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UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Module III – Fire Analysis

Fire Fundamentals: Definitions

Joint EPRI/NRC-RES Fire PRA Workshop

August 21-25, 2017

A Collaboration of the Electric Power Research Institute (EPRI) & U.S. NRC Office of Nuclear Regulatory Research (RES)

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, …

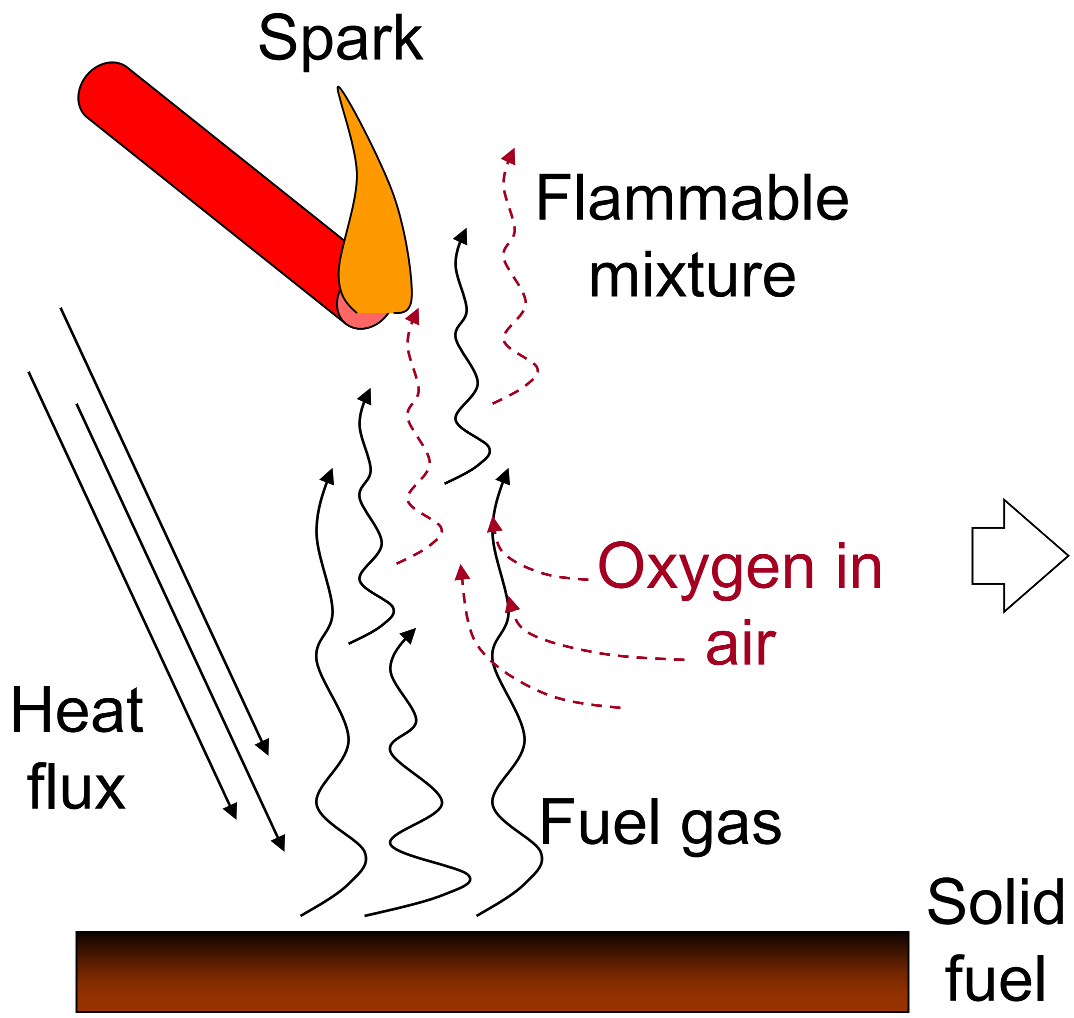
Materials that May Burn

- 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?


