Heat Transfer in Fires

Fire

• Fire can be described in many ways - here are a few:

- NFPA 921: "*A rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities.“*
- Webster's Dictionary: *"A fire is an exothermic chemical reaction that emits heat and light"*

• Fire can also be explained in terms of the Fire Tetrahedron

- a geometric representation of what is required for fire to exist,

❑ *fuel*, *an oxidizing agent*,

❑*heat*, and

❑*an uninhibited chemical reaction*.

Measuring Fire

- ***Heat Energy*** is a form of energy characterized by vibration of molecules and capable of initiating and supporting chemical changes and changes of state (NFPA 921).
- In other words, it is the energy needed to change the temperature of an object - add heat, temperature increases; remove heat, temperature decreases.
- Heat energy is measured in units of Joules (J), however it can also be measured in Calories (1 Calorie = 4.184 J) and BTU's (1 BTU = 1055 J).

- ***Temperature*** is a measure of the degree of molecular activity of a material compared to a reference point.
- Temperature is measured in degrees Farenheit (melting point of ice = 32 º F, boiling point of water = 212 º F) or degrees Celsius (melting point of ice = 0 º C, boiling point of water = 100 º C).

Temperature **°C (°F)**	**Response**
37.0 °C (98.6 °F)	Average normal human oral/body temperature [1]
38 °C (101 °F)	Typical body core temperature for a working fire fighter [2]
43 °C (109 °F)	Human body core temperature that may cause death [3]
44 °C (111 °F)	Human skin temperature when pain is felt [4]
48 °C (118 °F)	Human skin temperature causing a first degree burn injury [4]
54 °C (130 °F)	Hot water causes a scald burn injury with 30 s exposure [5]
55 °C (131 °F)	Human skin temperature with blistering and second degree burn injury [4]
62 °C (140 °F)	Temperature when burned human tissue becomes numb [4]
72 °C (162 °F)	Human skin temperature at which tissue is instantly destroyed [4]
100 °C (212 °F)	Temperature when water boils and produces steam [6]
250 °C (482 °F)	Temperature when charring of natural cotton begins
>300 °C (>572 °F)	Modern synthetic protective clothing fabrics begin to char [7]
≥400 °C (≥752 °F)	Temperature of gases at the beginning of room flashover [8]
≈1000 °C (≈1832 °F)	Temperature inside a room undergoing flashover [8]

- ***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.
- Depending on the size of the fire, HRR is also measured in Kilowatts (equal to 1,000 Watts) or Megawatts (equal 1,000,000 Watts).

- ***Heat Flux*** is the rate of heat energy transferred per surface unit area - kW/m^2.

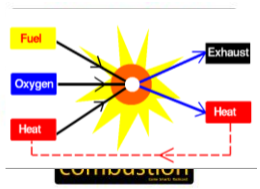
Heat Flux (kW/m^2)	Example
1	Sunny day
2.5	Typical firefighter exposure
3-5	Pain to skin within seconds
20	Threshold flux to floor at flashover
84	Thermal Protective Performance Test (NFPA 1971)
60 - 200	Flames over surface

Fundamentals of Heat Transfer

- Concept of **Specific heat**
- **Joule, watt, calorie**
- *Concept of* ***Latent heat***

Fundamentals of Heat Transfer

- Fire is combustion
- The process of combustion and its sustenance is all about heat transfer.



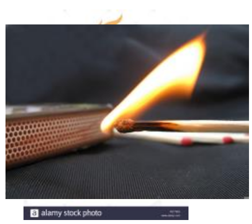
Fundamentals of Heat Transfer

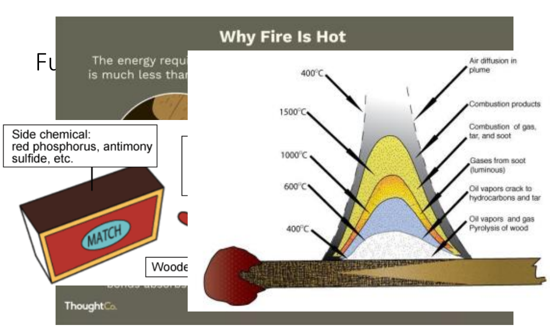
rate of heat produced,

the heat conveyed to other materials

the materials present.

