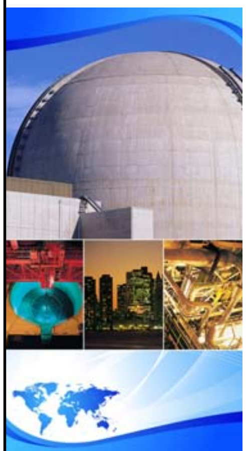


EPRI/NRC-RES FIRE PRA METHODOLOGY

Definitions

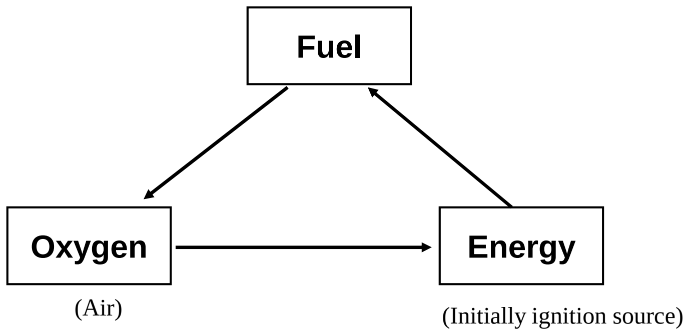
A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)

What is a Fire?

- Fire is an exothermic chemical reaction involving a fuel and oxygen in the air
  - Requires presence of:
    - Material that can burn, the fuel
    - Oxygen (air)
    - Energy (initial ignition source)
  - Ignition source can be a spark, short in an electrical device, etc.

What is a Fire?

- Fire Triangle



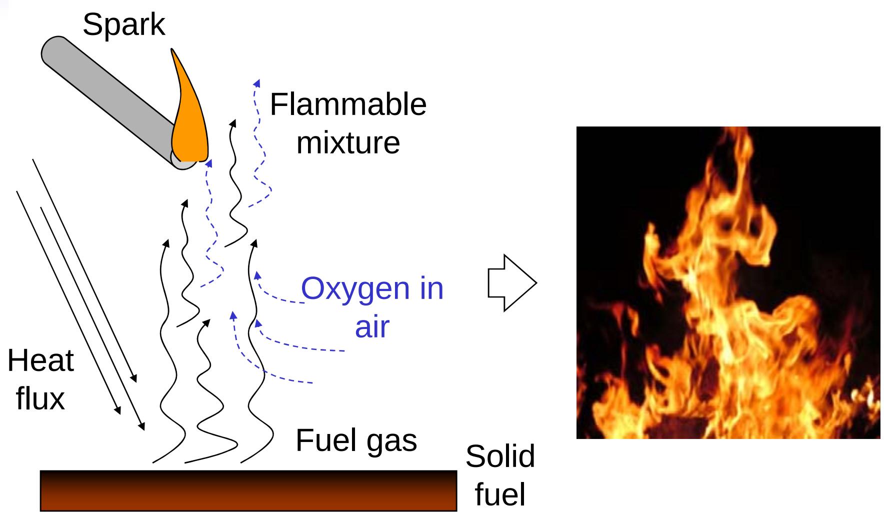
Materials that May Burn

- Materials that can burn are generally categorized by:
  - Ease of ignition (ignition temperature or flash point)
    - Flammable materials (e.g., gasoline)
    - Combustible materials (e.g., wood, high ignition temperature oils, and diesel fuel)
  - State
    - 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

What is Fire?



Flame Characteristics

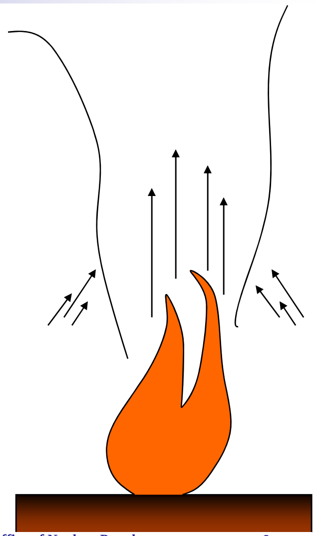
- Flame characteristics
  - Flame color depends on the material burning
  - Most flames are visible to the naked eye
  - Flame temperature can range from 1,500ºF to 3,500ºF – For example . . .
    - Laminar flames ~ 3,500 ºF, e.g., a candle flame
    - Turbulent flames ~ 1,500 ºF, e.g., a fire place

Effects of a Fire

- A fire generates heat, smoke and combustion products
  - Heat is the main adverse effect of concern in a nuclear power plant
  - Heat generated by the fire is transferred by radiation and convection
  - Products of combustion include soot and other species such as HCL, etc.
    - Smoke and soot can adversely affect equipment
    - Smoke can be a hindrance to plant operators

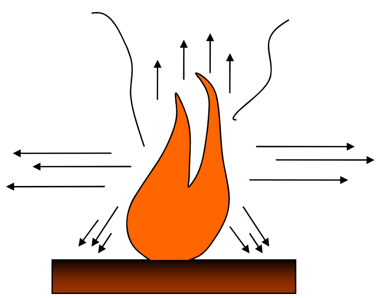
Fire Plume

- A fire plume . . .
  – Draws fresh air from the surroundings
  – A part of the air gets used in the flame
  – Air drawn above the flames gets heated up
  – The hot gases rise and envelope items above the fire with very hot gases
  – Hot gases transfer the larger portion of the energy generated by a fire by convection



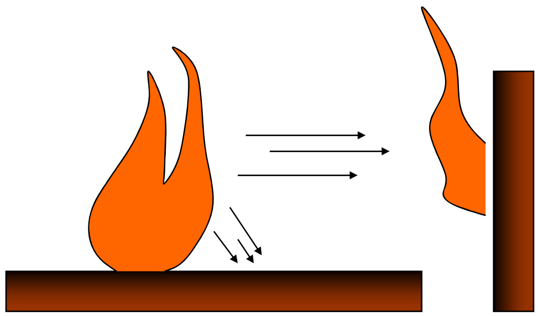
Radiative Heat of a Fire

- Radiative heat from a fire is emanated from the flame in all directions
  – A part of the radiative heat evaporates the fuel to continue the combustion process



Flame Spread and Fire Propagation

- Flame spread is a series of ignitions that can lead to fire propagation to adjacent or nearby items



Definitions

- Pyrolisis – Breakdown of the molecules of a solid material from exposure to heat into gaseous molecules that combust in the flame.
- Spontaneous Ignition – Ignition of a combustible or flammable material without an ignition source, which is generally done by raising material temperature above its auto-ignition temperature.
- Smoldering – A slow combustion process without visible flames that occurs in a porous solid fuel (e.g., burning of charcoal brickets or wood in a fire pit). 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

- Fire Plume - A fire plume is a buoyant column of hot air rising above the base of a fire
- 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.

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.)
- 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)
- Laminar Flame – A flame with laminar flow of gases (e.g. typical candle flame). Most flames greater than 1 ft tall demonstrate turbulent (non-laminar) behavior because of increased gas velocities caused by increased heat.

