of the major causes of firefighter burn injuries and flashover in a compartment fire.

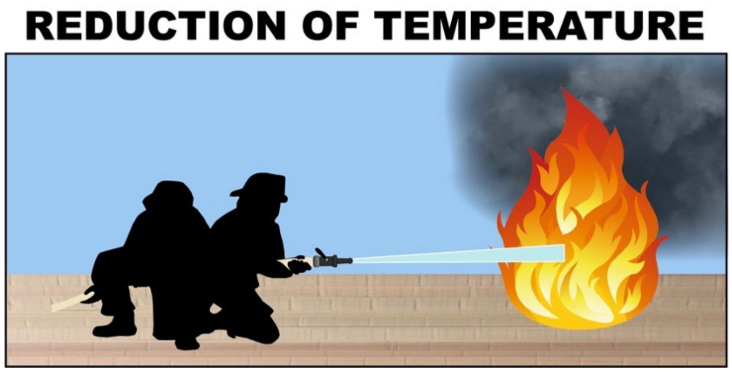


UL-FSRI *Understanding How Heat Transfers Through Turnout Gear*

Uninhibited Chemical Chain Reaction: The last part of the Fire Tetrahedron is the self-sustained uninhibited chemical chain reaction involved in flaming combustion. Understand that a chemical chain reaction occurs when fuels are broken down by heat and the reaction will cause the fire to continue to burn until the fuel or oxygen is exhausted, or an extinguishing agent is applied in sufficient quantity to interfere with the ongoing reaction.

Extinguishment Theory: The extinguishment of fire is carried out by limiting or removing one or more of the essential elements in the combustion process (removing one of the sides of the fire triangle or tetrahedron). This is accomplished by one of four methods: heat reduction, fuel removal, oxygen removal or chemical flame inhibition.

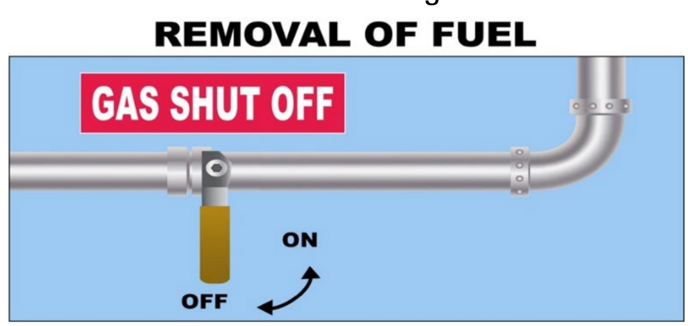
Heat Reduction: The most common method used to accomplish extinguishment is the application of water. This process of extinguishment is dependent on reducing the temperature of the fuel to a point where it does not produce sufficient vapor to burn.

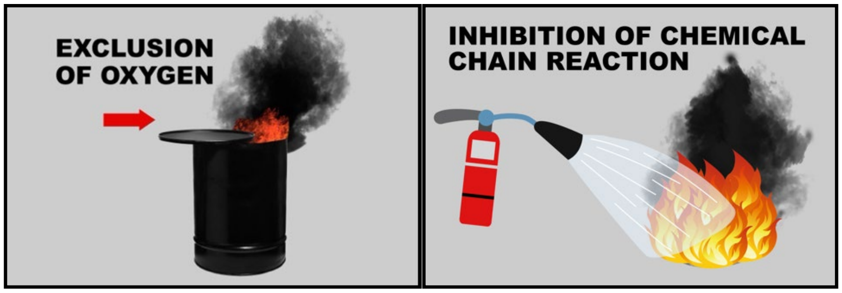


Fuel Removal: In some cases, a fire is effectively extinguished by removing the fuel source. Removal of the fuel source may be accomplished by stopping the flow of liquid or gaseous fuel or by removing solid fuel in the path of the fire. Another method of fuel removal is to allow the fire to burn until the fuel is consumed.

Extinguishment by Oxygen Reduction: Reducing the oxygen content in an area also extinguishes the fire. Reduction of the oxygen content can be accomplished by flooding an area with an inert gas, such as carbon dioxide, which displaces the oxygen; or the oxygen can be reduced by separating the fuel from the air such as by blanketing it with foam or placing a cover on a pot. None of these methods work on those rare fuels that are self-oxidizing.

Extinguishment by Chemical Flame Inhibition: Some extinguishing agents, such as dry chemical (sodium bicarbonate) and older systems such as Halon (halogenated hydrocarbons), interrupt the flame-producing chemical reaction and stop flaming. This method of extinguishment is effective on gas and liquid fuels, because they must flame to burn. Smoldering fires are not easily extinguished by this method because non-flaming combustion (represented by the fire triangle) does not require the presence of the chemical chain reaction present in flaming combustion (represented by the fire tetrahedron). Cooling is the preferred way to extinguish a smoldering fire.





Classes of Fires

CLASS OF FIRE	TYPE OF FIRE	SUITABLE SUPPRESSION	NFPA CLASS	SYMBOL
A	**COMMON COMBUSTIBLES** wood, paper, cloth, rubber, and many plastics	Water Dry Chem Foam	A	
B	**FLAMMABLE LIQUIDS AND GASES** gasoline, oils, paint, lacquer, and tar	Dry Chem Carbon Dioxide Foam	B	
C	**ENERGIZED ELECTRICAL EQUIPMENT** computers, computers, servers, transformers, and appliances	Purple K Dry Chem Carbon Dioxide	C	
D	**COMBUSTIBLE METALS** magnesium, lithium, aluminum, titanium	Class D Powder	D	
K	**COOKING OILS AND FATS** vegetable or animal oils and fats	Wet Chemical Carbon Dioxide Foam	K	

Solid Fuel Combustion: As solid fuels are exposed to heat, they absorb energy and increase in temperature. As the temperature of the solid rises, the solid fuel begins to decompose and break down. When it breaks down, it releases gas. Solid fuel when exposed to enough heat, will transform into a gas. The gas ignites and produces fire during flaming combustion.

Pyrolysis: The chemical decomposition of a solid material that is caused by the absorption of heat. When pyrolysis of a material occurs, gas is released from the solid material. Pyrolysis often precedes combustion.

Liquid Fuel Combustion: For liquid fuels to burn, they must release vapors and those vapors must mix with air so that the concentration of fuel is within the explosive/flammable range. A liquid fuel with a higher vapor pressure generates more fuel vapor than a liquid fuel with a lower vapor pressure. If heat is added to a fuel vapor, once the fuel concentration is within the explosive/flammable range, it is possible for it to ignite. A fire may then begin and grow wherever a flammable mixture is present.

Flash Point: The lowest temperature of a liquid at which that liquid gives off sufficient vapors to ignite but will not continue to burn. Liquid fuels are classified according to their fire hazard characteristics. The classifications are based on the flash point of the liquid. Depending on the flash point temperature, liquids are grouped as to whether they are flammable (more of a hazard) or combustible liquids (less of a hazard).

Flammable Liquid: A flammable liquid is a liquid that has a flash point below 100'F

Combustible Liquid: A combustible liquid is a liquid that has a flash point equal to or greater than 100'F.

