Module III – Fire Analysis

Fire Fundamentals Introduction and Overview

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

Welcome to Module 3 – Fire Analysis

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- and you are…

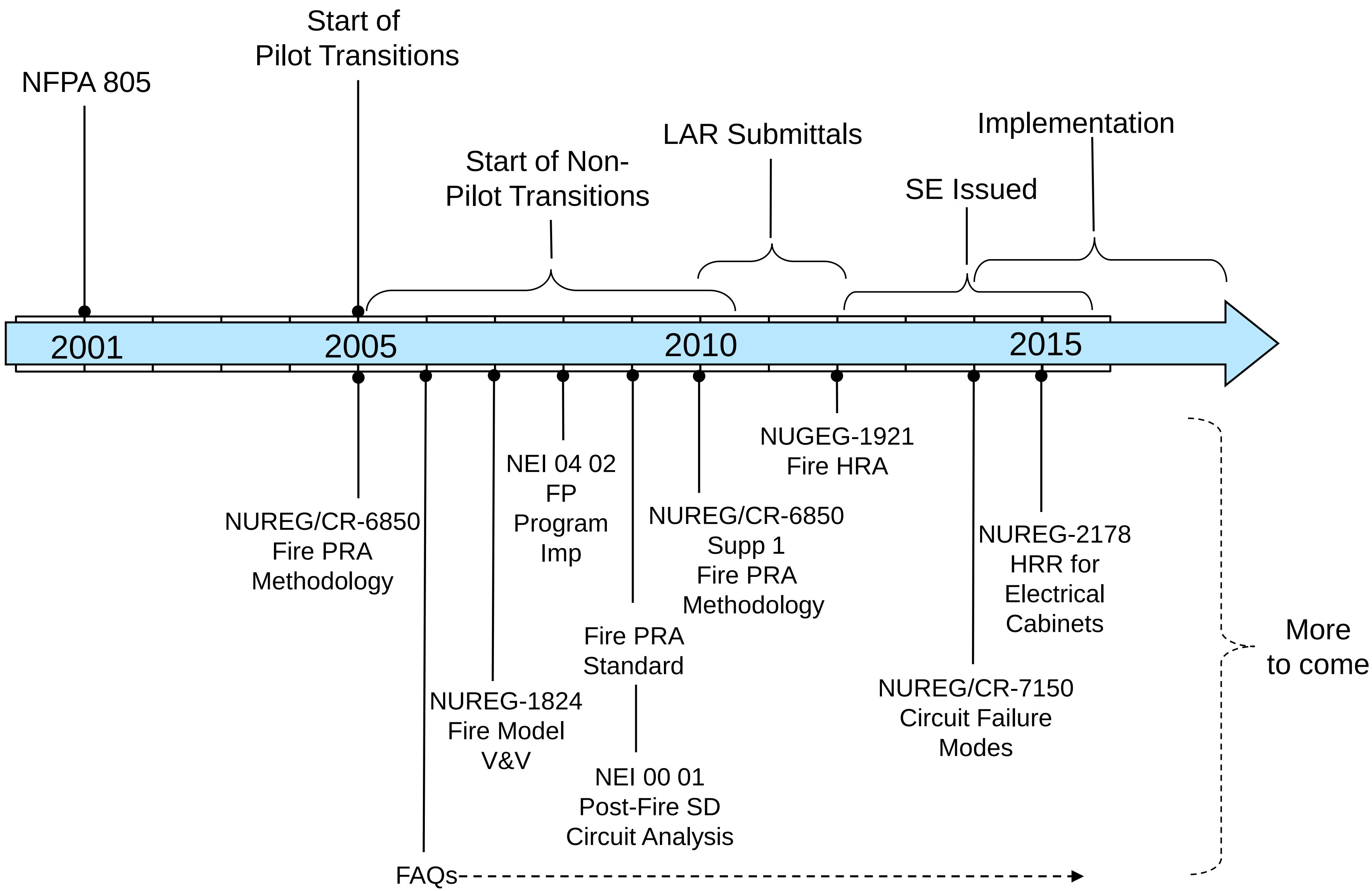


Figure only include a sampling of key documents associated with analytical methods. Other documents governing NFPA 805 transition and FP programs such as Regulatory Guides etc., are not included.

Getting us all on the same page…
Scope of Module 3

- Module 3 covers those aspects of a nuclear power plant (NPP) at-power, internal fire, probabilistic risk assessment (PRA) that support the analysis of fire phenomena
  - At-power: the plant is assumed to be operating at steady state, nominal 100% power at the time that a fire occurs
  - Internal fire: fires within the boundaries of the plant (which we will define…) but not fires outside the plant boundaries (e.g., not forest fires or off-site transportation accidents…)
  - Fire phenomena: identify fire sources, characterize fire growth and spread, assess impact on the surroundings, credit fire intervention by detection and suppression, predict damage times for important plant components and cables – *develop a fire timeline*…
  - Risk: based on how likely it is that a fire will lead to core damage and/or a release of radioactive materials from the plant site

Getting us all on the same page…
PRA elements that we won't cover

- Module 1: PRA / systems analysis - the analysis of the NPP as an engineered system
  - Identification of important systems and components
  - Characterization of system dependencies and failure modes
  - Development of the post-fire plant response model (PRM) – the event tree / fault tree analysis
  - Calculation of conditional core damage probability (CCDP) and conditional large early release probability (CLERP)
  - Uncertainty analysis
  - Final risk quantification – core damage frequency (CDF) and large early release frequency (LERF)

Getting us all on the same page…
PRA elements that we won't cover

- Module 2: Electrical/Circuit Analysis – supporting analyses of electrical control and power circuits
  - Deterministic analysis of cable failure modes and effects
  - Deterministic spurious operation analysis
  - Probabilistic failure mode likelihood analysis
  - Power distribution system layout
  - Circuit protection coordination analysis

Getting us all on the same page…
PRA elements that we won't cover

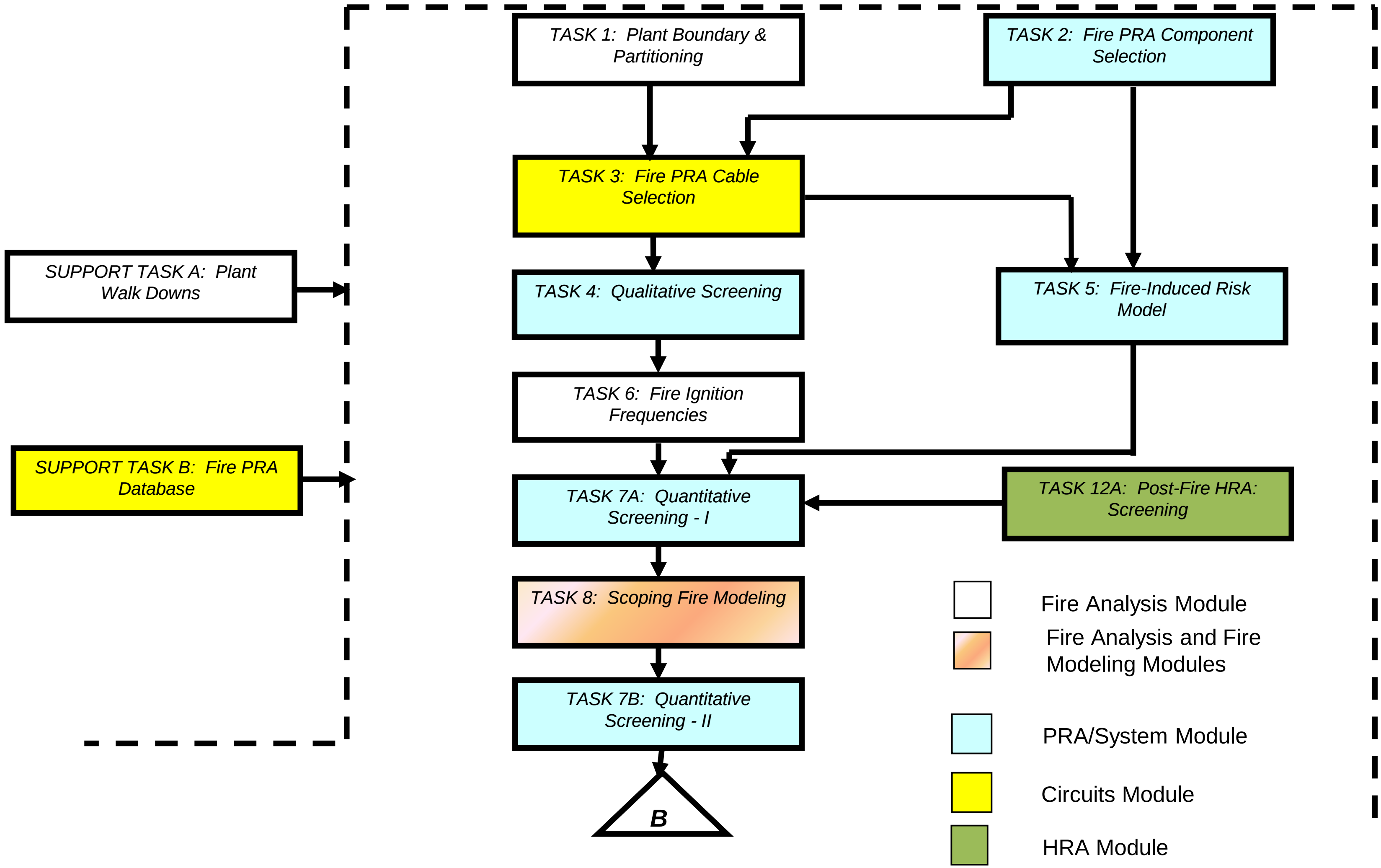
- Module 4: Human Reliability Analysis (HRA) – the identification and quantification of human actions important to plant safety
  - Review of plant response procedures
  - Identification of human failure events (HFEs) to be included in the PRM
  - Quantification of the human error probability (HEP) values for important HFEs as a part of PRM quantification

Getting us all on the same page…
PRA elements that we won't cover

- Module 5: Advanced Fire Modeling – the application of fire modeling tools to predict fire behavior and effects
  - Complementary to Module 3
  - Covers one more specific topical area in greater detail – the actual use of fire modeling tools
  - Covers a range of fire modeling tools from closed-form empirical correlations to 3-D fluid dynamics-based compartment fire models
  - We will talk about fire modeling and its role in the overall process of fire analysis, but in far less detail

Overall fire PRA structure

Module 3 covers tasks in white and white/orange



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Overall fire PRA structure

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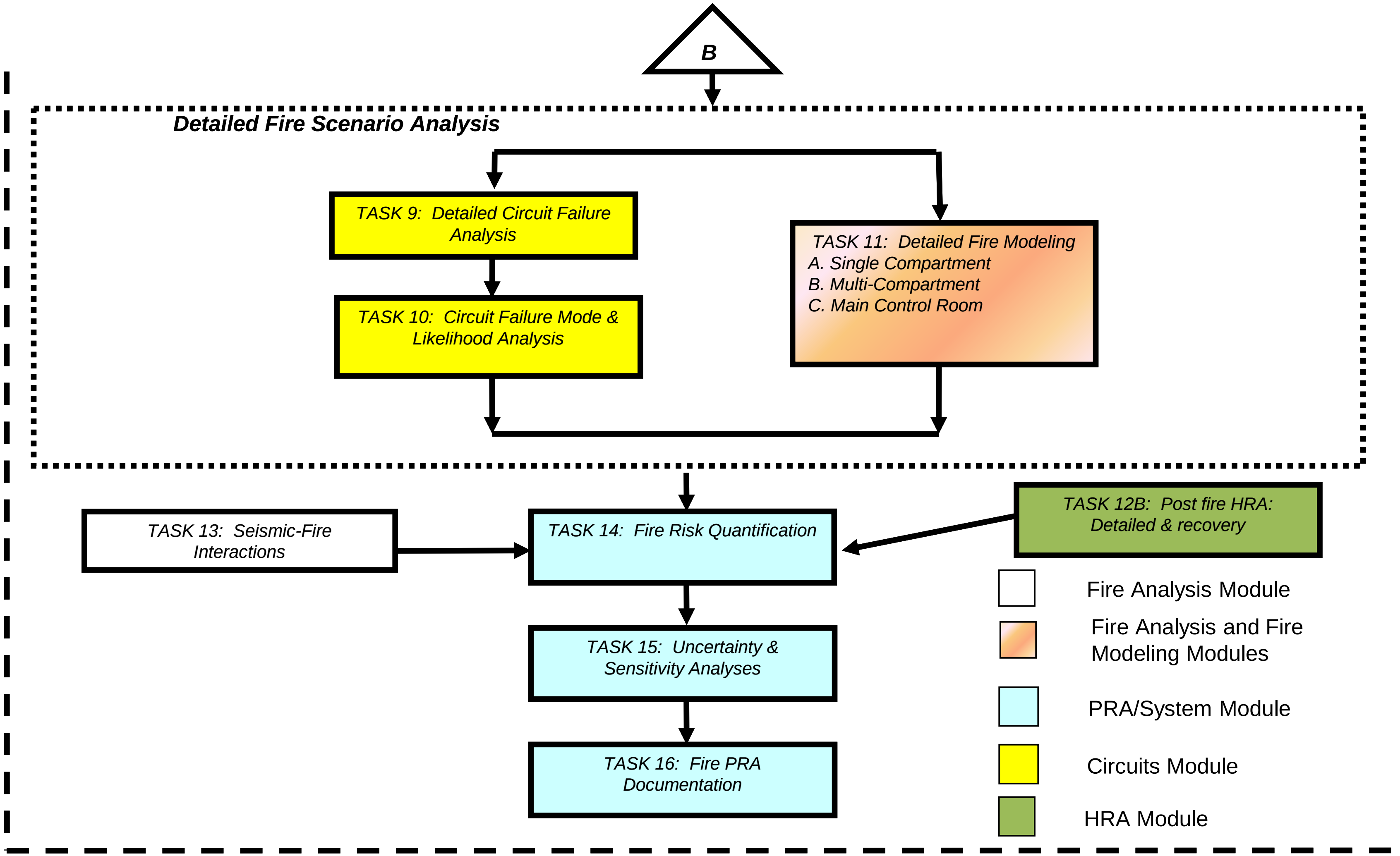


Scope of Module 3: Fire Analysis

- Tasks covered by Module 3 are:
  - Task 1: Plant Partitioning
  - Task 6: Fire Ignition Frequency
  - Task 8: Scoping Fire Modeling
  - Task 11: Detailed Fire Scenario Analysis
  - Task 13: Seismic/Fire Interactions (briefly)
  - Support Task A: Plant Walkdowns
- In each task we will discuss the requirements of the ASME/ANS PRA Standard, Part 4
  - What are the requirements and the expectations
  - How they can be met

Task 1: Plant Partitioning (1 of 3)

- Objectives:
  - Define the global analysis boundary of the FPRA
  - Divide the areas within the global analysis boundary into fire compartments
- The fire compartments become the “basic units” of analysis
  - Generally we screen based on fire compartments
  - Risk results are often rolled up to a fire compartment level
- A note on terminology:
  - The PRA standard uses “physical analysis units” rather than “fire compartments”
  - Definitions are quite similar, overall role in analysis is identical
    - Don’t let the terminology difference trip you up – intent is the same

Task 1: Plant Partitioning (2 of 3)

- The global analysis boundary is intended to be a liberal definition of the region potential interest
  - It will likely encompass areas of essentially no risk, but that is OK, screening steps will identify these

- The fire compartments are a matter of analysis convenience
  - Fire compartments may equal fire areas if you so choose
  - You can also subdivide fire areas into multiple compartments
    - May require cable routing resolution at the compartment level
  - The sum of the fire compartments must equal the global analysis boundary
    - No omissions, no overlap between compartments

Task 1: Plant Partitioning (3 of 3)

- Ultimately, the FPRA is expected to provide some resolution to each defined fire compartment and to all locations within the global analysis boundary

- Module will cover:
  - Guidance and criteria for defining the global analysis boundary
  - Guidance and criteria for defining fire compartments

- Ultimately, there is not a lot of new guidance in this task
  - A lot like what was done in the IPEEE days

Task 6: Fire Ignition Frequency (1 of 3)

- Objective: To define fire frequencies suitable to the analysis of fire scenarios at various stages of the FPRA

- Fire frequencies will be needed at various resolutions:
  - An entire fire area
  - A fire compartment (or physical analysis unit)
  - A group of fire ignition sources (e.g., a bank of electrical cabinets)
  - A single ignition source (e.g., one electrical panel)

Task 6: Fire Ignition Frequency (2 of 3)

- Task begins with generic industry-average statistics on fire
  - EPRI fire event database
  - Events filtered for applicability and sorted into ignition source bins
  - Plant-wide fire frequency is provided for each bin
- The real “trick” is to convert the generic values into values specific to your plant and to a given fire scenario
  - Approach is based on ignition source counting and apportionment of the plant-wide frequency based on local population

Task 6: Fire Ignition Frequency (3 of 3)

- Quite a bit is new relative to fire frequency:
  - The fire event data have been re-analyzed entirely to suit the new method
    - That means older IPEEE-vintage frequencies are obsolete
  - There has been a switch towards component-based fire frequencies and away from generic room-based fire frequencies
  - Some areas have received special treatment
    - e.g., main control room

Task 8: Scoping Fire Modeling (1 of 2)

- Objective: To identify (and screen out) fire ignition sources that are non-threatening and need not be considered in detailed fire modeling

- Non-threatening means they cannot:
  - Spread fire to other combustibles, or
  - Damage any FPRA equipment item or cable

Task 8: Scoping Fire Modeling (2 of 2)

- Scoping fire modeling introduces a number of key concepts associated with the treatment of fire sources and damage targets
  - The Fire Severity Profile approach
  - Damage criteria for cables and equipment
  - Assumptions associated with specific fire sources

Task 11: Detailed Fire Modeling (1 of 3)

- Objective: To identify and analyze specific fire scenarios

- Divided into three sub-tasks:
  - 11a: General fire compartments (as individual risk contributors)
  - 11b: Main Control Room analysis
  - 11c: Multi-Compartment fire scenarios

Task 11: Detailed Fire Modeling (2 of 3)

- Task 11 involves many key elements
  - Selection of specific fire scenarios
    - Combinations of fire sources and damage targets
  - Analysis of fire growth/spread
    - Application of fire models
  - Analysis of fire damage
    - Time to failure
  - Analysis of fire detection and suppression

Task 11: Detailed Fire Modeling (3 of 3)

- Task 11 comes with a wide range of supporting appendices including:
  - Specific fire sources such as high energy arc faults, turbine generator fires, and hydrogen fires
  - Treatment of fire severity and severity factors
  - Treatment of manual fire suppression
  - Treatment for main control board fires

- Module will cover key appendices

Task 13: Seismic/Fire Interactions

- Objective: A *qualitative* assessment of potential fire/seismic interactions

- Module will cover this task *briefly*
  - No significant changes from IPEEE guidance (e.g., the Fire PRA Implementation Guide)

Next up: Fire scenarios

Before we move on…

Any questions on where our module fits into the overall fire PRA structure?

Fire scenarios in risk analysis
A key concept

- Recall that our primary measure of risk is fires leading to core damage
  - Off-site release of radioactive materials also calculated, but we can work to the core damage level for our purposes
- Given that we are looking for fires that may:
  - Cause an initiating event – an upset to normal at-power plant operations such that reactor shutdown is required, or
  - Damage mitigating equipment – that set of plant equipment that operators would rely on to achieve safe shutdown
- We do this through fire scenarios that will:
  - Represent the range of potential fire sources in the plant,
  - Analyze the impact of fires on the surroundings,
  - Assess fire protection systems and features, and
  - Assess the plant and operator’s response to fire-induced damage
- Each fire scenario gives some contribution to total CDF

Fire scenarios in risk analysis
A key concept

- A fire scenario is a set of elements representing a fire event:
  - The ignition source, e.g., electrical cabinets, pumps
  - Intervening combustibles, e.g., cables
  - Damage targets (e.g., power, instrumentation or control cables) whose fire-induced failure may cause an initiating event and/or failure of mitigating equipment
  - Fire protection features that could mitigate fire damage, e.g., automatic sprinklers
  - The compartment where the fire is located and its characteristics
  - Ultimately… an event timeline

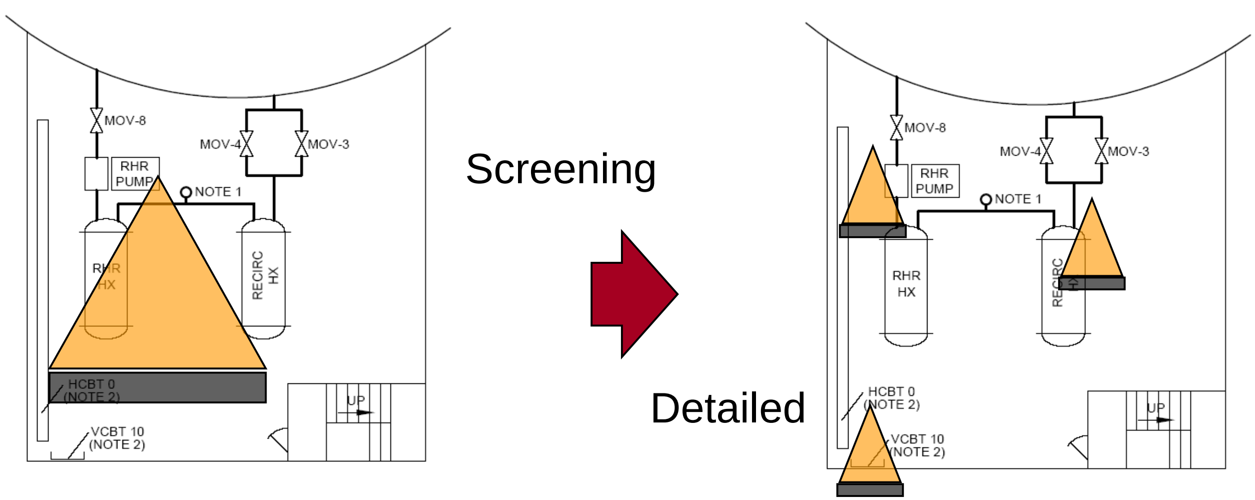
Fire Scenario Time Line

Timeline includes the following elements (not necessarily in this order):

1. Scenario starts with ignition of a fire in a specific fire source
2. Fire growth involving the affected fuel,
3. Heat transfer from the fire to other items within the zone of influence,
4. Propagation of the fire to other materials,
5. Damage to identified PRA targets (e.g., cables and equipment),
6. Detection of the fire
   – Detection can actually occur before ignition given an incipient detection system…
7. Automatic initiation of suppression systems if present,
8. Manual fire fighting and fire brigade response,
9. Successful fire extinguishment ends the scenario.

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.



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Fire Scenario Initial Screening Stage

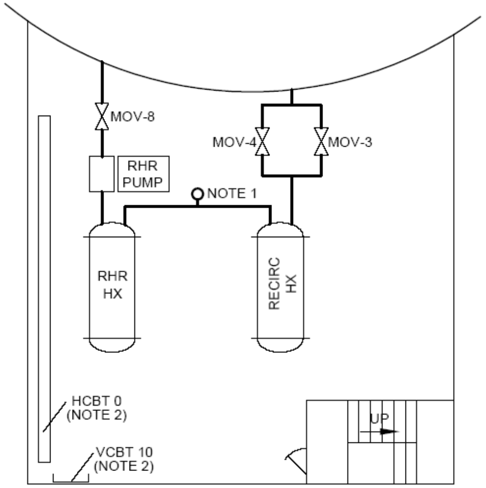
- In the initial stages of screening, fire scenarios are defined in terms of compartments and loss of all items within each compartment.
  - Assumes all items fail in the worst failure mode
  - Detection and suppression occur after the worst damage takes place
  - Fire does not propagate to adjacent 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



NOTES:

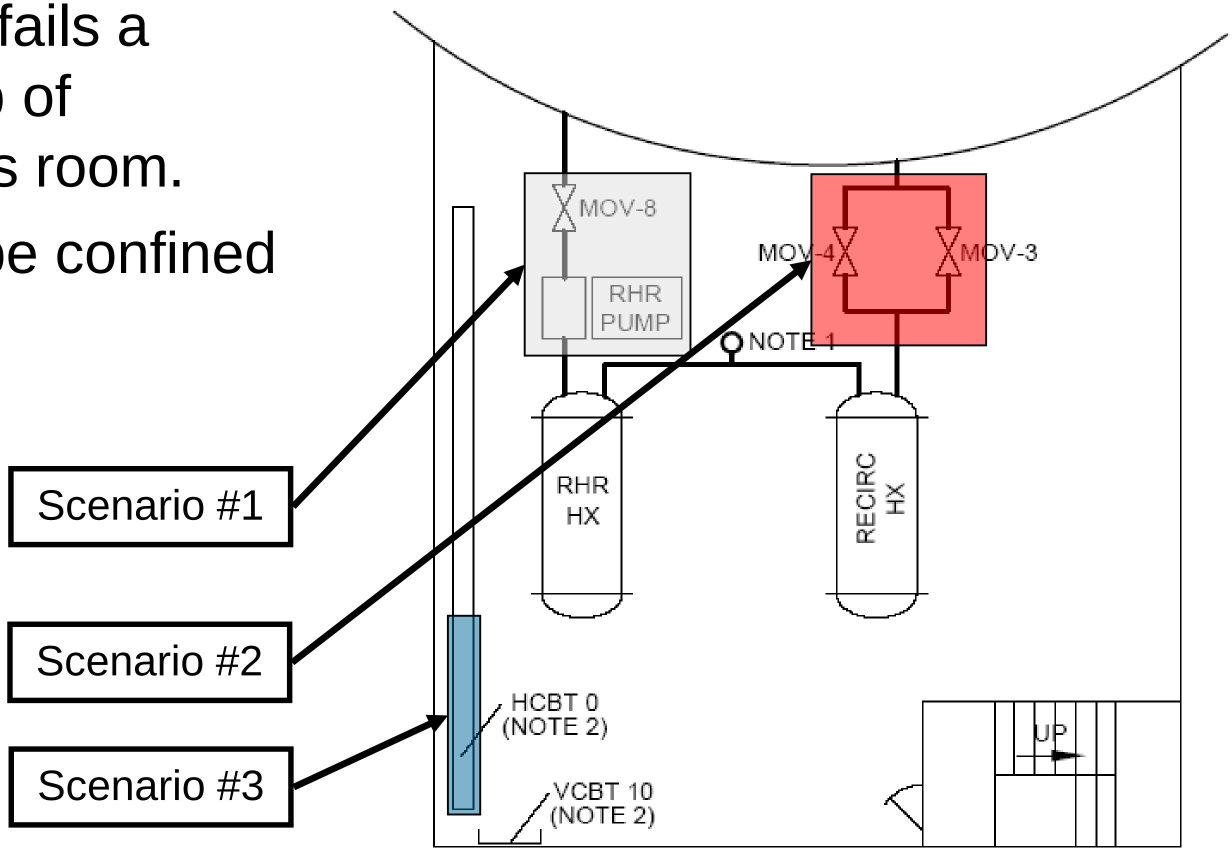
1. VERTICAL PIPE PENETRATION TO UPPER ELEVATION.

2. PENETRATION TO UPER FLOOR IS SEALED.

HCBT: HORIZONTAL CABLE TRAY
VCBT: VERTICAL CABLE TRAY

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

- Selecting scenarios is dependent on the objectives of the fire risk quantification
  - How many fire scenarios are enough to demonstrate the objective?
  - Which scenarios are the appropriate ones given objectives?
  - What fire conditions are actually modeled?
  - Analysis should represent a complete set of fire sources and conditions as relevant to the analysis objectives
  - A full-scope fire PRA tries to capture all fire scenarios that may represent contributors to plant core damage risk
- 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?
  - Fires that don’t propagate or cause damage are generally not risk contributors

Select and Describe Fire Scenarios

1. Scenarios begin with an ignition source – what/where does the fire start and what are the fire characteristics
2. Consider intervening combustibles – fire propagation beyond the fire source needs to be considered
3. There should be at least one damage target identified. Often it is a set of damage targets rather than just one (e.g., a group of important cables).
4. Include fire protection system and features (active or passive) that may influence the outcome of the event (there is a pain/gain decision point here)

Select and Describe Fire Scenarios

5. Sometimes, multiple ignition sources or targets can be combined into one scenario (e.g., a bank of cabinets all with the same cables overhead)
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 closed doors, ventilation conditions, spatial details (e.g., target position relative to fire source), etc.

Scenario Quantification

General quantification of CDF is based on a five-part formula:

$$CDF_{scenario} = \lambda \cdot W \cdot SF \cdot P_{ns} \cdot CCDP$$

- λ = Ignition frequency for the postulated ignition source group (e.g., pumps)
- W = A weighting factor for the likelihood that the fire occurs in a specific ignition source (this pump…) or plant location (this room…)
- SF = A severity factor reflecting percentage of fires large enough to generate the postulated damage if left unsuppressed
- P_{ns} = Non suppression probability – the probability that given the fire, it goes unsuppressed long enough that the target set is damaged
- CCDP = The conditional core damage probability – probability that given loss of the target set, operators fail to achieve safe shutdown and the core is damaged.

In practice, we often quantify scenarios in a progression of more detailed steps:

- A fire in a specific plant location

$$CDF_{is} \approx \lambda_g \cdot W_{is} \cdot 1 \cdot 1 \cdot 1$$

- …That is severe enough to threaten targets

$$CDF_{is} \approx \lambda_g \cdot W_{is} \cdot SF \cdot 1 \cdot 1$$

- …That goes unsuppressed long enough to cause damage

$$CDF_{is} \approx \lambda_g \cdot W_{is} \cdot SF \cdot P_{ns} \cdot 1$$

- …That prevents safe shutdown

$$CDF_{is} \approx \lambda_g \cdot W_{is} \cdot SF \cdot P_{ns} \cdot CCDP$$

Training Objectives

- Our intent:
  - To deliver practical implementation training
  - To illustrate and demonstrate key aspects of the procedures
- We expect and want significant participant interaction
  - Class size should allow for *questions and discussion*
  - We will take questions about the *methodology*
  - We *cannot* answer questions about a *specific application*
  - *We* will moderate discussions, and *we* will judge when the course must move on

Methods - What is Covered in this Module

- Approved fire PRA Frequently Asked Questions (FAQs); Supplemental guidance and methods developed as part of the transition to 10CFR50.48(c), NFPA 805
- Published NRC or joint industry & NRC methods
  - NUREG/CR-6850 and Supplement 1 / EPRI 1011989 & 1019259
  - EPRI 3002002936 / NUREG-2169, *Nuclear Power Plant Fire Ignition Frequency and Non-Suppression Probability Estimation Using the Updated Fire Events Database: United States Fire Event Experience Through 2009*
  - NUREG-2178, Volume 1 / EPRI 3002005578, *Refining and Characterizing heat Release Rates for Electrical Enclosures During Fire (RACHELLE-FIRE)*, April 2016
- ASME / ANS PRA Standard (RA-Sb-2013)

Methods – What is not Covered in this Module

- On-going research by EPRI and/or NRC
  - High Energy Arcing Faults Zone of Influence
  - Conditional Plant Trip Probability
- Working draft of:
  - The ASME/ANS PRA Standard Part 4: Publication planned for mid 2019
  - RF-II Volume 2 (obstructed radiation, cabinet to cabinet fire spread, fire location factor, main control board, and motor and dry transformer heat release rates, main control board fires): In draft for public comment on ADAMS
  - Fire growth profiles and plant personnel suppression of electrical cabinets: NUREG-2230 in draft for public comment on ADAMS

Questions?

Module III – Fire Analysis

Fire Fundamentals: Definitions

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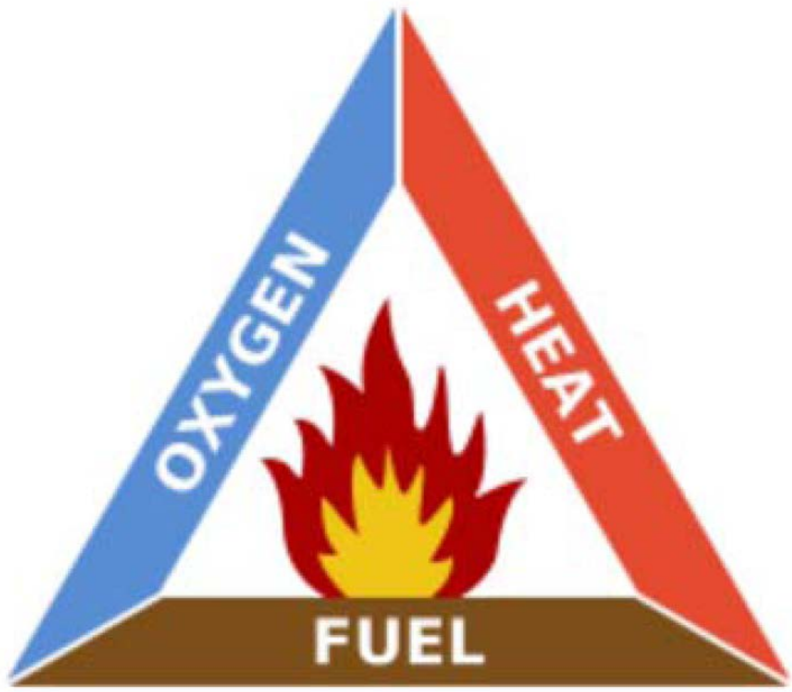
What is a Fire?

- 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, …



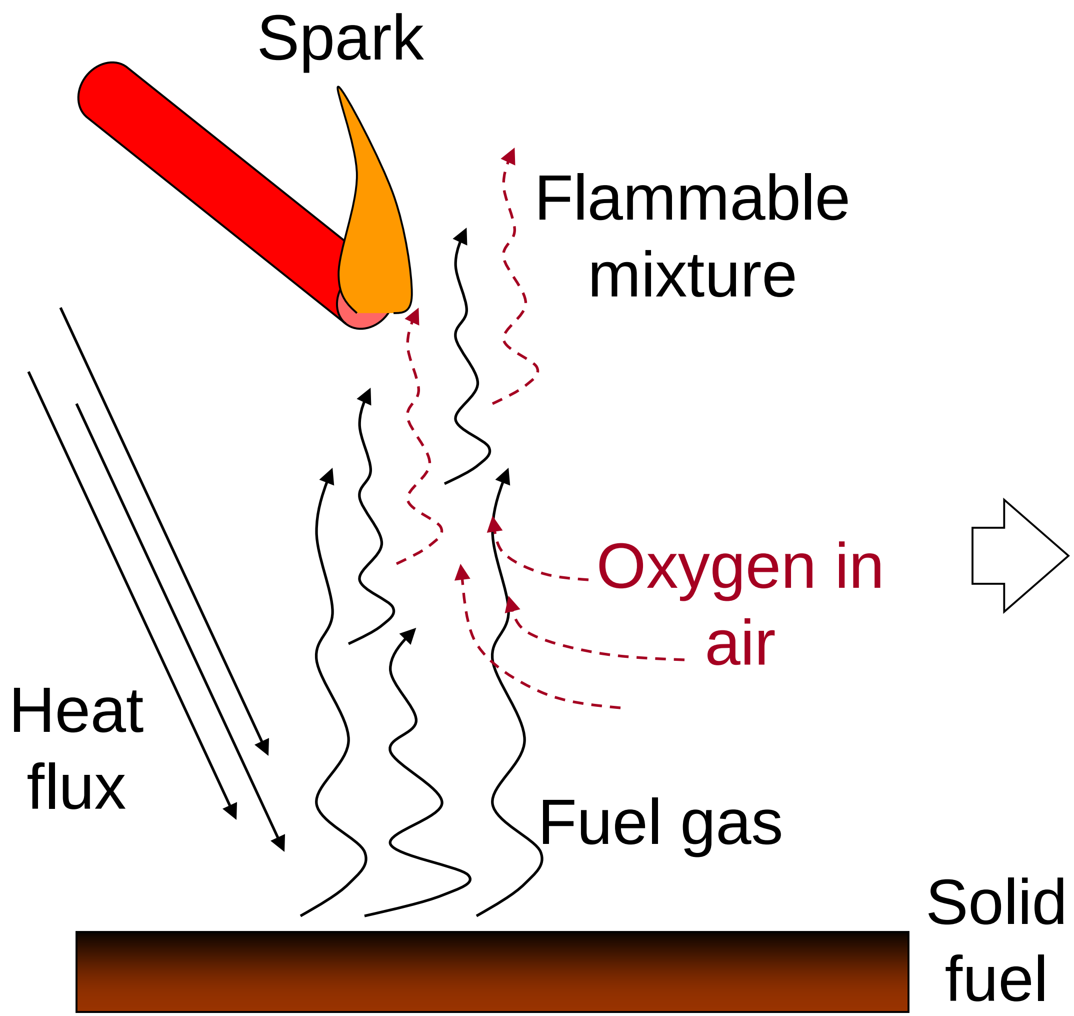
Materials that May Burn

- 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?


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 1,500ºF to 3,500ºF

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

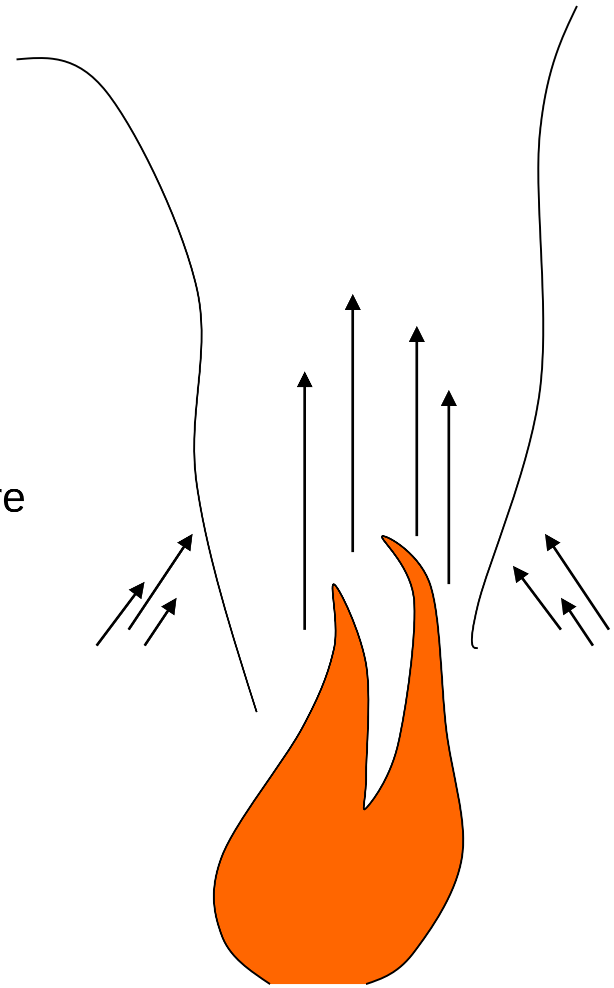
Effects of a Fire

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. …

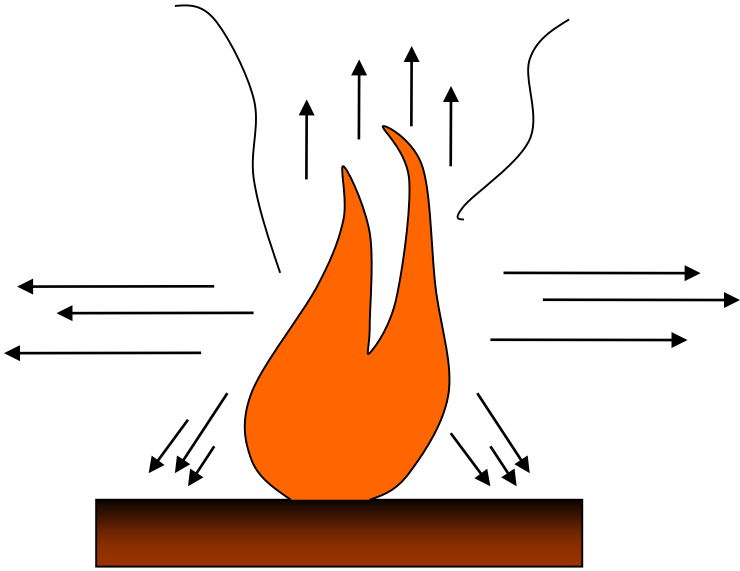
- Lower or Cold Gas Layer – The gasses that remain between the bottom of the HGL and the floor and that generally remain at near ambient temperatures

- 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:
    - $X_r = 1.0 - X_c$

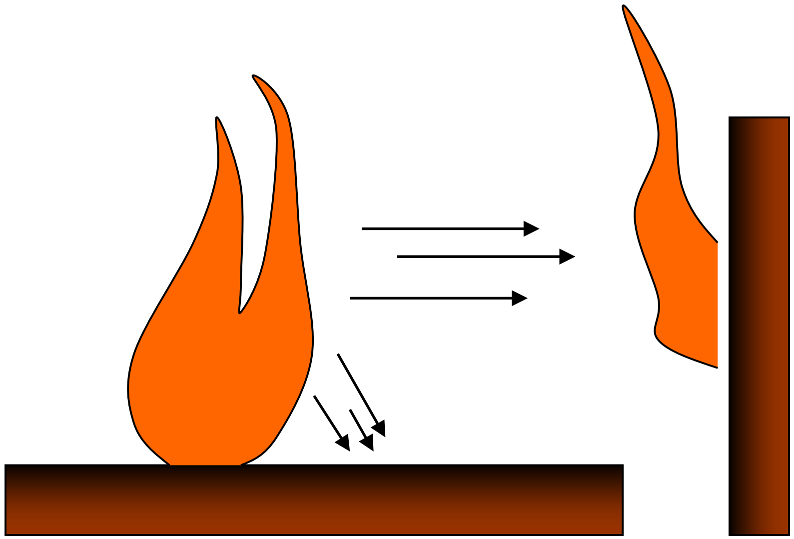
      (if it's heat from the fire and it's not convection, it must be radiation…)
    - $X_r \sim 0.4$ is typical



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

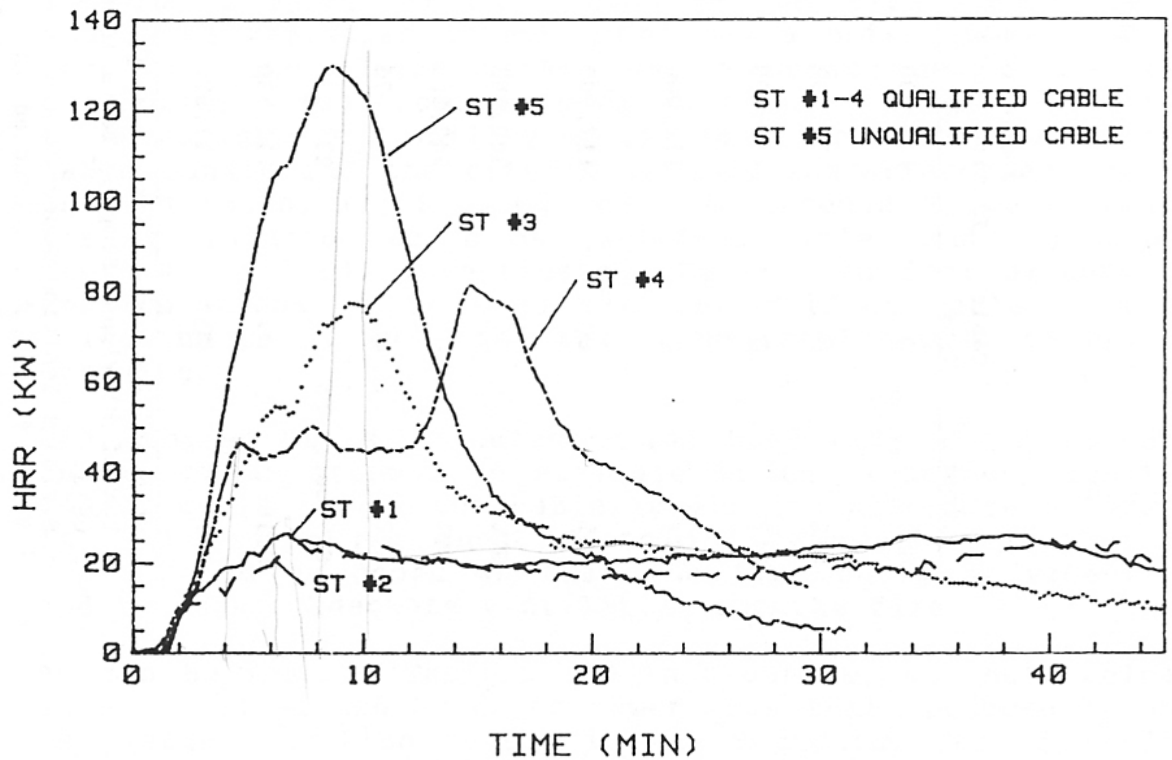


Figure 8. Heat Release Rate Plots for Scoping Tests #1 through 5

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

Module III – Fire Analysis

Fire Fundamentals: Fires in the Open and Fully Ventilated Fires

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

Recall: Fuel limited fires

- A fire where the fuel burning rate is limited only by the surface burning rate of the material.
- Sufficient air is always available for the fire (plenty of oxygen to support burning)
- Fire generates hot gases (convective fraction) and emits radiative heat (radiative fraction)
- Generally applies to fires in the open or fires in large compartments
  – A nuclear power plant has lots of large compartments…

Heat Release Rate (HRR)

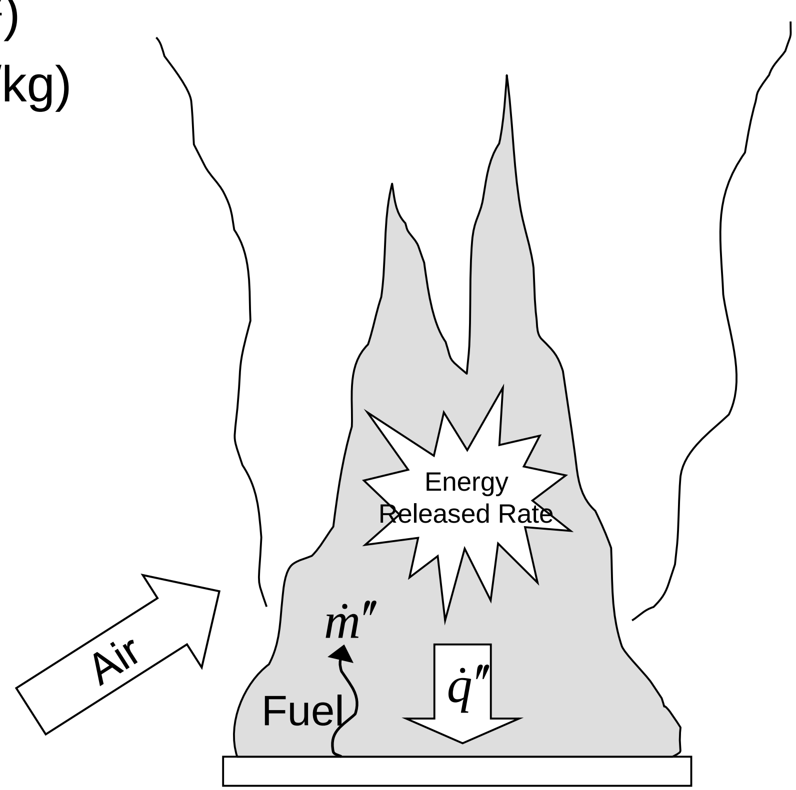
- For a simple fire, the HRR can be estimated using the following equation:

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

  - $\dot{m}''$ is the burning mass flux (kg/s·m^2)
  - ΔH_c is the net* heat of combustion (kJ/kg)
  - A is the burning area (m^2)

So HRR ends up as kJ/s or kW

* "net" heat of combustion implies that a burn efficiency has been included – fuels don't burn at 100% efficiency in real fires



Heat Release Rate

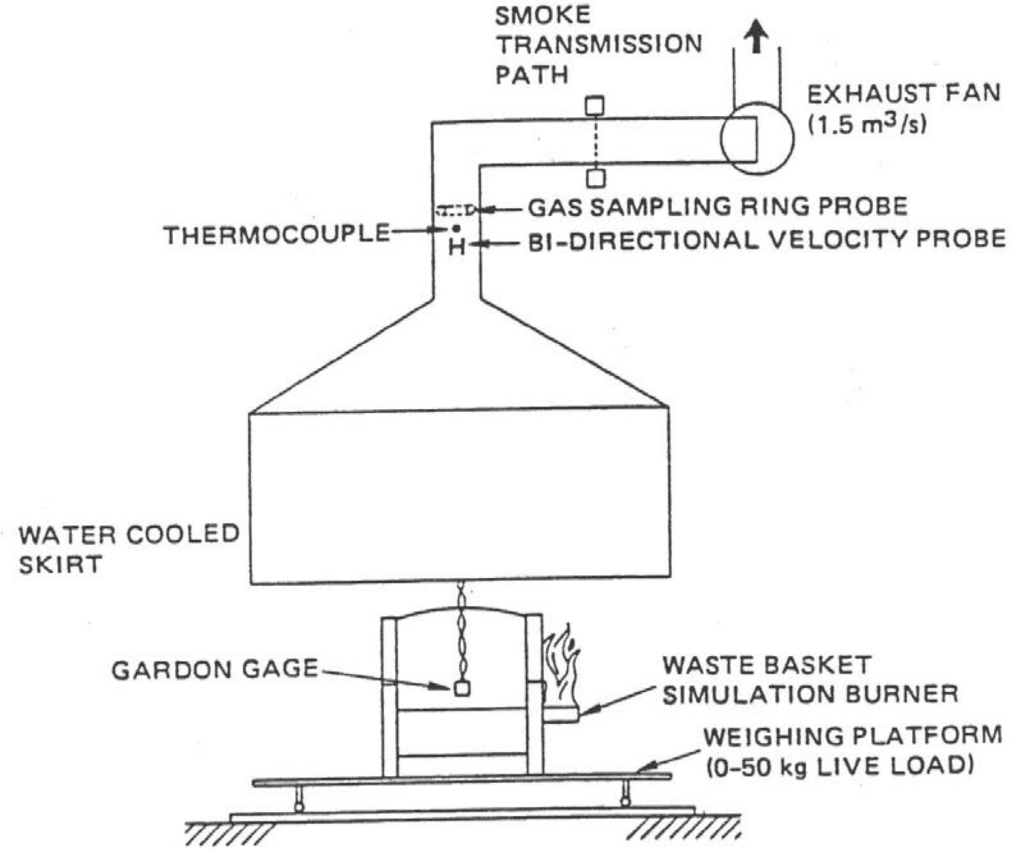
- HRR can be estimated experimentally using oxygen consumption calorimetry

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

where:

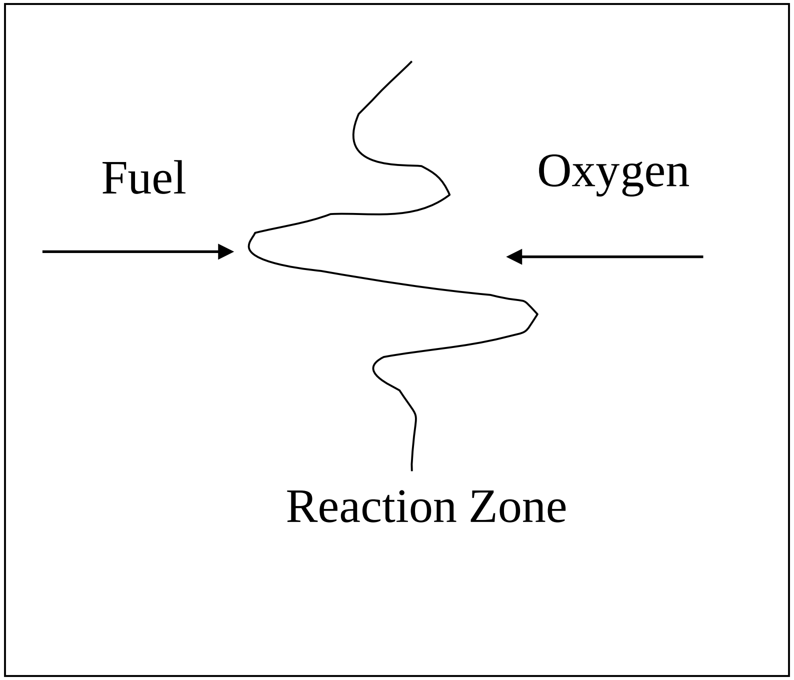
ΔH_c ~ 13.1 MJ/kg_{O2}

for many common fuels



Flames

- Laminar – very small fires
- Turbulent – most real fires



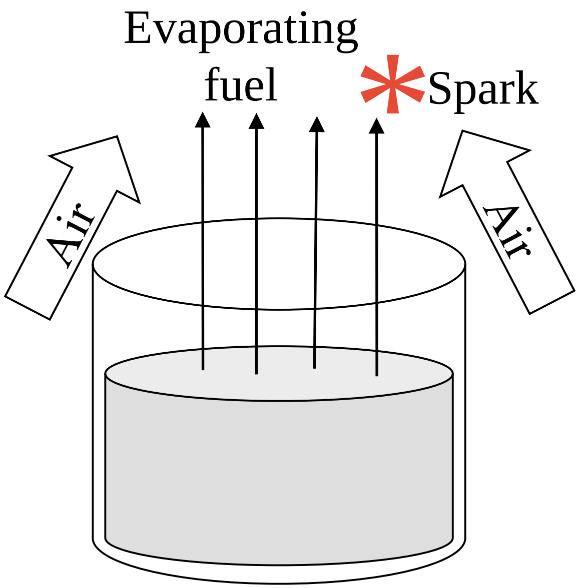
Ignition of Gases

- 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.

- With no pilot present, a gaseous fuel in air can still ignite if the mixture is at or above the auto-ignition temperature.
  - The auto-ignition temperature is usually measured for a stoichiometric mixture – just the right mix so that no fuel or oxygen remains after the reaction.

Ignition of Liquids

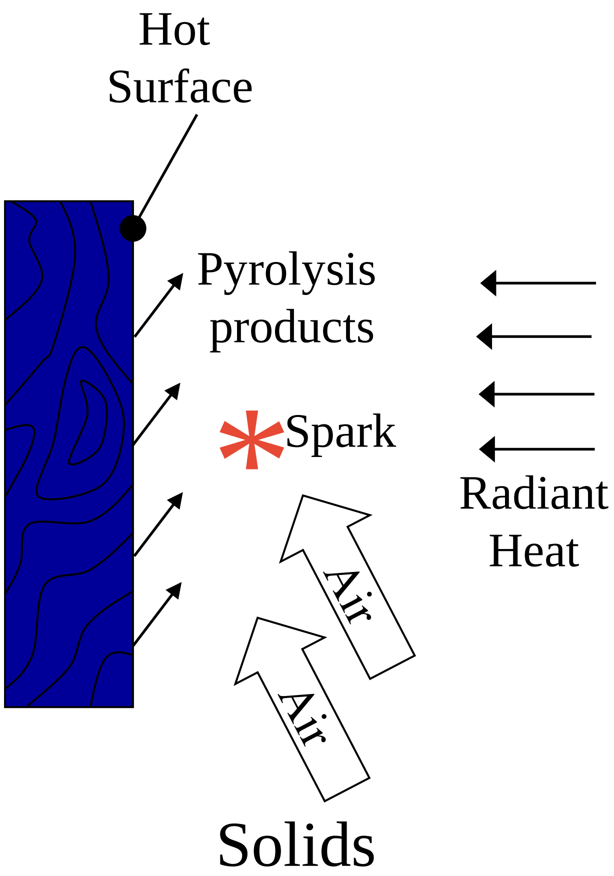
- For a liquid to ignite, it must first evaporate sufficiently to form a flammable mixture of gaseous fuel and oxygen
  - This occurs at a liquid temperature called a flash-point temperature.
  - In general, this temperature can be called the piloted ignition temperature and the same term carries over 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 in order to ignite.
- The auto-ignition temperature of a gas will be higher than the boiling point of the liquid.



Liquids

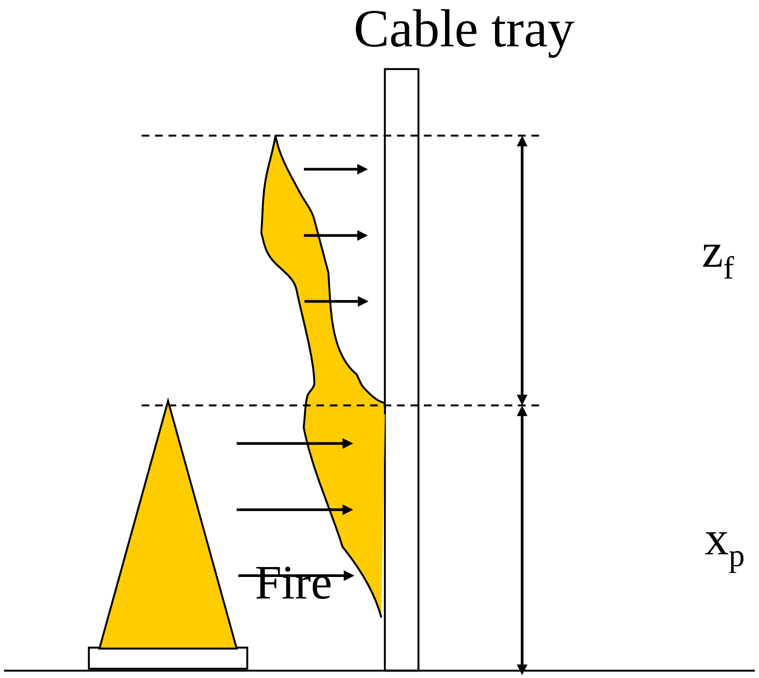
Ignition of Solids

- Solids do not evaporate like liquids when heated. Solids form gaseous decomposition compounds, generally leaving behind char, in a process called pyrolysis.
- At some point, the gases reach the lower flammability limit and may ignite by piloted ignition or, if hot enough, 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



Flame Spread

- Motion of vaporization front at the ignition temperature for solids and liquids
  - The surface is heated by the existing flames
  - More material pyrolyzes (or evaporates) ahead of the flame front
  - The existing flame acts as the pilot
  - The flame (fire) spreads…



Typical Flame Spread Rates

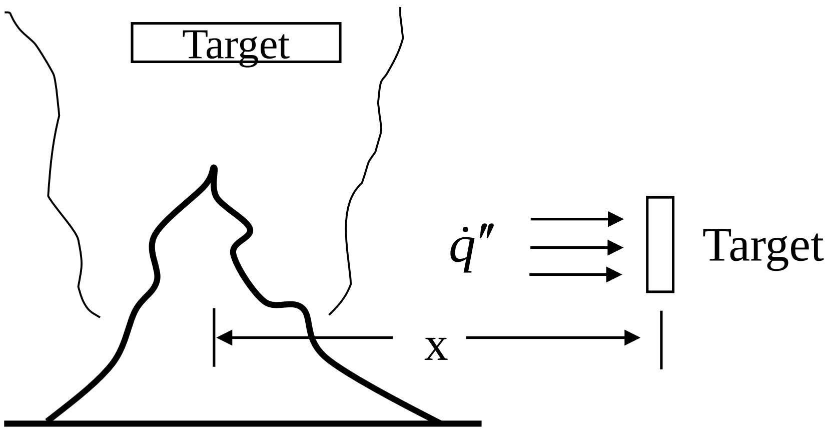
- It is very difficult to compute flame spread rates because formulas are not completely available, rates may not be steady, and fundamental fuel properties are not generally available.
- Nevertheless, we can estimate approximate magnitudes for spread rates for various cases.

Spread case	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 near the fire where damage or fire propagation is expected.

- For fires in the open we consider:
  - Flame Radiation
  - Convection, especially inside the fire plume



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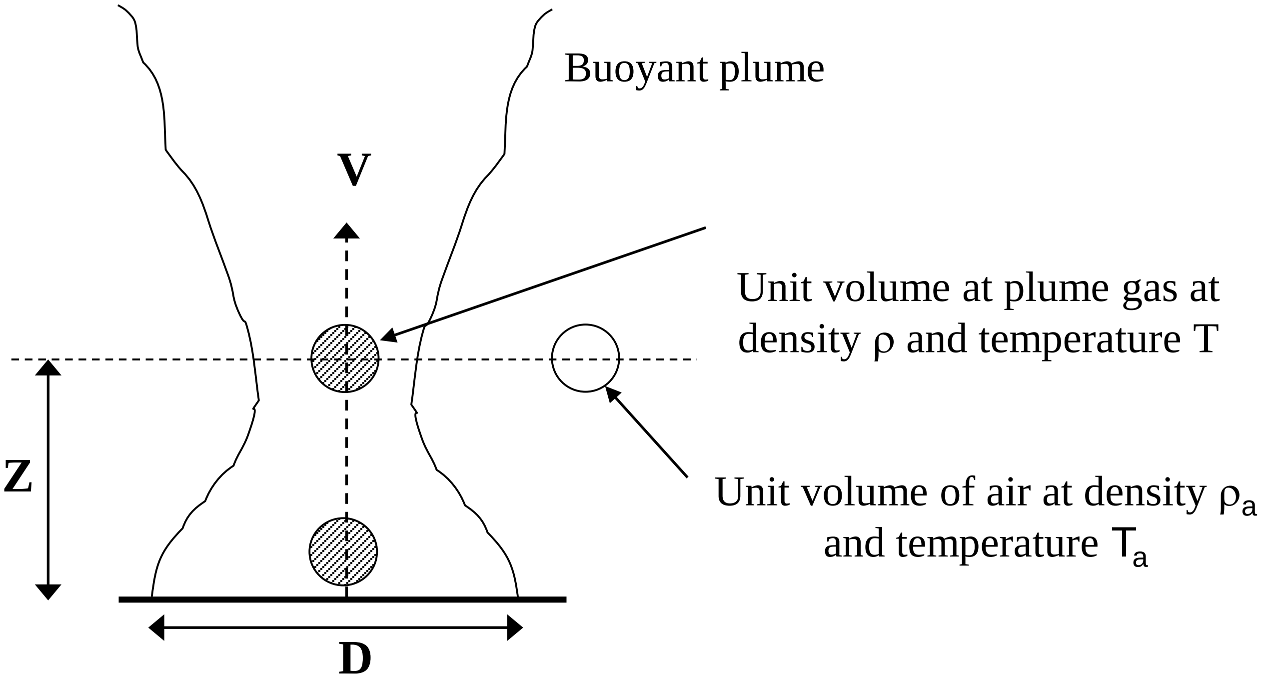
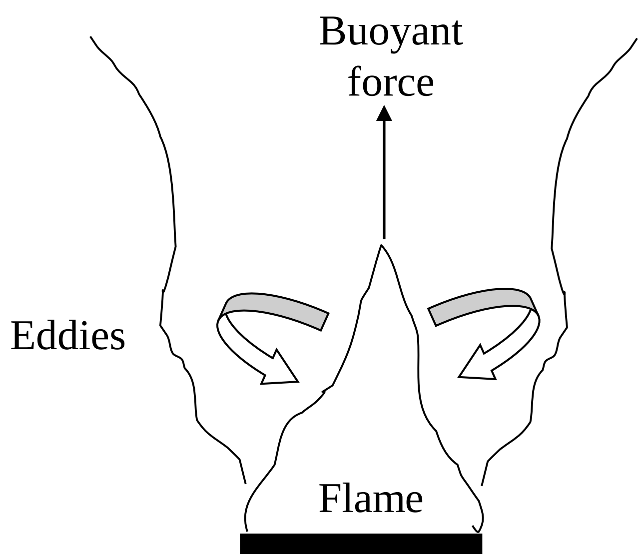
Buoyant Flow

- Temperature rise causes a decrease in gas density
- Potential energy converted into kinetic energy – gasses flow upwards



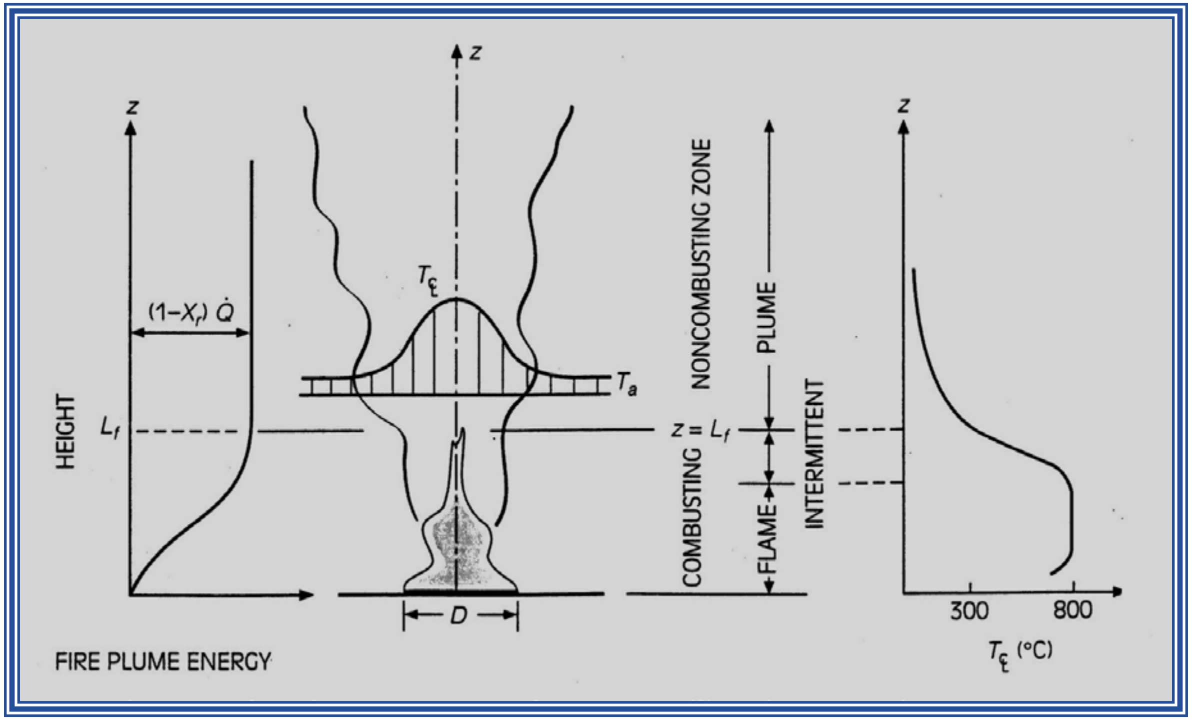
Turbulent Entrainment

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

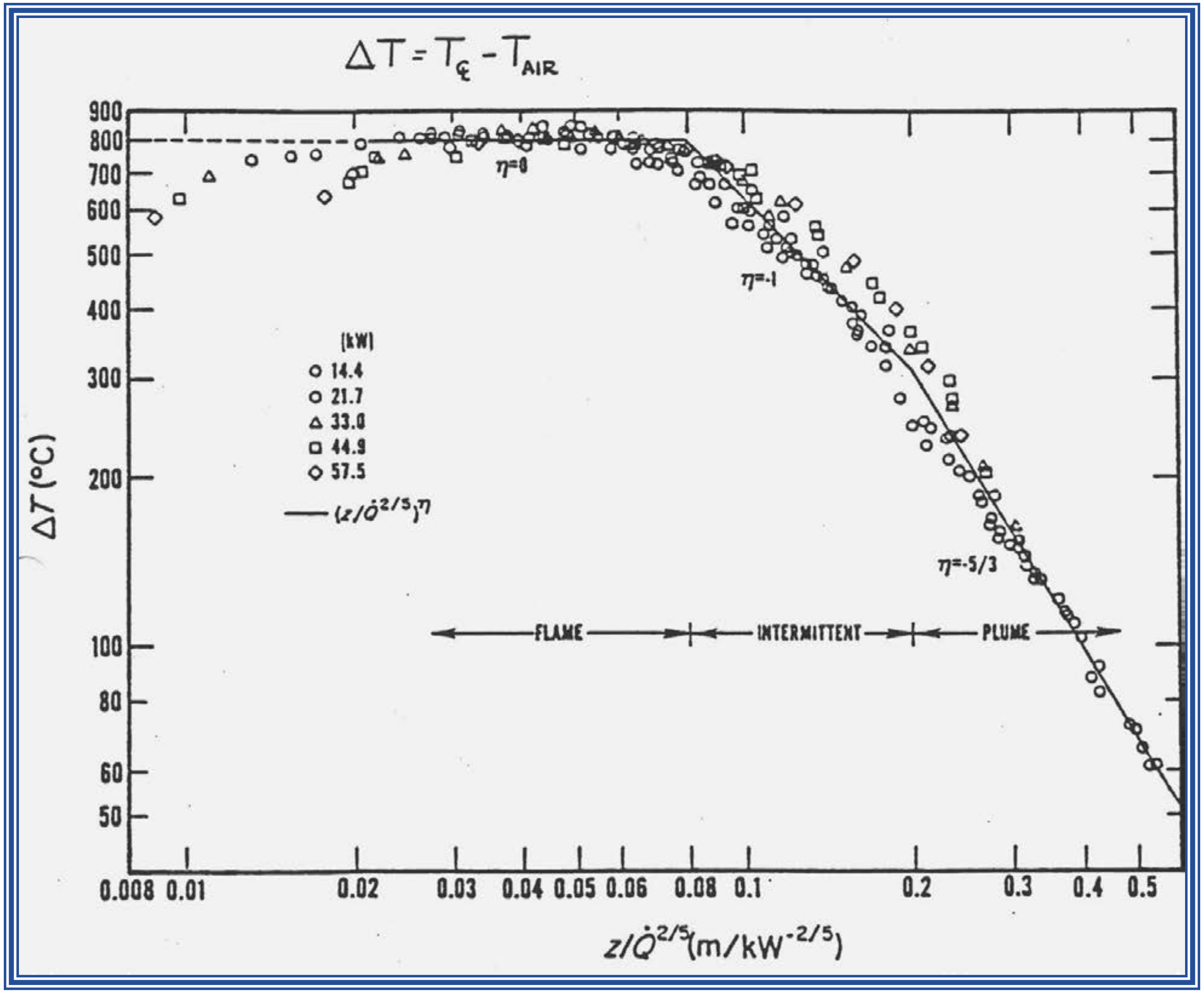


Turbulent Fire Plume

- 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

Heskdestad's Flame Height Correlation

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

Input

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

Result

L - Flame height [m]	1.5

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

where:

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

Heskestad's Plume Temperature Correlation

Input

T_{amb} - Ambient temp. [C]	20
Q_f - HRR [kW]	250
F_e - Fire elevation [m]	0
H_p - Target Elevation [m]	3.7
D - Fire Diameter [m]	1
k_f – Location factor	1 (…2 or 4)
X_r – Radiative Fraction	0.4

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: Radiative fraction (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**

Module III – Fire Analysis

Fire Fundamentals
Compartment Fires

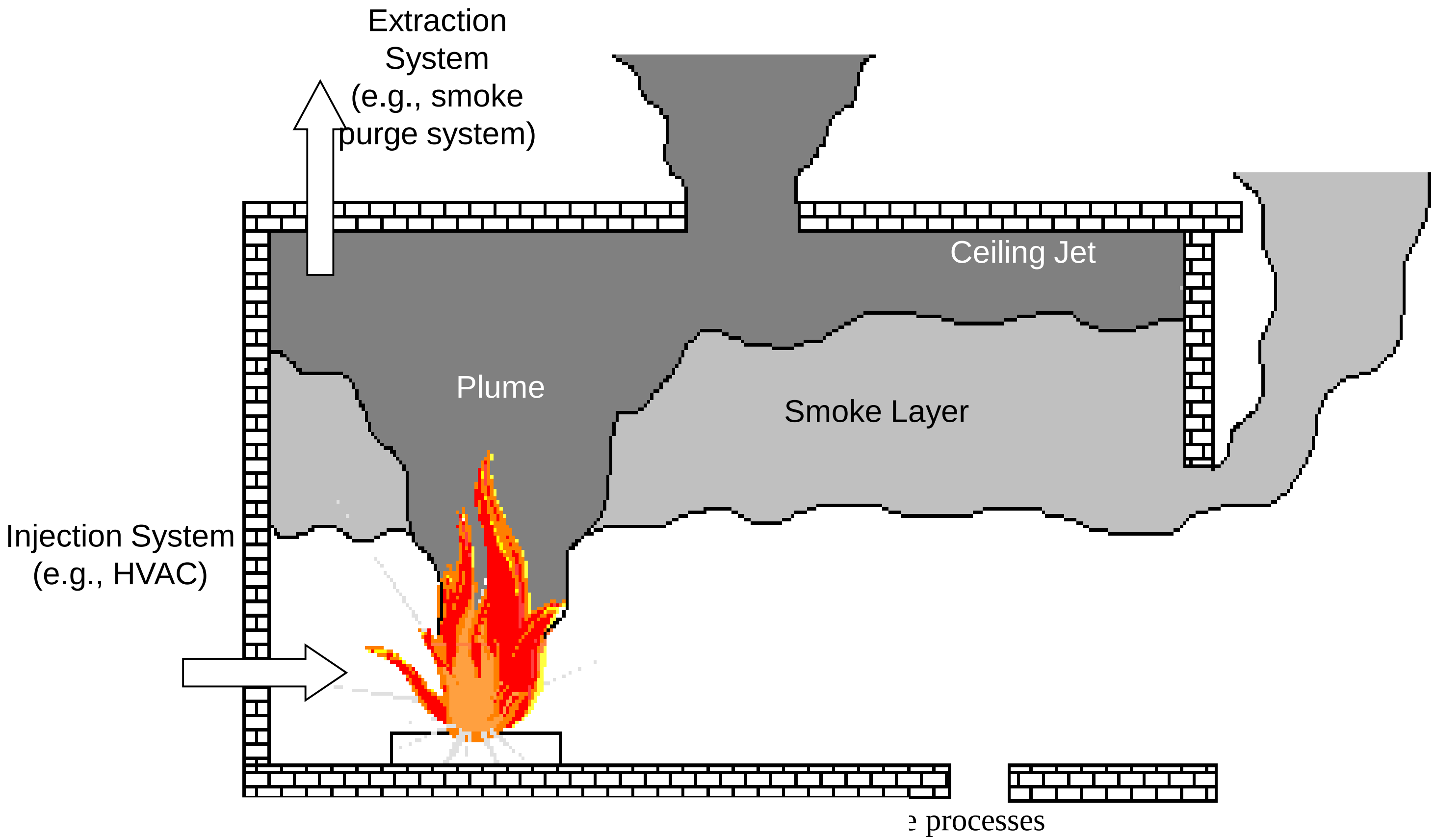
Joint EPRI/NRC-RES Fire PRA Workshop
July 15-19, 2019

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

Outline

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

Qualitative Description



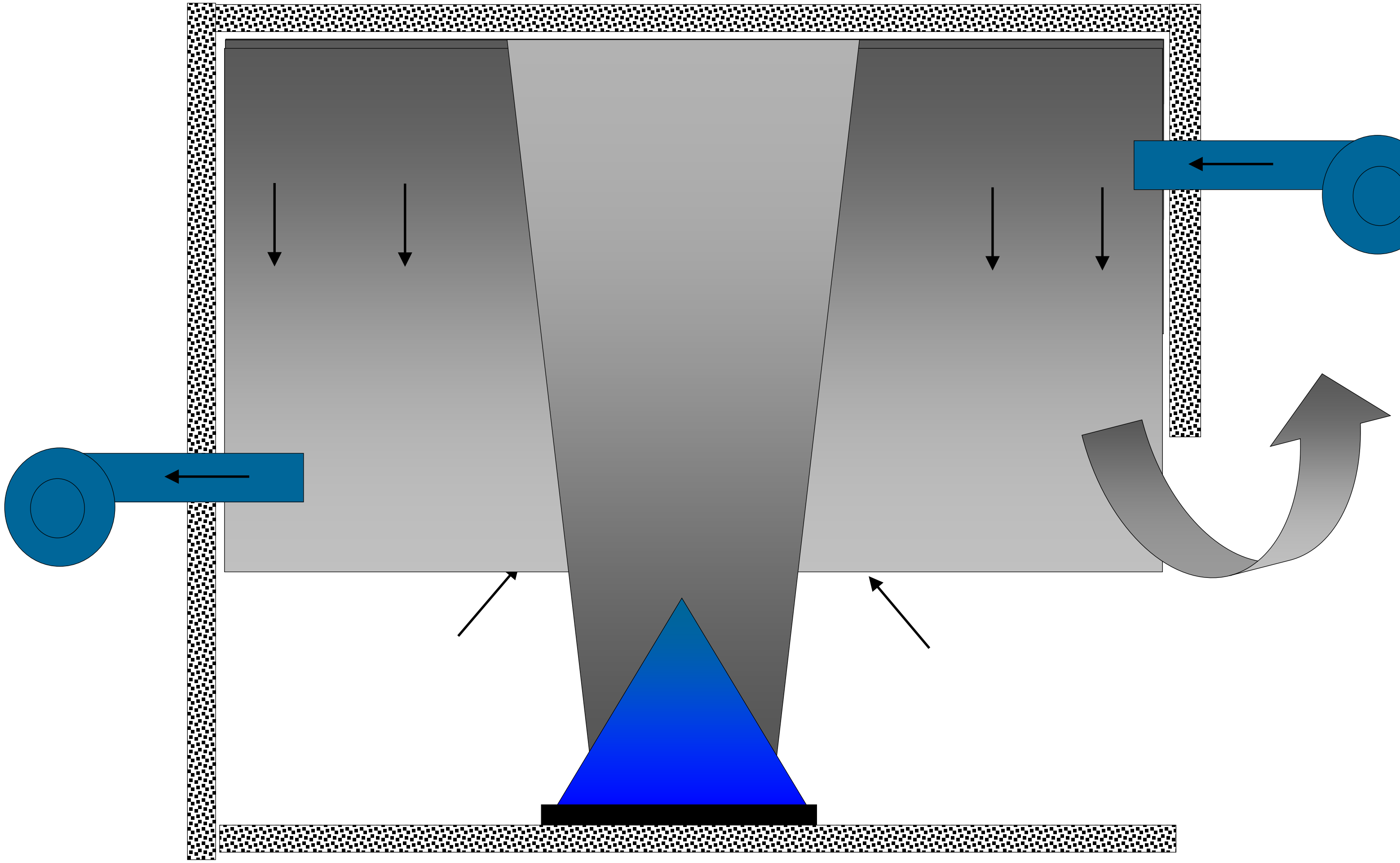
Phases in a Compartment Fire

- Ignition: Process that initiates an exothermic combustion reaction
  - Piloted or auto (spontaneous) ignition
  - 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 heat-up
- 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/m^2 to 20 kW/m^2

