Module III – Fire Analysis
Fire Fundamentals: Definitions

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What is a Fire?

- Fire:
  - destructive burning as manifested by any or all of the following: light, flame, heat, smoke (ASTM E176)
  - the rapid oxidation of a material in the chemical process of combustion, releasing heat, light, and various reaction products. (National Wildfire Coordinating Group)
  - the phenomenon of combustion manifested in light, flame, and heat (Merriam-Webster)
  - Combustion is an exothermic, self-sustaining reaction involving a solid, liquid, and/or gas-phase fuel (NFPA FP Handbook)
What is a Fire?

- Fire Triangle – hasn’t change much…
- Fire requires presence of:
  - Material that can burn (fuel)
  - Oxygen (generally from air)
  - Energy (initial ignition source and sustaining thermal feedback)
- Ignition source can be a spark, short in an electrical device, welder’s torch, cutting slag, hot pipe, hot manifold, cigarette, …
Materials that May Burn

- Materials that can burn are generally categorized by:
  - Ease of ignition (ignition temperature or flash point)
    - Flammable materials are relatively easy to ignite, lower flash point (e.g., gasoline)
    - Combustible materials burn but are more difficult to ignite, higher flash point, more energy needed (e.g., wood, diesel fuel)
    - Non-Combustible materials will not burn under normal conditions (e.g., granite, silica...)
  - State of the fuel
    - Solid (wood, electrical cable insulation)
    - Liquid (diesel fuel)
    - Gaseous (hydrogen)
Combustion Process

- Combustion process involves . . .
  - An ignition source comes into contact and heats up the material
  - Material vaporizes and mixes up with the oxygen in the air and ignites
  - Exothermic reaction generates additional energy that heats the material, that vaporizes more, that reacts with the air, etc.
  - Flame is the zone where chemical reaction is taking place

- Flame - A flame is the visible (light-emitting) part of a fire. It is caused by an exothermic reaction taking place in a thin zone where fuel vapors and oxygen in the air meet.
What is Fire?

- Fuel gas
- Heat flux
- Solid fuel
- Flammable mixture
- Oxygen in air
- Spark
Flame Characteristics

- Flame characteristics
  - Flame color depends on the material burning and how it burns
    - The nature of the combustion products
    - How hot material burns
    - How “cleanly” the material burns
      - How efficient the burning is, oxygen availability
  - Most flames are visible to the naked eye
    - What you actually see is glowing particulate (e.g. soot)
    - Fuels that burn cleanly (less soot), have less visible flames
      - e.g., Hydrogen produces a nearly invisible flame
  - Flame temperature can range from 1,500°F to 3,500°F
Definitions

Three “modes” of heat transfer are in play during a fire:

- **Conduction** – Heat transfer through a solid material or between two adjacent stationary solids directly through the contact interface between them
  - Example: Cooling your hand by putting it on a cold surface

- **Convection** – Heat transfer between a moving fluid and the surface of a solid or liquid material
  - Example: Blowing across a spoonful of hot soup to cool it

- **Radiation** – Heat transfer between two objects separated by open space via the transfer of electromagnetic energy. Requires that the objects be within line of sight of each other and separated by a relatively transparent medium (e.g., air or vacuum).
  - Example: Warming your hands by the camp fire
Effects of a Fire

What does a fire do to its surroundings?

- A fire generates heat, smoke and various combustion products
  - Heat is the main adverse effect of concern in a nuclear power plant
- Heat generated by the fire is transferred to nearby targets mainly by radiation and convection
  - Conduction plays a role in fuel heating and heat absorption into a target but, for most cases, not in direct transfer of heat from the fire to targets
- Products of combustion also include carbonaceous soot and other species such as HCl, HCN, water vapor, CO, CO₂, ...
  - Smoke and soot can adversely affect equipment
  - Smoke can hinder plant operators and fire response
  - HCl and HCN can be irritants for plant personnel
  - CO kills…
Fire Plume

- **Fire plume**: the buoyant stream of heated air and combustion products rising above a fire
- The fire plume forms quickly over the fire…
  - The fire produces very high temperature combustion products which rise from the fuel surface due to buoyancy
  - Rising combustion products draw in and mix with fresh air from the surroundings (**entrainment**)
    - Some of the available oxygen is consumed in the combustion process
  - Entrained air is heated as it absorbs energy from the fire
  - The mixture of hot gases rises forming the fire plume
  - The plume can envelope items above the fire with very hot gases
  - The energy carried away by the fire plume generally accounts for over half of the energy generated by a fire
The fire plume (continued)