Fire Point: Fire point is the lowest temperature at which a liquid will ignite and achieve sustained burning.

Vapor Pressure: Vapor pressure is the ability of a liquid or solid fuel to vaporize. The higher the vapor pressure, the more vapors are released (the easier it is to off-gas).

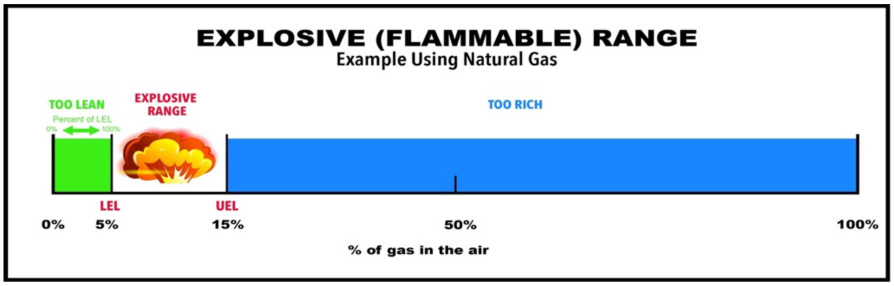
Vapor Density: The vapor density of gas refers to its density compared to air. Gases that have a vapor density around 1 will mix evenly with air. A gas with a vapor density greater than 1 is heavier than air. It will sink and collect in low areas. Gases that have vapor densities less than 1 are lighter than air and will rise to the top of a compartment.

Gaseous Fuel Combustion: In a fire, oxygen must chemically react with combustible fuel in a rapid oxidation process. For flaming combustion to begin and continue, the concentration of fuel vapor in the burning mixture (air and fuel) must be between the upper and lower explosive limits for that fuel. When the concentration of fuel in the air lies between the lower explosive limit (LEL) and the upper explosive limit (UEL), there is danger of the fuel igniting if a flame or other ignition source is present.

Lower Explosive Limit (LEL): The lower explosive limit is the lowest concentration by volume of flammable gas in air that will support flame propagation. This is also known as lower flammability limit.

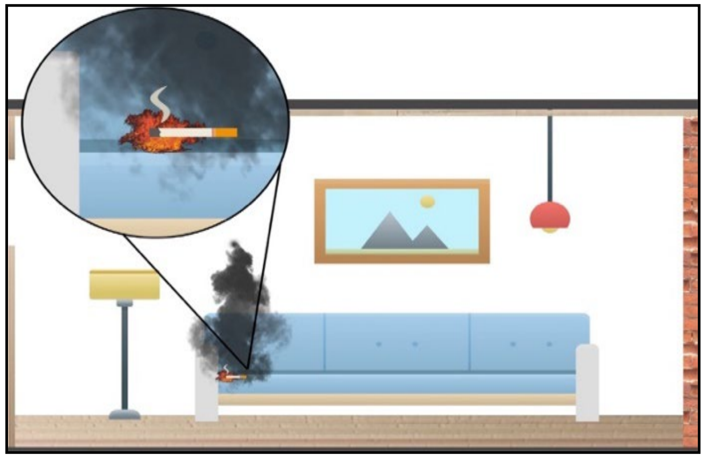
Upper Explosive Limit (UEL): The upper explosive limit is the highest concentration by volume of flammable gas in air that will support flame propagation. This is also known as upper flammability limit.

Explosive Range (aka Flammable Range): The range of gas to air mixtures in which ignition can occur. It is the range of gas to air mixture that exists between the lower explosive limit and the upper explosive limit.



Compartment Fire Development: To help understand fire behavior, the development of a fire in a compartment (room/enclosure etc.) has been broken down into 4 different stages:

- Incipient Stage
- Growth Stage
- Fully Developed Stage
- Decay Stage



In each of these stages, the fire will have discernable characteristics (different fire conditions) which are used to identify the stage the fire is in. Since certain fire phenomenon are likely to occur during certain stages of fire development, a firefighter's understanding and ability to identify these stages will help the firefighter better size up fire conditions and make better tactical decisions on the fireground. It is important to note that while most fires will pass through all 4 stages, some fires may not, e.g.: An arson fire may begin in the growth stage. In addition, some fires may pass through some stages more than one time. E.g.: A fire in the decay stage may redevelop into the growth stage following ventilation.

Incipient Stage: The incipient stage is the earliest stage of a fire and begins with the actual ignition. The fire is generally small during this stage and burning is usually limited to the original materials of ignition. During this stage of fire development, radiant heat warms the adjacent fuels and continues the process of pyrolysis, increasing the volume of fire. A plume of hot gasses and flame rise from the fire and mixes with the cooler air in the room. As this plume reaches the ceiling, hot gasses begin to spread horizontally across the ceiling.

In the incipient stage, there is plenty of oxygen and fuel available to burn. Oxygen levels in the air have not been significantly reduced by the fire. Some heat is being generated but the temperature in the room may only slightly increase. **Incipient fires can be readily extinguished with the use of the proper fire extinguisher.** It is essential to recognize that the transition from an incipient fire into the growth stage can occur quickly (sometimes in seconds) depending on the type and configuration of fuel involved.

Growth Stage: The growth stage covers a wide spectrum of fire development. It is the period that usually begins when the original fire spreads to additional materials. As the fire grows, it may spread to other objects by any combination of heat transfer (conduction, convection or radiation), by direct flame impingement, or if foams or plastic materials are involved, they can melt, and drip liquid which is on fire. This burning liquid can pool on the floor while burning and ignite secondary items.

Similar to the incipient stage, during the growth stage there is plenty of oxygen and fuel available to burn. During the very beginning of this stage, oxygen levels in the room may not have been significantly reduced by the fire. Oxygen rich air will be drawn into the flame as convection carries the heat to the uppermost regions of the confined area.

The presence of this heated air will cause the temperature to begin to rise in the area and if left unchecked, may start a series of events that will lead to rapid fire development and flame spread. **Rollover** and **flashover** occur during the Growth Stage.

Fully Developed Stage (Full Room Involvement): After a compartment fire has flashed over, the fire ***that remains within the compartment*** which has flashed over is considered to be in the fully developed stage. The burning fuels in the compartment are releasing the maximum amount of heat possible for the available fuel and/or oxygen, producing large volumes of fire gases. These gases may travel throughout the building and into building voids while mixed into heavy smoke. The larger the volume of fire and larger the volume of smoke produced; the larger the impact on survivability will be, even in remote areas of the building.

Flammable products of combustion are likely to flow from the fire room into adjacent rooms or out through openings to the exterior of the building. Flames will extend out of the compartment openings because there is insufficient oxygen for complete combustion within the compartment itself.

Note: The fire is only fully developed within the compartment(s) that has flashed over. Fire spreading out of this compartment into other compartments or rooms may be in the growth stage and subject to additional rollover and flashover conditions.

Decay Stage (Fuel Limited or Ventilation Limited): A fire enters the decay stage when all of the available fuel is consumed or when the oxygen concentration falls below 15% and flaming combustion is diminished. Both of these situations can result in the combustion reaction coming to a stop and the fire being completely extinguished if fuel or oxygen is never introduced. However, if a fire enters the decay stage due to reduced oxygen concentration, which is very common in the modern fire environment, any change in the ventilation of the compartment that adds oxygen before combustion has completely ceased, can cause the fire to rapidly redevelop. It is important to note that the cause for any fire to enter the decay stage is because the fire is either ***fuel limited*** or ***ventilation limited***.