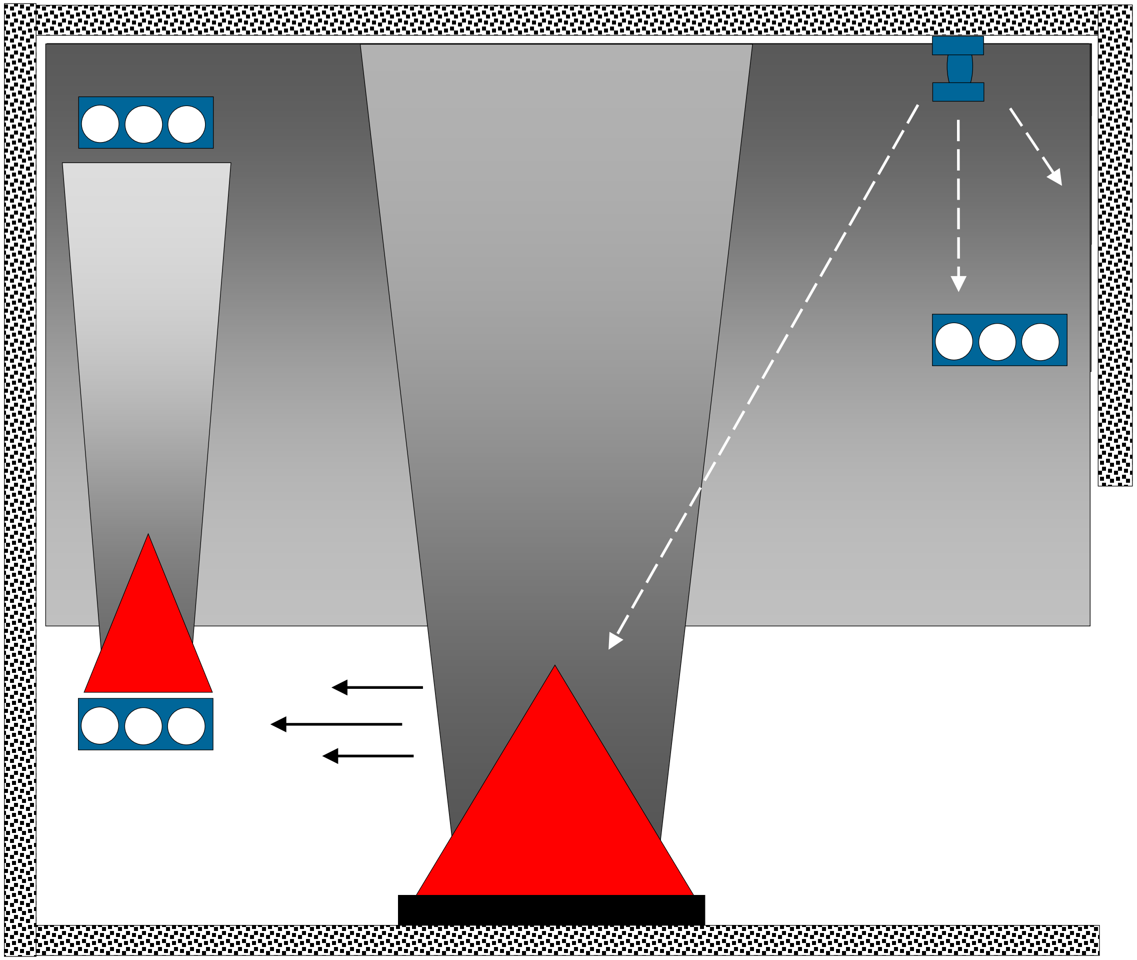
Phases in a Compartment Fire

- 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, fire intensity decreases
  - 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 205°C (401°F) for thermoplastic cables and 330°C (626°F) for thermoset cables
    - Main focus of NPP analysis
  - Post-flashover fire:
    - Focus in structural stability and safety of firefighters
    - Not generally an issue for NPP applications

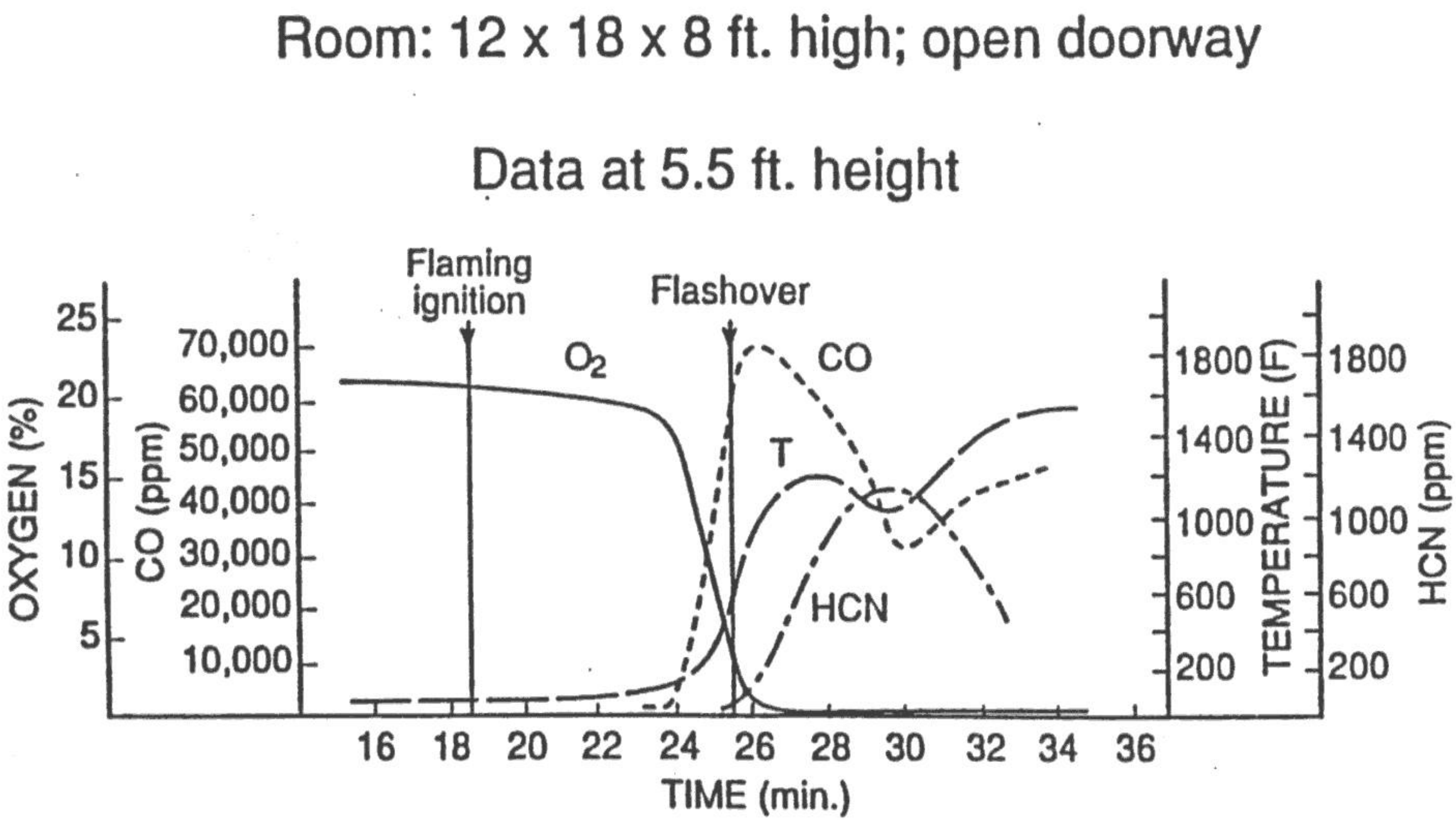
Compartment Fires



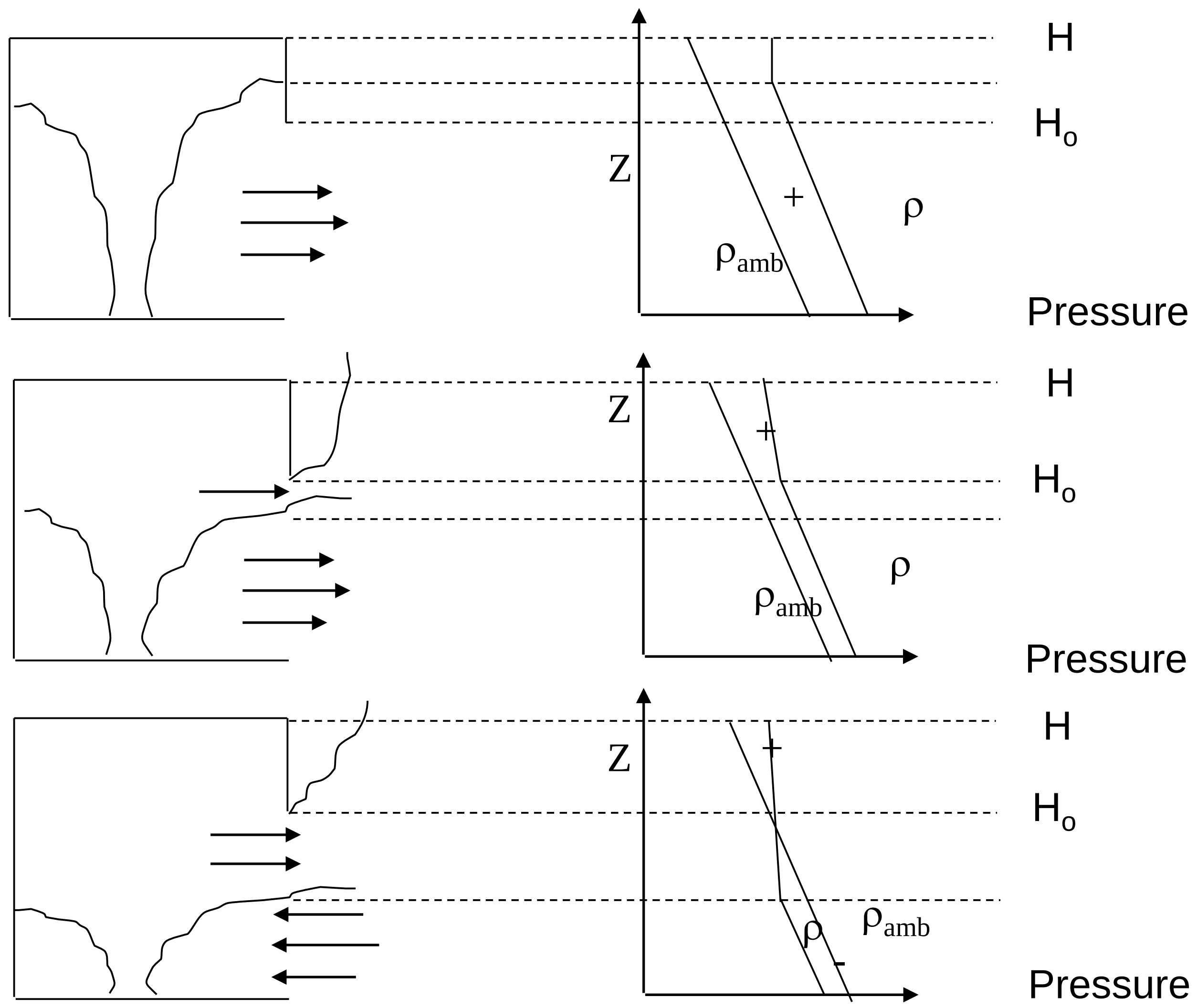
Compartment Fires



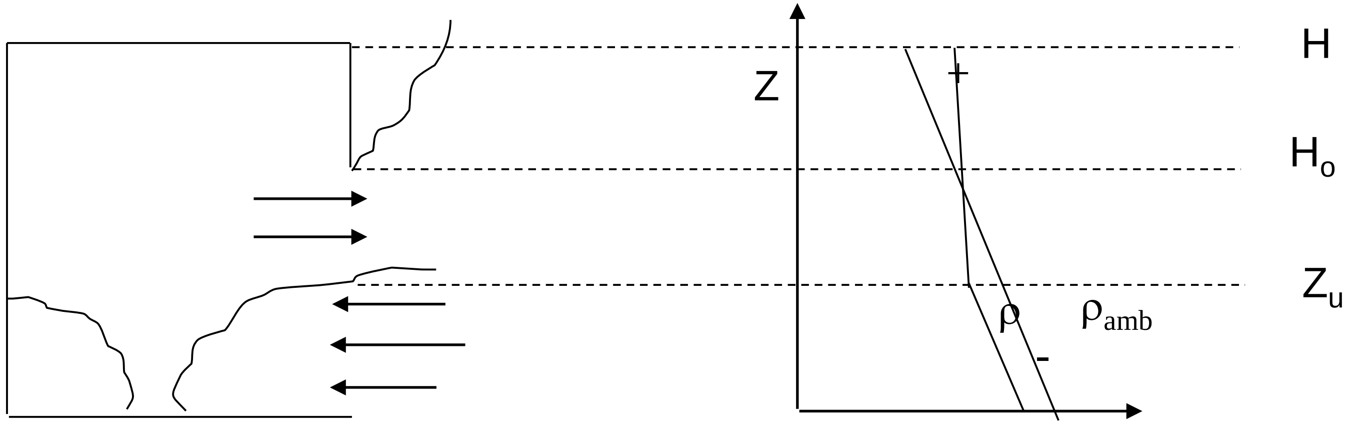
Sense of Scale



Pressure Profiles & Vent Flows



Pressure Profiles & Vent Flows



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

Inside Profile

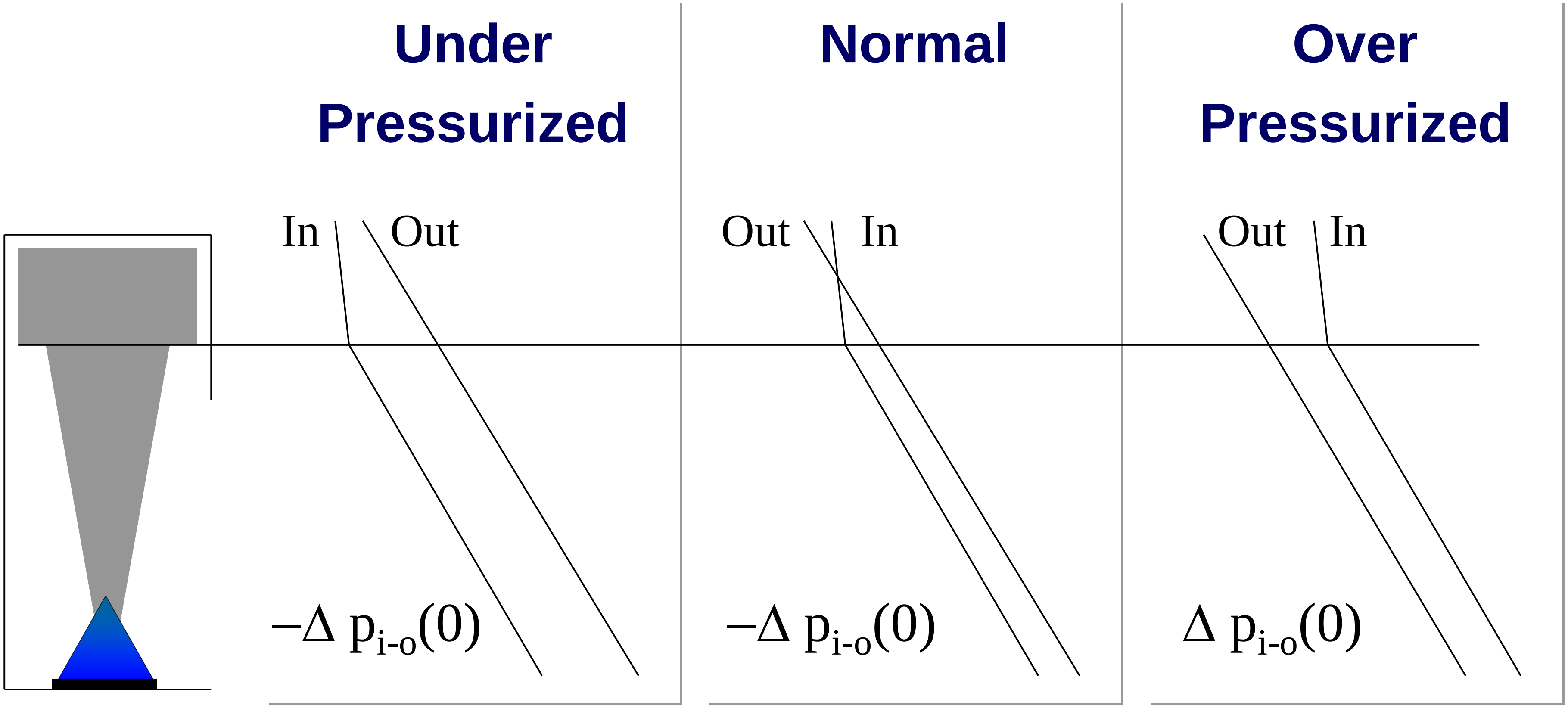
$$P_o(h) = P_o(0) - \rho_o gh$$

Outside Profile

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

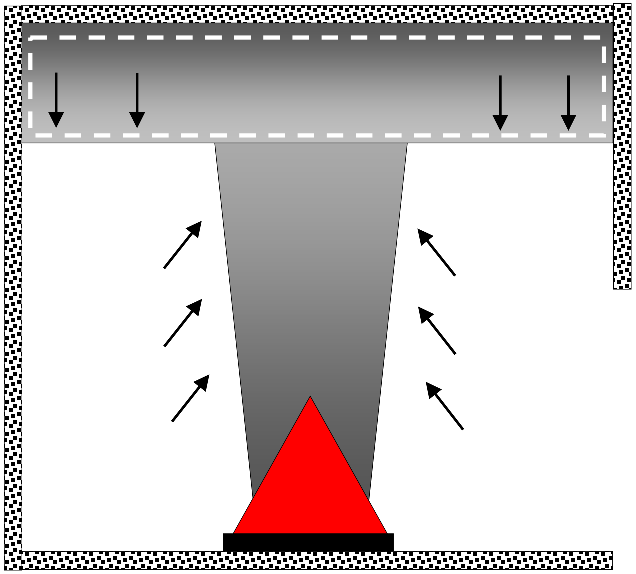
ΔP Profile

Pressure Profiles & Vent Flows



Hot Gas Layer or 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



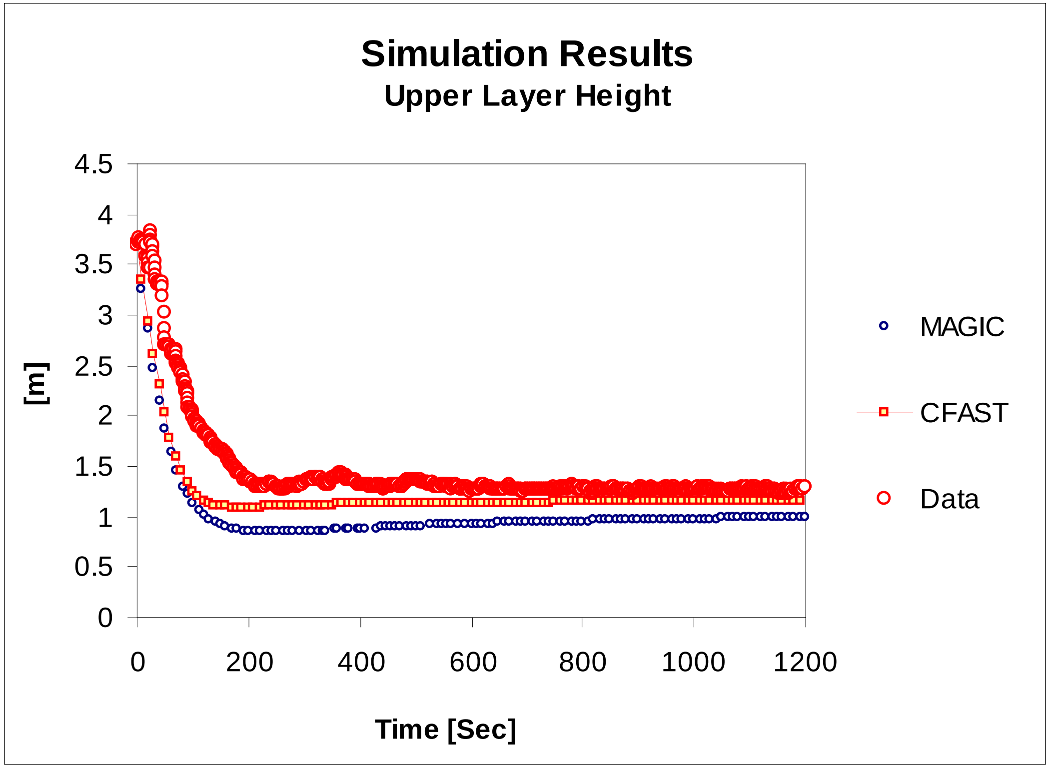
Hot Gas or Smoke Layer

Room size:

– 22 x 7 x 3.7 m

Fire: ~1 MW

Door: 2 x 2 m



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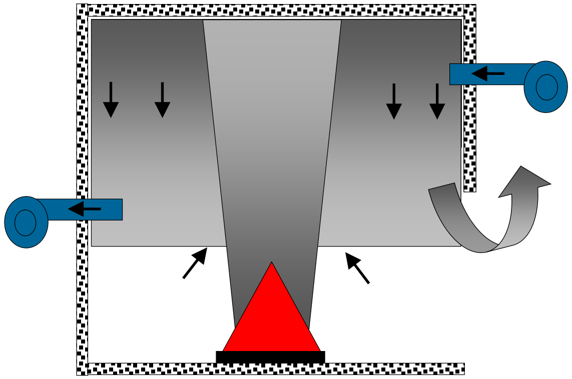
Hot Gas or Smoke Layer

- 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



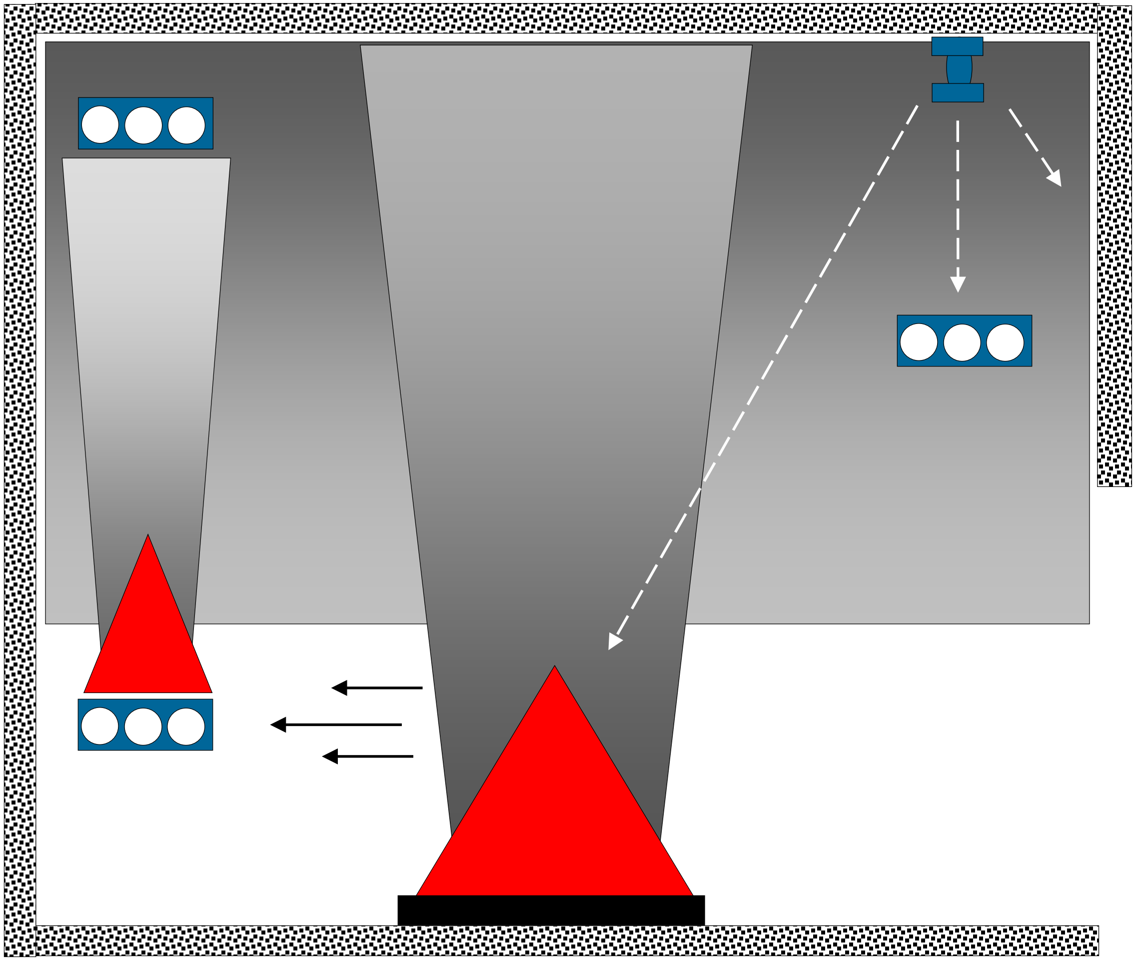
Heat Transfer

- …To walls
  - Convection and radiation
  - Conduction losses
- …To targets
  - Convection and radiation

- Heat losses from the compartment include:
  - Conduction through walls
  - Convection (gas flow) and radiation escaping through openings and vents

Heat Transfer

- Conduction
- Convection
- Radiation



Module III – Fire Analysis

Fire Fundamentals – Detection and Suppression

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

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 (by plant personnel)
  - Smoke detectors
  - Heat detectors
  - Flame/flash detectors
  - Incipient detection systems
  - Delayed detection

Prompt Detection

Prompt detection applies when a fire occurs in the presence of workers (often due to worker activities):

- Continuous fire watch
- Hot-work or other activity-specific fire watch
- Continuously manned rooms, e.g., the control room

Also applies to explosions:

- Hydrogen releases leading to explosion
- High energy arc fault fires

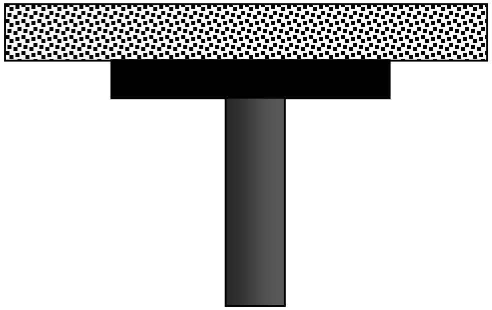
Smoke Detectors

- Spot type smoke detectors are the most common type of fixed fire detection
  - Ionization detection
  - Optical density detection
- Generally, smoke particles must move into the devices detection chamber for the device to actuate
  - Response is driven by convective flow of fire products to the device
- Devices need power
  - For NPP, generally have line power plus backup battery

Heat Detectors

- Heat detectors can be used in much the same way smoke detectors are used:
  - Localized heat detectors
  - May be used in areas where smoke detector not appropriate or simply overly sensitive
- Other examples of heat detectors:
  - Sprinkler heads – a melting link releases the flow of fire suppression water
  - Linear heat detectors – twisted wire pairs where insulation melts easily causing a short circuit and detection signal

Ceiling-mounted detector



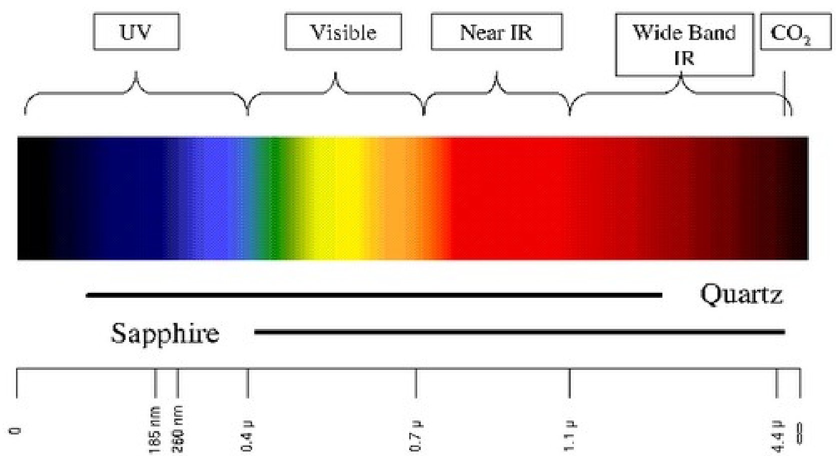
Locally-mounted detectors

Heat Detectors (cont.)

- Two broad types of spot heat detectors:
  - Temperature set-point – activates when temperature reaches set point
  - Rate of rise – activates when the temperature is seen to increase at a rate (degree per second) greater than set point
- Visually very similar, hard to tell apart by visual observation (have to ask)
- Heat detectors (including sprinkler heads) are generally characterized by a response time index (RTI) and an activation value (temperature or rate of rise)
  - RTI: a parameter describing how fast the device responds to the surrounding gas temperature

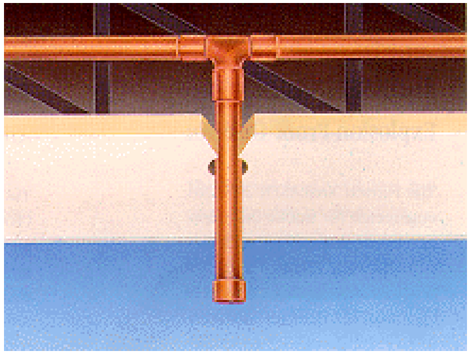
Flame detectors

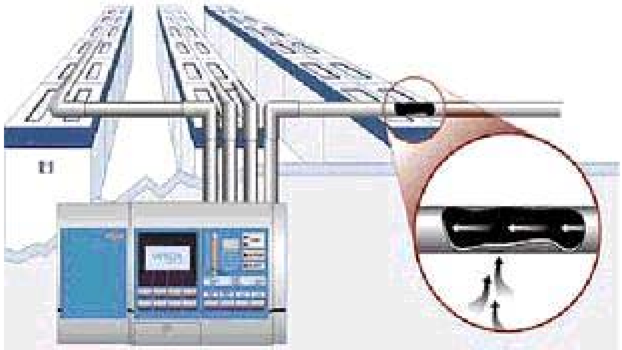
- Not very common in NPP applications
- Generally associated with a very specific fire hazard:
  - A particular fire source in a location where rapid detection is desired
- Devices are typically characterized by the wavelength of light they are sensitive to and the threshold sensitivity value
  - Can operate at very specific wave length or over a very broad spectrum
  - Very fast acting given a sufficient input signal (they work at the speed of light…)



Incipient Detection

- Relatively new concept in fire detection
- Most common examples are based on air sampling systems
  - Condensation particular detectors
  - Laser scattering particulate detectors
- Designed to detect trace pyrolysis products during incipient stage of a fire (i.e., before actual flames appear)
- Typically used where conventional fire detectors can't provide sufficiently rapid response.
- The objective is to allow time for plant personnel to prevent potential fire impacts





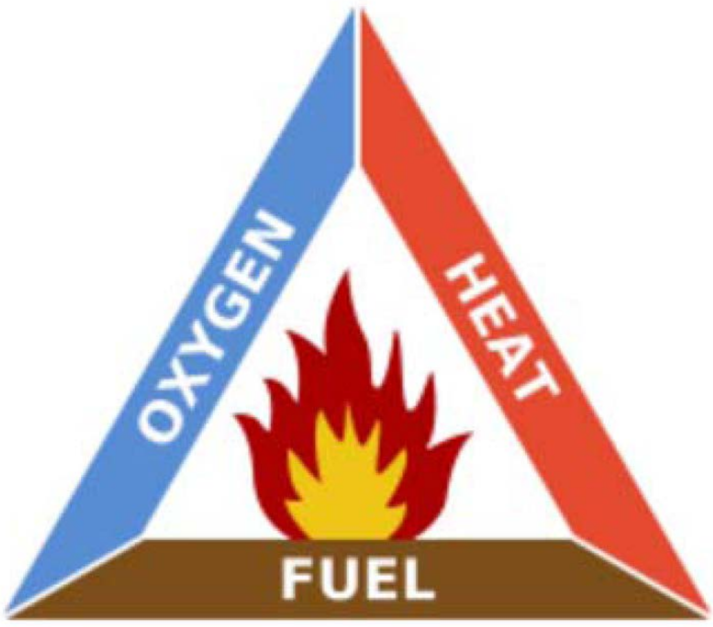
Delayed Detection

- Eventually any actual fire of the type we postulate <u>will</u> be detected
  - If there is no fixed detection system present or fixed detection fails to function then we credit delayed detection
- Roving fire watch
- General plant personnel (including roving security 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 the burning fuel and adjacent items
    - e.g.: water spray
  - Removing/displacing oxygen
    - e.g.: CO_2
  - Separating burning surface from impinging heat flux from the flame
    - e.g.: AFFF (Foam)
  - Interfering with the chemical oxidation process
    - e.g.: Halon, dry chemical

Break the fire triangle!



Fire Suppression vs. Control

- Fire suppression
  - "Control and extinguishing of fires" [Reg. Guide 1.189]
- Fire control
  - A controlled condition where the spread of the fire and its effects is contained.
- The primary objective is to estimate the time to fire control
  - In the context of a fire PRA it is assumed that achieving fire control will lead to target-set damage slow down significantly so that no further damage is realized.
  - In most cases time to control and extinguishing are virtually the same. However, in very few reported cases controlled fires were allowed to burnout.

Fire Suppression

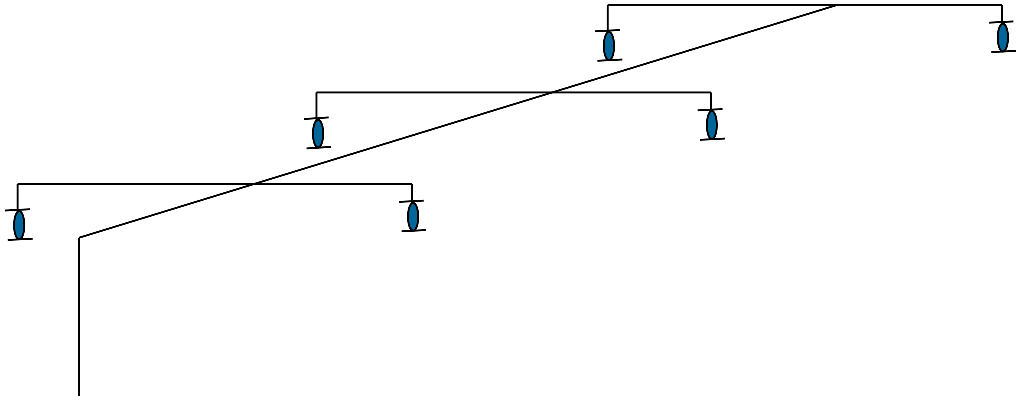
- We can and will credit multiple means of fire suppression as available in a given situation:
  - Prompt suppression (fire watch)
  - Water based fixed systems:
    - Automatic sprinklers
    - Dry-Pipe/Pre-action sprinklers
    - Deluge systems
  - Gaseous suppression systems (automatic or manual activation):
    - CO_2
    - Halon
  - Manual suppression:
    - Fire brigade
    - General plant personnel (hand-held extinguishers)
    - Manual activation of fixed suppression systems

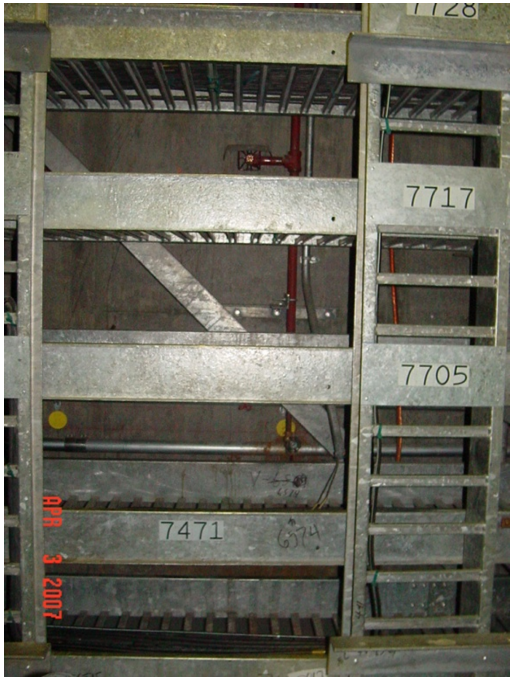
Prompt Suppression

- Applies to hot-work fire watch in particular but…
  - …already factored into fire frequency
  - hot work fires suppressed promptly by a posted fire watch are <u>not</u> counted in fire frequency calculations
- Applies to continuous fire watch if they are trained and instructed to suppress fires (e.g., rather than to simply report fires)
- For more general suppression by plant personnel quick response to fires is factored into manual suppression timing curves (to be discussed later)
  - e.g., MCR operators are generally trained in the use of portable extinguishers so MCR fire suppression curve is very aggressive…

Wet Pipe Fire Sprinklers

- Most common of the water-based systems
- Fusible links at each discharge nozzle
- Water readily available (pipe is charged)
- May see full room coverage, localized zone coverage, directed water spray in trays, …





Dry-Pipe/Pre-Action Sprinklers

- Similar to wet-pipe sprinkler but feed pipes are maintained dry
  - There is an upstream shutoff valve that keeps the water away from sprinkler heads
- Either a fire detection system or manual actions open the shutoff valve filling and pressurizing the feed pipes
  - Turns the system into a wet system
- Fusible links at sprinkler heads still need to open from exposure to heat from the fire before water spray starts

Deluge System

- Similar to dry pipe sprinkler but all discharge nozzles are open (no fusible link)
  - Feed pipes are dry beyond a shut-off valve
- A fire detection signal or manual action opens the main shutoff valve
- All nozzles discharge water at the same time upon opening of the shutoff valve
- Generally used for protecting high fire hazard sources
  - Spray is often directed towards a specific hazard with potential for large fires
  - e.g. a big oil tank or oil-filled transformer
- Generally involves very high water volumes since all heads are open
  - Sprinkler heads will open more selectively depending on fire location and intensity
  - Deluge systems spray all heads at once

Carbon Dioxide

- CO_2 gas is used as a fire suppressant - displaces oxygen from the fire
- Life safety considerations – displaces oxygen for humans as well as the fire so it will kill
  - Look for warning signs on the doors
  - If you are in a room with CO_2 suppression and the alarm goes off, get out
- System types:
  - Automatic room flooding CO_2 - generally released after heat or flame detection, a life safety alarm and delay time for evacuation of area
  - Manual room flooding CO_2 – requires an operator or fire brigade personnel to activate the system manually – still has time delay for personnel safety
  - May also see CO_2-based manual hose stations
- Room flooding systems must maintain proper suppression agent concentration for a soak time of several minutes
  - Typical room flooding goal is 60% by volume CO_2

Halon

- Halon interferes with the chemical oxidation process
- No life safety issues – does not displace oxygen, safe for use in occupied space
- System types:
  - Automatic room flooding – suppression agent is generally released after smoke or heat detection and a life safety alarm and delay time
  - Manual room flooding – requires an operator or fire brigade personnel to activate the system after smoke detection
  - Also used in hand-held extinguishers, but becoming more and more rare
- Must maintain proper suppression agent concentration for a soak time (typically 15 minutes)
- Halon is not being manufactured any more and existing systems are being phased out because of environmental considerations
  - Fluorocarbon based product banned by the Montreal protocol on ozone depleting substances

Manual Fire Suppression

- Credited in most fire scenarios
- Includes both general plant personnel and the fire brigade
  - Typical plants maintain a professional brigade of operators and other plant personnel trained in advanced fire fighting techniques
  - Some general plant personnel will likely have basic fire extinguisher training
- Manual fire suppression is triggered by fire detection event
  - Approach assumes that fire suppression efforts begin as soon as a fire is detected, but likelihood of fire suppression is based on time
- Typically begins with use portable extinguishers provided fire is not too big
  - This is not always successful and may take several attempts before fire is suppressed
- Fire brigade will use water (fire hoses) if needed, but we assume general plant personnel will not use a fire hose

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.

Module III – Fire Analysis

Fire Scenarios

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

Let's talk about fire scenarios in a risk analysis…

- In fire PRA we look for and analyze fires that may:
  - Cause an initiating event – an upset to normal at-power plant operations such that reactor shutdown is required
  - Damage mitigating equipment – that set of plant equipment that operators would rely on to achieve safe shutdown
- To do this we:
  - Identify fire sources,
  - Analyze the potential impact of fires on the surroundings,
  - Assess fire protection systems and features,
  - Assess the plant and operator's response to fire-induced damage
- The final result is expressed as a fire-induced core damage frequency (CDF) – an estimate of the frequency of fires leading to core damage

So what is a 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) whose fire-induced failure may cause an initiating event and/or complicate post-fire safe shutdown
  - Fire protection features, e.g., automatic sprinklers
  - The compartment where the fire is located
  - A time line

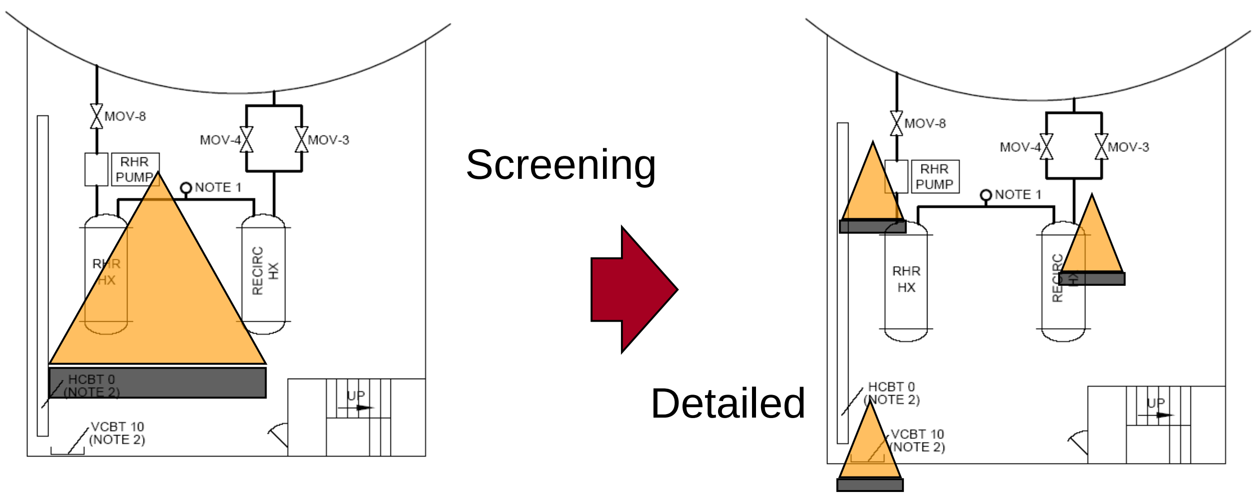
Fire Scenario Time Line

Timeline includes the following elements (not necessarily in this order):

1. Scenario starts with ignition of a fire in a specific fire source
2. Fire growth involving the affected fuel,
3. Heat transfer from the fire to other items within the zone of influence,
4. Propagation of the fire to other materials,
5. Damage to identified PRA targets (e.g., cables and equipment),
6. Detection of the fire
   - Detection can actually occur before ignition given an incipient detection system…
7. Automatic initiation of suppression systems if present,
8. Manual fire fighting and fire brigade response,
9. Successful fire extinguishment ends the scenario.

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*

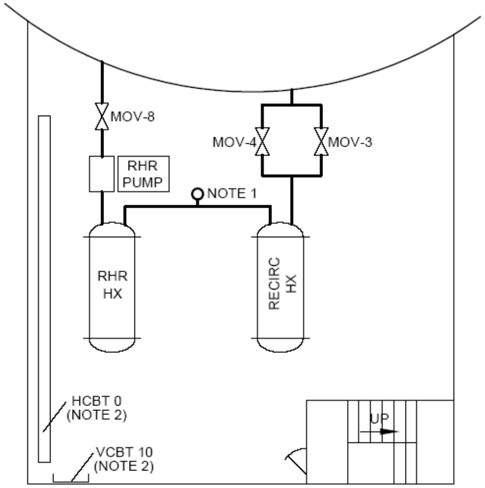
- In the initial stages of screening, fire scenarios are defined in terms of compartments and loss of all items within each compartment.
  - Assumes all items fail in the worst failure mode
  - Detection and suppression occur after the worst damage takes place
  - Fire does not propagate to adjacent 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



NOTES:

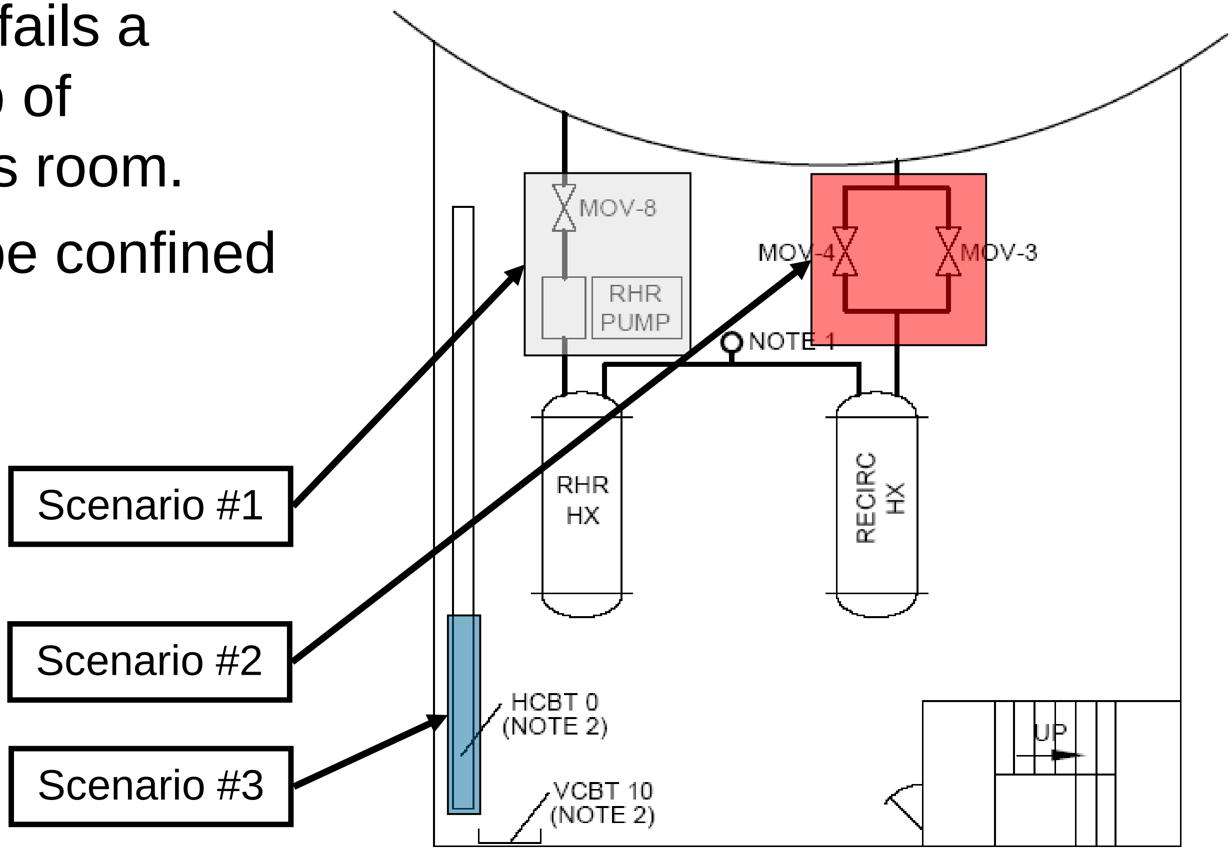
1. VERTICAL PIPE PENETRATION TO UPPER ELEVATION.

2. PENETRATION TO UPER FLOOR IS SEALED.

HCBT: HORIZONTAL CABLE TRAY
VCBT: VERTICAL CABLE TRAY

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

- Selecting scenarios is dependent on the objectives of the fire risk quantification
  - How many fire scenarios are enough to demonstrate the objective?
  - Which scenarios are the appropriate ones given objectives?
  - What fire conditions are actually modeled?
  - Analysis should represent a complete set of fire sources and conditions as relevant to the analysis objectives
  - A full-scope fire PRA tries to capture all fire scenarios that may represent contributors to plant core damage risk
- 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?
  - Fires that don't propagate or cause damage are generally not risk contributors

Select and Describe Fire Scenarios

1. Scenarios begin with an ignition source – what/where does the fire start and what are the fire characteristics
2. Consider intervening combustibles – fire propagation beyond the fire source needs to be considered
3. There should be at least one damage target identified. Often it is a set of damage targets rather than just one (e.g., a group of important cables).
4. Include fire protection system and features (active or passive) that may influence the outcome of the event (there is a pain/gain decision point here)

Select and Describe Fire Scenarios

5. Sometimes, multiple ignition sources or targets can be combined into one scenario (e.g., a bank of cabinets all with the same cables overhead)
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 closed doors, ventilation conditions, spatial details (e.g., target position relative to fire source), etc.

Scenario Quantification

General quantification of CDF is based on a five-part formula:

$$CDF_{scenario} = \lambda \cdot W \cdot SF \cdot P_{ns} \cdot CCDP$$

- λ = Ignition frequency for the postulated ignition source group (e.g., pumps)
- W = A weighting factor for the likelihood that the fire occurs in a specific ignition source (this pump…) or plant location (this room…)
- SF = A severity factor reflecting percentage of fires large enough to generate the postulated damage if left unsuppressed
- P_{ns} = Non suppression probability – the probability that given the fire, it goes unsuppressed long enough that the target set is damaged
- CCDP = The conditional core damage probability – probability that given loss of the target set, operators fail to achieve safe shutdown and the core is damaged.

In practice, we often quantify scenarios in a progression of more detailed steps:

- A fire in a specific plant location $$CDF_{is} \approx \lambda_g \cdot W_{is} \cdot 1 \cdot 1 \cdot 1$$
- …That is severe enough to threaten targets $$CDF_{is} \approx \lambda_g \cdot W_{is} \cdot SF \cdot 1 \cdot 1$$
- …That goes unsuppressed long enough to cause damage $$CDF_{is} \approx \lambda_g \cdot W_{is} \cdot SF \cdot P_{ns} \cdot 1$$
- …That prevents safe shutdown $$CDF_{is} \approx \lambda_g \cdot W_{is} \cdot SF \cdot P_{ns} \cdot CCDP$$

Module III – Fire Analysis

Task 1 – Plant Partitioning

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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Plant Partitioning
Scope (per 6850/1011989)

Task 1 covers the following topics:

- Plant Partitioning Analysis
  - Define Global Analysis Boundary
  - Partition into physical analysis units (PAUs)

Corresponding PRA Standard Element

- Task 1 maps to element PP – Plant Partitioning
  - PP Objectives (per the PRA Standard):
    - To define the global analysis boundary
    - To define physical analysis units

PP HLRs (per the PRA Standard)

- HLR- PP-A: The Fire PRA shall define global boundaries of the analysis so as to include all plant locations relevant to the plant-wide Fire PRA (1 SR)

- HLR-PP-B: The Fire PRA shall perform a plant partitioning analysis to identify and define the physical analysis units to be considered in the Fire PRA (7 SRs)

- HLR-PP-C: The Fire PRA shall document the results of the plant partitioning analysis in a manner that facilitates Fire PRA applications, upgrades, and peer review (4 SRs)

Support Task A: Plant Walkdowns
Just a Quick Note….

- You *cannot* complete a Fire PRA without walkdowns
- Expect to conduct a number of walkdowns, especially for key areas (e.g., those analyzed in detail)
- Walkdowns can have many objectives and support many tasks:
  - Partitioning features, equipment/cable mapping, fire ignition source counting, fire scenario definitions, fire modeling, detection and suppression features, operator actions HRA
- Walkdowns are generally a team activity so coordinate them to optimize personnel time and resources
- Take a camera and/or tablet if you can, keep good records
- Corresponding PRA Standard SR: PP-B7

Plant Partitioning
General Comment/Observation

- The recommended practice for Task 1 has changed little from prior methods.
  - That means you can likely benefit from a previous analysis
    - e.g., your IPEEE fire analysis
  - However: watch out for new equipment/cables, new initiators when screening
- May need to work closely with the cable routing experts to ensure coordination among the plant partitioning schemes
  - A naming convention is one important issue here

Task 1: Plant Partitioning
Key Definitions: PAU vs. Fire Area/Zone

- PAUs are defined in the context of the Fire PRA only
  - They become the basis for analysis management
- Fire Areas are defined in the context of your regulatory compliance fire protection program
- Fire Zones are generally defined in the context of fire protection features (e.g., detection, suppression, hazards)
  - Fire zones have no direct meaning to the Fire PRA context and we avoid using this term
- BTW…
  - PAU is “standard-speak”
  - 6850/1011989 used the term “compartments”
  - We’ll use Compartments and PAUs interchangeably

Task 1: Plant Partitioning
Task Objectives and Output

- There are two main objectives to Task 1:
  1. Define the Global Analysis Boundary
     - The maximum physical extent of the plant that will be considered in the Fire PRA
  2. Divide the areas within the Global Analysis Boundary into analysis Physical Analysis Units
     - The basic physical units that will be analyzed and for which risk results will be reported

- Task output is the definition of these two aspects of the analysis

Internal vs. external in PRA space and the implications of the Global Analysis Boundary

- The language here is changing!
- Historically we talked about "internal events" and "external events"
  - Terms used to mean that the failures setting off an accident sequence either occurred *internal* or *external* to plant *systems/components*
  - Fire attacks equipment from the outside versus random failures that occur within the system/component
  - Historically, fire was referred to as an external event
- The PRA standard used a different split:
  - Internal Hazards
  - External Hazards
- Under the standard:
  - Internal fires are an internal hazard
  - External fires are an external hazard

Internal vs. external in PRA space and the implications of the Global Analysis Boundary

- Key notion: The global analysis boundary defines the split between *internal* and *external* fires
  - This notion has now been accepted as a part of the standard at least in the context of fire

- So going forward…
  - We are talking about internal fires…
  - Which are part of the internal hazard group

- Be careful - folks will still refer to fires as an external event
  - Not a big deal, but don't be surprised

Task 1: Plant Partitioning
Task Input

- No real input from any other task is required (it is, after all, Task 1)
  - You may also find yourself iterating back to this task later in the analysis – that is fine, just be careful to track any changes
  - A word of Caution: Many things will be traced and assigned based on the fire compartments. If you change partitioning decisions later, there are consequences relative to information tracking

- What do you need to support this Task?
  - Layout drawings that identify major structures, walls, openings
    - Drawings that identify Fire Areas are especially helpful
  - Plan and elevation drawings are helpful
  - You *will* need to do a walkdown to support/verify decisions

Task 1: Plant Partitioning
Task Breakdown in Steps

- Task 1 has four steps:

  Step 1: Selection of Global Plant Analysis Boundary

  Step 2: Plant Partitioning

  Step 3: Compartment Information Gathering and Characterization

  Step 4: Documentation

Task 1: Plant Partitioning
Step 1:Selection of Global Plant Analysis Boundary

- We generally recommend a *liberal* definition of the global analysis boundary
  - It's OK to include obviously unimportant areas, we'll drop them quickly, but better to do this formally
  - Alternative is to explain choices/exclusions in your documentation

- Encompass all areas of the plant associated with both normal and emergency reactor operating including support systems and power production

- Sister units should be included unless they are physically and functionally separated
  - Separated means: no shared areas, no shared systems, no shared components and associated cables, no conjoined areas (e.g., shared walls)

Task 1: Plant Partitioning
Selection of Global Plant Analysis Boundary

- Begin with your protected area: everything within the protected area should be included in the Global Analysis Boundary
  - In most cases that will capture all risk-important locations

- If necessary, expand the boundary to include any other locations that house equipment or cables identified in Tasks 2 or 3
  - This is the Task 2/3 link mentioned before!
  - Example: If your offsite power related equipment is outside the protected area, you need to expand the Global Analysis Boundary to capture it

- Corresponding PRA Standard SR: PP-A1

Task 1: Plant Partitioning
Selection of Global Plant Analysis Boundary

- By the end of the analysis, you need to provide a fire risk disposition for all locations within the global analysis boundary
  - Some locations may screen qualitatively
  - Some may screen quantitatively
  - Some <u>will</u> be quantified in detail
  - Bottom line – all locations need some resolution

Task 1: Plant Partitioning
Step 2: Plant Partitioning (into PAUs)

- We divide the Global Analysis Boundary into smaller pieces (PAUs) for the purpose of tracking and reporting risk results

- A PAU can be many things, but when it comes down to it, a PAU is:

  A well-defined volume within the plant … that is expected to substantially contain the adverse effects of fires

Task 1: Plant Partitioning
Plant Partitioning into Fire Compartments

- This task is often subjective – judgment *is* required

- Ideally: PAU = Room
  - Locations that are fully defined by physical partitioning features such as walls, floors, and ceilings

- But the ideal is not the only solution - other features and elements may be credited in partitioning
  - That's where judgment comes into play!
  - You must decide what to credit as a partitioning feature and then document and justify your choices
  - Cable routing should be an influencing factor

Task 1: Plant Partitioning
Plant Partitioning into Fire Compartments

- A good starting point is your Fire Areas, but you are *by no means limited* to equating PAUs to Fire Areas
  - A Fire Area may be partitioned to two or more PAUs
  - You may combine two or more Fire Areas into a single PAU
- In the end: { ∑ PAUs } ≡ { Global Analysis Bnd. }
  - No omissions
  - No overlap
- Corresponding PRA Standard SR: PP-B6

Task 1: Plant Partitioning
Plant Partitioning into Fire PAUs

- So what can you credit as a partitioning feature:
  - Bottom line: anything you can justify – see text for examples
    - You do need to justify your decisions with the exception of structural elements maintained as rated fire barriers
  - In the end, your partitioning decisions should not affect the risk results, but . .
  - Don't go crazy – there are disadvantages to over-partitioning
  - General guideline: try to minimize the need to develop and analyze multi-compartment scenarios

- Corresponding PRA Standard SR: PP-B1

Task 1: Plant Partitioning
Plant Partitioning into Fire PAUs

- It is not recommended to partition based on:
  - Radiant energy shields
  - Beam pockets
  - Equipment obstructions (e.g., pipes)
  - Per the PRA Standard: raceway wraps and other localized fire barriers ***may not be credited*** in partitioning
- Spatial separation credited as partitioning scheme requires justification
  - e.g., significant separation distances with no ignition sources, very limited fuel loads

- Corresponding PRA Standard SRs: PP-B2, B3, B4 and B5

Task 1: Plant Partitioning
Plant Partitioning into Fire PAUs

- Final Point: You need a system to identify/name your PAUs
  - Something both consistent and logical – but whatever works for your application and plant
  - Often makes sense to use Fire Area designations in naming schemes
    - Example: Fire Area 42 might become PAUs 42A, 42B…
  - Use your naming scheme consistently throughout the Fire PRA
    - Documentation, equipment/cable routing database, etc.

Task 1: Plant Partitioning
Step 3: PAU Information Gathering

- Later tasks need certain information about each PAU. They include, but are not limited to the following:
  - PAU boundary characteristics
  - Ventilation features, and connections
  - Fire protection features
  - Identification of all adjacent PAUs
  - Access routes to the fire PAU

Task 1: Plant Partitioning
PAU Information Gathering

- A thorough plant walkdown is needed to confirm and gather information about each fire PAU

- It is unlikely that all information will be collected and documented during the first pass

- As work on fire PRA progresses, additional information, as needed, is collected and documented

- This task, similar to other later tasks, is expected to be revisited and PAU definitions modified as additional information is obtained

Task 1: Plant Partitioning
Summary

- Plant Partitioning is the first task of the fire PRA

- Task is done in three steps:
  1. Define global plant analysis boundaries to include all those area that will be addressed by the fire PRA
  2. Define fire PAUs in such a way that all the areas identified in the preceding step are covered, there are no overlaps and there is a balance between size and number of PAUs selected
  3. Confirm the selected PAUs through a walkdown and record important information that will be used later.

Mapping HLRs & SRs for the PP Technical Element to NUREG/CR-6850, EPRI 1011989

Technical Element	HLR	SR	6850 Sections	Comments
PP	A	The Fire PRA shall define global boundaries of the analysis so as to include all plant locations relevant to the plant-wide Fire PRA		
		1	1.5.1	
	B	The Fire PRA shall perform a plant partitioning analysis to identify and define the physical analysis units to be considered in the Fire PRA		
		1	1.5.2	
		2	1.3.2 and 1.5.2	
		3	1.3.2 and 1.5.2	
		4	1.3.2 and 1.5.2	Cable raceway fire barriers are not explicitly addressed in 6850
		5	1.3.2 and 1.5.2	
		6	1.5.2	
		7	1.4.3, 1.5.2 and 1.5.3	
	C	The fire PRA shall document the results of the plant partitioning analysis in a manner that facilitates Fire PRA applications, upgrades, and peer review		
		1	n/a	The requirements within these SRs are not specifically addressed in Section 1.5.4 of 6850.
		2	n/a	
		3	1.5.4	
		4	1.5.2	

Module III – Fire Analysis

Task 6 – Fire Ignition Frequency

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Fire Ignition Frequencies
Purpose of Task 6 per NUREG/CR-6850 / EPRI 1011989

- Task 6 establishes fire source ignition frequencies
  - How often do we expect to see a particular type of fire or a fire in a particular location?
- Just for reference – what sort of numbers are we talking about?
  - Plant-wide frequency for <u>all</u> fire sources is *roughly**

    0.2 fire events per year (or 2.0E-1/yr)
  - That is *roughly** one fire somewhere in the plant every 5 years
  - Most of these fires are small, quickly suppressed, and cause no damage beyond the ignition source
  - We are still interested in these events because we'll ask the risk question:

    "What would happen if a similar fire occurs that is not quickly suppressed and/or in a critical location more sensitive to fire damage?"

*Emphasis on *roughly* - *t*his is an illustrative discussion only. The actual plant wide fire frequency depends on which source you use. The original 6850/1011989 value was 2.89E-1/ry. We'll talk about these topics as we continue…

Corresponding PRA Standard Element

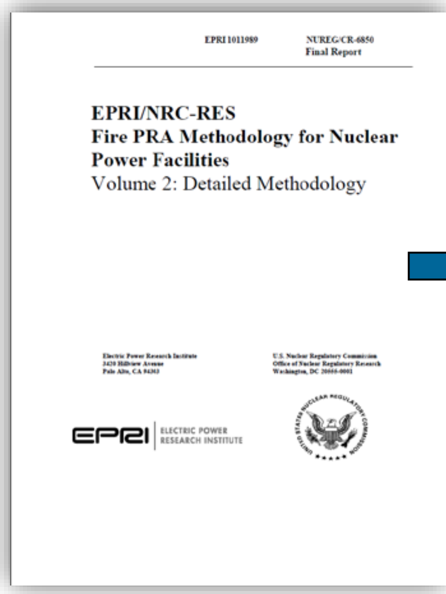
- Task 6 maps to element IGN – Ignition Frequency
  - IGN Objectives (per the PRA Standard):
    - Establish the plant wide frequency of fires of various types on a generic basis for NPPs
    - Tailor the generic fire frequency values to reflect a particular plant
    - Apportion fire frequencies to specific physical analysis units, and/or fire scenarios

IGN HLRs (per the PRA Standard)

- HLR IGN-A: The Fire PRA shall develop fire ignition frequencies for every physical analysis unit that has not been qualitatively screened (10 SRs)

- HLR IGN-B: The fire PRA shall document the fire frequency estimation in a manner that facilitates Fire PRA applications, upgrades, and peer review (5 SRs)

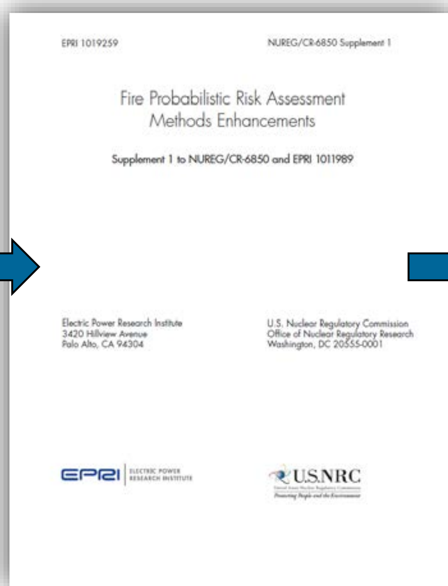
Fire Ignition Frequency Evolution


EPRI 1011989 NUREG/CR-6850 Final Report

EPRI/NRC-RES
Fire PRA Methodology for Nuclear Power Facilities
Volume 2: Detailed Methodology

NUREG/CR-6850 and EPRI 1011989

Original methodology and frequencies


EPRI 1019259 NUREG/CR-6850 Supplement 1

Fire Probabilistic Risk Assessment Methods Enhancements

Supplement 1 to NUREG/CR-6850 and EPRI 1011989

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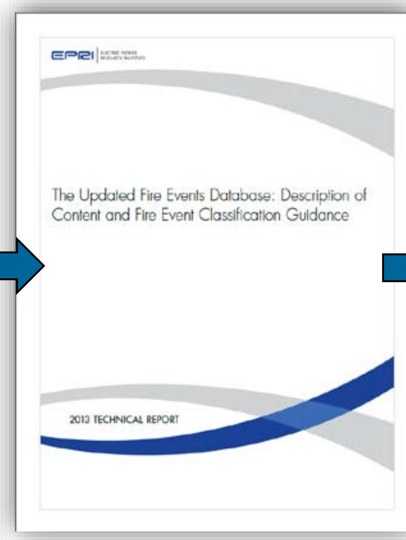
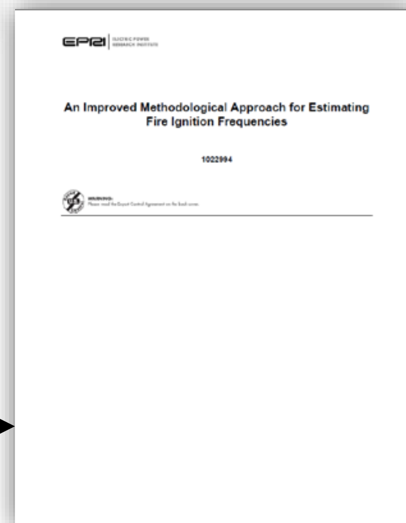
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

NUREG/CR-6850 S. 1 and EPRI 1019259

Updated counting guidance and updated frequencies from FAQ process


The Updated Fire Events Database: Description of Content and Fire Event Classification Guidance

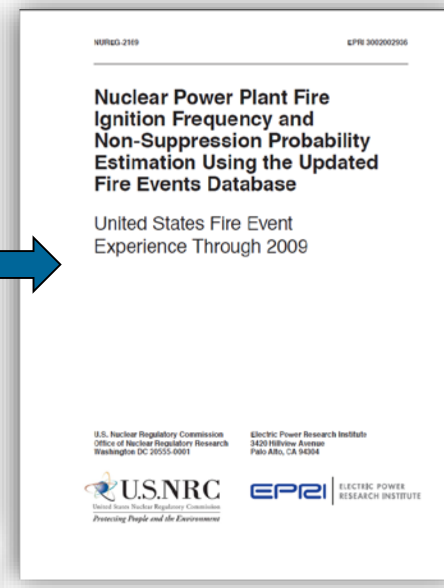
2013 TECHNICAL REPORT


An Improved Methodological Approach for Estimating Fire Ignition Frequencies

1022994

EPRI 1022994 and EPRI 1025284

Improved fire frequency calculation methodology and fire event collection and classification through 2009.


NUREG-2169 EPRI 3002002936

Nuclear Power Plant Fire Ignition Frequency and Non-Suppression Probability Estimation Using the Updated Fire Events Database

United States Fire Event Experience Through 2009

NUREG-2169 and EPRI 3002002936

Updated methodology with additional decade of data event data. Most recent fire frequencies for at-power and LPSD.