Definitions

- Conduction – Heat transfer between two adjacent stationary media through the interface between them (e.g., putting your hand on a cold surface)
- Convection – Heat transfer between a moving fluid and a solid or liquid material (e.g., blowing over a hot food to cool it down)
- Radiation – Heat transfer through open space via electromagnetic energy between two materials of different temperatures that are within line of sight of each other (e.g., infra-red radiation from a very hot material).

Definitions

- Mass Loss Rate (Burning Rate) – The rate of mass loss of a burning material in a fire. It is commonly expressed in terms of mass per unit area per unit time (e.g., 10 g per cm^2 per second).
- Heat Release Rate (HRR) – The energy release per unit time from a combustible material (kW)
- Heat Flux – Heat transferred expressed per unit time per unit area (kW/m^2). Its is a good measure of fire hazard.

Definitions

- Heat Release Rate Profile – The heat release rate as a function of time.
  - Example . . .

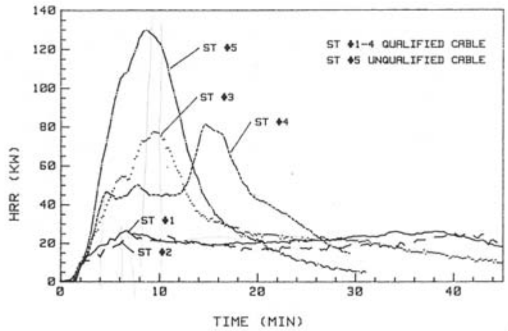


Figure 8. Heat Release Rate Plots for Scoping Tests #1 through 5

Definitions

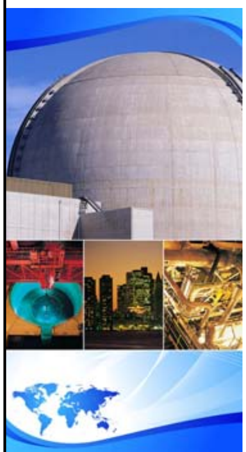
- Fire in the Open – A fire event where heat generated from the fire is limited by the surface burning rate of the material. In other words sufficient air is always available for the fire.
- Compartment Fire – A fire inside a compartment, which may be affected by:
  - Oxygen availability
  - Feedback form compartment boundaries

Definitions

- Upper and Lower Flammability –Concentration of a flammable gas in air in a pre-mixed flame that can sustain combustion. If the mixture is close to lower flammability limit, it is too lean. If the mixture is close to the upper flammability limit, it is too fuel rich.
- 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

- 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 heatup other materials to the point of auto-ignition.



EPRI/NRC-RES FIRE PRA METHODOLOGY

Fires in the Open and Fully Ventilated Fires

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

Fire in the Open

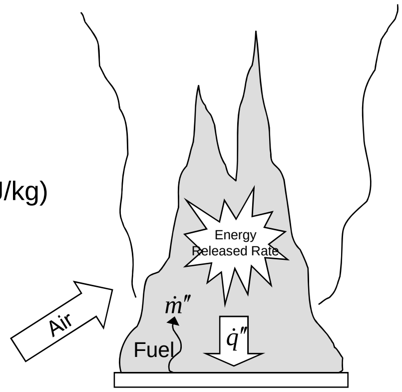
- A fire event where heat generated from the fire is limited by the surface burning rate of the material.
- Sufficient air is always available for the fire.
- Generates hot gases and radiative heat

Heat Release Rate

- The heat release rate from a fire can be estimated using the following equation:

$$\dot{Q} = \dot{m}'' \cdot A \cdot \Delta H_c$$

  - $\dot{m}''$ is the burning mass flux
  - ΔHc is the heat of combustion (kJ/kg)
  - A is the burning area (m2)

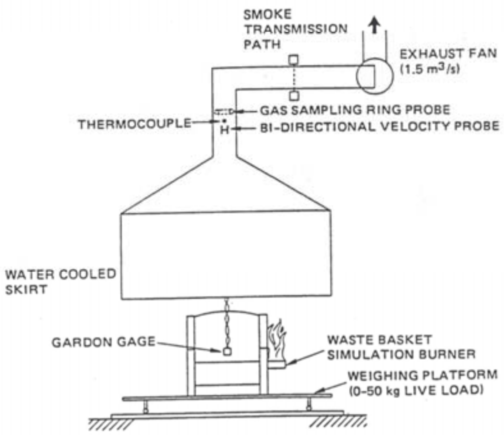


Heat Release Rate

- Can be estimated experimentally using oxygen consumption calorimeters

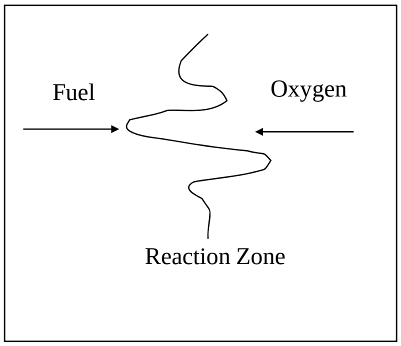
$$\dot{Q} = \dot{m}_{O_2} \cdot \Delta H_c (kJ / kg_{O_2})$$

  - ΔH_c = 13.1 kJ/kg_{O2}



Flames

- Laminar
- Turbulent



Ignition of Gases

- With a spark or small flame (pilot) present, ignition is based on whether the gaseous fuel concentration is between the upper (rich) and lower (lean) flammability limits.
  - The fuel-air (oxidizer) mixture is said to be flammable if a flame will propagate in this mixture.
- For no pilot present, a gaseous fuel in air can also ignite if the mixture is at or above the auto-ignition temperature.
  - The auto-ignition temperature is usually measured for a stoichiometric mixture in which no fuel and oxygen remain after the reaction.

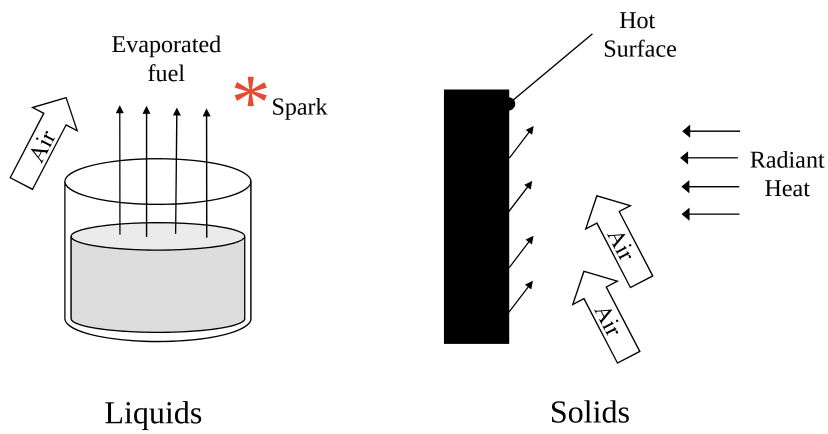
Ignition of Liquids

- For a liquid to ignite, it must first evaporate sufficiently to form a flammable mixture in the presence of a pilot.
  - This occurs at a liquid temperature called a flash-point temperature.
  - In general, this can be called the piloted ignition temperature and the term carries over to solids.
  - The flash-point is the temperature at which the amount of liquid evaporated from the surface achieves the lower flammable limit.
- If no pilot is present, the mixture must be heated to the auto-ignition temperature.
- Auto-ignition temperature of gases is above its boiling point.