The character of a fire and its ability to sustenance





Flame

Fundamentals of Heat Transfer

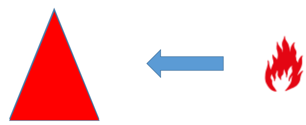
Why is heat transfer so important to understand?

- to understand how a fire may have spread from one area of a structure to another through no readily visible path.
- Indicates how a fire may start in one building and spread to another, again with no direct contact being made by flame.

Heat transfer is defined by NFPA 921 Guide to Fire and Explosion Investigation as

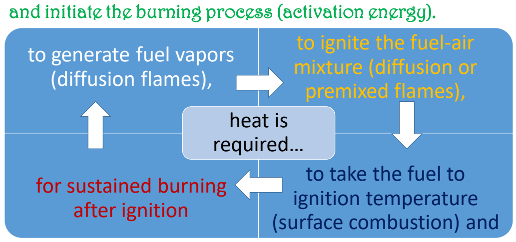
“the transport of heat energy from one point to another caused by a temperature difference between those points.”

Fundamentals of Heat Transfer

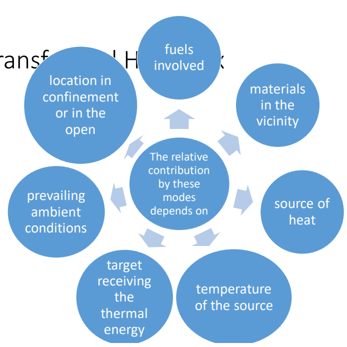


Heat Transfer and Heat Flux

Combustion requires energy to activate the fuel components and initiate the burning process (activation energy).



Heat Transf



Heat Transfer and Heat Flux

- In general, however, heat transfer during a fire is primarily by convection and radiation while heat transfer by conduction is relatively low.

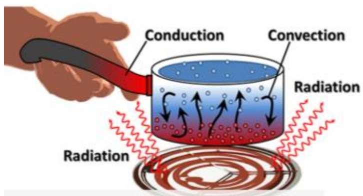
Modes of Heat Transfer

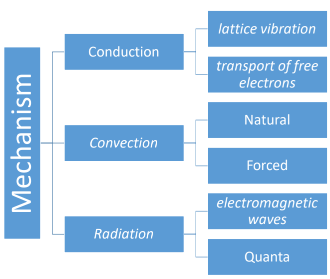
The spread of fire from one body to another may materialize by:

- continuity of a burning object with combustibles that are not burning,
- physical transport of burning objects (like sparks), or
- transfer of heat energy through one of the three modes of heat transfer Conduction, Convection, Radiation

- *Heat transfer* is a major factor in the ignition, growth, spread, decay and extinction of a fire.
- It is important to note that heat is *always* transferred *from* the hotter object *to* the cooler object
  - ❑heat energy transferred to and object increases the object's temperature, and
  - ❑heat energy transferred from and object decreases the object's temperature.

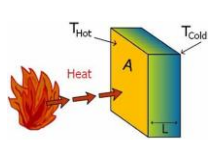
MODES OF HEAT TRANSFER





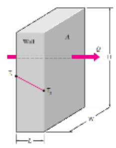
Conduction

- "Conduction" is the *transfer of heat from one part of a substance to another part of the same substance, or from one substance to another* ***in physical contact*** *with it,* ***without*** *appreciable* ***displacement*** *of molecules forming the substance.*



HEAT TRANSFER BY CONDUCTION

- **FOURIER'S LAWS OF HEAT CONDUCTION**
- *The rate of flow of heat through a simple homogeneous solid is…*



FOURIER'S LAWS OF HEAT CONDUCTION

$$Q = -\, k \,.\, A \,\frac{dt}{dx}$$

- The governing equation for heat transfer by conduction is:

$$\dot{q} = \frac{kA(T_{Hot} - T_{Cold})}{L}$$

Where
- *T* is temperature (in Kelvin),
- *A* is the exposure area (meters squared),
- *L* is the depth of the solid (meters), and
- *k* is a constant that unique for different materials known as the *thermal conductivity* and has units of (Watts/meters*Kelvin).