Summary of Available Reference Material

- ***NUREG/CR-6850 / EPRI 1011989***
  - Overall methodology
  - General bin descriptions
- ***Supplement 1***
  - Chapter 3: *Ignition source counting guidance for electrical cabinets* **FAQ 06-0016**
  - Chapter 4: *Ignition source counting guidance for high-energy arcing faults (HEAFS)* **FAQ 06-0017**
  - Chapter 5: *Ignition source counting guidance for main control board (MCB)* **FAQ 06-0018**
  - Chapter 6: *Miscellaneous fire ignition frequency binning issues* **FAQ 07-0031**
  - Chapter 7: *Bus duct (counting) guidance for high energy arcing faults* **FAQ 07-0035**
  - Chapter 10: *Fire ignition frequency* **FAQ 08-0048**
- ***Recent FAQs***
  - **FAQ 12-0064** *Hot work/transient fire frequency: influencing factors*
  - **FAQ 14-0008** *Main control board treatment (counting)*
- ***NUREG-2169 / EPRI 3002002936***
  - Updated fire ignition frequencies through 2009

Fire Ignition Frequencies
High level summary

- General approach
  - Fire event data
  - Sources of data
  - Types of ignition sources
- Task 6 procedure
  - Step by step
  - Counting example

Fire Ignition Frequencies
A note on terminology

- We have noted that different documents use different terms for the physical plant partitions used in fire PRA
  - NUREG/CR-6850 / 1011989 refers to “fire compartments”
  - The standard refers to “physical analysis units” or PAUs
- This makes <u>no difference</u> to Task 6 fire frequency analysis
  - You are developing fire ignition frequencies for whatever set of fire locations you have defined
  - Whether you call it a fire area, fire compartment or PAU does not really matter – it is what is in that location that counts
    - The total frequency for any location is simply the sum of the frequencies for the ignition sources present in that location
  - Once you get to the scenario level (individual fire sources or fire source groups) the differences are totally irrelevant
    - You are estimating fire frequency for a very specific ignition source

Fire Ignition Frequencies
General approach

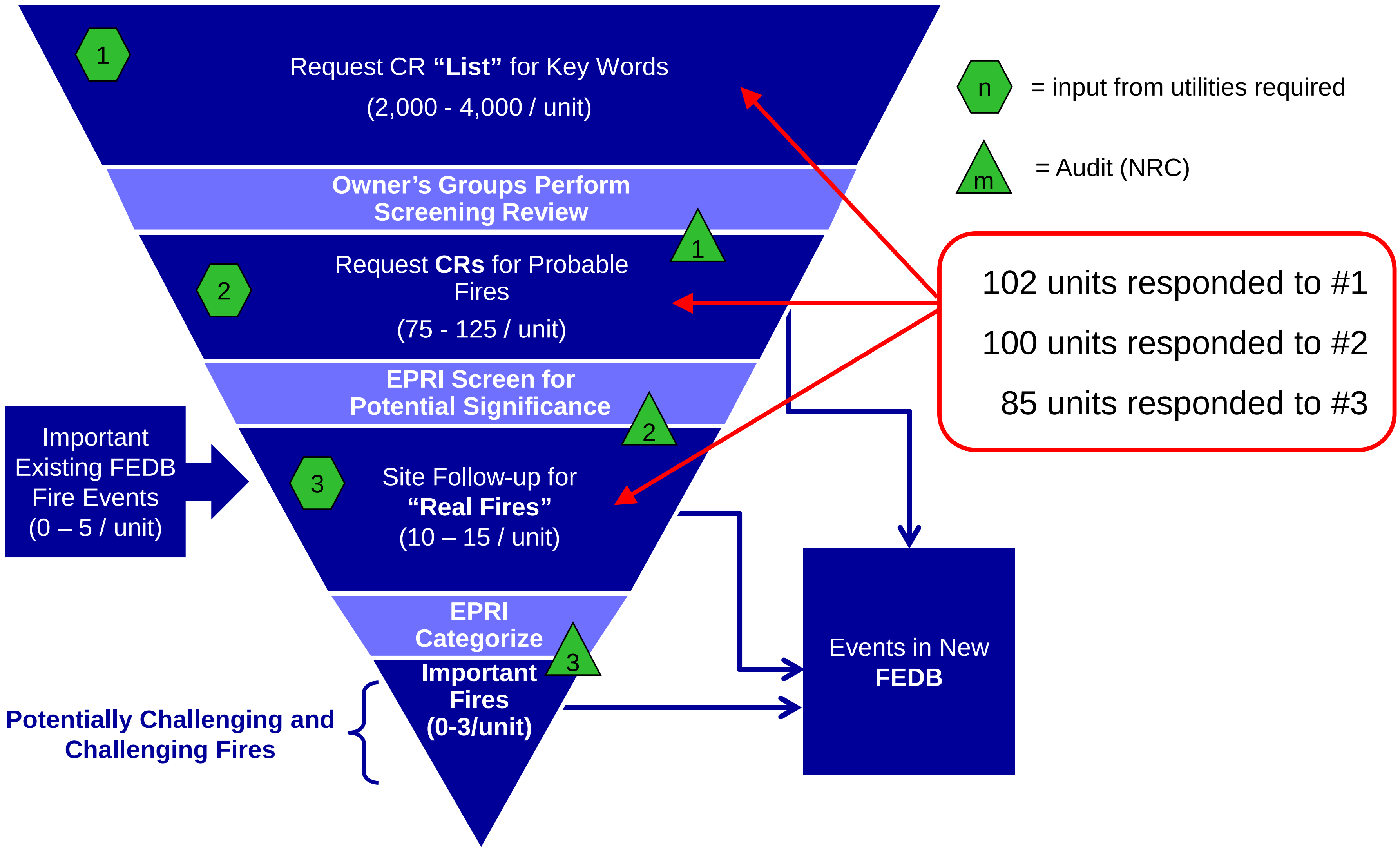
- The generic fire frequencies are based on the collective experience of the US nuclear power industry
  - EPRI Fire Event Database (FEDB) included data from 1968 through December 2000 including over 1400 records
  - EPRI published the Updated Fire Events Database in 2013 extending the collective experience through 2009 (approximately 2000 records)
- Although the database quality and supporting information has advanced in the Updated FEDB, there are still some limitations
  - Inconsistent reporting practices – reporting has been largely voluntary
  - Uneven data collection – different folks at different times have added data using different sources and bases
  - Completeness of event descriptions – reports tend to focus more on plant response to event than the details of fire
- Industry data collection through INPO has enhanced the collection efforts through a standardized reporting process

Fire Ignition Frequencies
Fire Event Data

- In the end each event is "binned" considering four primary factors
  - Was it a *risk-relevant* fire (potentially challenging or greater)?
  - What was the fire source?
  - How was the fire put out?
  - How long did the fire last?
- The historical fire event set is used to estimate generic fire frequencies
  - Generic frequencies are in events/reactor-year
  - Numbers are for one unit (i.e., frequency plant-wide for a single plant unit)
- Event sources (* indicated as primary source for Updated FEDB)
  - Mandatory reporting to NRC*
    - Licensee event reports (LERs)
    - Event notifications (ENs)
  - Comprehensive NRC records search
  - Voluntary reporting to industry sources
    - Nuclear Energy Insurance Limited (NEIL) and American Nuclear Insurers (ANI)
  - Ad-hoc additions based on specific PRA studies
    - IPEEE analysis during early to mid 1990s
  - Plant fire reports*
- Individual follow up for key events or for events requiring additional information

Corresponding PRA Standard SRs: IGN-A1, IGN-A5, & IGN-A10

Fire Events Database Screening



Not all events in the database are risk-relevant Identification of the events that “count” to risk

- Challenging (CH) fires that had an observable and substantive effect on environment outside the ignition source
- Potentially challenging (PC) fires are those that could have grown or caused damage under foreseeable alternate circumstances
  - May be potentially challenging even if no damage occurred
  - Ask: what could happen given the same sort of fire in a different location, failures of fire protection defense in depth, or delays in successful intervention?
- Non-challenging (NC) fires that did not cause or would not have caused adjacent objects or components to become damaged regardless or location for essentially any amount of time. These fires are not counted in frequency
  - Not a location of interest to PRA (e.g., parking lot fires, off-site fires…)
  - Occurred during plant construction
  - Case specific rules such as:
    - Hot work fires suppressed by a fire watch using a single extinguisher
    - “Smoked” component reports (e.g., a “burned out relay” with no suppression needed, no signs of damage beyond that one failed component)
- Some event records we simply could not tell (Undetermined (U PC-CH or U NC-PC)

Fire Ignition Frequencies
Counting the fire events

- For EPRI 3002002936 / NUREG-2169 frequencies:
  - Challenging, potentially challenging, and undetermined (PC-CH) fires count as one event each
  - Undetermined (NC-PC) fire events count as 0.5 events
- For original and supplement 1 frequencies:
  - Potentially challenging events count as one event each
  - Weighted the unknowns to get final event count, so
    - We assume that resolution of all unknowns would yield the same split between PC and NC as we got for those events we could resolve
    - If we had 100 raw events in a bin…
    - We classify 30 as non-challenging…
    - We classify 40 as potentially challenging…
    - The other 30 were unknown…
    - Each unknown event would be weighed based on ratio of PC to total resolved: $W = [40 \div (40+30)] = 4/7$
    - So for this example our total event count would be:

$$57.1 = [40 + 30 \times W)]$$

Fire Ignition Frequencies Assumptions

- The model developed for estimating fire ignition frequencies is based on the following assumptions:
  - The generic frequencies are fire events per reactor year per operating unit
  - Frequencies remain constant over time
  - Each fire event is assigned to an Ignition Source Bin and frequencies are calculated for each bin
    - See Table 6-1, Bins 1-37 (electrical cabinets, motors, pumps)
  - Total unit-wide ignition frequency for each ignition source bin is the same for all units in the US fleet
    - Unit A at Plant X has the same plant-wide frequency of electrical cabinet fires as Unit B Plant Y
  - Within a plant, the ignition frequency is the same for each individual member of a given ignition source bin
    - At Unit A of Plant X, each individual electrical cabinet is assigned the same fire frequency (frequency of cabinet A = frequency in cabinet B)

Fire Ignition Frequencies
Available data

- There are now three sources of fire ignition frequency data:
  - NUREG/CR-6850 and EPRI 1011989 (2005)
    - Original fire PRA data for fire ignition frequencies from 1965 through 2000
    - Event details are limited and typically uninformative on fire attributes
    - Consider events prior to the implementation of Appendix R fire protection programs
  - EPRI 1016737 / Supplement 1 / FAQ 08-0048 (2008)
    - Update of original fire ignition frequencies that considered potential industry trends (i.e., towards reduced fire frequencies)
      - EPRI / industry proposed that some ignition source bin frequencies have decreased based on analysis of post 1990s data
      - This set weights the more recent data (1991 forward) more heavily
    - If using this set, review the NRC staff position on FAQ 08-0048 (ML092190457)
    - As of May 2015, NUREG-2169, EPRI 3002002936 supersedes FAQ 08-0048 (ML15134A046)

Fire Ignition Frequencies
Available data (continued)

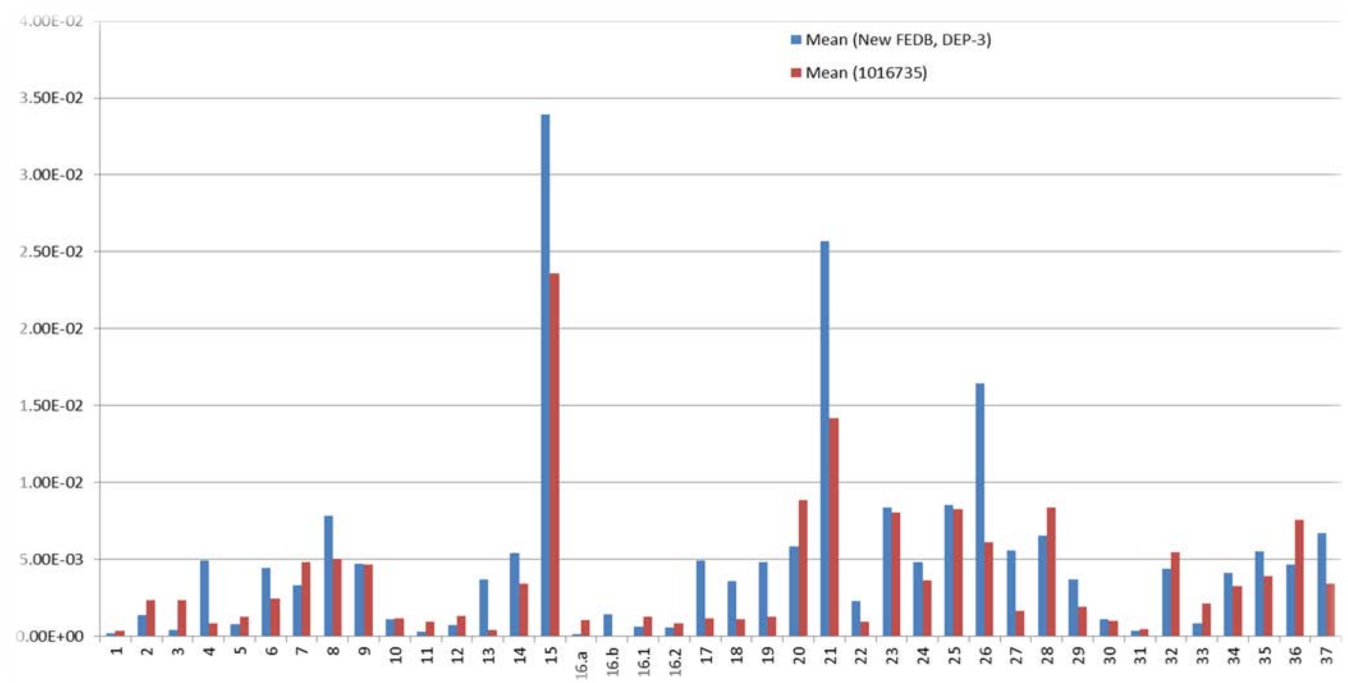
- EPRI 3002002936 / NUREG-2169 (2014)
  - Included additional decade of fire event data (through 2009)
  - Improved methodology / different calculations for sparse versus medium or dense event sets per EPRI 1022994
  - Most current and complete event set
    - Split data into three time periods
      - 1968-1989 – used to develop prior
      - 1990-1999 – used as update period for sparse bins (20 year update)
      - 2000-2009 – used as update period for medium and dense bins (10 year update)
    - Fire event density determined by 2000-2009 time period
      - Sparse bins (< 2.5 events)
      - Medium or dense bins (≥ 2.5 events)

Fire Ignition Frequencies
Generic data sources – NUREG-2169

Bin	Location	Ignition Source	Power Modes	FPRA Counts		
				1968–1989	1990–1999	2000–2009
14	Plant-Wide Components	Electric motors	AA	6.5	4	4.5
15	Plant-Wide Components	Electrical cabinets (non-HEAF)	AA	64.5	29.5	25.5
16.a	Plant-Wide Components	HEAF for low-voltage electrical cabinets (480–1000 V)	AA	0.5	0	0
16.b	Plant-Wide Components	HEAF for medium-voltage electrical cabinets (>1000 V)	AA	1	2.5	2
16.1	Plant-Wide Components	HEAF for segmented bus ducts	AA	5	0	2
16.2	Plant-Wide Components	HEAF for iso-phase bus ducts	AA	2	0	1
17	Plant-Wide Components	Hydrogen tanks	AA	3	1	4
18	Plant-Wide Components	Junction boxes	AA	2	1	3
19	Plant-Wide Components	Miscellaneous hydrogen fires	AA	4.5	0	4
20	Plant-Wide Components	Off-gas/H_2 recombiner (BWR)	BP	22.5	2.5	0
21	Plant-Wide Components	Pumps	AA	32.5	14	23

Fire Ignition Frequencies
Comparison of generic data sources

- Total sum of all bins
  - NUREG/CR-6850 EPRI 1011989 2.89E-01
  - EPRI 1016735 1.50E-01
  - Updated FEDB 2.10E-01



Fire Ignition Frequencies
A note on nomenclature

- Fire frequency = **λ** = (fire ignition events) / (specified time period)
  – Time period of interest is either a reactor year (ry) or calendar year (cy)
  – We generally work on an ry basis (more on this a bit later)
- You will see subscripts that designate location and/or source type
  – λ_{MCR} = fire frequency for the *main control room*…
  – $\lambda_{HW,J}$ = fire frequency for *hot work* in *location " J "* …
  – Be careful because subscripts are context driven
- We can estimate frequency at many levels of detail
  – The entire plant (e.g., the generic tables in 6850/1011989…)
  – A building
  – A PAU
  – Ultimately we often want frequency for a specific *fire ignition source* in a *specific location*

Fire Ignition Frequency
Ignition source binning differences

- Caution – fire ignition source bin numbers and frequency basis for ***electrical cabinet HEAFs*** vary among the frequency data sets

	Mapping of electrical cabinet HEAFs by source document		
Fire source binning basis:	NUREG/CR-6850 / EPRI 1011989 (based on event set 1965-2000)	Supplement 1 / FAQ 08-0048 and EPRI 1016735 (heavily weighted 1990s data)	NUREG-2169 / EPRI 3002002936 (sparse event set with 20 year update and legacy data used for prior)
One bin for all cabinet HEAF	Bin 16	Bin 15.2	Not available
Split bins for cabinet HEAF based on voltage level	Bins 16.a and 16.b (Supp.1 Chapter 4)	Not available	Bins 16.a and 16.b

Fire Ignition Frequency
Ignition source binning differences

- Caution – there are two sets of frequency values for bus ducts

	Mapping of bus duct HEAF frequency sets by source document		
Fire source binning basis:	NUREG/CR-6850 / EPRI 1011989 (based on event set 1965-2000)	Supplement 1 / FAQ 08-0048 and EPRI 1016735 (heavily weighted 1990s data)	NUREG-2169 / EPRI 3002002936 (sparse event set with 20 year update and legacy data used for prior)
Bus Duct HEAFs	FAQ 07-0035 (Supp. 1 Ch. 7) No bin numbers provided	Bins 16.1 and 16.2	Bins 16.1 and 16.2

Fire Ignition Frequencies
General approach

- Start with pre-calculated unit-level generic fire ignition frequencies (λ_{IS})
- These are given for roughly 40 ignition source bins, for example:
  - Bin 21: general pump fires = 2.72E-02/ry
    - About 1 fire every 37 years…
  - Bin 15: general fires in electrical cabinets = 3.0E-2/ry
    - About 1 fire every 100 years…
  - Bin 37: transient fuel fires in the turbine building = 6.71E-03/ry
    - About 1 fire every 150 years…
  - Bin 4: main control board (MCB) fires = 4.91E-3/ry
    - About 1 fire every 205 years…
  - Bin 1: battery fires = 1.96E-4/ry
    - About 1 fire every 5000 years…

Fire Ignition Frequencies
General approach

- We then distribute *(partition or apportion)* the unit-level frequency to suit needs of a scenario analysis
  - Again, to a building, room, PAU, or to individual members of the ignition source bin
- Some bins are partitioned by population, others by location
  - Fixed ignition sources we generally count and apportion based on local population versus plant-wide population
    - How many are “here” versus total in the “plant”
    - Exceptions: cables and junction boxes (more later)
  - Non-fixed ignition sources are apportioned by location
    - Hot work and transients
    - Qualitative weighting factor method
- We will cover details of both approaches

Fire Ignition Frequencies
General approach

- The fire frequency for a location (e.g., a PAU) or for a scenario is the simple sum of the fire frequencies for each ignition source present in the location or that contributes to the scenario:

$$\lambda_J = \sum_{i=1}^{n} \lambda_{ISi} W_{J,ISi}$$

Where:

λ_J : Fire frequency for location J

n : Total number of unique ignition sources in location/scenario J

λ_{ISi} : Plant-wide fire frequency for ignition source bin "i" (IS_i)

$W_{J,ISi}$: Ignition source weighting factor for IS_i in location/scenario J

- Corresponding PRA Standard SR: IGN-A7

Fire Ignition Frequencies
General approach

- There is a second weighting factor to consider for multi-unit sites:

$$\lambda_J = \sum_{i=1}^{n} \lambda_{ISi} \cdot W_{J,ISi} \cdot W_L$$

- W_L is a location weighting factor used only for shared locations at multi-unit sites under specific conditions
  - Common applications: turbine building and main control room
    - There may be others…
  - For shared locations, you may need to double (or triple) the fire frequency to reflect contributions from multiple plant units
- We will cover this under Step 7

Fire Ignition Frequencies

- What are some examples of NPP fire ignition sources?

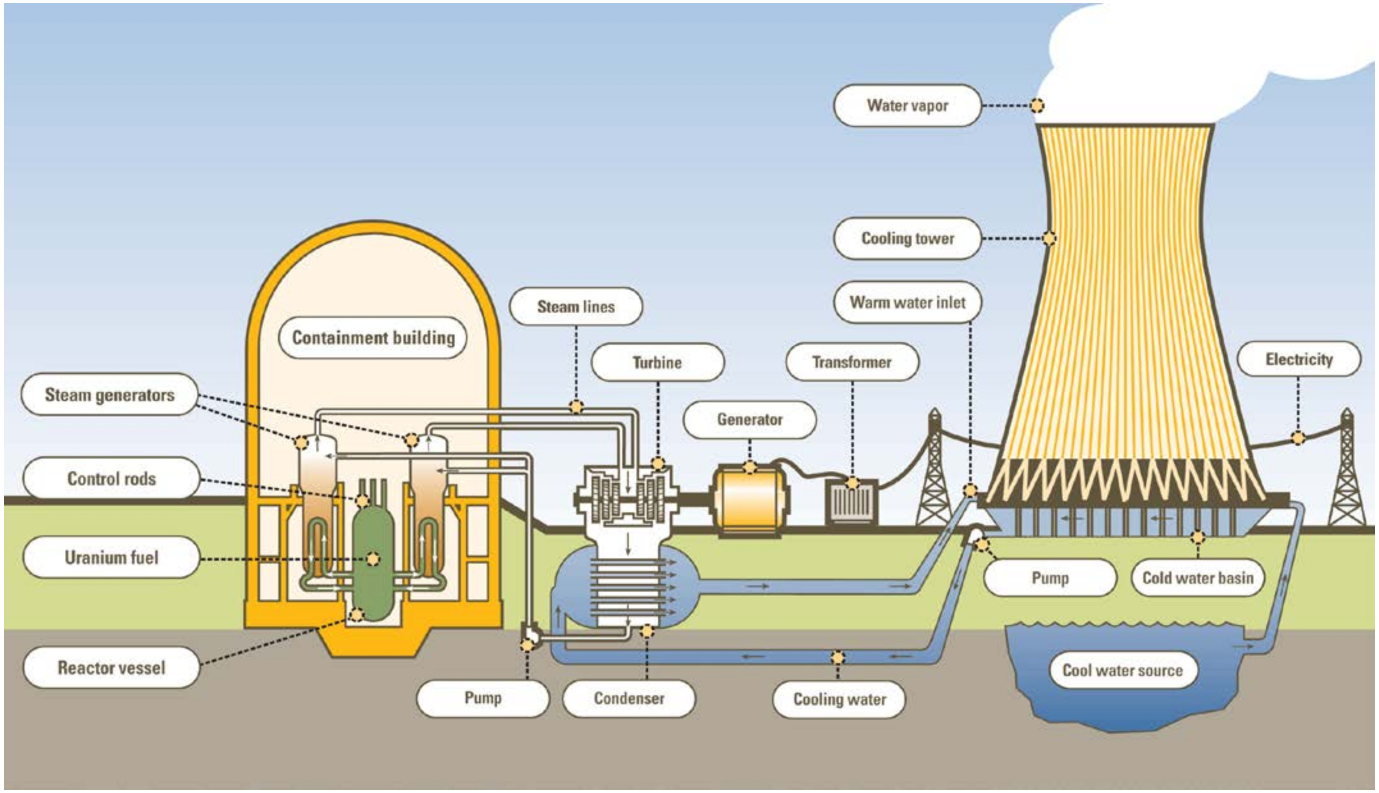


Photo from: http://newenergyandfuel.com/wp-content/uploads/2013/01/Nuclear-Plant-Block-Diagram.gif

Fixed Fire Ignition Sources

- Batteries
- Reactor Coolant Pumps
- Main Control Board
- Diesel Generators
- Air Compressors
- Battery Chargers
- Dryers
- Electric Motors
- Electrical Cabinets
- High Energy Arcing Faults
- Hydrogen Tanks
- Misc. Hydrogen Fires
- Off-gas/H_2 Recombiners
- Pumps
- RPS MG Sets
- Transformers
- Ventilation Subsystems
- Yard Transformers
- Boilers
- Main Feedwater Pumps
- Turbine Generator Excitor
- Turbine Generator Hydrogen
- Turbine Generator Oil

Fire Ignition Frequency
Non-countable sources

- PWR Containment
  - Transients and Hotwork
- Reactor / Control / Auxiliary Building
  - Cables fires caused by welding and cutting
  - Transient fires caused by welding and cutting
  - Transients
- Turbine Building
  - Cables fires caused by welding and cutting
  - Transient fires caused by welding and cutting
  - Transients
- Plant-Wide Locations
  - Cables fires caused by welding and cutting
  - Transient fires caused by welding and cutting
  - Transients
- All Locations
  - Self ignited cables fires
  - Junction boxes

Fire Ignition Frequencies
Plant Level Ignition Source Bins (Table 6-1)

Table 6 -1
Fire Frequency Bins and Generic Frequencies

ID	Location	Ignition Source (Equipment Type)	Mode	Generic Freq (per rx yr)	Split Fractions for Fire Type: Electrical	Oil	Transient	Hotwork	Hydrogen	HEAF[1]
1	Battery Room	Batteries	All	7.5E-04	1.0	0	0	0	0	0
2	Containment (PWR)	Reactor Coolant Pump	Power	6.1E-03	0.14	0.86	0	0	0	0
4	Control Room	Main Control Board	All	2.5E-03	1.0	0	0	0	0	0
8	Diesel Generator Room	[illegible]sel Generators	All	2.1E-02	0.16	0.84	0	0	0	0
11	Plant-Wide	Cable fires caused by [illegible]tting	Power	2.0E-03	0	0	0	1.0	0	0
[illegible]	[illegible] Components	[illegible]	All	4.6E-03	1.0	0	0	0	0	0
15	Plant-Wide Components	Electrical Cabinets	All	4.5E-02	1.0	0	0	0	0	0
20	Plant-Wide Components	Off-gas/H2 Recombiner (BWR)	Power	4.4E-02	0	0	0	0	1.0	0
27	Transformer Yard	Transformer – Catastrophic[2]	Power	6.0E-03	1.0	0	0	0	0	
32	Turbine Building	Main Feedwater Pumps	Power	1.3E-02	0.11	0.89	0	0	0	0

1. See Appendix M for a description of high-energy arcing fault (HEAF) fires.
2. See Section 6.5.6 below for a definition.

Ignition Frequency Bin

Note that these slides use the original 6850/1011989 frequency table, not the updated table from the supplement or EPRI 3002002936 / NUREG-2169.

Fire Ignition Frequencies
Plant Level Ignition Source Bins

Table 6-1
Fire Frequency Bins and Generic Frequencies

ID	Location	Ignition Source (Equipment Type)	Mode	Generic Freq (per rx yr)	Split Fractions for Fire Type					
					Electrical	Oil	Transient	Hotwork	Hydrogen	HEAF[1]
1	Battery Room	Batteries	All	7.5E-04	1.0	0	0	0	0	0
2	Containment (PWR)	Reactor Coolant Pump	Power	6.1E-03	0.14	0.86	0	0	0	0
4	Control Room	Main Control Board	All	2.5E-03	1.0	0	0	0	0	0
8	Diese Room				0.16	0.84	0	0	0	0
11	Plant- Comp				0	0	0	1.0	0	0
14	Plant- Comp				1.0	0	0	0	0	0
15	Plant- Comp				1.0	0	0	0	0	0
20	Plant- Comp				0	0	0	0	1.0	0
27	Trans				1.0	0	0	0	0	
32	Turbi				0.11	0.89	0	0	0	0

ID	Location
1	Battery Room
2	Containment (PWR)
4	Control Room
8	Diesel Generator Room

1. See Appendix M for a description of high-energy arcing fault (HEAF) fires.
2. See Section 6.5.6 below for a definition.

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Fire Ignition Frequencies
Plant Level Ignition Source Bins

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Fire Frequency Bins and Generic Frequencies

ID	Location	Ignition Source (Equipment Type)	Mode	Generic Freq (per rx yr)	Split Fractions for Fire Type					
					Electrical	Oil	Transient	Hotwork	Hydrogen	HEAF[1]
1	Battery Room	Batteries	All	7.5E-04	1.0	0	0	0	0	0
2	Containment (PWR)	Reactor Coolant Pump	Power	6.1E-03	0.14	0.86	0	0	0	0
4	Control Room	Main Control Board	All	2.5E-03	1.0	0	0	0	0	0
8	Diesel Ge Room									
11	Plant-Wid Compone									
14	Plant-Wid Compone									
15	Plant-Wid Compone									
20	Plant-Wid Compone									
27	Transform									
32	Turbine B									

1. See Appendix M
2. See Section 6.5.6 below for a definition.

ID	Location	Ignition Source (Equipment Type)
1	Battery Room	Batteries
2	Containment (PWR)	Reactor Coolant Pumps
4	Control Room	Main Control Boards
8	Diesel Generator Room	Diesel Generators

Note that these slides use the original 6850/1011989 frequency table, not the updated table from the supplement.

Fire Ignition Frequencies
Plant Level Ignition Source Bins

Table 6 -1
Fire Frequency Bins and Generic Frequencies

ID	Location	Ignition Source (Equipment Type)	Mode	Generic Freq (per rx yr)	Split Fractions for Fire Type					
					Electrical	Oil	Transient	Hotwork	Hydrogen	HEAF[1]
1	Battery Room	Batteries	All	7.5E-04	1.0	0	0	0	0	0
2	Containment (PWR)	Reactor Coolant Pump	Power	6.1E-03	0.14	0.86	0	0	0	0
4	Control Room	Main Control Board	All	2.5E-03	1.0	0	0	0	0	0
32	Turbine Building	Main Feedwater Pumps	Power	1.3E-02	0.11	0.89	0	0	0	0

Ignition Source (Equipment Type)	Mode	Generic Freq (per rx yr)	Split Fractions for Fire Type					
			Electrical	Oil	Transient	Hotwork	Hydrogen	HEAF[1]
Batteries	All	7.5E-04	1.0	0	0	0	0	0
Reactor Coolant Pump	Power	6.1E-03	0.14	0.86	0	0	0	0
Transients and Hotwork	Power	2.0E-03	0	0	0.44	0.56	0	0
Main Control Board	All	2.5E-03	1.0	0	0	0	0	0

1. See Appendix M for a description of high-energy arcing fault (HEAF) fires.
2. See Section 6.5.6 below for a definition.

Note that these slides use the original 6850/1011989 frequency table, not the updated table from the supplement.

Fire Ignition Frequencies
Plant Level Ignition Source Bins

Table 6-1
Fire Frequency Bins and Generic Frequencies (Continued)

ID	Location	Ignition Source (Equipment Type)	Mode	Generic Freq (per rx yr)	Split Fractions for Fire Type					
					Electrical	Oil	Transient	Hotwork	Hydrogen	HEAF[1]
15	Plant-Wide Components	Electrical Cabinets	All	4.5E-02	1.0	0	0	0	0	0
16	Plant-Wide Components	High Energy Arcing Faults[1]	All	1.5E-03	0	0	0	0	0	1.0
17	Plant-Wide Components	Hydrogen Tanks	All	1.7E-03	0	0	0	0	1.0	0
18	Plant-Wide Components	Junction Boxes	All	1.9E-03	1.0	0	0	0	0	0
19	Plant-Wide Components	Misc. Hydrogen Fires	All	2.5E-03	0	0	0	0	1.0	0
20	Plant-Wide Components	Off-gas/H2 Recombiner (BWR)	Power	4.4E-02	0	0	0	0	1.0	0
21	Plant-Wide Components	Pumps	All	2.1E-02	0.54	0.46	0	0	0	0
22	Plant-Wide Components	RPS MG Sets	Power	1.6E-03	1.0	0	0	0	0	0
23a	Plant-Wide Components	Transformers (Oil filled)	All	9.9E-03	0	1.0	0	0	0	0
23b	Plant-Wide Components	Transformers (Dry)			1.0	0	0	0	0	0
24	Plant-Wide Components	Transient fires caused by welding and cutting	Power	4.9E-03	0	0	0	1.0	0	0

Fire Ignition Frequencies
About the mode column…

- For each plant, two time periods were established based on operating mode:
  - Power operations (including low-power) – total years spent in power operation since initial commercial operation or ***reactor years (ry or rx yr)***
  - Shutdown operations – total time since initial commercial operation spent in non-power operating modes
- Some frequency bins cover all modes of operation, some only cover power operations (including low-power)
- Both sets represent ignition frequencies *per mode-year*
  - Some are simply power-modes-only and some are applicable to all modes
- Applied to at-power fire PRA the generic frequencies (in all references) are all ***per ry***

Fire Ignition Frequencies
And what about the standard…

- IGN-A5 says (same for all CC's):

  "… INCLUDE in the fire frequency calculation the plant availability, such that the frequencies are weighted by the fraction of time the plant is at-power."

- This means that to meet IGN-A5, convert the generic frequencies:

  FROM per reactor year (ry) TO *per calendar year* (cy)

- You do that by multiplying the generic frequencies by the *plant-specific* average annual availability factor
  - These are typically in excess of 90% for most plants today
- The risk results you get will then be *per cy* numbers (instead of per ry)
- Why? Creates common basis for estimating total plant risk numbers that include the contribution from all sources including shutdown operations

Fire Ignition Frequencies
Task 6 procedure

Task 6 develops location and item specific fire frequency values for each fire frequency bin using an 8-step process:

- Step 1. Mapping plant ignition sources to generic sources,
- Step 2. Plant fire event data collection and review,
- Step 3. Plant specific updates of generic ignition frequencies,
- Step 4. Mapping plant-specific locations to generic locations,
- Step 5. Location weighting factors,
- Step 6. Fixed fire ignition source counts,
- Step 7. Ignition source weighting factors, and
- Step 8. Ignition source and compartment (PAU) fire frequency evaluation.

- Relevant PRA Standard Supporting Requirement: IGN-A7

Fire Ignition Frequencies
Steps 1&6 – Mapping and Counting Ignition Sources

- In practice, Steps 1 and 6 are done together so we'll cover them together here
  - Step 1 is ignition source mapping
  - Step 6 is fixed ignition source counting
- Both are done by visual inspection
- In short, the process is:
  - Perform a *thorough* walkdown of the plant (preferably with tablet in hand)
  - Identify any and all potential fire ignitions sources
  - Map each source to one of the 37 ignition source bins
  - And, oh by the way…, count them (Step 6)
  - Keep a list with name, bin assignment, and location as you go
  - If you want to get fancy, link the list to photos
- Now for the long version…

Fire Ignition Frequencies

Steps 1&6 – Mapping and Counting Ignition Sources

- In step 1 <u>everything</u> in the plant that is capable of starting a fire should be mapped to one of the 37 pre-defined ignition source bins.
- Nominally covers <u>all</u> locations within the global analysis boundary, but…
- EXCLUDE locations that screen out qualitatively
  - Qualitative screening is Task 4 which is covered in Module 1
  - Locations with no *fire PRA equipment or cables* and no *plant trip initiators* don't require quantitative analysis – they screen out on a qualitative basis
    - Parking lots, office buildings, warehouses, security access buildings,…
  - The fire frequency classification excluded fire events in these types of locations
    - Classified as non-challenging based on *location not of interest to fire PRA*
  - For consistency *<u>do not apportion</u>* any fire frequency to such locations
    - That means we don't count ignition sources in those locations
    - Exclude them from the transient and hot work location sets as well (more later…)

Fire Ignition Frequencies
Steps 1&6 – Mapping and Counting Ignition Sources

- Steps 1 & 6 specifically focus on fixed equipment, but watch for transients and hot work activities as well
  - There are several location based bins for transients and hot work
  - You don't "count" these as sources per-se, but you do have to characterize likelihood and, for transients, the type expected in each plant location
  - Make note of what you see and where you see it
  - We will talk about the weighting factor approach later but you must use judgment to assign relative weighting factors to each PAU
  - Insights gained during the plant walkdown can help this process
  - Again, more on this later…

Fire Ignition Frequencies
Steps 1&6 – Mapping and Counting Ignition Sources

If an ignition source does not map directly to one of the 37 available bins you have two options:

- You may be able to match to an existing bin even if fit is not perfect
  - Look for a bin with similar characteristics *relative to fire likelihood*
    - e.g., a motor-driven widget may map to motors if the widget part is not significant
  - Provide explanation for why you think fit is OK, again, *relative to frequency*
- Create a new bin for the item, but then you need a fire frequency
  - A plant-specific history of fires may be enough to establish frequency
    - Caution: a history of no fires at one plant probably won't be enough by itself
  - Relevant experience at other plants may help
  - Fire history in other industries may be used… with caution
  - You will be on the hook to quantify and justify your frequency assumptions
- One example we ran into: a gas-fired emergency generator unit

Fire Ignition Frequencies
Steps 1&6 – Mapping and Counting Ignition Sources

- For each of the 37 ignition source bins there is corresponding description and counting guidance
- We'll highlight a few bins, but for the others refer to the report:
  - **Bin 1 – Batteries (Battery Room):** Each bank of interconnected sets of batteries located in one place should be counted as one battery set. Cells may not be counted individually.
  - **Bin 4 – Main Control Board (Control Room):** A control room typically consists of one or two (depending on the number of units) main control boards as the central element of the room. The control room may also include plant computers, other electrical cabinets containing plant relays, and instrumentation circuits, a kitchen type area, desks, bookshelves, and etc. Aside from the main control board, the ignition source weighting factors of the remaining ignition sources of the control room should be based on the approach specific to each ignition source.
    - **FAQ 06-018 (Supplement 1)** – clarification of MCB definition (horseshoe or equivalent)
      - There is a one-to-one correspondence between Appendix L and Bin 4
      - All other electrical cabinets in MCR should be counted with Bin 15
    - **FAQ 14-008** – updates the definition to include the rear side of the MCB

Fire Ignition Frequencies
Steps 1&6 – Mapping and Counting Ignition Sources

- Counting guidance examples continued:
  - **Bin 15 – Electrical Cabinets (Plant-Wide Components):** Electrical cabinets represent such items as switchgears, motor control centers, DC distribution panels, relay cabinets, control and switch panels (excluding panels that are part of machinery), fire protection panels, etc. …The following rules should be used for counting electrical cabinets:
    - Simple wall-mounted panels housing less than four switches may be excluded from the counting process (these become junction boxes…)
    - ***Well-sealed*** electrical cabinets that have robustly secured doors (and/or access panels) and that house only circuits below 440V should be excluded from the counting process
    - Free-standing electrical cabinets should be counted by their ***vertical segments***

Fire Ignition Frequencies
Steps 1&6 – Mapping and Counting Ignition Sources

- Counting guidance examples continued:
  - **FAQ 06-0016 (Supplement 1)** – Provides updated counting guidance for electrical cabinets
  - Clarifies guidance on counting electrical cabinets and for treating "outlier" cabinets
    - Cabinet counting guidance gets applied to a wide range of cabinet sizes
    - Ignition frequency is more a function cabinet contents than cabinet size
    - A basis is needed to address outlier conditions
  - Each user should establish criteria for identifying outliers and a basis for counting them
  - Examples of possible rule-set approaches:
    - Establish a nominal 'standard' or reference cabinet size
    - Consider cabinet internals relative to a defined 'standard' or reference configuration

Fire Ignition Frequencies
Steps 1&6 –FAQ 06-0016 Counting Example

- An analyst defines a ‘standard’ cabinet as nominally 4’ long and 3’ deep and an outlier is any cabinet with any horizontal dimension greater than 8’

6’ long cabinet,

no partitions

Cabinet is not an outlier –
Count = 1

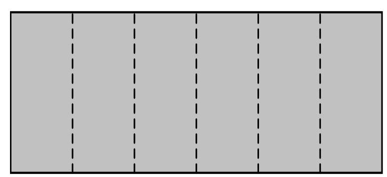
4’ long cabinet,

no internal partitions

Cabinet is same as standard –
Count = 1

Larger cabinet with

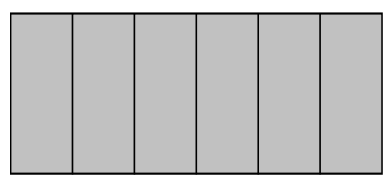
non-solid internal partitions



Internal dividers are not solid –
Count = 6

Larger cabinet with

solid internal partitions



Internal dividers are solid –
Count = 6

Fire Ignition Frequencies
Steps 1&6 –FAQ 06-0016 Counting Example (continued)

- How to count using example rule set…

Three independent cabinets – Count = 3

12 ft wide, 3 ft deep

Panel is an outlier, using a 4' standard cabinet – Count = 3

9 ft wide, 6 ft deep

Cabinet is an outlier, no evaluation of contents, based on reference cabinet – Count = 3 due to variation from the standard length and depth

9 ft wide, 6 ft deep
walk through cabinet

The counts should depend on the cable termination load and devices in the panel by comparing it with a reference cabinet.

Fire Ignition Frequencies
Steps 1&6 – Mapping and Counting Ignition Sources

- Some specific exclusions for certain bins
  - **Bin 14 – Electric motors**: exclude small motors of 5 hp or less and *totally enclosed* motors.
  - **Bin 21 – Pumps**: exclude small sampling pumps, and other pumps of 5 hp or less
  - **Bin 23 – Transformers**: exclude dry transformers of 45 KVA or less
  - **Bin 26 – Ventilation subsystems**: exclude small subsystems powered by motors of 5 hp or less (consistent with electric motors Bin 14)
- **FAQ 07-0031 (Supplement 1)** provides clarification and extension beyond 6850 / 1011989 that are reflected in the bullets above

Fire Ignition Frequencies
Steps 1&6 – FAQ 06-0017

- Ignition source counting guidance for high energy arcing faults (HEAFs) in electrical switching equipment
  – Issue: Originally all HEAF events were lumped in one ignition source bin (16) that were applied across all voltages 440V or greater. However, cabinet voltage should impact fire frequency
  – Resolution: **FAQ 06-0017 Supplement 1** splits Bin 16 into 2 parts:
    - **16.a Low-voltage panels (440 to 1,000V)** – 1.52 E-04/ry (mean)
    - **16.b Medium-voltage panels (> 1000V)** – 2.13E-03/ry (mean)
  – This treatment carries forward for Supplement 1 & new fire ignition frequencies in EPRI 3002002936 / NUREG-2169
  – Counting method remains unchanged (i.e., vertical sections)

Fire Ignition Frequencies
Steps 1&6 – FAQ 07-0035

- Guidance for counting HEAFs in bus ducts
  - Issue: NUREG/CR-6850 / EPRI 1011989 was silent on this topic
  - Resolution: **FAQ 07-0035 Supplement 1**
    - Acknowledge the potential for such events (e.g., Diablo Canyon 5/2000)
    - Provides plant wide frequency and counting/partitioning guidance
    - Provides zone of influence and scenario development guidance
    - Two categories of bus duct are defined:
      - 16.1 Segmented Bus Duct
      - 16.2 Iso-Phase Bus Duct
    - Bins 16.1 and 16.2 in Supplement 1 Chapter 10 and new frequencies NUREG-2169 / EPRI 3002002936
      - Beware the bin numbering issue – not 16a/16b…
      - FAQ 07-0035 did not list bin number with frequencies

Fire Ignition Frequencies
Steps 1&6 – Mapping and Counting Ignition Sources

- Counting guidance examples continued:
  - Some things we don't count at all, we use a relative weighting factor based on location characteristics (more on this later):
    - Hot work and transients
      - Qualitative relative weighting factor by location
    - Cables
      - We will use a relative mass/volume weighting factor
    - Junction boxes
      - We apportion to a location using cable factors

Fire Ignition Frequencies
FAQ 12-0064

- This FAQ is unique and you should download a copy
  - NRC ADAMS Accession Number: ML12346A488
- Impacts some of the fire frequency mapping guidance
  - Clarification of mapping of plant-specific locations to generic locations
  - Modifies / expands the transient and hot work weighting factor methods
- Presented in the form of Chapter 6 redline / strikeout revisions
  - This format is unique for Fire PRA FAQs, but necessary because the changes impact many parts of Chapter 6
- We will cover this in more detail, but in general
  - Clarification of where the *Location = "Plant Wide Components*" bin apply
    - Short version: "everywhere else…" not "everywhere"
  - Revised (slightly expanded) ranking factors for hot work and transients

Fire Ignition Frequencies
FAQ 12-0064

- FAQ clarifies the intent of the *"location = plant-wide components*" bin
  - These bins do not apportion to *every* location throughout the plant
  - They are apportioned only to locations / components not explicitly covered by another *corresponding* ignition source bin
- Example 1:
  - There are transient fire bins for the Turbine Building (Bin 37), Containment (Bin 3), and for the Control/Aux/Reactor building complex (Bin 7)
  - Bin 25 is the corresponding "plant-wide components-transients" bin
  - Bin 25 applied to the ***rest of the plant***, i.e. all locations ***except*** those mapped to bins 3, 7 or 37
- Example 2:
  - Main feedwater pumps have their own bin (32), so…
  - "Plant-wide components – pumps" bin 21 excludes the MFW pumps
  - Same goes for reactor coolant pumps (bin 2)

Fire Ignition Frequencies FAQ 12-0064

- Other cases that also overlap:
  - Main control board (bin 4) vs. electrical cabinets (bin 15)
  - Battery chargers (bin 10) vs. electrical cabinets (bin 15)
  - Specific yard transformer (bins 27-29) vs. general transformers bin (23a/b)
  - The various location-based hot work fire bins
- Bottom line: In general only one bin contributes to the frequency of:
  - Any given location for location-based bins (hot work and transients)
  - Any given fixed fire ignition source
  - Exceptions:
    - Some ignition source bins have multiple fire types that are reflected as split fractions in the table – one bin, multiple fire types
    - Electrical cabinets have general thermal fires and high energy arc faults (HEAF)
      - These were bins 15 and 16 originally,
      - but were re-named in FAQ 48 as 15.1 and 15.2
      - And finally in NUREG-2169 as 15 and 16.a and 16.b

Fire Ignition Frequencies
Steps 1 & 6 – Concluding remarks

- At the end of the step 1/6 you will have:
  - Been on several plant walkdowns
  - Identified all fixed ignition sources and:
    - Mapped each to a location
    - Mapped each to the generic fire ignition source bins
    - Created a new bin if you found something truly unique
    - Counted them
  - Hopefully, you also made some observations on transients and hot work

Fire Ignition Frequencies
Steps 1 & 6 – Concluding remarks

- Some hints:
  - Every ignition source needs some sort of identifier so you can track them through the analysis
  - Document so that you, or someone else, can tell what was counted and what name or identifier was assigned to each item – photos may be helpful
  - Also document what was excluded from the count and why
  - Counting is mainly about being consistent in application

Fire Ignition Frequencies
Step 2 – Plant Fire Event Data Collection

- The generic fire frequencies are just that – generic
- If the plant under analysis has some "unusual" fire experience, then that should be reflected by updating the fire frequencies
- What constitutes "unusual" is a matter of judgment
  - Every plant in the country has had some fires even though they may not have had "reportable" fires
  - The question really is whether or not the plant's experience is consistent with the rest of industry, example:
    - FAQ 07-0035 found roughly a dozen high energy arc faults in bus ducts, but…
    - Six had occurred at the same plant over the course of three years
    - That constitutes "unusual" experience…
  - Note that it is not unusual for a plant to have experienced no fires in a given ignition source bin
    - We have roughly 40 total bins and given plant-wide total fire frequency or 2E-1/ry, we would only expect about 6-10 fires over a nominal 40 year lifetime

Fire Ignition Frequencies
Step 2 – Plant Fire Event Data Collection

- Common practice is to perform a Bayesian update of the generic fire frequencies to reflect plant-specific fire experience
- You need to gather plant-specific fire event data to establish plant-specific fire ignition frequencies
  - Gather and review plant reports relating to fire events over some reasonable time period
    - 10-15 years minimum, more if possible
    - Look at the screening criteria and think about your event experience in the same context – are they risk relevant or not?
      - Screening criteria
        - NUREG/CR-6850 EPRI 1011989 Appendix C "*Potentially challenging screening criteria*"
        - EPRI 1025284, updated challenging and potentially challenging criteria
  - First question to ask is "are plant specific fire ignition frequencies warranted?"
    - Plant has experienced a repeated set of similar events
    - Events that cannot be mapped to a bin
    - Unusual fire occurrence patterns
  - May be selective in which plant specific frequency bins are updated
    - Not an all or nothing situation

Fire Ignition Frequencies
Step 3 – Calculate Plant Specific Frequencies *(λ_{IS})*

- The Bayesian update approach is the accepted method used to estimate plant-specific fire ignition frequencies
  - PRA standard endorses/requires Bayesian methods in the SRs related to formal data analysis
    - You’ll find this in the Internal Events section (Part 2) rather than the fire section (Part 4)
    - Look for the “DA” technical element
  - Generic frequency uncertainty distributions are used as the prior, plant specific data is used to do update
- Note that this approach does raise possible double-counting issue since same events identified in update may already be in the FEDB
  - Generally not considered a significant issue, but be aware…

- Corresponding PRA Standard SRs: IGN-A4, IGN-A6, and IGN-A10

Fire Ignition Frequencies
Steps 2 & 3 – Illustrative example

- The following events have taken place at the unit under analysis over the past 10 years of plant operation:
  - Event 1: Fire in MCC-A because breakers were not properly engaging the bus bars.
  - Event 2: Fire in 125VAC-A panel. The fire was extinguished when 4kV bus-A was de-energized from the control room. Fire resulted from arcing of supply lead to one of the fittings connecting to a controller to the bus.
- Both fires can be included in the frequency analysis
- Both events would map to "Electrical Cabinets – non HEAF"
  - Per NUREG/CR-6850 / 1011989 and EPRI 3002002936 / NUREG-2169 this is bin 15
  - EPRI 1019259 (Supplement 1 to NUREG/CR-6850) calls this bin 15.1
- 2 electrical cabinet fires in 10 years is high compared to generic frequency so an update would be appropriate
- Given 2 fires in 10 years Bayesian update would increase mean fire frequency from 0.024/ry to 0.084/ry

Fire Ignition Frequencies
Step 4 – Mapping Plant-Specific Locations

- Not a major step, but plant-specific locations should be mapped to the locations defined by the ignition source bins
  - Several ignition source bins are explicitly location based, especially hot work and transients
  - You will need to define what constitutes the following “locations” for the plant being analyzed:
    - Battery rooms
    - Turbine building
    - Control/auxiliary/reactor buildings
    - Control room
    - Containment
    - Transformer yard
    - Everywhere else…
  - Names often don’t match exactly – you have to match based on function

Fire Ignition Frequencies
Step 5 – Location Weighting Factor (W_L)

- Recall our fire frequency equation from earlier:

$$\lambda_J = \sum_{i=1}^{n} \lambda_{IS,i} \cdot W_{J,ISi} \cdot W_L$$

- W_L is a weighting factor that only applied to multi-unit sites
  – W_L = number of units that share locations at the site
  – If W_L = 1, it has no effect at all and we simply drop it
- Takes a bit of common sense to apply, and how you use it depends a lot on what scope of the analysis is (i.e., one unit only versus all site units) and on the specific scenarios
  – Don't just dive in and multiply all the frequencies by 2 because you are at a dual unit site
  – Use of W_L depends on how you are doing the analysis…

Fire Ignition Frequencies
Step 5 – Location Weighting Factor (W_L)

- Examples where $W_L > 1$ applies even if we are analyzing one unit:
  - Main control room abandonment:
    - Two units share one control room but we are only analyzing Unit 1
    - The likelihood of fire leading to MCR abandonment for Unit 1 must consider uncontrolled fires in Unit 2 MCR equipment
    - It is all the same space, but each unit has it's own "stuff"
    - That means nominal fire frequency doubles ($W_L = 2$)
  - Catastrophic turbine generator fires in a shared turbine hall
    - Same sort of issue – fires in sister unit may impact unit under analysis
  - General shared equipment areas – e.g., pump room with pumps for both units
    - This one is a bit tricky – done carefully you can use W_L
    - Alternative is to count only the one unit under analysis and use Step 7 approach – simply add the extra pumps to local count (but not plant-wide count) even though they are sister unit equipment (example coming up…)

Fire Ignition Frequencies
Step 5 – Location Weighting Factor (W_L)

- W_L works best when we are analyzing all units of a multi-unit site
- Example: We are working a two-unit site and analyzing both units
  – We can use (W_L = 2) which effectively doubles the base frequencies for all ignition source bins
  – Then we can simply identify and count ignition sources for both units and partition using Step 7 (next up…)
  – In terms of fire frequency, this eliminates the need to worry about what equipment goes with which unit
    - A cabinet is a cabinet…
- One caution:
  – This works well when units are essentially the same and have shared areas
  – Not good when units are very different styles of plant
    - e.g., a BWR and PWR happen to share a site
  – Not recommended when each unit is stand-alone (no shared locations)

Fire Ignition Frequencies
Step 7 – Ignition source weighting factors ($W_{J,IS}$)

- Again, recall our frequency equation:

$$\lambda_J = \sum_{i=1}^{n} \lambda_{IS,i} \cdot W_{J,ISi} \cdot W_L$$

- $W_{J,IS}$ = weighting factor for ignition sources in a given scenario
  – For fixed ignition sources it is calculated based on the *local* versus *plant-wide* population ratio for each type of fixed ignition source in the scenario
  – For transient and hot work, there is a qualitative approach that weights locations relative to each other
  – We calculate one or more weighting factors for each fire scenario we analyze
    - Generally one per ignition source bin represented in the scenario
  – Corresponding PRA standard SRs: IGN-A7 & IGN-A9

Fire Ignition Frequencies
Step 7 – Ignition source weighting factors ($W_{J,IS}$)

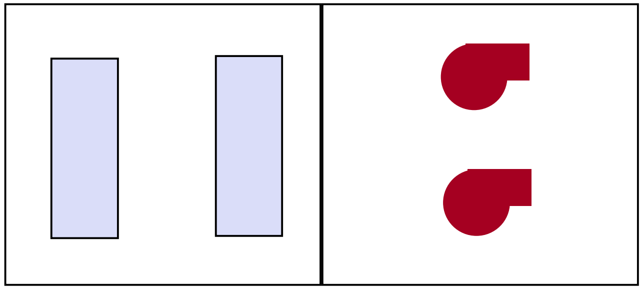
- Scenarios can involve anything from a building to a single piece of equipment – whatever sources contribute to the fire scenario
  - Example 1:
    - At an early stage we postulate room-wide burn-out screening scenarios
    - We would include all of the ignition sources in the room
    - We calculate an ignition source weighting factor for each unique ignition source bin represented in the room
    - Scenario fire frequency is sum of all these contributing fire sources
  - Example 2:
    - Scenario is a bank of electrical cabinets threatening overhead cables
    - All the cabinets have the same fire characteristics and same potential to damage the cables
    - We'll only need one location weighting factor to represent the bank of cabinets since all are members of the same ignition source bin (15)

Fire Ignition Frequencies
Step 7 – Ignition source weighting factors ($W_{J,IS}$)

- The general process for **fixed ignition sources**:
  - We start from the total number of relevant items in each bin ***plant-wide***
    - Recall that we counted these in step 6
    - Caution: be consistent relative to W_L if you are at a shared site…
  - We count the ignition sources that contribute to the scenario of interest
  - The scenario-specific ignition source weighting factor is then the simple ratio of the *local* count to the *plant-wide* count
  - Example: estimate the fire frequency for PAU J:
    - PAU J contains 2 pumps assigned to Bin 21
    - We counted 50 Bin 21 pumps plant-wide
    - $W_{J,21}$ = 2/50 = 0.04
    - λ_{21} = 2.7E-2/ry (from 3002002936 / NUREG-2169)
    - $\lambda_{J,21}$ = 0.04 × 2.7E-2/ry = 1.08E-3/ry
    - Repeat for each ignition source bin represented in PAU J…

Fire Ignition Frequencies
Step 7 – Ignition source weighting factors ($W_{J,IS}$)

- Single unit plant



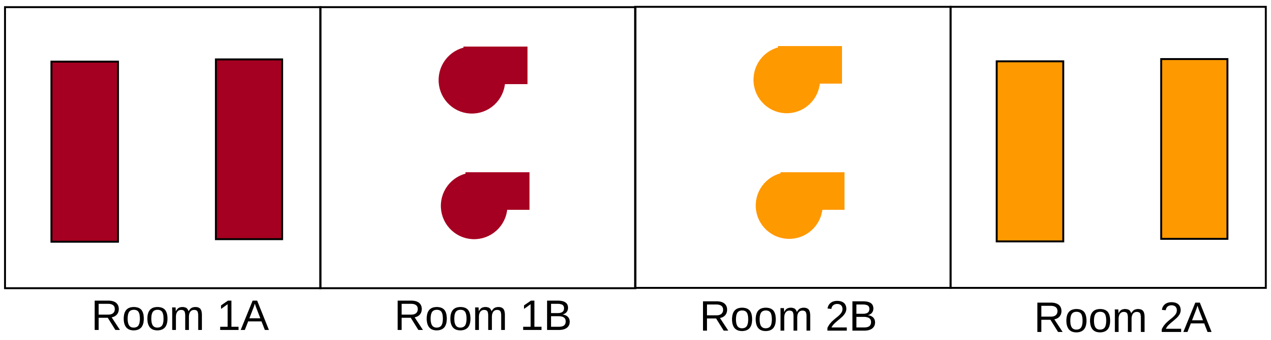
Count	Room 1A	Room 1B	Total
Elec. Cab.	2		2
Pump		2	2

$$\lambda_{pmp-i} = \lambda_g \cdot W_{is} \cdot W_L = \lambda_g \cdot \frac{1}{2} \cdot 1$$

$$\lambda_{room-1B} = \lambda_{pmp-i} \cdot N_{pmp} = \lambda_{pmp-i} \cdot 2$$

Fire Ignition Frequencies
Step 7 – Ignition source weighting factors ($W_{J,IS}$)

- Two units, two units in scope



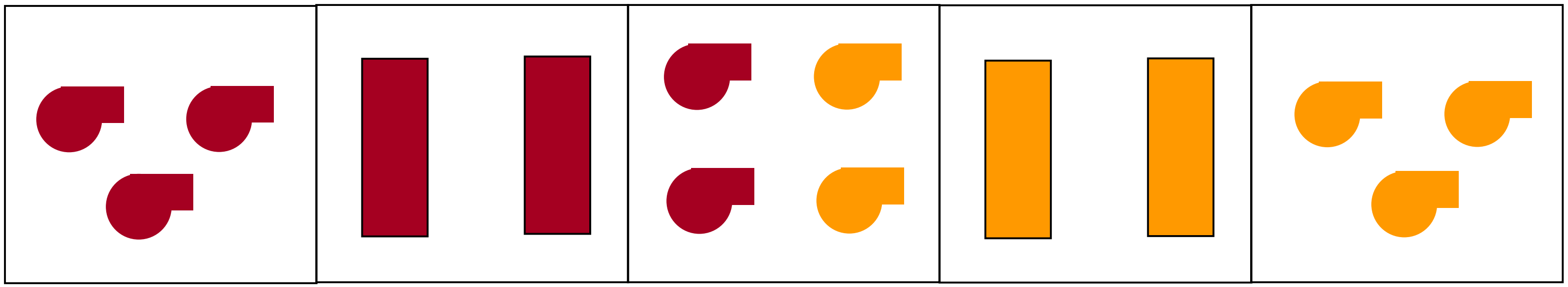
Count	1A	1B	2A	2B	Total
Elec. Cab.	2		2		4
Pump		2		2	4

$$\lambda_{pmp-i} = \lambda_g \cdot W_{is} \cdot W_L = \lambda_g \cdot \frac{1}{4} \cdot 2$$

$$\lambda_{room-1B} = \lambda_{pmp-i} \cdot N_{pmp-1B} = \lambda_{pmp-i} \cdot 2$$

Fire Ignition Frequencies
Step 7 – Ignition source weighting factors ($W_{J,IS}$)

- Two Units, Two Units in scope, shared room



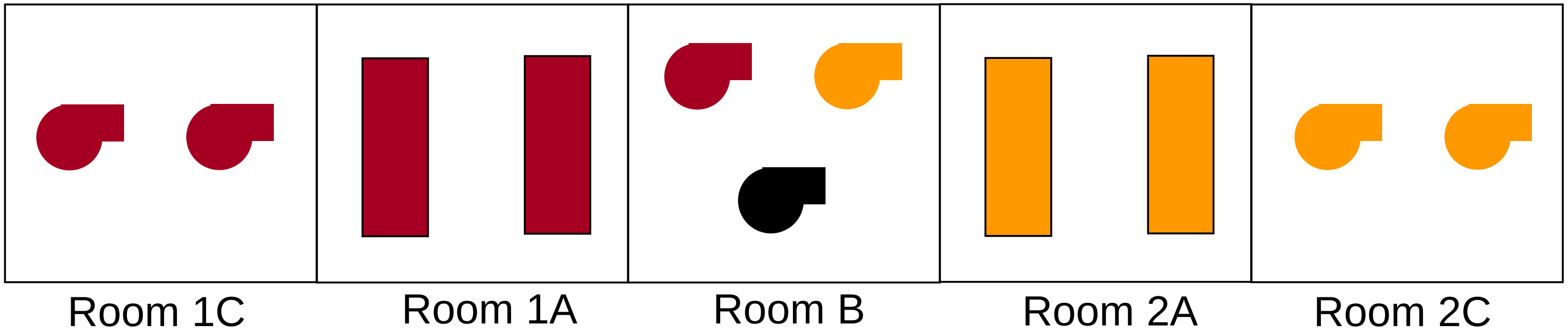
Count	1A	1C	2A	2C	B	Total
Elec. Cab.	2		2			4
Pump		3		3	4	10

$$\lambda_{pmp-i} = \lambda_g \cdot W_{is} \cdot W_L = \lambda_g \cdot \frac{1}{10} \cdot 2$$

$$\lambda_{room-B} = \lambda_{pmp-i} \cdot N_{pmp-B} = \lambda_{pmp-i} \cdot 4$$

Fire Ignition Frequencies
Step 7 – Ignition source weighting factors ($W_{J,IS}$)

- Two units, two units in scope, shared room, swing pump

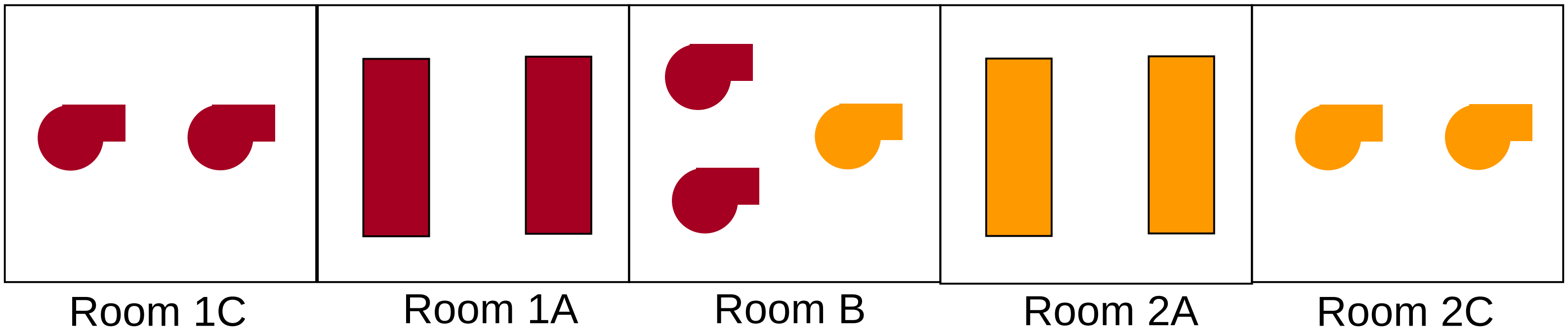


Count	1A	1C	2A	2C	B	Total
Elec. Cab.	2		2			4
Pump		2		2	3	7

$$\lambda_{pmp-i} = \lambda_g \cdot W_{is} \cdot W_L = \lambda_g \cdot \frac{1}{7} \cdot 2 \qquad \lambda_{room-B} = \lambda_{pmp-i} \cdot N_{pmp-B} = \lambda_{pmp-i} \cdot 3$$

Fire Ignition Frequencies
Step 7 – Ignition source weighting factors ($W_{J,IS}$)

- Two units, one unit in scope, shared room



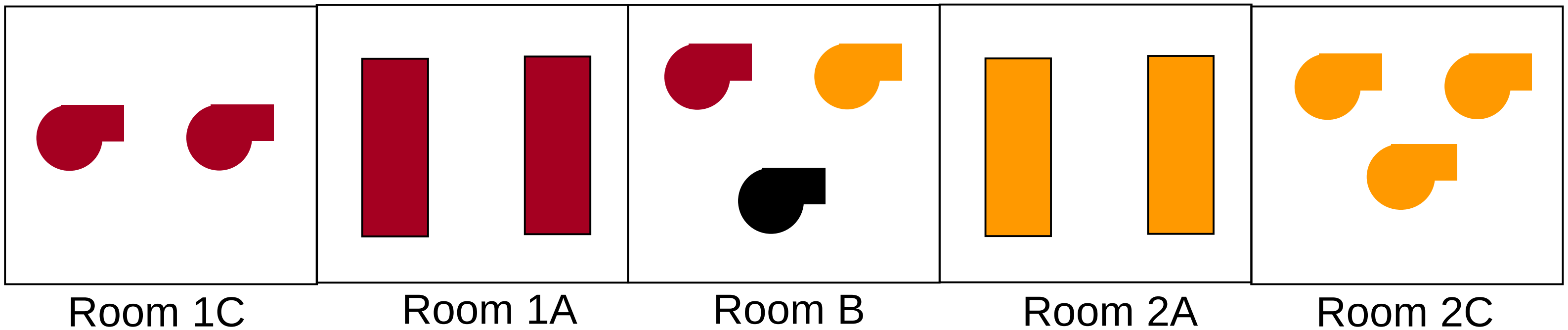
Count	1A	1C	2A	2C	B	Total
Elec. Cab.	2					2
Pump		2			2	4

$$\lambda_{pmp-i} = \lambda_g \cdot W_{is} \cdot W_L = \lambda_g \cdot \frac{1}{4} \cdot 1$$

$$\lambda_{room-B} = \lambda_{pmp-i} \cdot N_{pmp-B} = \lambda_{pmp-i} \cdot 3$$

Fire Ignition Frequencies
Step 7 – Ignition source weighting factors ($W_{J,IS}$)

- Two units, one in scope, shared room, swing pump



Count	1A	1C	2A	2C	B	Total
Elec. Cab.	2					2
Pump		2			1.5	3.5

$$\lambda_{pmp-i} = \lambda_g \cdot W_{is} \cdot W_L = \lambda_g \cdot \frac{1}{3.5} \cdot 1$$

$$\lambda_{room-B} = \lambda_{pmp-i} \cdot N_{pmp-B} = \lambda_{pmp-i} \cdot 3$$

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Transients and hot work fires

- There is a new FAQ out that modifies the approach for non-fixed ignition sources
  - Transient fires
  - Transient fires caused by hot work
  - Cable fires caused by hot work
- Reference is **FAQ 12-0064** (ML12346A488)
  - Issued January 2013
- We will present the methods *as modified by this FAQ*
  - The set of ranking factor values has been expanded
  - Fractional values now allow more credit for very strict administrative controls in a location
    - Application of the fractional values generally requires a review of plant records to verify that controls have not been violated

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Transients and hot work fires

- All three fire types are handled in a similar manner, but factors will vary
- General approach:
  - The PAUs that make up the location “set” (L) for each of the transient and hot work bins are defined (see slide 32…)
  - The PAUs that make up a location set are assigned a numerical ranking value based on certain characteristics (covered shortly…)
  - The PAUs within a set are ranked *relative to each other*
  - The ranking values for all PAUs in the set are summed to get a total for the set (this becomes the normalizing factor for the set)
  - The fraction of the fire frequency assigned to a given location (J) is calculated based on ratio of ranking for location to set total:

$$W_{IS,J,L} = \text{(rank for the location J) / (total for all locations in the set L)}$$

Fire Ignition Frequencies
Step 7: $W_{IS,J,L}$ – Transients

- Transient fire bins are **3, 7, 25** and **37**
- General transients covers all the fires that didn't fit in the other frequency bins and that were not associated with hot work
  - Trash
  - Liquids not actually inside a component (e.g. oil, solvents…)
  - Portable heaters
  - Portable lighting
  - Stored materials
  - Staged materials and associated packing materials
  - Scaffolding
  - Temporary computers or instruments
  - Rad protection dress-up areas
  - Temporary structures inside plant…

Fire Ignition Frequencies
Step 7: $W_{IS,J,L}$ – Transients

- Transient fire frequencies are apportioned based on qualitatively estimated ranking level for three factors:
  - General electro/mechanical **maintenance**
    - Excludes hot work
  - **Occupancy** level and traffic density
    - Implication is that people bring stuff with them
  - **Storage** (temporary and permanent)
    - Combustible and flammable materials
    - Includes liquids
    - Staging area

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Transients

- There are five ranking levels that applied to all three ranking factors:
  - **No (0)** - Can be used only for those PAUs where transients are precluded by design
    - Administrative restrictions do not qualify for a ‘0’ ranking*
  - **Very low (0.3)** – applies only to locations with the strictest levels of administrative control - strict prohibitions in force and verified effective (no violations)
  - **Low (1)** – Reflects minimal level of the factor
  - **Medium (3)** – Reflects average level of the factor
  - **High (10)** – Reflects the higher-than-average level of the factor

- … plus one rating level that applied to general maintenance factor only:
  - **Very high (50)** – Reflects the significantly higher-than-average level of the factor (only for “maintenance” influencing factor).

* Corresponding PRA Standard SR: IGN-A9

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Transients – Table 6-3 (FAQ 12-0064)

Table 6-3 Summary Description of Transient Fire Influencing Factors		
Influencing Factor	**Ranking value**	**Where Applicable**
General Electro-Mechanical (E/M) Maintenance (excluding hot work)	**No (0)**	General electro-mechanical maintenance activities during power operation are precluded by design and/or operation (see discussion in Section 6.5.7.2).
	Very Low (0.3)	A “0.3” rating may be applied only to locations meeting the strictest of access controls, that are largely devoid of equipment, and that contain no equipment subject to frequent maintenance. This rating may be applied provided that (1) access to the location is strictly controlled (see discussion above), and (2) the location contains no plant equipment or components other than cables, fire detectors, junction boxes and other minor plant support equipment such as normal and emergency lighting, access control panels, plant paging or communications equipment, alarms or alarm panels, and security monitoring or support equipment. In general, the presence of any piece of equipment that was

■ ■ ■

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Transients – Table 6-3 (FAQ 12-0064)

…

Table 6-3
Summary Description of Transient Fire Influencing Factors

Influencing Factor	Ranking value	Where Applicable
		counted as a fire ignition source during Step 6 would preclude assignment of "very low" for this factor. Conversely, it cannot be assumed that the lack of countable fire ignition sources implies that the very low ranking factor applies. If equipment items are present that may require maintenance but do not meet the counting criteria (e.g., smaller pumps, motors or ventilation subsystems) then the very low ranking factor would not apply. Application of this ranking value requires verification that no violations of the controls associated with transient combustibles and activities have occurred over a reasonable prior time period (i.e., five years). This rating may not be applied to the MCR but may be applied to a cable spreading room (CSR) devoid of other equipment, and cable vault and tunnel areas meeting the criteria. Other plant locations may also be assigned the "very low" (0.3) ranking factor provided all of the defined criteria are met.

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Transients

- A ranking value for each factor is assigned to each PAU

$$Ranking_{J,L} \rightarrow \{ n_{genmaint,J,L} , n_{occup,J,L} , n_{storage,J,L} \}$$

- The total for the room is the simple sum of the three assigned values:

$$N_{GT,J,L} = (n_{genmaint,J,L} + n_{occup,J,L} + n_{storage,J,L})$$

- The total for the location set is the sum of the values for each PAU:

$$N_{GT,L} = \Sigma N_{GT,J,L} \quad \textit{(summed over J, for all PAUs included in location set L)}$$

- The PAU_J general transients weighting factor is the ratio of these two values:

$$W_{GT,J,L} = N_{GT,J,L} \; / \; N_{GT,L}$$

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Transients caused by hot work

- This is for bins **3, 6, 24,** and **36**
- Process is similar but there is only <u>one</u> ranking factor:
  - Hot work maintenance activities - welding and cutting
- Ranking values for $N_{WC,J,L}$ are:
  - **No (0)** - Can be used only for those PAUs where hot work is precluded by design
    - <u>Administrative restrictions do not qualify for a ‘0’ ranking</u> *
  - **Extremely low (0.1)** – only allowed in MCR (requires verification)
  - **Very low (0.3)** – only applies two places:
    - Cable spreading room (CSR) (required verification)
    - MCR if it did not qualify for 0.1 ranking
  - **Low (1)** – Reflects minimal level hot work
  - **Medium (3)** – Reflects average level of hot work
  - **High (10)** – Reflects the higher-than-average level of hot work
  - **Very high (50)** – Reflects the significantly higher-than-average level of hot work

*See IGN-A8 – assign an ignition frequency greater than zero to every PAU (CC-I/II) or PAU and risk relevant ignition source (CC-III)

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Transients caused by hot work

Influencing Factor	Ranking value	Where Applicable
Hot work	**No (0)**	Hot work activities during power operation are precluded by design and/or operation (see discussion in Section 6.5.7.2).
	Extremely Low (0.1)	This specialized Hot Work factor of 0.1 may be applied to the MCR provided plant procedures prohibit hot work in the MCR during power operations. Application requires that a review of plant records be performed and the review confirms that no violations of, or exceptions to, the MCR hot work restrictions while at power have been recorded over some reasonable prior time period (i.e., five years).
	Very Low (0.3)	May be applied to the CSR and to cable vault and tunnel areas provided that (1) access to the location is strictly controlled (see discussion above), (2) the location contains no plant equipment or components other than cables, fire detectors, and junction boxes, (3) hot work during power operations is prohibited by plant procedures, and (4) a review of plant records is performed and confirms that no violations of those plant procedures have been recorded over some reasonable prior time period (i.e., five years). This 0.3 ranking may also be applied to the MCR if the previous conditions for an extremely low ranking of 0.1 are not satisfied.

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Transients caused by hot work

- Each PAU (J) within a location set (L) gets a hot work ranking factor:

PAU weighting factor -> $N_{WC,J,L}$

- Normalizing factor for the location set (L) as a whole:

$N_{WC,L} = \Sigma N_{WC,J,L}$ *(summed over J, for all PAUs included in location set L)*

- The PAU_J "transients caused by welding and cutting" weighting factor is the ratio of the PAU to the location set:

$$W_{GT,J,L} = N_{WC,J,L} \;/\; N_{WC,L}$$

Fire Ignition Frequencies
Step 7 - $W_{IS,J,L}$ – Cables fires caused by hot work

- Cable fires caused by hot work is similar, but adds a factor based on the relative cable mass/volume in each PAU (J) of the location set (L)

  $W_{cable,J,L}$ = Ratio of cable load in PAU (J) over the total cable load for all members of location set (L)

  – Check your fire hazards analysis (FHA combustible fuel loads)
- Use the hot work weighting factors you already have ($N_{WC,J,L}$)
- The normalizing factor is:

$$N_{HWCF,L} = \sum W_{cable,J,L} \times N_{WC,J,L} \quad \text{(sum over all PAUs in the location set)}$$

- The weighting factor for PAU J is:

$$W_{HWCF,J,L} = [\, W_{cable,J,L} \times N_{WC,J,L} \,] \,/\, N_{HWCF,L}$$

Fire Ignition Frequencies
Step 7 – Final notes on weighting factors

- Weighting factors are always relative ***within each frequency bin / location set***
  - Each ignition source bin where we apply weighting factors defines a location set
  - *DO NOT* weigh across bins, *DO NOT* weight across location sets:
    - For transients in the turbine building (Bin 37), weigh locations in the turbine building against each other
    - For transients in the Aux/Control/Reactor building complex (Bin 7), weigh locations in that complex against each other
    - Do NOT compare the turbine building to the control building. That comparison is built into the base frequencies

Fire Ignition Frequencies
Step 7 – Final notes on weighting factors

- A ranking of **3** is considered Normal/Average/Typical
  - Decide what is "typical" for the location set overall – just the one set
  - Define that condition as "3" in your ranking scheme
  - Everything else is up or down from the typical condition
  - You **do not** need to average the rankings for a set and show the average is 3…
- The method is designed to reflect real differences in the likelihood of these kinds of fires in different locations
  - You need to exercise the full range of ranking values to take full advantage of the method
  - Otherwise, frequency for each bin will be distributed evenly to each PAU

Fire Ignition Frequencies
Step 8 – Fire Frequency Evaluation

- The fire frequency (generic or plant-specific) for each ignition source, $\lambda_{IS,J}$, can now be calculated using the data quantified in the preceding steps

$$\lambda_{J,L} = \Sigma\, \lambda_{IS}\, W_L\, W_{IS,J,L}$$

summed over all ignition sources

Where:

$\lambda_{J,L}$: Fire frequency associated with PAU J at location L

λ_{IS}: Plant level fire ignition frequency associated with ignition source IS

W_L: Location weighting factor

$W_{IS,J,L}$: Ignition source weighting factor

Corresponding PRA Standard: IGN-A7

Fire Ignition Frequencies
Concluding remarks

- Fire ignition frequency evaluation (Task 6) uses a mix of plant specific and generic information to establish the ignition frequencies for specific fire compartments or PAUs and from that for specific fire scenarios.
  - Generic fire ignition frequencies based on industry experience
  - Elaborate data analysis method
  - Frequencies binned by equipment type
  - Methodology to apportion frequencies according to relative characteristics of each fire compartment or PAU

Mapping HLRs & SRs for the IGN Technical Element to NUREG/CR-6850 / EPRI 1011989

Technical element	HLR	SR	6850 sections	Comments
IGN	A	The Fire PRA shall develop fire ignition frequencies for every physical analysis unit that has not been qualitatively screened.		
		1	Appendix C	The generic frequencies have been modified in EPRI 1019259 to reflect changes in fire event frequency trends. The methodology used in that study is also consistent with this SR.
		2	6.5.1	
		3	n/a	Using engineering judgment to establish a frequency is not addressed in 6850/1011989.
		4	6.5.2, 6.5.3	
		5	6.5.3 and Appendix C	The generic frequencies of EPRI 1019259 are also consistent with this SR.
		6	6.5.3	
		7	6.5.1, 6.5.4, 6.5.5, 6.5.6, 6.5.7	
		8	n/a	Although it is effectively implied in Section 6.5.7.2, this SR is not explicitly discussed in 6850/1011989.
		9	6.5.7	Inherent in transient weighting factor ranking approach
		10	6.5.3, Appendix C	Generic frequencies consistent with this SR
	B	The Fire PRA shall document the fire frequency estimation in a manner that facilitates Fire PRA applications, upgrades, and peer review.		
		1	n/a	Documentation is covered in minimal detail in 6850/1011989
		2	n/a	
		3	n/a	
		4	n/a	
		5	n/a	

Together…Shaping the Future of Electricity

Module III – Fire Analysis

Fire Fundamentals Introduction and Overview

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

Scoping Fire Modeling Objectives

The objectives of this module are:

- Describe the process of screening ignition sources
- Describe the concept of zone of influence (ZOI)
- Describe the recommended walkdown
- Review the walkdown forms
- Describe how to update the fire ignition frequencies calculated in Task 6 with the screening results

Scoping Fire Modeling Interfaces

- Inputs for this task
  - PRA equipment list, Task 2
  - List of ignition sources in each compartment, Task 6
  - Room geometry
  - Types of ignition sources and targets

- Output from this task
  - Revised compartment fire ignition frequencies
  - List of potential fire scenarios to be analyzed in Task 11

Scoping Fire Modeling
Screening Ignition Sources

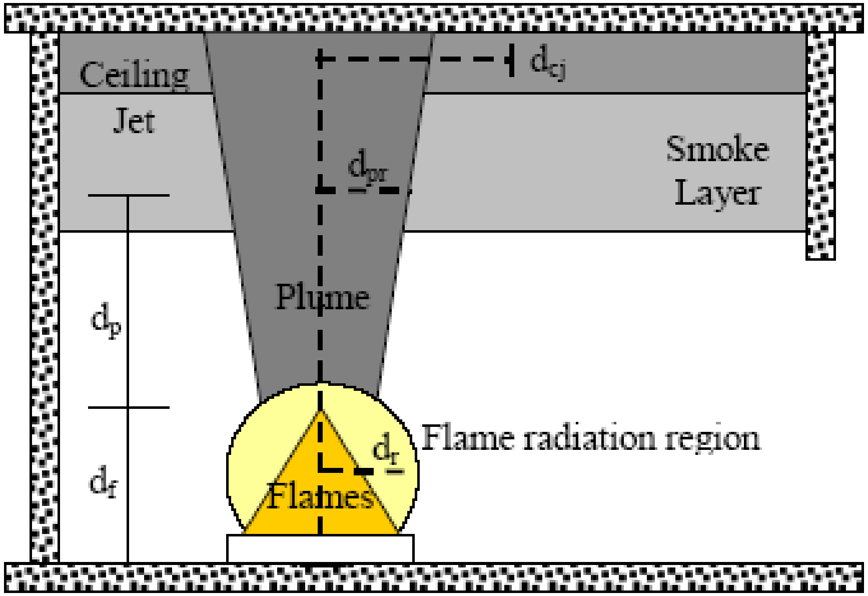
Any ignition source can be screened if a postulated fire will not damage or ignite equipment in the compartment

- By screening the ignition source, its frequency contribution is eliminated, reducing the compartment frequency
- It is recommended to use the 98th percentile of the HRR probability distribution
- A walkdown is strongly recommended
  - Related SRs: FSS-D10, D11

Scoping Fire Modeling
The Zone of Influence (ZOI)

The zone of influence is the region in the compartment where a target will be damaged if exposed to fire conditions generated by a specific ignition source

- The ZOI has 5 distinct regions:
  - Flames
  - The fire plume
  - The ceiling jet
  - The hot gas layer
  - Flame radiation region



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Scoping Fire Modeling
Task 8: Recommended Steps

5 steps for conducting Task 8

1. Preparation for walkdown
2. Plant walkdown and screen ignition sources
3. Verification of screened ignition sources
4. Calculation of severity factors
5. Calculation of revised fire frequency

Scoping Fire Modeling
Step 1: Preparation for Walkdown

It is recommended that walkdown forms be prepared for each compartment to be visited:

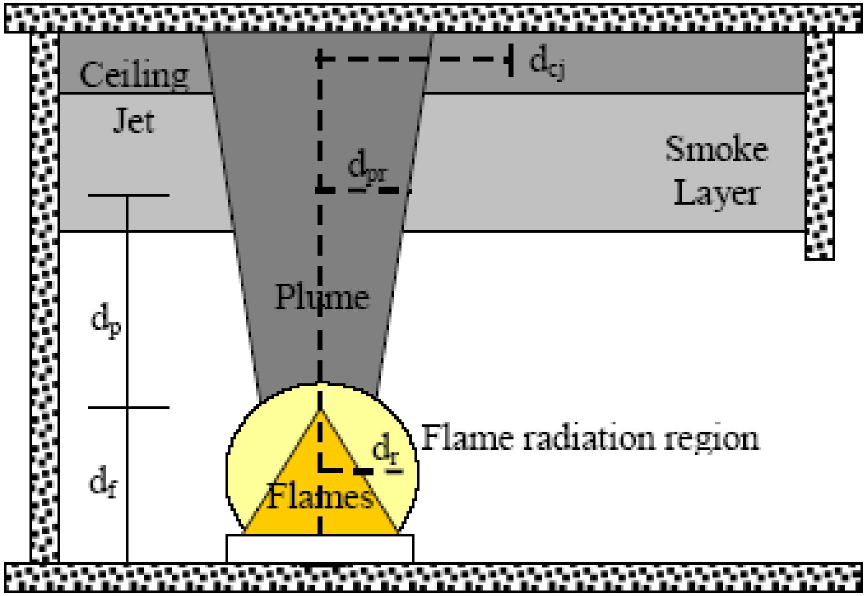
- Create a list of ignition sources in each compartment
  - Equipment counted in Task 6
  - Flag equipment in the PRA equipment list created in Task 2
  - Assigned a HRR to each ignition source (98th percentile of the pdf)
- Collect damage criteria information for the equipment in the room
  - Qualified/Unqualified cables, solid state equipment etc.
- Develop and document zone of influences in each compartment
- Corresponding PRA Standard SRs: FSS-D10 and D11

Scoping Fire Modeling
Step 1: Models for Zone of Influence

- Smoke or hot gas layer: MQH model

$$T = T_{amb} + 6.85 \cdot \left(\frac{\dot{Q}_f^2}{A_o \sqrt{H_o}\, h_k A_T} \right)^{1/3}$$

$$h_k = \begin{cases} \sqrt{\dfrac{k \cdot d_m \cdot c_p}{t}} & t < t_p \\ \dfrac{k}{th} & t \geq t_p \end{cases} \qquad t_p = \frac{th^2}{4 \cdot \left(k \big/ \left(d_m \cdot c_p \right) \right)}$$



Input Parameters:

- T_{amb}: Ambient temperature (°C)
- Q_f: Fire heat release rate (kW)
- A_o: Opening area (or sum of opening areas) (m^2)
- H_o: Height of opening [m]
- A_T: Internal surface area of the room (not including opening area) (m^2)
- k: Thermal conductivity of wall material (kW/m-°C)
- d_m: Density of wall material (kg/m^3)
- c_p: Specific heat of wall material (kJ/kg-°C)
- th: Wall thickness (m)
- t: Time value (sec)

Scoping Fire Modeling
Step 1: Example Calculation for Room Temperature

$$T = T_{amb} + 6.85 \cdot \left(\frac{\dot{Q}_f^2}{A_o \sqrt{H_o} h_k A_T} \right)^{1/3}$$

$$h_k = \begin{cases} \sqrt{\dfrac{k \cdot d_m \cdot c_p}{t}} & t < t_p \\ \dfrac{k}{th} & t \geq t_p \end{cases} \qquad t_p = \frac{th^2}{4 \cdot \left(k / (d_m \cdot c_p) \right)}$$

MQH Temperature Correlation	
Inputs	
Ambient temperature [C]	20
Duration [sec]	1200
Opening area [m2]	3
Height of opening [m]	3
Room length [m]	37
Room width [m]	37
Room height [m]	8
Thermal conductivity [kW/mK]	0.0014
Density [kg/m3]	2000
Specific heat [kJ/kg]	0.88
Wall thickness [m]	0.6
HRR [kW]	9500
Results	
Room Temp [C]	**327**

Scoping Fire Modeling
Step 1: Models for Zone of Influence

- Flame height and fire plume: Heskestad's models

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

Input Parameters:

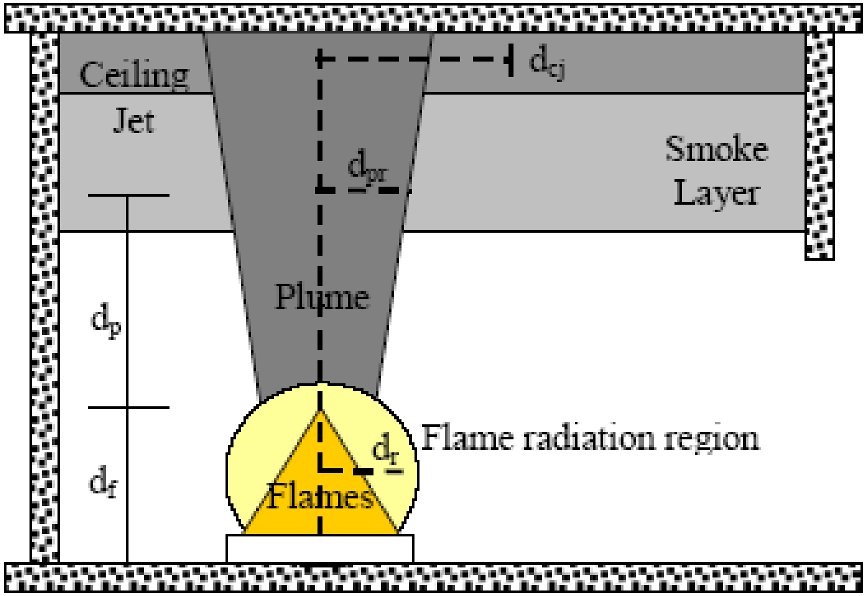
- Q_f: Fire heat release rate (kW)
- D: Fire diameter (m)

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

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

Input Parameters:

- T_{amb}: Ambient temperature (°C)
- k_f: Fire location factor
- Q_f: Fire heat release rate (kW)
- F_e: Fire elevation (m)
- H_p: Target height measured from the floor (m)
- X_r: Irradiated fraction of the heat release rate (FIVE recommends 0.4)
- D: Plume diameter (m)



Scoping Fire Modeling
Step 1: Example Calcs for Flame Height and Plume Temp

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

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

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

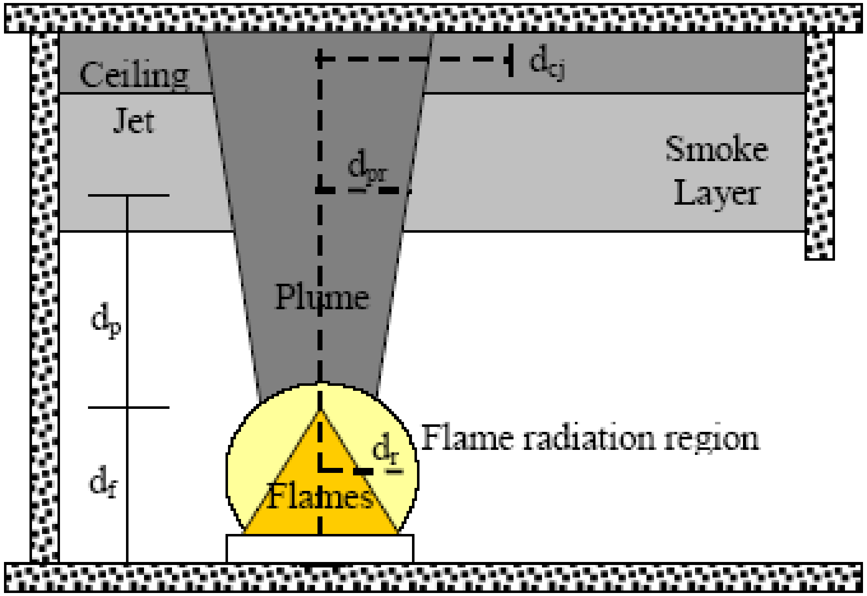
Heskdestad's Flame Height Correlation	
Inputs	
Fire diameter [m]	0.6
HRR [kW]	250
Results	[m]
Flame height [m]	**1.5**

Heskestad's Plume Temperature Correlati	
Inputs	
Ambient temperature [C]	20
Fire location factor	1
HRR [kW]	1375
Fire elevation [m]	0
Target Elevation [m]	3.7
Radiation Fraction	0.40
Fire Diameter [m]	1
Results	
Plume Temp [C]	**328**

Scoping Fire Modeling
Step 1: Models for Zone of Influence

- 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: Irradiated fraction of the heat release rate (FIVE recommends 0.4)
- D: Fire diameter (m)

Scoping Fire Modeling
Step 1: Example calculation for flame radiation

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

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**

Scoping Fire Modeling
Step 2: Walkdown (Screen Ignition Sources)

During the walkdown, equipment in the room is subjected to fire conditions from each ignition source using the ZOI.