Ignition of Solids

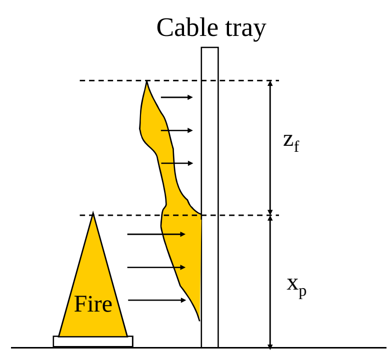
- Solids do not vaporize like liquids when heated. They form gaseous decomposition compounds leaving behind possible char in a process called pyrolysis.
- At some point, the gases ignite by piloted ignition or auto-ignition.
- Typically, piloted ignition temperatures for solids range from 250°C (~480°F) to 450°C(~840°F).
- Auto-ignition temperatures can exceed 500°C (~930°F).
  - For a given material, these temperatures are not constants and can change with the nature of heating.
  - For practical purposes, a (piloted) ignition temperature (T_{ig}) may be treated as a property of a combustible solid.
- We shall consider thin (less than ~1 mm) and thick solids to have different time responses to ignition when exposed to impinging heat flux

Ignition



Flame Spread

- Motion of vaporization front at the ignition temperature for solids and liquids



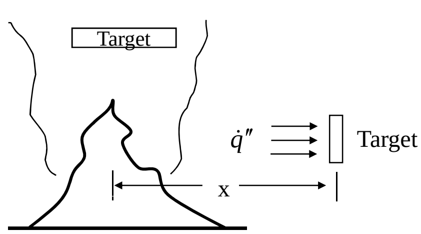
Typical Flame Spread Rates

- It is very difficult to compute flame spread rate because formulas are not completely available, rates may not be steady, and fuel properties are not generally available. Nevertheless, we can estimate approximate magnitudes for spread rates based on the type of system. These estimates are listed below:

Spread	Rate (cm/s)
Smoldering solids	0.001 to 0.01
Lateral or downward spread on thick solids	0.1
Upward spread on thick solids	1.0 to 100. (0.022 to 2.2 mph)
Horizontal spread on liquids	1.0 to 100.
Premixed flames (gaseous)	10. to 100.(laminar)
	$\approx 10^5$ (detonations)

Zone of Influence

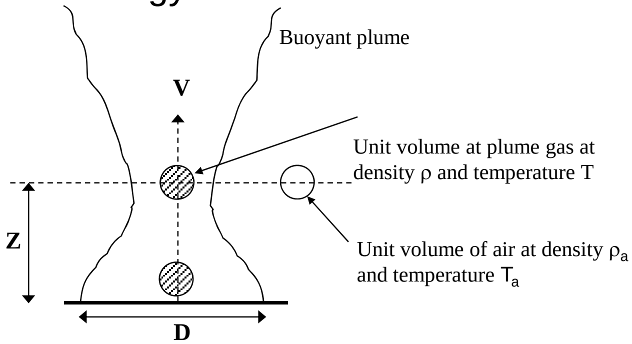
- Regions nearby the fire where damage is expected. For fires in the open:
  - Flame Radiation



  - Convection inside the fire plume

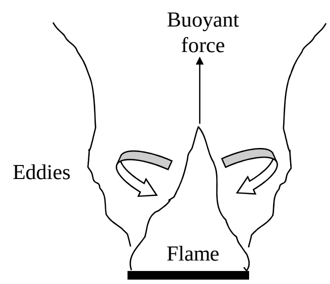
Buoyant Flow

- Temperature rise gives a decrease in density
- Potential energy converted into kinetic energy



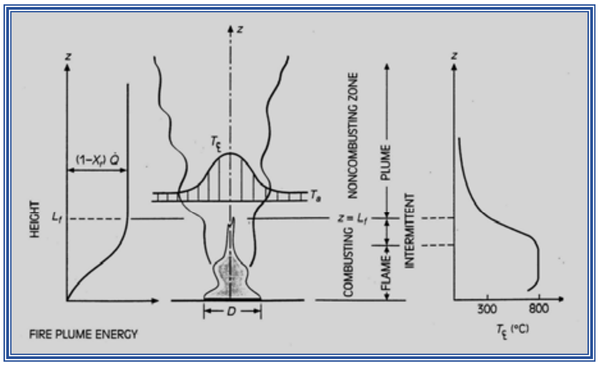
Turbulent Entrainment

- Entrainment is air drawn into the fire plume by upward movement of the buoyant plume
- Engulfment of air into the fire plume
- Eddies: fluctuating and rotating balls of fluid, large scale rolling-up fluid motion on the edge of the plume.

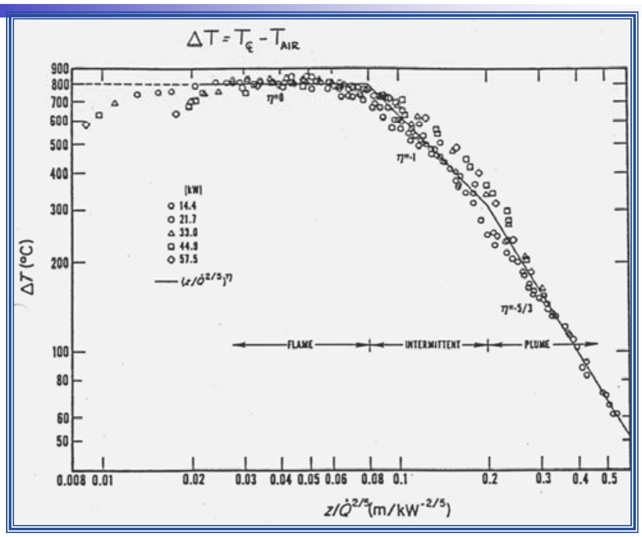


Turbulent Fire Plume

- Very low initial fuel velocity
- Entrainment and flame height controlled by buoyancy



Fire Plume Temperature Along the Centerline



Example Case - Zone-of-Influence Calculation
Flame Height and Plume Temperature

$$L = 0.235\dot{Q}_f^{2/5} - 1.02D$$

Heskdestad's Flame Height Correlation

Input
D - Fire diameter [m] 0.6
Q_f - HRR [kW] 250

Result
L - Flame height [m] 1.5

$$T_{pl} = T_{amb} + 25\left(\frac{\left(k_f \dot{Q}_f (1-\chi_r)\right)^{2/5}}{\left((H_p - F_e) - z_o\right)}\right)^{5/3}$$

$$z_o = 0.083\dot{Q}_f^{2/5} - 1.02D$$

Heskestad's Plume Temperature Correlation

Input
T_{amb} - Ambient temperature [C] 20
Q_f - HRR [kW] 250
F_e - Fire elevation [m] 0
H_p - Target Elevation [m] 3.7
z_0 - Fire Diameter [m] 1