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

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^{o}F to 3,500^{o}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

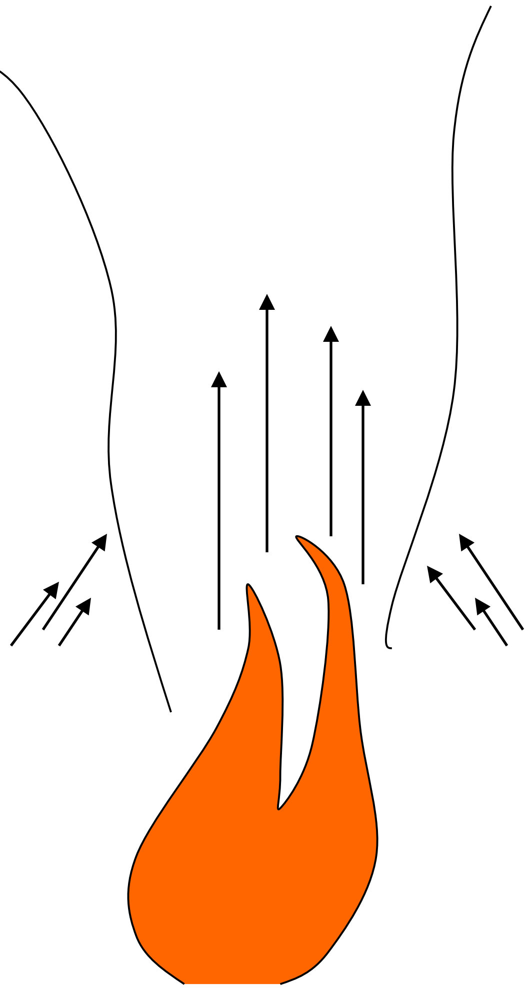
Effects of a Fire

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, CO_2, …
  - 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. …

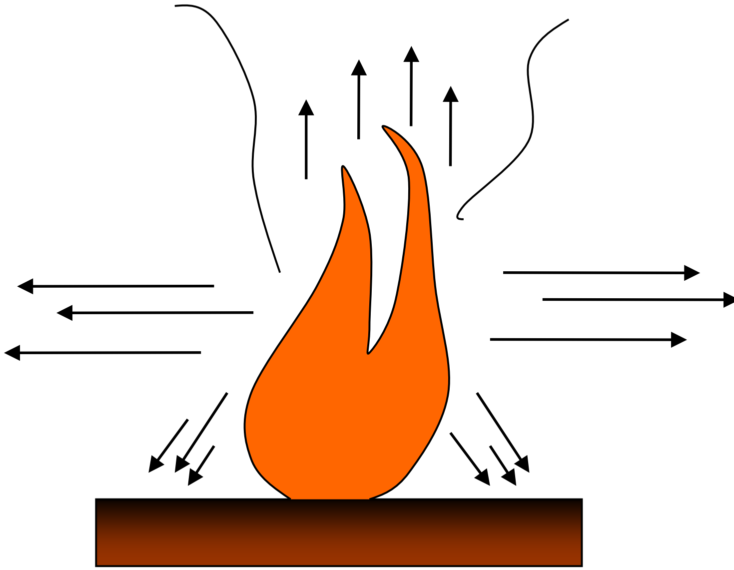
- Lower or Cold Gas Layer – The gasses that remain between the bottom of the HGL and the floor and that generally remain at near ambient temperatures