Fuel Limited: If there is adequate ventilation and the fire consumes the available fuel in the compartment to the point that the heat release rate begins to decline, the fire enters the decay stage. This is because whatever fuel was burning has been entirely consumed and there is no additional fuel to burn. The fire has become fuel controlled.

Ventilation Limited: If there is adequate fuel available and the fire consumes enough of the available oxygen in the compartment, the heat release rate will also begin to decline, and the fire will enter the decay stage because the flames do not have enough oxygen. There is still plenty of fuel that is available to burn, and the fuel, even while it is smoldering, is pyrolyzing and emitting a large volume of flammable gases into the compartment. In this situation, if no oxygen is introduced, after a lengthy time, combustion will cease and the fire will be completely extinguished. However, if oxygen is introduced before combustion has ceased, rapid fire development and/or backdraft may result.

UL-FSRI: *Fire Development Changes When a Fire Becomes Ventilation Limited*

THERMAL LAYERING

Thermal Layering: The thermal layering of gases is the tendency of gases to form into layers according to temperature. The hottest gases tend to be near the top of the layering, while the cooler ones make up the bottom. Other terms that are sometimes used to describe this layering of gases are "heat stratification" and "thermal balance".

Thermal layering inside a compartment fire, is further broken down into two separate categories: The **upper layer** which is composed of the hot fire gases and the **lower layer** which is the cooler air below the hot fire gases. It is important to understand these terms for tactical reasons e.g. a thermal imaging camera can identify the thermal interface if the camera itself is positioned in the lower layer (cooler layer) looking at the upper layer (hot layer). A camera held in the hot layer will not be able to see the thermal interface.

Upper Layer: Buoyant smoke and gases collected by the ceiling and walls of an enclosure that begin to form a relatively uniform layer of heated smoke and gases throughout the upper area of a compartment.

As a fire develops in a compartment, over time, the hot rising smoke and fire gases spread across the ceiling and mushroom down into the room as they collect in a thick, relatively uniformed layer of hot gases throughout the upper layers of the enclosure.

Once the upper hot layer is formed, the additional flow of gases from the fire continues to collect along the ceiling forcing the upper layer to descend downward into the room as the fire heat release rate and upper layer temperatures increase.

Decreasing the heat of the fire within the enclosure will decrease the temperature and formation of hot gases that collect in the upper layer. If the heat is reduced, it can result in the contraction of gases in the upper layer. The contraction of upper layer gas volume will cause the upper layer to lift.

Directly decreasing the temperature of the upper layer (i.e., through the application of water) will also result in a contraction of the upper layer gas volume as a result of the hot smoke cooling. This can delay or prevent flashover.

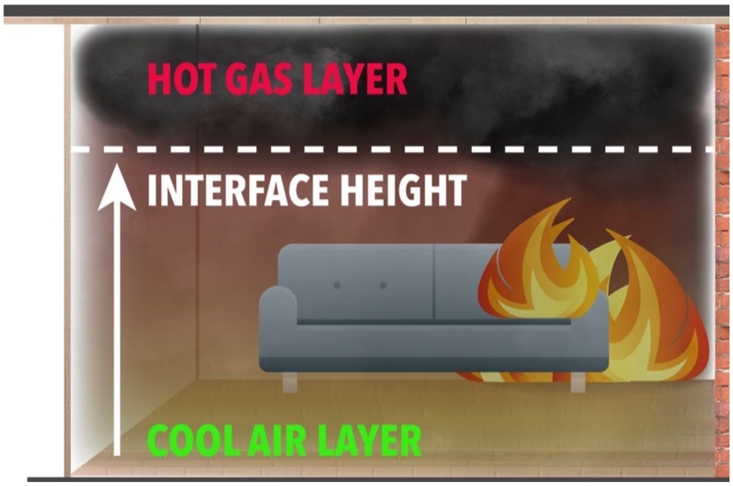
Lower Layer: The lower layer is the zone beneath the upper layer which consists primarily of ambient air that is entrained into the fire.

The cooler lower layer consists of air, at temperature and humidity levels closer to ambient conditions, drawn in through ventilation openings in the enclosure. As the hot gases rise in the buoyant plume, the cooler air is pulled in towards the fire.

THERMAL INTERFACE AND INTERFACE HEIGHT

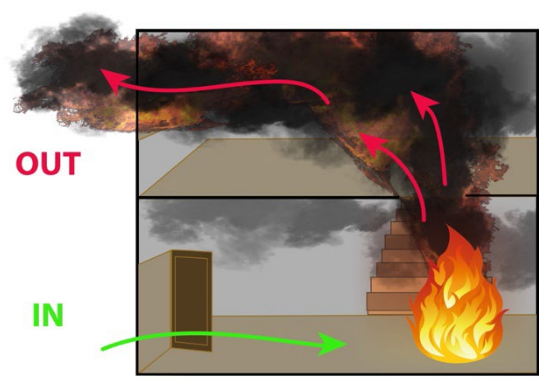
Thermal Interface: The boundary between the upper and lower layers which is represented by a sharp transition from the hot smoke in the upper layer to the cool ambient air of the lower layer is called the Thermal Interface.

Interface Height: The vertical distance from the floor of the enclosure to the thermal interface.

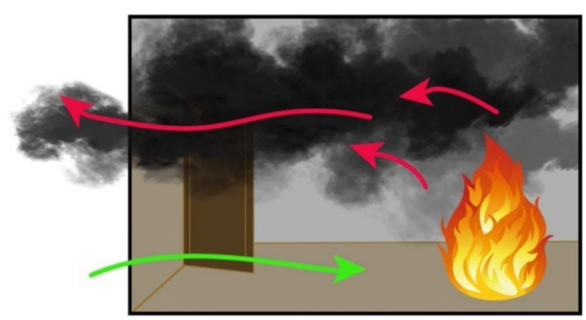


Neutral Plane: The flow of smoke and fire gases through an opening is described as either unidirectional or bidirectional. **Unidirectional flow** occurs when the flow through the opening flows in one direction only (either into or out of the opening). **Bidirectional flow** occurs when an opening acts as both an inlet and an outlet for flows at the same time.