Result
T_{pl} - Plume Temp [C] 328

Example Case - Zone-of-Influence Calculation
Radiation Heat Flux

- Flame Radiation: Point Source Model

$$\dot{q}''_{irr} = \frac{\dot{Q}_f \chi_r}{4\pi R^2}$$

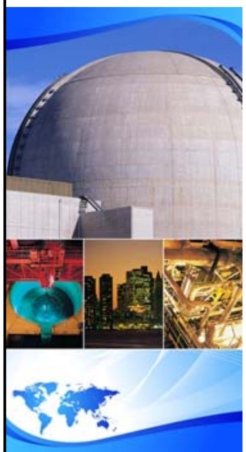
Input Parameters:
- Q_f: Fire heat release rate (kW)
- R: Distance from flames (m)
- X_r: Radiation fraction of the heat release rate (FIVE recommends 0.4)
- D: Fire diameter (m)

Example Case - Zone-of-Influence Calculation

Radiation Heat Flux

$$\dot{q}''_{irr} = \frac{\dot{Q}_f \chi_r}{4\pi R^2}$$

Point Source Flame Radiation Model	
Inputs	
Fire heat release rate [kW]	317
Radiation fraction	0.40
Distance from flames [m]	1.5
Results	
Heat flux [kW/m2]	**4.5**



EPRI/NRC-RES FIRE PRA METHODOLOGY

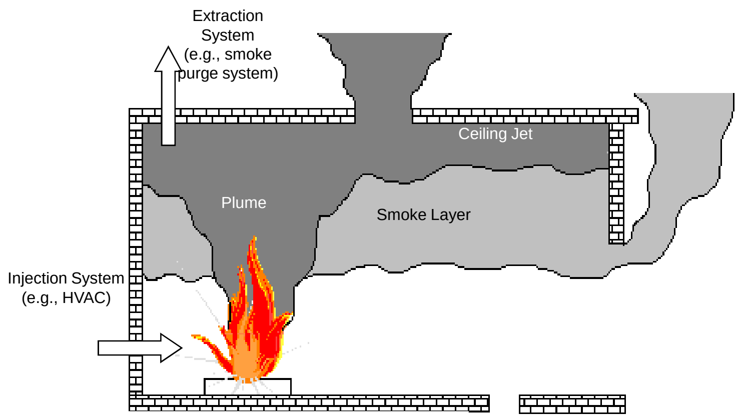
Compartment Fires

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

Outline

- Enclosure fire dynamics – qualitative description
- Pressure profiles and vent flows
- The hot gas layer
- Heat transfer
- Combustion products

Qualitative Description



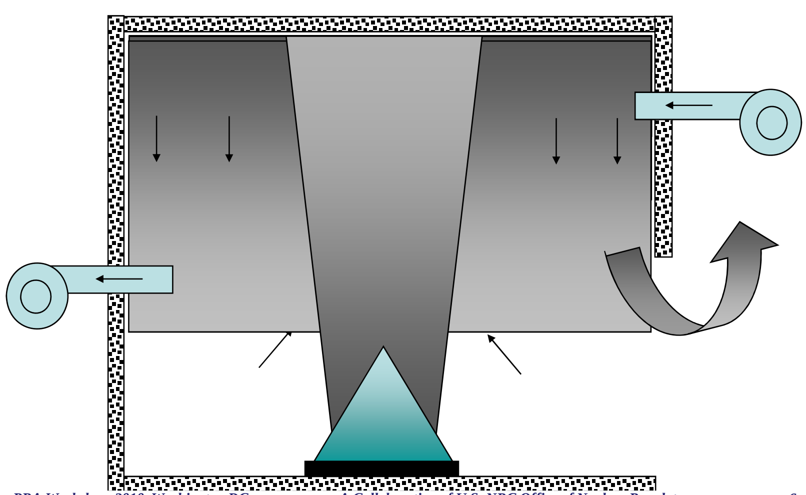
Phases in a Compartment Fire

- Ignition: Process that produces an exothermic reaction
  - Piloted or spontaneous
  - Accompanying process can be flaming or smoldering combustion
- Growth
  - Can occur at different rates depending on type of fuel, interactions with surroundings, and access to oxygen
- Hot gas layer buildup and room heatup
- Flashover: Rapid transition to a state of total surface involvement of combustible materials within an enclosure
  - Temperatures between 500°C (930°F) to 600°C (1,110°F), or
  - Heat fluxes between 15 kW/m2 to 20 kW/m2

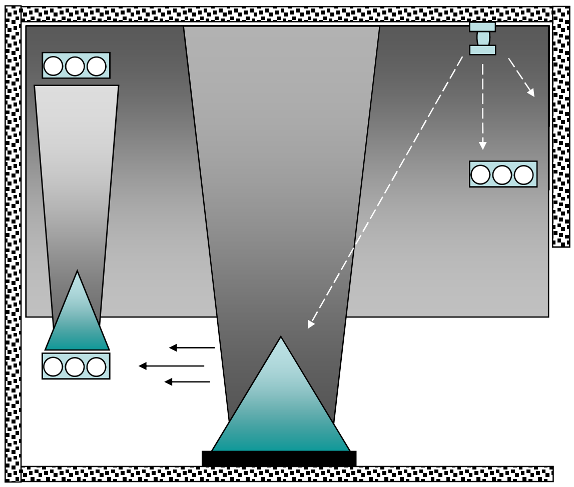
Phases in a Compartment Fire

- Fully developed fire: The energy released in the enclosure is at its greatest level and is very often limited by the available oxygen
  - Gas temperatures between 700°C (1,300°F) and 1200°C (2,200°F)
- Decay: Fuel becomes consumed
  - Hazard indicators (temperature and heat fluxes) start to decrease
- Other terminology may include
  - Pre-flashover fire
    - Focus on life safety and sensitive targets
    - In NPP, cables damage at 218°C (424°F) for thermoplastic cables and 330°C (626°F) for thermoset cables
  - Post-flashover fire:
    - Focus in structural stability and safety of firefighters