Thermal Conductivity (K)

- $\mathbf{Q} = \mathbf{K\,A^*}\,(t_1 - t_2)/L$
- *unit of thermal conductivity…*
- *W/m° C.*

Thermal Conductivity (K)

- Thermal conductivity (a property of material) depends essentially upon the following *factors* :

(i) Material structure

(ii) Moisture content

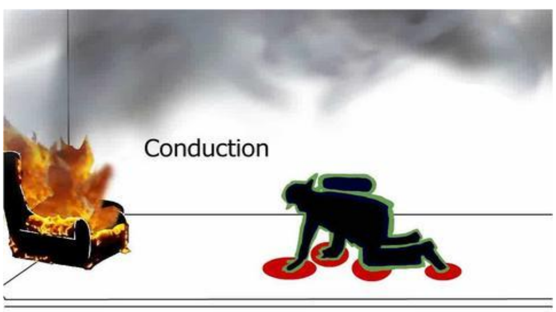
(iii) Density of the material

(iv) Pressure and temperature (operating conditions).

Thermal Conductivity

- Thermal conductivity of *most **metals** decreases with the increase in temperature (aluminium and uranium being the exceptions).*
- In most of ***liquids*** the value of thermal conductivity tends to decrease with *increase in* temperature (water being an exception) due to decrease in density with increase in temperature.
- In case of **gases** the value of thermal conductivity *increases with increase in temperature.*

Copper = 387	**Gypsum = 0.48**
Steel = 45.8	**Oak = 0.17**
Glass = 0.76	**Pine = 0.14**
Brick = 0.69	**PPE = 0.034 - 0.136**
Water = 0.58	**Air = 0.026**



Summary

- Conduction is the form of heat transfer that takes place within solids when one portion of an object is heated.
- Energy is transferred from the heated area to the unheated area at a rate dependent on the difference in temperature and the thermal conductivity (k) of the material.

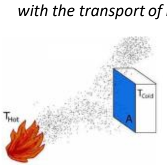
Example

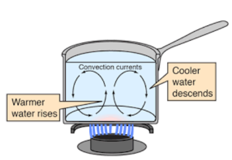
- Metal I-Beam or truss located in a room and passing through a wall to another room that is being impinged upon by a fire.
- As the beam or truss heats, the temperature increases along the I-Beam or truss to the cooler end.
- The end opposite the fire heats up, and if it reaches the auto ignition temperature of combustible materials close to it, a second fire will start.
- The subsequent second fire may lead one to identify two separate points of origin.

Heat Transfer by Convection

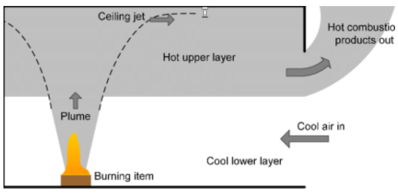
Convection

- *"Convection" is the transfer of heat within a fluid by mixing of one portion of the fluid with another.*
- Convection is possible only in a fluid medium and is *directly linked with the transport of medium itself.*





Heat Transfer by Convection



Heat Transfer by Convection

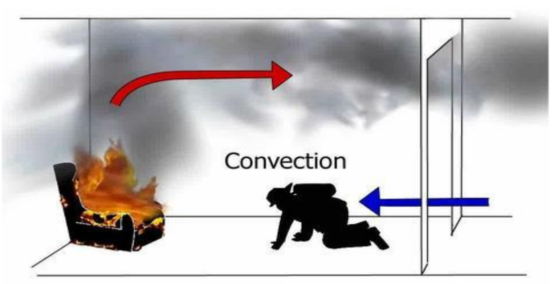
Heat Transfer by Convection

- Fire scenarios can demonstrate a combination of both forms of convective heat transfer and analyses must address both phenomena.
- Newton's law: $Q = h\ A\ \Delta t$

The governing equation for heat transfer by convection is:

$$\dot{q} = h(T_{Hot} - T_{Cold})A$$

Where:
T is temperature (in Kelvin),
A is the area of exposure (in meters squared), and
h is a constant that is unique for different materials known as the *convective heat transfer coefficient*, with units of $W/m^2{*}K$.
These values are found *empirically*, or, by experiment.
For free convection, values usually range between 5 and 25.
But for forced convection, values can range anywhere from 10 to 500.