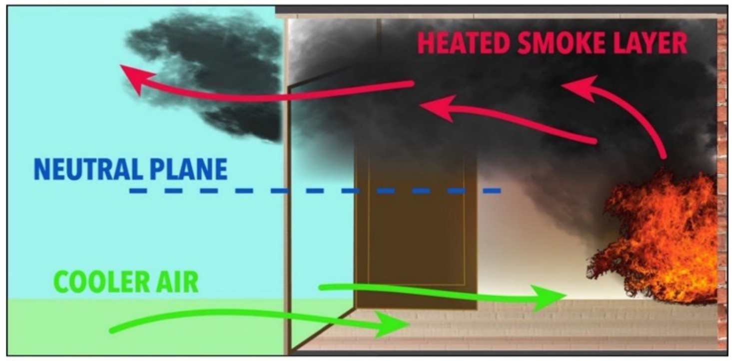
UNI-DIRECTIONAL FLOWPATH

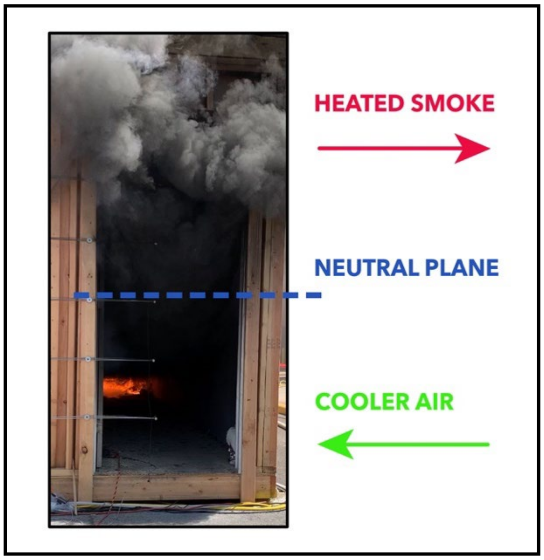


BI-DIRECTIONAL FLOWPATH



The horizontal line along a window or door or other ventilation opening where no flow occurs due to the equality of internal and external pressures. Above the neutral plane the flow of smoke and gases will be outwards and below the neutral plane the flow of cool air will be inwards.





The volume of hot smoke generated by the fire largely determines the pressure distribution in the compartment under fire conditions. As the hot smoke rises and accumulates, the pressure at the ceiling will rise. Similarly, the pressure at the floor will be lower, as cool air is entrained. Above the neutral plane the pressure inside the enclosure will be higher than the exterior pressure and cause the direction of flow to be outward. Similarly, below the neutral plane the pressure inside the enclosure will be less than the exterior pressure, and the flow of cool air will be inward toward the fire.

The horizontal line between the inflow and outflow at a ventilation opening (i.e., at the plane where there is zero pressure difference and thus zero flow in or out of the opening) is known as the neutral plane. The position of the neutral plane can often be observed during a fire, given that the outflow often consists of visible smoke or fire.

Note: The neutral plane is different from the thermal interface because the neutral plane only occurs at a ventilation opening. Neutral plane indicates **pressure differences** at an opening and may be used by firefighters outside the building to help determine the fire location within a building.

Thermal Interface and interface height refer to the separation between the hot upper layer and the cool lower layer within a compartment. Thermal Interface and the interface height indicate **heat differences** (how much volume of a compartment is filled with heat). It can be used by firefighters to identify how far the hot upper layer has banked down and the possibility of flashover.

SMOKE: The smoke encountered at most fires consists of a mixture of oxygen, nitrogen, carbon dioxide, carbon monoxide, hydrogen cyanide, finely divided carbon particles (soot), and a miscellaneous assortment of products that have been released from the material involved.

Two of the most toxic gases are **carbon monoxide** and **hydrogen cyanide** which are both chemical asphyxiants and are responsible for many fire deaths. These gases are highly toxic and pose a significant threat to human life.

The combination of fire gases produced during combustion and present in smoke are flammable and contribute greatly to rapid fire development. For this reason, firefighters shall consider smoke to be additional fuel.

When air is heated it becomes more buoyant (hot air rises). In addition to buoyancy, more than three-quarters of air is made up of nitrogen. The energy released by the fire causes the nitrogen to expand which drives a significant increase in the volume of the air.

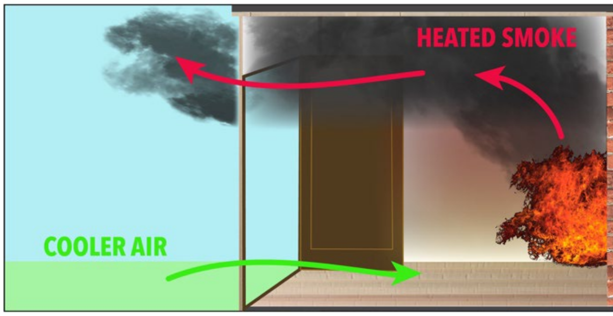
The buoyancy of hot air and expansion of nitrogen can push significant volumes of smoke through openings to the exterior or to other parts of the structure. Because smoke is suspended in air, the smoke is a visible indicator of how much hot air is rising and how fast the nitrogen is expanding. The value of "reading smoke" is tremendous in performing a size up of the fire.

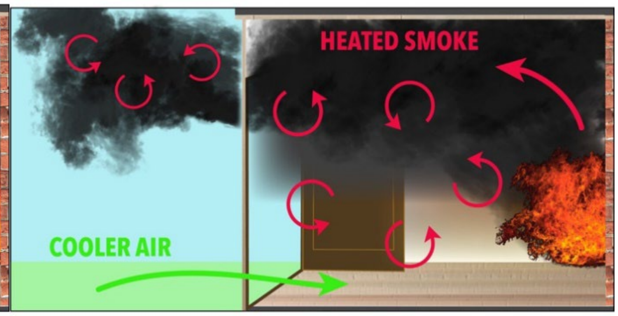
To accurately size up a fire by reading smoke, a firefighter must evaluate five characteristics of the smoke: Volume, Velocity, Density, Color and Stratification.

Smoke Volume: In many instances, smoke may be the only visible indicator of a fire. The volume of smoke may indicate the size, location and stage of the fire within a structure. However, the volume of smoke may not always be visible and can be concealed by various building configurations.

Smoke Velocity: Smoke velocity is an indicator of pressure that has built up within a structure. The pressure is developed by buoyancy and expansion due to the amount of heat released by the fire. Smoke flow can be either **laminar** (smooth) or **turbulent** based on the velocity and temperature. Cooler smoke appears to flow smoother. Hotter smoke will appear to boil and move quickly upwards in a turbulent fashion.

A. Turbulent Smoke indicates extreme heat (closer to the fire)
B. Laminar Smoke indicates low heat (either because it is a small fire, or the smoke is remote from the fire and has cooled)





LAMINAR SMOKE **TURBULENT SMOKE**

Smoke Density: The apparent density "thickness" of the smoke can be a good indicator of the efficiency of the combustion process. In the early fuel-limited stages where there is plenty of oxygen, the rate of smoke production is lower than in later stages when the fire is becoming ventilation-limited. A large fire which is severely ventilation limited, will produce large volumes of thick dense smoke.

A. Dense smoke can indicate the fire is a ventilation-limited fire.

SMOKE COLOR

Black: Dark smoke often indicates fuel-rich conditions, due to restricted air supply (ventilation limited). Where flaming or smoldering combustion occurs, the carbon in the fuel is released as soot in the smoke, resulting in a very dark color. If the air supply is sufficient, more of the carbon will react and will produce a lighter colored smoke and brighter flame. If air supply is restricted, less carbon reacts and becomes suspended in the smoke producing a darker colored smoke.

Thick dark smoke indicates an abundance of fuel that was not burned in the fire and is now suspended in the smoke. Given the right conditions, this suspended fuel can ignite.