Compartment Fires



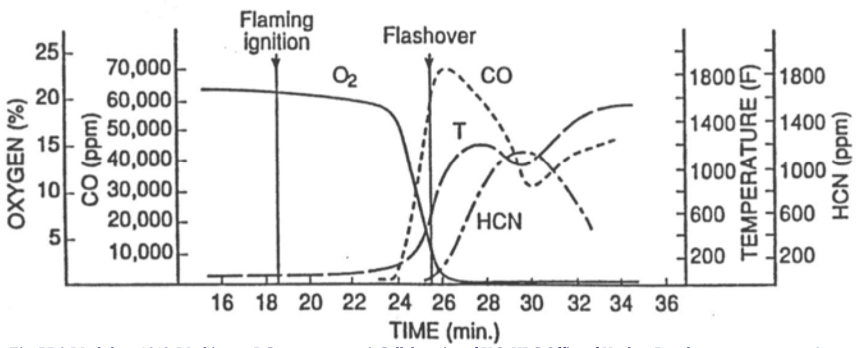
Compartment Fires



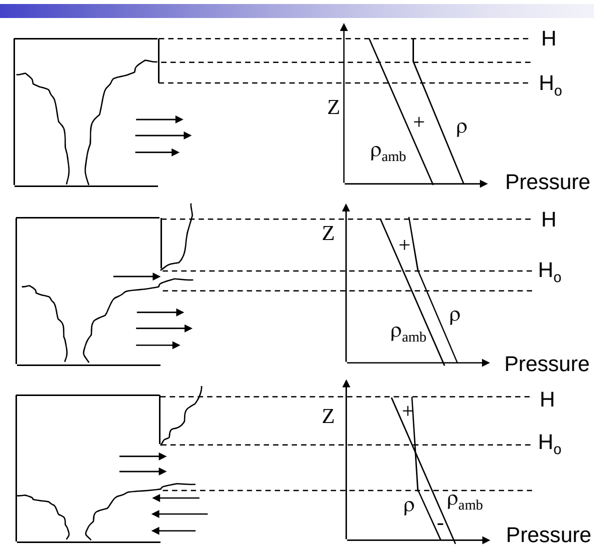
Sense of Scale

Room: 12 x 18 x 8 ft. high; open doorway

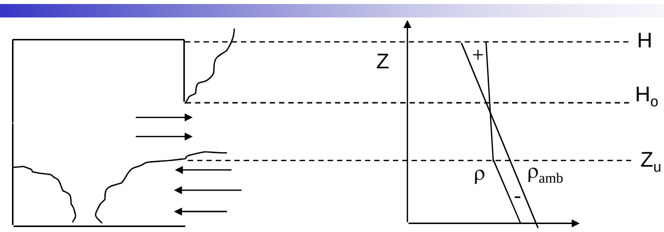
Data at 5.5 ft. height



Pressure Profiles & Vent Flows



Pressure Profiles & Vent Flows



$$P_i(h) = P_i(0) - \rho_o g Zu - \rho_u g(h - Zu)$$

Inside Profile

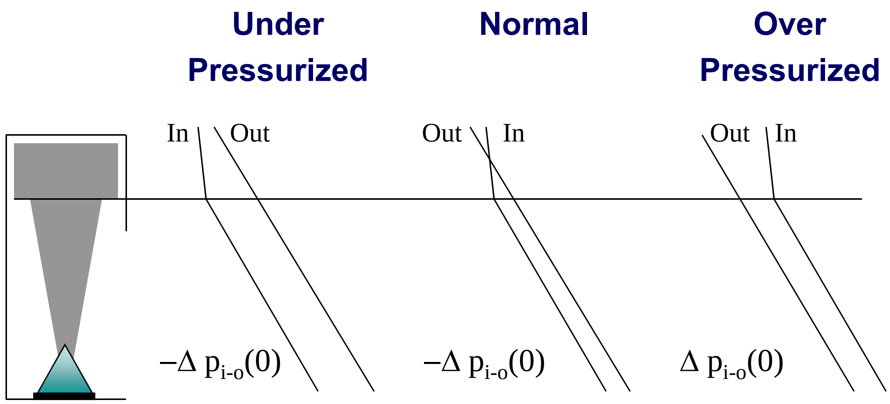
$$P_o(h) = P_o(0) - \rho_o gh$$

Outside Profile

$$\Delta P_{i-o}(h) = \Delta P_i(0) + \rho_o g(h - Zu) + \rho_u g(Zu - h)$$

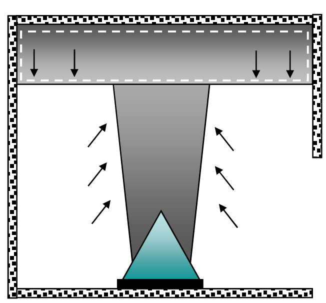
ΔP Profile

Pressure Profiles & Vent Flows



Smoke Layer

- Accumulation of hot gases in the upper part of the room
- Mass: entrainment (~90%) and combustion products (~10%)
- Volume: entrainment, combustion products, and expansion due to energy added
- Temperature rise: expansion generates a larger volume than corresponding mass resulting in lower gas densities.
- Conservation of mass and energy

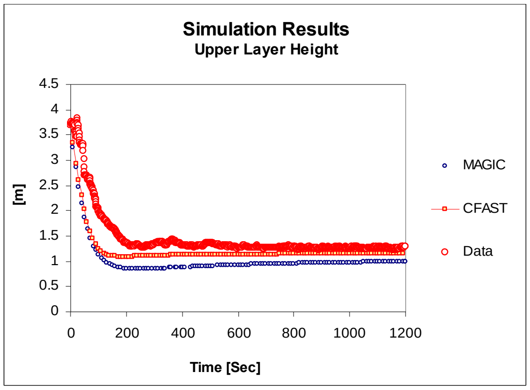


Smoke Layer

Room size:
- 22 x 7 x 3.7 m

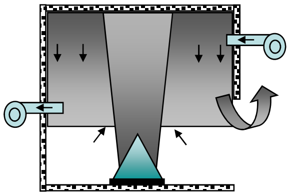
Fire: ~1 MW

Door: 2 x 2 m



Smoke Layer

- Conservation of Mass
  - Rate of change of mass in the control volume
    - Accumulation
  - Mass flow through the control surface
    - Plume flow
    - Supply and exhaust systems
    - Flow through doors and windows

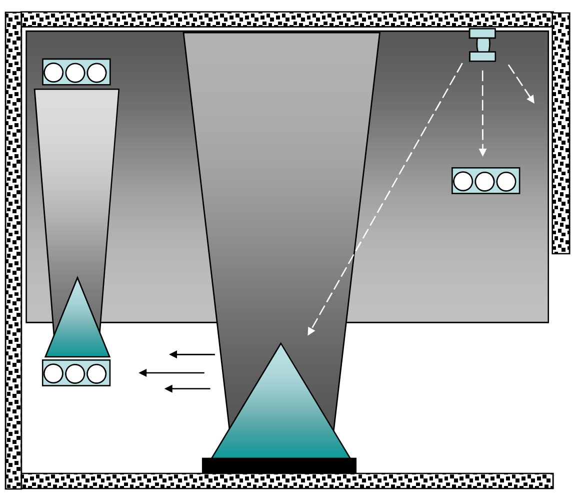


Heat Transfer

- To walls
  - Convection and radiation
  - Conduction losses
- To targets
  - Convection and radiation
- Heat losses
  - Conduction through walls
  - Convection and radiation through openings and vents

Heat Transfer

- Conduction
- Convection
- Radiation



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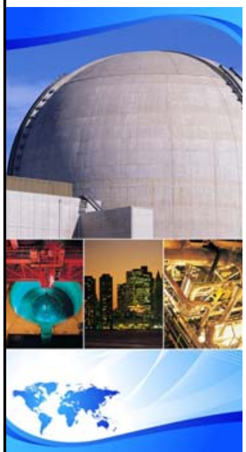


EPRI/NRC-RES FIRE PRA METHODOLOGY

Detection and Suppression

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

Objectives

- Fire PRA credits fire detection and suppression features when appropriate
- The objective of this presentation is to briefly describe typical detection and suppression features that are credited

Fire Detection

- Typical fire detection features credited in the Fire PRA
  - Prompt detection
  - Smoke detection
  - Heat detection
  - Incipient detection
  - Delayed detection

Prompt Detection

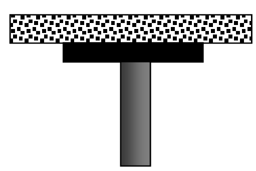
- Continuous fire watch
- Hotwork fire watch
- Continuously manned rooms, e.g., the control room

Smoke Detection

- Spot type smoke detectors
  - Ionization detection
  - Optical density detection
- Generally, smoke particles move into the chamber for the device to actuate
- Needs power (generally line and backup battery)

Heat Detection

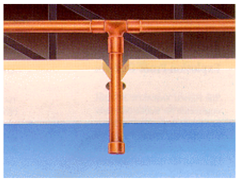
- Heat detectors
  - Detection devices
  - Sprinkler heads
  - Linear heat detectors



- Generally characterized by a response time index and an activation temperature
  - Response Time Index (RTI): a parameter describing how fast the device responds to the surrounding gas temperature
  - Activation Temperature: the temperature at which the detection device actuates

Incipient Detection

- Examples include air sampling systems
- Typically used where conventional fire detectors can't provide sufficiently rapid response.
- The objective is for plant personnel to prevent potential fire impacts



Delayed Detection

- Roving fire watch
- Plant personnel
- Control room indication
  - The control room receives a process alarm and dispatches an operator to inspect the situation.