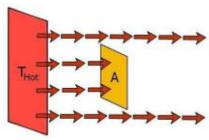


Summary

- "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.
- An example of convection is air contacting heating elements, as in a furnace, and being heated to comfort temperature.
- Convection plays a significant role in fire investigation because it is one of the initial means for fire to spread by the hot or super heated gases and products of combustion spreading out into the upper portions of the room or area of origin.
- This is why we see soot and other products of combustion spread throughout a structure and even in rooms that are a significant distance away and have no direct flame impingement.

Radiation

- *"Radiation" is the transfer of heat through space or matter by means other than conduction or convection.*



Heat Transfer by Radiation

- Radiation is an important mode of heat transfer in large fires that may cause the fire to spread to other combustible materials.
- In the case of radiant heat transfer between two surfaces, the tendency of the cooler body to get heated depends on the type of surface of the cooler body.

Heat Transfer by Radiation

Heat Transfer by Radiation

- The famous Stefan-Boltzmann equation states the energy emitted by a body as Q = ε σ A t^4
- where σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^2K) and
- ε is the emissivity of the surface, which is a measure of the efficiency of the surface as a radiator of heat.

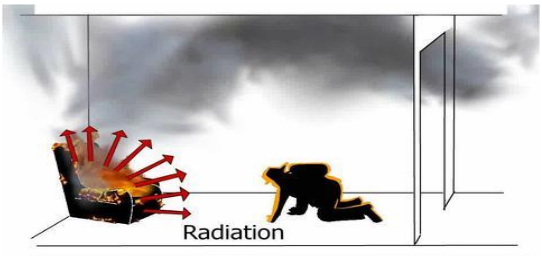
The governing equation for heat transfer by radiation is:

$$\dot{q} = (\varepsilon \alpha T_{Hot}^{4})A$$

Where
T is temperature (in Kelvin),
A is the area of exposure (in meters squared),
α is the thermal diffusivity (a measure of how quickly a material will adjust it's temperature to the surroundings, in meters squared per second) and
ε is the emissivity (a measure of the ability of a materials surface to emit energy by radiation).

Effects of thermal radiation

Incident thermal radiation (kW/m^2)	*Effect*
37.5 sustained	Damage to equipment and exposed steel structures
30.0 sustained	Limit for Class 1 building materials
12.5 sustained	Melting plastic
4.0	Blistering on skin on brief exposure
1.6	Severe hot feeling
1.0	Received at sea level on the equator at noon



Summary

- "Radiation is the transfer of heat energy from a hot surface or gas, the radiator, to a cooler material, the target, by electromagnetic waves without the need of an intervening medium.
- Radiant energy can be transferred only by line of sight and will be reduced or blocked by intervening materials."
- A good example of radiation heat transfer is the "heat from the sun being radiated to the earth through a vacuum."
- Another example of radiant heating is the heat that you feel that is being radiated from a fireplace when you stand in front of it.

Temperatures Vs Heat in Fire

time to ignition

Fire

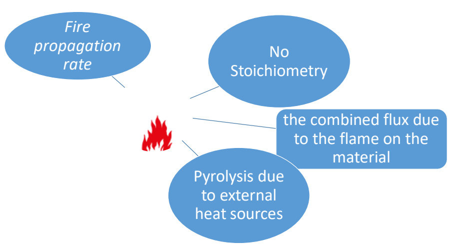
critical heat flux (CHF)

thermal response parameter (TRP)

Temperatures Vs Heat in Fire

- combustion is a rapid exothermic chemical reaction but combustion itself may be of different types.
- temperature is important in a fire
- vital parameters to determine sustenance and spread of fire…
- temperature
- total heat generated by the combustion process,
- as well as the heat release rate (HRR).
- temperatures like flash point, fire point and ignition temperatures

During a fire scenario….