Brown: Brown smoke can indicate the early stages of the pyrolysis of timber products. The brown color is caused by the process of wood breaking down. In a wood framed building, the presence of brown smoke may indicate that the structure is involved.

Grey: Grey smoke indicates that at least some flaming combustion or smoldering combustion is present. Dark smoke that has travelled some distance can cool and large carbon particles suspended in the smoke can adhere to surfaces. The further the smoke travels, the more carbon it can lose, resulting in a grey smoke. In a building issuing dark smoke from some areas and grey smoke from other areas, usually the areas with grey smoke are remote from the fire.

White: Application of water to a large fire will generate large amounts of steam which can mix with smoke and create condensation that gives the appearance of white smoke. In this situation, the white color can indicate water is on the fire. The more white condensation that is visible, combined with a reduction in the volume and velocity of dark smoke, indicates progress is being made in extinguishment.

White smoke (not steam) is produced when certain fuels are heated to their pyrolysis temperature and volatile components are released. If the heat continues to increase and there is insufficient oxygen even for smoldering combustion, then the production of white smoke will continue. White smoke can have a very high fuel content (white ghost), represents a significant danger, and should never be treated lightly. When white smoke mixes with oxygen and finds an ignition source, there is potential for a very sudden and powerful ignition.

Smoke Stratification:

A. Smoke usually stratifies in layers sometimes corresponding with the upper and lower layer. As a fire develops within an enclosure, the thermal interface will lower. The interface height can usually be observed by observing the smoke stratification or using the thermal imaging camera.
B. The location of the interface (its height in the room) and the neutral plane is important when assessing the potential for rapid fire development.
    1. A high interface could indicate the fire is in early stages of development or that you are remote from the fire area.
    2. A sudden rise in the interface could indicate that ventilation has occurred.
    3. Gradual lowering of the interface often indicates a buildup of hot fire gases, a situation that could progress to rollover and flashover if left uncontrolled.
    4. A sudden lowering of the interface could indicate a rapid intensification of the fire.
    5. A neutral plane that is at or near floor level may indicate that the fire is on a floor below.

<u>FLOW PATH & FIRE TRAVEL</u>

The flow path of a fire describes the route that smoke and flame move away from the seat of the fire toward any outlet(s), as well as the corresponding flow of air into the fire from any inlet(s). Normal Air inside a compartment is made up of gases (such as oxygen and nitrogen). When this air is heated, the gases expand, and the expansion of gases create pressure.

Flow Path: The area(s) within a structure fire where fire, heat, smoke and air flows from an area of higher pressure to an area of lower pressure.

Flow Path Management: It is possible to reduce the rate of fire growth if the inlet(s) and/or outlet(s) can be closed or restricted. In addition, the purposeful management of the flow path can increase firefighter safety during operations.

There may be several flow paths within a structure depending upon the building design and the available ventilation openings (i.e. doors, windows, shafts). The flow within the flow path may be characterized as being unidirectional, bidirectional or dynamic. The shape and position of the smoke/air track at a vent opening can be an important indicator of the intensity of the fire.

Velocity and Direction: When an opening is created in a fire area, the heated gases will flow out of the top of the opening, and cool air will flow in through the bottom of the opening.
A sudden inward movement of the air track could indicate the potential for rapid fire development. In these cases, the sudden inward rush of air will cause the fire to intensify and be followed by an outward rush of smoke and/or flame.

Smoke or flame being discharged from the entire ventilation opening (no neutral plane visible) usually indicates that it is an outlet and that there is at least one inlet located somewhere else in the structure.

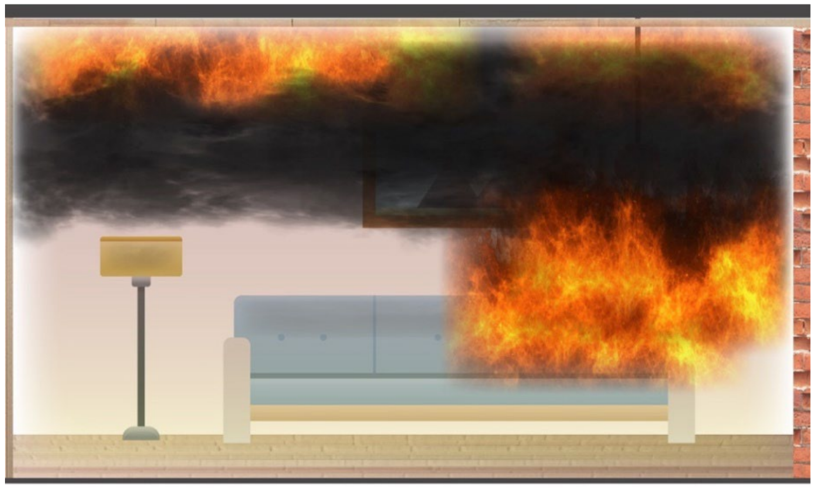
An opening that is both a ventilation inlet and outlet will show signs of laminar (smooth) or turbulent flow at the neutral plane depending on the stage and intensity of the fire.

A. **Unidirectional Flow**
   A unidirectional flow is a flow of smoke, flame or air moving in a single direction across the full area of the opening. A unidirectional flow path can exist as either an exhaust or an inlet.
B. **Bidirectional Flow**
   Bidirectional flow describes a smoke/air flow moving in opposing directions within the same openings.
C. **Dynamic Flow**
   A unidirectional or bidirectional flow of smoke/air that presents irregular stratification and shape, or alternates in direction (pulsates) is identified as dynamic flow.

Under normal fire conditions, there should be a clearly identified unidirectional flow or clearly delineated bidirectional flow of smoke/flame from a vent opening.

Under normal wind conditions, a room with only one opening will display a bidirectional smoke/air track with a visible neutral plane. In a wind-impacted scenario, the opening can aggressively alternate from a total inlet to a total exhaust outlet with a range of unique vent profiles. This would be an example of Dynamic Flow.

[UL-FSRI: *Fire Flows from High Pressure to Low Pressure*]



DANGEROUS FIRE EVENTS

Generally speaking, in a developing compartment fire, rollover occurs before flashover. Understanding and being able to recognize rollover and flashover conditions and being able to identify a ventilation-induced flashover environment and other dangerous fire events are key factors in Fire Dynamics Size-Up. The following section will describe dangerous fire events such as rollover, flashover, ventilation-induced flashover, backdraft, black fire, smoke explosion, flash fire, BLEVE and Boilover.

Rollover

As the fire develops and the thermal layer has been formed, pockets of flame may begin to form in the upper layer as the first indication that unburned fuel in the hot smoke may be coming close to its auto-ignition temperature. If it does ignite, a rollover occurs.

Rollover: A condition where the unburned fire gases that have accumulated at the top of a compartment ignite and flames travel through the hot gas layer across the ceiling.

Rollover is when the heated gasses rising from the fire accumulate at the ceiling level. These heated gases are pushed, under pressure, and spread horizontally across the ceiling. While these gasses are banking down, they are forming the upper layer and are mixing with oxygen. The upper layer becomes a flammable mixture of heated gases. When their flammable range is reached, they ignite and a fire develops, with fire expanding very rapidly and rolling over the ceiling away from the main body of fire. Rollover occurs during the growth stage.