Fire Suppression

- Fire can be suppressed by:
  - Cooling down the burning fuel and adjacent items – example: water spray
  - Removing oxygen – example: CO_2
  - Separating burning surface from impinging heat flux from the flame – example: Foam

Fire Suppression

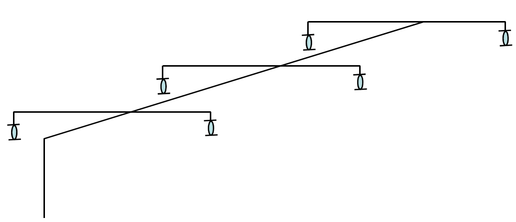
- Prompt suppression
- Automatic sprinklers
- Dry-Pipe/Pre-action sprinklers
- Deluge systems
- CO2: Automatic or Manual
- Halon: Automatic or Manual
- Fire brigade

Prompt Suppression

- Hotwork fire watch
- Some of the operators are generally trained in the use of portable extinguishers

Automatic Sprinklers

- Fusible links at the nozzles
- Water readily available
- Full room coverage, localized, in trays, etc.



Dry-Pipe/Pre-Action Sprinklers

- Sprinkler pipes are maintained dry (upstream shutoff valve keeps the water away from sprinkler heads)
- A smoke detection system opens the shutoff valve that fills the pipes (turns the system into a wet system)
- Sprinkler heads need to open from exposure to heat from the fire.

Deluge Sprinklers

- Pipes are maintained dry
- All sprinkler heads are open
- A smoke or heat detection system signals the main shutoff valve open
- All sprinklers discharge at the same time upon opening of the shutoff valve
- Generally used for protecting large liquid filled transformers and high fire hazard areas

Carbon Dioxide

- CO_2 gas is used to displace oxygen from the fire.
- Automatic CO_2- Suppression agent is generally released after smoke detection and a life safety alarm and delay time
- Manual CO_2- Requires an operator or fire brigade personnel to activate the system after smoke detection
- Must maintain proper suppression agent concentration for a soak time
- Life safety considerations

Halon

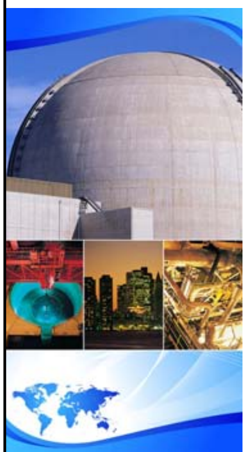
- Automatic Halon- Suppression agent is generally released after smoke detection and a life safety alarm and delay time
- Manual Halon- Requires an operator or fire brigade personnel to activate the system after smoke detection
- Must maintain proper suppression agent concentration for a soak time
- Not being manufactured any more and existing ones are being phased out because of environmental considerations

Fire Brigade

- Credited in most fire scenarios
- Typically characterized by the response time and time to start suppression activities in each room
- Typically use portable extinguishers (gaseous) first, followed by water (fire hose) if needed
- Typically plants maintain a professional brigade or operators/plant personnel are trained in fire fighting techniques

Passive Fire Protection

- Passive fire protection refers to fixed features put in place for reducing or preventing fire propagation.
- Such features include coatings, cable tray barriers, fire stops, self-closing dampers, penetration seals, self-closing doors, and fire-rated walls.



EPRI/NRC-RES FIRE PRA METHODOLOGY

Analysis Tools

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

Analysis Tools: Outline

- Fire Modeling in a Fire PRA
- How fire develops in a scenario
- What damage is generated
- When damage is generated
- Timing of detection and suppression activities

Five Steps of Fire Modeling

1. Define modeling objectives
2. Select and describe fire scenarios
3. Select the appropriate model(s)
4. Run/apply the model
5. Interpret modeling results

Fire Modeling

- **Fire modeling**: an approach for predicting various aspects of fire generated conditions
- **Compartment fire modeling**: modeling fires inside a compartment
- Requires an idealization and/or simplification of the physical processes involved in fire events
- Any departure of the fire system from this idealization can seriously affect the accuracy and validity of the approach

Capabilities

- Areas of application
  - Thermal effects of plumes, ceiling jets and flame radiation
  - Room heat up, and hot gas layer
  - Elevated fires and oxygen depletion
  - Multiple fires
  - Multi-compartments: corridors and multi-levels
  - Smoke generation and migration
  - Partial barriers and shields
  - Fire detection
- Special models or areas for future research
- Cable fires
- Fire growth inside the main control board
- Fire propagation between control panels
- High energy fires
- Fire suppression
- Hydrogen or liquid spray fires

Fire Models

- **Hand calculations**: Mathematical expressions that can be solved by hand with a relatively small computational effort
  - Quasi steady conditions
  - Usually semi-empirical correlations developed with data collected from experiments
- **Zone models**: Algorithms that solve conservation equations for energy and mass in usually two control volumes with uniform properties
- **Field models**: Algorithms that solve simplified versions of the Navier-Stokes equations. The room is divided into large number of cells and conservation equations are solved in each of them.
- **Special models**: There are fire scenarios critical to NPP applications that are beyond capability of existing computational fire models
  - Fire experiments,
  - Operating experience, actual fire events
  - Engineering judgment

Hand Calculations

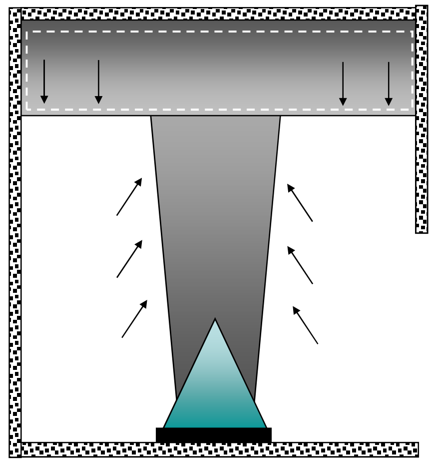
- Heat release rate, flame height and flame radiation
- Fire plume velocity, temperature heat flux, and entrainment
- Ceiling jet velocity, temperature, and heat flux
- Overall room temperature
- Target temperature, and time to target damage

Example of Hand Calcs: FDT's

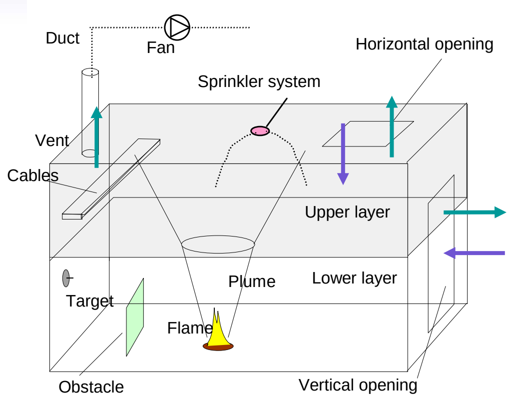
- **FDTs** are a series of Microsoft Excel® spreadsheets issued with **NUREG-1805, "Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program**."
- The primary goal of FDTs was to be a training tool to teach NRC Fire Protection Inspectors.
- The secondary goal of FDTs was to be used in plant inspections and support other programs that required Fire Dynamics knowledge such as, SDP and NFPA 805.