- Take the opportunity to verify & improve Task 6 counting
- Document location of ignition sources and reasons for screen/no-screen decisions
- If ignition sources are not screened, document location of affected equipment and which fire-generated condition affected it.
- Do not screen:
  - Oil fires
  - Cables
  - Interconnected cabinets

Scoping Fire Modeling
Step 3: Verify Screened Ignition Sources

It is important to verify that fire damage to the ignition source itself is not risk significant

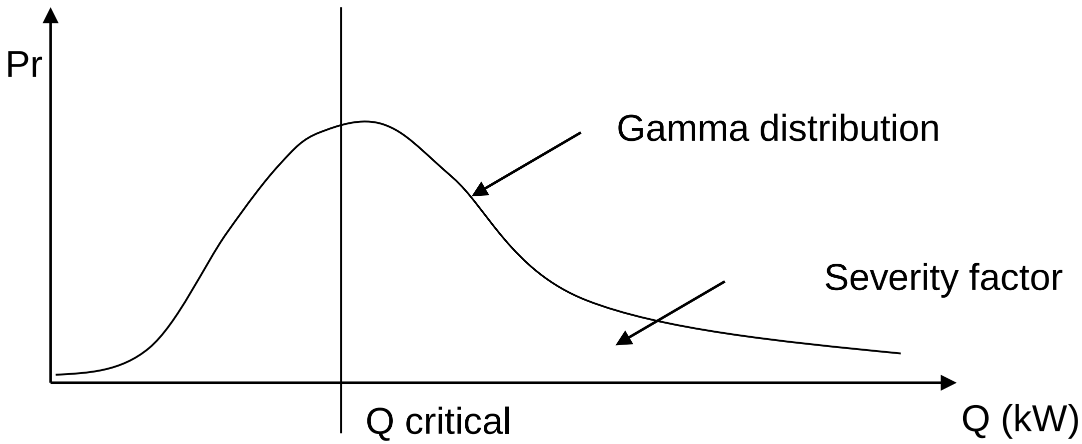
1. Do not screen equipment in the PRA equipment list
2. If loss of the ignition source results in a trip (automatic or manual), but no equipment contributing to the CCDP is lost, compare the ignition source fire frequency with the random frequency of the trip it causes.
3. If loss of the ignition source results in both a trip (automatic or manual) and loss of one or more components contributing to the CCDP, add a fire-induced sequence using the ignition source fire frequency and the corresponding CCDP model with the damaged components set to fail (failure probability = 1.0).

Scoping Fire Modeling
Task 8: Calculation of Severity Factors

For each unscreened ignition source, calculate the severity factor using the appropriate probability distribution for peak HRR.

- Determine the heat release rate required for damaging equipment
- This require information gathered during the walkdowns!

Scoping Fire Modeling
Task 8: Calculation of Severity Factors



Case	Ignition Source	HRR kW (Btu/s)		Gamma Distribution	
		HRR	98th	α	β
1	Vertical cabinets with qualified cable, fire limited to one cable bundle	69	211	0.84	59.3
2	Vertical cabinets with qualified cable, fire in more than one cable bundle	211	702	0.7	216
3	Vertical cabinets with unqualified cable, fire limited to one cable bundle	90	211	1.6	41.5
4	Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	232	464	2.6	67.8
5	Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	232	1002	0.46	386
6	Pumps (electrical fires)	69	211	0.84	59.3
7	Motors	32	69	2	11.7
8	Transient Combustibles	142	317	1.8	57.4

Table E-5
Discretized Distribution for Case 4 Heat Release Rate (Vertical Cabinets with Unqualified Cable, Fire in more than One Cable Bundle Closed Doors)

Bin	Heat Release Rate - kW (Btu/s)			Severity Factor (P_i)
	Lower	Upper	Point Value	
1	0 (0)	53 (50)	36 (34)	0.082
2	53 (50)	106 (100)	80 (76)	0.213
3	106 (100)	158 (150)	131 (124)	0.224
4	158 (150)	211 (200)	184 (174)	0.177
5	211 (200)	264 (250)	235 (223)	0.122
6	264 (250)	317 (300)	288 (273)	0.077
7	317 (300)	369 (350)	341 (323)	0.046
8	369 (350)	422 (400)	394 (373)	0.027
9	422 (400)	475 (450)	446 (423)	0.015
10	475 (450)	528 (500)	499 (473)	0.008
11	528 (500)	580 (550)	552 (523)	0.004
12	580 (550)	633 (600)	603 (572)	0.002
13	633 (600)	686 (650)	656 (622)	0.001
14	686 (650)	739 (700)	709 (672)	0.001
15	739 (700)	Infinity	816 (773)	0.001

Scoping Fire Modeling
Task 8: Calculation of Revised Fire Frequency

Plant ____________

Fire Area ____________

Compartment ____________

Dmage Criteria	
Temperature [C]	205
Heat flux [kW/m2]	6

Pre-Walkdown Inputs		WALKDOWN INPUTS						Input	
Equip ID	HRR PDF	Fire Condition	Dist to Target (m)	Calculated HRR [kW]	Critical 98th HRR [kW]	Screen ?	SF	(Task 6) λ	Adjusted λ
Cabinet A	1	Flames	0.5	49	211	No	3.4E-01	1.0E-04	3.44E-05
Cabinet B	1	Plume	3	401	211	Yes	0.0E+00	1.0E-04	0
Cabinet C	3	Ceiling jet	1.5	4870	211	Yes	0.0E+00	1.0E-04	0
Pump	6	Plume	2	179	211	No	3.0E-02	1.0E-04	2.97E-06
Motor	7	Flame radiation	2.5	1178	69	Yes	0.0E+00	1.0E-04	0
					Adusted compartment frequency, λ_C =				3.7E-05

Scoping Fire Modeling
Concluding Remarks

Task 8 is intended for screening fixed ignition sources. As a result of the screening, the compartment frequencies may be reduced, and a preliminary list of potential fire scenarios for detailed evaluation in Task 11 is developed.

- A detailed walkdown is recommended
- Analysts should take the opportunity to review the equipment count made for Task 6 and/or improve it.

Module III – Fire Analysis

Fire Fundamentals: Appendix G – Heat Release Rates

Joint RES/EPRI Fire PRA Workshop
July 15-19, 2019

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

Heat Release Rates
Objectives

The objectives of this module are:

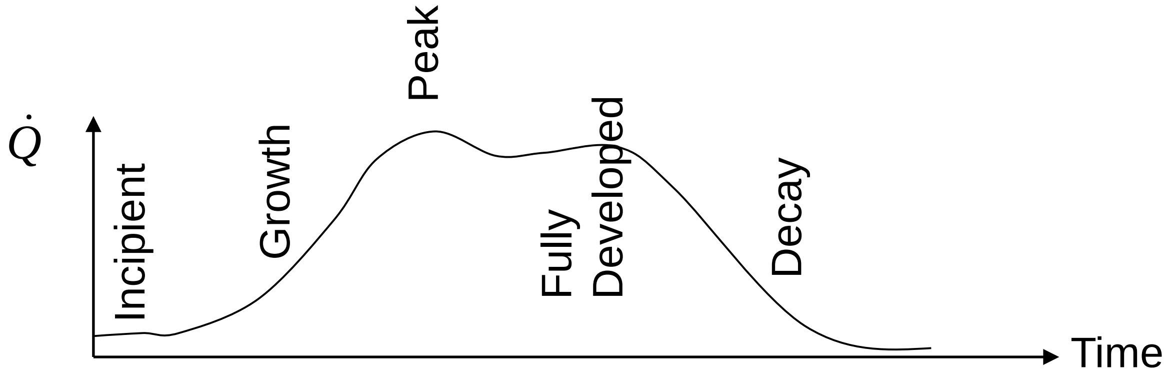
1. Define heat release rate and heat release rate profile
2. Review the recommended peak heat release rate values for typical ignition sources in NPPs
3. Describe the method provided for developing heat release rate profiles for fixed and transient ignition sources in NPPs

NOTE: Appendix G recommends values for ignition sources only. Heat release rates associated with fires propagating outside of the ignition source have to be evaluated accordingly.

Heat Release Rates
Definition

Definition: Heat generated by a burning object per unit time.

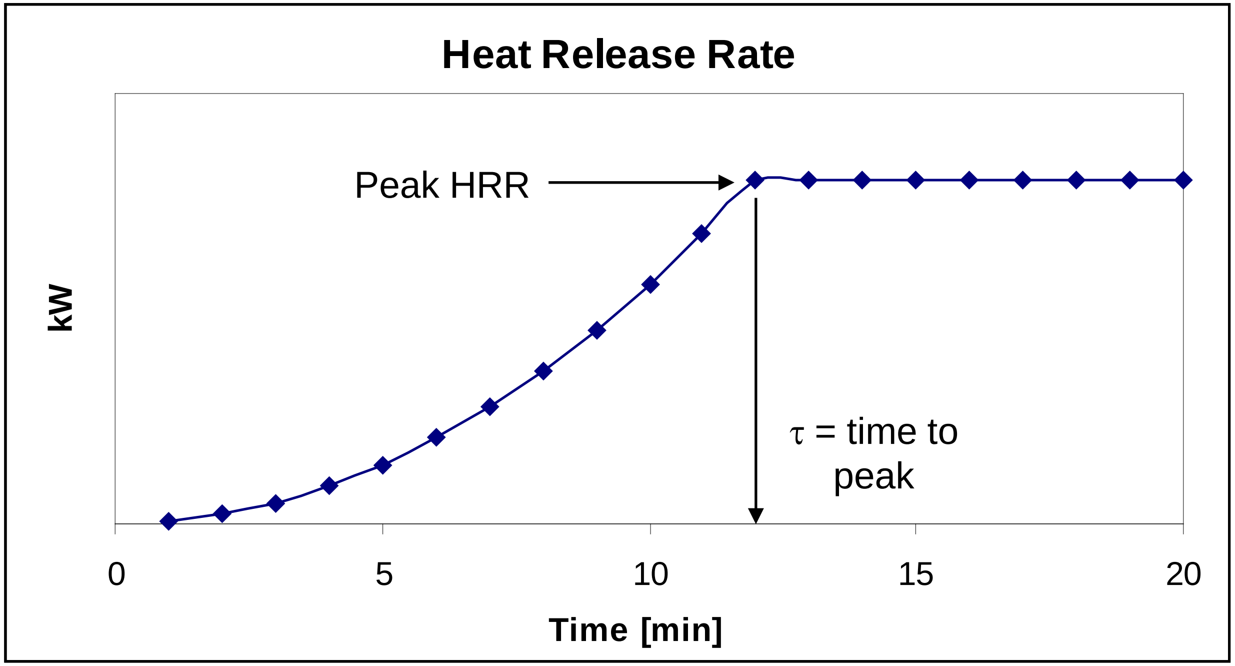
- $\dot{Q} = \dot{m}'' \cdot \Delta H_c \cdot A$ BTU/sec or KW
- m" is burning rate [kg/s-m^2], ΔH_c is heat of comb [kJ/kg], A is area [m^2]
- Equivalent terms: energy release rate, fire intensity, fire power
- HRR profile describes fire intensity as a function of time



Heat Release Rates
Fire Growth in Electrical Cabinets

The t^2 function is recommended for modeling the growth phase of the fire:

$$\dot{Q}(t) = Min\left(\dot{Q}_{peak}, \dot{Q}_{peak} \cdot \left(\frac{t}{\tau}\right)^2\right)$$



Heat Release Rates
HRR Profile

The HRR profile can be expressed as a constant or as a function of time:

- Incipient stage: Not recommended to be modeled
  - Duration and intensity are uncertain
- Growth: Depends on the fuel and geometry of the scenario
  - Based on engineering judgment and/or experimental observations
- Fully developed: Usually after the fire reaches its peak intensity
  - Also known as steady burning
  - Starts at ignition if the growth period is not considered
  - A constant fire intensity should be the peak heat release rate of the profile
- Decay: In general, less hazardous conditions than the growth and fully developed stage

FAQ 08-0052: Transient Fires

- Manual Suppression Curve
- Fire Growth Time:
  - Common trash can (refuse in a trash receptacle):
    - Can be associated with a t^2 fire growth that grows from zero to peak in approximately 8 minutes.
  - Common trash bag (refuse in plastic bags not in a receptacle):
    - Can be associated with a t^2 fire growth that grows from zero to peak in approximately 2 minutes.
  - Flammable or combustible liquid spills:
    - Negligible growth time (near infinite growth rate)
    - Assume peak heat release rate for the spill through the entire duration of the fire (ignition through burnout)

Heat Release Rates
Fixed Ignition Sources

The methodology recommends heat release rate values for various fixed ignition sources

- Vertical cabinets
  - Open/closed
  - Qualified/unqualified cables
- Pumps (electrical fires)
- Electric motors
- HRR for flammable liquid fires should be calculated using the equation

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

- Separate guidance for cables, pressurized oil, and hydrogen fires

Heat Release Rates
Recommended Peak HRR Values

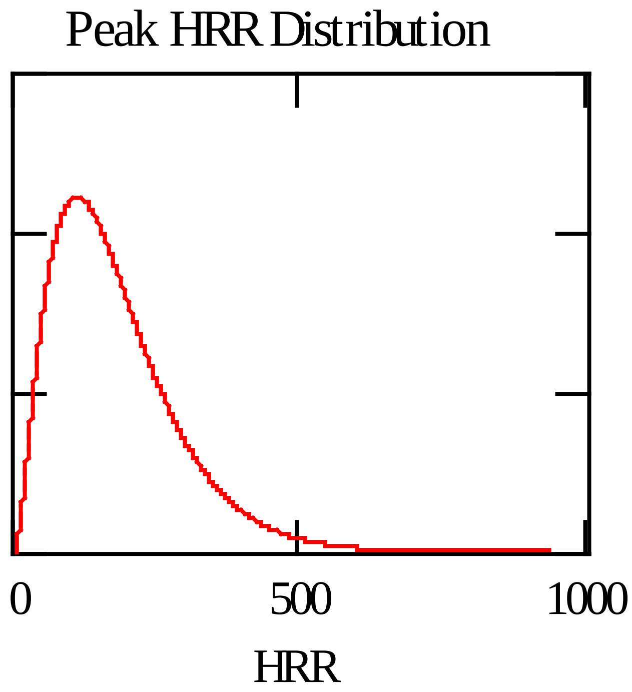
Recommended peak HRR values were developed based on expert judgment (Table G-1)

- Panel included EPRI and NRC representatives with expertise in fire behavior/phenomena and PRA.
- Values are expressed as probability distributions. The panel identified the 75th and 98th percentiles of the distribution for peak HRR.
- Primary sources of information included NUREG/CR-4527 and VTT publications
- Gamma distribution selected:
  - Only positive values starting at 0 kW
  - Values in the same order of magnitude
- Corresponding PRA Standard SR: FSS-D5, E3

Heat Release Rates
Recommended Peak HRR Values

Example distribution developed by the expert panel

- 75^{th} = 232 kW
- 98^{th} = 464 kW
- α = 2.6
- β = 67.8



Heat Release Rates
Recommended Peak HRR Values (Table G-1)

Ignition Sources	HRR kW/ (Btu/s)		Gamma Distribution	
	75th	98th	α	β
Vertical cabinets with qualified cable, fire limited to one cable bundle	69[1] (65)	211[2] (200)	0.84 (0.83)	59.3 (56.6)
Vertical cabinets with qualified cable, fire in more than one cable bundle	211[2] (200)	702[3] (665)	0.7 (0.7)	216 (204)
Vertical cabinets with unqualified cable, fire limited to one cable bundle	90[4] (85)	211[2] (200)	1.6 (1.6)	41.5 (39.5)
Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	232[5] (220)	464[6] (440)	2.6 (2.6)	67.8 (64.3)
Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	232[5] (220)	1002[7] (950)	0.46 (0.45)	386 (366)
Pumps (electrical fires)[8]	69 (65)	211[2] (200)	0.84 (0.83)	59.3 (56.6)
Motors[8]	32 (30)	69 (65)	2.0 (2.0)	11.7 (11.1)
Transient Combustibles[9]	142 (134)	317 (300)	1.8 (1.9)	57.4 (53.7)

*See report for footnotes

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Heat Release Rates
Fire Growth in Electrical Cabinets

The methodology suggests a fire growth rate for electrical cabinet fires

- The fire grows to its peak HRR in approximately 12 min
- The fire burns at its peak HRR for approximately 8 min
- Based on experiments reported in NUREG/CR-4527

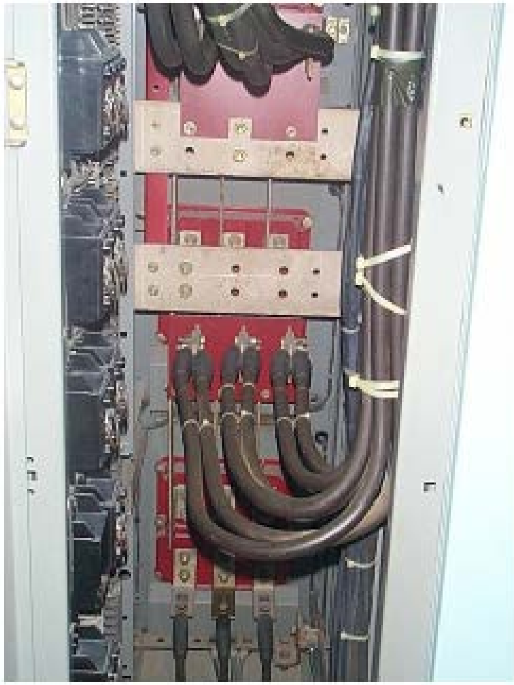
Test	Units in Minutes		
	Time to Peak	Steady Burning	Time to Decay
ST1	7	8	15
ST2	6	11	17
ST3	10	8	18
ST4	14	3	17
ST5	8	9	17
ST6	8	17	25
ST7	18	7	25
ST8	10	20	30
ST9	10	10	20
ST10	10	20	30
ST11	18	2	20
PCT1	11	10	21
PCT2	12	2	14
PCT3	13	14	27
PCT4a	16	0	16
PCT4c	16	0	16
PCT5	17	0	17
PCT6	11	0	11
Test 21	4	14	18
Test 22	9	2	11
Test 23	10	0	10
Test 24	12	0	12
Average	**11.4**	**7.1**	**19**

Heat Release Rates
Assigning HRR Values to Electrical Cabinets

- Visual examination of cabinet interior is recommended
- Identify openings in the cabinet walls
- Identify type of cable: qualified/unqualified
- Identify cable bundles
- Qualitatively determine if a fire can propagate from one bundle to another
- Select the appropriate peak HRR probability distribution

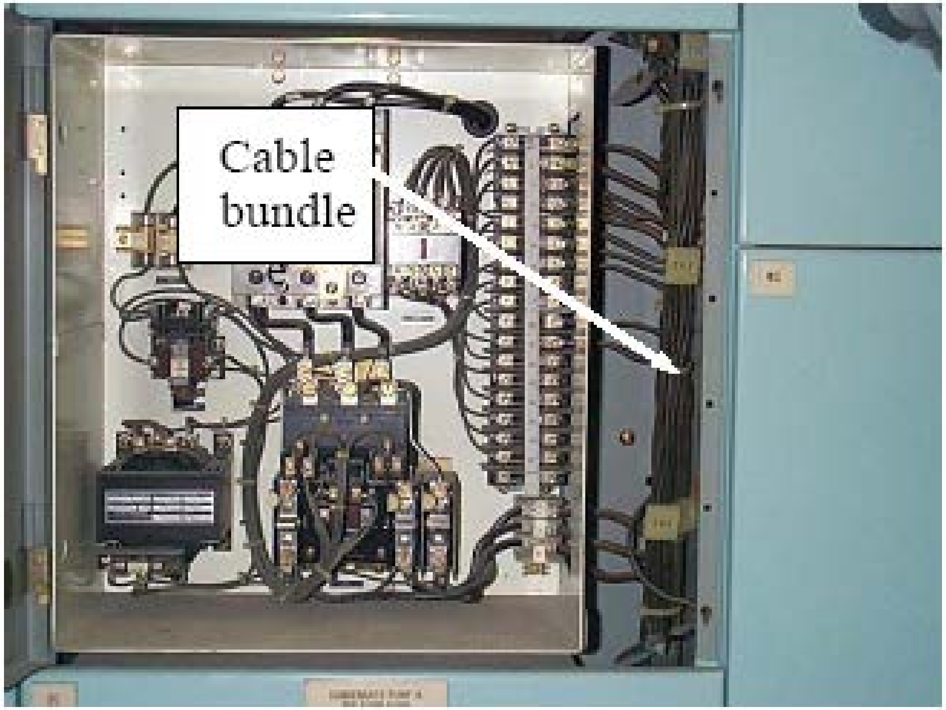
Heat Release Rates
Examples

- More than one cable bundle
- Assuming qualified cable, select distribution with percentiles:
  - 75^{th} = 211 kW
  - 98^{th} = 702 kW



Heat Release Rates Examples

- Only one cable bundle
- Assuming qualified cable, select distribution with percentiles:
  - 75th = 69 kW
  - 98th = 211 kW



FAQ 08-0042: “Fire Propagation From Electrical Cabinets”

- Purpose & Scope
  - Provide clarification on conflicting language in NUREG/CR-6850 related to the description of fire propagation from unvented cabinets
    - Guidance in Appendix G is in conflict with the guidance in chapters 6 and 11 of NUREG/CR-6850
  - The scope of this FAQ is limited to the clarification of the conflicting guidance provided in NUREG/CR-6850 related to fire propagation outside unvented cabinets.
  - Reference:
    - EPRI 1019259, Supplement 1 to NUREG/CR-6850

FAQ 08-0042: Solution

- Chapter 11 of NUREG/CR-6850 provides the consensus position on fire propagation outside of unvented cabinets
  - The following, from the second paragraph on section G.3.3 should be disregarded:

~~Electrical cabinets that are not vented do not propagate a fire. … It is assumed that in the absence of other ventilation *(other than those listed in Table G.3)*, penetrations will not allow sufficient air exchange to replace oxygen consumed by the fire, and an incipient fire will self-extinguish when there is no longer enough oxygen to support combustion. [Italics added for clarity.]~~

FAQ 08-0042: Solution

- Modified language includes description of electrical cabinet features that should be present to prevent fire propagation outside the cabinet
  - Fire sealed (not fire rated) at cable entry points
  - No vents
  - Robustly secured

FAQ 08-0043: "Location of Fires Within Electrical Cabinets"

- Purpose & Scope
  - This FAQ provides clarification on the location of fires within an electrical cabinet.
  - The scope of this FAQ is limited to describing the location of a fire postulated in an electrical cabinet in a Fire PRA.
- Reference:
  - EPRI 1019259, Supplement 1 to NUREG/CR-6850

FAQ 08-0043: Solution

- For cabinets with no vents, the fire should be postulated approximately 1’ below the top of the cabinet
- Analysts should inspect cabinets to determine vent location or the possibility of door openings.
  - For vented cabinets, fires should be postulated at the location of the vents
  - Fire should be postulated at the top of open doors

Heat Release Rates
Transient Ignition Sources

The peak HRR for transient fires is also characterized with a gamma probability distribution

- Gamma distribution percentiles:
  - 75^{th} = 142 kW, 98^{th} = 317 kW
  - $\alpha = 1.9$, $\beta = 53.7$

- Applicable only to localized transient combustibles (trash cans, etc.)

- Not applicable to flammable liquid transient fires

Heat Release Rates
Concluding Remarks

Peak HRR values are recommended for some typical fixed and transient ignition sources in NPP fire scenarios

- Values are for localized ignition source (not for fires propagating outside the ignition source)
- HRR for flammable liquid fires can be calculated from fundamental equations
- HRR for “solid” ignition sources are generally expressed as probability distributions based on experimental data and expert judgment
- Revised HRRs for electrical cabinets are discussed in a separate presentation

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Module III – Fire Analysis

Appendix H: Damage Criteria and Damage Time

Joint EPRI/NRC-RES Fire PRA Workshop
July 15-19, 2019

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

Damage Criteria
Characterizing targets

- A target is something other than the fire ignition source that may become involved in the fire
  - Defined as a part of the fire scenario
- Generally there are two target types:
  - Damage target: A component (or cable) that is important to plant operations that may be damaged by an exposing fire
  - Secondary ignition target: Any object that is combustible and that may be ignited by an exposing fire thereby spreading the fire
- One object can actually be both
  - e.g., the first cable tray above a fire ignition source…
- This presentation is mainly about *damage targets*, but the same general approach applies to ignition targets as well

Damage Criteria
Damage Thresholds

- Damage (or Failure) Threshold: the minimum value of an exposure environment parameter that *can* lead to the failure of the damage target of interest within the time scale of the fire
  - Can be a temperature – exposure to high temperatures such as in a hot gas layer or fire plume
  - Can be a radiant heat flux – generally due to direct radiant heating from the luminous flame zone of a fire
  - In theory, it could be a minimum smoke density, but we aren't that smart (more on smoke shortly)
- Corresponding PRA Standard SRs: FSS-C5, C6 and D9

Damage Criteria
Damage Thresholds

- Damage thresholds are of primary interest to Task 8 – Scoping Fire Modeling, but also play a role in Task 11 – Detailed Fire Modeling
- 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.
  – Damage thresholds are most useful when screening out specific fire ignition sources in Task 8:
    - If the closest target is outside the ZOI (no damage) <u>and</u> fire cannot ignite any secondary combustibles, then we screen that source out of the analysis as non-threatening (more later)
  – When we get to Task 11, we'll need damage time (more later)
- *Also Note:* If an electrical cable is damaged, we assume that it will also be ignited
    - Based on testing experience – arcing causes piloted ignition

Damage Criteria
Damage Thresholds

- The *damage threshold* is specific to the damage target based on target type and target characteristics
  - What type of component?
  - What are it's vulnerabilities (e.g., heat, smoke, water…)?
  - What is the weak link relative to damage and the fire scenario?

- Most fire scenarios focus on:
  - Electrical cables (power, control, and instrumentation)
  - Electronics and integrated circuit devices

Cables
Classification of cables by insulation type

Cable insulations fall into one of 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 (Marriam-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
  - Thermoplastic is more common in older plants, also used in non-vital applications such as lighting and communications
  - Thermoset is more common in newer plants
  - Practices also vary based on utility preference at the time of construction

Damage Criteria
Cable damage thresholds

- The following are defined as generic damage thresholds for the most common damage targets – cables:

Table H-1 Damage Criteria for Electrical Cables – Generic Screening Criteria for the Assessment of the Ignition and Damage Potential of Electrical Cables [See Ref 8-1]

Cable Type	Radiant Heating Criteria	Temperature Criteria
Thermoplastic	6 kW/m^2 (0.5 BTU/ft2s)	205°C (400°F)
Thermoset	11 kW/m^2 (1.0 BTU/ft2s)	330°C (625°F)

*if you have case specific information, you may use alternate values if you can establish a technical basis – many specific cable types will have much higher damage thresholds if you can establish a more specific insulation type for target cables

Damage Criteria
Sensitive Electronics

- Electronic devices refers mainly to control components that are based on integrated circuit type devices
  - Circuit cards, amplifiers, D/A and A/D converters, signal conditioning devices, communications equipment, computers, instrument transmitters, etc.
- Does not include electro-mechanical devices that lack integrated circuit elements
  - Relays, switches, indicating lights, breakers, etc.
- Typical damage thresholds for electronics are much lower than cables:
  - 3 kW/m^2 (0.25 BTU/ft^2) and 65^{o}C (150°F)
  - FAQ 13-004 Treatment of Sensitive Electronics

Damage Criteria
Sensitive Electronics

- FAQ 13-004 discusses an approach for treating "sensitive electronics" targets in fire scenarios
  - Points out that there is no clear definition of what constitute "sensitive electronics" in NUREG/CR-6850
  - Proposed treatment assumes that equipment that is sensitive to increased temperatures will be located inside electrical enclosures
  - Guidance is based on FDS fire simulations
    - 317kW transient fire located 1 m from a cabinet
    - Radiometer located inside the cabinet to measure internal heat fluxes
  - In order to reach damaging heat fluxes inside the cabinet, conditions outside the cabinet are consistent with the damage criteria for Themoset cables

Damage Criteria
Some other specific cases

- Some items are considered invulnerable to fire-induced damage:
  - Ferrous metal pipes and tanks
  - Passive components such as flow check valves
  - Concrete structural or partitioning elements except when considering random failure likelihood in multi-compartment scenarios
    - i.e., we *do not* consider fire-induced structural failure of concrete
- Things you still need to watch for:
  - Soldered piping (e.g., air/gas lines that are soldered copper)
  - Flexible boots/joints/sleeves on piping (e.g., the Vandellos scenario)
  - Exposed structural steel given a very large fire source (e.g., catastrophic loss of the main TG set – more later)

Damage Criteria
Everything else…

- For other devices (e.g., motors, switchgear, etc.) we typically look to either the supporting cables or controls
  - A electric motor driven pump is fed by power cables, and those cables are generally more vulnerable to fire damage than the pump itself
  - A switchgear is supported by both power and control cables – typically loss of the control cables means loss of functionality (no control power means breaker will not auto-cycle and cannot be remotely cycled)
  - A battery charger usually contains some integrated circuit cards that control charging rate and monitor battery status
  - A motor operated valve… again, look at the cables

Damage Criteria
Damage Thresholds

- For additional rules related to damage criteria, see H.1.1; e.g.:
  - Cables in conduit: potential damage targets, but will not contribute to fire growth and spread – no credit to conduit for delaying the onset of thermal damage.
  - Cables coated by a fire-retardant coating: treat as exposed cables for damage purposes – coating may slow the subsequent spread of fire, but we are NOT specific here.

Damage Criteria
Damage Thresholds

- Plant-specific or product-specific damage thresholds *may be used* if appropriate basis is established
  - NUREG/CR-6850 provides some references for information specific to many popular types and brands of cables
  - Example:

Table H-4
Failure Temperatures for Specific Cable Products as Reported in Table 5 of Reference H.2

Cable Manufacturer	Description of Cable Tested	Failure Threshold (°C)
Brand Rex	Cross-linked polyethylene (XLPE) Insulation, Chlorosulfonated Polyethylene (CSPE) Jacket, 12 AWG, 3-Conductor (3/C), 600 Volt (V)	385
Rockbestos	Firewall III, Irradiation XLPE Insulation, Neoprene Jacket, 12 AWG, 3/C, 600 V	320-322
Raychem	Flamtrol, XLPE Insulation, 12 AWG, I/C, 600 V	385-388
Samuel Moore	Dekoron Polyset , Cross-Linked Polyolefin (XLPO) Insulation, CSPE Jacket, 12 AWG, 3/C and Drain	299-307
Anaconda	Single Conductors Removed From: Anaconda Y Flame- Guard Flame Retardant (FR) Ethylene Propylene (EP), Ethylene Propylene Rubber (EPR) Insulation, Chlorinated Polyethylene (CPE) Jacket, 12 AWG, 3/C, 600 V	381
Anaconda	Anaconda Flame-Guard EP, EPR Insulation, Individual CSPE Jacket, Overall CSPE Jacket, 12 AWG, 3/C, I000 V	394
Okonite	Okonite Okolon, EPR Insulation, CSPE Jacket, 12 AWG, I/C, 600 V	387

Damage Criteria
Damage Time

- It is both appropriate and desirable to consider, not just the possibility of damage, but also the time before damage occurs
  - This is part of Task 11 – Detailed Fire Modeling
- It takes time to heat a target to its damage temperature
  - If the air temperature (or heat flux) equals the damage threshold, damage times may be prolonged (e.g., 30-60 minutes or more)
  - As exposure conditions become more severe, time to damage decreases (e.g., if immersed in flames, may be a few seconds)
- A damage time gives us a "hook" to credit fire intervention:
  - It tells you how long you have to put the fire and prevent damage
  - We can then ask "what is the probability that given the fire, it will be put out before damage occurs?"
  - More details on that process later in the week, but for now we'll talk a little about estimating damage time

Damage Criteria
Damage time – three common approaches

- Predict when a fire grows large enough to create damaging environment at the target location (generally most conservative)
- Empirical approach (intermediate approach, e.g., SDP*)
  - Predict the peak exposure condition (temperature or heat flux)
  - Use a look-up table to estimate time to damage
  - Catch: look-up tables currently only available for generic thermoset and thermoplastic cables
- Direct modeling of target thermal response based on fire environment (generally most realistic)
  - Use a fire model to predict the temperature response of the target
  - When the predicted temperature of the target reaches the damage threshold, assume target failure
  - Catch: need fire model that does target response calculation
  - Simplest example: THIEF model for cables (more later)

* Significance Determination Process

Damage Criteria
Damage time – time to threshold

- One simple approach is to assume damage occurs when the conditions at the target location first reach the damage threshold
  - Generally gives the most conservative answer of the three approaches
- If you can characterize fire growth versus time, then you can use that to predict the fire environment over time even using simple correlations that are based on fire heat release rate
  - Plume temperature correlation
  - Radiant heating correlation
  - Steady state hot gas layer temperature correlation
- If you are in a hot gas layer situation, you can predict transient temperature profile using a fire model like CFAST or MAGIC
  - Won't help much unless you have a transient fire growth profile because HGL develops to steady state very quickly in these models

Damage Criteria
Damage time – the look-up tables

- The empirical time to damage tables are an intermediate approach
  - Still very simple but somewhat conservative
- Given exposure temperature, look-up tables give estimated time to damage

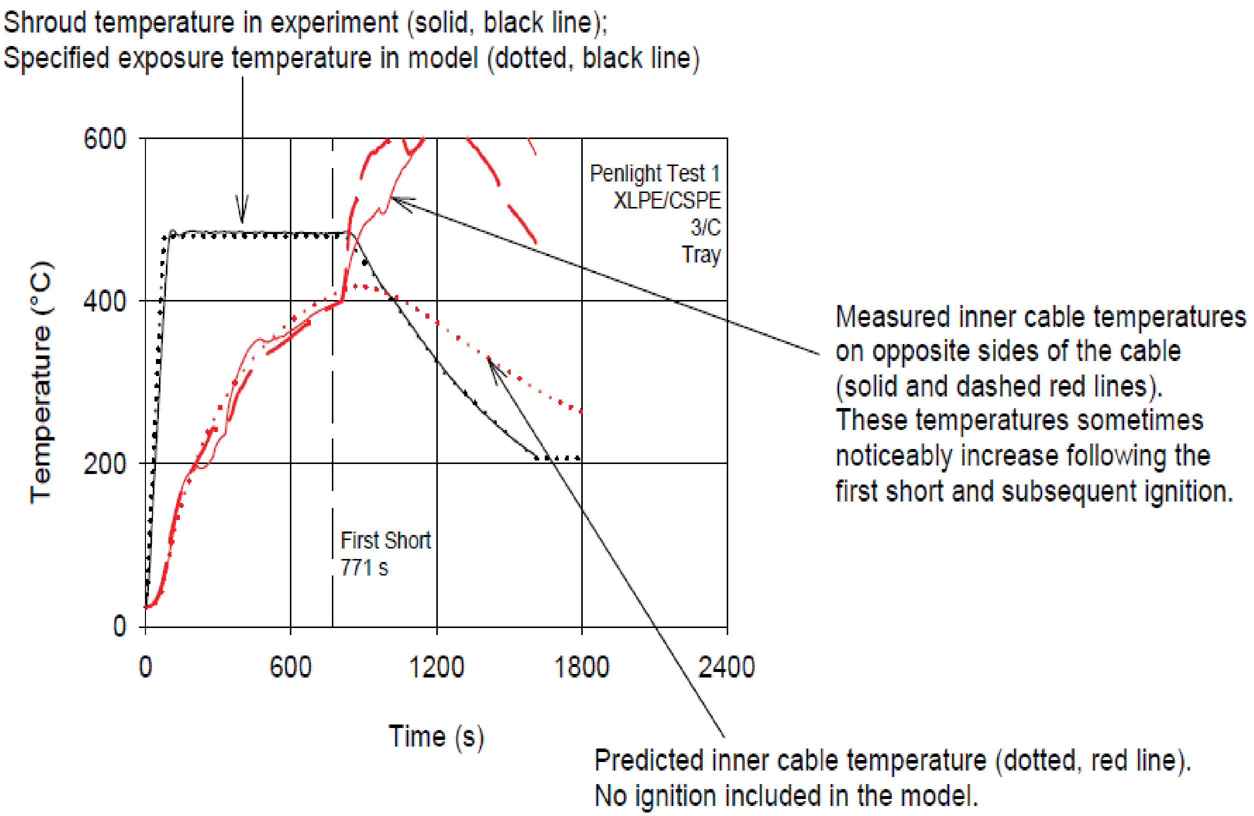
Table H-5: Failure Time-Temperature Relationship for Thermoset cables (Table A.7.1 from reference H.6).

Exposure Temperature		Time to Failure (minutes)
^{o}C	^{o}F	
330	625	28
350	660	13
370	700	9
390	735	7
410	770	5
430	805	4
450	840	3
470	880	2
490 (or greater)	915 (or greater)	1

Damage Criteria
Damage time – direct response modeling (e.g., THIEF)

- See: NUREG/CR-6931 V3
- Simple one-dimensional homogeneous heat transfer model

- Assumes a single cable in air (or in a conduit in air)
- Input is an air temperature profile
- Output is cable temperature vs time
- Assume damage when cable temperature exceeds threshold
- Now part of CFAST and FDS; FDTs coming



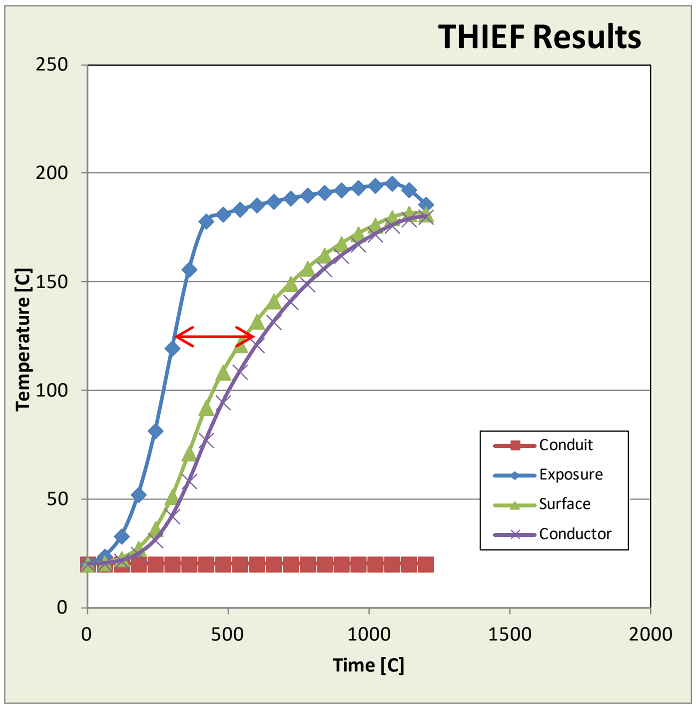
Thermally-Induced Electrical Failure (THIEF) Example

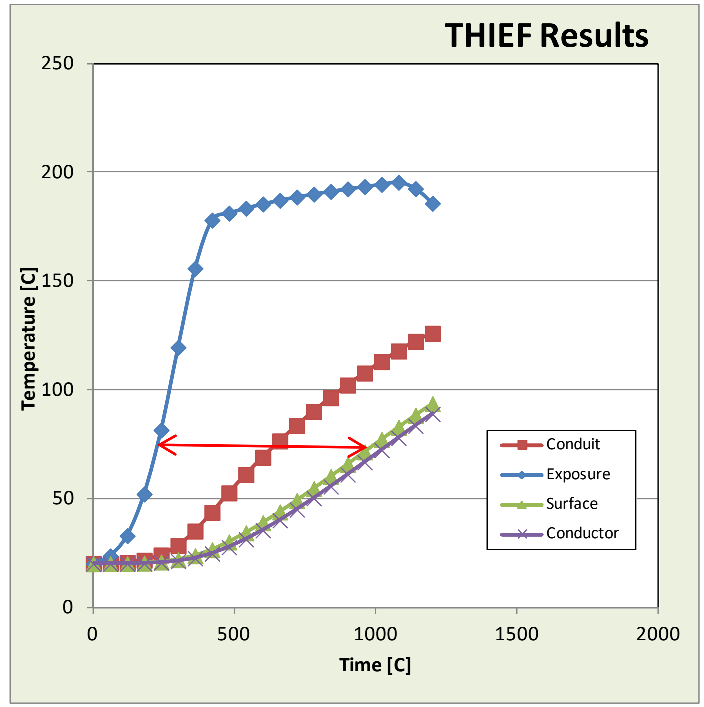
No Conduit

Cable diam	20	mm
Mass per length	0.3	kg/m
Jacket thickness	1.6	mm
Conduit diameter	14	mm
Conduit thickness	0	mm
Damage temp	205	C
Ambient temp	20	C

Cable Inside Conduit

Cable diam	20	mm
Mass per length	0.3	kg/m
Jacket thickness	1.6	mm
Conduit diameter	14	mm
Conduit thickness	5	mm
Damage temp	205	C
Ambient temp	20	C





Damage Criteria
Smoke Damage

- Appendix T provides an extended discussion of current knowledge regarding smoke damage
  - This is about smoke and the failure of equipment
  - It is not about the impact of smoke on people

- We are interested in short-term damage
  - Within the time scale of the fire scenario including plant shutdown
  - We do not consider longer term issues such as corrosion leading to failure some days or weeks after a fire

- Corresponding PRA Standard SR: FSS-D9

Damage Criteria
Smoke Damage

- Bottom Line: Some components are known to be vulnerable to smoke damage, but it takes a dense exposure to cause short term damage

- So what are the vulnerable components?
  - High voltage switching equipment (arcing)
  - High voltage transmission lines (arcing)
  - Devices such as strip chart recorders that are dependent on fine mechanical motion (binding)
  - Un-protected printed circuit cards (deposition and shorting)
    - e.g., exposed within a panel and not provided with a protective coating

Damage Criteria
Smoke Damage

- Smoke damage is assessed on an empirical basis:
  - We don't set quantitative thresholds
  - We don't try to use fire models
  - You should consider the potential failure of vulnerable components due to smoke as a part of your damage target set

Damage Criteria
Smoke Damage

- Assume that vulnerable components adjacent to or connected to the fire source will be damaged by smoke:
  - Within the same electrical cabinet or housing as a fire source
    - e.g. given a panel fire, the whole panel is lost due to smoke and/or heat
  - In an adjacent cabinet if the cabinet-to-cabinet partitions are not well-sealed
  - In a common *stack* of electrical cubicles
  - In a nearby cabinet with a direct connection to the fire source
    - e.g., a shared or common bus-duct

Questions?

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Module III – Fire Analysis

Appendix E: Fire Severity

Joint EPRI/NRC-RES Fire PRA Workshop
July 15-19, 2019

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

Fire Severity
Purpose

- A uniform methodology has been developed to define the severity of a fire.
  - Severity factor concept
  - Based on heat release rate
  - Standardized cases
- Applicable SRs: FSS-C2, C3, C4,

Fire Severity
Severity Factor Concept

- Severity Factor is . .
  - A simplified, one parameter representation of a very complex phenomenon (i.e., fire) influenced by a large number of factors.
  - Defined as the conditional probability that, given a fire has occurred, it is of certain severity (it is defined here through heat release rate).
  - Quantified in combination with *Non-Suppression Probability.*

Fire Severity
Severity Factor Concept

Bin #	HRR (kW)	Bin Probability	Probability fire is at least this big	Damage?
1	11	0.445	1.000	No
2	36	0.219	0.555	No
3	61	0.129	0.336	No
4	87	0.078	0.207	No
5	112	0.048	0.129	Yes
6	137	0.030	0.081	Yes
7	162	0.019	0.051	Yes
8	187	0.012	0.032	Yes
9	212	0.020	0.020	Yes
	Total	1		

$$\lambda_{damage} = \lambda_{Fire} \times 0.129$$

Fire Severity
Severity Factor Concept

Bin # (i)	HRR (kW)	Bin Probability (P_i)	Damage	t_s (min)	$P_{NS,i}$	$P_i * P_{NS,i}$
1	11	0.445	No	∞	0	0
2	36	0.219	No	∞	0	0
3	61	0.129	No	∞	0	0
4	87	0.078	No	∞	0	0
5	112	0.048	Yes	28	0.03	0.0014
6	137	0.03	Yes	24	0.06	0.0018
7	162	0.019	Yes	20	0.09	0.0017
8	187	0.012	Yes	16	0.15	0.0018
9	212	0.02	Yes	13	0.21	0.0042
					Net damage probability:	**0.011**

Time available for suppression:

$$t_s = t_{damage} - t_{detection}$$

Net probability of damage:

$$P_{NSnet} = \sum_{i=1,9} (P_i * P_{NS,i})$$

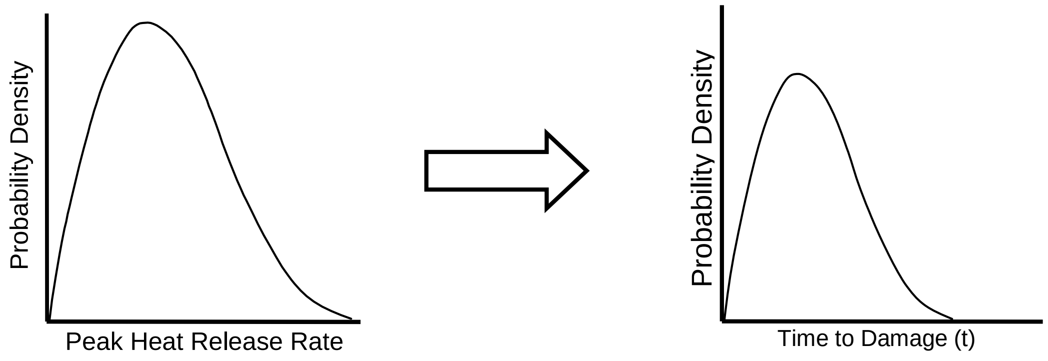
$$P_{NSnet} = 0.011$$

Frequency of damage:

$$\lambda_{damage} = \lambda_{IS,i} \times 0.011$$

Fire Severity
Probability of Damage Estimation

- Probability of damage before time t is estimated using complex fire spread and propagation models.
  - Heat release rate is a key parameter of the analysis
  - Assuming a known heat release rate, specific features of the compartment, ignition source, and target set configuration, time to damage can be calculated.
  - Since heat release rate is expressed with a probability distribution, the time to damage can be expressed with a probability distribution



Fire Severity
Heat Release Rate Distributions

The heat release rate of the following equipment classes have been defined:

Case	Ignition Source	HRR (Btu/s)	
		75th	98th
1	Vertical cabinets with qualified cable, fire limited to one cable bundle	65	200
2	Vertical cabinets with qualified cable, fire in more than one cable bundle	200	665
3	Vertical cabinets with unqualified cable, fire limited to one cable bundle	85	200
4	Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	220	440
5	Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	220	950
6	Pumps (electrical fires)	65	200
7	Motors	30	65
8	Transient Combustibles	135	300

Fire Severity
Heat Release Rate Distributions

Lets focus on one of these cases:

Case	Ignition Source	HRR (Btu/s)	
		75th	98th
1	Vertical cabinets with qualified cable, fire limited to one cable bundle	65	200
2	Vertical cabinets with qualified cable, fire in more than one cable bundle	200	665
3	Vertical cabinets with unqualified cable, fire limited to one cable bundle	85	200
4	Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors	220	440
5	Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors	220	950
6	Pumps (electrical fires)	65	200
7	Motors	30	65
8	Transient Combustibles	135	300

Fire Severity
Heat Release Rate Distribution - Example

Table E-1
HRR Distribution for Vertical Cabinets with Qualified Cables, Fire Limited to One Cable Bundle

Bin	Heat Release Rate (Btu/s)			Severity Factor (P_i)
	Lower	Upper	Point Value	
1	0	25	10.5	0.446
2	25	50	36	0.219
3	50	75	61	0.129
4	75	100	87	0.078
5	100	125	112	0.048
6	125	150	137	0.030
7	150	175	162	0.019
8	175	200	187	0.012
9	200	225	212	0.007
10	225	250	237	0.005
11	250	275	262	0.003
12	275	300	287	0.002
13	300	325	312	0.001
14	325	350	337	0.001
15	350	Infinity	405	0.001

This is the corresponding distribution binning table as presented in the original report which all contain an error

The 98th percentile value should be the largest fire postulated

Fire Severity
Heat Release Rate Distribution - Example

Table E-1 - MODIFIED

HRR Distribution for Vertical Cabinets with Qualified Cables, Fire Limited to One Cable Bundle

Bin	Heat Release Rate (Btu/s)			Severity Factor (P_i)
	Lower	Upper	Point Value	
1	0	25	10.5	0.446
2	25	50	36	0.219
3	50	75	61	0.129
4	75	100	87	0.078
5	100	125	112	0.048
6	125	150	137	0.030
7	150	175	162	0.019
8	175	200	187	0.012
9	200	Infinity	200	0.020

This is the same table modified to reflect 98th percentile value as largest bin (2% of fires)

Document, document, document…

Fire Severity
Severity Factor for General Pump Oil Fires

- Oil fire severities for general pumps are established from the following steps (per ML12171A583)

1. Determine the amount of oil that can be spilled in the room.
   - Determine the amount of oil available in the system for the large and very large oil spill fires. The pump oil fire plant-wide fire frequency remains unchanged.
2. Assign fire severity factors (split fractions) as follows:
   - Assign a severity factor of 0.05 (5%) to *very large fires: scenarios involving 100% of* the total oil inventory spilled and ignited.
   - Assign a severity factor of 0.07 (7%) to *large fires: scenarios involving 10% of the* total oil inventory spilled and ignited.
   - Assign a severity factor of 0.88 (88%) for *small fires: scenarios involving a leak that leads* to a fire that only impacts the pump.

FAQ 08-0044: MFW pump fires

- FAQ questioned application of pump fire guidance to MFW pumps
  - Spill of very large oil volume led to unrealistic (high) frequency for very large oil fires
- Solution provides a new approach for MFW pumps:
  - Determine the amount of oil available in the system for the large and very large oil spill fires. The MFW pump oil fire plant-wide fire frequency remains unchanged.
  - Assign a severity factor of 0.0034 (0.34%) to *very large fires: scenarios involving 100% of* the total oil inventory spilled and ignited.
  - Assign a severity factor of 0.0306 (3.06%) to *large fires: scenarios involving 10% of the* total oil inventory spilled and ignited.
  - Assign a severity factor of 0.966 (96.6%) for *small fires: scenarios involving a leak that leads* to a fire that only impacts the MFW pump.

  - Reference:
    - EPRI 1019259, Supplement 1 to NUREG/CR-6850

FAQ 14-009: Well Sealed MCCs

- The scope of this FAQ is limited to well-sealed, robustly-secured MCCs operating at 440V or greater, and does not apply to other electrical cabinets, notably those already covered by High Energy Arcing Fault (HEAF) analysis
- Factor of 0.23 can be used to represent the fraction of fires assumed to breach a well-sealed MCC cabinet
- Factor was derived from review of fire events data in EPRI's Fire Events Database
- The FAQ includes guidance for the application of severity factors to fires that breach the integrity of a well sealed MCC

Fire Severity
Severity Factor for Other Ignition Sources

- The following notes address ignition sources not covered in the preceding discussions:
  - Cable fires:
    - Heat release rate is established using fire propagation modeling
    - Severity factor = 1.0 may be used where target damage can be ascertained
  - High-energy arcing faults:
    - Severity factor = 1.0 within zone of influence
  - Catastrophic transformer fires in the transformer yard:
    - Severity factor = 1.0 within zone of influence
  - Non-catastrophic transformer fires in the transformer yard:
    - Generally not modeled, otherwise use severity factor = 1.0 within zone of influence
  - Other fires in the transformer yard:
    - Depending on the item burning, the heat release rate of similar devices may be used.

Fire Severity
Frequency Bins and HRR Distributions

Table 11-1
Recommended Severity Factors . . . for Ignition Sources in the Frequency Model

ID	Location	Ignition Source	HRR Distribution Category
1	Battery Room	Batteries	Electric motors
2	Containment (PWR)	Reactor coolant Pump	Pumps (Electrical)/Oil spills
4a	Control Room	Electrical cabinets	Applicable electrical cabinet
4b	Control Room	Main control board	See Appendix L
5	Control/Auxiliary/ Reactor Building	Cable fires caused by welding and cutting	Assume 1.0
6	Control/Auxiliary/ Reactor Building	Transient fires caused by welding and cutting	Transients
21	Plant-Wide Components	Pumps	Pump (Electrical)/Oil spills

Fire Severity
Concluding Remarks

- Severity Factor provides an adjustment to ignition frequency to account for the severity of the fire.
  - It is tied to the heat release rate
  - It is estimated in concert with probability of non-suppression
  - Specific cases have been developed
  - Guidance is provided for other cases

Module III – Fire Analysis

Task 11: Detailed Fire Modeling, and the PRA Standard's Fire Scenario Selection and Analysis Technical Element

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

Corresponding Technical Element
…and a note on structure

- Task 11 maps to FSS – Fire Scenario Selection and Analysis
  – FSS has 8 HLRs and a total of 50 SRs
  – FSS has more SRs than any other fire technical element
- We are going to quickly go over structure of FSS technical element, and then we will get into the various elements of Task 11 in more detail

Corresponding Technical Element
…and a note on structure (cont.)

- Task 11 has 3 subtasks and there are presentations for each:
  - 11a - Single compartment analysis
  - 11b - Main control room analysis
  - 11c - Multi-compartment analysis
- We will cover the FSS HLRs just once (here)
- SRs specific to a subtask will be cited as appropriate, but…
  - While there are SRs that are subtask specific:
    - e.g., FSS-B for MCR abandonment, FSS-G for multi-compartment scenarios…
  - Some SRs will apply to all subtasks:
    - e.g., define targets, characterize source, provide basis…

Corresponding Technical Element
…and a note on structure (cont.)

- This training also covers several 6850/1011989 "special models"
  - Detailed analysis tools for specific problems (methodology)
- Recall that the standard sets high-level scope and quality metrics, but does not prescribe methodology
- The special model presentations map to SRs where a direct link does exist:
  - e.g., define failure thresholds, characterize ignition source…
- SRs other than those we cite will likely apply:
  - e.g.: basis, validation, defining input variables, uncertainty…
- Note that 6850/1011989 provides a basis for the modeling tools it presents

Technical Element FSS

- FSS Objectives (per the PRA Standard):
  - To select the fire scenarios to be analyzed
  - To characterize the selected fire scenarios
  - To determine the likelihood and extent of risk-relevant fire damage for each selected fire scenario including
    - An evaluation of the fire generated conditions at the target location including fire spread to secondary combustibles
    - An evaluation of the thermal response of damage targets to such exposure
    - An evaluation of fire detection and suppression activities
  - To examine multi-compartment fire scenarios

FSS HLRs (per the PRA Standard)

- **HLR- FSS-A:** The Fire PRA shall select one or more combinations of an ignition source and damage target sets to represent the fire scenarios for each unscreened physical analysis unit upon which estimation of the risk contribution (CDF and LERF) of the physical analysis unit will be based. (6 SRs)
- **HLR-FSS-B:** The Fire PRA shall include an analysis of potential fire scenarios leading to the MCR abandonment. (2 SRs)
- **HLR-FSS-C:** The Fire PRA shall characterize the factors that will influence the timing and extent of fire damage for each combination of an ignition source and damage target sets selected per HLR-FSS-A. (8 SRs)

FSS HLRs (per the PRA Standard)

- **HLR- FSS-D:** The Fire PRA shall quantify the likelihood of risk-relevant consequences for each combination of an ignition source and damage target sets selected per HLR-FSS-A. (11 SRs)

- **HLR-FSS-E:** The parameter estimates used in fire modeling shall be based on relevant generic industry and plant-specific information. Where feasible, generic and plant-specific evidence shall be integrated using acceptable methods to obtain plant-specific parameter estimates. Each parameter estimate shall be accompanied by a characterization of the uncertainty. (4 SRs)

FSS HLRs (per the PRA Standard)

- **HLR- FSS-F**: The Fire PRA shall search for and analyze risk-relevant scenarios with the potential for causing fire-induced failure of exposed structural steel. (3 SRs)
- **HLR-FSS-G**: The Fire PRA shall evaluate the risk contribution of multi-compartment fire scenarios. (6 SRs)
- **HLR-FSS-H**: The Fire PRA shall document the results of the fire scenario and fire modeling analyses including supporting information for scenario selection, underlying assumptions, scenario descriptions, and the conclusions of the quantitative analysis, in a manner that facilitates Fire PRA applications, upgrades, and peer review. (10 SRs)

Mapping HLRs & SRs for the FSS Technical Element to NUREG/CR-6850, EPRI 1011989

Technical Element	HLR	SR	6850 Sections	Comments
FSS	A	The Fire PRA shall select one or more combinations of an ignition source and damage target sets to represent the fire scenarios for each unscreened physical analysis unit upon which estimation of the risk contribution (CDF and LERF) of the physical analysis unit will be based.		
		1	11.3.3, 11.5.1.3, 11.5.2.6	
		2	11.3.2, 11.5.1.5, 11.5.2.5	
		3	11.5.1.5	These sections of 6850/1011989 imply the requirements of these SRs.
		4	11.3.2, 11.5.1.5	
		5	11.5.1.6, 11.5.2.7	
		6	11.5.2.7	
	B	The Fire PRA shall include an analysis of potential fire scenarios leading to the MCR abandonment.		
		1	11.5.2.11	
		2	11.5.2.11, 11.5.3	

Mapping HLRs & SRs (continued)

Technical Element	HLR	SR	6850 Sections	Comments
FSS	C	The Fire PRA shall characterize the factors that will influence the timing and extent of fire damage for each combination of an ignition source and damage target sets selected per HLR-FSS-A.		
		1	8.5.1, 11.3.3, 11.3.4, 11.5.1.3	Section 8 of 6850/1011989 partly address the requirements of this SR
		2	8.5.1, 11.3.3, 11.3.4, 11.5.1.3	
		3	11.3.3, 11.3.4, 11.5.1.3	These sections of 6850/1011989 imply the requirements of this SR.
		4	11.5.1.9, Appendices E and G	Section 11.3 of 6850/1011989 directs the reader to these Appendices where discussions relevant to the requirements of this SR are provided.
		5	8.5.1.2, Appendix H	
		6	11.5.1.7.6, Appendix H	
		7	n/a	Appendix P of 6850/1011989 implies the requirements of this SR but does not explicitly address it.
		8	11.5.1.7.3, Appendices M and Q	Referenced section and appendices of 6850/1011989 do not fully address the requirements of this SR.

Mapping HLRs & SRs (continued)

Technical Element	HLR	SR	6850 Sections	Comments
FSS	D	The Fire PRA shall quantify the likelihood of risk-relevant consequences for each combination of an ignition source and damage target sets selected per HLR-FSS-A.		
		1	11.5.1.7.1	
		2	11.5.1.7.1	
		3	11.5.1.7.1	Several other sections and appendices of 6850/1011989 collectively address the requirements of this SR.
		4	11.5.1.7.1, Appendices E, F, G, H, M, N, O, R, S	
		5	Appendices E, G, P	
		6	11.5.1.7.1, Appendices H, M, N, O, P	
		7	11.5.1.8, Appendix P	
		8	11.5.1.8, Appendix P	
		9	11.5.1.5, 11.5.1.7.1, Appendix T	
		10	8.5.2, 11.4.3	Referenced sections of 6850/1011989 imply the requirements of this SR.
		11	8.5.2, 11.4.3	

Mapping HLRs & SRs (continued)

<table>
<tr><th>Technical Element</th><th>HLR</th><th>SR</th><th>6850 Sections</th><th>Comments</th></tr>
<tr><td rowspan="9">FSS</td><td rowspan="5">E</td><td colspan="3">The parameter estimates used in fire modeling shall be based on relevant generic industry and plant-specific information. Where feasible, generic and plant-specific evidence shall be integrated using acceptable methods to obtain plant-specific parameter estimates. Each parameter estimate shall be accompanied by a characterization of the uncertainty.</td></tr>
<tr><td>1</td><td rowspan="2">11.3, 11.5.1, Appendices G, H, L, N, O, R, and S</td><td rowspan="2">6850/1011989 does not discuss plant-specific fire modeling parameters. However, the discussions in the referenced sections and appendices imply the requirements of this SR.</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td><td>11.3, 11.5.1, Appendices E, G and P</td><td></td></tr>
<tr><td>4</td><td>n/a</td><td>The requirement in this SR is not explicitly addressed in 6850/1011989</td></tr>
<tr><td rowspan="4">F</td><td colspan="3">The Fire PRA shall search for and analyze risk-relevant scenarios with the potential for causing fire-induced failure of exposed structural steel.</td></tr>
<tr><td>1</td><td>n/a</td><td rowspan="3">Failure of exposed structural steel from fire impact is not explicitly discussed in 6850/1011989. Appendix Q addresses passive fire protection features but does not address exposed structural steel.</td></tr>
<tr><td>2</td><td>n/a</td></tr>
<tr><td>3</td><td>n/a</td></tr>
</table>

Mapping HLRs & SRs (continued)

Technical Element	HLR	SR	6850 Sections	Comments
FSS	G	The Fire PRA shall evaluate the risk contribution of multicompartment fire scenarios.		
		1	11.5.4.6	
		2	11.5.4	
		3	11.5.4	
		4	11.5.4.4	
		5	11.5.4.4	
		6	11.5.4.5, 11.5.4.6	
	H	The Fire PRA shall document the results of the fire scenario and fire modeling analyses including supporting information for scenario selection, underlying assumptions, scenario descriptions, and the conclusions of the quantitative analysis, in a manner that facilitates Fire PRA applications, upgrades, and peer review.		
		1	n/a	Documenting the analysis and the results is discussed in Chapter 16 and in several parts of Chapter 11 of 6850/1011989. The specific requirements of these SRs is generally not explicitly addressed.
		2	n/a	
		3	n/a	
		4	n/a	
		5	n/a	
		6	n/a	
		7	n/a	
		8	n/a	
		9	n/a	
		10	n/a	

Module III – Fire Analysis

Task 11a: Detailed Fire Modeling and Single Compartment Scenarios

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

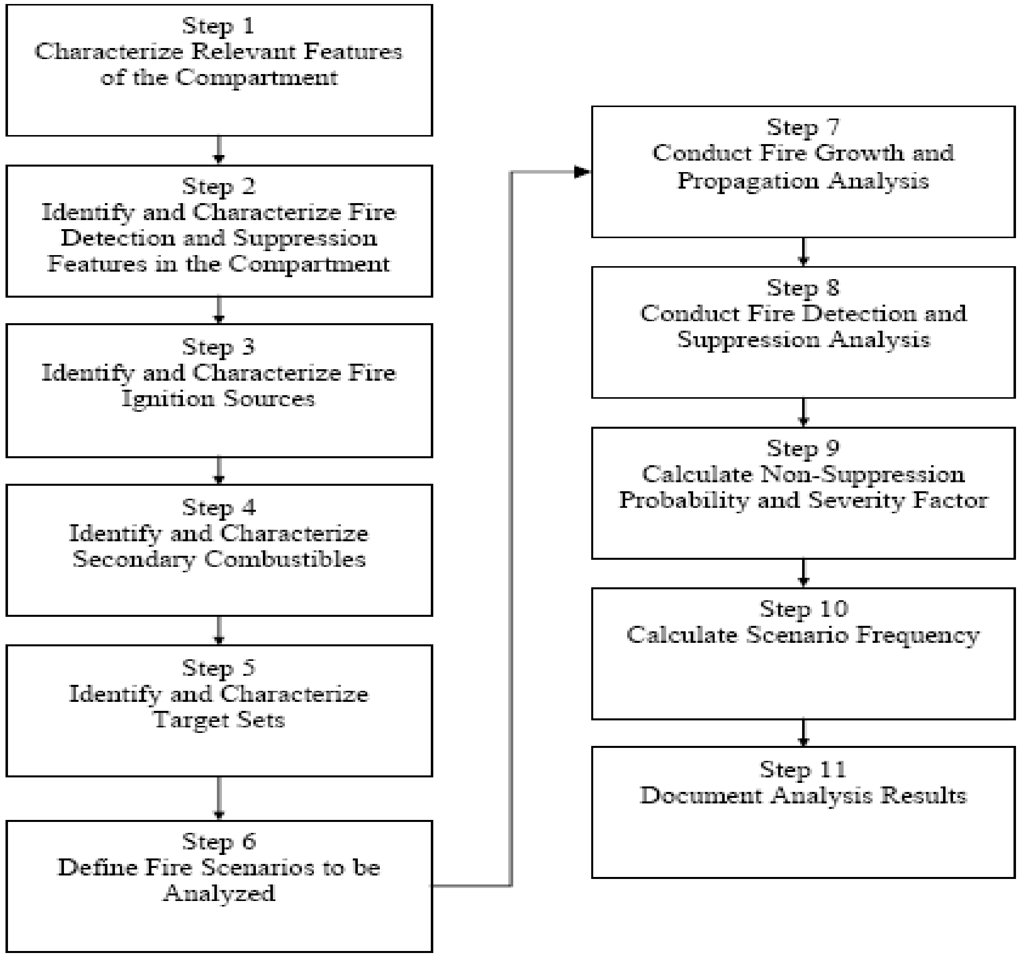
Objectives

- Describe the process of fire modeling for a single fire compartment
- The outcome of this activity is the extent and timing of fire damage within the compartment

Module III: Fire Modeling
Role and Scope

- **Fire modeling:** An approach for predicting various aspects of fire generated conditions
  - Requires idealization and/or simplifications of the physical processes involved
  - Departure of the fire system from this idealization can affect the accuracy and validity
- **Fire scenario:** A set of elements representing a fire event
  - Fire source/initiation
  - Fire growth
  - Fire propagation (room heating, HEAF, intervening combustibles, etc.)
  - Active fire protection features, e.g., detection/suppression
  - Passive fire protection features, e.g., fire stops
  - Target sets (cables), habitability, etc.

Module III: Process
General Task Structure



Module III: Process
Characterize Fire Compartment

- Information on compartment geometry that can impact fire growth
  - Size and shape, e.g., ceiling soffit or beam pocket
  - Boundary construction and material
  - Ventilation
- Fire protection systems and features
  - Fixed detection systems
  - Fixed fire suppression systems, water or gaseous
  - Manual detection
  - Fire brigade
  - Internal fire barriers and stops, e.g., ERFBS

Module III: Process
Identify/Characterize Ignition Sources

- Location within the compartment, type, size, initial intensity, growth behavior, severity/likelihood relationship, etc.
- Estimate frequency of ignition for the ignition source.
- Example of fire events involving typical ignition sources
  - Oil or liquid spill fires (Characterization described in Appendix G)
  - Oil or flammable liquid spray fires (Characterization described in Appendix G)
  - General fires involving electrical panels (Characterization described in Appendices G, L & S)
  - High energy arcing faults events (Characterization described in Appendix M)
  - Cable fires (Characterization described in Appendix R)
  - Hydrogen fires (Characterization described in Appendix N)
  - Transient fuel materials (Characterization described in Appendices G & S)
- Corresponding PRA Standard SR: FSS-A1, FSS-C1 through C4

Module III: Process
Identify/Characterize Secondary (Intervening) Combustibles

- May include,
  - Overhead raceways,
  - Cable air-drops,
  - Stored materials,
  - Electrical panels,
  - Construction materials, etc.