Growth of Fire

- Concept of heat of combustion
- In real fires, however, different fuels may be burning simultaneously and also, fires normally do not reach complete combustion even if there is adequate ventilation.
- A part of the chemical heat release rate is transferred beyond the ignition zone through the fuel as conductive heat flux and another part as convective and radiative heat fluxes from the flame.

Growth of Fire

If this heat transfer meets the criteria
(Critical Heat Flux and Thermal Response Parameter)…

increase in flame height, → chemical heat release rate → heat flux transfer → the process repeats itself for further fire growth

Growth of Fire

- As the fire propagates and grows, pyrolysis and hence, mass loss due to gasification of the burning material also increases till it reaches a steady state.
- The mass loss rate depends on factors such as the heat flux reaching the burning material from the flame and external sources, the heat flux lost from the fuel surface by reradiation and the heat of gasification.

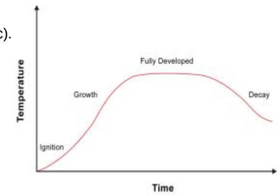
stages of a fire

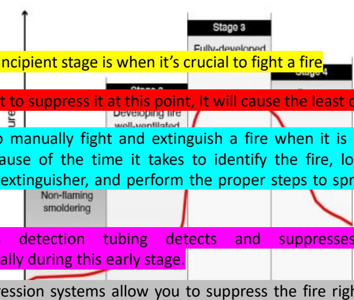
- The NFPA and most other standards classify four stages of a fire.

1. Ignition
2. Growth
3. Fully Developed
4. Decay

Fire Development is a function of many factors including

- fuel properties,
- fuel quantity,
- ventilation (natural or mechanical),
- compartment geometry (volume and ceiling height),
- location of fire, and
- ambient conditions (temperature, wind, etc).





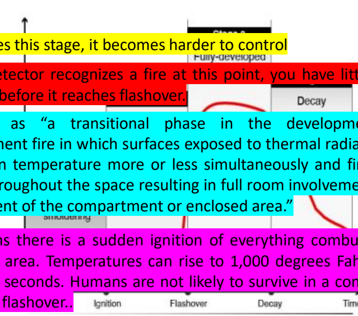
Ignition / Incipient stage is when it's crucial to fight a fire

it is easiest to suppress it at this point, It will cause the least damage

difficult to manually fight and extinguish a fire when it is in this stage because of the time it takes to identify the fire, locate a handheld extinguisher, and perform the proper steps to spray the fire.

Firetrace's detection tubing detects and suppresses fires automatically during this early stage.

Fire suppression systems allow you to suppress the fire right after ignition without needing a person to be present.

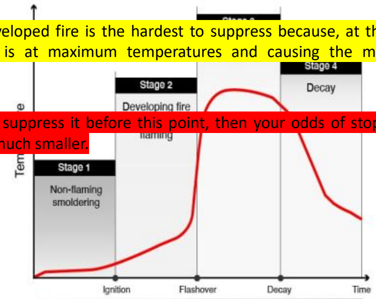


fire reaches this stage, it becomes harder to control

If a fire detector recognizes a fire at this point, you have little time to put it out before it reaches flashover.

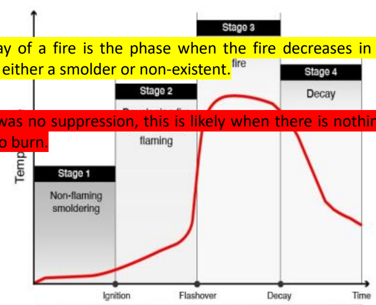
flashover as "a transitional phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach its ignition temperature more or less simultaneously and fire spreads rapidly throughout the space resulting in full room involvement or total involvement of the compartment or enclosed area."

This means there is a sudden ignition of everything combustible in a contained area. Temperatures can rise to 1,000 degrees Fahrenheit in just a few seconds. Humans are not likely to survive in a compartment that has a flashover..