Zone Models

- Usually two zones
  - Upper layer with hot gases
  - Lower layer with clear and colder air
- Mass and energy balance in the zones
  - Entrainment
  - Natural flows in and out
  - Forced flows in and out
- Fire is treated as a point of heat release



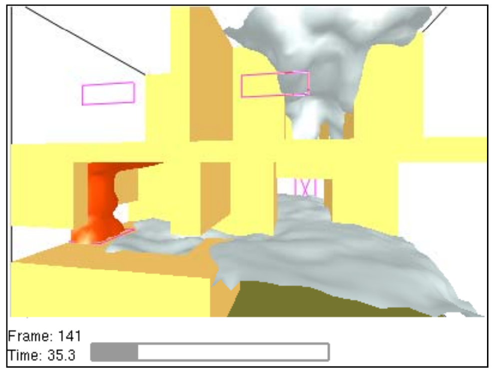
Example of a Zone Model: MAGIC



- **Gaseous phase combustion, governed by pyrolysis rate and oxygen availability**
- **Heat transfer between flame, gases and smoke, walls and surrounding air, thermal conduction in multi-layer walls, obstacles to radiation**
- **Mass flow transfer: Fire-plumes, ceiling-jet, openings and vents**
- **Thermal behavior of targets and cables**
- **Secondary source ignition, unburned gas management**
- **Multi-compartment, multi-fire, etc.**

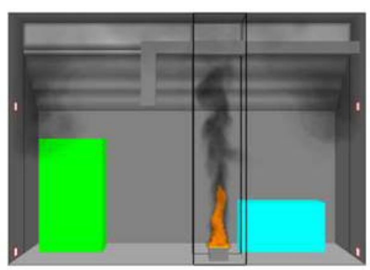
Field Models

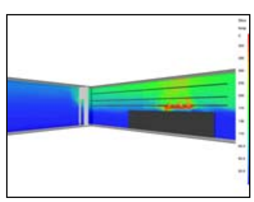
- Solve a simplified form of the Navier Stokes equations for low velocity flows
- Calculation time in the order of hours, days or weeks
- May help in modeling complex geometries

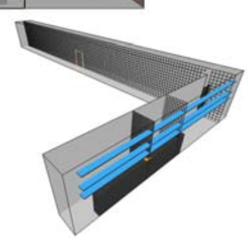


Example of Field Model: FDS

- Fire Dynamics Simulator
- Developed and maintained by NIST







Special Models

- Cable fires
- High energy arcing faults and fires
- Fire growth inside the main control board
- Fire propagation between control panels
- *The method described here is documented in the, EPRI 1011989 & NUREG/CR-6850, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities."*

Which Model to Choose

- Hand calculations available
  - Combustion - Heat release rates, flame heights
  - Fire generated conditions
    - Plume temperatures and velocities
    - Ceiling jet temperatures and velocities
    - Flow through vents
    - Enclosure temperature
    - Time and temperature to flashover
    - Target temperature and time to target damage
  - Heat transfer: irradiation from flames, plume and ceiling jet convective flux
- Analysts may need to go back and find additional parameters required

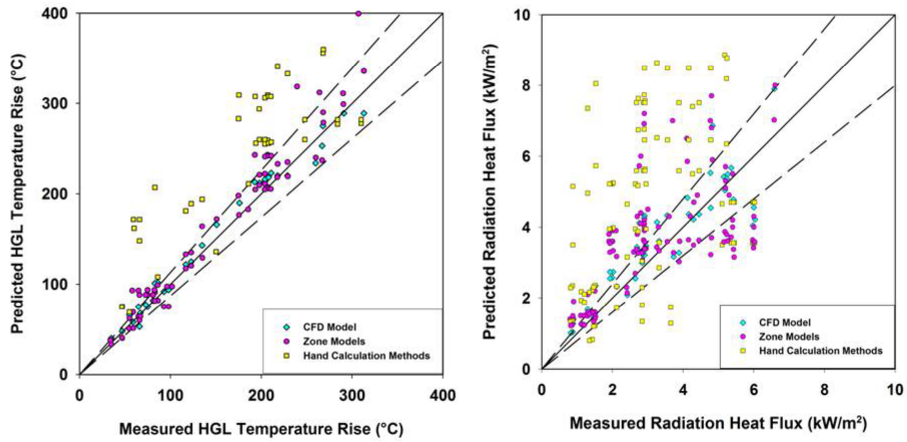
Verification and Validation

- ***Verification:*** the process of determining that the implementation of a calculation method accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method. *Is the Math right?*
- ***Validation:*** the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method**.** *Is the Physics right?*
- *See NUREG-1824*

Verification and Validation

Parameter				Fire Model		
		FDTs	FIVE-Rev1	CFAST	MAGIC	FDS
Hot gas layer temperature ("upper layer temperature")	Room of Origin	YELLOW+	YELLOW+	GREEN	GREEN	GREEN
	Adjacent Room	N/A	N/A	YELLOW	YELLOW+	GREEN
Hot gas layer height ("layer interface height")		N/A	N/A	GREEN	GREEN	GREEN
Ceiling jet temperature ("target/gas temperature")		N/A	YELLOW+	YELLOW+	GREEN	GREEN
Plume temperature		YELLOW–	YELLOW+	N/A	GREEN	YELLOW
Flame height		GREEN	GREEN	GREEN	GREEN	YELLOW
Oxygen concentration		N/A	N/A	GREEN	YELLOW	GREEN
Smoke concentration		N/A	N/A	YELLOW	YELLOW	YELLOW
Room pressure		N/A	N/A	GREEN	GREEN	GREEN
Target temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Radiant heat flux		YELLOW	YELLOW	YELLOW	YELLOW	YELLOW
Total heat flux		N/A	N/A	YELLOW	YELLOW	YELLOW
Wall temperature		N/A	N/A	YELLOW	YELLOW	YELLOW
Total heat flux to walls		N/A	N/A	YELLOW	YELLOW	YELLOW

Verification and Validation



Fire PRA Workshop, 2010, Washington DC
Introduction to Fire Analysis

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

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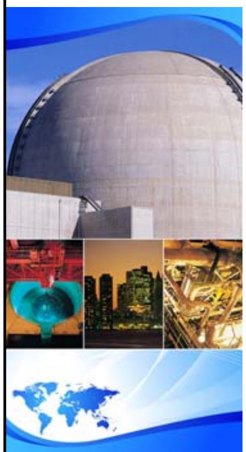
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Sandia National Laboratories