- The information provided should describe:
  - Relative proximity of the secondary combustibles to the fire ignition source
  - Configuration of the secondary combustible

Module III: Process
Identify/Characterize Target Sets

- Each target set should be a subset of the fire PRA components and circuits (i.e., cables) present in the compartment
  - Target sets associated to PRA components can be identified by examining the associated CCDP, once damaged component failure probabilities are set to 1.0
  - Those subgroups with very small CCDP may be ignored as insignificant contributors to fire risk
  - Check for possibility of spurious actuations due to cable fires inside the compartment under analysis. Spurious actuations may generate the need of evaluating important scenarios
- Fire modeling should have information on target location within the compartment available
  - If complete routing information is not available, the analyst must justify target selection process and the corresponding impacts in the Fire PRA model
  - Routing by exclusion OK (from a compartment, from a set of raceways…)
- Identify failure modes of equipment due to fire damage to the equipment or associated circuits

Corresponding PRA Standard SR: FSS-A2 through A4

Module III: Process
Select Fire Scenarios

- Fire scenarios should take the following into consideration:
  - Selected scenarios should reflect the objective of fire modeling, in this case impacting the components and circuits of interest to safety (targets)
  - Selected scenarios should represent a complete set of fire conditions that are important to the objective
  - Selected scenarios should challenge the conditions being estimated, e.g., scenarios that challenge habitability if manual action is of interest
  - The list of postulated fire scenarios should include those involving fixed and transient ignition sources
- Corresponding PRA Standard SR: FSS-A5

Module III: Process
Select Fire Scenarios (cont'd)

- Approach to selection of fire scenarios is highly dependent on fire compartment hazard profile, i.e., location and amount of fire sources and combustibles and the location and number of potential targets. In general,
  - In compartments with few fire sources and many target sets (e.g., a switchgear room), start with an ignition source, postulate potential growth and propagation to other combustibles and then postulate damage to the closest target set that may be exposed to the specific fire
  - In compartments with many fire sources and few potential targets (e.g., a PWR turbine building), start with potential target sets
  - In compartments with many fire sources and many potential targets (e.g., a PWR auxiliary building),
    - Nearby source/target combinations, and
    - Always include that fire scenario most likely (all factors considered) to cause wide-spread damage (may be driven by fire source characteristics, fire spread potential, or by fire protection systems and features)

Module III: Process
Conduct Fire Growth and Propagation

- Select fire modeling tool depending on the characteristics of each scenario
  - Empirical rule sets
  - Hand calculations
  - Zone models
  - Field models
- Analyze fire growth and spread to secondary combustibles
- Estimate resulting environmental conditions
- Estimate time to target set damage
- Corresponding PRA Standard SRs: FSS-C6, D1 through D6

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

Fire Modeling 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 arcing fault fires
  - Fire suppression
  - Hydrogen or liquid spray fires

The Fire Modeling Process (NUREG-1934/EPRI 1023259)

Fire Modeling Process:

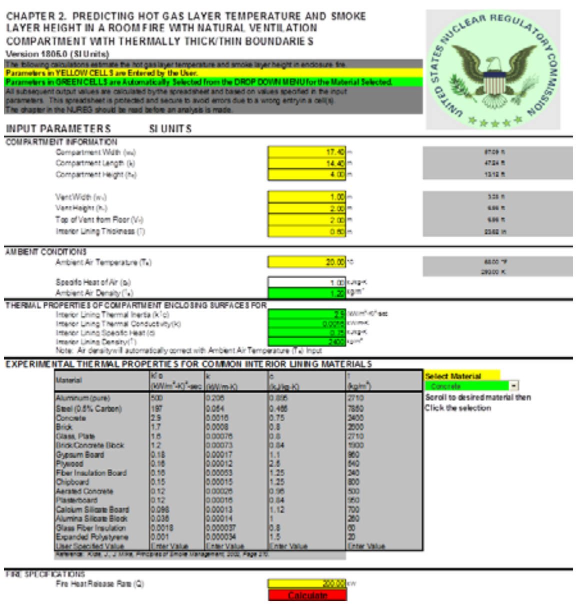
1) Define goals and objectives
2) Characterize the fire scenarios
3) Select fire models
4) Calculate fire-generated conditions
5) Conduct sensitivity and uncertainty analyses
6) Document the analysis

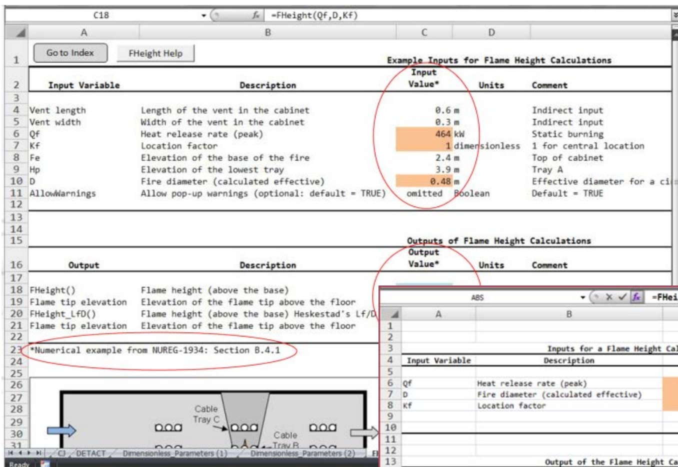
Fire Models

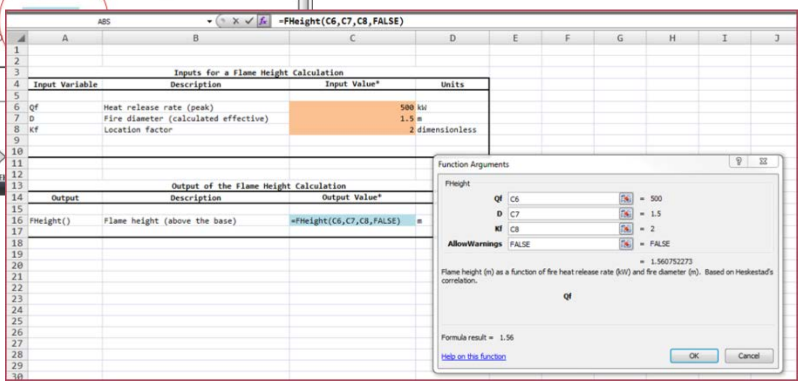
- **Hand calculations**: Mathematical expressions that can be solved by hand with a relatively small computational effort
  - Quasi steady conditions
  - Usually semi-empirical correlations developed with data from experiments
- **Zone models**: Algorithms that solve conservation equations for energy 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







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Example of Hand Calcs: FDT^s

- **FDT^s** 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 FDT^s was to be a training tool to teach NRC Fire Protection Inspectors
- The secondary goal of FDT^s was to be used in plant inspections and support other programs that required Fire Dynamics knowledge such as SDP and NFPA 805

Module III: Process
Hand Calcs – NUREG-1805

02.1_Temperature_NV.xls
02.2_Temperature_FV.xls
02.3_Temperature_CC.xls
03_HRR_Flame_Height_Burning_Duration_Calculation.xls
04_Flame_Height_Calculations.xls
05.1_Heat_Flux_Calculations_Wind_Free.xls
05.2_Heat_Flux_Calculations_Wind.xls
05.3_Thermal_Radiation_From_Hydrocarbon_Fireballs.xls
06_Ignition_Time_Calculations.xls
07_Cable_HRR_Calculations.xls
08_Burning_Duration_Soild.xls
09_Plume_Temperature_Calculations.xls

09_Plume_Temperature_Calculations.xls
10_Detector_Activation_Time.xls
13_Compartment_ Flashover_Calculations.xls
14_Compartment_Over_Pressure_Calculations.xls
15_Explosion_Claculations.xls
16_Battery_Room_Flammable_Gas_Conc.xls
17.1_FR_Beams_Columns_Substitution_Correlation.xls
17.2_FR_Beams_Columns_Quasi_Steady_State_Spray_Insulated.xls
17.3_FR_Beams_Columns_Quasi_Steady_State_Board_Insulated.xls
17.4_FR_Beams_Columns_Quasi_Steady_State_Uninsulated.xls
18_Visibility_Through_Smoke.xls

Module III: Process
Hand Calcs – NUREG-1805

CHAPTER 2. PREDICTING HOT GAS LAYER TEMPERATURE AND SMOKE LAYER HEIGHT IN A ROOM FIRE WITH NATURAL VENTILATION COMPARTMENT WITH THERMALLY THICK/THIN BOUNDARIES

Version 1805.0 (SI Units)

The following calculations estimate the hot gas layer temperature and smoke layer height in enclosure fire.
Parameters in YELLOW CELLS are Entered by the User.
Parameters in GREEN CELLS are Automatically Selected from the DROP DOWN MENU for the Material Selected.
All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).
The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS SI UNITS

COMPARTMENT INFORMATION

Compartment Width (w_c)	17.40	m	57.09 ft
Compartment Length (l_c)	14.40	m	47.24 ft
Compartment Height (h_c)	4.00	m	13.12 ft
Vent Width (w_v)	1.00	m	3.28 ft
Vent Height (h_v)	2.00	m	6.56 ft
Top of Vent from Floor (V_T)	2.00	m	6.56 ft
Interior Lining Thickness (δ)	0.60	m	23.62 in

AMBIENT CONDITIONS

Ambient Air Temperature (T_a)	20.00	°C	68.00 °F 293.00 K
Specific Heat of Air (c_p)	1.00	kJ/kg-K	
Ambient Air Density (ρ_a)	1.20	kg/m³	

THERMAL PROPERTIES OF COMPARTMENT ENCLOSING SURFACES FOR

Interior Lining Thermal Inertia ($k\rho c$)	2.9	$(kW/m^2\text{-}K)^2$-sec
Interior Lining Thermal Conductivity (k)	0.0016	kW/m-K
Interior Lining Specific Heat (c)	0.75	kJ/kg-K
Interior Lining Density (ρ)	2400	kg/m^3

Note: Air density will automatically correct with Ambient Air Temperature (T_a) Input

EXPERIMENTAL THERMAL PROPERTIES FOR COMMON INTERIOR LINING MATERIALS

Material	$k\rho c$ $(kW/m^2\text{-}K)^2$-sec	k (kW/m-K)	c (kJ/kg-K)	ρ (kg/m^3)
Aluminum (pure)	500	0.206	0.895	2710
Steel (0.5% Carbon)	197	0.054	0.465	7850
Concrete	2.9	0.0016	0.75	2400
Brick	1.7	0.0008	0.8	2600
Glass, Plate	1.6	0.00076	0.8	2710
Brick/Concrete Block	1.2	0.00073	0.84	1900
Gypsum Board	0.18	0.00017	1.1	960
Plywood	0.16	0.00012	2.5	540
Fiber Insulation Board	0.16	0.00053	1.25	240
Chipboard	0.15	0.00015	1.25	800
Aerated Concrete	0.12	0.00026	0.96	500
Plasterboard	0.12	0.00016	0.84	950
Calcium Silicate Board	0.098	0.00013	1.12	700
Alumina Silicate Block	0.036	0.00014	1	260
Glass Fiber Insulation	0.0018	0.000037	0.8	60
Expanded Polystyrene	0.001	0.000034	1.5	20
User Specified Value	Enter Value	Enter Value	Enter Value	Enter Value

Reference: Klote, J., J. Milke, Principles of Smoke Management, 2002, Page 270.

Select Material

Concrete

Scroll to desired material then Click the selection

FIRE SPECIFICATIONS

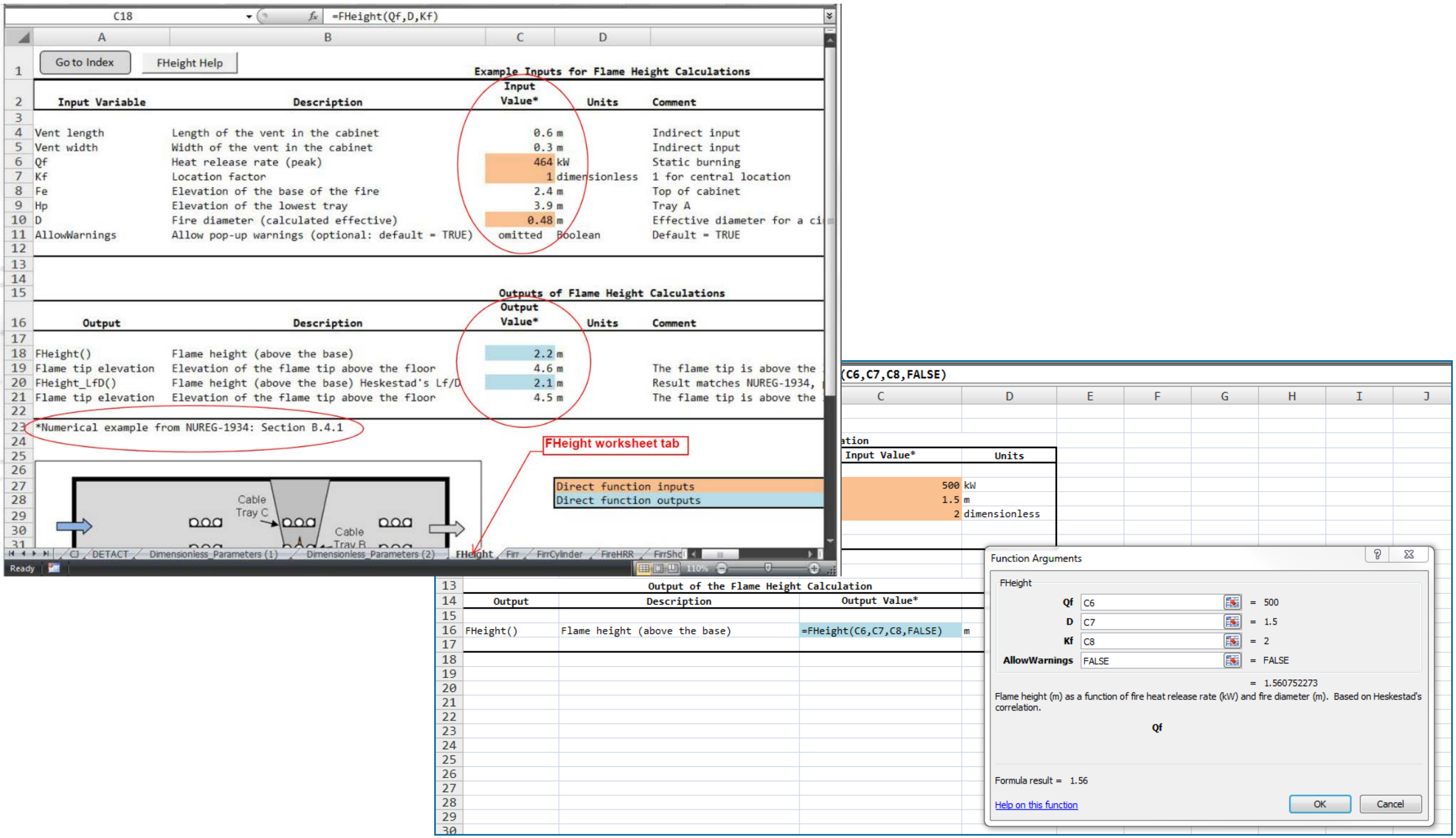
Fire Heat Release Rate (Q)	200.00	kW

Calculate

Module III: Process
Hand Calcs – FIVE-Rev2

- EPRI version of the fire modeling equations
  - Very similar to NRC FDT^s
- EPRI 3002000830, published in 2014
  - Spreadsheet based
  - Programmed in VBA
- Contains most of the hand calculations in the original EPRI publication and some other models available in the fire protection engineering literature
  - 4 stage heat release rate profile based on t^2 growth
  - Heskestad's flame height model
  - A radiation model from a cylindrical flame to targets
  - Models for velocity of plume and ceiling jet flows
  - Model for plume diameter as a function of height
  - MQH model for room temperature
  - Model for visibility through smoke

Module III: Process
Hand Calcs – FIVE-Rev2



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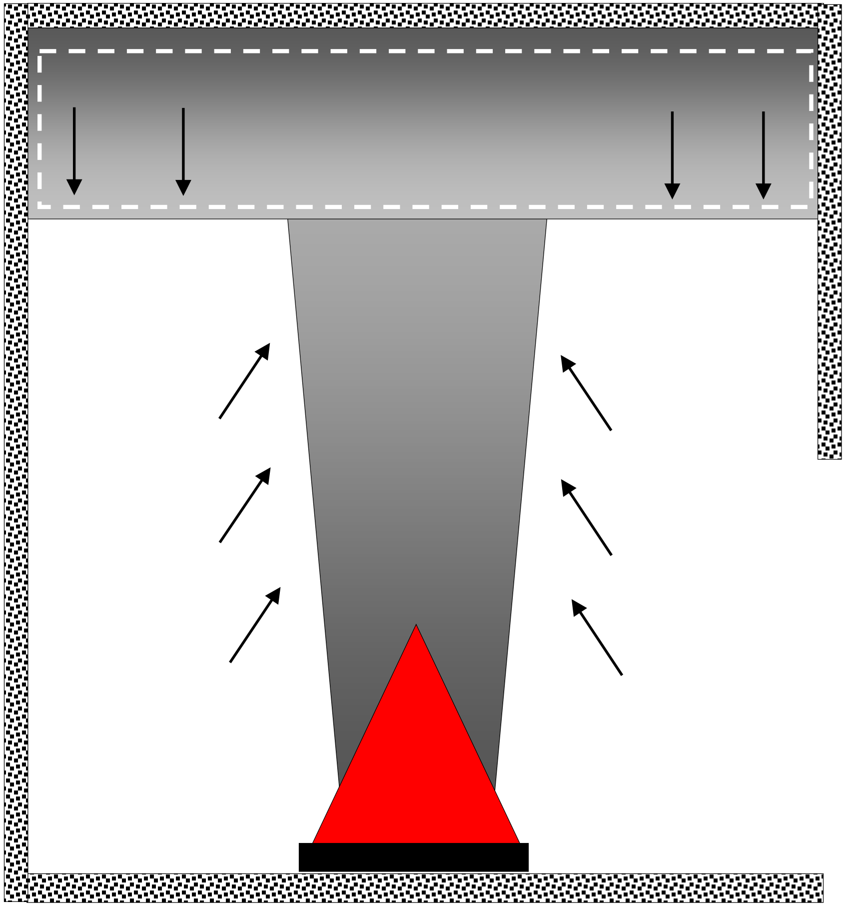
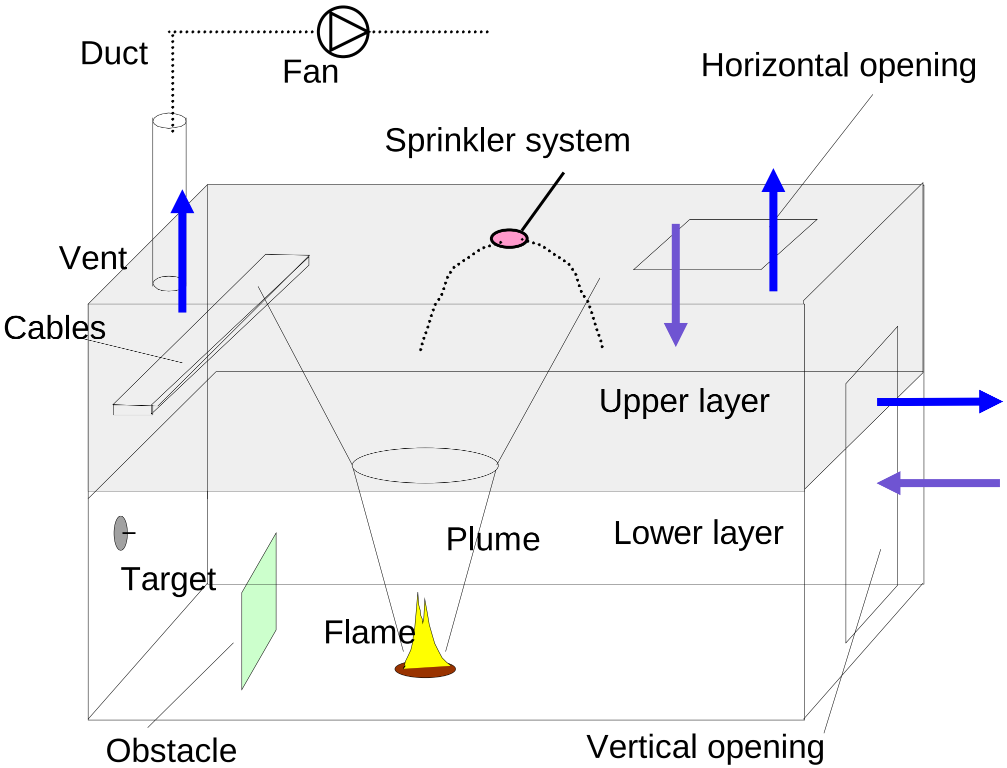
Zone Models

- Two zones
  - Upper hot gas layer
  - 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

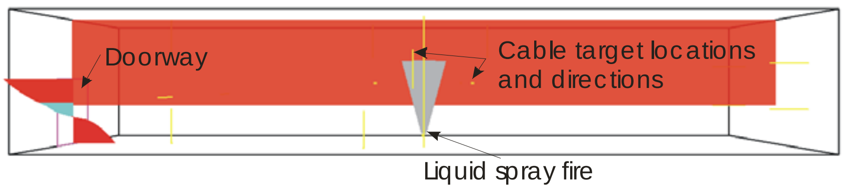


Example of a Zone Model: MAGIC

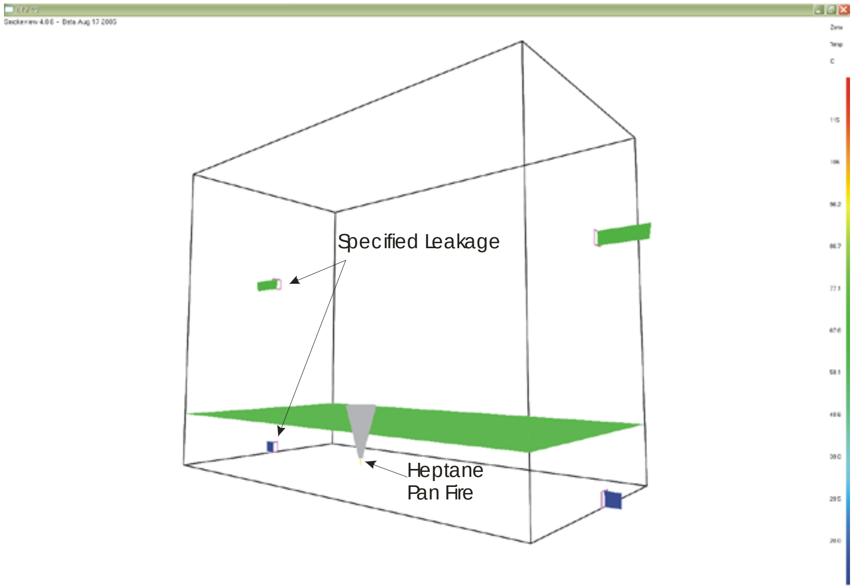


- **Gaseous phase combustion, governed by pyrolysis rate and oxygen availability**
- **Heat transfer between flame, gases and smoke, walls and surrounding air, thermal conduction in multi-layer walls, obstacles to radiation**
- **Mass flow transfer: Fire-plumes, ceiling-jet, openings and vents**
- **Thermal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

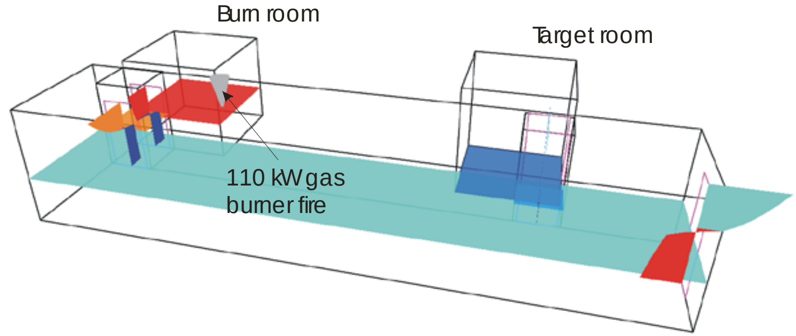
CFAST



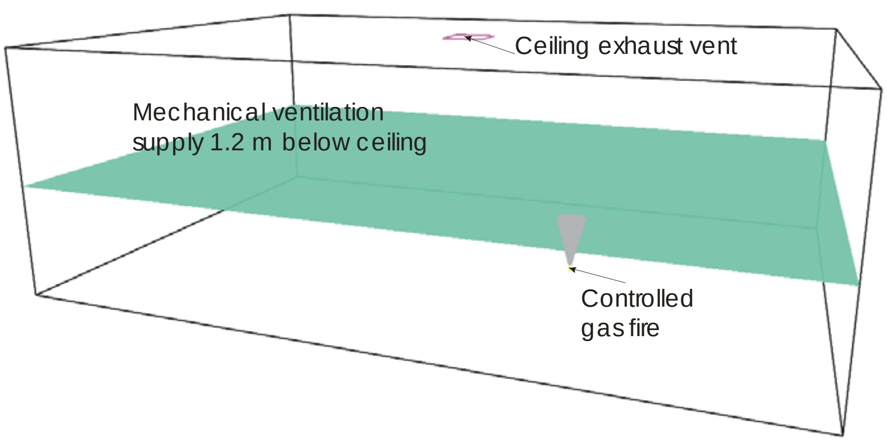
Doorway
Cable target locations
and directions
Liquid spray fire



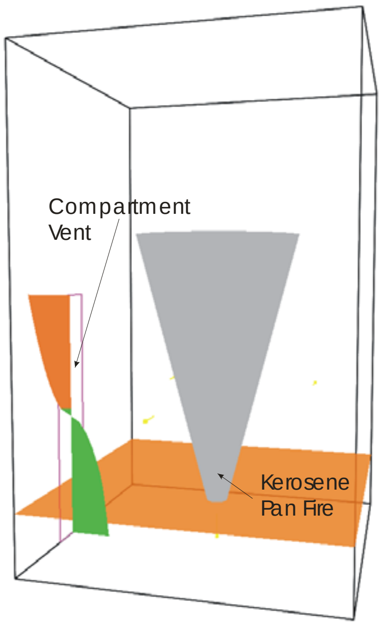
Specified Leakage
Heptane
Pan Fire



Burn room
Target room
110 kW gas
burner fire

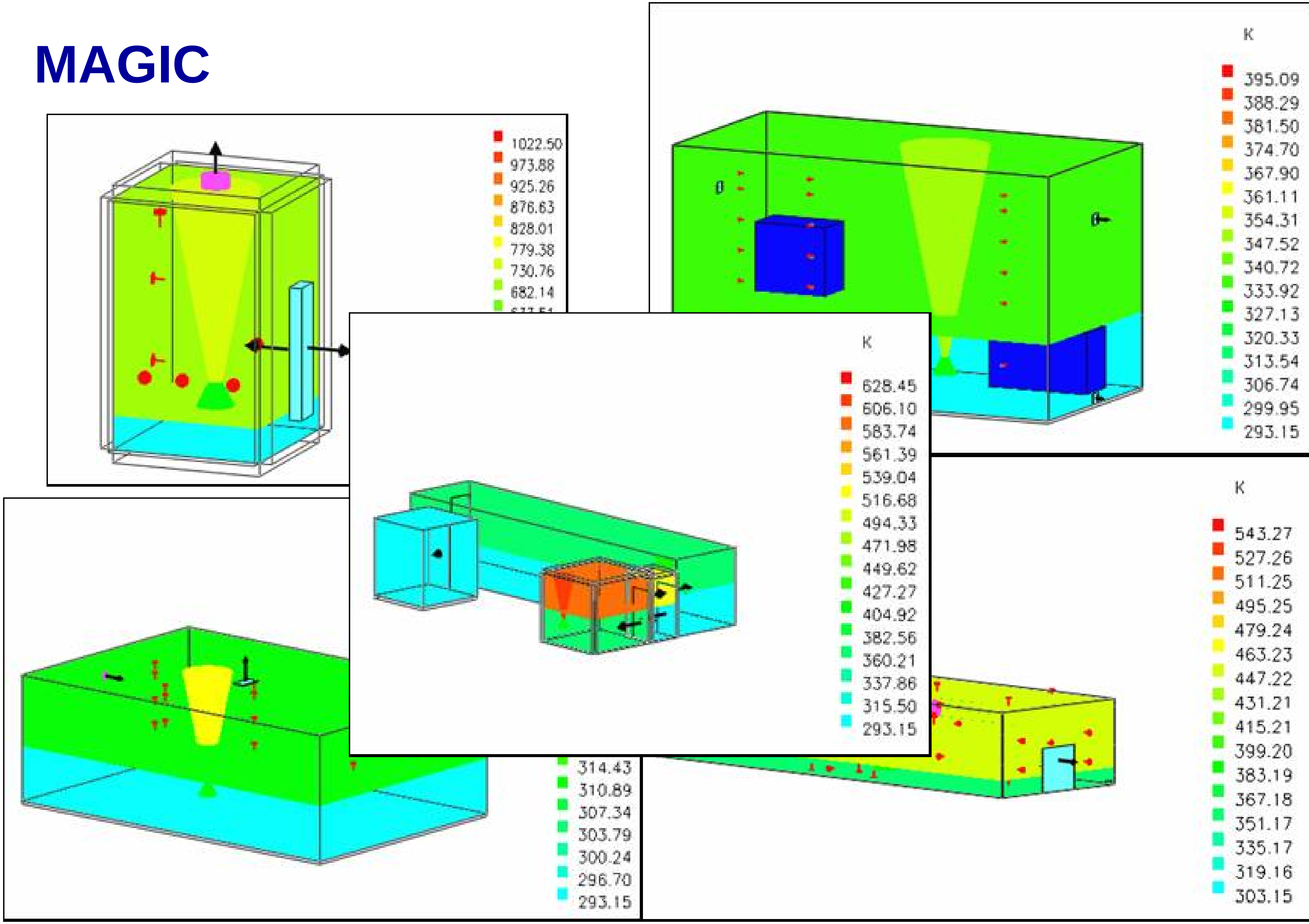


Ceiling exhaust vent
Mechanical ventilation
supply 1.2 m below ceiling
Controlled
gas fire



Compartment
Vent
Kerosene
Pan Fire

MAGIC


1022.50
973.88
925.26
876.63
828.01
779.38
730.76
682.14
K
395.09
388.29
381.50
374.70
367.90
361.11
354.31
347.52
340.72
333.92
327.13
320.33
313.54
306.74
299.95
293.15
K
628.45
606.10
583.74
561.39
539.04
516.68
494.33
471.98
449.62
427.27
404.92
382.56
360.21
337.86
315.50
293.15
314.43
310.89
307.34
303.79
300.24
296.70
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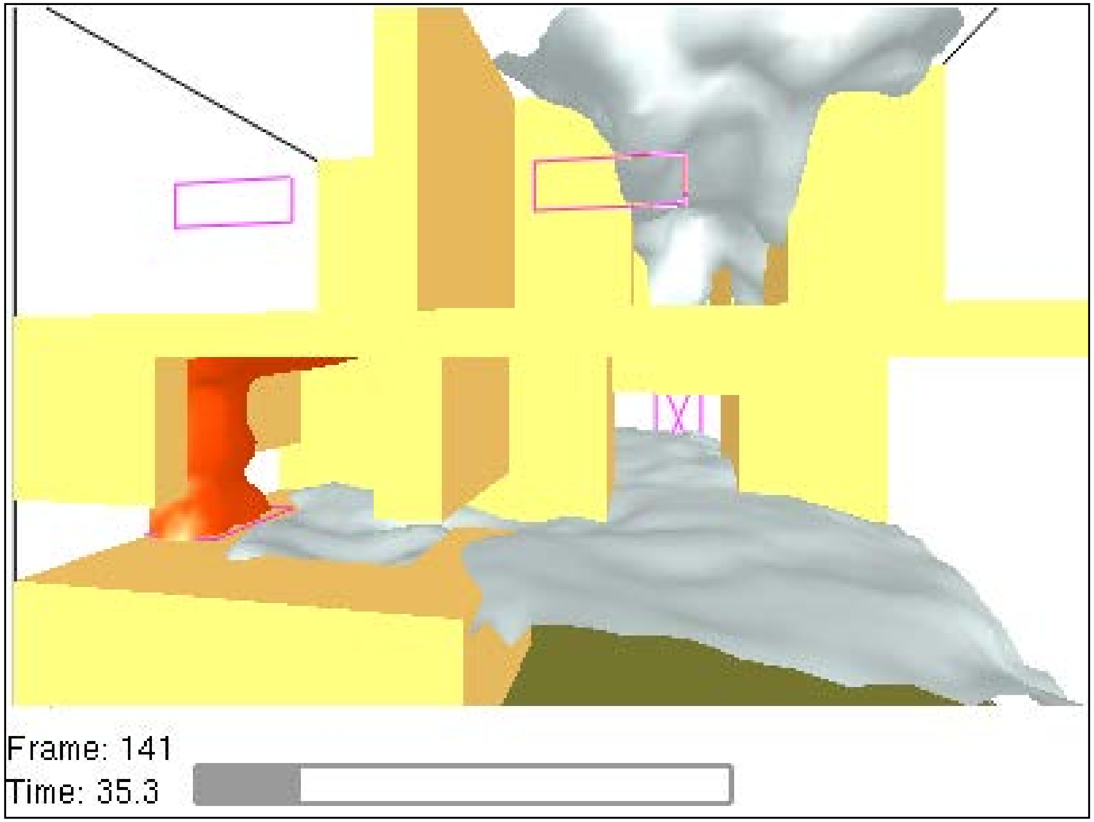
K
543.27
527.26
511.25
495.25
479.24
463.23
447.22
431.21
415.21
399.20
383.19
367.18
351.17
335.17
319.16
303.15

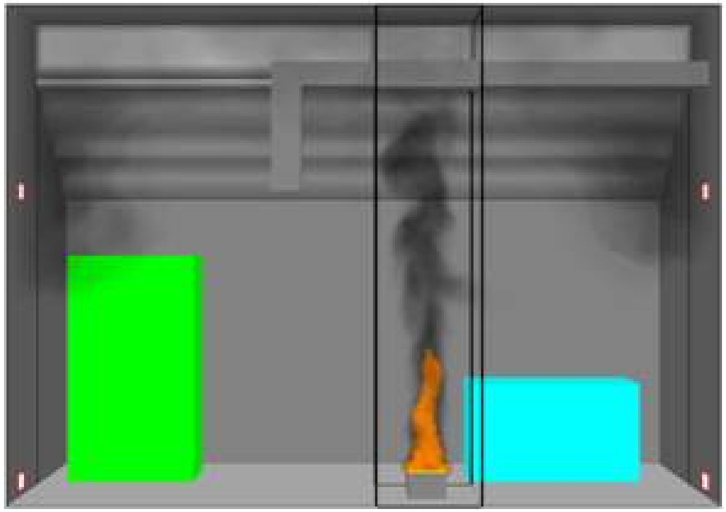
Field Models

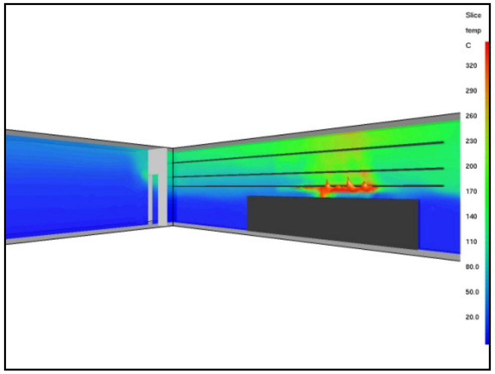
- Solve a simplified form of the Navier Stokes equations for low velocity flows
- Calculation time in the order of hours, days or weeks
- May help in modeling complex geometries

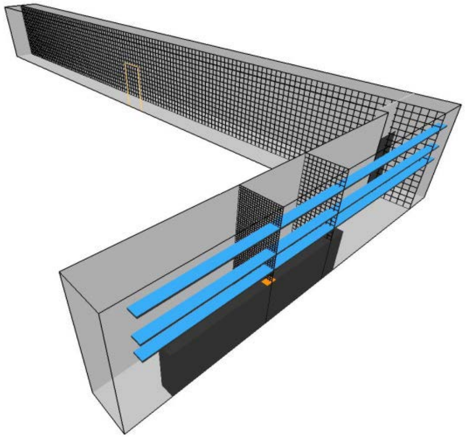


Example of Field Model: FDS

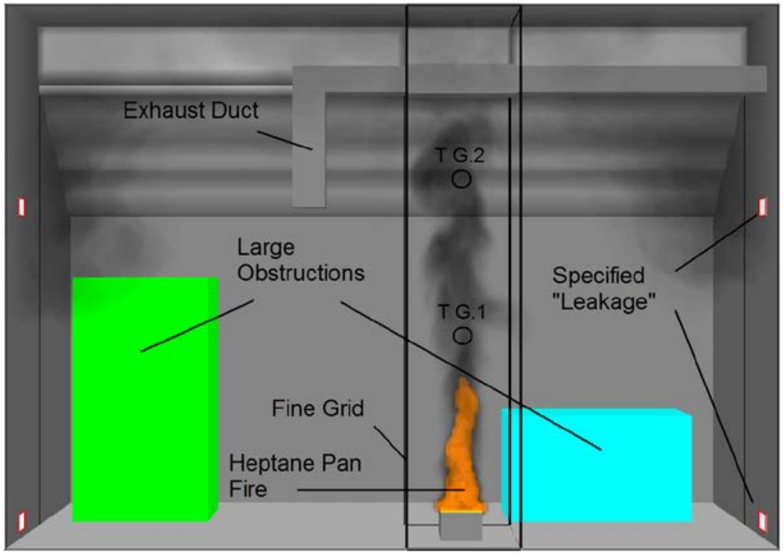
- Fire Dynamics Simulator
- Developed and maintained by NIST

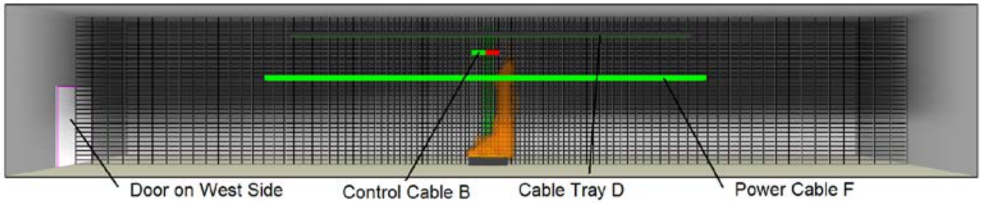


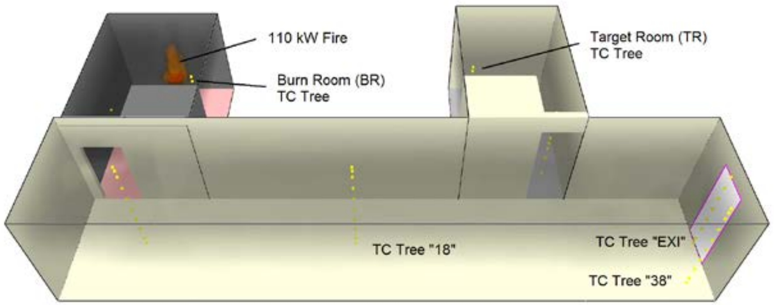


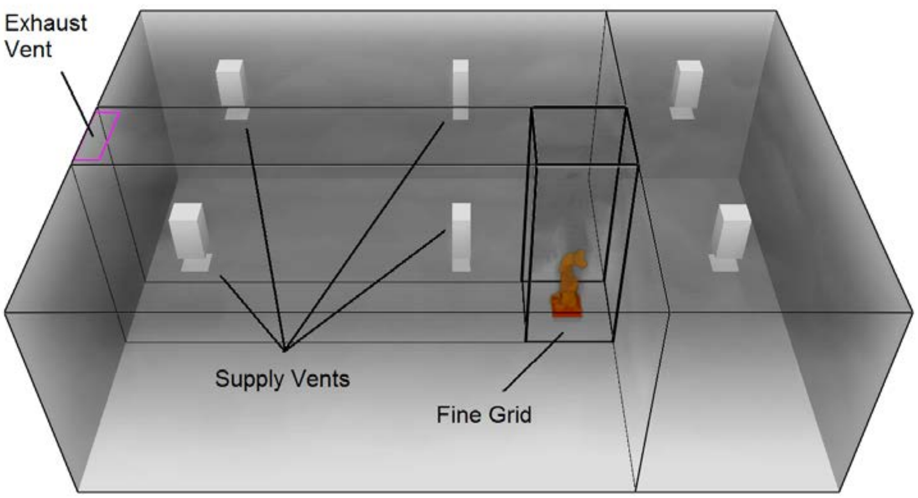


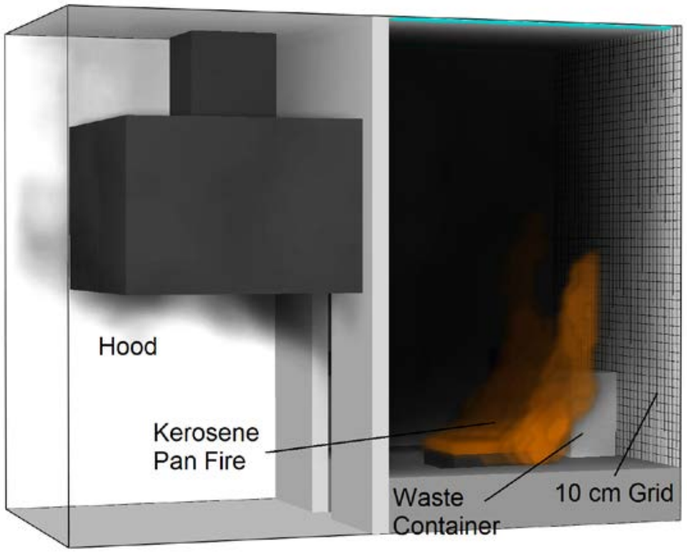
Fire Dynamics Simulator (FDS)











Which Model to Choose?

- NUREG-1934 (EPRI 1023259)
- 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 (NUREG-1824/EPRI 1011999)

- ***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 (EPRI 1011999) and Supplement 1 to NUREG-1824 (EPRI 3002002182)*

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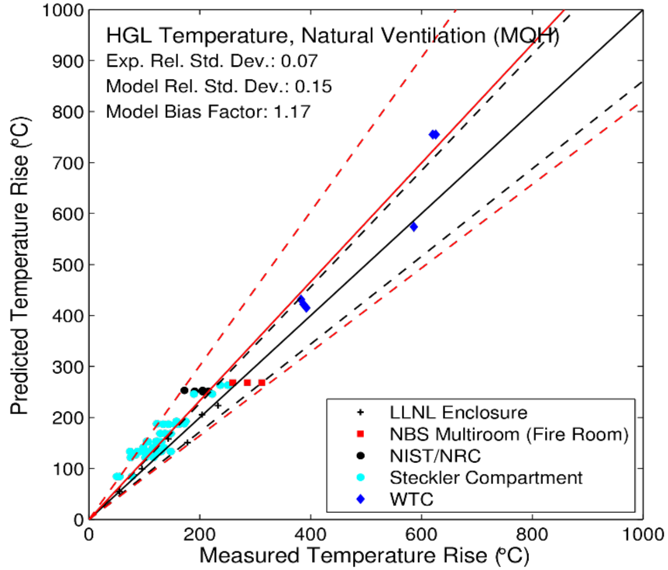
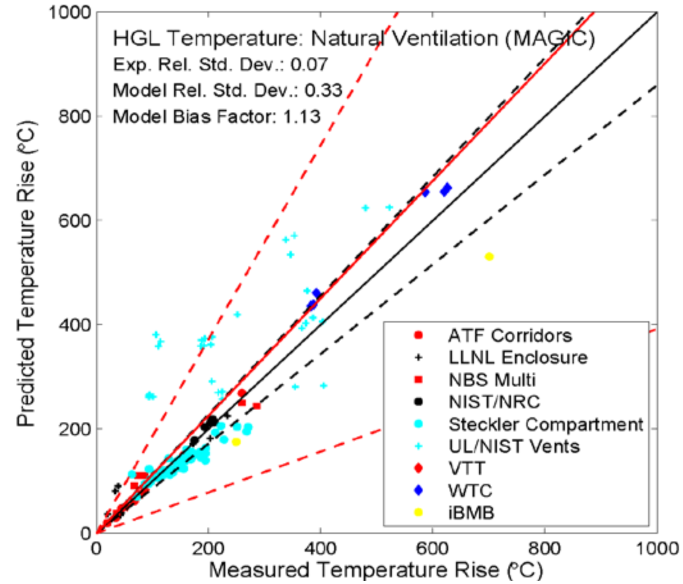
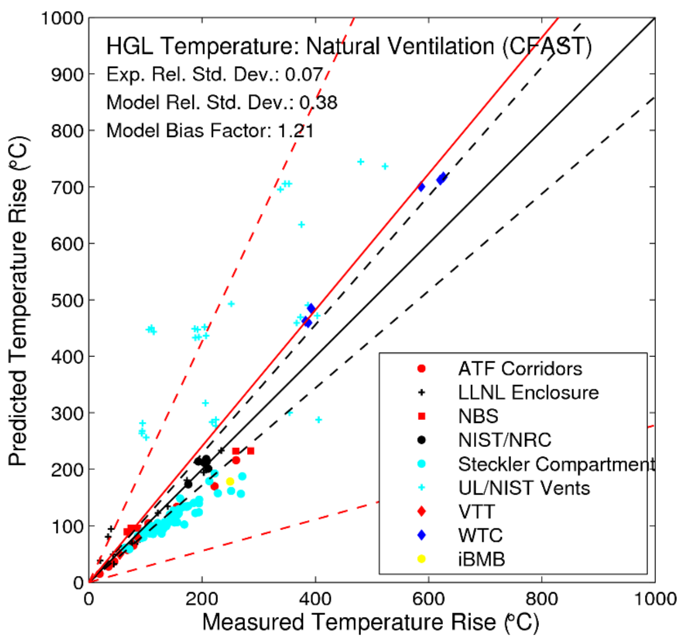
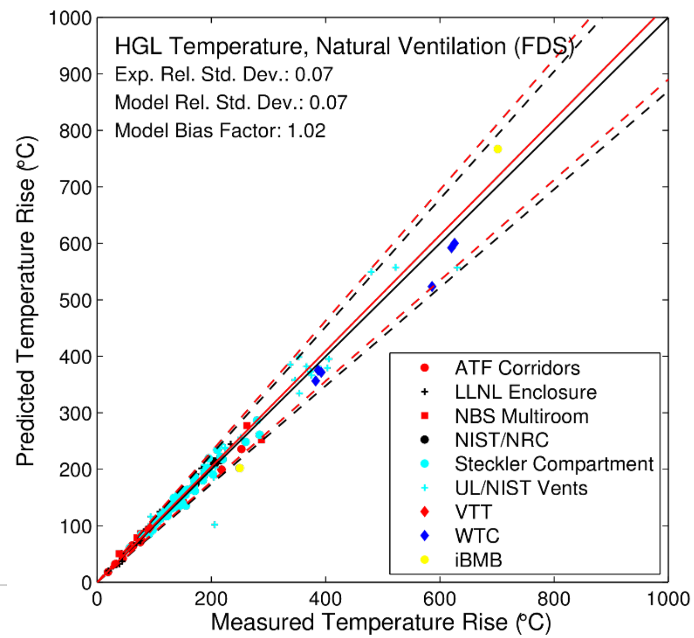
Verification and Validation (NUREG-1824-Supplement 1)









Verification and Validation (NUREG 1824 Supplement 1)

Output Quantity	Empirical Correlations			CFAST		MAGIC		FDS		Exp
	Corr.	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	δ	$\tilde{\sigma}_M$	$\tilde{\sigma}_E$
HGL Temp. Rise, Natural Ventilation	MQH	1.17	0.15	1.21	0.38	1.13	0.33	1.02	0.07	0.07
HGL Temp. Rise, Forced Ventilation	FPA	1.29	0.32	1.13	0.23	1.04	0.15	1.14	0.20	0.07
	DB	1.18	0.25							
HGL Temp. Rise, No Ventilation	Beyler	1.04	0.37	0.99	0.24	1.07	0.16	1.16	0.11	0.07
HGL Depth	ASET/YT	-	-	1.01	0.29	1.08	0.27	1.04	0.06	0.05
Ceiling Jet Temp. Rise	Alpert	0.86	0.11	1.06	0.42	1.04	0.46	0.99	0.12	0.07
Plume Temp. Rise	Heskestad	0.80	0.33	1.09	0.29	1.03	0.19	1.12	0.21	0.07
	McCaffrey	0.90	0.31							
Oxygen Concentration	N/A			1.08	0.28	1.01	0.22	0.99	0.13	0.08
Smoke Concentration	N/A			3.42	0.68	3.71	0.66	2.63	0.60	0.19
Pressure Rise	N/A			1.37	0.63	1.32	0.20	1.00	0.23	0.23
Target Temp. Rise	Steel	1.29	0.45	1.25	0.49	1.04	0.38	0.99	0.17	0.07
Target Heat Flux	Point Source	1.39	0.50	1.04	0.59	0.85	0.66	0.97	0.26	0.11
	Solid Flame	1.17	0.44							
Surface Temp. Rise	N/A			1.02	0.22	0.93	0.28	0.98	0.12	0.07
Surface Heat Flux	N/A			0.94	0.26	0.76	0.33	0.89	0.17	0.11
Cable Failure Time	THIEF	0.90	0.11	-	-	-	-	1.10	0.16	0.12
Sprinkler Activation Time	Sprinkler	1.11	0.41	1.01	0.20	0.91	0.20	0.93	0.15	0.06
Smoke Detector Act. Time	Temp. Rise	1.07	0.58	1.77	0.39	1.44	0.38	1.22	0.34	0.34

Module III: Process
Fire Detection/Suppression Analysis

- Assess fire detection timing
- Assess timing, reliability, and effectiveness of fixed fire suppression systems
- Assess manual fire brigade response
- Estimate probability of fire suppression as a function of time
- Corresponding PRA Standard SRs: FSS-D6, D7, D8

Module III: Process
Calculate Severity Factor

- The time to target damage, and as a result the non-suppression probability, is a function of the postulated heat release rate

- The severity factor should be calculated in combination with the non-suppression probability

- Corresponding PRA Standard SRs: FSS-C4, D5

Use of Special Models

- There are fire scenarios critical to NPP applications that are beyond capability of existing computational fire models
  - Cable fires
  - High energy arcing faults and fires
  - Fire growth inside the main control board
  - Fire propagation between control panels
  - *The methods described here are documented in EPRI 1011989 & NUREG/CR-6850, “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities.”*

Module III: Process Document Analysis Results

- The first tier documentation should be sufficient in detail to allow for an independent reader to understand
  - Scenarios postulated, the basis for their selection and analysis,
  - The tools utilized in the analysis and basis for selection,
  - The final results of the analysis
- The second tier documentation should provide the details of each individual analysis performed including:
  - Details of scenario selection process,
  - The fire modeling analyses performed
- All specific considerations and assumptions should be recorded clearly

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Module III – Fire Analysis

Detection and Suppression

Appendix P

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

Detection & Suppression Objectives

The objectives of this module are:

- Describe the process for calculating the non-suppression probability
- Describe the assumptions underlying the recommended approach for determining the non-suppression probability.
- Related SR: FSS-C7

Detection & Suppression Generalities

- Time to target damage and non-suppression probabilities are independent calculations
  - It's like a probabilistic horse race – will damage win or will suppression win?
  - We calculate time to damage through fire modeling and use that as an input to detection/suppression analysis
  - We then ask what's the probability that suppression succeeds before damage occurs?
- Fire models cannot model the effects of all the different fire detection and suppression strategies available in NPP fire scenarios
  - We do pretty well with simple things like smoke detection time, sprinkler head activation time
  - We currently don't do things like water droplets interfering with fire physics (although there are folks working on those kinds of problems…)

Detection & Suppression
Crediting a Fire Det. or Supp. System

Detection and suppression systems can and should be credited in the fire PRA if they are *effective* and *available*

- Effectiveness – Will the system detect/control the fire?
  - Designed, installed and maintained according to the code of record and fire protection engineering judgment
  - Based on the specific characteristics of the postulated fire scenario

- Availability – Probability of the system actually operating as designed upon demand

Detection & Suppression
Fire Detection and Suppression Systems

The following fire detection and suppression systems are considered in the recommended approach:

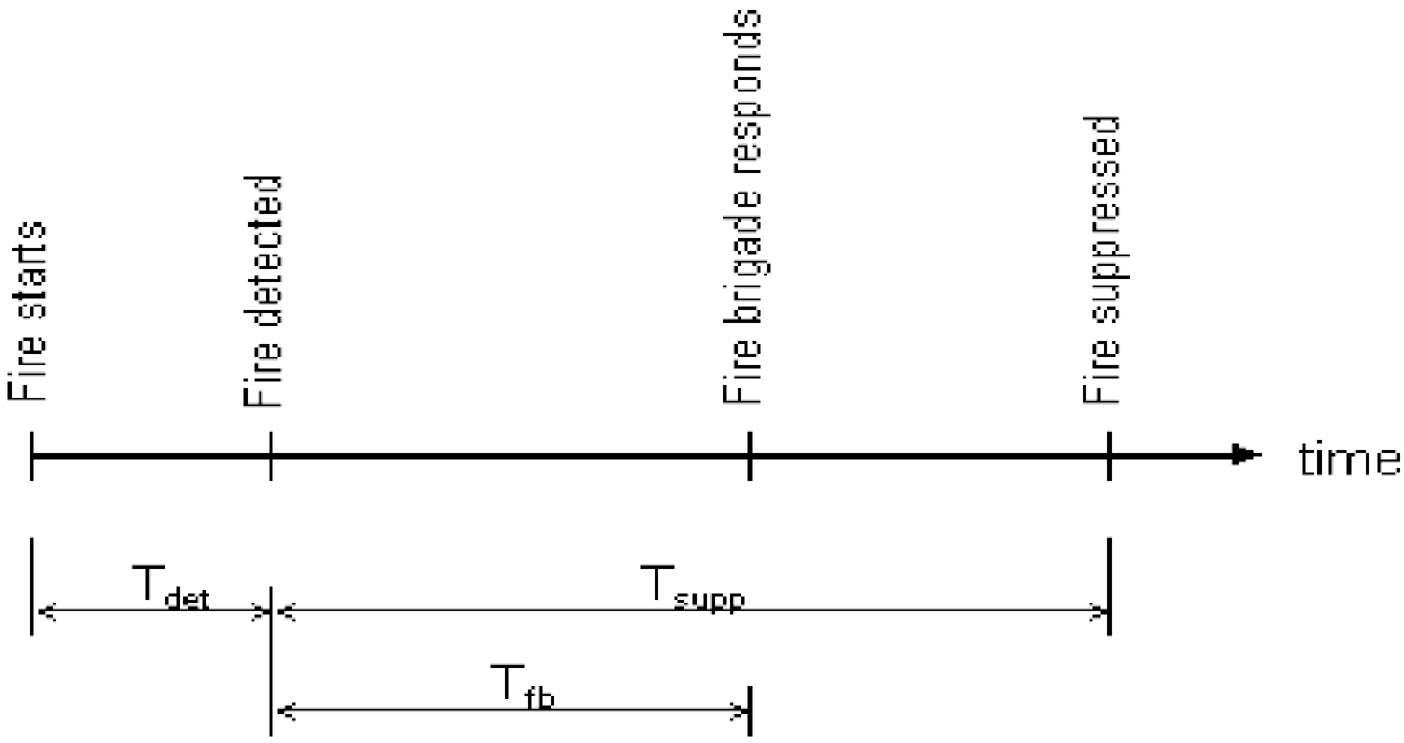
- Fire Detection
  - Prompt detection
  - Automatic detection
  - Delayed detection (by plant personnel)
  - Incipient detection*

- Fire Suppression
  - Prompt suppression
  - Automatic suppression
  - Manual suppression

*covered in a separate presentation

Detection & Suppression Conceptual Relationship

- T_{det}: time interval from start of fire up to time when fire is initially detected
- T_{supp}: time interval from when fire is detected until it is suppressed
- T_{fb}: time from fire detection until fire brigade begins to apply suppressant agents



Availability of new data

- Similar to the ongoing improvement work with fire ignition frequencies, manual NSP data has also been updated since NUREG/CR-6850
  - All data sources excluded fire suppression events prior to 1/1/1981 (pre Appendix R)
- NUREG/CR-6850
  - Contains original methodology and original suppression curves
- FAQ 08-0050 (Supplement 1 Chapter 14)
  - Updated methodology to eliminate delay time for brigade arrival
- EPRI 3002002936 / NUREG-2169
  - Same methodology as FAQ
  - Added additional event experience through 2009

FAQ 08-0050
Manual Non-Suppression Probability

- Issue:
  – NUREG/CR-6850 / EPRI 1011989 assumes fire fighting begins after detection <u>and</u> brigade arrival on the scene
  – Too little credit to manual fire suppression before the fire brigade arrives on the scene compared to experience
- Resolution
  – Updated guidance for treatment of manual suppression and the fire brigade response
  – Includes a process to adjust the non-suppression analysis for scenario-specific fire brigade responses.
- Reference
  – Supplement 1 to NUREG/CR-6850 (EPRI 1019259) Chapter 14

FAQ 08-0050: Solution
How the P_{ns} curves were re-calculated

- 6850/1011989 used manual suppression time if available, and fire duration if no suppression time is identified from fire event records
  - Many cases deferred to duration
- FAQ uses the *fire duration time* for all events (time from detection to suppression)
  - Fire duration time is either the same or longer than suppression time
  - Result: the base P_{ns} curves are *slightly* more conservative, but…
- FAQ also assumes fire control and suppression activities start at the time of detection
  - No time delay for brigade arrival
  - Credits suppression by plant personnel other than fire brigade
  - More than makes up for shift in curves
- FAQ presents new non-suppression (P_{ns}) curves for all bins
- Includes method to adjust for above or below average fire brigade response time

Detection & Suppression
FAQ 50 changes the calculation of P_{ns}

Original 6850/1011989 approach:

$$P_{ns} = e^{-\lambda\left[t_{damage} - \left(t_{detection} + t_{brigade-response}\right)\right]}$$

Revised FAQ 50 approach:

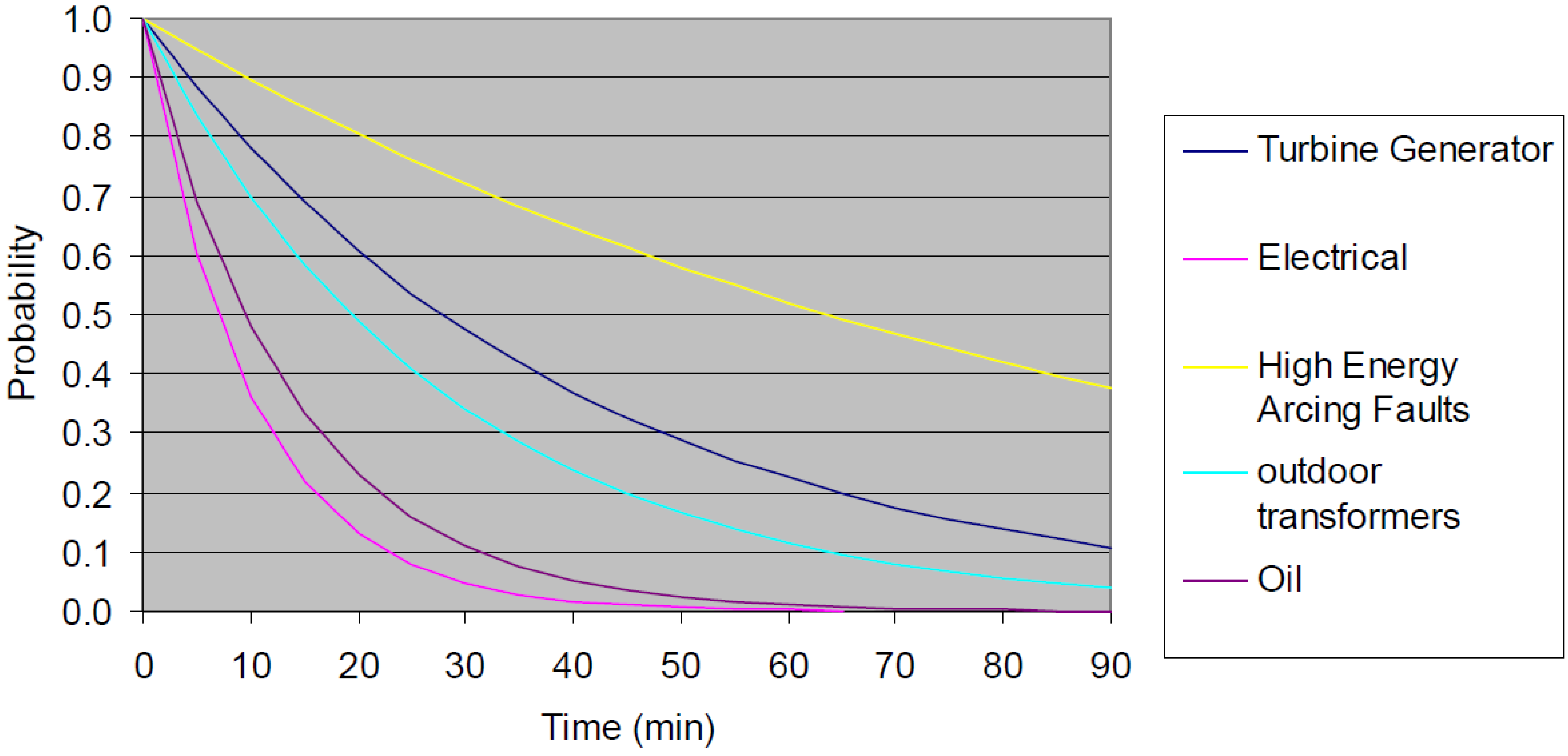
$$P_{ns} = e^{-\lambda\left[t_{damage} - t_{detection}\right]}$$

Where λ is the suppression rate constant

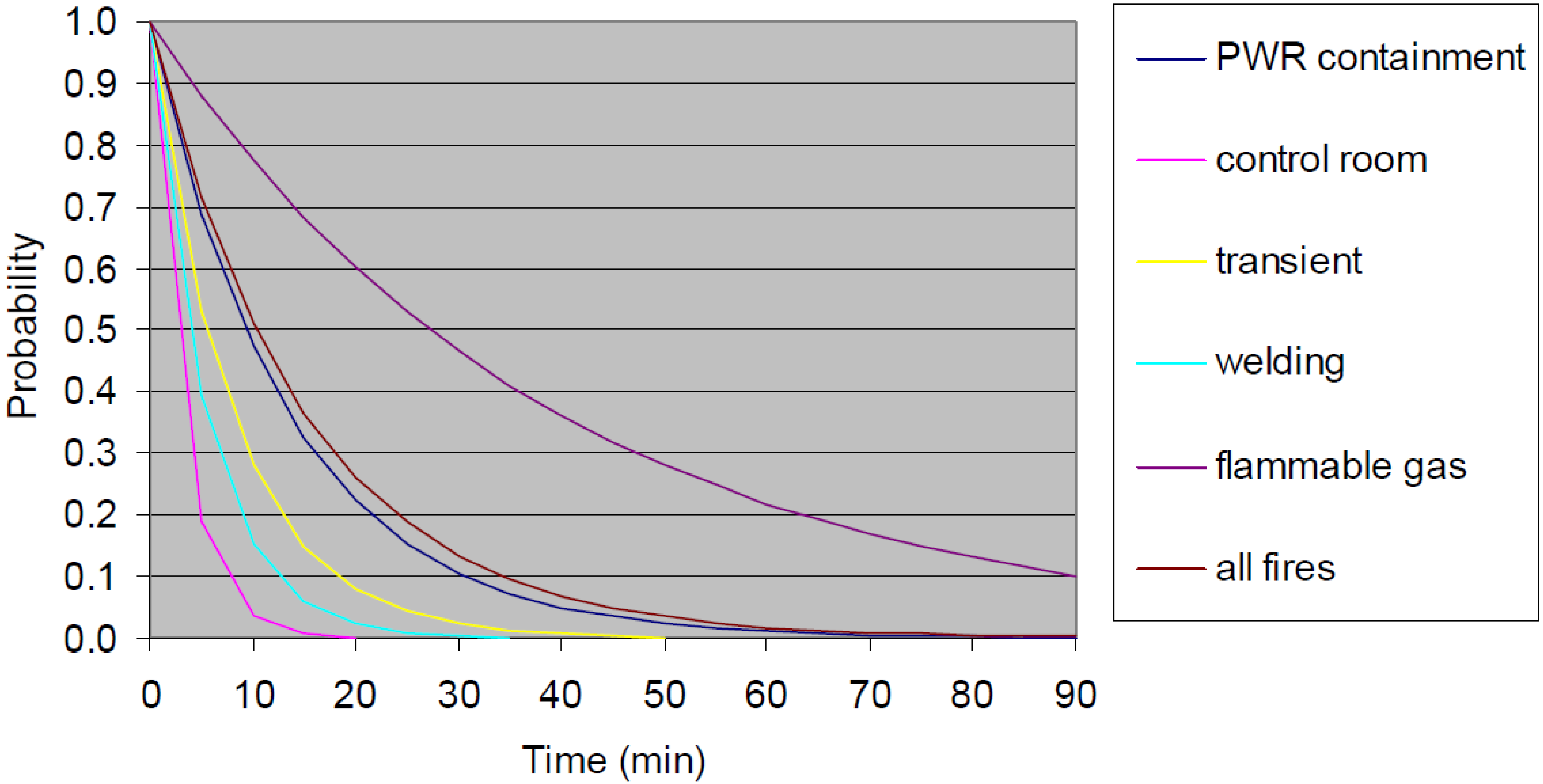
FAQ 08-0050: Solution
P_{ns} curves

		Original NUREG/CR-6850		Revised Analysis	
Suppression Curve	**No. of original events/revised events**	**Original Total Suppression Time**	**Original Mean Suppression Rate [/min]**	**Revised Total Duration**	**Revised Mean Suppression Rate [/min]**
T/G fires	21/21	749	0.03	846	0.025
Control room	6/6	18	0.33	18	0.33
PWR containment	3/3	23	0.13	40	0.075
Outdoor transformers	14/14	373	0.04	390	0.036
Flammable gas	5/5	195	0.03	197	0.025
Oil fires	36/36	404	0.09	474	0.076
Cable fires	5/5	21	0.24	31	0.161
Electrical fires	114/113	942	0.12	1113	0.102
Welding fires	19/18	99	0.19	106	0.188
Transient fires	24/22	199	0.12	174	0.126
High-energy arcing faults	3/3	239	0.01	276	0.011
All fires	245[21] /246	3113	0.08	3655	0.067

Detection & Suppression
Revised Suppression Curves (1 of 2)



Detection & Suppression
Revised Suppression Curves (2 of 2)



Detection & Suppression
Selection of a suppression curve

The suppression curve should be selected based on the type of postulated fire. There are 13 suppression curves available (see next two slides)

- For prompt suppression by a welding fire watch, use the welding suppression curve
- If the fire watch is not successful, an appropriate suppression curve should be selected depending on the combustibles ignited due to hot work activities

Detection & Suppression
Selection of a suppression curve

- **Transients** – all transient fire event not specified as belonging to any of the following categories were used.
- **Welding** – usually labeled *transient fires caused by welding and cutting* or *cables fires caused by welding and cutting*. This curve is used for calculating the probability of **prompt suppression**.
- **Electrical** – events involving electrical cabinets, electric motors, indoor transformers, and junction boxes among other electrical equipment. Electrical events in the control room, transformer yard, and T/G excitor were excluded. HEAFs are also excluded form this curve.
  - Note: events including overheating equipment, such as bearings due to lack of lubricating oil were included in this set.
- **Cable** – events for cables in raceways. Records with insufficient details, such as simply reporting a “cable/wiring” fire were included in this data set. Does not include extension cord fires or cable/wire fires within electrical equipment.
- **Oil** – includes events were a lubricating substances was ignited.
- **Flammable Gas** – includes only events involving hydrogen fires. Fires in off-gas/h_2 recombiners were also included.
- **Transformer Yard** – includes events occurring in the transformer yard.
  - Excludes events with fixed fire suppression and events where the fire brigade decided to let the fire burn out.

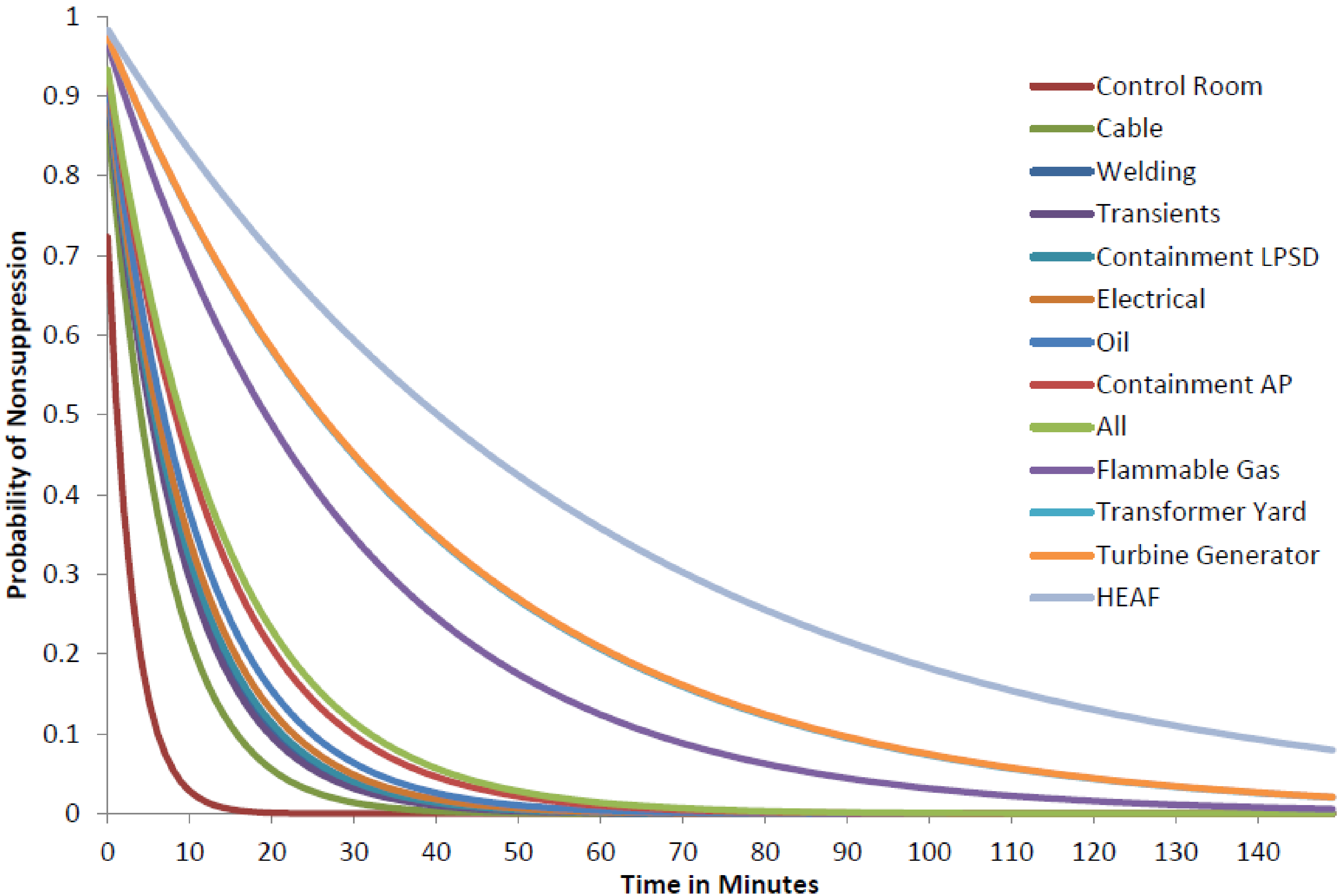
Detection & Suppression
Selection of a suppression curve

- **Containment PWR** – for events occurring in PWR containment during at-power conditions. The fire brigade access to the building in the event of a fire is relatively different from other locations in the plant. Events in this data set include all fire events occurring in containment.
- **Containment (LPSD)** – new suppression curve that is applied to LPSD only conditions. Applicable when containment is open to maintenance and operations staff when the plant is not at power. Primarily for hotwork, but can include electrical or other in-containment fires. Applicable to both PWR and BWR.
- **Control Room** – include fires within the control room regardless of ignition source.
- **Turbine Generator** – includes events labeled as T/G oil, T/G hydrogen, T/G excitor. Some T/G hydrogen events were excluded from this data set because they were suppressed with an automatic system.
- **HEAFs** – includes events labeled as high-energy arcing faults.
- **All events** – includes all events not considered as *prompt suppression.* This generated a generic suppression time probability curve that may be used for those cases where the analyst cannot find a proper match from the preceding list of categories.

NSP Update
From EPRI 3002002936 / NUREG-2169

		NUREG/CR-6850, Supplement 1		Updated FEDB Analysis	
Suppression Curve	**Number Supplement 1 Events/ Updated Events**	**Total Suppression Time (minutes)**	**Mean Suppression Rate [/min]**	**Updated Total Suppression Time (minutes)**	**Updated Mean Suppression Rate [/min]**
T/G fires	21/30	846	0.025	1167	0.026
Control room	6/12	18	0.33	37	0.324
PWR containment (AP)	3/3	40	0.075	40	0.075
Containment (LPSD)	N/A/31	N/A	N/A	299	0.104
Outdoor transformers	14/24	390	0.036	928	0.026
Flammable gas	5/8	197	0.025	234	0.034
Oil fires	36/50	474	0.076	562	0.089
Cable fires	5/4	31	0.161	29	0.138
Electrical fires	113/177	1113	0.102	1815	.098
Welding fires	18/52	106	0.188	484	0.107
Transient fires	22/42	174	0.126	386	0.111
HEAFs	3/8	276	0.011	602	0.013
All fires	246/442	3655	0.067	6583	0.067

Updated NSP Curve Plots (EPRI 3002002936 / NUREG-2169) Probability vs. time to suppression



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Updated Non-Suppression Curves
EPRI 3002002936 / NUREG-2169

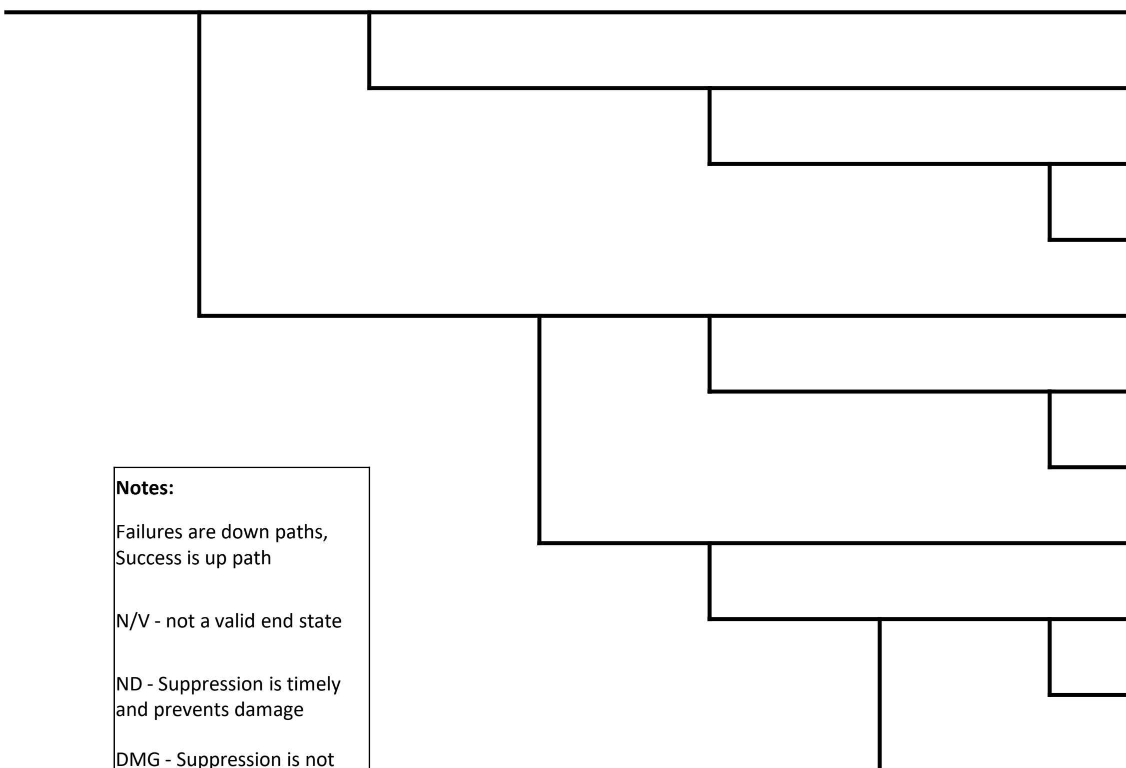
Time (min)	T/G fires	HEAFs	Outdoor transformers	Flammable gas	Oil fires	Electrical fires	Transient fires	PWR containment (AP)	Containment (LPSD)	Welding	Control room	Cable fires	All fires
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5	0.879	0.936	0.879	0.843	0.641	0.614	0.572	0.687	0.595	0.584	0.198	0.502	0.715
10	0.773	0.876	0.772	0.710	0.411	0.377	0.328	0.472	0.355	0.341	0.039	0.252	0.511
15	0.680	0.819	0.678	0.599	0.263	0.232	0.188	0.325	0.211	0.200	0.008	0.126	0.365
20	0.598	0.767	0.596	0.505	0.169	0.142	0.108	0.223	0.126	0.117	0.002	0.063	0.261
25	0.526	0.717	0.524	0.425	0.108	0.087	0.062	0.153	0.075	0.068	*	0.032	0.187
30	0.462	0.671	0.460	0.359	0.069	0.054	0.035	0.105	0.045	0.040	*	0.016	0.133
35	0.407	0.628	0.404	0.302	0.044	0.033	0.020	0.072	0.027	0.023	*	0.008	0.095
40	0.358	0.588	0.355	0.255	0.028	0.020	0.012	0.050	0.016	0.014	*	0.004	0.068
45	0.314	0.550	0.312	0.215	0.018	0.012	0.007	0.034	0.009	0.008	*	0.002	0.049
50	0.277	0.515	0.274	0.181	0.012	0.008	0.004	0.024	0.006	0.005	*	0.001	0.035
55	0.243	0.481	0.241	0.153	0.007	0.005	0.003	0.016	0.003	0.003	*	*	0.025
60	0.214	0.451	0.212	0.129	0.005	0.003	0.002	0.011	0.002	0.002	*	*	0.018
65	0.188	0.422	0.186	0.108	0.003	0.002	*	0.008	0.001	0.001	*	*	0.013
70	0.165	0.394	0.164	0.091	0.002	0.001	*	0.005	*	*	*	*	0.009
75	0.145	0.369	0.144	0.077	0.001	*	*	0.004	*	*	*	*	0.007
80	0.128	0.345	0.126	0.065	*	*	*	0.002	*	*	*	*	0.005
85	0.112	0.323	0.111	0.055	*	*	*	0.002	*	*	*	*	0.003
90	0.099	0.302	0.098	0.046	*	*	*	0.001	*	*	*	*	0.002
95	0.087	0.283	0.086	0.039	*	*	*	*	*	*	*	*	0.002
100	0.076	0.265	0.075	0.033	*	*	*	*	*	*	*	*	0.001

Detection & Suppression
Event Tree format

- The event tree approach is one way to deal with suppression
  - Works well
  - Quantifies various outcomes (success/failure)
  - Very flexible
- You may need to modify the event tree to suit application
  - The generic event tree is a simple single-stage version
  - We will show one example of a more complex tree
- For the simple tree only **one target set**
  - Success means the fire is put out before damage occurs
  - Failure means suppression is not “timely” and the target set is damaged
- Remember: all fires are put out eventually – it is a question of timing

Detection & Suppression
Detection-Suppression Event Tree

Fire Ignition	Prompt		Automatic		Manual	
	Detection	Suppression	Detection	Suppression	Detection	Suppression



Sequence	End State	Outcome
A	ND	Propmt detection and prompt suppression succeed
B	ND	Automatic suppression succeeds
C	ND	Prompt detection and manual suppression succeed
D	DMG	All means of suppression fail
E	ND	Automatic suppression succeeds
F	ND	Automatic detection and successful manual suppression
G	DMG	All means of suppression fail
H	ND	No auto detection but auto suppression succeeds
I	ND	Delayed manual detection and successful manual suppresion
J	DMG	Delayed manual detection but manual suppression fails
K	DMG	Fire is not detected in time to prevent damage

Notes:

Failures are down paths, Success is up path

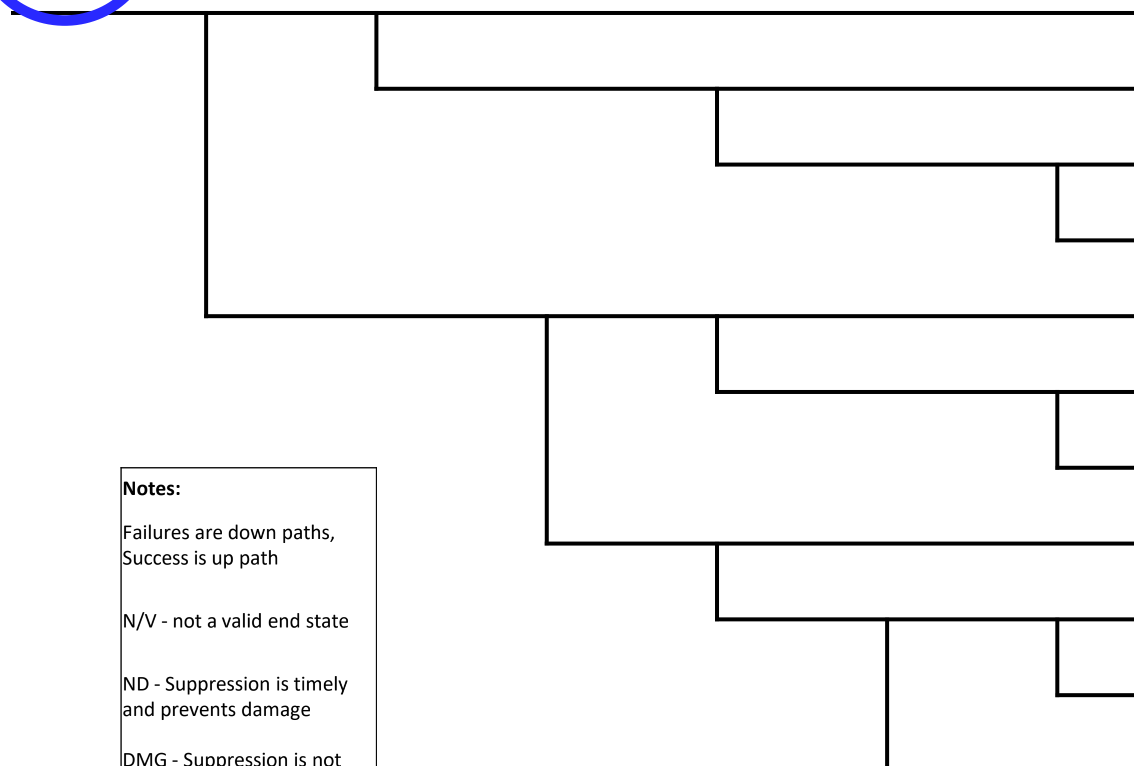
N/V - not a valid end state

ND - Suppression is timely and prevents damage

DMG - Suppression is not timely and damage occurs

Detection & Suppression
Detection-Suppression Event Tree

Fire Ignition	Prompt		Automatic		Manual	
	Detection	Suppression	Detection	Suppression	Detection	Suppression



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Detection & Suppression
Fire ignition event

- There are two ways to enter the event tree:
  - Enter with 1.0 – a fire has ignited…
    - This makes it the outcome a conditional probability – “given that a fire has been ignited…”
  - Enter with a fire frequency (events/yr)
    - This makes the outcome a frequency for each end state
    - Branch point probabilities have no units so frequency units come through

Detection & Suppression
Detection-Suppression Event Tree

Sequence	End State	Outcome
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Detection & Suppression
Prompt Detection and Suppression

- Prompt detection
  - Assume 1.0 if a continuous fire watch is credited or in-cabinet detection is available for fires postulated inside cabinets
  - Justify the use of 1.0 if an incipient fire detection system is available
  - Assume 0 if automatic or delayed detection only are credited
- Prompt suppression
  - Credit prompt suppression in hot work fire scenarios
  - Probability is obtained from the welding suppression curve

Detection & Suppression
Detection-Suppression Event Tree

Sequence	End State	Outcome
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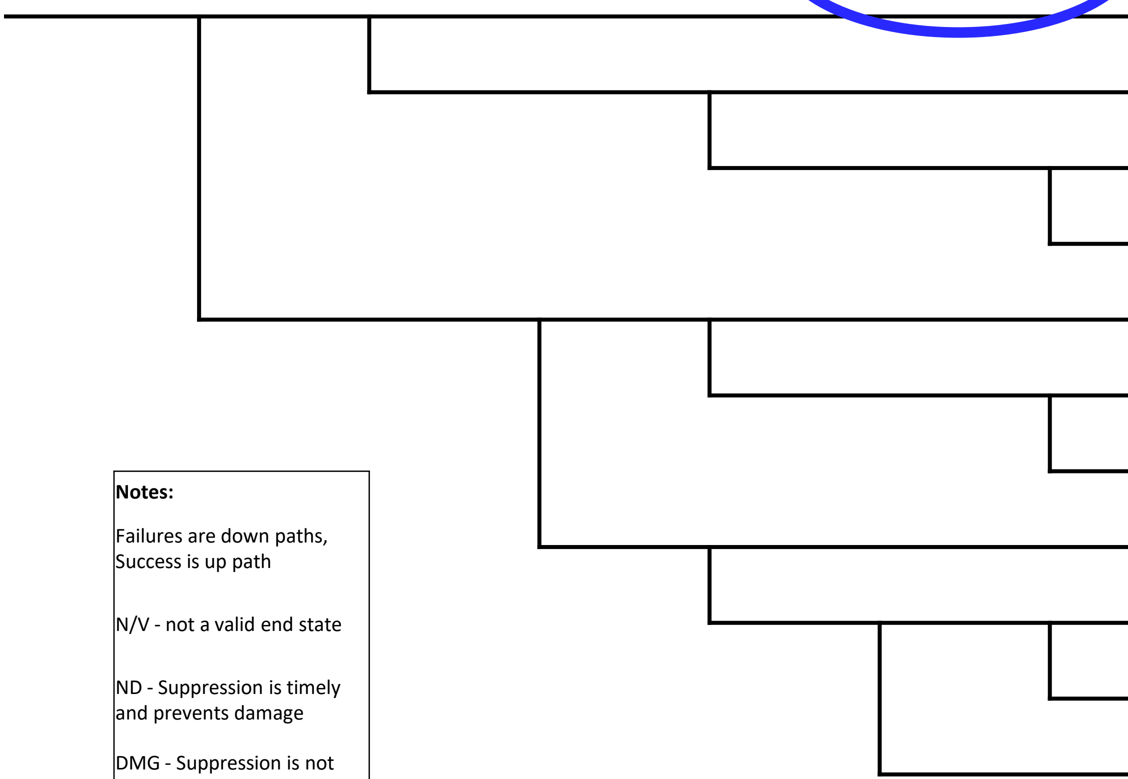
Detection & Suppression
Automatic Detection and Suppression

- Automatic detection
  - Assume a probability of failure no larger than 0.05. This the unreliability for Halon systems reported in NSAC-179L
  - Check for availability!