- The fire plume typically carries away ~40%-70% of total heat production from the fire

- The Convective fraction ($X_c$) is the fraction of the net energy produced by the fire and emitted into the surroundings via heated gasses in the plume
  - $X_c \sim 0.6$ is a typical assumption for most fires

- The fire plume is very important to fire PRA. We often analyze fires where important plant cables are located in the fire plume.
  - Temperatures are higher in the fire plume than anywhere other than the flame zone itself
Definitions

So what happens when the plume hits the ceiling?

- **Ceiling Jet** – When the fire plume hits the ceiling, the flowing gasses turn 90° and form a relatively thin layer of flowing gas just below the ceiling
  - Important to the activation of sprinklers and fire detectors (more later…)

…and when the ceiling jet hits the walls?

- **Wall plume** – if/when the ceiling jets reaches a wall, the gasses will turn downward flowing down the wall
  - The wall absorbs energy from the gasses cooling them
Definitions

In the longer term, the compartment will fill with hot gasses…

- **Hot Gas Layer** – As a fire progresses within an enclosure, the heated air and combustion products tend to collect as a heated layer between the ceiling and somewhere above the floor (sometimes called the smoke layer or upper layer as well)

vs. …

- **Lower or Cold Gas Layer** – The gasses that remain between the bottom of the HGL and the floor and that generally remain at near ambient temperatures

- The **depth** of the HGL (distance from the ceiling to the bottom of the HGL) will be determined largely by ventilation conditions (e.g., an open door, open window…)

Radiative Heating from a Fire

- Radiative heat is produced by the luminous flames and emitted in all directions
  - Some radiative energy points back towards the fuel and acts to evaporate more fuel to continue the combustion process (thermal feedback)
  - The rest points away from the fire into the surroundings
  - The radiative fraction \( (X_r) \) is the fraction of the net energy produced by the fire and emitted into the surroundings via radiation:
    - \( X_r = 1.0 - X_c \)
      (if it’s heat from the fire and it’s not convection, it must be radiation…)
    - \( X_r \sim 0.4 \) is typical
Flame Spread and Fire Propagation

- Flame spread is the propagation of combustion across a fuel surface, to an adjacent fuel material, or to nearby items
  - Radiation, convection, and conduction can all act to heat fuels near the existing burn region
  - Ignition can occur when temperatures ahead of the existing flame reach the point of ignition, and the flame spreads

- Flame spread *usually* refers to spread across or within a single object or fuel package
- Fire propagation *usually* refers to fire spread from one object to another
- Neither is universal so be careful…
Definitions

- **Pyrolysis** – the breakdown of the molecules of a solid material from exposure to heat into gaseous molecules that may combust in the flame.

- **Smoldering** – A slow combustion process without visible flames that occurs in a porous solid fuel
  - e.g., charcoal briquettes in the barbeque or wood in a fire pit as the fire burns down
  - Generally occurs because of limited oxygen access to the burning surfaces. It can generate large quantity of carbon monoxide which is lethal if inhaled.
Definitions

- **Piloted ignition** – Ignition of a combustible or flammable material in the presence of a pre-existing flame (the “pilot” flame)

  vs. …

- **Non-piloted (or spontaneous) ignition** – Ignition of a combustible or flammable material without an ignition source, which is generally caused by raising material temperature above its **auto-ignition temperature**.

- Piloted ignition generally occurs at a lower temperature than spontaneous ignition
  - the pilot flame provides that extra “oomph” to achieve ignition

- **Spontaneous combustion** is a little different – the initiation of combustion due to self heating of a fuel without an external heating source or pilot flame (e.g., a pile of oily rags…)
Definitions

- **Diffusion Flame** – The flame of a burning material (liquid or solid) where the combustion process occurs at the interface where vaporized fuel comes into contact with the oxygen in the air (e.g., flame on top of a candle or the wood in a fireplace.)

  vs. …

- **Pre-mixed Flame** – The flame of burning gaseous material that is mixed with air upstream of the flame (e.g., the flame of a gas range or gas fired furnace)