Rollover is different from flashover because in rollover primarily the gasses are burning ***not*** the entire contents of the room. However, during a rollover event, such a significant amount of radiant heat (energy) is added to the room, that usually within seconds, flashover will occur. For this reason, the presence of rollover indicates that flashover is imminent.

FLASHOVER

Flashover is a transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperatures and ignite more or less simultaneously.

Flashover: The simultaneous ignition of all of the combustible materials in a compartment and all of the gases built up in the compartment produced by pyrolysis.

During flashover, the environment of the room is changing from a two-layer condition (Upper Layer and Lower Layer/ hot on top, cooler on the bottom) to a single well mixed, untenable hot gas condition from floor to ceiling. The temperature in the compartment typically exceeds 1100' F. In order for flashover to occur, there must be an enclosed space such as a single room. Virtually all combustible surfaces in the enclosed space become ignited during flashover.

The transition period between pre-flashover fire conditions to post-flashover can occur rapidly. During flashover, the volume of fire will increase to fill the entire volume of space in the room; with fire and burning gases likely extending out of any openings in the room (windows, doors, etc.) with substantial velocity.

Flashover occurs during the growth stage. Once flashover has occurred, the fire within the compartment is said to be in the Fully Developed Stage.

Note: The Geometry (the size, shape and volume) of a room affects the formation of the upper layer and thus the heat transfer within a given fire compartment. A flashover may take longer to occur in compartments that have *peaked ceilings* or cathedral ceilings since these features make it difficult for the upper layer to form. Lack of upper layer formation limits the amount of radiant heat produced and radiated back towards the fire and other fuels in the compartment.

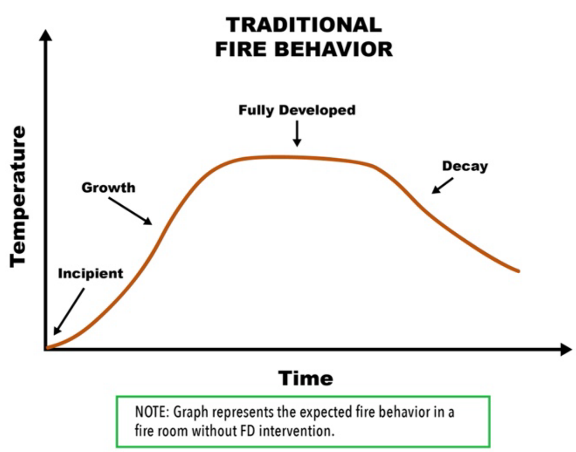
Ventilation-Induced Flashover: When a fire enters the decay stage before flashover occurs due to a reduction in oxygen, but then redevelops and flashover occurs when oxygen is admitted to the fire, is called a ventilation-induced flashover.

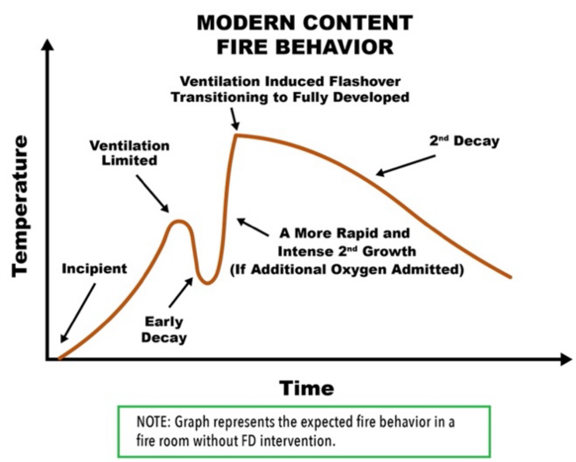
Ventilation-Induced Flashover: A flashover initiated by the introduction of oxygen into a pre-heated, fuel rich (smoke filled) oxygen deficient area.

Ventilation-Induced Flashover has become prevalent with modern content fires. Modern content fires rapidly consume more of the available oxygen within the fire compartment creating conditions favorable for a ventilation-induced flashover to occur.

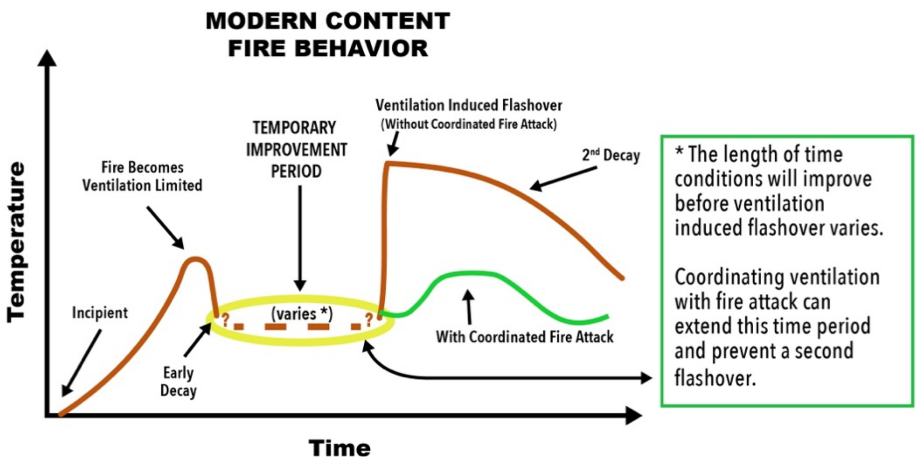
Ventilation-Induced Flashover occurs when oxygen is introduced to a fire which has entered an early decay stage. Once ventilation-induced flashover occurs, the fire within the compartment is said to be in the Fully Developed Stage.

Ventilation-Induced Flashover is similar to a backdraft except a backdraft involves significantly more pressure, causing an explosion.

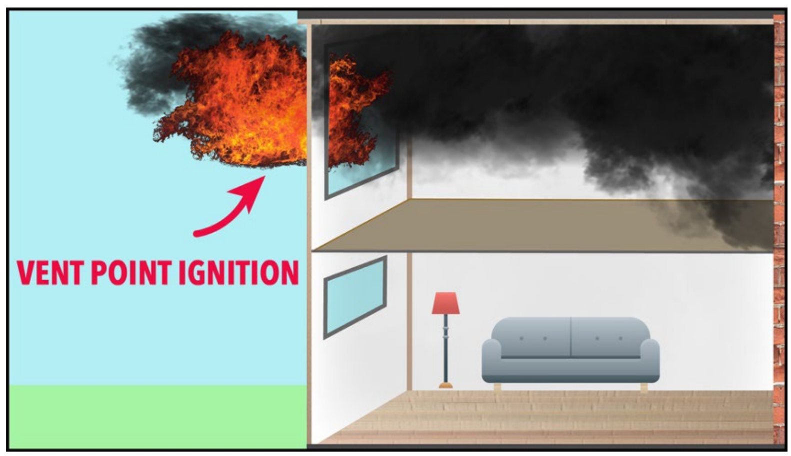




Ventilation will *initially* relieve built up heat and smoke even when conducted ahead of hoseline operations. While all ventilation openings may have an impact on the fire, a member taking a window of a fire room in the oxygen deficient early decay stage will have more immediate effect on fire regrowth than opening the fire apartment door down the hall. If water is not applied to the seat of the fire soon after ventilation occurs, this **temporary improvement period** may be followed by a rapid deterioration of conditions, potentially leading to flashover.