SAIC Science Applications International Corporation



EPRI/NRC-RES FIRE PRA METHODOLOGY

Fire Scenarios

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

Fire Scenario

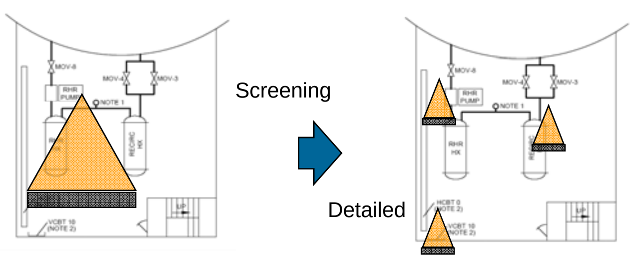
- A set of elements representing a fire event:
  - The ignition source, e.g., electrical cabinets, pumps
  - Intervening combustibles, e.g., cables
  - Targets, e.g., power, instrumentation or control cables
  - Fire protection features, e.g., automatic sprinklers
  - The compartment where the fire is located
  - A time line

Fire Scenario Time Line

1. Starts with a specific ignition source
2. Fire growth involving the affected fuel,
3. Heat transfer from the fire to other items within the zone of influence,
4. Damage of the affected items (e.g., cables and equipment items),
5. Propagation of the fire to other materials,
6. Detection of the fire (Note: this step could occur right after #2, or even #1 if there is very early warning smoke detection present)
7. Automatic initiation of suppression systems of the area,
8. Fire brigade response,
9. Successful fire extinguishment.

Fire Scenario - *Level of Detail*

- In practice, varying levels of detail are used to define the fire scenarios in a typical Fire PRA.
  - Level of detail may depend on initial stages of screening, anticipated risk significance of the scenario
- In principle, at any level of detail, a fire scenario represents a collection of more detailed scenarios.



Fire Scenario *Initial Screening Stage*

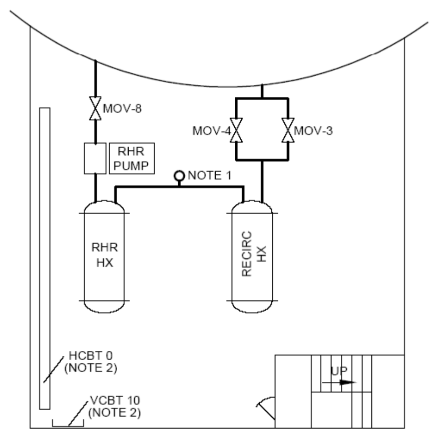
- In the initial stages of screening, fire scenarios are defined in terms of compartments and loss of all items within each compartment.
  - Assumes all items fail in the worst failure mode
  - Detection and suppression occur after the worst damage takes place
  - Fire does not propagate to adjacent compartments
- In multi-compartment fire propagation analysis, a similar definition is used in the initial screening steps for combinations of adjacent compartments.

Detailed Scenario Identification Process

- In the detailed analysis tasks, the analyst takes those fire scenarios that did not screen out in the initial stage and breaks them down into scenarios using greater level of detail.
  - Level of detail depends on the risk significance of the unscreened scenario
  - Details may be introduced in terms of . . .
    - Sub-groups of cables and equipment within the compartment
    - Specific ignition sources and fuels
    - Fire detection and suppression possibilities

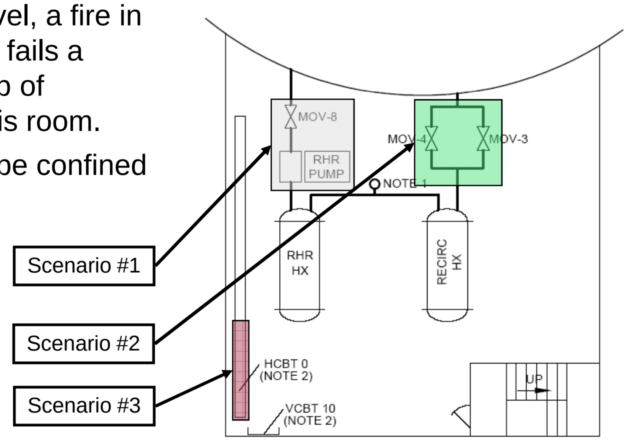
Example – Screening Level

- At the screening level, a fire in this compartment fails all equipment and cables shown in this diagram.
- The fire is assumed to be confined to this room



Example – Detailed Analysis

- At the detailed level, a fire in this compartment fails a specific sub-group of components in this room.
- The fire may still be confined to this room



Select and Describe Fire Scenarios

- Selection of fire scenarios:
  - How many fire scenarios are enough to demonstrate the objective?
  - Which scenarios are the appropriate ones?
- Selecting scenarios is dependent on the objectives of the fire risk quantification
  - Fire conditions that are actually modeled
  - Represent a complete set of fire conditions relevant to the objectives
- Selection of scenarios is dependent on the hazard characteristics of the area
  - Combustibles, layouts, fire protection
- The fire scenario should challenge the conditions being considered
  - Can the fire cause damage? vs. Which fire can cause damage?

Select and Describe Fire Scenarios

1. Scenarios should have an ignition source and at least one target or other measurable objectives
2. Consider the range of possible intervening combustibles
3. Scenarios should capture targets as well as fire's ability to ignite or damage them
4. Include in the scenario any fire protection system (active or passive) that may influence the outcome of the event

Select and Describe Fire Scenarios

5. Sometimes, multiple ignition sources or targets can be combined into one scenario
6. Sketch the scenario on a compartment layout drawing and try to qualitatively describe the conditions that a fire might generate. After the analysis, compare this qualitative prediction with the modeling results.
7. Do not neglect the importance of details such as ceiling obstructions, soffits, open or close doors, etc.

Scenario Quantification

- Ignition frequency: fire frequency for the postulated ignition source
- Apportioning factor: probability that the ignition occurs in a specific ignition source or plant location
- Severity factor: probability that the fire is severe enough to generate the postulated damage
- Non suppression probability: probability of failing to suppress the fire
- Circuit failure probability: probability that the affected circuits will generate the postulated equipment impact
- Conditional core damage probability

$$CDF = \lambda \cdot W \cdot SF \cdot P_{ns} \cdot P_{cf} \cdot CCDP$$

Scenario Quantification

- A fire in a specific plant location
  - That is severe enough
    - That is unsuppressed
      - That generates the postulated circuit failure mode
        - That prevents safe shutdown

$$\lambda_{is} = \lambda_g \cdot W \cdot 1 \cdot 1 \cdot 1$$

$$\lambda_{is} = \lambda_g \cdot W_{is} \cdot SF \cdot 1 \cdot 1$$

$$\lambda_{is} = \lambda_g \cdot W_{is} \cdot SF \cdot P_{ns} \cdot 1$$

$$\lambda_{is} = \lambda_g \cdot W_{is} \cdot SF \cdot P_{ns} \cdot P_{cf}$$

$$\lambda_{CDF} = \lambda_{is} \cdot ccdp$$