Fully developed fire is the hardest to suppress because, at this point, the fire is at maximum temperatures and causing the most heat damage.

failed to suppress it before this point, then your odds of stopping the fire are much smaller.



The decay of a fire is the phase when the fire decreases in intensity until it is either a smolder or non-existent.

If there was no suppression, this is likely when there is nothing left for the fire to burn.

Fire severity

- Fire severity is a quantitative measure of the effects of a fire on the environment, typically considering both the damage to vegetation and the impacts on the soil.
- Fire severity is described along a spectrum,
  - Unburned/low severity,
  - Moderate severity, and
  - High severity.

- Fire severity is driven by multiple factors that affect how a fire behaves.
- Those factors are often depicted in what's called a "fire behavior triangle."
- The three major factors in the triangle are:
  - The weather conditions during the fire (wind, temperature, humidity)
  - The topography of the landscape (slope, aspect)
  - The amount, arrangement, and types of fuels that are present during the fire

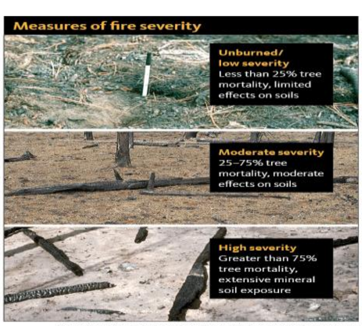
- When fires burn during extreme weather conditions, weather almost always overrides the other local factors when fuels are present.
- Weather that can lead to rapid fire growth and extreme conditions
  - wind speeds are greater than 20 miles per hour at slightly above ground level,
  - temperatures are at 80ºF or greater, and
  - relative humidity is less than 20 percent.
- Weather conditions on a fire can change daily or even within the day.

- Fire severity is also influenced by topography.
- Fires tend to be more severe on mid- and upper-slope positions than on lower slopes because wind speeds and convection winds are often greater on the upper slopes due to drainages, canyons, and saddles that channel upslope winds.
- In most cases, south- and west-facing slopes burn more severely than north-facing slopes because these aspects get more sun for longer periods.
- Natural barriers such as rock outcroppings and waterways can help to slow the spread of a fire and decrease the severity.

- The amount, arrangement, type of fuels (including live and dead vegetation), and the duration of the burn are important factors that determine how a given fire will respond to the landscape and to the degree of fire severity.
- For example, high-severity burned areas are generally associated with two types of forests:
  - Dense, multi-layered forests with "ladders" of flammable materials that allow a ground fire to ignite the canopy; and
  - Uniform, young, even-aged forests.

Factors contributed to an overall increase in fire severity

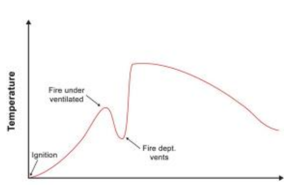
- warmer and drier climate conditions,
- past management practices (removal of fire-resistant trees and excess fuels left on the site),
- an increase in human-caused fires, and
- fire suppression (which allows the amount of fuel to increase)
- For example, areas of central, eastern, and southwestern Oregon, where fires have historically burned frequently at low and moderate severities, are now experiencing a greater proportion of high-severity fires.



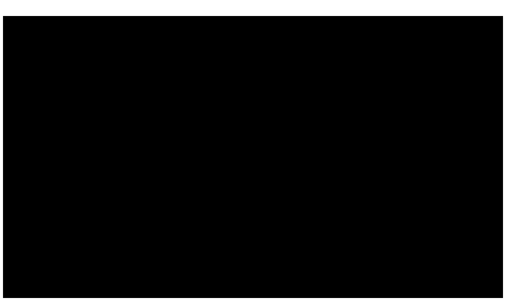
Top and middle photos: Stephen Fitzgerald, © Oregon State University
Bottom photo: Dave Powell, Umatilla National Forest

- A high-severity fire in a watershed can have negative effects on water quality due to runoff and sedimentation, or on aquatic species due to increased water temperatures from overstory vegetation damage or death.
- However, high-severity fires don't always lead to negative impacts on resources of value.
- They can also provide habitat for some species and enhance early seral biodiversity.
- In fact, many species of birds, mammals, insects, and plants depend on high-severity fire to meet their ecological requirements.
- The black-backed woodpecker is one good example.
- This bird uses patches of dead trees for nesting and foraging.