- 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



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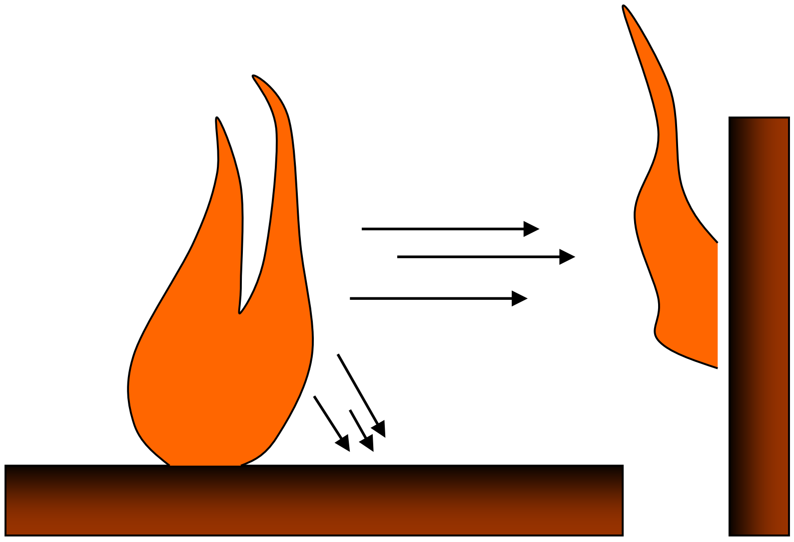
Flame Spread and Fire Propagation

- 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

vs. …

- 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 ocurr
    - 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 ($g/cm^2 \cdot s$).
- 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/m^2). 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

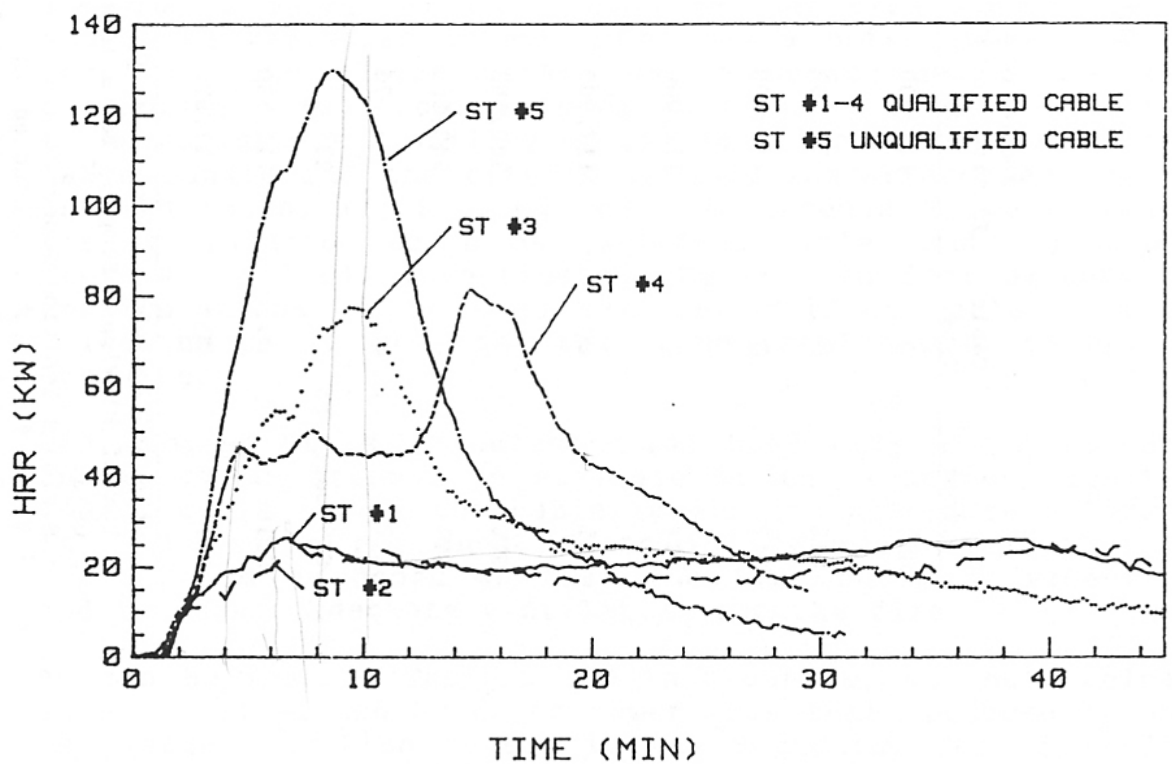


Figure 8. Heat Release Rate Plots for Scoping Tests #1 through 5

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