- Automatic suppression (from NSAC-179L)
  - Halon systems = 0.05
  - CO_2 systems = 0.04
  - Wet pipe sprinklers = 0.02
  - Deluge or pre-action = 0.05
  - Check for availability!

Detection & Suppression
Detection-Suppression Event Tree

Fire Ignition	Prompt		Automatic		Manual		Sequence	End State	Outcome
	Detection	Suppression	Detection	Suppression	Detection	Suppression			



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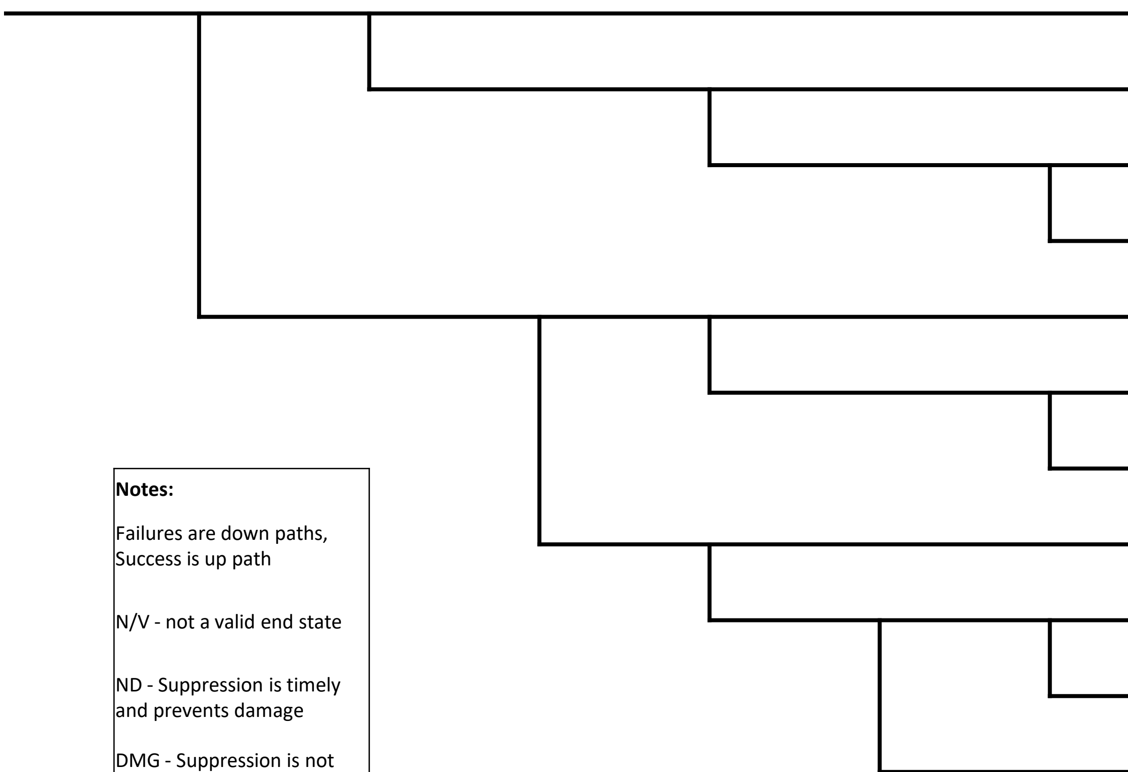
Detection & Suppression
Delayed Detection and Suppression

- Manual/delayed detection
  – Assume 1.0 – All fires will eventually be detected (max = 15min)
  – Compare time to target damage vs. time to detection and suppression

- Manual suppression
  – Probability of manual suppression is obtained from the suppression curves we already discussed
  – Can includes possibility of manual actuation of fixed fire suppression systems
    - Credit here should include human reliability analysis and consideration of dependencies (e.g., failure of the fire water system)

Detection & Suppression
Detection-Suppression Event Tree

Fire Ignition	Prompt		Automatic		Manual	
	Detection	Suppression	Detection	Suppression	Detection	Suppression



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Detection & Suppression End States

- The sequence number is just numbering the outcomes
- For the simple event tree, the end states are either no damage (ND), or loss of the target set (DMG)
  - We will show a more complicated version with more possible outcomes
- The probability of each end state is simply the product of the branch probabilities leading to the end state

Detection & Suppression Dependencies

The following dependencies in suppression analysis could be important:

- Between automatic detection and suppression
  - Example: control panel for a gaseous suppression system
- Between actuated barriers and fire suppression systems
- Between safe shutdown capabilities and automatic suppression
  - Example: crediting fire fighting water for core injection, heat removal or secondary heat removal
- Between manual and automatic suppression

Detection & Suppression Conceptual Example

The scenario consists of an MCC fire affecting a target in the hot gas layer.

- The room is equipped with a smoke detection system and automatic sprinklers
- Using fire modeling
  - Time to smoke detection = 1 min
  - Time to sprinkler activation = 8 min
  - Time to target damage = 15 min
- From fire drill records and/or plant procedures
  - Time to delayed detection is assumed to be 15 min

Detection & Suppression
Example for the 6850/1011989 approach

Fire	Prompt Detection	Prompt Suppression	Automatic Detection	Automatic Suppression	Manual Detection	Manual Fire Brigade	Sequence	End State	Pr(non-suppression)
FI	PD	PS	AD	AS	MD	FB			
1	0	0					A	Not valid	
		1		0.98			B	Not valid	
				0.02		0.78	C	Not valid	
						0.22	D	Not valid	
	1		0.95	0.98			E	ND	
				0.02		0.76	F	ND	
						0.24	G	DMG	4.6E-03
			0.05	0.98			H	ND	
				0.02	0		I	Not Valid	
					1		J	DMG	1.0E-03
								Total	**5.6E-03**

Note typos in your set at bottom of tree (yellow boxes)…

- No prompt detection
- Failure of auto. det.
  - **P = 0.05**
- Failure of sprinklers:
  - **P = 0.02**

  Both require justification
- Manual suppression:
  - Damage time: 15 min
  - Auto detect: 1 min
  - Time available for manual suppression:

    15 - 1 = 14 min
  - Use electrical fire curve:

    P = EXP(-0.102·14)

    P = 0.24
- Overall solution for this scenario, DMG outcome:

$$P_{ns} = G + J$$

$$P_{ns} = 5.6E-3$$

Detection & Suppression
Concluding remarks on general approach

The non-suppression probability is credited in Task 11, detailed fire modeling

- Target damage is evaluated assuming no detection/suppression capabilities in the room
- The time to target damage is an input to the detection and suppression analysis.
- The recommended approach includes an event tree capturing prompt, automatic, and delayed detection and suppression capabilities
- The event tree may need to be modified depending on the scenario

And now for a more complicated example…

- When you assume a single target set, the whole set is lost when the first member of the set is lost
- The way fires really work is that damage spreads over time until the fire is suppressed
  - The fire grows…
  - Spreads…
  - More targets become damaged…
- A more realistic approach is to define multiple target sets based on spatial location and separation from the fire
  - e.g., targets in the plume vs. targets in the hot gas layer
  - Each target set is lost when first member is of the set is lost, but time to damage for the different sets may be quite different

Module III – Fire Analysis

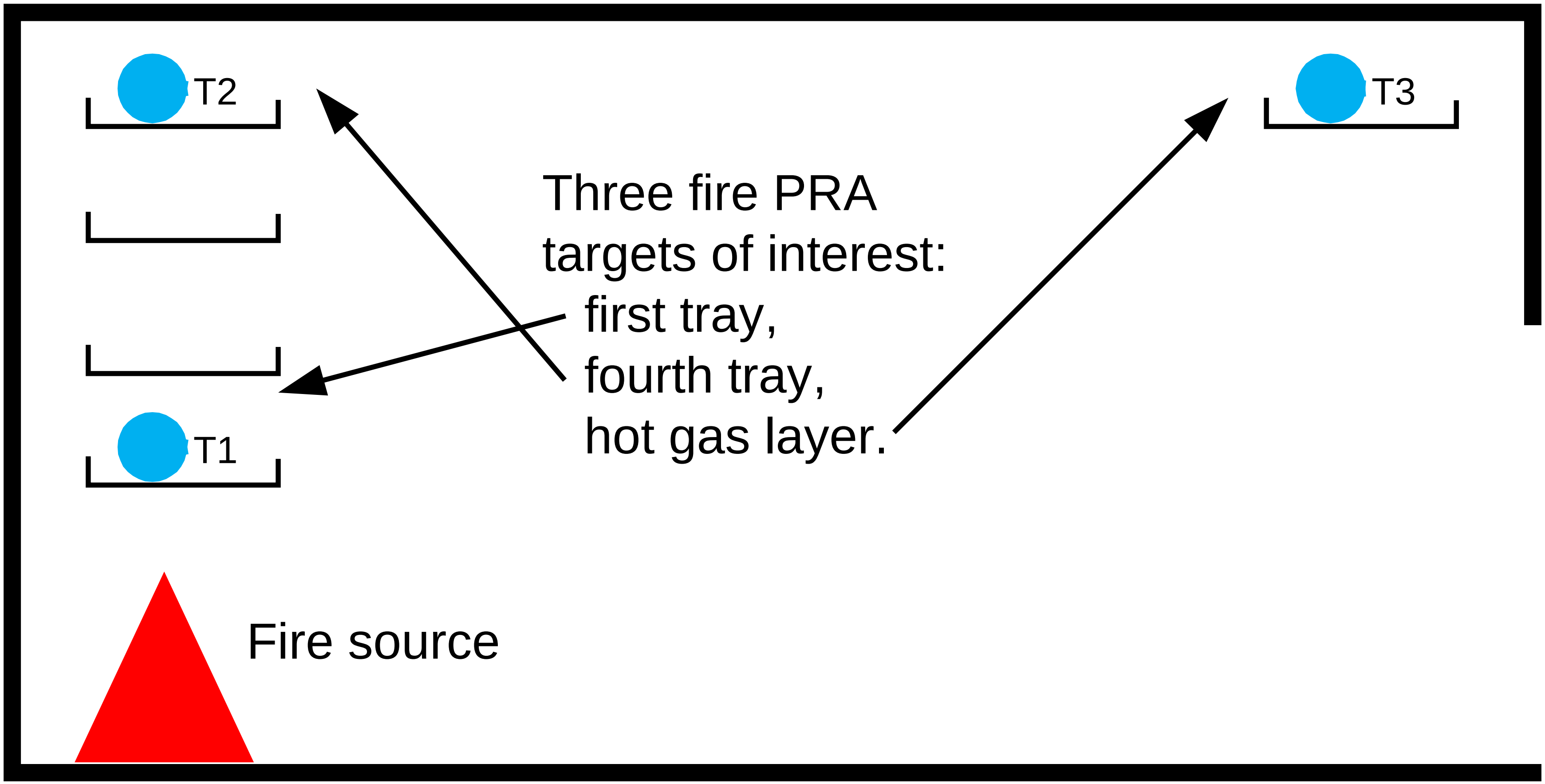
Special Topics in Detection and Suppression Analysis – General Approach for Treatment of Progressive Damage States

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

Common challenge: multiple fire PRA damage targets with some degree of spatial separation



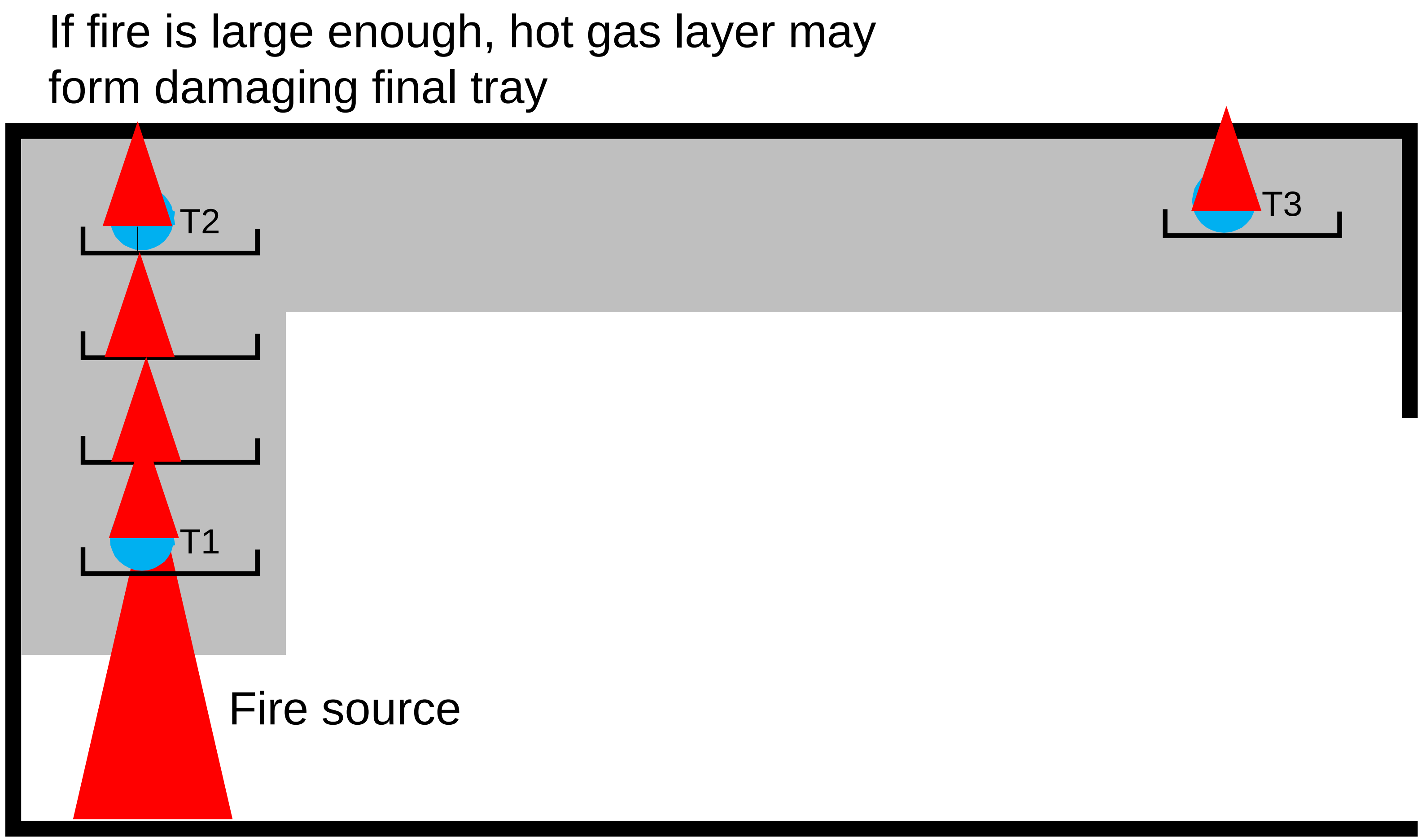
Damage state progresses in time

Fire will damage closest tray first:

Damage state progresses in time

As fire grows and spreads, it will progress through tray stack eventually reaching fourth tray:

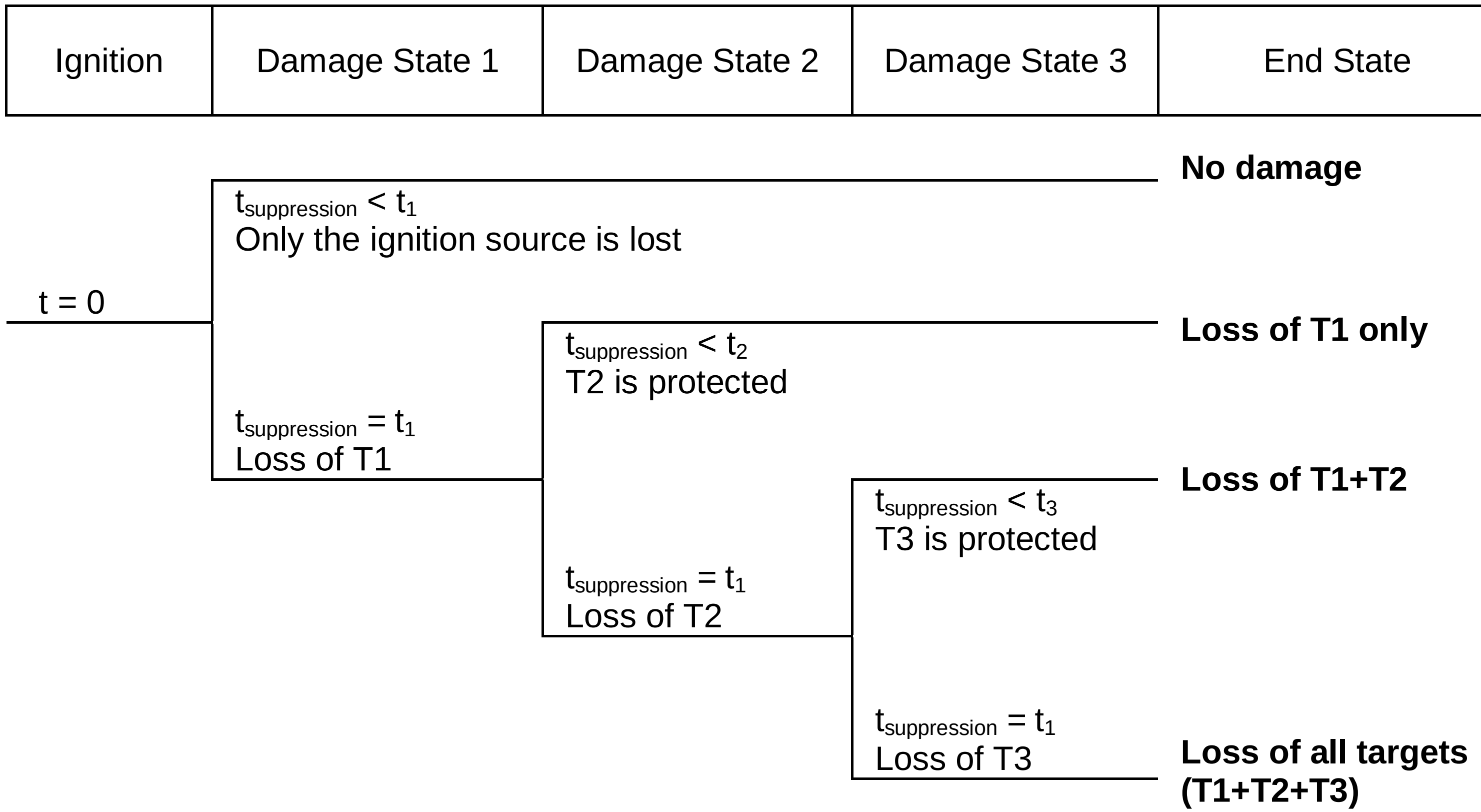
Damage state progresses in time



You can build an event tree to reflect a progressive damage state increasing with time

- The key is that the fire must burn long enough to cause the postulated damage, and the more extensive damage states take additional time
  - t_1 = time to damage for T1
  - t_2 = time to damage for T2
  - t_3 = time to damage for T3
  - $t_1 < t_2 < t_3$
- The likelihood of successful fire suppression gets better and better with longer times
  - Said another way – the probability of non-suppression gets smaller and smaller with longer time available before damage
  - $P_{NS}(t_1) > P_{NS}(t_2) > P_{NS}(t_3)$
- We can reflect this credit through a modified suppression event tree:

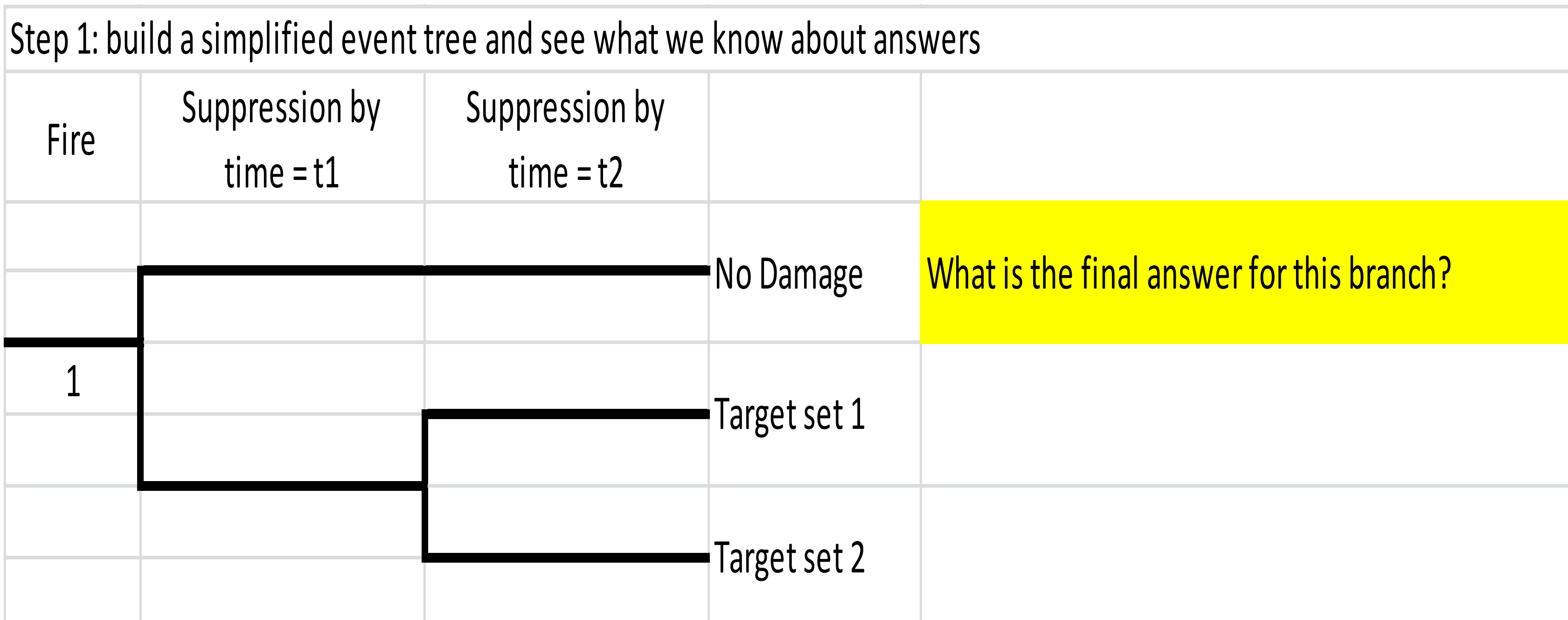
A modified suppression event tree for a three-stage set of fire PRA targets



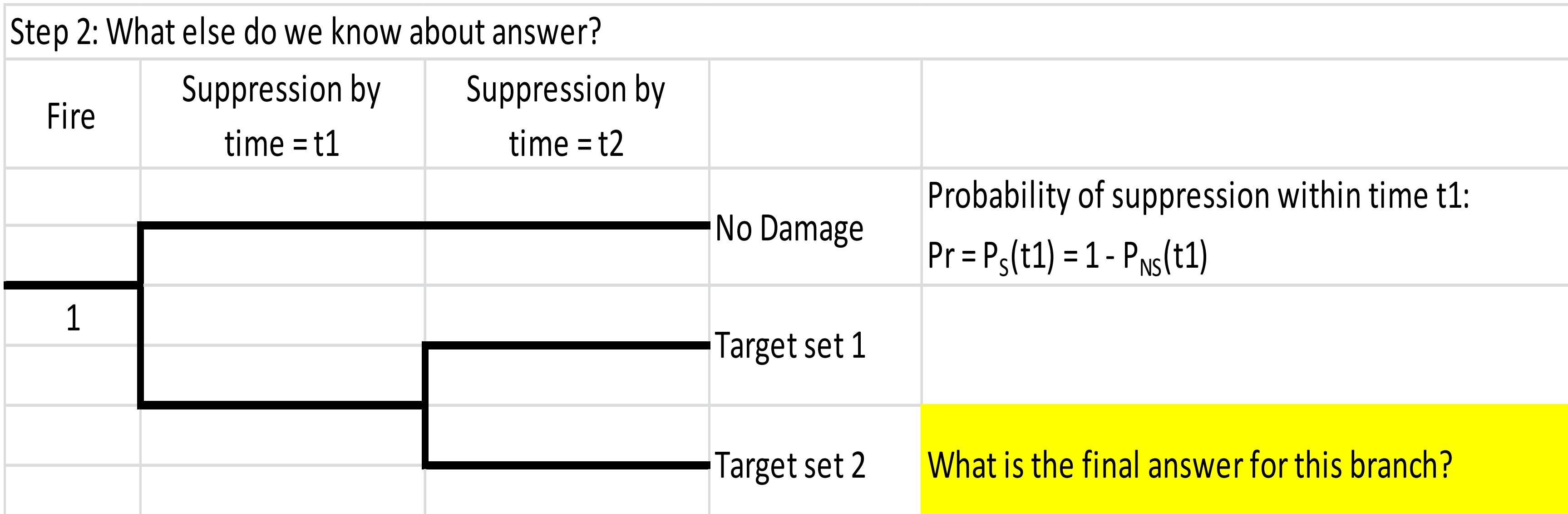
The key is to properly calculate the branch point split fractions

- Branch point values depend on time to damage and the applicable non-suppression probability curve, but…
- The events are *dependent*
  - You can't just pick numbers off suppression curve for each branch
- For example - the second split fraction, for damage to T2, is:
  - the *conditional probability* that *given the fire was not suppressed before time* $t=t_1$, the fire will remain unsuppressed through time $t=t_2$
  - Same goes for final split fraction
- The formal approach to calculate these conditional split fractions lies beyond the scope of our course
  - You need to integrate the density function across time intervals…
- We can, however, illustrate the concept with an even simpler example that we can solve by inspection

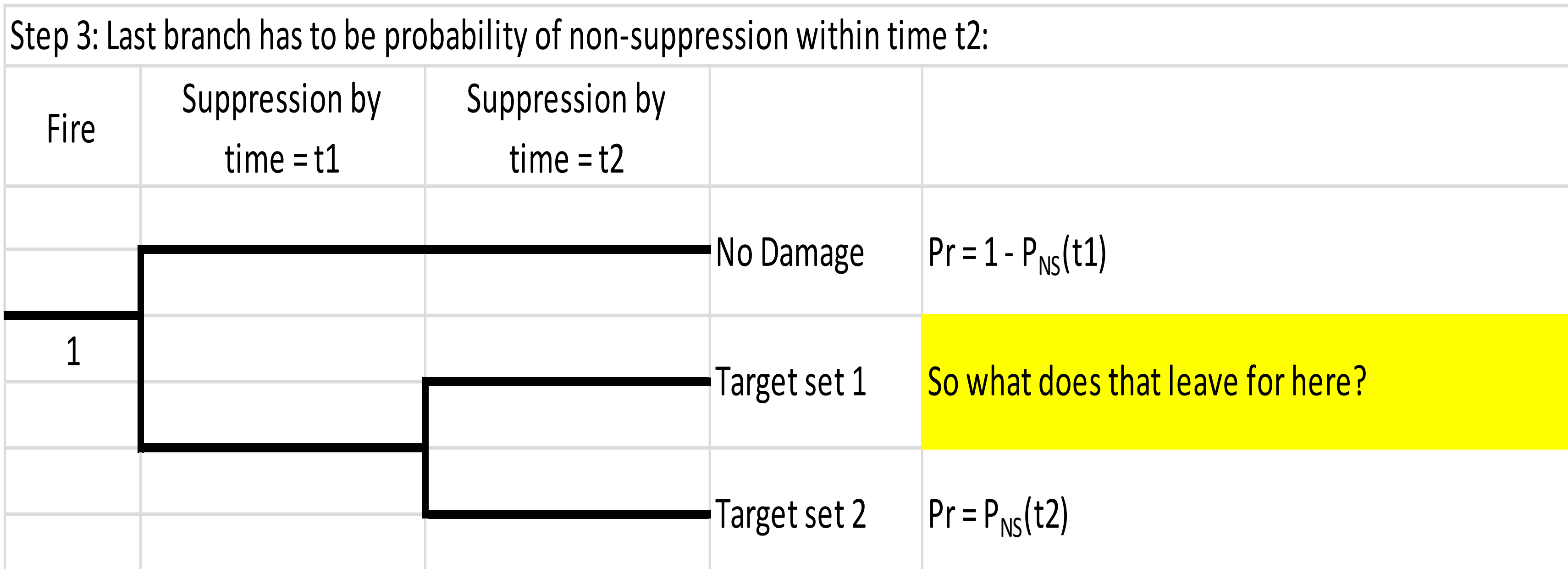
Reduce our problem to a two-stage damage state



Two-stage example (cont.)

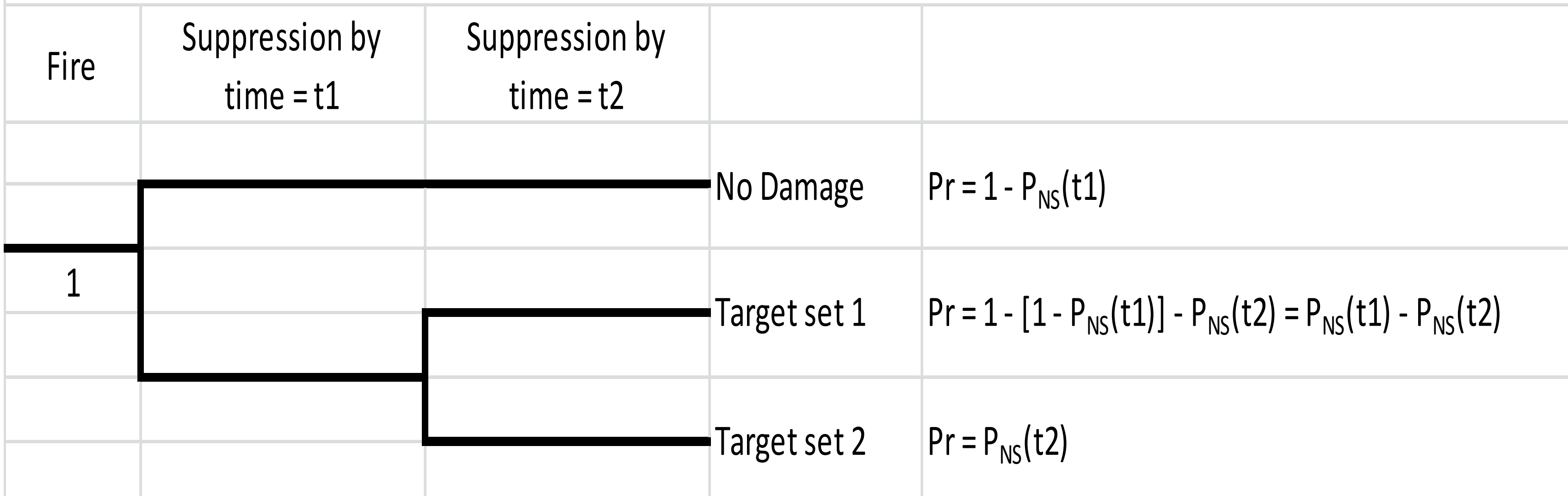


Two-stage example (cont.)

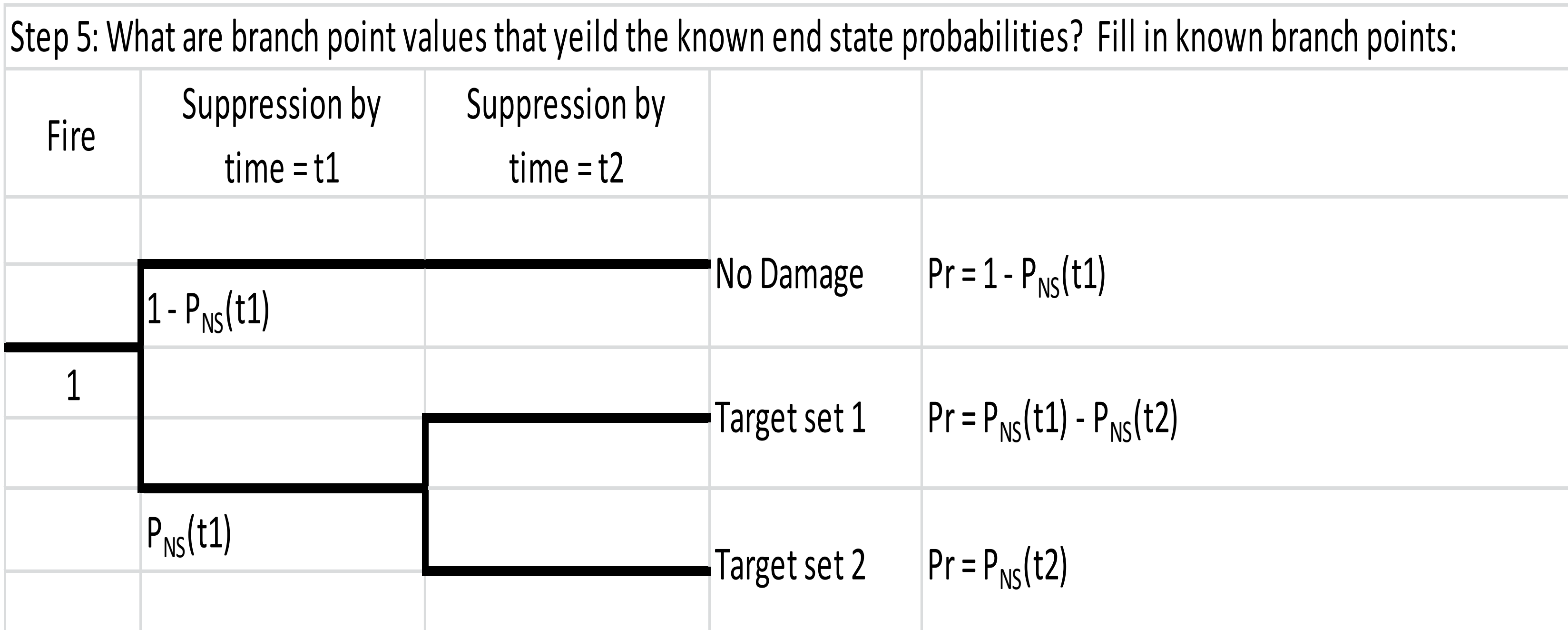


Two-stage example (cont.)

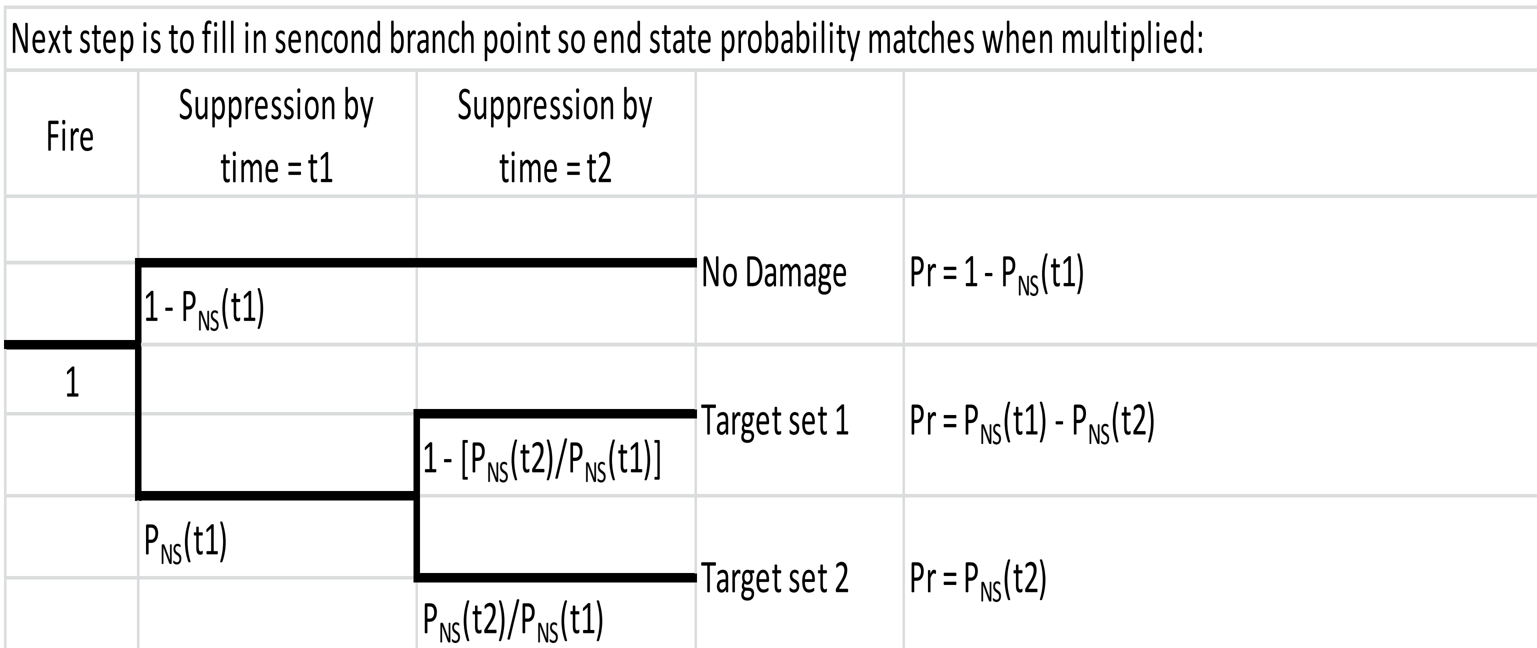
Step 4: Middle branch has to be the residual left over from a total of 1 for all branches:



Two-stage example (cont.)



Two-stage example (cont.)



Two-stage example (conclusion)

One final simplification is possible given the behavior of exponentials:

$P_{NS}(t) = e^{-\lambda t}$

so

$P_{NS}(t2)/P_{NS}(t1) = e^{-\lambda t2}/e^{-\lambda t1} = e^{-\lambda(t2-t1)} = P_{NS}(t2\text{-}t1)$

Fire	Suppression by time = t1	Suppression by time = t2		
	$1 - P_{NS}(t1)$		No Damage	$Pr = 1 - P_{NS}(t1)$
1		$1- [P_{NS}(t2\text{-}t1)]$	Target set 1	$Pr = P_{NS}(t1) - P_{NS}(t2)$
	$P_{NS}(t1)$	$P_{NS}(t2\text{-}t1)$	Target set 2	$Pr = P_{NS}(t2)$

Summary – multi-stage damage states

- The multi-stage damage state approach is a powerful tool
  - Any scenario with multiple targets threatened by the same fire source with discrete damage times
  - The key is some degree of spatial separation between targets
    - Tray stacks
    - Above the fire versus away from the fire
- The more damage stages you develop the more complicated it gets
  - You may need to seek the help of a good statistics person
- Two-to-three discrete states is relatively easy and works for many scenarios
- The event tree approach help
  - Individual end states must be properly weighed
  - Very easy to double count overlapping damage states

Module III - Fire Analysis

Incipient Detection

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

Objectives

- Understand
  - what constitutes a “very early warning” fire detection system
  - different types of smoke detection technologies
  - current regulatory guidance

- Present overview of
  - completed research
  - quantitative risk-scoping study

Outline

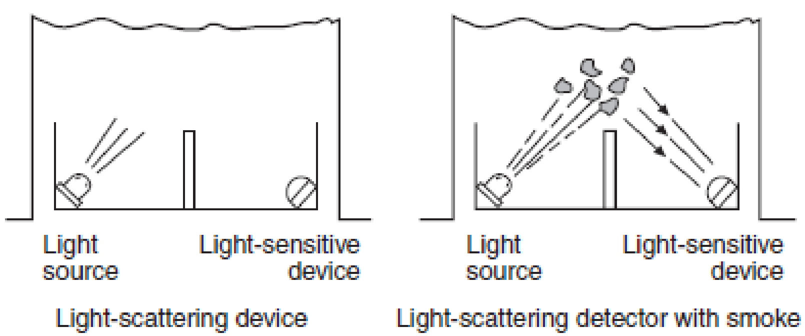
- Background on smoke detection principles and technology
- What constitutes very early warning fire detection system
- Current regulatory guidance on the use of "Incipient Fire Detection"
- Research testing program and accompanying risk-scoping study
- Comments on draft report

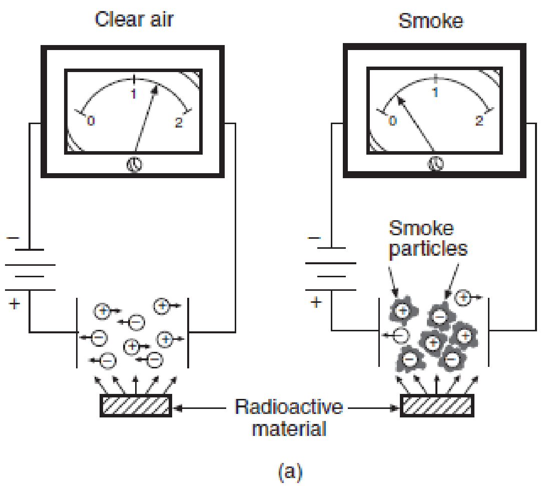
Smoke Detection Principles

- Fire produces a variety of changes in the ambient conditions
  - fire signatures (aerosol, energy release, gas, transport, etc.)
- Smoke detection technologies generate an electrical signal
- When selecting a smoke detector, the highest signal to noise ratio in the earliest period of fire development is preferred
- Smoke detectors monitor the signal and alarm when a setpoint is reached.
  - Setpoint is typically reported as percent per foot obscuration (%/ft obsc.)
- Modern smoke detectors are capable of having the set point configured from a fire alarm control panel.

Smoke Detector Technologies

- Photoelectric
  - Light obscuration
  - Light-scattering
- Ionization
- Cloud Chamber
-

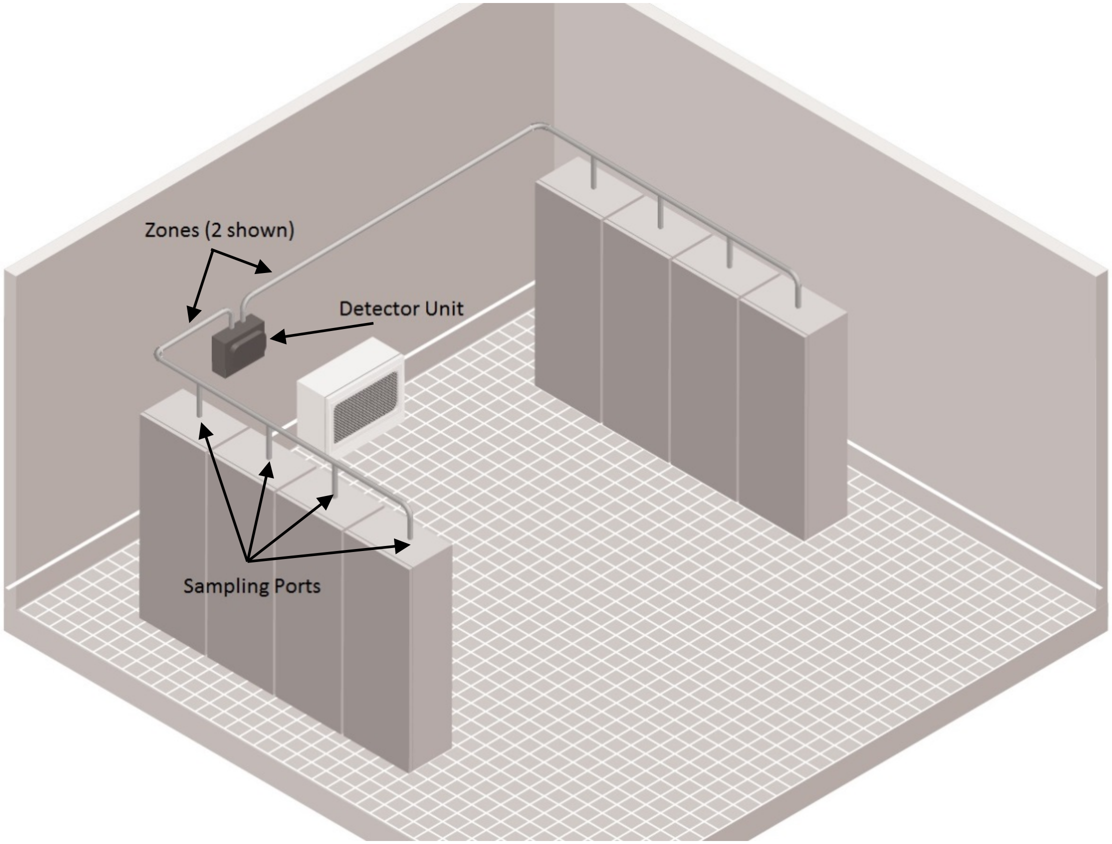




(c)

Photos Ref. NFPA Fire Protection Handbook Section 14, Chapter 2, Twentieth Edition

Spot Type vs Air Sampling Detectors (ASD)



Very Early Warning Fire Detection (VEWFD) System

- NFPA 76, "Fire Protection of Telecommunications Facilities," defines VEWFD systems as,

  > Systems that detect low-energy fires before the fire conditions threaten telecommunications services.

- NFPA 76 specifies, in part, a VEWFD shall
  - "alert" sensitivity of 0.20%/ft obsc. / "alarm" sensitivity of 1.0%/ft. obsc.
    - Both setpoints are above ambient and at each sampling point (port/detector).
  - 200 ft^2 coverage for area wide / 4 ft^2 coverage for air return grill

Use in U.S. NPP Fire PRA

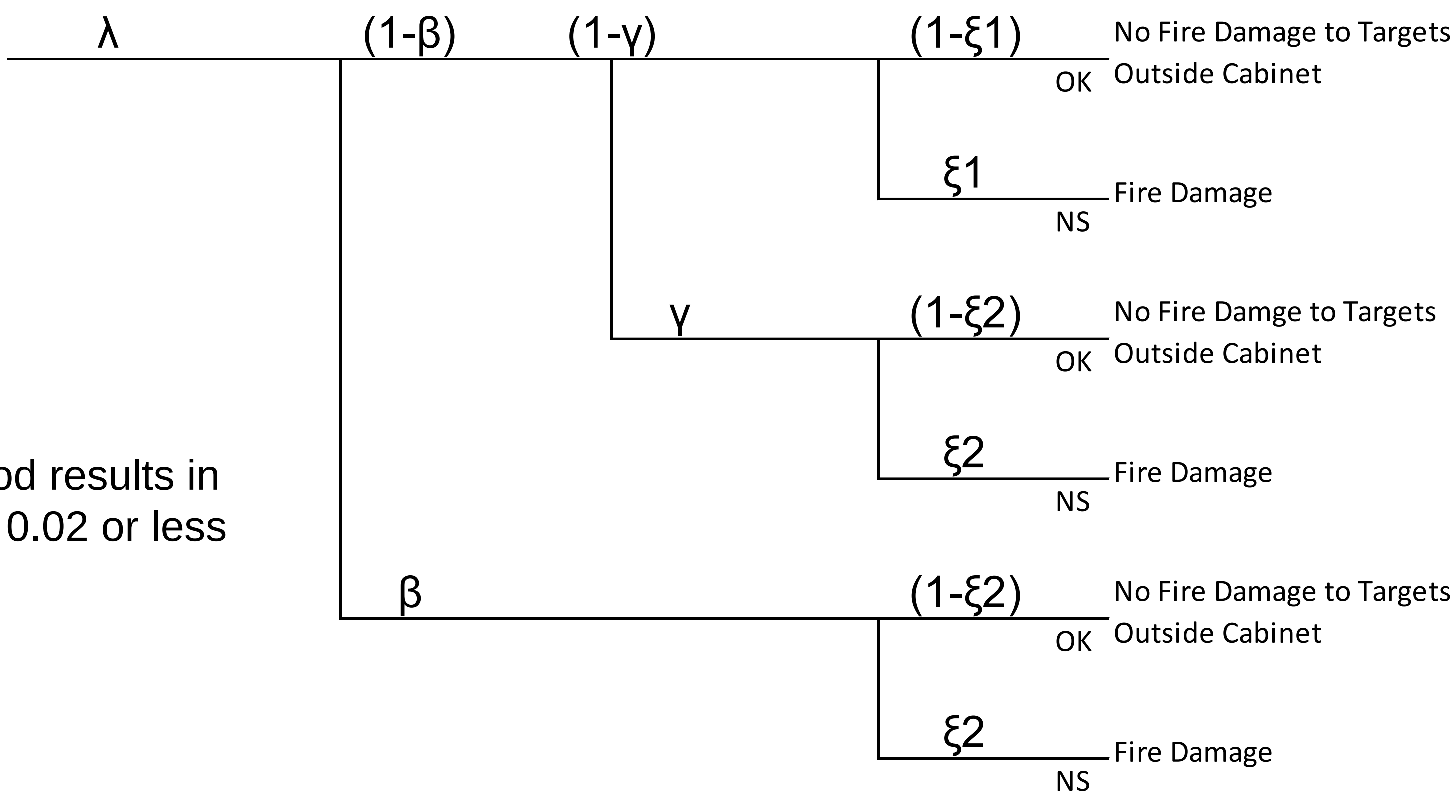
- Use in nuclear power plants (NPPs) is to provide advanced warning
  - Provide more time for operator response
  - More time = higher success of suppressing fires
- Some plants have used ASD since mid-1990s as risk reduction measure
  - Robinson IPEEE
- Some plants use ASD as an enhanced detect system without quantifying performance via risk assessment
  - TMI, exemption for thermo-lag 330 performance issue.
- Current interest to reduce CDF in plants developing a fire PRA

FAQ 08-0046, Incipient Fire Detection (2009)

- Provided an interim staff position regarding the use of VEWFD systems in fire PRA
- Determines the probability of non-suppression (P_{ns})
  - Event tree used to quantify
  - Structure and several parameter estimates based on EPRI 1016735
- Several limitations on use
  - Only electrical enclosure less than 250V
  - Only in-cabinet detection (not applicable to area-wide)
  - Fast acting components are ratio out
- FAQ based on NFPA standard objectives and system performance expectations provided by vendors.
  - DATA NEEDED

FAQ 08-0046 Simplified Event Tree

Fire Initiating Event	Detector System Availability and Reliability	Successful Operator Response to Alert	Fire Suppressed	End Point



Method results in P_{ns} of 0.02 or less

NRC/RES Confirmatory Research Program

- Initiated to provide data
- Evaluates
  - Operating experience (USA/Canada, Nuclear/Non-Nuclear)
  - Literature (vendor, journal, standard, listings, codes of practice)
  - Operator performance
  - System performance via testing
- Provides
  - Test results
  - Risk scoping study
    - Parameter estimates based on operating experience (fire events database), testing, fire PRA methodology
- Documented in NUREG-2180, DELORES-VEWFIRE

Experimental Approach

- Detectors
  - 5 ASD VEWFD systems
  - 1 VEWFD spot-type
  - 2 conventional
- Scales of testing
  - Laboratory
    - 1 small cabinet, 2 full size cabinets from Bellefonte
  - Full scale small room
    - 2 banks of up to 5 fully interconnected cabinets
    - Area-wide – ceiling & air return
  - Full scale
    - 2 banks of 5 cabinets with up to 3 partially interconnected
    - Area-wide – ceiling & air return

Laboratory Scale Testing
Small Cabinet

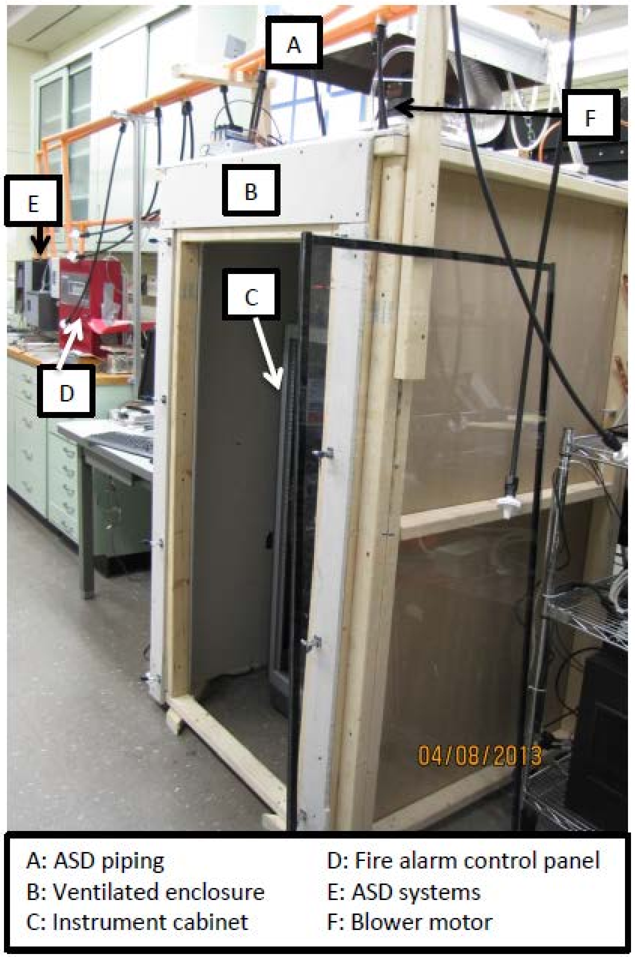


Figure 4-14. Laboratory instrument cabinet experimental configurati

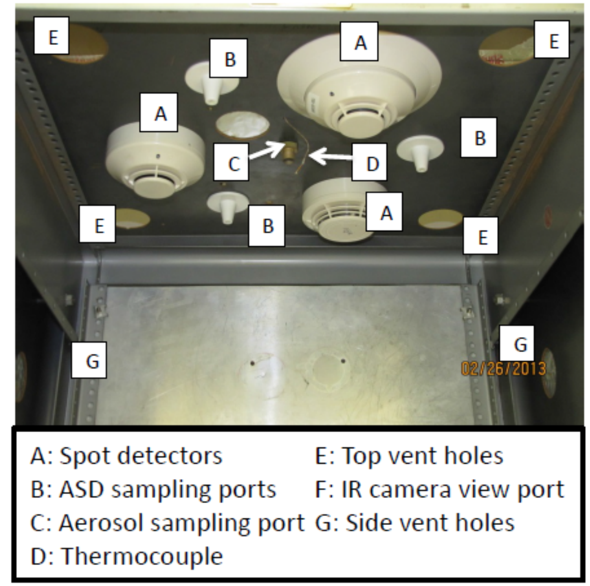


Figure 4-15. Instrument cabinet ceiling view

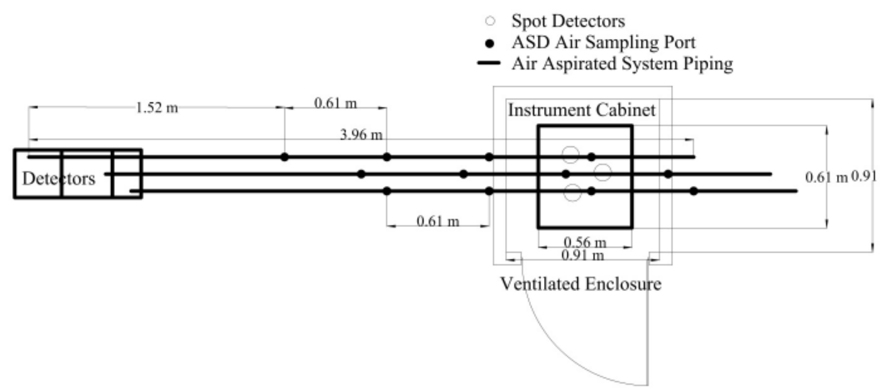
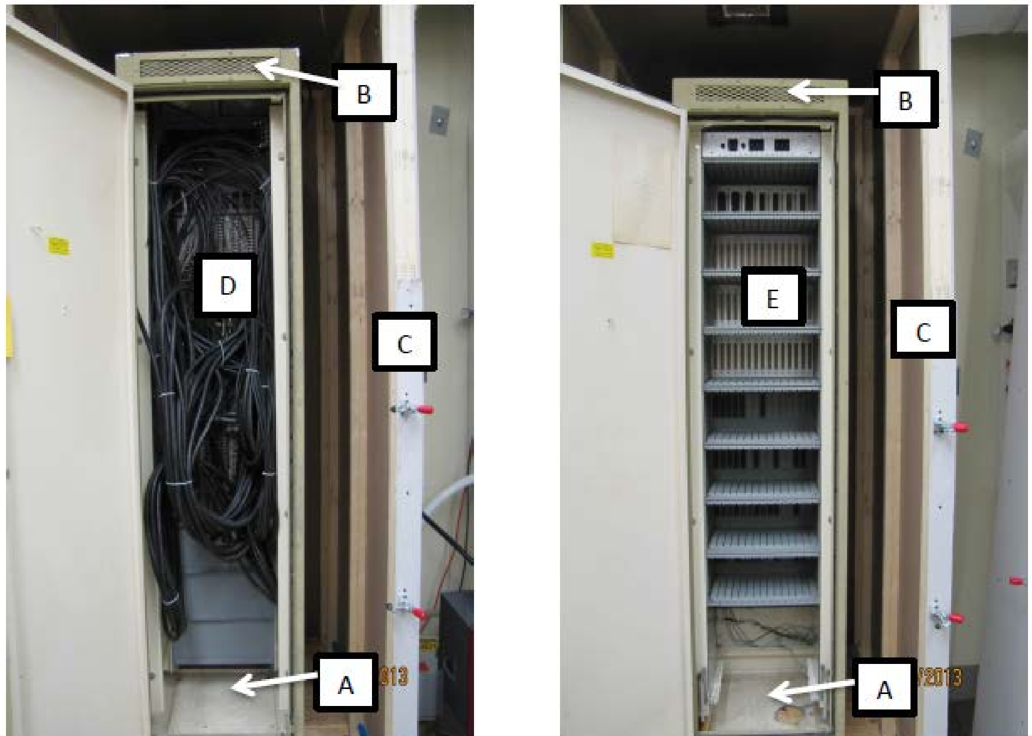


Figure 4-17. ASD pipe layout for the instrument cabinet experimental setup

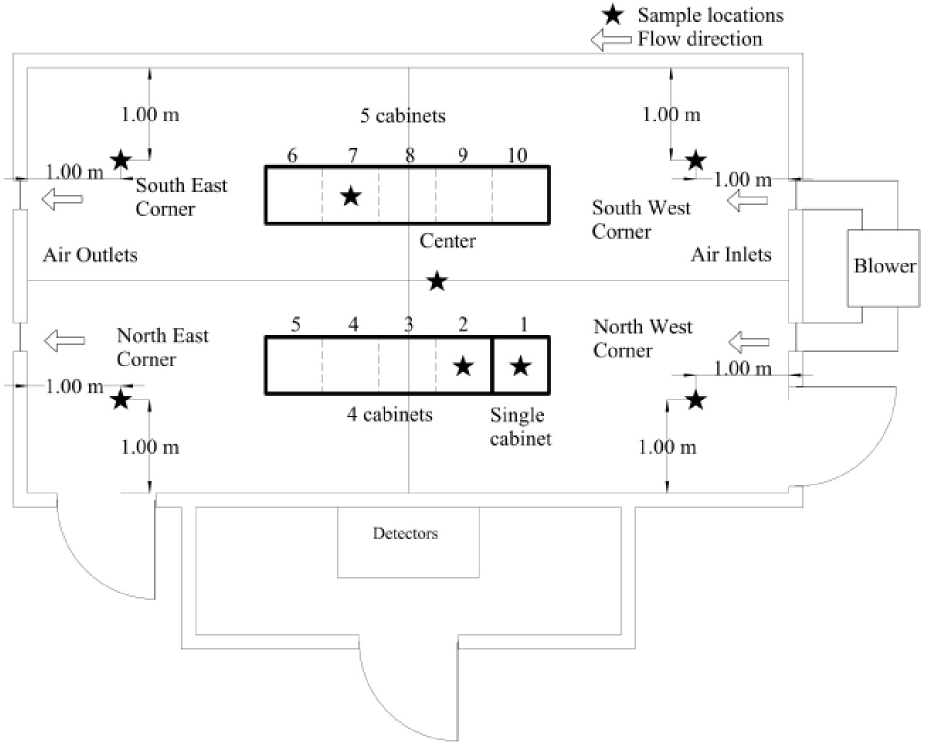
Laboratory Scale Testing Large Cabinets

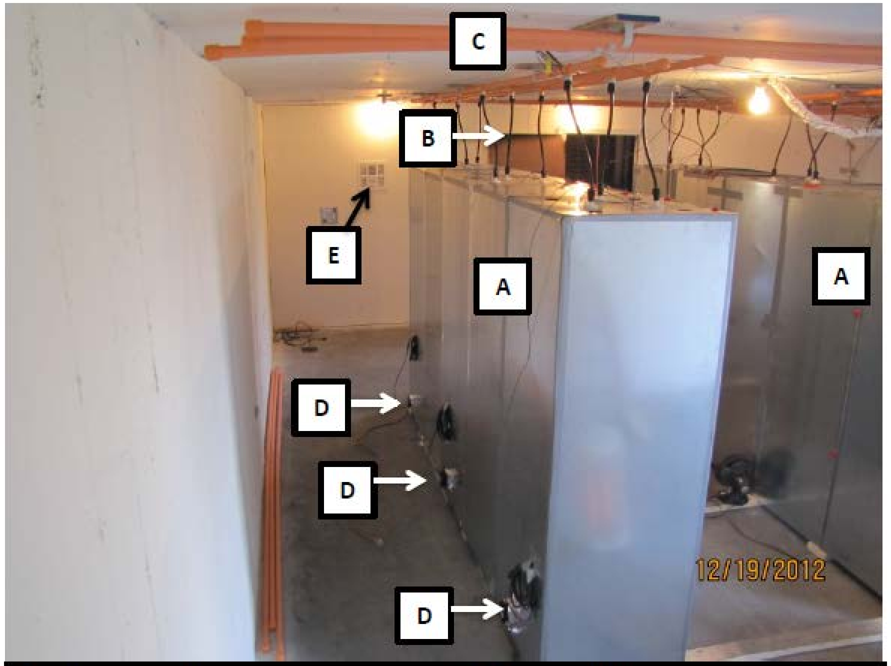


A: Source location
B: Air vents
C: Cabinet enclosure
D: Naturally ventilated cabinet
E: Force ventilated cabinet

Figure 4-19. NPP cabinets used in large cabinet experiments

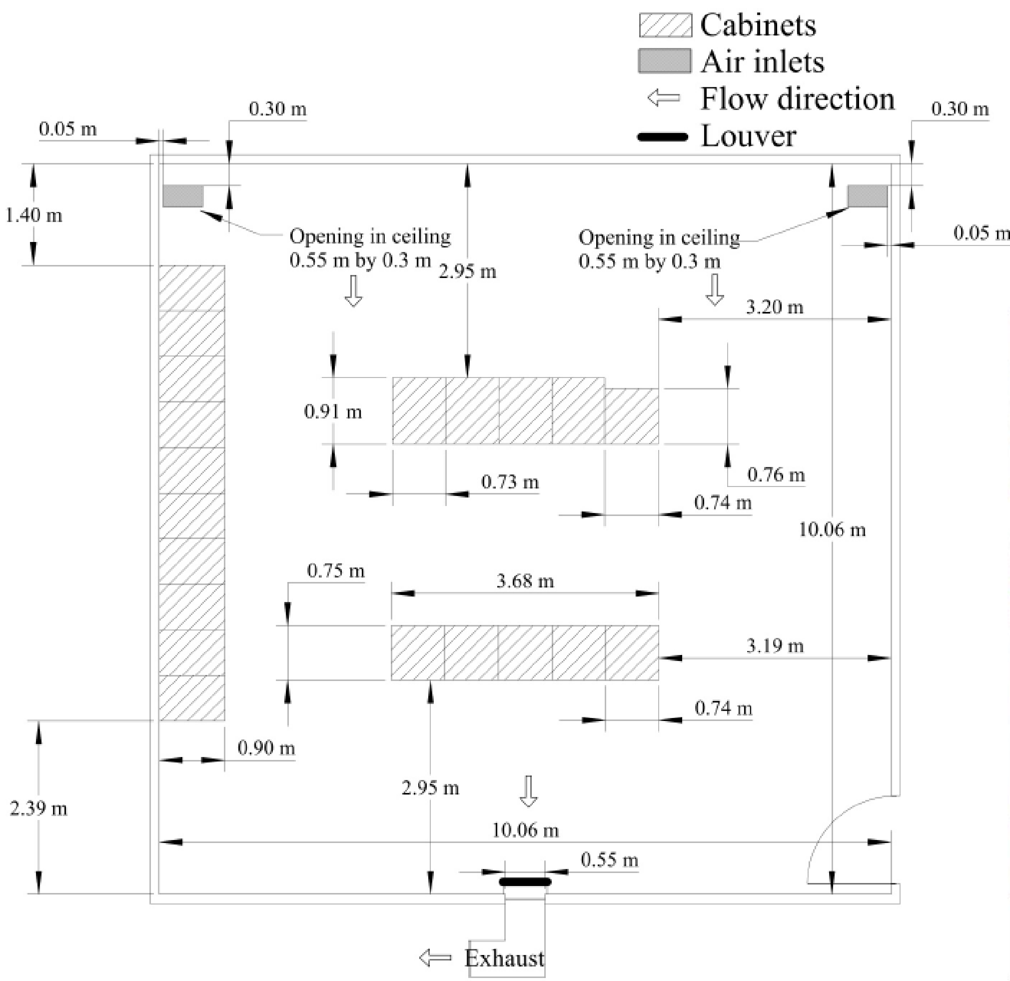
Full Scale – Small Room

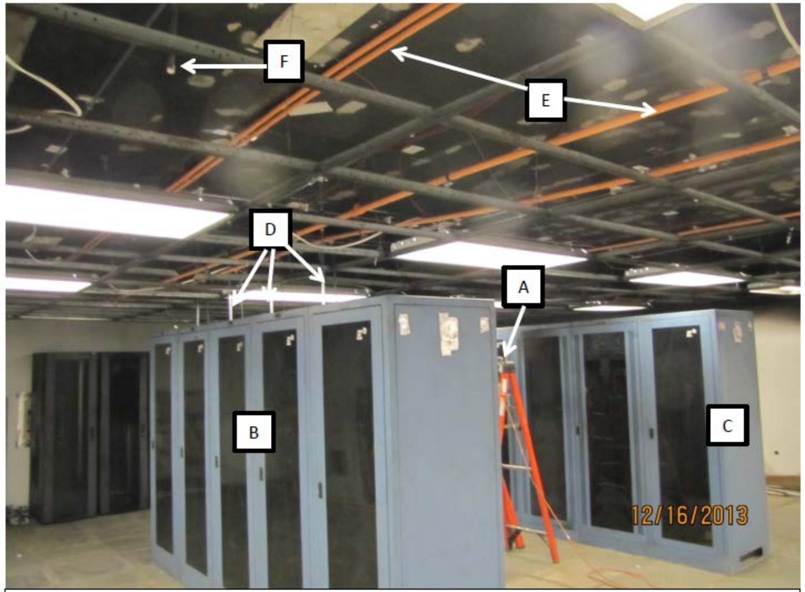




A: Cabinet mock-ups
B: Sampling tubes
C: ASD pipes
D: Cabinet ventilation fans
E: Room ventilation air inlet

Full Scale – Large Room

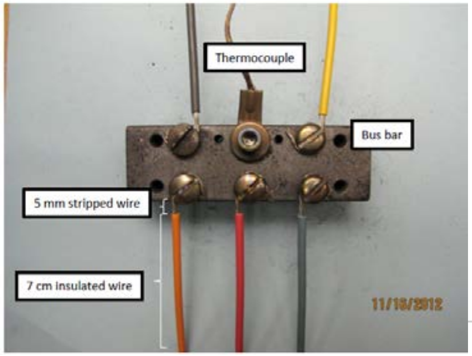


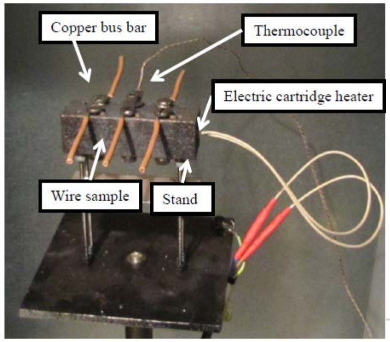


A: Source location
B: Test Cabinets, Instrumented
C: Test Cabinets, Not instrumented
D: In-Cabinet ASD Sampling Lines
E: Area-wide ASD piping
F: Area-wide sampling port

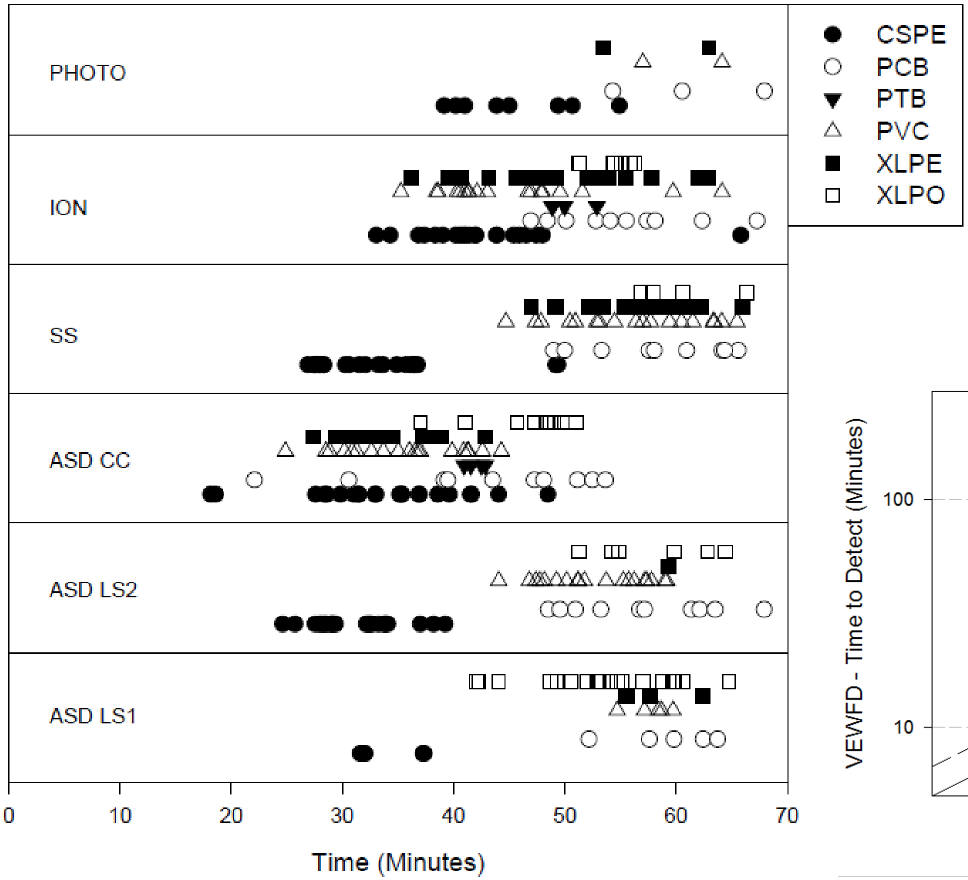
Smoke Source

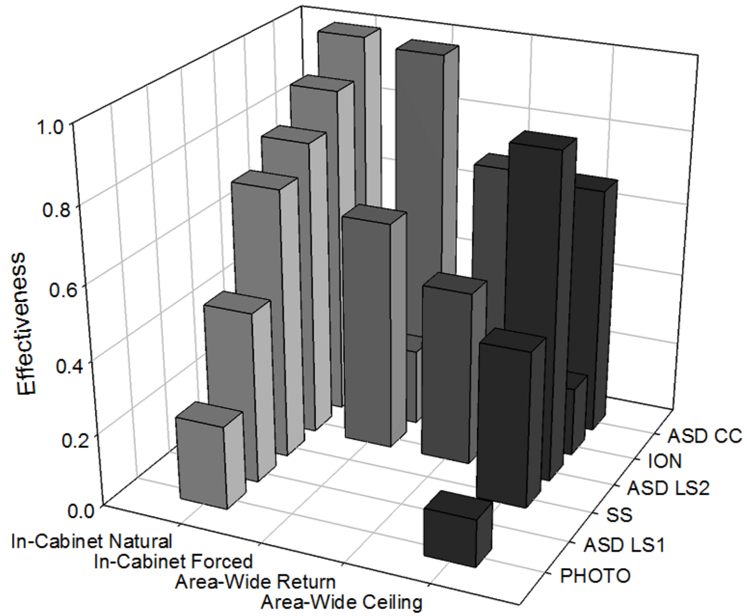
- Had to be developed to mimic a prolonged overheating incipient stage condition
  - Cartridge heater in copper bus bar with material attached to exterior
  - Material is elevated to piloted ignition temperatures
  - Modified cable bundle used in some tests
  - 3 heating ramp periods (HRPs), 15-, 60-, 240-minutes