- Most of the fires we are concerned with involve diffusion flames
Definitions

- **Laminar Flame** – a flame with smooth, regular and very uniform flow of gases
  - In a laminar flame the mixing of air and fuel vapors is not very efficient and the flame zone is very narrow
  - Laminar flames ~3,500 °F (~1925 °C) e.g., a candle flame

- **Turbulent Flame** – a flame with a more irregular and chaotic flow of gases including the formation of large vortices
  - Turbulent flames are more efficient because mixing entrained air with fuel vapors/products creates a larger region where combustion can occur
  - Turbulent flames ~1,500 °F (~815 °C), e.g., most real fires

- Most flames greater than a few inches tall demonstrate turbulent (non-laminar) behavior because of increased gas velocities caused by increased heat.
Definitions

Some key fire characteristics…

- **Mass Loss Rate (Burning Rate)** – The rate of mass loss of a burning material in a fire
  - May be expressed as either mass released per unit time (g/s) or mass released per unit area per unit time (g/cm²·s).

- **Heat Release Rate (HRR)** – The energy released from a fire per unit time (kW)
  - HRR is generally expressed as net energy release which accounts for thermal feedback to the fuel and combustion efficiency – i.e., the net rate of energy released by the fire

- **Heat Flux** – the rate of heat transfer expressed as energy delivered per unit time per unit area (kW/m²). Heat flux is a good measure of fire hazard.
Definitions

- **Heat Release Rate Profile** – The fire’s HRR expressed as a function of time
  - Example: NRC/SNL electrical cabinet fire tests . . .
  - A complete HRR profile may involve 5 stages:
    - Incipient
    - Growth
    - Steady state or peak burning
    - Decay
    - Burnout

![Graph showing HRR profiles](image)

Figure 8. Heat Release Rate Plots for Scoping Tests #1 through 5
Definitions

- **Fire in the Open** – A fire occurring in a large or unconfined space such that there is no feedback between the fire and the ambient environment vs. …

- **Compartment Fire (Enclosure Fire)** – A fire occurring in an enclosed space such that the fire impact its surroundings creating a feedback effect; e.g.
  - The walls get hot and feed radiant energy back to the fire
  - A HGL forms and feeds radiant energy back to the fire
  - The HGL descends to the floor and reduces the oxygen available to the fire

- We deal mainly with compartment fires
Definitions

- **Fuel Limited Fire** – A fire where the fuel burning rate is limited only by the surface burning rate of the material.
  - Plenty of oxygen…

vs. …

- **Oxygen Limited Fire** – A fire (typically inside a compartment or enclosure) where the fuel burning rate is limited by oxygen availability
  - Not enough air for fire to grow beyond a certain point

- We tend to deal primarily with fuel limited fires, but cabinet fires, for example, may be oxygen limited
Definitions

- **Lower flammability limit** – the minimum concentration of fuel vapor in air in a pre-mixed flame that can sustain combustion
  - A mixture that is too lean (not enough fuel) will not burn
- **Upper flammability limit** – the maximum concentration of fuel vapor in air that can sustain combustion
  - A mixture that is too rich (too much fuel) will not burn
- **Stoichiometric ratio** - the optimum theoretical mix of fuel and air to achieve complete combustion of that fuel
  - Fuel burns completely and consumes all available oxygen
- **Fuels will burn in air only if the concentration is between the lower and upper flammability limits**
Definitions

- **Zone-of-Influence (ZOI)** – The area around a fire where radiative and convective heat transfer is sufficiently strong to damage equipment or cables and/or heat other materials to the point of ignition.

- **Fire Modeling vs. Fire Analysis Tasks** – Fire modeling is the analytical process of estimating the behavior of a fire event in terms of the heat flux impinging material near the fire and behavior of those materials as a result of that.
Definitions

We classify cable insulation materials based on two major categories:

- **Thermoplastic (TP):** capable of softening or fusing when heated and of hardening again when cooled (Merriam-Webster)
  - TP materials melt when heated and solidify when cooled

- **Thermoset (TS):** capable of becoming permanently rigid when heated or cured (Merriam-Webster)
  - On heating TS materials may soften, swell, blister, crack, smolder and/or burn but they won’t melt

- Both types are used in U.S. NPPs
- Much more on cables to come.
Questions…

… before we move on?

- Up next:
  - Fundamental concepts of fire behavior, modeling and analysis