- One can't manipulate weather or topography to affect fire severity, we can manipulate fuels.
- Land managers use treatments such as thinning and prescribed fire, where appropriate, to prevent excessive fuel buildup.
- These efforts can help minimize the impact of a fire on the vegetation and soil.
- However, such measures must be deployed over large areas in order to affect a fire's behavior and severity.



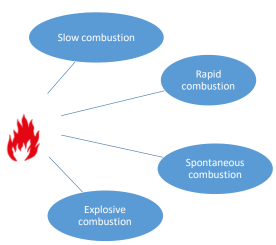
Spontaneous Heating and Spontaneous Combustion



Spontaneous Heating and Spontaneous Combustion

- *pilot ignition:* preheating and ignition by an external source
- Spontaneous heating: process of self-heating due to microbial growth and biochemical oxidation reactions of living organisms.

Types of combustion :



Difference between rapid and spontaneous combustion

Rapid combustion	Spontaneous combustion
1. It is to be initiated once.	1. It take place by itself.
2. External heat is required to start it once.	2. No external heat is required to start it.
3. Large amoutn of heat and light is evolved in a short time.	3. Small amount of heat and light is evolved.
4. Example: Burning of domestic cooking gas in a gas burner.	4. Burning of white phosphorous on its own when kept exposed in air for some time.

Spontaneous Heating and Spontaneous Combustion

- To develop into self-ignition, the activities must be exothermic and three factors interact to control the chain of events, viz.,
  - The dimensions of the stored material,
  - The ambient temperature and
  - Heat conduction through the material.

Spontaneous Heating and Spontaneous Combustion

- Spontaneous heating and fire in coal mines is a major problem worldwide
- Majority of fires existing today in different coalfields are mainly due to spontaneous combustion of coal.
- The auto oxidation of coal ultimately leads to spontaneous combustion which is the major root cause for the disastrous of coal mine in leading and coal producing countries like USA, China, Australia, India and Germany.
- It is a slow process and the heat evolved is carried away by air.

Spontaneous Heating and Spontaneous Combustion

- process of self-heating of coal or other carbonaceous material resulting eventually in its ignition is termed as “spontaneous heating” or “auto oxidation”.
- Coal can interact with oxygen in the air at ambient temperature liberating heat.
- If the heat is allowed to accumulate the interaction rate increases and may ultimately lead to fires – known as spontaneous fires.

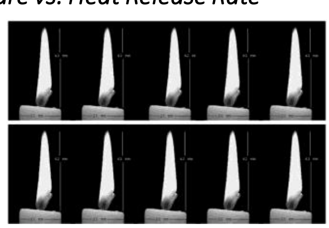
Spontaneous Heating and Spontaneous Combustion

- The exact mechanism of the reaction of oxygen with coal is not completely understood as the chemical nature of coal is not yet fully established.
- Most popular hypothesis is that the overall reaction proceeds through a chain mechanism with moisture facilitating the formation of free radicals that act as chain carrier.

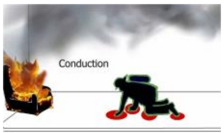
Heat Release Rate (HRR)

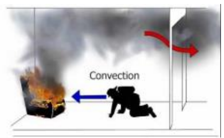
- size of a fire: People often perceive it by the height of flames or the damage done.
- Fire engineers, expressing the 'size' of a fire, by *heat release rate* (HRR).

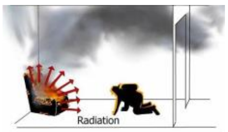
Temperature vs. Heat Release Rate

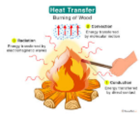


One candle vs. ten candles - same flame temperature but 10 times the heat release rate!


Conduction


Convection


Radiation


Heat Transfer
Burning of Wood