In oxygen depleted environments, this **temporary improvement period** can last for an unspecified amount of time; it can be seconds or several minutes. It is important to note that there is no way to accurately determine how long this temporary improvement period will last. Factors impacting fire rapid re-growth include size and location of the fire, size and location of the ventilation opening, building dynamics and flow paths established between the fire and ventilation opening(s). Firefighters can extend the temporary improvement period by coordinating ventilation with fire attack.



Black Fire: The occurrence of Black Fire is a condition when thick, turbulent superheated fuel rich black smoke has been heated well beyond its ignition point but is so rich with gasses it is beyond its flammable range and is too rich to burn. Black Fire occurs in areas of the fire building which are said to be in the Growth Stage. This can and often does include areas ***above*** or ***adjacent*** to rooms of fire that are fully involved and in the fully developed stage.

It is called Black Fire because at the area affected there will be no visible flames, just dark black superheated turbulent smoke. The smoke will be so hot that it will act as if it were fire. This means that the heat from Black Fire will be searing and destructive and it will pyrolyze and consume materials in its path. It can severely burn firefighters.

When Black Fire conditions are present, there is usually an area ahead of the Black Fire area where the main body of fire is free burning and heavily involved in flames. In the Black Fire Area itself, the smoke will be too rich to burn and there will be no visible flames. Behind the Black Fire area, as the smoke travels remote from the fire area and mixes with more air, there may be an area where the smoke ignites. This ignition can occur in a room behind firefighters who are operating in the black fire area causing them to become trapped. Ignition can also occur on the exterior of the building when the smoke ignites as it is released from a window or door and mixes with air in the atmosphere. This is known as **vent point ignition.**

Black Fire is an extremely dangerous condition to be operating in. Upon recognition of Black Fire Conditions, treat the Black Fire smoke as if it were flames. Immediately flow water into the smoke layer with a hoseline to aggressively cool the area. If you are unable to immediately cool the area, isolate our forces from the fire area by closing a door or some other means if possible, or retreat to an area of safety.

SMOKE EXPLOSION

A smoke explosion can occur either inside or outside the fire compartment when an accumulation of fuel-rich smoke mixes with additional air and falls within its flammable/explosive range. A smoke explosion can occur without warning and occurs ***without*** a sudden change in ventilation.

Smoke Explosion: A rapid fire development that occurs when a smoke-air mixture falls within its flammable range, either internal or external to the fire compartment, and is ignited in a manner resulting in a significant pressure front. A smoke explosion occurs without an immediate ventilation triggering event.

One common example occurs when smoke migrates and accumulates in hidden areas such as rooms remote from the fire area or void spaces (including cocklofts, attics, or voids within walls). This smoke then mixes with air to fall within its flammable range and encounters an ignition source (or is at a temperature above its auto-ignition temperature), resulting in a flame front propagating through the mixture.

If ignition occurs in a relatively confined space (cockloft, small room, etc.), or if obstacles promote turbulence, the flame front may accelerate, leading to an over pressure situation that may result in structural damage and/or injury or death of nearby firefighters.

BACKDRAFT

Backdrafts are caused when there is an introduction of oxygen to a compartment that has been pressurized by the smoke and fire gases of an oxygen-deficient fire in the Decay Stage. Similar to smoke explosions, backdrafts are accompanied by a significant over-pressure.

Backdraft: A deflagration resulting from the sudden introduction of air into a confined space containing oxygen-deficient products of incomplete combustion.

During a backdraft, the ignition pushes unburned fuel-rich gases ahead of the burning smoke-air mixture as it expands. A large fire ball results as the burning flammable and smoke-air mixture is forced, under pressure, from the compartment. The over-pressurization and dramatic fireballs produced during backdraft can result in damage to the structure and extension of the fire beyond the compartment, and pose several risks to firefighters who are in its path.

A backdraft may lead to a heavy fire condition or may expel all of the fire gases, leaving only localized combustion in its path.

Backdraft Indicators
No visible/active flaming within the compartment and extremely limited or no ventilation of the fire compartment

Sometimes but not always in conjunction with the following:
Pulsating smoke, usually pulsating in an in-and-out movement, giving the impression the "compartment is breathing." Grey-Yellow smoke seeping out from around closed and intact doors and windows. Doors and windows usually very hot and window glass discolored and/or cracked from the heat.

Note: It is important to note that while some or all of these indicators may be present to indicate the possibility of a backdraft, it is possible for a backdraft to occur without indications that the fire is in the decay stage being visible from the exterior of the compartment.

Note: **Distinguishing between Smoke Ignitions**

A. Backdrafts and Smoke Explosions will be considered the same; except that Backdrafts will occur immediately following ventilation of the affected compartment.
B. An event will be considered a Smoke Explosion if it occurred without immediate and direct ventilation of the affected area.

FLASH FIRE (PROPAGATING FLAME FRONTS)
Flash fires involve a flame moving through a flammable mixture with considerable speed, without developing a significant over-pressure.

Flash Fire: A fire that spreads by means of a flame front rapidly through a diffuse fuel, such as dust, gas or the vapors of an ignitable liquid, without the production of damaging pressure.

Flash fires can happen within a fire compartment (such as during overhaul) when embers or sparks can act as an ignition source or external to the compartment in any remote location where a flammable mixture has collected. Flash fires usually self-extinguish, although sometimes may ignite secondary fires.

Examples of Flash Fires include ignition of dust in a wood shop, vapors from a roach bomb or vapors from a newly stained wood floor.

Note: Flash fires which occur in a confined space can cause an over pressure condition and result in an explosion. This condition would be referred to as an explosion. (e.g., dust explosion).

BOILING LIQUID EXPANDING VAPOR EXPLOSION (BLEVE)

A BLEVE is an explosion caused by the rupture of a vessel containing a pressurized liquid that has reached temperatures above its boiling point.

Characteristics of the stored liquid, as well as the storage container, are important in determining whether there is potential for a BLEVE to occur. When a liquid is heated above its boiling temperature, it will vaporize, causing an increase in pressure in the container. If the boiling liquid is in a sealed, rigid container, the pressure in the container will increase as more liquid boils. If the container is vented, the extra pressure will be released to equalize the pressure inside the container with that outside the container (atmosphere). If the container is not vented, or if the relief vent cannot release the building pressure fast enough, the pressure inside the storage container will increase.

A BLEVE occurs when (1) the liquid in a pressurized vessel is at or heated to a temperature that exceeds it boiling point and (2) the container ruptures, either due to excessive build-up in pressure, or due to tank failure caused by mechanical or thermal damage.

When the rupture is catastrophic, the contents of the vessel will boil almost immediately on release, causing a rapidly expanding vapor cloud. Depending on the temperature, pressure and type of liquid involved, this expansion may be so rapid that it is classified as an explosion and can cause significant damage to its surroundings. If the liquid involved is flammable, the expanding vapor cloud may also be flammable and ignite creating a fire.