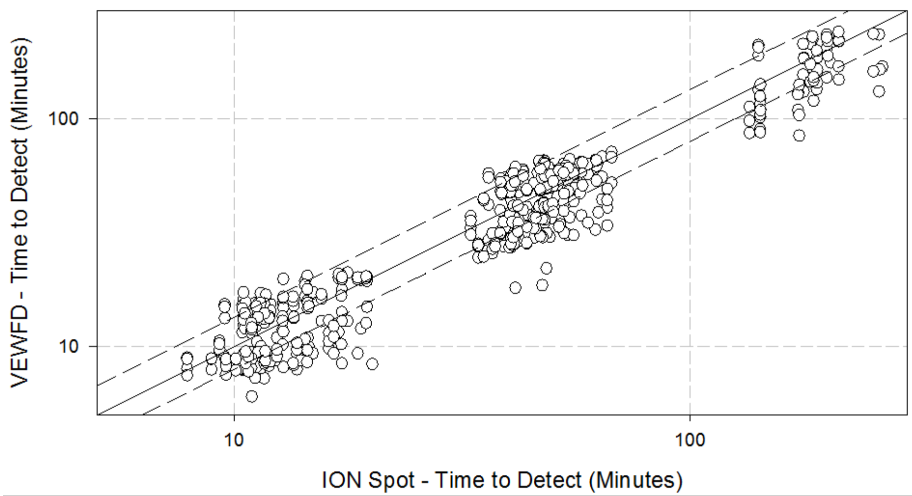




Generic Results



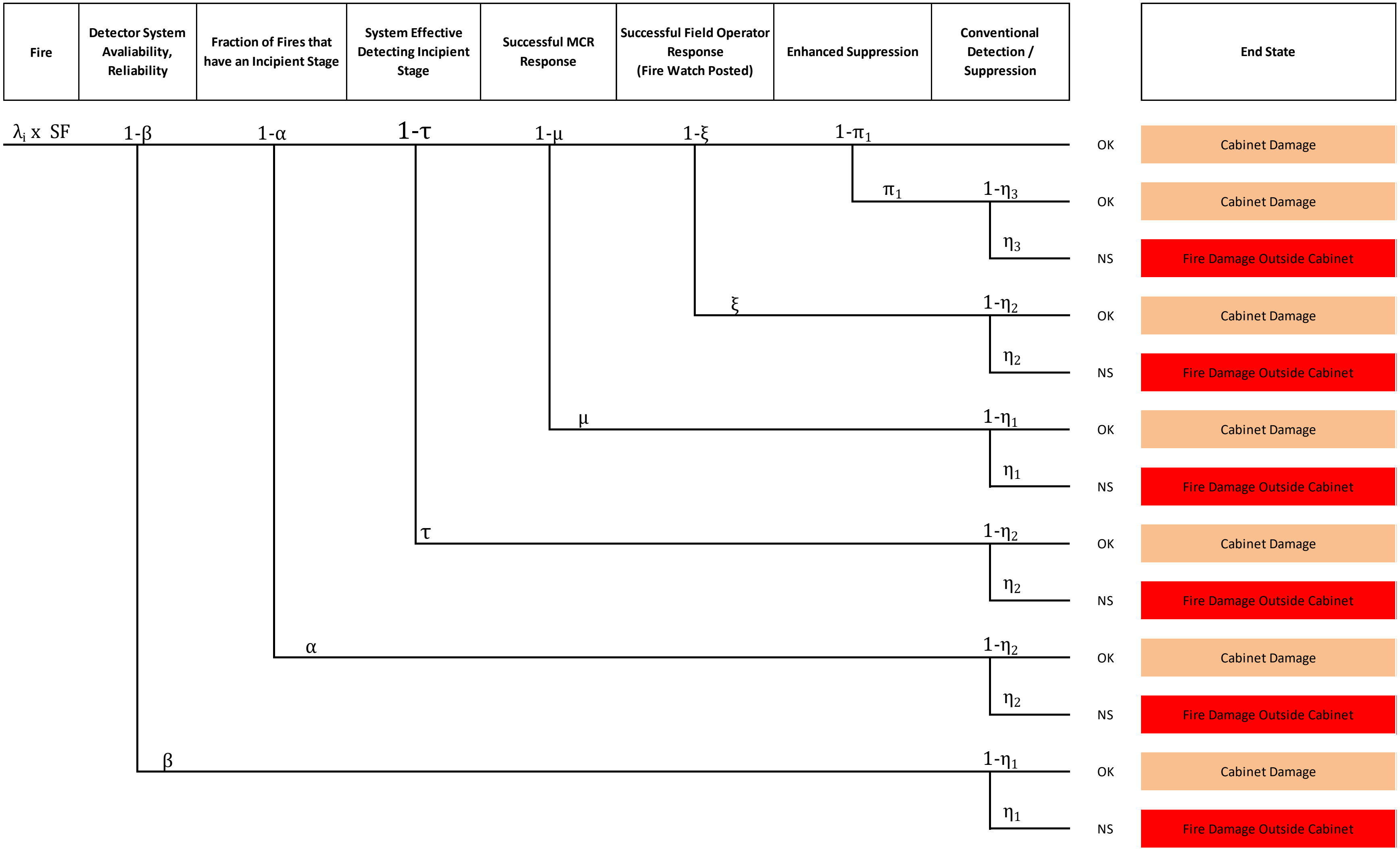




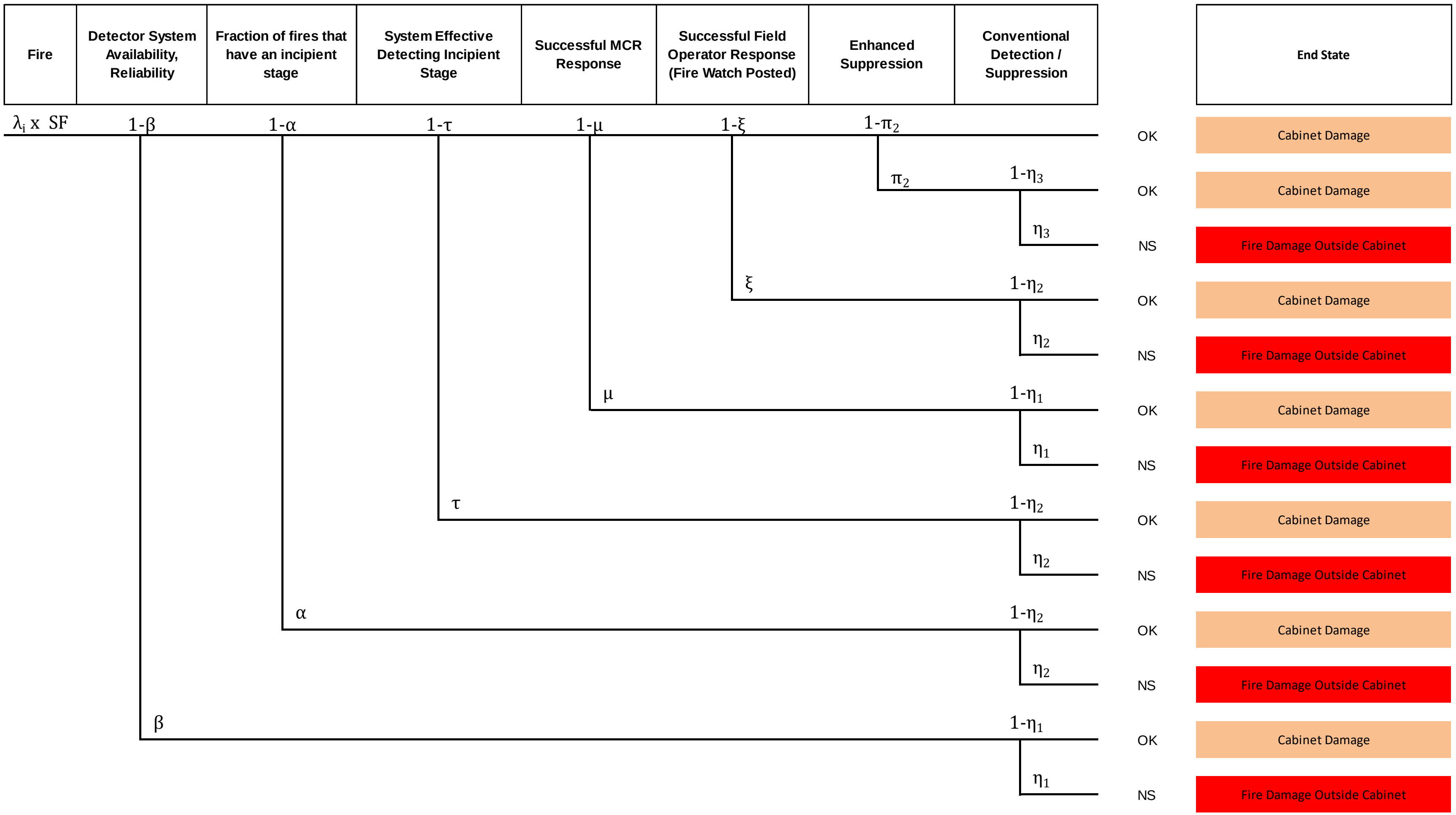
Risk Scoping Study

- Quantify probability of non-suppression (P_{ns}) using event tree model
- Event tree parameters estimated using available operating experience, test data, human reliability engineering tools, and non-suppression curves.
- Two Event Trees
  - In-Cabinet
  - Area-wide

In-Cabinet Event Tree



Area-Wide Event Tree



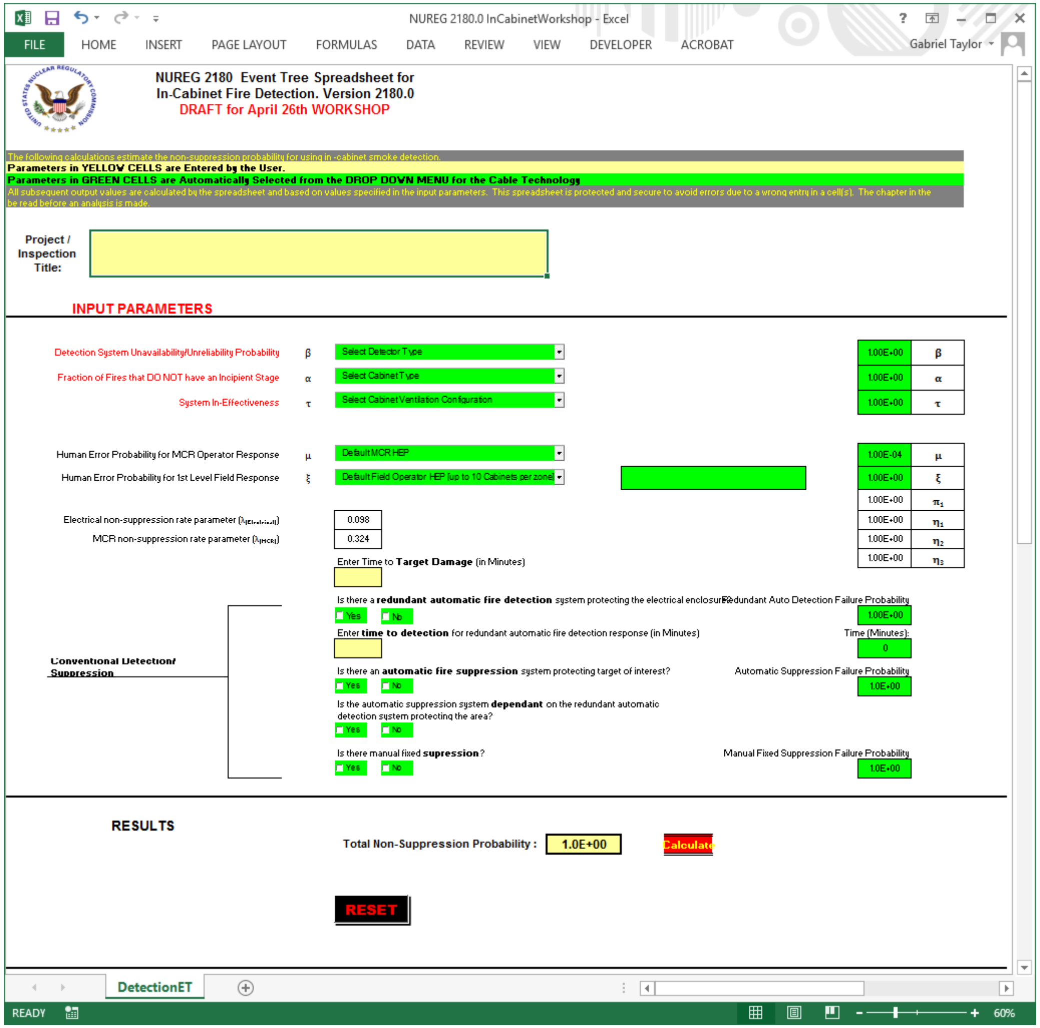
Conclusions

- For area-wide applications, the ASD VEWFD systems outperformed conventional spot-type detectors
- For in-cabinet applications, the ASD VEWFD systems performed inline with in-cabinet ionization detectors
- Risk scoping study provides a more detailed evaluation of the performance of smoke detection systems used to protect electrical enclosures
- The P_{ns} estimated by the risk scoping study is more scenario specific and time dependent, rather than a one size fits all approach (FAQ 08-0046)

Research Insights

- %/ft. obscuration may not be the best metric to evaluate the generic performance of VEWFD systems
  - Smoke characteristics vary by material, degradation rate and mode
  - Light scattering may perform better detecting large particles (e.g., CSPE), while cloud chamber/ion may perform better detecting a large number of small particles (e.g., ETFE)
- Cloud chamber difficult to verify system meets NFPA 76 sensitivity settings

Spreadsheet Tools Available



Format

- Two Sheets (in-cabinet; area-wide)
- Follows NUREG-1805 approach
  - Inputs
  - Results
  - Solved Event Trees
- Estimates the P_{ns} for damage outside cabinet
- Application specific damage states not addressed

Appendix H

- User guide for VEWFD event tree non-suppression probability calculation tool
- Provides a step-by-step procedure for using the excel spreadsheets.

NUREG-2180 Public Comments

- Draft Report – July 7, 2015
  - Federal Register Notice (80 FR 38755)
  - 60 Public Comment Period
  - 207 External Comments
  - 45 Internal Comments
- 47 Duplicate Comments
- Remaining 205 Comments
  - Clarification (63)
  - Technical (85)
  - Editorial (55)
  - Supplemental Information (2)

NUREG-2180 Current Status

- Public Meeting – April 26, 2016
  - Report Overview
  - Resolution of Public Comments
  - Additional Operating Experience
- Industry Pilot in Progress
  - Results of table top exercise will be added as an appendix to the final report
  - Pilot should be completed July 31, 2016

Reminder

NUREG-reports are a technical document

NUREG-reports do not constitute regulatory guidance, unless endorsed via a RG or other means (SER, etc.)

Module III – Fire Analysis

Task 11 – Special Models
Part 1: Cables Fires, Cabinet Fire Spread, High Energy Arc Faults, Passive Barriers

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

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

Module III – Fire Analysis

Task 11 – Special Models
Part 1a: Cables Fires

Joint EPRI/NRC-RES Fire PRA Workshop
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Fire Models

- Generally computational fire models are developed to estimate extent and timing of fire growth

- There are fire scenarios critical to NPP applications that are beyond capability of existing computational fire models
  – Special models are developed for prediction of consequences of such scenarios, based on a combination of:
    - Fire experiments,
    - Operating experience, actual fire events
    - Engineering judgment

Special Models

- Cable fires (modified from IPEEE approaches)
  - Cable tray stack and fire spread models
- High energy arcing faults (new)
  - Switchgear room
- Fire propagation to adjacent cabinets (consolidation)
  - Relay room
- Passive fire protection features (consolidation)

Special Models (Part 2)

- Main control board (new)
- Hydrogen fires (new)
- Turbine generator fires (new)

Cable Fires

- No generalized analytical theory is available to accurately model cable fires in all possible configurations in commercial nuclear plants.
- Most of the information compiled for Appendix R of NUREG/CR-6850 is in the form of flammability parameters derived from experiments or correlations also developed from experimental data.
- The amount of experimental evidence and analytical tools available to model cable tray fires is relatively small when compared to the vast number of possible fire scenarios that can be postulated for NPPs
- Simplification of these scenarios will be needed

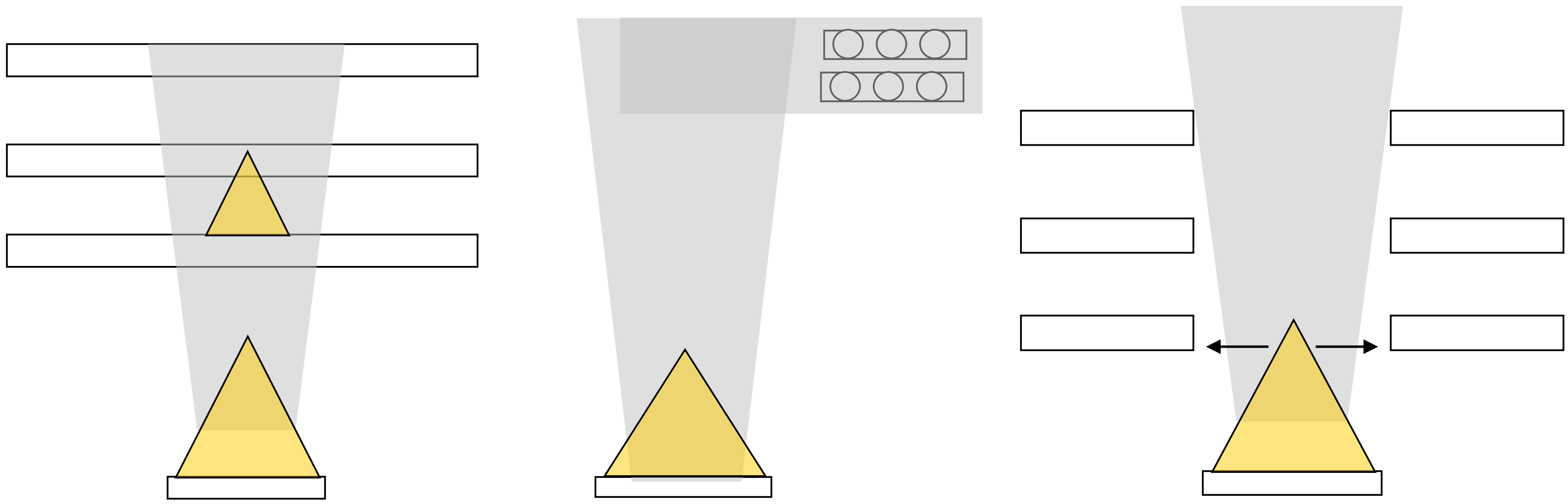
Cable Fires

Scenarios involving cable fires may start as:

- Self-ignited cable fires
  - Postulate self ignited cable fires in unqualified cables only
  - Self ignited cable fires should be characterized by a cable mass ratio (mass of cables in the room / mass of cables in the plant) representative of the scenario.
  - Cable mass ratio is equivalent to the severity factor
- Or as secondary fires caused by fixed or transient fire sources
  - Cable fires caused by welding & cutting should be postulated in both qualified and unqualified cables.

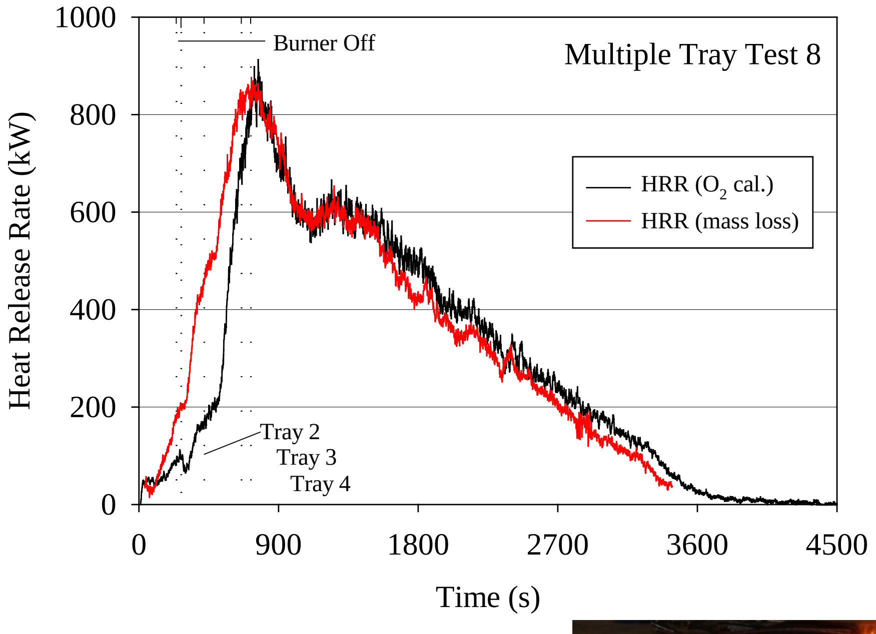
Cable Fires

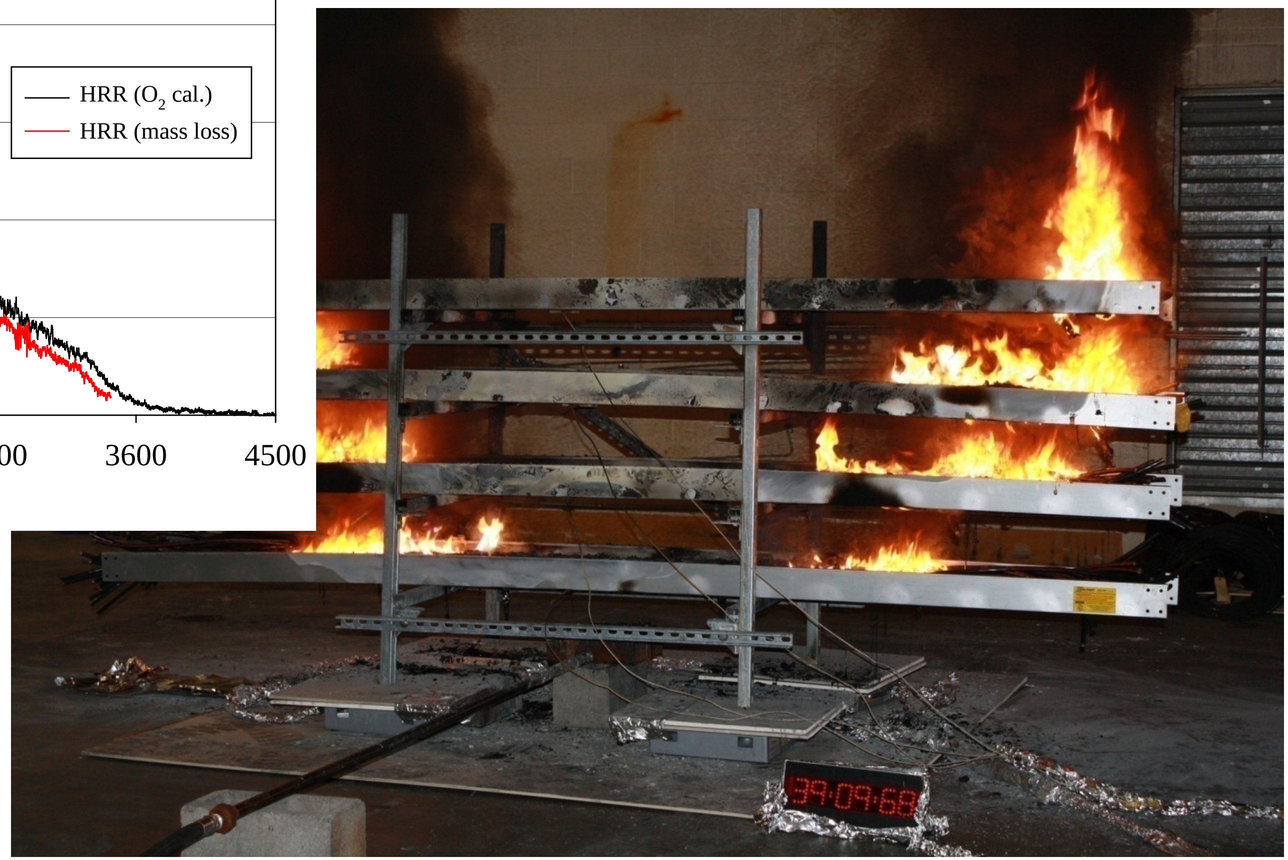
Cable tray ignition: Simplified cases



Thermoplastic Cable

CHRISTIFIRE Report, NUREG/CR-7010





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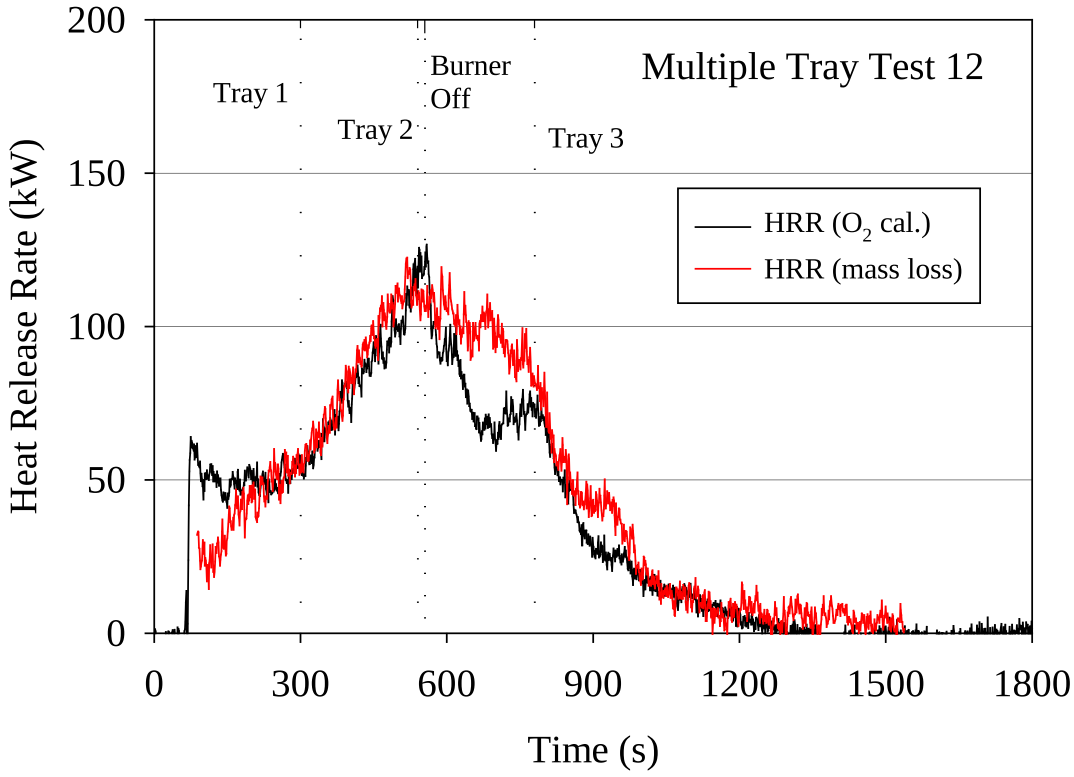
Protecting People and the Environment

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Thermoset Cable



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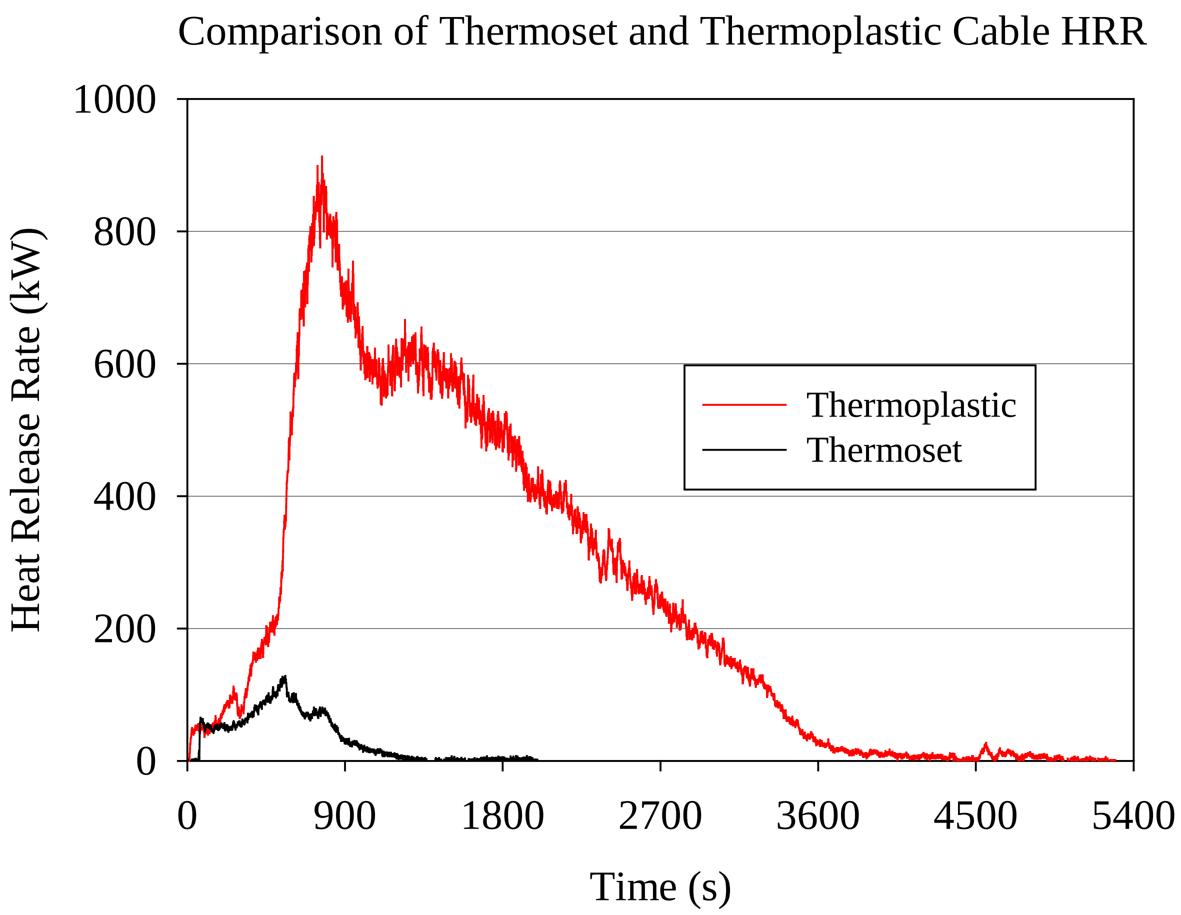
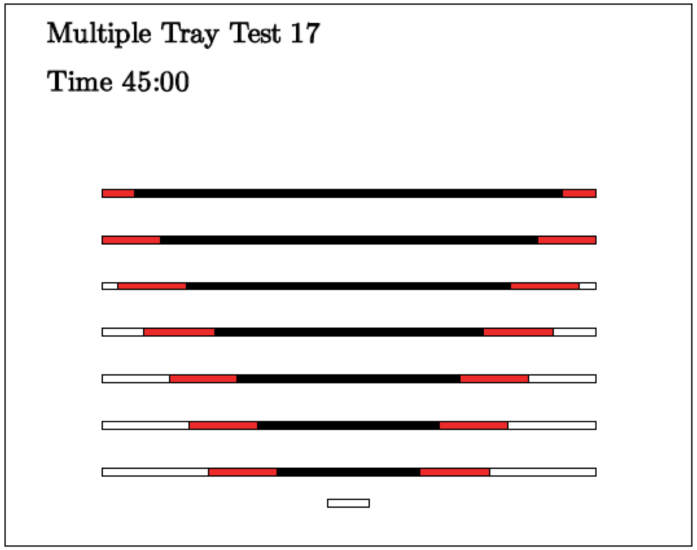
Example: Thermoset vs. Thermoplastic

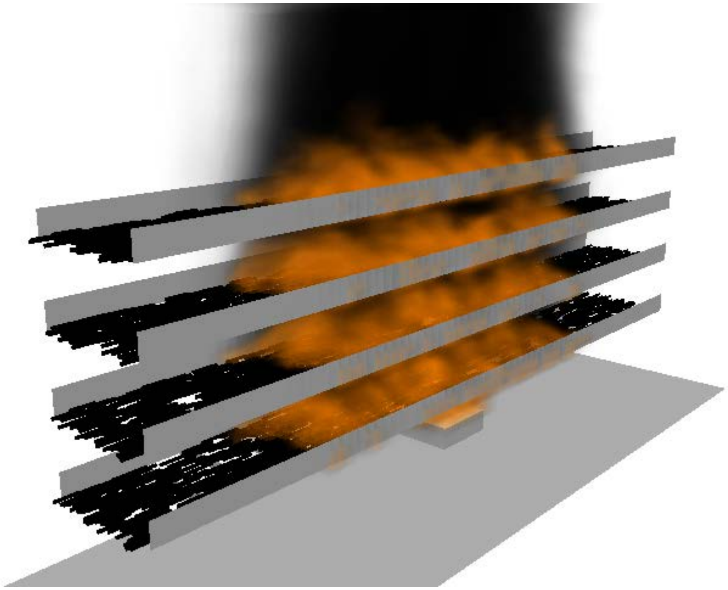


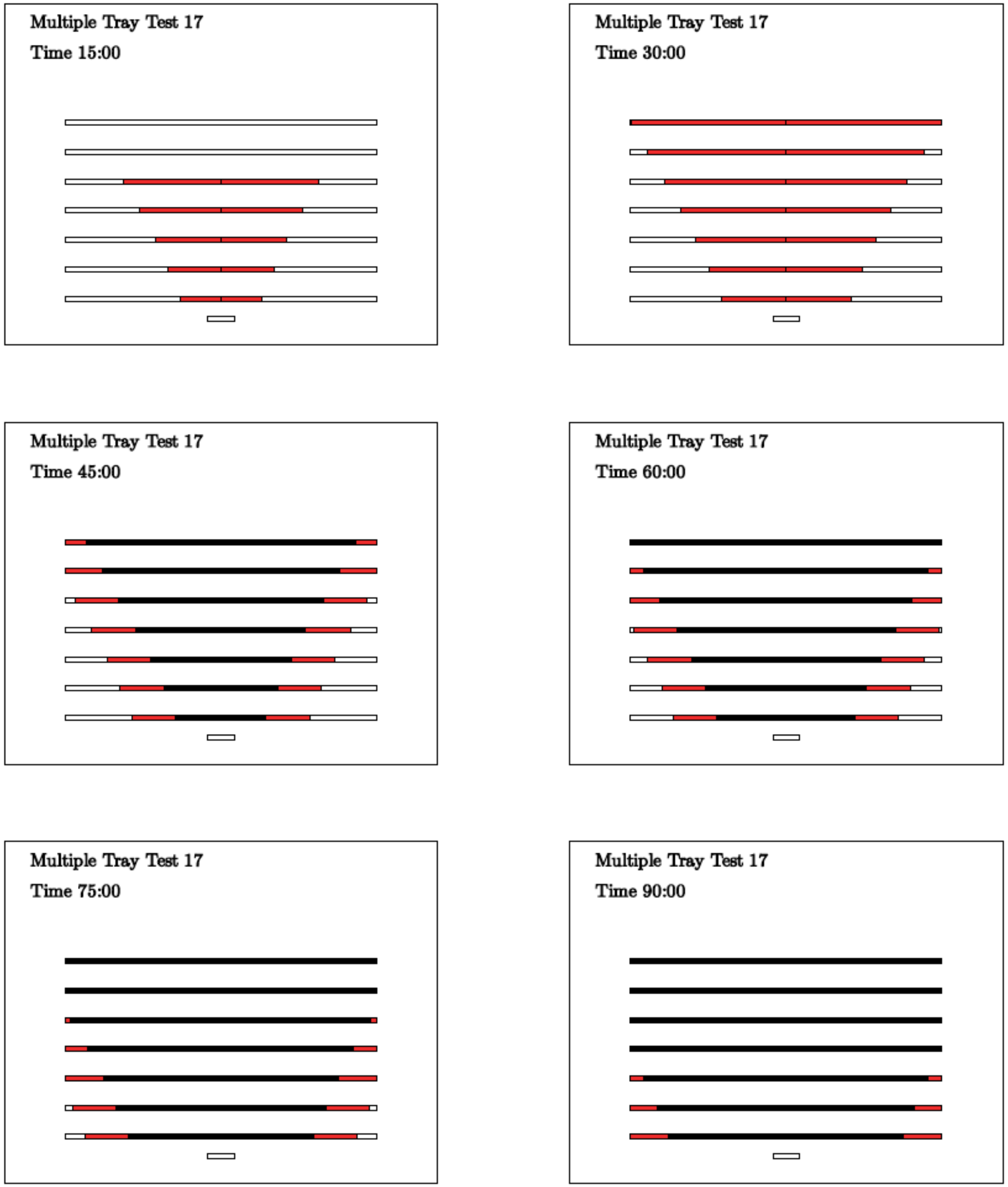
Modeling

The Easy Way



The Hard Way





FLASH-CAT

Flame Spread over Horizontal Cable Trays

Required Data

Cable mass/length

Non-metal mass fraction

Ignition

5-4-3-2-1 minute rule

Upward Spread

35° spread angle

Burning Rate

250 kW/m^2 thermoplastics

150 kW/m^2 thermosets

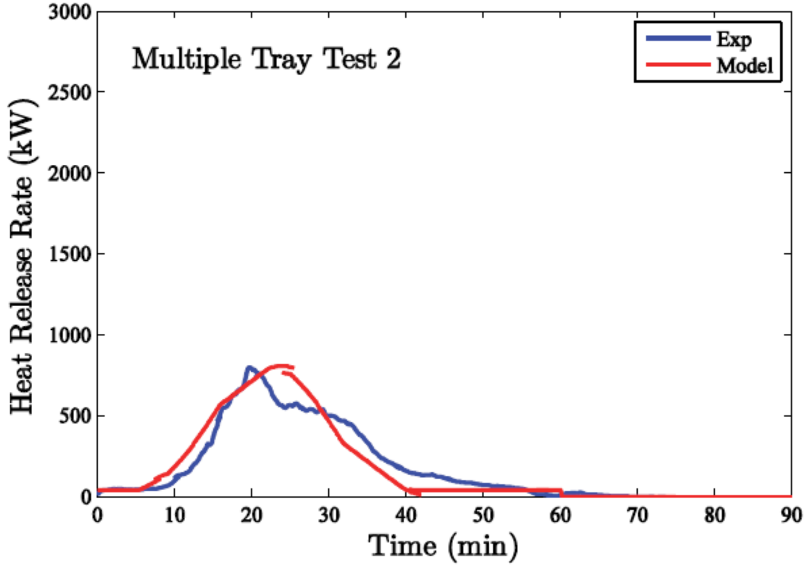
Lateral Spread

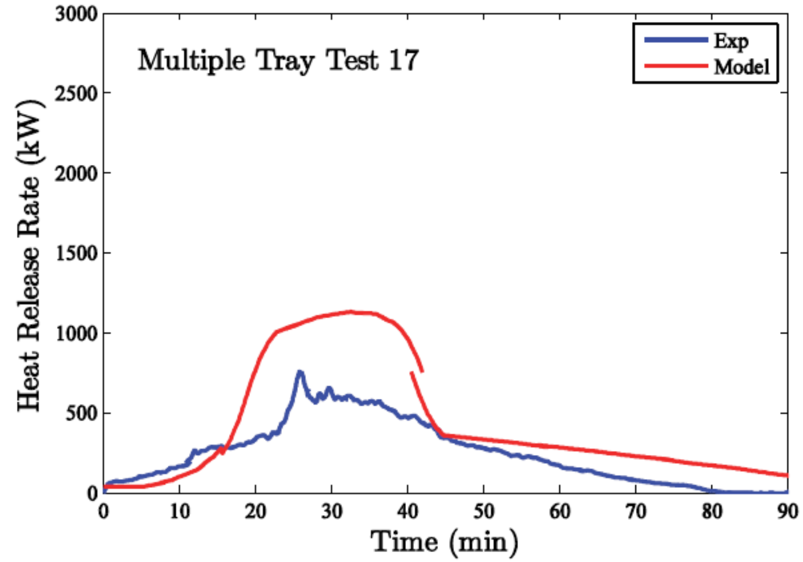
3.2 m/h thermoplastics

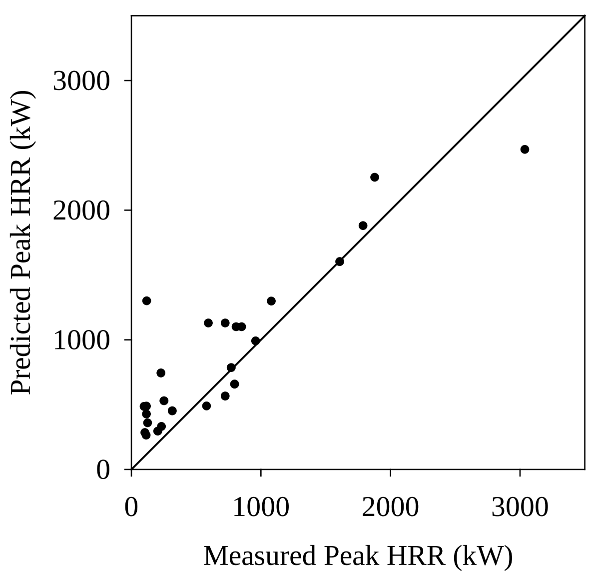
1.1 m/h thermosets

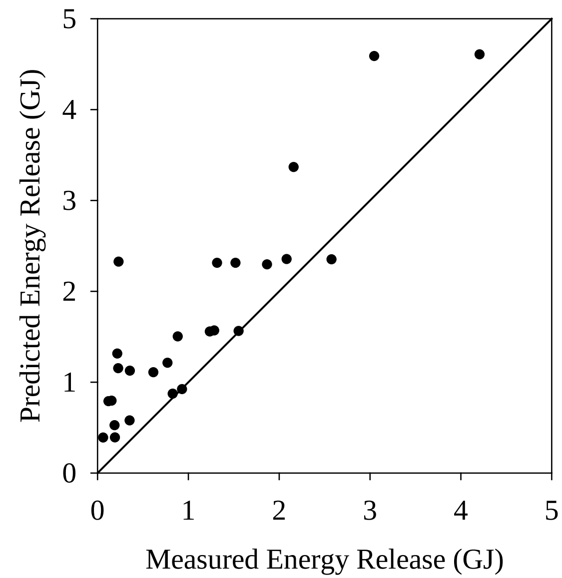
Heat of Combustion

16 MJ/kg for all


Multiple Tray Test 2
Exp
Model
Heat Release Rate (kW)
Time (min)
0
500
1000
1500
2000
2500
3000
0
10
20
30
40
50
60
70
80
90


Multiple Tray Test 17
Exp
Model
Heat Release Rate (kW)
Time (min)
0
500
1000
1500
2000
2500
3000
0
10
20
30
40
50
60
70
80
90


Predicted Peak HRR (kW)
Measured Peak HRR (kW)
0
1000
2000
3000
0
1000
2000
3000


Predicted Energy Release (GJ)
Measured Energy Release (GJ)
0
1
2
3
4
5
0
1
2
3
4
5

Cable Fires

Modeling cable fires- Appendix R of NUREG/CR-6850

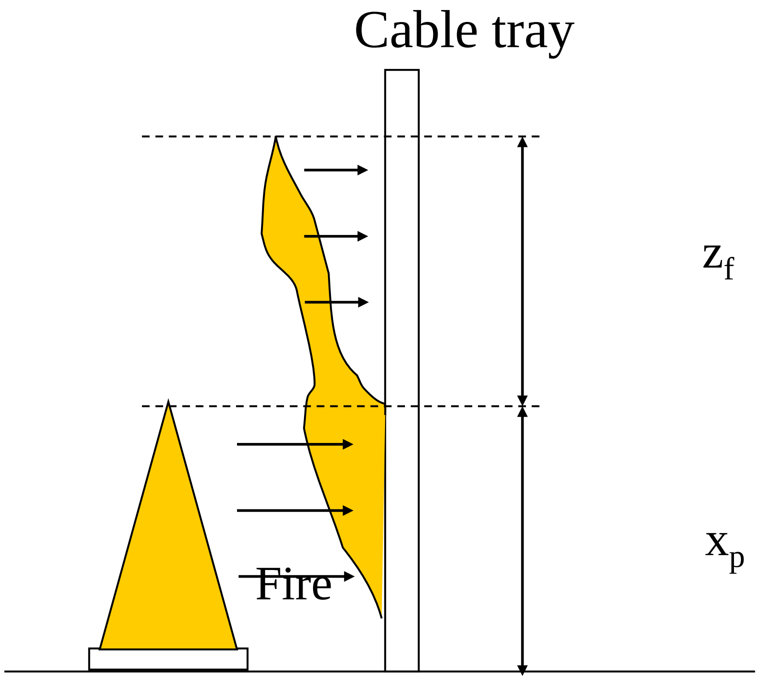
- Cable tray heat release rate using bench scale data
  - Replaced with the modeling approach in CHRISTIFIRE Report
- Horizontal Flame spread rates
  - Similar to the ones observed in the CHRISTIFIRE fire test series
- Fire propagation in cable trays
  - Similar to the ones observed in the CHRISTIFIRE fire test series

Cable Fires

Flame spread

- k_f is a constant with a value of 0.01 m^2/kW

$$z_f = x_p \cdot \left(k_f \dot{Q}'' - 1\right)$$

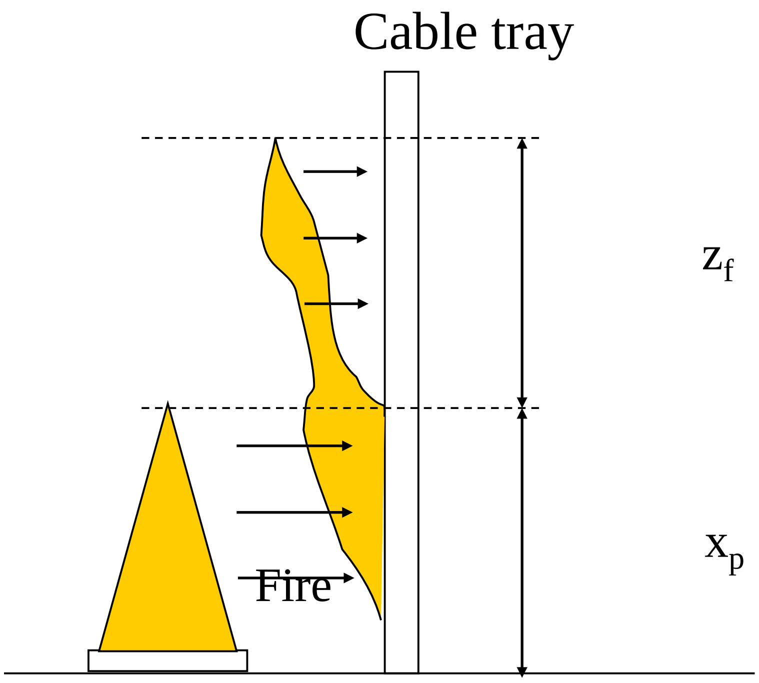


Cable Fires

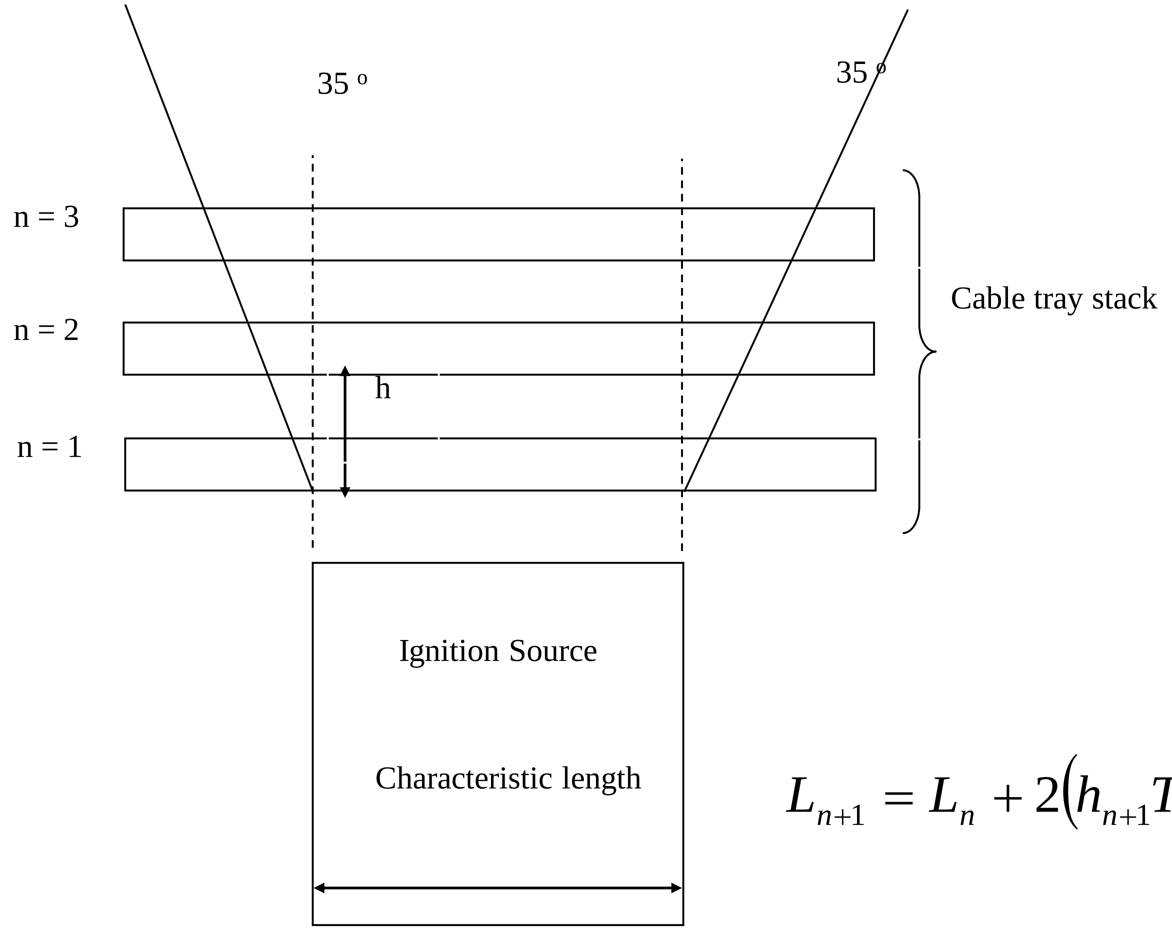
Flame spread model

$$v = \frac{4\left(\dot{q}''_f\right)^2 \delta_f}{\pi (k\rho c)\left(T_{ig} - T_{amb}\right)^2}$$

- Horizontal trays
  - δ is assumed to be 2 mm
  - q" is assumed as 70 kW/m^2
- Vertical trays
  - δ is assumed to be z_f
  - q" is assumed as 25 kW/m^2



Fire Propagation in Cable Tray Stacks With RG 1.75 Separation (1 of 3)



$$L_{n+1} = L_n + 2\left(h_{n+1} Tan\left(35^o\right)\right)$$

Fire Propagation in Cable Tray Stacks With RG 1.75 Separation (2 of 3)

- First tray to second tray: 4 minutes after ignition of first tray
- Second tray to third tray: 3 minutes after ignition of second first tray
- Third tray to fourth tray: 2 minutes after ignition of third tray
- Fourth tray to fifth tray: 1 minute after ignition of fourth tray
- Balance of trays in stack: 1 minute after ignition of fifth tray

Fire Propagation in Cable Tray Stacks With RG 1.75 Separation (3 of 3) (cont'd)

- If there is a second stack of cable trays next to the first stack, spread to the first (lowest) tray in the second stack will be assumed to occur concurrent with spread of fire to the third tray in the original stack .
- Subsequent spread of fire in the second stack will mimic the continued growth of fire in the first stack (e.g., the second tray in the second stack will ignite within 2 minutes of the first tray in the second stack - at the same time as the fourth tray in the first stack.)
- Fire spread will occur at the same rate to stacks on either or both sides of the original stack

FAQ 08-0049: "Cable Tray Fire Propagation"

- Purpose & Scope
  - Clarify use of the empirical model for fire propagation within a cable tray stack as presented in Appendix R of NUREG/CR-6850 – EPRI 1011989
  - The clarifications in the FAQ are limited to the use of the empirical model for fire propagation in a cable tray stack

- Reference:
  - EPRI 1019259, Supplement 1 to NUREG/CR-6850

FAQ 08-0049: Solution

- The FAQ clarifies that the model for fire propagation among cable trays should be used only for the configurations described in Appendix R of NUREG/CR-6850
  - Angle of propagation
  - Rate of propagation
  - Cable tray stacks within the zone of influence
- DO NOT extend the model beyond, <u>at most,</u> three cable tray stacks

FAQ 08-0049: Ongoing and Future Work

- NRC has been doing research program to assess cable tray fire behavior (NIST)
  - Full scale testing of fire propagation in cable trays
  - Test for different cable types
  - Measuring both heat release rate and flame propagation rates
  - Intent is to develop better models and guidance for predicting cable fire behavior
- First phase complete
  - See CHRISTIFIRE NUREG/CR-7010 vol. 1
- Second phase complete
  - See CHRISTIFIRE NUREG/CR-7010 vol. 2
- Third phase in progress
  - See CHRISTIFIRE NUREG/CR-7010 vol. 3

CHRISTIFIRE 2, Corridor Cable Fires

CHRISTIFIRE 2

Vertical Cable Fires

Module III – Fire Analysis

Task 11 – Special Models
Part 1b: High Energy Arc Fault (HEAF) Fires

Joint EPRI/NRC-RES Fire PRA Workshop
July 15-19, 2019

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High Energy Arcing Faults (1 of 15)

Definition

- Rapid release of electrical energy in the form of heat, vaporized copper, and mechanical force.
- An arc is a very intense discharge of electrons between two electrodes that are carrying an electric current. The arc is created by the flow of electrons through charged particles of gas ions that exist as a result of vaporization of the conductive material.

High Energy Arcing Faults (2 of 15)

Scope:

- Switchgears
- Load centers
- Bus bars

Greater than or equal to 440 V

- Oil filled outdoor transformers are addressed separately
- Bus ducts are addressed separately (via FAQ 07-0035)

High Energy Arcing Faults (3 of 15)

General characteristics of switchgear based HEAF events (from FEDB)

- Indications of heavy smoke in the area, which may delay identification of the fire origin and whether the fire is still burning
- In nearly all of these events, the HEAF initiates in the feed breaker cubicle, because this is where most of the electrical energy in a high-energy cabinet resides
- HEAFs occurring in 480V switchgears did not report damage beyond the switchgear itself, but some resulted in the cabinet opening

High Energy Arcing Faults (4 of 15)

General characteristics of HEAF events (from FEDB)

- Initial use of fire extinguishers may be ineffective in severe HEAF events regardless of the extinguishing agent (CO_2, Halon, or dry chemical). The fires were eventually suppressed with water by the fire brigade
- No conclusions can be made regarding the effectiveness of fixed fire suppression systems for the ensuing fire. Only one event was successfully suppressed, with an automatic Halon system
- Durations of the fires involving HEAF range from minutes to over an hour. The short durations generally reflect events that do not result in large ensuing fire(s), either in the device itself or external fires.

High Energy Arcing Faults (5 of 15)

General characteristics of HEAF events (from FEDB)

- Sustained fires after the initial HEAF involve combustible materials (cable insulation, for the most part) near the cabinet
- Damage may extend to cables and cabinets in the vicinity of the high-energy electrical cabinet
- Damage to cabinet internals and nearby equipment (if observed) appears to occur relatively early in the event

High Energy Arcing Faults (6 of 15)

The arcing or energetic fault scenario in these electrical devices consists of two distinct phases, each with its own damage characteristics and detection/suppression response and effectiveness.

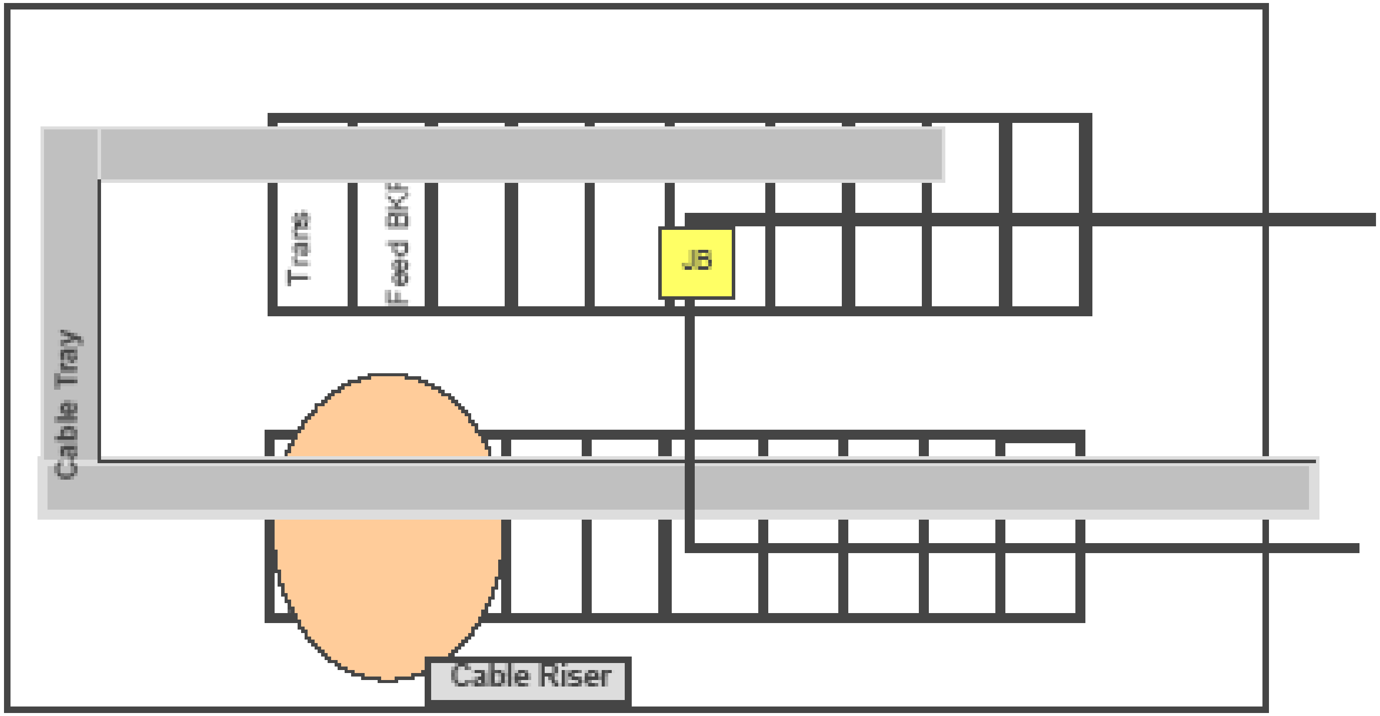
- The first phase is a short, rapid release of electrical energy followed by ensuing fire(s) that may involve the electrical device itself, as well as any external exposed combustibles, such as overhead exposed cable trays or nearby panels, that may be ignited during the energetic phase.

High Energy Arcing Faults (6 of 15) (cont'd)

- The second phase, i.e., the ensuing fire(s), is treated similar to electrical cabinet fires described here, with one distinction. Any closed electrical cabinet subject to a HEAF is opened to a fully ventilated fire. In dealing with postulated switchgear and load center fires, both phases should be considered.

High Energy Arcing Faults (7 of 15)

The zone of influence



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High Energy Arcing Faults (8 of 15)

High-Energy Phase: The zone of influence

- The initial arcing fault will cause destructive and unrecoverable failure of the faulting device, e.g., the feeder breaker cubicle, including the control and bus-bar sections.
- The next upstream over-current protection device in the power feed circuit leading to the initially faulting device will trip open, causing the loss of all components fed by that electrical bus. This fault may be recoverable if the initial faulting device can be isolated from the feeder circuit.
- The release of copper plasma and/or mechanical shock will cause the next directly adjoining/adjacent switchgear or load center cubicles within the same cabinet bank and in all directions (above, below, to the sides) to trip open.

High Energy Arcing Faults (9 of 15)

High-Energy Phase: The zone of influence

- Any unprotected cables that drop into the top of the panel in an open air-drop configuration will ignite
  - Cables in conduit or in a fire wrap are considered protected in this context. In other words, if cables are protected (i.e., not exposed) by conduit or fire wrap, they are assumed damaged, but not ignited, and they do not contribute to the fire load.
  - Armored cables with an exposed plastic covering are considered unprotected in this context.
- Exposed cables, or other exposed flammable or combustible materials or transient fuel materials located within this same region (0.9 m (*3′*) horizontally) will be ignited

High Energy Arcing Faults (10 of 15)

High-Energy Phase: The zone of influence

- Any unprotected cables in the *first* overhead cable tray will be ignited concurrent with the initial arcing fault provided that this first tray is within 1.5 m (*5′*) vertical distance of the top of the cabinet. The cable tray fire will propagate to additional trays consistent with the approach provided for the treatment of cable tray fires elsewhere in this document, assuming that the time to ignition of the first tray is zero rather than the normal 5 minutes.
  - This applies to any cable tray located directly above the panel.
  - This applies to any cable tray above the aisle way directly in front of, or behind, the faulting cabinet, provided some part of that tray is within 0.3 m (12") horizontally of the cabinet's front or rear face panel.
  - Cables in conduit or in a fire wrap are considered protected in this context.
  - Armored cables with an exposed plastic covering are considered unprotected in this context

High Energy Arcing Faults (11 of 15)

High-Energy Phase: The zone of influence

- Any vulnerable component or movable/operable structural element located within 0.9 m (*3'*) horizontally of either the front or rear panels/doors, and at or below the top of the faulting cabinet section, will suffer physical damage and functional failure.
  - This will *include* mobile/operable structural elements like fire dampers and fire doors.
  - This will *include* potentially vulnerable electrical or electromechanical components such as cables, transformers, ventilation fans, other cabinets, etc.
  - This will *exclude* fixed structural elements such as walls, floors, ceilings, and intact penetration seals.
  - This will *exclude* large components and purely mechanical components such as large pumps, valves, major piping, fire sprinkler piping, or other large piping (1" diameter or greater).
  - This may *include* small oil feed lines, instrument air piping, or other small piping (less than 1" diameter).

High Energy Arcing Faults (12 of 15)

Detection and Suppression

- The amount of smoke from any damaging HEAF event is expected to activate any smoke detection system in the area
- Manual suppression by plant personnel and the fire brigade may be credited to control and prevent damage outside the initial ZOI from ensuing fires
- Separate suppression curves are developed for these fires documented in Appendix P to the Fire Modeling procedure
  - NSP rates updated in NUREG-2169 (EPRI 3002002936)
  - Revised HEAF NSP in 17-0013 (ML18075A083)

High Energy Arcing Faults (13 of 15)

Modeling HEAF in the Fire PRA

- Identify the equipment in the room where a HEAF can be generated. As indicated earlier, this equipment includes, for the most part, 4160 V to 440 V switchgear cabinets, load centers, and bus bars

- Two types of initiating events should be postulated for each identified equipment:
  - A HEAF event with an ensuing fire, and
  - A regular equipment fire (no HEAF)

High Energy Arcing Faults (14 of 15)

Non-Suppression Probability and Severity Factors

- Assign a generic frequency for HEAFs listed in Task 6, and apportion it with the location and ignition source weighting factors to the equipment under analysis
- Assume targets in the ZOI are damaged at time zero
- The probability of no manual suppression for the targets in the ZOI is 1.0
- The severity factor for a scenario consisting of targets in the ZOI only is 1.0
- Probability of no automatic suppression for targets in the ZOI is 1.0
- The probability of no manual suppression for targets outside the ZOI can be calculated using the detection suppression event tree described in Appendix P, with the HEAF manual suppression curve

High Energy Arcing Faults (15 of 15)

Example

- Consider a HEAF scenario consisting of a switchgear cabinet affecting two targets. A stack of three cable trays is above the cabinet. The first tray in the stack is 0.9 m (3′) above the cabinet. It has been determined that one of the targets is in the first tray. The other target is in the third tray.
- According to the approach provided in Section M.3, the first target is assumed ignited at the time of the HEAF. The second target is damaged at time 7 minutes (4 minutes for fire propagation from the first to the second tray, and 3 minutes for fire propagation from the second to the third tray).
  - A scenario involving target in the first tray
  - A scenario involving the two targets

$$CDF_i = \lambda_g \cdot W_L \cdot W_{is} \cdot CCDP_i$$

$$CDF_i = \lambda_g \cdot W_L \cdot W_{is} \cdot P_{ns} \cdot CCDP_i$$

FAQ 07-0035 – Bus Duct HEAF

- Issue:
  - The guidance was silent on bus duct fires
- Resolution:
  - This was an unintended oversight
  - Evidence for bus duct HEAF exists
    - Diablo Canyon, May 2000
    - Columbia, August 2009
  - A method for bus duct HEAF was developed
- Reference:
  - EPRI 1019259, Supplement 1 to NUREG/CR-6850

Bus Duct HEAF (1 of 4)

- Bus duct physical configurations can influence the HEAF event
- Four basic types:
  - Cable ducts
  - Non-segmented or continuous bus ducts
  - Segmented bus ducts
  - Iso-phase bus ducts
- HEAF only associated with segmented and iso-phase
  - Separate approaches developed for segmented and iso-phase ducts
  - No HEAF for cable ducts or non-segmented ducts

Bus Duct HEAF (2 of 4)

General characteristics of bus duct HEAF events

- Rapid release of energy
- Potential for physical and thermal damage
- Potential for secondary fires
- Potential for release of molten metals

Bus Duct HEAF (3 of 4)

Zone of influence of HEAF events for <u>segmented bus ducts</u>.

- Assume HEAF event at transition points of segmented bus ducts
- Molten metal to be ejected from bottom of the bus duct in right conical form at 15° angle
- Molten metal to be ejected outward up to 1.5 feet spherical zone of influence
- Subsequent fires depend on cables and other combustible materials within the zone of influence

Bus Duct HEAF (4 of 4)

Analyzing HEAF events for iso-phase bus ducts.

- Assume a 5 foot spherical damage zone centered at the fault point
- Covers initial fault and hydrogen gas explosion and fire
- Subsequent fires depend on cables and other combustible materials within the zone of influence
- If fault is assumed at main transformer termination point, oil fire may need to be considered

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Module III – Fire Analysis
Task 11 – Special Models
Part 1c: Cabinet-to-Cabinet Propagation Model

Joint EPRI/NRC-RES Fire PRA Workshop
July 15-19, 2019

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Fire Propagation To Adjacent Electrical Cabinets (1 of 3)

Analytical fire models may be used in all types of fire propagation and damage scenarios.

- Appendix S of NUREG/CR-6850 discusses empirical approaches for determining:
  - Fire propagation to adjacent cabinets
  - Fire induced damage in adjacent cabinets
- Empirical approach based on SNL and VTT experiments

Fire Propagation To Adjacent Electrical Cabinets (2 of 3)

The empirical model for fire propagation consists of the following rules:

- Assume no fire spread if either:
  - Cabinets are separated by a double wall with an air gap, or
  - Either the exposed or exposing cabinet has an open top, *and* there is an internal wall, possibly with some openings, *and* there is no diagonal cable run between the exposing and exposed cabinet.
- If fire spread cannot be ruled out, or cabinets are separated by a single metal wall, assume that no significant heat release occurs from the adjacent cabinet for 10 minutes if cables in the adjacent cabinet are in direct contact with the separating wall, and 15 minutes if cables are not in contact with the wall.

Fire Propagation To Adjacent Electrical Cabinets (3 of 3)

The empirical model for fire damage consists of the following rules:

- Assume loss of function in an adjacent cabinet if there is not a double wall with an air gap.
- Assume no damage in the second adjacent cabinet occurs until after the fire propagates to the adjacent cabinet. Assume damage can occur earlier if there are large openings in a wall and plenum areas in which a hot gas layer is likely to form.
- Assume no damage to an adjacent cabinet if:
  - There is a double wall with an air gap, and
  - There are no sensitive electronics in the adjacent cabinet (or the sensitive electronics have been “qualified” above 82^{o}C).
- Assume damage to sensitive electronics occurs at 10 minutes if there is a double wall with an air gap.
- Assume damage to sensitive electronics can be prevented before 10 minutes if the fire is extinguished and the cabinet is cooled, e.g., by CO_2 extinguishers.

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Module III – Fire Analysis

Task 11 – Special Models
Part 1d: Passive Fire Protection Features

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Passive Fire Protection Features (1 of 8)

Most of the fire protection capabilities of passive fire protection features cannot be evaluated using analytical fire modeling tools.

- Empirical approaches
- Limited analytical approaches
- Probabilistic approaches

Passive Fire Protection Features (2 of 8)

Passive fire protection refers to fixed features put in place for reducing or preventing fire propagation. Some examples are:

- Coatings
- Cable tray barriers
- Fire stops
- Dampers
- Penetration seals
- Doors
- Walls

Empirical approach

Probabilistic approach

Limited analytical approach

Passive Fire Protection Features (3 of 8)

The analytical approach for modeling the response of passive fire protection features to fire generated conditions consists of a heat transfer analysis.

- The boundary conditions are the fire generated conditions. In general, these consist of the heat flux exchanges at the surface of the passive feature.
  - Thermo-physical properties of the material are necessary. These properties are readily available for some materials like concrete or steel.
- Models can be used for estimating the temperature profile throughout the thickness of the barrier
- Effects of cracks and gaps in doors or walls should be evaluated only with the objective of analyzing smoke migration.

Passive Fire Protection Features (4 of 8)

- Empirical approaches are possible if you can match your conditions to the fire tests that have been performed
- SNL tests performed in the 1970's on several coatings
  - Cable tray configurations included single cable tray and a two-tray stack
  - Exposure fires included gas burner or diesel fuel pool fire
  - Tests results:
    - coated nonqualified cables did not ignite for at least 12 minutes
    - coated, nonqualified cables did not fail for at least 3 minutes and in some cases 10 minutes or more.
  - Tests are very difficult to extrapolate – high plant-to-plant variability
- A basis needs to be established for any credit given to coatings

Coating	Time to Ignition (min)	Time to Damage (min)
Lower Tray Response		
FlameMaster 71A	13	10
FlameMaster 77	13	6
Vimasco #1A	12	3
Carboline Intumastic 285	No	10
Quelcor 703B	12	11
Upper Tray Response		
FlameMaster 71A	No	11
FlameMaster 77	No	11
Vimasco #1A	12	7
Carboline Intumastic 285	No	19
Quelcor 703B	12	11

Passive Fire Protection Features (5 of 8)

- The empirical approaches consist of replicating the thermal response of fire protection features observed in fire tests in the postulated fire scenarios.
  - Cable tray barriers and fire stops: SNL tests 1975-1978
  - Same configuration as coating tests
  - The following systems were tested:
    - Ceramic wool blanket wrap, solid tray bottom covers, solid tray top cover with no vents, solid tray bottom cover with vented top cover, one-inch insulating barrier between cable trays, and fire stops.
  - Propagation of the fire to the second tray was prevented in each case.
- Again, a basis needs to be established for any credit taken
  - Tests are not definitive for all cases

Passive Fire Protection Features (6 of 8)

- Barriers seem to substantially delay cable damage for qualified cable. The barriers did not delay cable damage for nonqualified cable.

- Results considered most appropriate to exposure fires with smaller HRR and to cable trays in a stack threatened by fires in lower trays.
  - Each barrier prevents cable tray ignition until well after the fire brigade reaches the scene (i.e., greater than 20 minutes),
  - Each barrier prevents damage in *qualified* cable with solid tray bottom covers until well after the fire brigade reaches the scene.

- Again: use the test data, but establish a basis for your application!
  - NRC is investigation cable coatings but results remain preliminary – stay tuned for more…

Passive Fire Protection Features (7 of 8)

Probabilistic modeling of passive fire suppression systems

- Dampers: Equipment unavailability obtained from inspection results
- Penetration seals: Equipment unavailability obtained from inspection results

Passive Fire Protection Features (8 of 8)

- Something new that is being used by some plants that you may see:
  - HEAF Shields – a solid barrier (e.g., steel sheet), perhaps with insulation on top of it, installed above a cabinet that is subject to HEAF events
- The idea is for the solid steel sheet to deflect materials ejected during the initial high-energy phase of the arc fault event and thereby prevent the early ignition (time=0) of overhead cables
  - Builds on the concepts of the HEAF model discussed previously
- This concept remains <u>untested</u>
  - There is currently no accepted generic basis for crediting such barriers in fire PRA (e.g., no FAQ…)
  - No clear design/installation guidelines have been established
  - If you encounter such barriers, <u>you</u> will have to develop your own basis for any credit taken

Module III – Fire Analysis

Task 11 – Special Models
Part 2: Main Control Board Fires, Turbine Generator Fires, Hydrogen Fires

Joint EPRI/NRC-RES Fire PRA Workshop
July 15-19, 2019

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Module III – Fire Analysis

Task 11 – Special Models Part 2a: Fires in the Main Control Board

Joint EPRI/NRC-RES Fire PRA Workshop

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Module III-11, Pt. 2: Special Models Part 2
Scope of this Module

- Module III-11, Pt. 2 covers the three remaining “Special Models”
  - Main Control Board Fires (Appendix L)
  - Turbine Generator (TG) Fires (Appendix O)
  - Hydrogen Fires (Appendix N)

Module III-11, Pt. 2: Special Models Part 2
Main Control Board Damage Likelihood Model

- The main control board (MCB) presents many analysis challenges
  - Design practices vary widely
    - Configuration of the boards themselves
    - Relay rack room versus main control room
    - Separation and partitioning within MCB
  - MCB may be important to risk, but IPEEE vintage approaches were identified as a weakness of those studies
  - Fire models cannot currently predict in-panel fire behavior, so an alternative approach is needed
  - **New FAQ!** FAQ 14-0008. Provides clarification of what constitutes the Main Control Board.
- A method is provided to assess the likelihood that a fire in the MCB will grow large enough to damage a specific target set as defined by a specific physical region of the board

Module III-11, Pt. 2: Special Models Part 2
Main Control Board Damage Likelihood Model

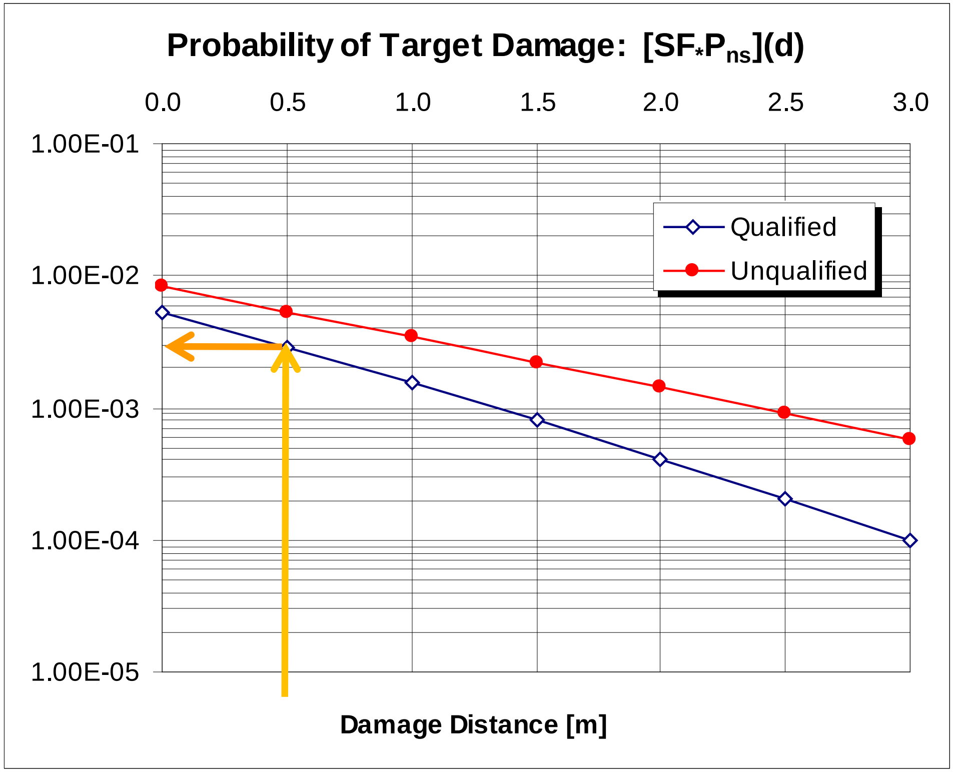
- The MCB model is built on several assumptions that are specific to the MCB and the MCR
  - MCB fire frequency partitioning approach
  - Suppression times for MCR fires
  - Fire characteristics of a MCR type control panel (peak HRR and growth profile)
  - Damage limits for control components
- This model applies ONLY to the MCB itself
  - Not intended for other electrical cabinets/panels
  - Not intended for MCR “back-panels”
  - Not intended for the relay room or other similar areas

Module III-11, Pt. 2: Special Models Part 2
Main Control Board Damage Likelihood Model

- To use the model you must first identify your target set
  - Example: two control switches on the MCB
- Determine the separation distance between the most remote members of the damage set (those furthest apart)
  - Consider cable routing within the panel!
- Using this distance, go to the probability curve and estimate the conditional probability that given a fire somewhere in the MCB, the specific zone encompassing the target set will be damaged
- The resulting number includes BOTH the severity factor AND the probability of non-suppression
  - It does not include fire frequency!