BOILOVER

An event in the burning of certain combustible liquids in an open-top tank when, after a long period of quiescent burning, there is a sudden increase in fire intensity associated with the expulsion of burning oil from the tank (NFPA).

When water is added to the fuel, it sinks to the bottom of the container and has little effect on extinguishing the flames which are on the surface of the fuel. Under certain conditions, the water vaporizes into steam causing it to expand more than 1700 times in volume. The rapidly expanding steam expels the fuel upward and out of the container, which ignites and results in a large plume of burning liquid outside of the container.

Boilover commonly occurs in residential kitchen fires when water is added to a grease/oil fire in an attempt to extinguish the fire. Boilover can be more catastrophic when occurring in a larger flammable liquid fire such as a transformer fire or tanker truck fire. In most cases, water (without a suppression additive) has little extinguishing effect on flaming liquid fires.

STACK EFFECT

"Stack Effect" is a term used to describe the movement of air throughout a building that occurs when the temperature of the interior of a building is different than the temperature of the external environment. Stack Effect occurs in buildings of all sizes including private dwellings; although in hi-rise buildings it is significantly more prominent.

Stack Effect encompasses two distinct dynamics; it affects internal vertical air movement inside the building (up and down the shafts), as well as horizontal air movement (into or out of a floor within the building). Horizontal air movement occurs as air is exchanged between the building's interior and the external environment (in and out windows) or is exchanged within the building from a given floor into or out of a vertical shaft.

Impact of the Stack Effect

The Stack Effect impacts air movement in a building in two distinct ways:

A. It impacts the vertical direction and magnitude of air movement inside the building itself. Air inside the building can either move up or down the vertical shafts. This movement will affect the movement of smoke throughout the building.
B. It impacts the horizontal direction and magnitude of air being exchanged between (1) the interior of the building and the external environment and (2) the horizontal air movement on each individual floor to and from the vertical shafts. Air can either be pulled into the building through available openings (windows, doors), or it can be pushed out of the building. Likewise, air can be pulled into a particular floor from a vertical shaft or pushed out of a particular floor into the shaft. This horizontal movement can affect fire and/or smoke conditions depending on the direction of air movement.

Stack Effect Neutral Pressure Zone

Near the center of the building there will exist an area that experiences no horizontal air exchange at all (air will not be pulled into or pushed out of an opening or pulled into or pushed out of a floor due to stack effect). This area is called the "**Stack Effect Neutral Pressure Zone**".

The magnitude of horizontal air movement at other parts of the building depends on the distance from this central point; the further the opening is from the middle floor of the building, the stronger the Stack Effect will be. This means that lateral air movement will be strongest at openings (windows) or locations on the uppermost and bottommost floors.

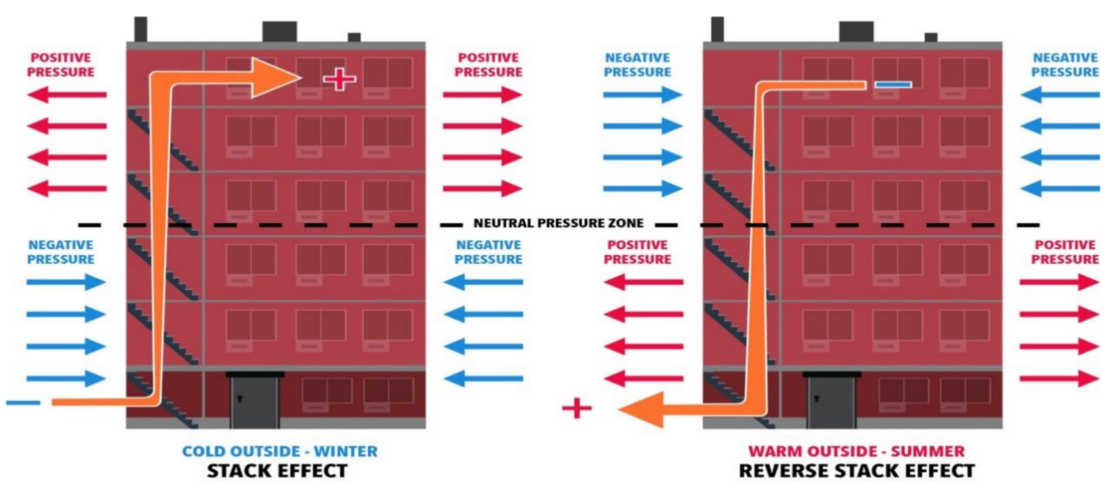
This condition can cause smoke and fire gasses to bypass several floors near the center of the building (near the stack effect neutral pressure zone), only to be pulled into floors somewhere above or below the center of the building depending on the direction of the stack effect.

Magnitude of the Stack Effect
The magnitude of the Stack Effect will be dictated by the size of the temperature differential between the interior of the building and the exterior environment and the height of the building.

A. Stack Effect will be more prominent in extreme weather, when air conditioning or heating systems make the temperature inside the building remarkably different from the outside temperature.
B. Taller buildings will experience a more powerful Stack Effect because more air will be moving over a longer distance inside the building. Also, the presence of large vertical shafts (stairways, elevators, compactors, etc.) will contribute to the strength of the Stack Effect.

Direction of the Stack Effect
The direction of the Stack effect will be dictated by whether the interior of the building is warmer or cooler than the external environment. There is a critical difference, as the air will move in opposite directions depending on this factor and will have the opposite impact on smoke movement and fire conditions in different parts of the building.

A. **Positive Stack Effect (Winter)** is when the interior of a building is warmer than the external environment.
B. **Negative Stack Effect (Summer**) is when the interior of a building is cooler than the external environment.



Two Different Situations:
Positive Stack Effect (Winter) vs. Negative Stack Effect (Summer)
Positive Stack Effect (Winter)

A. In cold weather, air inside occupied buildings is warmer than the air outside the building due to internal heating systems.
B. As a result, air and smoke movement inside the building will travel upwards via vertical shafts and attempt to exit the building via available openings near the top of the building. At the bottom of the shaft, a negative pressure will be generated, which will have the effect of pulling air into the shaft via available openings near the bottom of the building.
C. A fire on an upper floor will tend to want to vent out of the windows.
D. A fire on a lower floor will tend to draw air into the windows creating conditions similar to a wind impacted fire.
E. Smoke from a lower floor fire will be drawn up vertical shafts within the building and pulled back into floors with greater force as you go higher in the building and further away from the stack effect neutral pressure zone.

Negative Stack Effect (Summer)

A. In hot weather, air inside occupied buildings is cooler than the air outside the building due to internal air conditioning systems.
B. As a result, air inside the building will travel downwards via vertical shafts and attempt to exit the building via available openings near the bottom of the building. At the top of the shaft, a negative pressure will be generated, which will have the effect of pulling air into the shaft via available openings near the top of the building.
C. This is also known as "Reverse Stack Effect."
D. A fire on an upper floor will tend to draw air into the windows creating conditions similar to a wind impacted fire.
E. A fire on a lower floor will tend to want to vent out of the windows
F. Smoke from an upper floor fire will be drawn toward the vertical shafts within the building and will typically travel downward. It can be pulled back into floors with greater force as you go lower in the building and further below the stack effect neutral pressure zone.