Module III-11, Pt. 2: Special Models Part 2
Main Control Board Damage Likelihood Model

- Example:
  - Target set is two switches located 0.5 m apart from each other
  - Inspection shows that the cables leading to each switch are routed in opposite directions such that 0.5 m is the minimum separation distance between the switches The MCB contains only IEEE-383 certified low-flame-spread cables
  - The conditional probability that a fire occurring somewhere in the MCB will damage the target set is approximately 3.0E-3



Main Control Room Fire Analysis
Step 8: Fire Growth . . . (cont'd)

A probabilistic model of fire spread in the main control board estimates the likelihood that a set of targets separated by a predetermined distance would be affected by a fire.

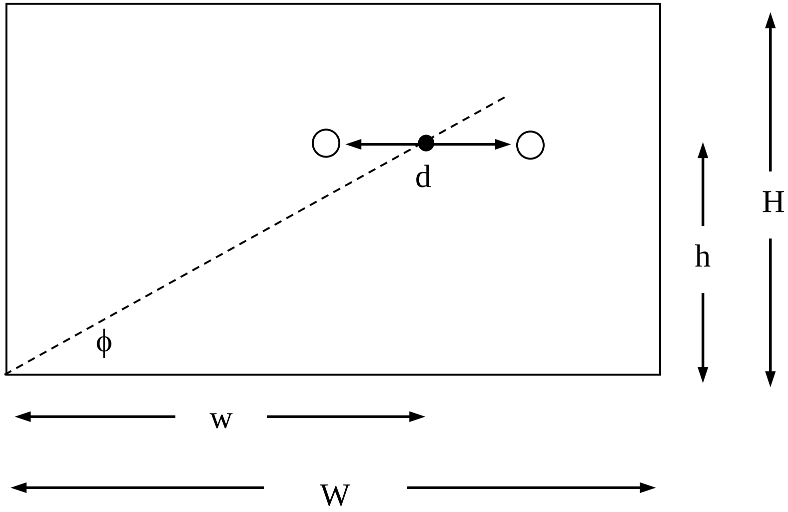
- Difficult to model fire spread within a cabinet using current state-of-the-art analytical tools.
- Probabilistic model based on EPRI's Fire Events Database and cabinet fire experiments reported in NUREG/CR-4527.
- The likelihood is a combination of severity factors and non-suppression probabilities

$$\lambda(d) = \lambda_{MCB} [SF \cdot P_{ns}](d)$$

Main Control Room Fire Analysis
Step 8: Fire Growth . . . (cont'd)

The likelihood is a combination of severity factors and non-suppression probabilities integrated over all possible fire events inside the panel that may damage the postulated target set.

- All possible fire origin locations



$$\lambda(d) = \lambda_{MCB}[SF \cdot P_{ns}](d)$$

$$[SF \cdot P_{ns}](d) = \frac{1}{H \cdot W} \int_0^H \int_0^W SF\left(d, w, h\right) \cdot P_{ns}(d, w, h)\, dw\, dh$$

Module III – Fire Analysis

Task 11 – Special Models Part 2b: Turbine Generator Fires

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Module II-11, Pt. 2: Special Models Part 2
Turbine Generator Set Fires

- Four types of fires can occur involving the turbine generator set, and each is treated differently:
  - Electrical fires in the exciter
  - Hydrogen fires
  - General oil fires
  - Catastrophic failure (e.g., blade ejection)

Module III-11, Pt. 2: Special Models Part 2
Turbine Generator Set Fires: Exciter Fires

- Exciter fires do occur, but all evidence indicates fires remain small and non-threatening
  - No evidence of any exciter fire that led to damage to anything other than the exciter itself
  - No attempt was made to estimate likelihood of a severe exciter fire (one that challenges external targets)

- Recommended Practice:
  - Assume exciter fires remain confined to the exciter
  - Verify for your application, but should not represent a significant risk contributor

Module III-11, Pt. 2: Special Models Part 2
Turbine Generator Set Fires: Hydrogen Fires

- Fire event database shows 13 T/G set hydrogen fires, two categorized as severe, with the rest being fires due to small leaks (generally associated with seals) with limited damage range

- For small fires:
  - Assume damage will be limited to within a few feet of the point of release
  - Secondary ignitions should be considered and treated if there are nearby combustibles
  - See more in Hydrogen Fires discussion (Appendix N)

Module III-11, Pt. 2: Special Models Part 2
Turbine Generator Set Fires: Hydrogen Fires

- For severe fires, widespread damage may occur due to an explosion or detonation of the hydrogen gas.
  - Assume fire may damage all Fire PRA cables and equipment within the line of site of the generator and its bearings (including above and below)
  - Hydrogen explosion could cause some structural damage as well
  - For further discussion – see Hydrogen Fires

Module III-11, Pt. 2: Special Models Part 2
Turbine Generator Set Fires: Catastrophic Failure (1/4)

- International experience includes a few fires initiated by catastrophic turbine failure that resulted in widespread damage including structural damage
  - Examples: Vandellos (1989), Narora (1993), Chernobyl Unit 2 (1991)
  - Events involved a combination of turbine blade ejection, hydrogen release, and large oil fires.
- Domestically, only one event came close to involving all of these elements (Salem, 1991)
  - Event involved minor damage due to existence of an automatic suppression system and prompt fire brigade response
  - Indicates that both automatic fire suppression systems and fire brigade should be credited to prevent catastrophic consequences

Module III-11, Pt. 2: Special Models Part 2
Turbine Generator Set Fires: Catastrophic Failure (2/4)

- Screening approach: assume the *conditional probability* that, given a T/G set fire, the event will involve catastrophic failure (e.g., blade ejection), hydrogen, and oil fires is:

  1 over 38 events or 0.025

  – With *successful fire control*, damage would be localized and limited to the T/G system, as was the case at Salem

  – In case of failure of all suppression, automatic and manual, assume loss of all Fire PRA cables and equipment in the Turbine Building

    - Possible failure of exposed structural steel as well
    - Related SRs: FSS-F1, F2, F3

  – Estimate screening CDF contribution, refine as appropriate

Module III-11, Pt. 2: Special Models Part 2
Turbine Generator Set Fires: Catastrophic Failure (3/4)

- Comments on the suppression credit for screening case:
  - Approach assumes fixed suppression is available
    - Deluge and/or sprinklers are typical for TB
    - If no fixed suppression, *do not apply the suppression credit*
  - Manual backup is also assumed to improve suppression success
  - *Timely fire control* (i.e., before widespread damage) is success here
    - Implies a somewhat extended time frame for action, but no specific time available is assumed
    - Failure of suppression still means damage to T/G system and nearby components
  - Generic screening value given the above: **P_{ns} = 0.02**
    - This is taken from sprinkler reliability, but is also intended to reflect other fixed suppression with manual backup
    - Example: Deluge system with fire brigade backup

Module III-11, Pt. 2: Special Models Part 2
Turbine Generator Set Fires: Catastrophic Failure (4/4)

- Table O-2 (page O-5) covers the cases, but is very confusing…

T/G fires involving H_2, oil, and possibly blade ejection	Catastrophic	0.025	Widespread damage inside the building, potential damage to the adjoining buildings, and to the structural integrity of the building.
		(5E-4/yr)	Suppression can prevent these consequences.
		(1E-5/yr)	

- – You start with total TG fire frequency* (sum bins 33,34,35): 2.0E-2 events/yr
- – Assume 1 in 38 is a catastrophic event (split fraction): <u>x 0.025</u>
- – For a raw frequency of catastrophic events: 5.0E-4 events/yr
- – Given fixed suppression apply generic suppression credit: <u>x 0.02</u>

For a total net frequency of unsuppressed catastrophic events: 1.0E-5 events/yr

* We are using the original 6850/1011989 frequencies because that is what table used and we want the numbers here to align with the table.

Module III – Fire Analysis

Task 11 – Special Models

Part 2c: Hydrogen Fires

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Module III-11, Pt. 2: Special Models Part 2
Hydrogen Fires

- This discussion (Appendix N) applies to general hydrogen fires
  - Including T/G set fires
  - Also fires from other sources of hydrogen leaks and releases (e.g., recombiners, storage tanks, piping, etc.)
- The intent was to provide general discussion of hydrogen fires and their potential effects
- The discussion stops short of recommending modeling approaches.

Module III-11, Pt. 2: Special Models Part 2
Hydrogen Fires

- Two general types of fires:
  - Jet fires originating at point of a H_2 leak
    - Critical question will be flame length
    - About 90% of the events are of this type (Page N-10 of NUREG/CR-6850)
  - Explosions
    - If there is a mechanism for the release of large quantities of H_2 (e.g., a large leak, a prolonged leak that might not be ignited early), then likelihood of a hydrogen explosion is high
    - References provide additional resources for assessing damage potential for an explosion scenario
    - Critical question will be the severity of the overpressure

Module III – Fire Analysis

Task 11: Special Models Part 3: Self Ignited and Hot Work Cable Fires (FAQ 13-005), Junction Boxes (FAQ 13-006)

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Background
Self-ignited and welding-ignited cable fires

- 6850/1011989 Appendix R (Section R.1) provides a method to calculate fire intensity based on an initial burning area plus spread
  - Initial fire area equal to square of tray width
  - Growth per linear spread rate and tray-to-tray fire spread model
- Historical fire experience shows only one case where fire spread as predicted by this model, and that case is an outlier
  - San Onofre – February and March, 1968 (2 fire events)
- Experimental measurements demonstrate cable fires with low ignition energy stay small and do not transfer/generate enough heat to sustain flame spread or fire growth beyond the immediate vicinity of ignition

Background
Historical Fire Events

- EPRI FEDB:
  - Cable fires caused by welding and cutting:
    - 10 fire events
    - 3 classified as non-challenging
    - The other 7 were very small, quickly suppressed and saw only localized damage with not significant fire spread
  - Self-ignited cable fires:
    - 46 fire events total classified as self-ignited cable fires
    - 25 events state that fires self-extinguished once the power source was removed (others not clear)
    - Damage was limited to the initiating cables in all but two cases
    - Significant exceptions were 2 fire events at San Onofre Nuclear Generating Station (SONGS) in 1968

Background
SONGS Historical Fire Events

- FEDB #2: February 7, 1968, approximately 4:45AM
  - Alarms received in the MCR
  - Loud noise was heard in the plant
  - Responders immediately observed a fire in cables at a containment electrical penetration assembly head area
  - The fire was extinguished quickly
    - Full report indicates suppression within 2 minutes although the FEDB indicates a duration of 30 minutes.
  - The fire confined to penetration head assembly but damaged all of the cables associated with that penetration
  - Fire did not spread and did not cause damage to any other cables outside head assembly
  - Root cause: cable overheating caused by a lack of air circulation within a weather protection cowl at the head of the electrical penetration assembly.

Background
SONGS Historical Fire Events

- FEDB #3 and #4 : March 12, 1968
  - Smoke was seen coming from a 480 V switchgear room
  - Indications of electrical faults 5-10 minutes before smoke was seen
  - Plant personnel lacked the equipment needed to enter the smoke-filled room
  - Firefighting support requested from U.S. Marine Corp firefighting unit
  - Off-site firefighters arrived but the pump on their fire truck failed to start
  - An alternate plant systems pump (an engine driven screen wash pump) used to supply water
  - Fire extinguished within 4 minutes
  - Utility report indicates fire burned unchecked for at least 35 minutes
  - Fire damaged a substantial section of three stacked cable trays (about 15 feet long)
  - Root cause: long term cable overheating

Background
SONGS Historical Fire Events

- Factors Contributing to Severity
  - Delays in fire suppression efforts caused by lack of breathing apparatus and pump failure
  - Electrical protection scheme only cleared on one phase resulting in a continual feed back heating source
  - Cables were per vintage design criteria, but severely overloaded by current standards (45A vs. 32A)
  - Cable temperature were roughly 150 °C, far in excess of 90 °C rating
  - Severe and premature degradation of the insulation
- More than 15 linear feet of three cable trays damaged in second fire
- However, no overheating to the grating and beams located 38 inches above the cable tray
- The SONGS events are considered outliers
  - Standards for cable ampacity, tray loading levels and circuit protection all updated

Background
SONGS Historical Fire Events – Recreation Tests

- Utility performed tests to recreate fire conditions
  - Reproduced actual plant conditions including both the electrical and physical loading conditions.
  - Simulated phase-to-phase short circuit and allowed for the power back-feed condition to persist as it did in the actual fire
- The tests did produce flaming combustion
- Information on cable operating temperatures as cited in previous slide
  - i.e., 150°C versus 90°C rated
- Verified that cable ampacity, while within allowed limits at the time, was excessive for tray loading conditions
- Insights eventually led to an entirely new approach and standards for tray installation ampacity ratings

Background
One foreign event of interest

- Fire event in France aggravated by ventilation limited configurations:
  - May 16, 2004
  - Cable fire in fire-resistant penetration carrying 6.6 kV electrical power cables between electrical building and turbine hall
  - Other important safety-related cables were also routed through this penetration, including 380 V power supply cables for line protection equipment and turbine bypass system actuators
  - Fire caused by overheating of the 6.6 kV cables - cables were undersized with a rated power of 9 MW
  - Cable penetration was closed at both ends allowing a build-up of heat causing an ‘oven’ effect and carbonization of the cables
  - Root cause: confinement of the cables in penetrations with inadequate natural circulation to cool cables

Background
Other Experimental Results

- 1976 RES/SNL cable fire testing:
  - Examined the potential for the development of self-ignited fire in qualified cables
  - Found that none of these experiments involving qualified cables resulted in propagation of fire beyond the tray of origin
  - Resulted in the NUREG/CR-6850 methodology not calling for postulated self-ignited cable fires in qualified cabling
- 1977 RES/SNL
  - Molten slag does not have heat capacity to sustain a minimum critical heat flux to act as an ignition source in cable fire experiments
  - For an open flame gas burner, minimum exposure time of 5 minutes is required to establish sustained combustion in a single cable tray
  - Relatively small flames resulting from a single over-heated cable cannot generate/transfer enough heat to propagate a substantial cable fire

Background
Other Experimental Results

- 2007 Braunschweig Technical University testing
  - Assessed the impact of cable preheating on fire behavior
  - Observed significant increases in both the peak fire heat release rate and the rate of fire spread for the preheated cables
    - Relevant to behavior seen in SONGS fires – preheated cables
- 2012 CHRISTI-Fire testing
  - Provided the results of small, intermediate and full-scale cable fire testing in horizontal trays
  - Confirmed that a substantial external fire was necessary to ignite and sustain burning of cables within a single tray
  - Confirmed that a fire within a single tray containing unqualified thermoplastic cable does not radiate enough energy to the unburned portion of the cables within the tray to initiate spread beyond the point of origin

FAQ 13-0005
Status and Methodology

- FAQ 13-0005
- Basic assumption is that a self-ignited or hot work-initiated cable fire will not spread or cause damage beyond the raceway of fire origin
  - One tray and one tray only for any given fire scenario
  - Assume loss of all cables in that one tray
  - A tray containing multiple fire PRA cables might have a relatively high CCDP

FAQ 13-0005
Status and Methodology

- Observations on the new approach:
  - Far simpler than original method
    - No need to model cable fire growth and spread
    - No need to model fire suppression (inherent in the empirical model)
      - No independent credit for fire suppression before damage
      - You always assume loss of one raceway and one raceway only with appropriate fire frequency
      - *Do not add additional suppression credit to this model*
  - Presents a more realistic empirical model of fire behavior and impact
    - Reduces conservatism that may have arisen from original methods

Methodology

- Before you get here…
  - You apportioned plant-wide fire frequency bins to individual PAUs
  - Already covered under Task 6 – no changes here
- Preliminary Analysis Steps:

1. Calculate CCDP values for each raceway in PAU_J
   - Assume loss (failure) all cables in each raceway, one raceway at a time
     - Note that conduits are also raceways
   - Calculation is repeated for every raceway located in the PAU that contains *at least one fire PRA target cable*
   - Raceways that do not contain any fire PRA target cables and may be neglected
     - i.e., You don't have to assume a plant transient for every case
2. Compile the values and sort from highest to lowest CCDP

Methodology, cont.

- First Screening Analysis:

1. Identify the raceway (Raceway-1,J) with the largest CCDP value ($CCDP_{max,J}$)
2. Estimate the screening CDF for the compartment as the product of the compartment fire frequency and $CCPD_{max,J}$

$$CDF_{IS,J} \approx \lambda_{IS,J} \times CCPD_{max,J}$$

  - Nominally repeat for self-ignited and welding cable fires, but in practice, their frequencies can be summed in this step

3. If this first screening level estimated CDF is low enough to meet PRA objectives, add this value to the PAU's total CDF and move to the next PAU
4. If the screening CDF value is too large to meet PRA objectives, conduct subsequent screenings as needed/desired for PAU_J

Methodology, cont.

- Subsequent (Iterative) Screening Steps: drill down CCDP sort list…

1. Apportion frequency from PAU_J down to just the last raceway analyzed
   - “Raceway-1,J” in first iteration, “Raceway-n,J” in subsequent iterations
   - For self-ignited cables, use cable volume ratio:
     - Weighting factor is the volume of Raceway-n vs. total cable volume for the PAU
     - $\lambda_{SICF,Raceway\text{-}n,J} = \lambda_{SICF,J} \times \{ V_{Raceway\text{-}n,J} / V_{Cable,J} \}$
   - For cable fires caused by welding and cutting, use an area ratio:
     - Weighting factor is plan area of Raceway-n vs. total plan area of all raceways in the PAU
     - $\lambda_{CWF,Raceway\text{-}n,J} = \lambda_{CWF,J} \times \{ A_{Raceway\text{-}n,J} / A_{Cable,J} \}$

2. Re-calculate CDF contribution for tray just analyzed using its own frequency value and CCDP:

$$CDF_{IS,Raceway\text{-}n,J} = \lambda_{IS,Raceway\text{-}n,J} \times CCPD_{Raceway\text{-}n,J}$$

Methodology, cont.

3. Identify the raceway with the next largest CCDP value

   $CCDP_{Raceway\text{-}2,J}$ or, more generally, $CCDP_{Raceway\text{-}n,J}$

4. Calculate the residual of the PAU fire frequency (not yet assigned to specific raceways) and calculate a new screening CDF for the rest of the PAU

   $$CDF_{Screening(n+1),J} = \left(\lambda_{IS,J} - \sum \lambda_{Raceway\text{-}i,J} \right) \times CCDP_{Raceway\text{-}(n+1),J}$$

   Sum over: i =1,n

5. The modified compartment CDF is then the sum of the accumulated sub-cases plus the latest screening contribution

   $$CDF_{IS,J} \approx \sum CDF_{IS,i,J} + CDF_{Screening(n+1),J}$$

   Sum over: i =1,n

6. <u>*Repeat "subsequent screening step" as many times as needed/desired…*</u>
   – Each iteration you resolve/refine contribution of last tray, calculate new screening contribution based on next tray and residual fire frequency

Summary

- A new method for both self-ignited cable fires and cable fires caused by welding and cutting has been developed
  - Much easier and faster to apply
- Method assumes one raceway only in any single scenario
- A progressive screening method allows you to refine PAU CDF contribution by drilling down through the raceways present based on CCDP
- FAQ 13-0006 is similar but applied to Junction Boxes
  - Similar technical basis as self ignited cable fires and cable fires due to hot work
  - Fire is limited to one junction box
  - Apportioning of junction box fires
  - Junction box cable content

Module III – Fire Analysis

Task 11b: Main Control Room Fire Analysis and Appendix L

Joint EPRI/NRC-RES Fire PRA Workshop
July 15-19, 2019

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

Main Control Room Fire Analysis Objectives

The objective of this presentation is:

- Describe the recommended approach for detailed fire modeling in the main control room. Specifically:
  - Differences between the main control room and other compartments
  - Criteria for abandonment due to fire generated environmental conditions
  - Description of how to analyze:
    - Conditional probability of damage to a target set
    - Forced control room abandonment time

Main Control Room Fire Analysis
What is Different in the MCR?

- The control and instrumentation circuits of all redundant trains for almost all plant systems are present in the control room.
  - Redundant train controls can be within a short distance of each other
  - Small fires within control panels could be risk-significant
  - Related SR: FSS-A6
- The room is continuously occupied, which provides the capability for “prompt detection and suppression.”
- Evaluating control room abandonment conditions is necessary
  - Abandonment refers to situations in which control room operators are forced to leave due to untenable fire generated conditions (temperature, toxicity, and visibility).
  - Related SRs: FSS-B and its two SRs

Main Control Room Fire Analysis Recommended Steps

- Step 1: Identify and characterize main control room features
- Step 2: Estimate control room fire frequency
- Step 3: Identify and characterize fire detection and suppression features and systems
- Step 4: Characterize alternate shutdown features
- Step 5: Identify and characterize target sets
- Step 6: Identify and characterize ignition sources
- Step 7: Define fire scenarios
- Step 8: Conduct fire growth and propagation analysis
- Step 9: Fire detection and suppression analysis and severity factor
- Step 10: Estimate failure probability of using alternate shutdown features
- Step 11: Estimate probability of control room abandonment
- Step 12: Calculate scenario frequencies
- Step 13: Document analysis results

Main Control Room Fire Analysis
Step 1: Identify and Characterize MCR Features

The specific features of the control room and the control board are identified.

- Control room dimensions
- Other adjacent compartments included in the MCR proper
- Location, shape, dimensions and special features of the control panels and other electrical panels
- Main control board layout and location of various controls and displays
- Cable penetration into the control room and into the control panels
- Ventilation system characteristics
- False ceiling features and the ceiling above it

Main Control Room Fire Analysis
Step 4: Characterize Alternate Shutdown Features

The features of alternate shutdown capability vary widely among NPPs

- In general, a control panel is installed at a location away from the control room where the operators can control and monitor key core cooling functions and parameters independent of the MCR.
- In other plants, alternate shutdown capability is achieved through a set of control points and control panels located at various points of the plant requiring coordinated actions of several operators.
- It is necessary for the fire risk analysts to understand the alternate shutdown capability of the plant.
  - For example, the analyst may select safety-related target sets on the panel that are not backed up by an alternate shutdown control or instrumentation circuit.

Main Control Room Fire Analysis
Step 5: Identify and Characterize Target Sets

The target sets can be identified by systematically examining combinations of control and instrumentation items found on the control panels, electrical cabinets, wireways, and cable raceways inside the MCR.

- Examine the control panels from one end to the other
- Groups of adjacent controls and instrumentation
- Cursory and conservative estimation of the CCDP/CLERP as the basis
- Elements of a set are located within the reach of a potential fire
- Exposure fire affecting multiple cabinets

- Corresponding PRA Standard SRs: FSS-A2 through A4

Main Control Room Fire Analysis
Step 6: Identify and Characterize Ignition Sources

The final product of this step is a list of ignition sources, their relevant characteristics, and fire ignition frequencies associated with each source

- Similar to Step 3.a of single compartment analysis
- Type, quantity, dimensions and heat release rate profile of each source
- Main control board as ignition source
- Assume fire might occur at any point on a control panel
- Other control panels, electrical cabinets, wireways, and cable raceways
- Kitchen appliances and other electrical devices?
- Transient combustible fires

Main Control Room Fire Analysis
Step 7: Define Fire Scenarios

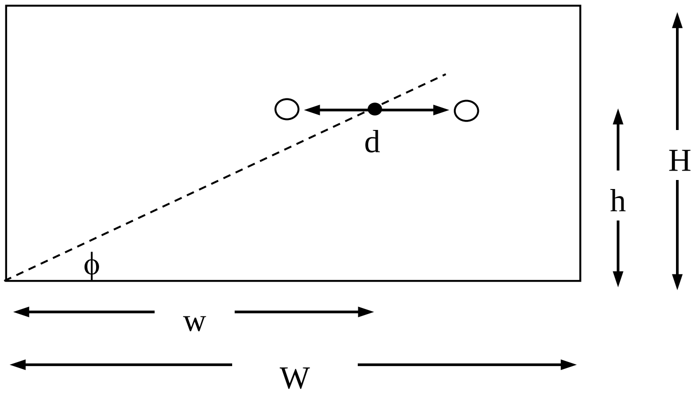
Four types of fire scenarios are specifically recommended for evaluation

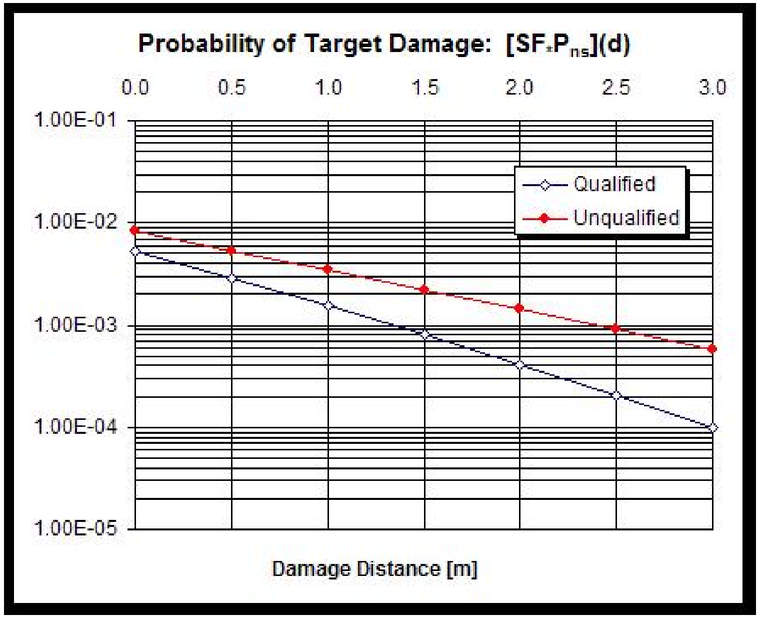
- Fire inside the main control board and stand-alone electrical cabinets that open into each other,
- Fires affecting two adjacent electrical cabinets that do not open into each other,
- Fires affecting two non-adjacent electrical cabinets, and
- Transient fires
- Corresponding PRA Standard SR: FSS-A6

Main Control Room Fire Analysis
Steps 8 and 9: Non-Supp Prob & Severity Factor

The non-suppression probability and severity factors are calculated as recommended in the approach for single compartment fires

- For fires inside a control panel, use the method described in Appendix L (covered previously)





Main Control Room Fire Analysis
Step 10: Estimate Failure Prob Using ASP

Two approaches may be followed:

- An overall failure probability is estimated representing the failure of successful usage of alternate shutdown means.
- The alternate shutdown procedure is integrated in the plant response model (i.e., the fault trees and event trees). The core damage sequences are adjusted to include failures associated with alternate shutdown means, and the human error probabilities are reevaluated based on the alternate shutdown procedures.
- *This is an area of ongoing research!*

Main Control Room Fire Analysis
Step 11: Estimate Prob of Control Room Abandonment

The final decision to abandon the control room is assumed to depend on habitability conditions.

- The analyst may postulate that the alternate shutdown procedure would be activated
- The time to activate the alternate shutdown procedure is suggested to be established based on plant operating procedures rather than control room habitability conditions
- Abandonment possibility should be examined for all postulated target damage scenarios

Main Control Room Fire Analysis
Step 11: Estimate Prob of Control Room Abandonment

Abandonment criteria based on habitability conditions

- Temperature, or heat flux
  - The heat flux at 6′ above the floor exceeds 1 kW/m^2. This can be considered as the minimum heat flux for pain to skin. A smoke layer of approximately 95°C (200°F) could generate such heat flux.

$$\dot{q}'' = \sigma \cdot T_{sl}^4 \approx 1.0 \quad kW/m^2$$

- The smoke or hot gas layer descends below 6′ from the floor
- Visibility
  - Optical density of the smoke is less than 3.0 m^{-1}. With such optical density, a light-reflecting object would not be seen if it is more than 0.4 m away. A light-emitting object will not be seen if it is more than 1 m away.
- A panel fire affects two target items 2.13 m (7′) apart

Main Control Room Fire Analysis
Step 11: Estimate Prob of Control Room Abandonment

The conditional probability of abandonment can be estimated based on the calculated evacuation time

- Determine the heat release rate generating abandonment conditions
- Calculate the severity factor for fires of this size
- Determine the time for abandonment
  - Time to reach untenable conditions such as 200°F hot gas layer or smoke density conditions of 3.0 m^{-1}
- Calculate non-suppression probability
- Multiply the severity factor and non-suppression probability to determine conditional abandonment probability
- Corresponding PRA Standard SRs: FSS-B1 and FSS-B2

- Note that this is typical HRR distribution discretization approach…

Main Control Room Fire Analysis
Step 11: Estimate Prob of Control Room Abandonment

- Probability of abandonment due to habitability can be determined based on:
  - The criteria for abandonment due to fire conditions
  - Fire modeling analysis using field models, zone models, or hand calculations. (Field models and zone models are the tools usually selected for this)
- NUREG-1934 includes a detailed example of a control room evaluation (Discussed in Module 5)

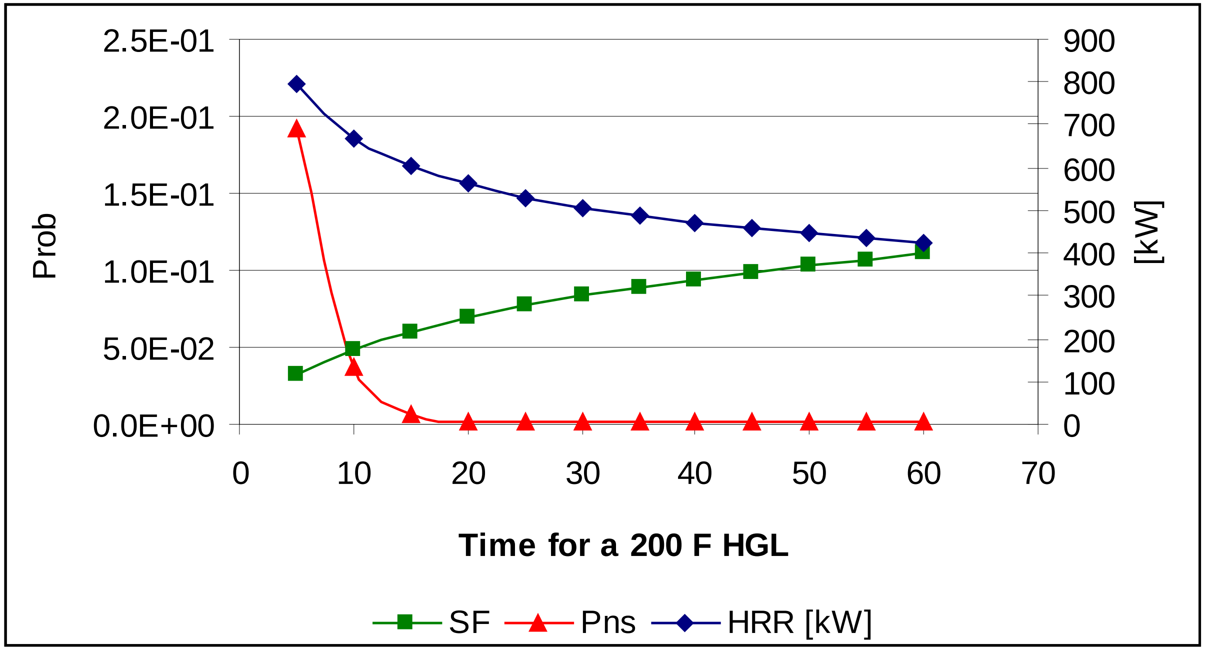
Main Control Room Fire Analysis Example

- Credit prompt detection
- Suppression by fire brigade
  - P_{ns} from CR suppression curve
- SF from probability distribution for vertical cabinets with unqualified cable and fire propagating to more than one bundle.

Inputs	
Ambient temperature [C]	20
Duration [sec]	
Opening area [m2]	4
Height of opening [m]	2
Room length [m]	20
Room width [m]	15
Room height [m]	6
Thermal conductivity [kW/mK]	0.0014
Density [kg/m3]	2000
Specific heat [kJ/kg]	0.88
Wall thickness [m]	0.15
Temperature for abandonment [C]	93

Main Control Room Fire Analysis

Example – (alternate discretization approach based on abd. time)



Duration [Min]	Required HRR [kW]	SF	Pns	SF*Pns
5	**794**	3.2E-02	1.9E-01	6.1E-03
10	**668**	4.8E-02	3.7E-02	1.8E-03
15	**603**	6.0E-02	7.1E-03	4.2E-04
20	**561**	6.9E-02	1.4E-03	9.4E-05
25	**531**	7.7E-02	2.6E-04	2.0E-05

One related current activity
MCR abandonment analysis methods

- MCR abandonment is a complex issue
  - Abandonment may arise from loss of habitability or control
  - How is abandonment decision made for loss of control?
  - When will abandonment occur – will it be timely?
  - Partial abandonment - Operators stay in the MCR to supplement alternate shutdown operations (control maintained from the MCR)
  - Quantifying transfer and alternate shutdown actions
- A FAQ was proposed by industry to address operations from alternate shutdown including abandonment
  - FAQ 13-0002 – only available in draft form
  - Proposed a framework for abandonment, containing relatively simple set of alternate shutdown conditions and related discussions

One related current activity
MCR abandonment analysis methods

Continued…

- NRC Staff agrees that questions are important and need resolution
  - Staff put out interim staff guidance as could not come to agreement on FAQ approach
    - ML14080A028
- Ongoing EPRI/RES research effort
  - First phase addressing qualitative considerations
    - Published in 2017 by EPRI, NRC publication in progress
      - Publicly available at epri.com, 3002009215 (NUREG-1921 Supplement 1)
    - Second phase to address quantification
      - Completed peer review and comment resolution
      - Publication in process, 3002013023 (NUREG-1921 Supplement 2)

Main Control Room Fire Analysis
Concluding Remarks

The main control room has unique characteristics that are addressed in detail in Task 11b.

- Recommended fire scenarios for the MCR
- Evaluation of MCR abandonment due to fire generated conditions
  - Loss of MCR habitability
  - Loss of control functions due to fire in MCR or elsewhere

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Module III – Fire Analysis

Task 11c – Multi-Compartment Fire Analysis

Joint EPRI/NRC-RES Fire PRA Workshop
July 15-19, 2019

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

Multi-Compartment Fires
Objective

Fire scenarios involving multiple, interconnected or adjacent fire compartments are analyzed in this part of Task 11.

- Fire propagation
- Smoke propagation
- A rare event in U.S. NPP fire experience
- Screening process

Multi-Compartment Fires
Overall Approach

Multi-compartment analysis is focused on screening of potential scenarios before any detailed analysis is attempted.

- Single compartment analysis to be conducted before this step
- Reduce number of multi-compartment combinations
- Same analytical approach as in Detailed Fire Modeling

- Corresponding PRA Standard SRs: FSS-G1 through FSS-G6

Multi-Compartment Fires
Definitions

The following two terms are specifically defined for this part of the analysis:

- *Exposing Compartment*: The compartment where fire ignition occurs
- *Exposed Compartments*: The compartments to which fire from the exposing compartment propagates

Multi-Compartment Fires
Analysis Steps

The following steps define one possible approach for multi-compartment fire risk analysis:

- Step 1.c: Exposing and Exposed Compartments Matrix
- Step 2.c: First Screening–Qualitative
- Step 3.c: Second Screening–Low Fire Load Exposing Compartments
- Step 4.c: Third Screening–Frequency of Occurrence
- Step 5.c: Fourth Screening–CDF Based
- Step 6.c: Detailed Analysis
- Step 7.c: Document the Analysis

Multi-Compartment Fires
Step 1.c: Exposing and Exposed Compartments Matrix

Develop a matrix to identify all potential multi-compartment fire scenarios that start with an *exposing* compartment and propagate into a set of *exposed* compartments.

- Well defined pathways
- Means of propagation (i.e., hot gas, smoke, etc.)
- Special characteristics to be noted (e.g., self closing doors, fire dampers and vents near the ceiling)
- More than one exposed compartment
- Supported by a walk-down

Multi-Compartment Fires
Step 1.c: Exposing and Exposed Matrix (cont'd)

The following rules are suggested to identify multi-compartment scenarios:

- Postulate only one barrier failure (e.g., door left open)
  - Unless there is a clear reason to assume common cause failure of multiple barriers
- Assume minimal smoke damage
- Hot gas can travel to all physically possible exposed compartments
  - For a large number of compartments open into each other, detailed analysis may be warranted

Multi-Compartment Fires
Step 1.c: Exposing and Exposed Matrix (cont'd)

Example:

#	Exposing Compartment		#	Exposed Compartment		#	Path	Comments
	ID	Name		ID	Name			
1	9	SWG Access Room	1.1	10	Swtich Gear Room A	1.1.1	Door	The door is 3-hr rated and normally closed
						1.1.2	Opening	Ventilation opening between rooms with fusible link activated fire dampers.
			1.2	11	Swtich Gear Room B	1.2.1	Door	The door is 3-hr rated and normally closed
						1.2.2	Opening	Ventilation opening between rooms with fusible link activated fire dampers.
			1.3	--	Stairway	1.3.1	Door	The door is 3-hr rated and normally closed
2	4A	RHR Room	2.1	4B	AFW Pump Room	2.1.1	Door	The door is 3-hr rated and normally closed
						2.1.2	HVAC Duct	There are two HVAC ducts with opening in both compartments providing intake and discharge
			2.2	--	Stairway	2.2.1	Door	The door is 3-hr rated and normally closed
3	4B	AFW Pump Room	3.1	4A	RHR Room	3.1.1	Door	The door is 3-hr rated and normally closed
						3.1.2	HVAC Duct	There are two HVAC ducts with opening in both compartments providing intake and discharge

Multi-Compartment Fires
Step 2.c: First Screening – Qualitative

The first screening of the scenarios can be based on the contents of the exposed compartments.

The following criteria may be used:

- The exposed compartment(s) do not contain any Fire PRA components or cables, or
- The fire PRA components and cables of the exposed compartment(s) are identical to or less than those in the exposing compartment.

- Corresponding PRA Standard SRs: FSS-G2 and FSS-G3

Multi-Compartment Fires
Step 3.c: Second Screening–Low Fire Load

Exposing compartments that do not include combustible loading sufficient for generating a hot gas layer in any of the exposed compartments can be screened out.

- Conservative HRR values
  - Ignition sources with highest 98% HRR
  - Add HRR of intervening combustibles
- Determine damaging HRR values
  - Hand calculations
  - Hot gas layer damage in exposed compartment
- Compare HRRs

- Corresponding PRA Standard SRs: FSS-G2 and FSS-G3

Multi-Compartment Fires
Step 4.c: Third Screening–Occurrence Frequency

Scenario likelihood is established from the following three parameters:

- Ignition frequency
- Combined severity factor and non-suppression probability
  - HRR comparison (preceding step) can give the severity factor
  - May assume P_{NS} = 1.0
- Barrier failure probability

- Corresponding PRA Standard SRs: FSS-G2 through FSS-G5

Multi-Compartment Fires
Step 4.c: Third Screening / *Barrier Failure*

Generally, data on barrier failure probability is sparse, and what is available is subject to many limitations.

- Initial attempt may be based on a screening value
  - May use Pr(barrier failure) = 0.1 for screening
- For scenarios that do not screen out, may use the following:
  - For water curtain, use detection and suppression approach
  - Verify that there are no plant-specific barrier failure problems
  - Use the following *generic* barrier failure probabilities
    - Type 1 – fire, security, and water tight doors – 7.4E-03
    - Type 2 - fire and ventilation dampers – 2.7E-03
    - Type 3 - penetration seals, fire walls – 1.2E-03

Multi-Compartment Fires
Step 5.c: Fourth Screening–CDF Based

Those scenarios that survive the preceding screening steps may be screened based on their CDF.

- Assume all PRA components and cables of exposing and exposed compartments are failed
- Estimate CCDP
- Use scenario frequency of preceding step
- Corresponding PRA Standard SR: FSS-G6

Multi-Compartment Fires
Step 6.c: Detailed Analysis

Those scenarios that do not screen out in the preceding steps may be analyzed using the same methods as for single compartments.

- Same set of steps as in single compartment analysis
- Include target sets from exposed compartment(s)
- Corresponding PRA Standard SR: FSS-G1

Multi-Compartment Fires
Concluding Remarks

Multi-compartment fire analysis should be performed to ensure completeness of the Fire PRA.

- Compartment partitioning process (Task 1) has a direct impact on this task
- Develop a matrix of exposing and exposed compartments to ensure completeness
- Screening analysis is necessary to limit the level of effort
- Barrier failure probabilities should be treated conservatively
- May have to revisit some of the partitioning definitions

Module III – Fire Analysis

Task 13: Seismic Fire Interactions

Joint EPRI/NRC-RES Fire PRA Workshop
July 15-19, 2019

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

Task 13 - Seismic Fire Interactions
Scope of this Task

- Task 13 covers the Seismic Fire Interactions review
  - Little has changed compared to the guidance available in the IPEEE days
  - The review remains a qualitative, walk-down based approach to identify and address potential vulnerabilities or weaknesses
  - The procedure does not recommend any quantitative work in this area

<u>The main goal of the outlined methodology is to verify that the the risk associated with seismically induced fires is low.</u>

Corresponding PRA Standard Element

- Task 13 maps to element SF – Seismic Fire
  - SF Objective (per the PRA Standard):
    - To qualitatively assess the potential risk implications of seismic/fire interaction issues

SF HLRs (per the PRA Standard)

- HLR- SF-A: The Fire PRA shall include a qualitative assessment of potential seismic/fire interaction issues in the Fire PRA (5 SRs)

- HLR-SF-B: The Fire PRA shall document the results of the seismic/fire interaction assessment in a manner that facilitates Fire PRA applications, upgrades, and peer review (1 SR)

Task 13: Seismic Fire Interactions
Seismically Induced Fires

A severe seismic event may cause fires inside or outside an NPP by damaging . . .

- Pipes and storage tanks containing flammable liquids or gases
- Electrical equipment

An EPRI study and NPPs experiencing earthquakes have demonstrated that these events are rare.

Task 13: Seismic Fire Interactions
Background

- Seismic Fire Interactions originated with the Fire Risk Scoping Study (NUREG/CR-5088, 1989)

- The conclusion of that study was:

  "It would appear that this is an issue which is more easily corrected than quantified. A series of simple steps was outlined which if implemented on a plant specific basis would significantly reduce the potential impact of such considerations."

  This conclusion remains valid today.

Task 13: Seismic Fire Interactions
Key Compartments

- The review should focus on those compartments that house equipment and cables needed to support post-seismic safe shutdown
  - Review your seismic-related procedures and identify key equipment (components and cables) and any required manual actions
  - To the extent possible, map equipment to compartments
  - Identify the associated compartments and focus efforts on these compartments
    - Areas/compartments housing the key equipment (components and cables)
    - Areas where a manual action takes place
    - Access paths for manual actions

Task 13: Seismic Fire Interactions
Seismically-Induced Fires

- Potential sources:
  - Unanchored electrical equipment such as that where motion during seismic event might cause a fire
  - Unanchored gas cylinders
  - Flammable gas piping
  - Flammable liquid piping or storage tanks

- If any *significant* sources are identified, consider potential plant modifications to minimize potential hazard.

- Corresponding PRA Standard SR: SF-A1

Task 13: Seismic Fire Interactions
Degradation of FP Systems and Features

- Review:
  - General plant practice related to seismic restraints for fire protection systems and features
  - Installed systems and features; assess potential for seismic-induced failure

- Assess potential significance of system or feature failure to post-seismic event operations.

- If any potential vulnerabilities are identified, consider fixes to reduce likelihood of failure.

- Corresponding PRA Standard SR: SF-A2

Task 13: Seismic Fire Interactions
Spurious Detection Signals

- A seismic event will likely trigger activation of various fire detection systems – especially smoke detectors
- Consider how the operators will respond to multiple fire detection signals
  - You can't ignore them even though many may be false
  - Have you identified the issue in your response procedures?
  - Have you (can you) prioritize your response based on the important compartments?
- Consider potential procedural enhancements to recognize and deal with this issue
- Corresponding PRA Standard SRs: SF-A2 and SF-A3

Task 13: Seismic Fire Interactions
Spurious Suppression Actuation/Release

- Review the fixed fire protection systems in key areas for the potential that they might spuriously operate
  - Got any of those mercury switches left?
  - How about a non-seismic deluge valve?
  - What happens if a sprinkler head is damaged or a pipe breaks?
  - Are storage tanks for gaseous suppressants seismically robust?

- If any potential vulnerabilities are identified, consider fixes to reduce likelihood of spurious suppressant release.

- Corresponding PRA Standard SR: SF-A4

Task 13: Seismic Fire Interactions
Manual Fire Fighting

- Access pathways to key areas – could something block the path and are there alternative paths?

- Required fire fighting assets – will assets remain available after an earthquake?
  - Especially fire water system and fire hoses

- Do post-seismic response procedures allow for manual fire fighting needs and responsibilities?

- If any potential vulnerabilities are identified, consider fixes

- Corresponding PRA Standard SR: SF-A5

Task 13: Seismic Fire Interactions
Summary

- Seismic fire interaction is considered a low risk phenomenon
- NPP and other industry experiences partly verify this premise
- A qualitative approach is suggested for verifying that plant specific conditions confirm low risk notion
- Systemic or procedural upgrades are recommended for identified potential vulnerabilities

Mapping HLRs & SRs for the PP Technical Element to NUREG/CR-6850, EPRI 1011989

Technical Element	HLR	SR	6850 Sections	Comments
SF	A	The Fire PRA shall include a qualitative assessment of potential seismic/fire interaction issues in the Fire PRA		
		1	13.3.1 and 13.6.2	
		2	13.3.2, 13.3.3, 13.6.3, 13.6.4, and 13.6.5	
		3	13.3.2,	
		4	13.3.1, 13.3.2, 13.3.3, 13.6.3, 13.6.4, and 13.6.5	Although 6850/1011989 does not explicitly reference seismic response procedures, the suggested guidance implies review of such procedures.
		5	13.3.4 and 13.6.6	
	B	The Fire PRA shall document the results of the seismic/fire interaction assessment in a manner that facilitates Fire PRA applications, upgrades, and peer review		
		1	13.6.7	6850/1011989 provides minimal discussions on documenting SF

NUREG-2178 and EPRI 3002005578

Peak Heat Release Rates and Effect of Obstructed Plume

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

What’s in NUREG-2178 Volume I?

- Expanded classification of cabinets / enclosures
- Revised heat release rate distributions
- Fuel assessment impacting peak HRR
- Fire diameter sizing guidance
- Obstructed plume
- Pilot application

Expanded Classification of Electrical Cabinets / Enclosures

- Working group identified changes to HRR distributions from Table G-1 in EPRI 1011989 / NUREG/CR-6850
  - Re-binning of cabinets for ease of implementation and to better represent the fire hazard
  - Heat release rates distributions based on electrical function or physical cabinet size

Group	Distribution Type	Binning Consideration	Physical Size
1	Switchgear and load centers	Electrical function	-
2	MCCs and battery chargers	Electrical function	-
3	Inverters	Electrical function	-
4a	Large enclosures	Volumetric size	Greater than $50ft^3$ ($1.4m^3$)
4b	Medium enclosures	Volumetric size	Greater than $12ft^3$ ($0.34m^3$) but less than $50ft^3$ ($1.4m^3$)
4c	Small enclosures	Volumetric size	$12ft^3$ ($0.34m^3$) or less

A few notes on the distributions

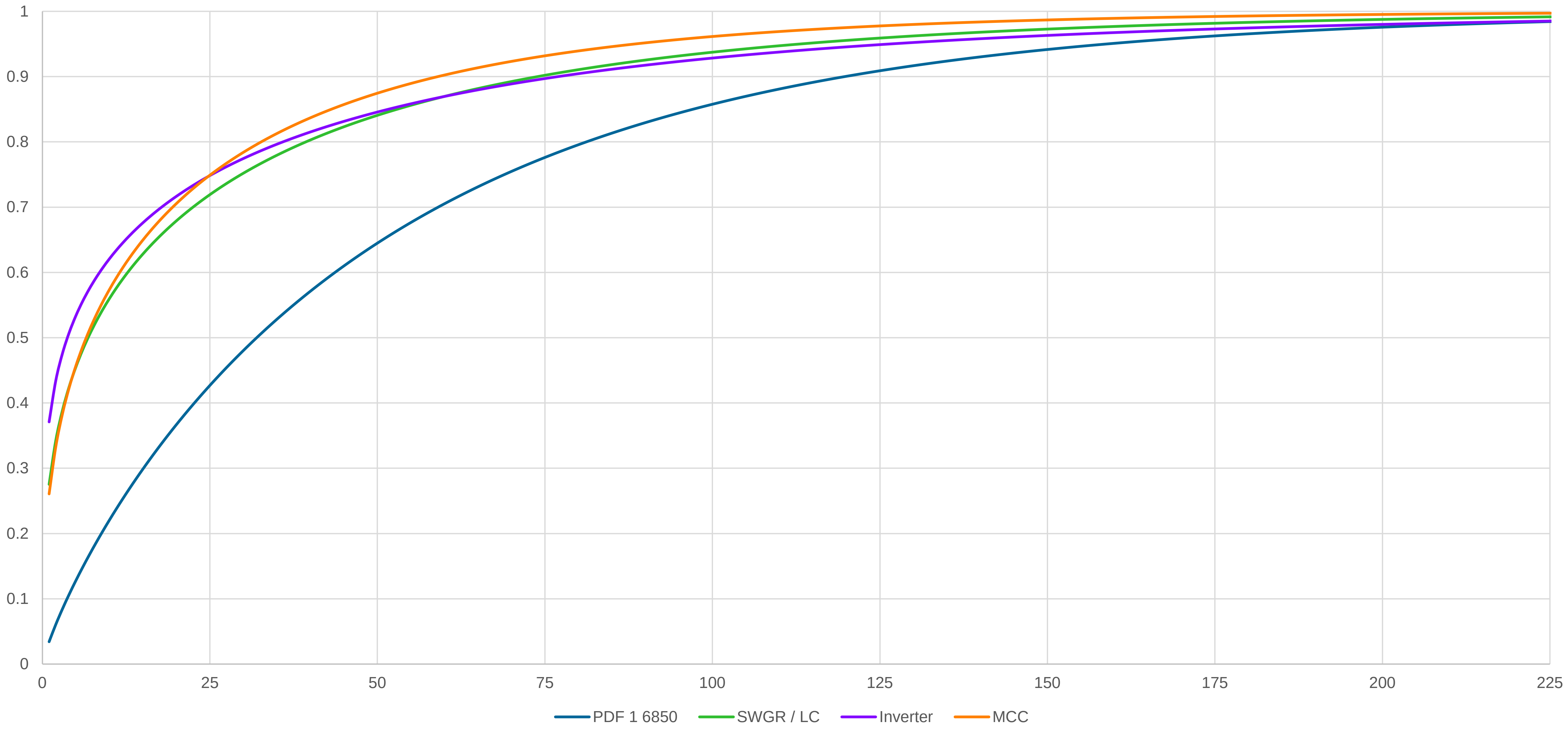
- Base distributions do not require inspection of cabinet internals, thus assume a certain nominal fuel loading
  - Methodology allows flexibility in assigning peak HRR upon internal cabinet assessment…more on that later
- Make sure to select the right fuel type
  - TS: Thermoset, Synthetic Insulated Switchboard (SIS), or *Qualified* Thermoplastic (passed IEEE-383 vertical flame spread test)
  - TP: Unqualified Thermoplastic

HRR for Functionally Based Groups (Table 4-1)

Binning Group	Fuel type*	75th percentile (kW)	98th percentile (kW)
1 – Switchgear and Load Centers	TS/SIS/QTP	**30**	**170**
	TP	**60**	**170**
2 – MCCs and Battery Chargers	TS/SIS/QTP	**25**	**130**
	TP	**50**	**130**
3 – Power Inverters	TS/SIS/QTP	**25**	**200**
	TP	**50**	**200**

*See Section 1.3 and Section 2.2.3 for full discussion on fuel type assignment

Comparison of New Functional HRR Distributions

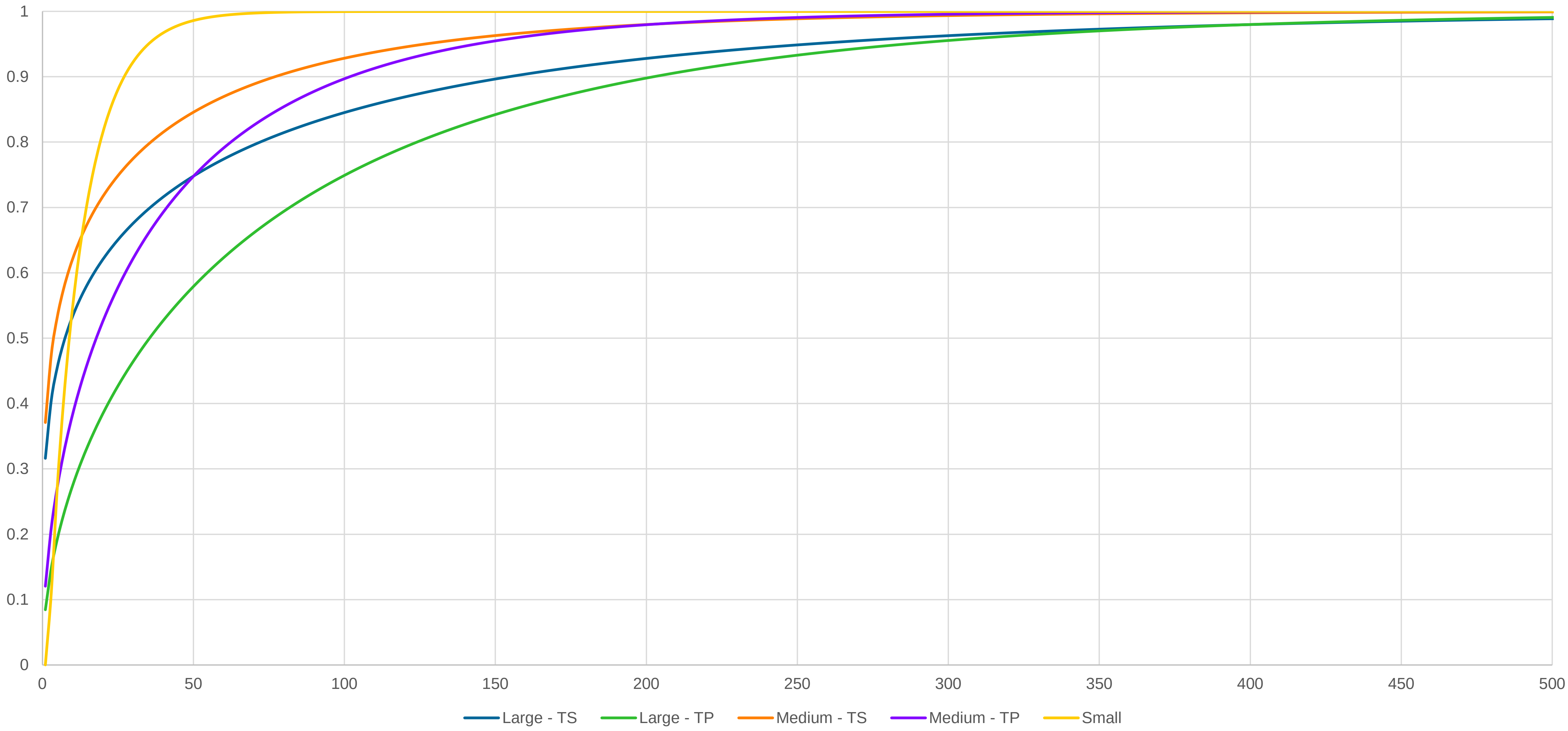


HRR for Volumetric Size Based Groups (Table 4-2)

Enclosure Class/Function Group	Ventilation (Open/Closed Doors)	Fuel Type*	75th Percentile (kW)	98th Percentile (kW)
4a - Large Enclosures >1.42 m^3 (>50 ft^3)	Closed	TS/SIS/QTP	**50**	**400**
	Closed	TP	**100**	**400**
	Open	TS/SIS/QTP	**100**	**700**
	Open	TP	**200**	**1000**
4b - Medium Enclosures ≤1.42 m^3 (50 ft^3) & > 0.34 m^3 (12 ft^3)	Closed	TS/SIS/QTP	**25**	**200**
	Closed	TP	**50**	**200**
	Open	TS/SIS/QTP	**40**	**325**
	Open	TP	**80**	**325**
4c - Small Enclosures ≤ 0.34 m^3 (12 ft^3)	N/A	All	**15**	**45**

***See Section 1.3 and Section 2.2.3 for full discussion on fuel type assignment**

Revised HRR Distributions for Closed Volumetric Category

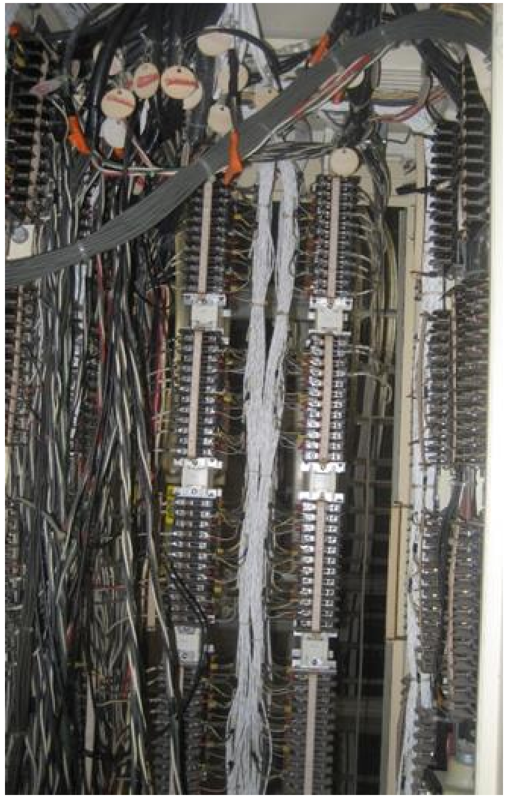


Additional Cabinet Considerations for HRR Development

- Variability in fuel load, configuration of combustibles, and ignition source strength that may exist in medium and large cabinet groupings
- To address variability, *optional* subgroups may be applied upon inspection of cabinet internals
  - Low fuel loading – light or moderate fuel loading, but not conducive to fire spread (such as tightly bundled cabling)
  - Very low fuel loading – sparse fuel load (limited in quantity and widely dispersed) and neatly arranged combustibles that would be unlikely to spread fire
- Cables routed in conduit or enclosed metal wire ways may reduce the fire intensity potential

Examples of Fuel Loading

Nominal Fuel Load



Low Fuel Load

Very Low Fuel Load

Special Cases in Consideration of HRR Development

- **No ignition sources present:** plant cabinets that are emptied / abandoned / installed as spare compartments or only contain cables with no terminations or end devices (pass-through cables)
  - Revised treatment: Eliminate, but document

Special Cases in Consideration of HRR Development

- **Cables enclosed in conduit:** Cables routed in rigid metal, flexible metal and liquid metal flexible conduit (LMFC)
  - Revised treatment:
    - Rigid metal conduit or flexible metal conduit: do not include in fuel load assessment
    - LMFC: due to the very low flammability the LMFC will burn less intensely. If most of loading if LMFC, can reduce the loading by one step down

Special Cases in Consideration of HRR Development

- **Metal enclosed wire ways and switch/device covers:** Cables that are routed in metal wire ways to separate redundant trains.
  - Revised treatment: If most routing is in wire ways the fuel loading may be reduced by one step

HRR for Volumetric Size Based Groups (Table 4-2)

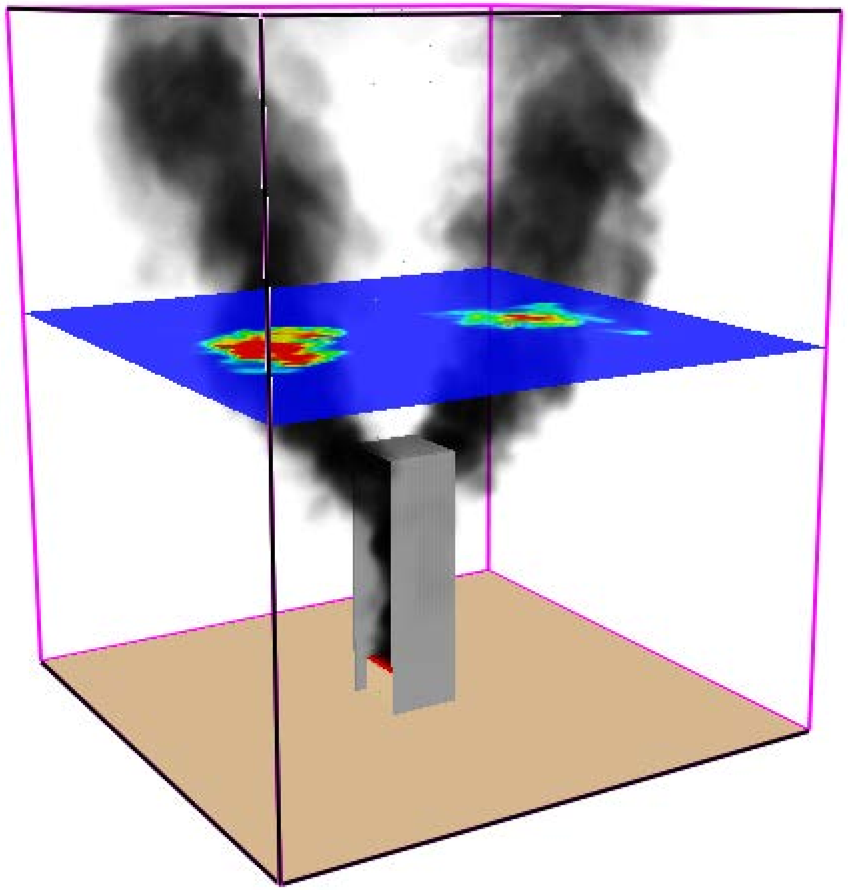
Enclosure Class/Function Group	Ventilation (Open/Closed Doors)	Fuel Type*	75^{th} Percentile (kW)	98^{th} Percentile (kW)	LOW LOADING 75^{th} Percentile (kW)	LOW LOADING 98^{th} Percentile (kW)	VERY LOW LOADING 75^{th} Percentile (kW)	VERY LOW LOADING 98^{th} Percentile (kW)
4a - Large Enclosures >1.42 m^3 (>50 ft^3)	Closed	TS/SIS/QTP	50	400	25	200	15	75
	Closed	TP	100	400	50	200	25	75
	Open	TS/SIS/QTP	100	700	50	350	15	75
	Open	TP	200	1000	100	500	25	75
4b - Medium Enclosures ≤1.42 m^3 (50 ft^3) & > 0.34 m^3 (12 ft^3)	Closed	TS/SIS/QTP	25	200	15	100	15	45
	Closed	TP	50	200	25	100	15	45
	Open	TS/SIS/QTP	40	325	15	150	15	45
	Open	TP	80	325	25	150	15	45

*See Section 1.3 and Section 2.2.3 for full discussion on fuel type assignment

Fire Diameter Sizing

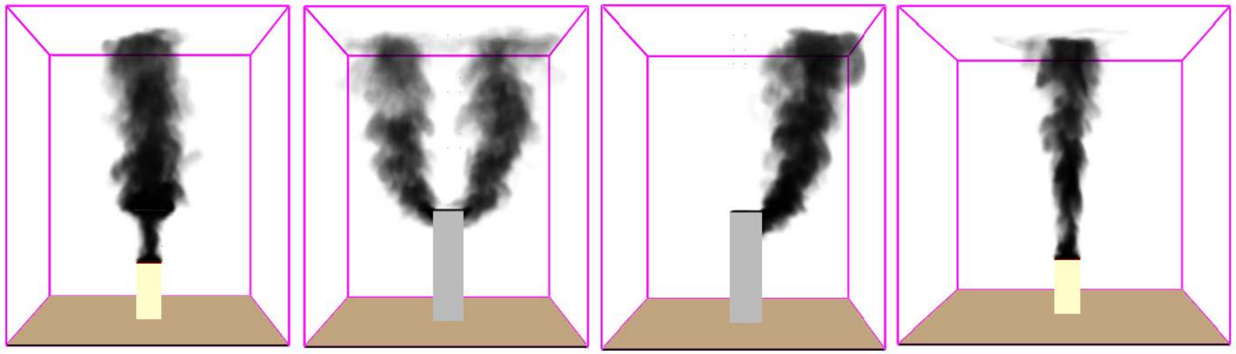
- Fire plume calculations require a specified fire diameter, but current methodology is silent on treatment, leaving the decision for the analyst
- Froude number: ratio of momentum driven flow to buoyance driven flow
  - The validated range in NUREG-1934 / EPRI 1011999 is 0.4-2.4
  - A high number implies a fire with a small diameter relative to fire intensity (momentum driven)
  - A low number implies fire dispersed over wide surface relative to fire intensity (buoyancy driven)
- A good practice for establishing fire diameter:
  – Use a fire diameter that yields an area equal to the enclosure’s footprint **unless** the result falls outside the validation range for the plume fire correlation being used.
  – If the fire diameter lies outside the range of the plume correlation for the fire HRR being postulated (i.e., the diameter is too large), then **reduce** the fire diameter to the maximum allowed based on the validation range of the plume correlation being applied.

Obstructed Plume

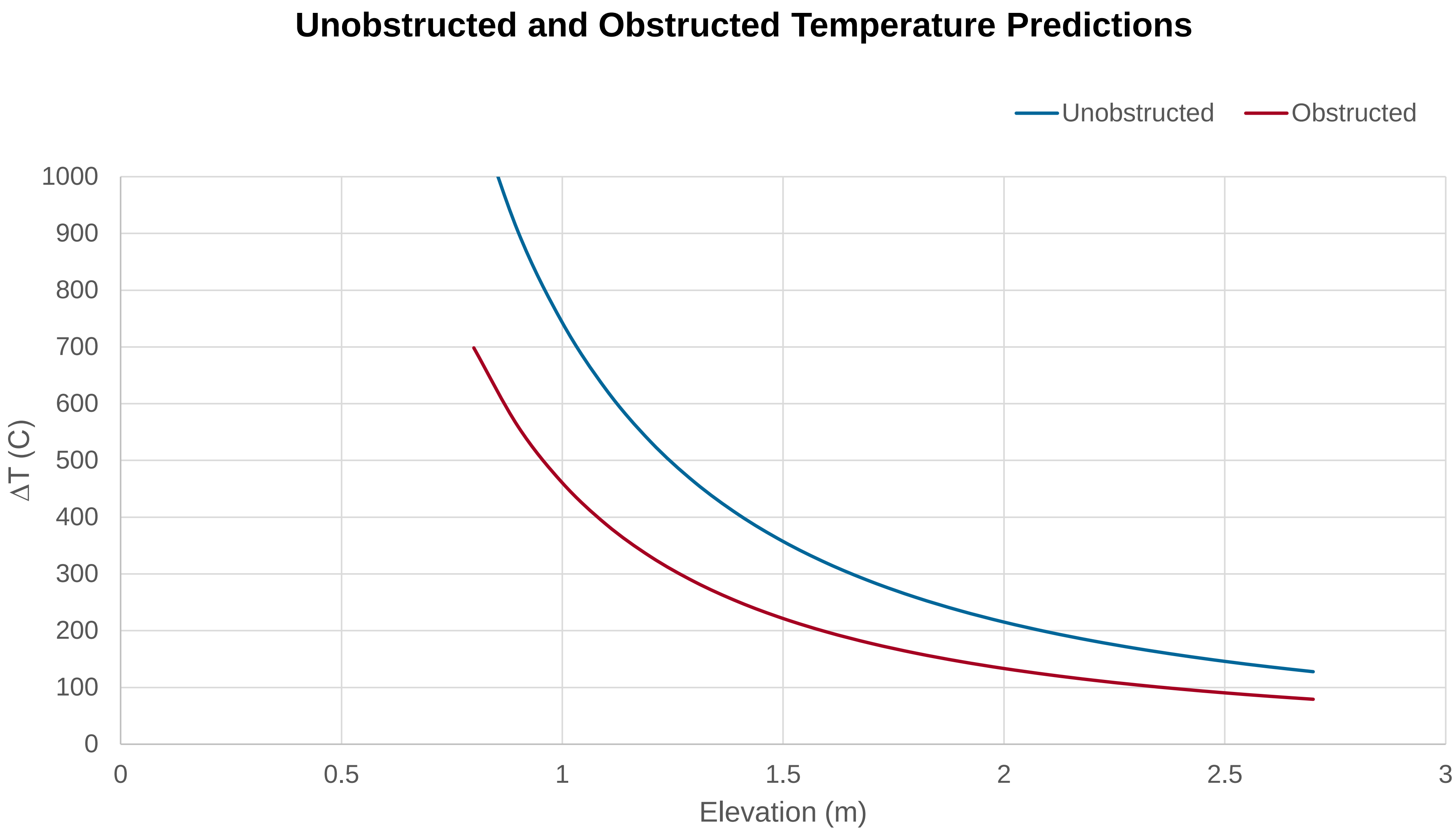


Obstructed Plume Simulations

- Fires often assumed to ignite inside cabinets and current plume calculations ignore the solid top of cabinet
- Utilized Fire Dynamics Simulator (FDS) to study the potential effects of obstruction on fire plume flow, temperature, and ultimately the zone of influence
- Ran 156 simulations varying 4 influencing factors
  - HRR, fire diameter, fire elevation, and number of cabinet walls



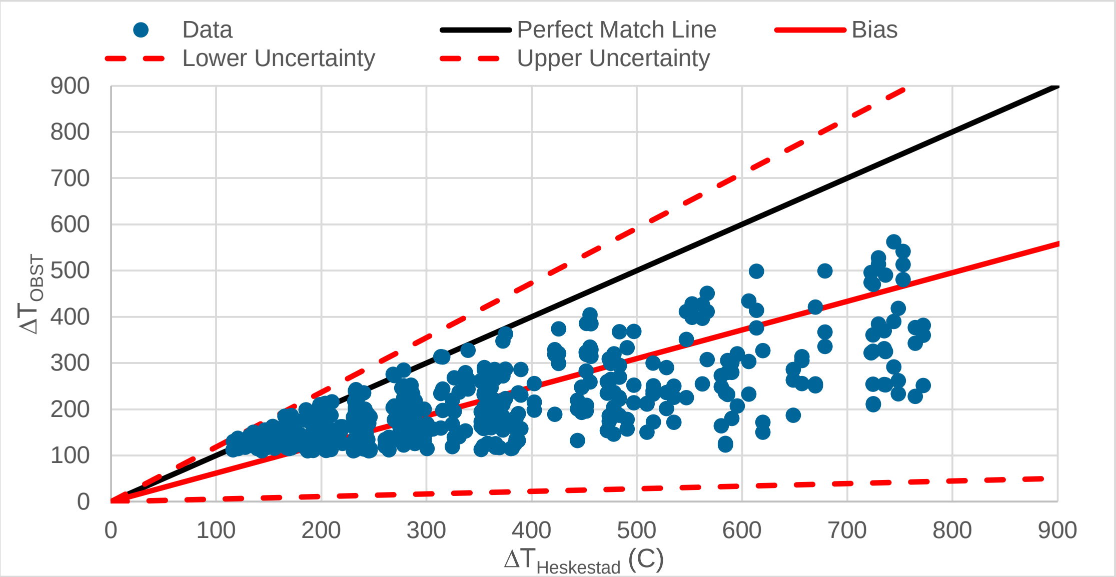
Obstructed Plume Summary of Results



Obstructed Plume Treatment in FPRA

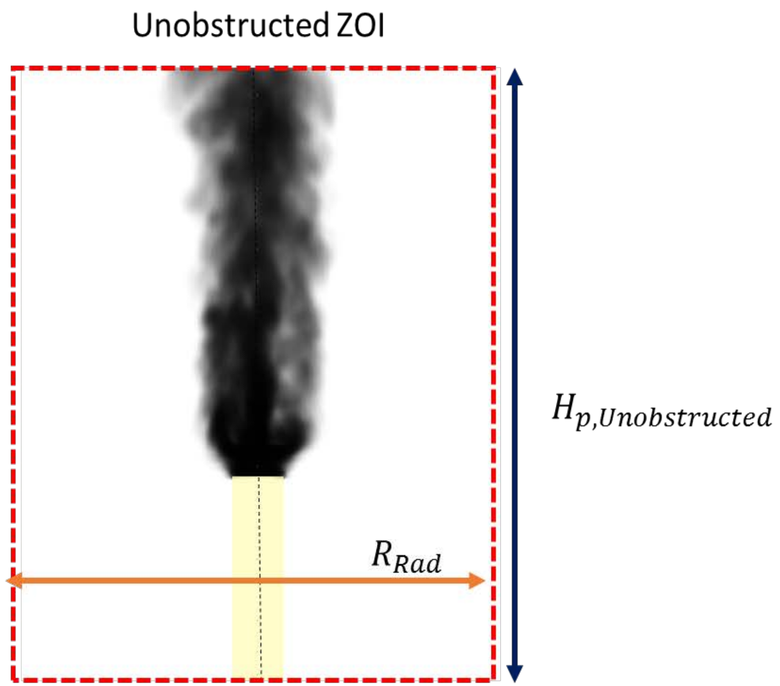
- When estimating <u>vertical</u> fire plume temperatures, a 38% reduction (bias of 0.62) is recommended for electrical cabinet fire scenarios (subject to some conditions)
  - Results in a reduction of ~24% in the zone of influence

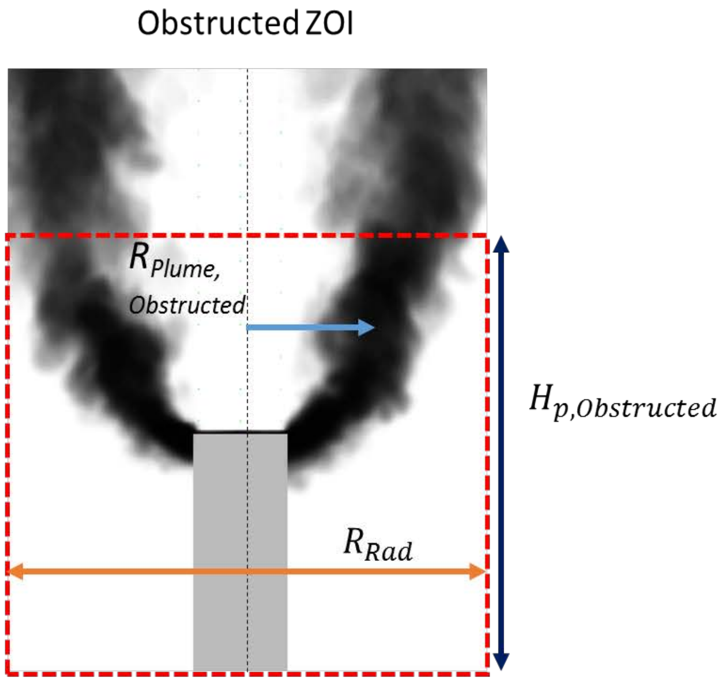
Heskestad versus Obstructed Plume Temperatures – Bias and Uncertainty



Obstructed Plume Treatment in FPRA

- Plume shift by obstructed plume is bounded by horizontal ZOI





Obstructed Plume Limitations

- Obstructed Plume correction cannot be applied for fire scenarios where:
  - **More than 5% of the total top surface area is open (excludes sealed penetrations)**
  - **Flame ZOI damages external targets or secondary combustibles**
  - Fire elevation is located in the bottom half of cabinet
  - Limited to thermal vertical ZOI component (not to be applied to flame, horizontal plume or HGL calculations) and only for electrical cabinet ignition sources

Insights from Pilot Application of NUREG-2178

- Application in 3 fire compartments resulted in an 87% reduction in CDF
  - No changes applied to fire growth or damage thresholds, only HRR
  - Severity factors reduced on average by 74%
    - This is pronounced for volumetric size distributions as most of the distributions are weighted toward the lower end
  - Smaller ZOIs
    - Number of targets reduced by 36% for 98^{th} percentile fires
    - Number of targets reduced by 54% for 75^{th} percentile fires
  - Still significant potential to develop HGL even with new HRRs due to ignition of secondary combustibles
  - Inspection of cabinet internals can result in significant benefit as loading in control cabinets can vary greatly
  - Applying the guidance can provide useful insights for decisions regarding the need or justification of installing modifications

Comparison of Heat Release Rates to EPRI 1011989 NUREG/CR-6850

Enclosure Class/Function Group	Ventilation (Open/Closed Doors)	Fuel Type*	75th Percentile (kW)	98th Percentile (kW)	6850 75th Percentile (kW)	6850 98th Percentile (kW)
1 – Switchgear and Load Centers	Closed	TS/SIS/QTP	30	170	69	211
	Closed	TP	60	170	90	211
2 – MCCs and Battery Chargers	Closed	TS/SIS/QTP	25	130	69	211
	Closed	TP	50	130	90	211
3 – Power Inverters	Closed	TS/SIS/QTP	25	200	69	211
	Closed	TP	50	200	90	211
4a - Large Enclosures >1.42 m^3 (>50 ft^3)	Closed	TS/SIS/QTP	50	400	211	702
	Closed	TP	100	400	232	464
	Open	TS/SIS/QTP	100	700	211	702
	Open	TP	200	1000	232	1002
4b - Medium Enclosures ≤1.42 m^3 (50 ft^3) & > 0.34 m^3 (12 ft^3)	Closed	TS/SIS/QTP	25	200	69/211	211/702
	Closed	TP	50	200	90/232	211/464
	Open	TS/SIS/QTP	40	325	69/211	211/702
	Open	TP	80	325	90/232	211/1002
4c - Small Enclosures ≤ 0.34 m^3 (12 ft^3)	N/A	All	15	45	69/90	211

Together…Shaping the Future of Electricity

NUREG-2178, Vol. 2 and EPRI 3002016052

Fire Modeling Guidance for Electrical Cabinets, Electric Motors, Indoor Dry-Transformers, and the Main Control Board

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

What's in NUREG-2178 Volume 2?

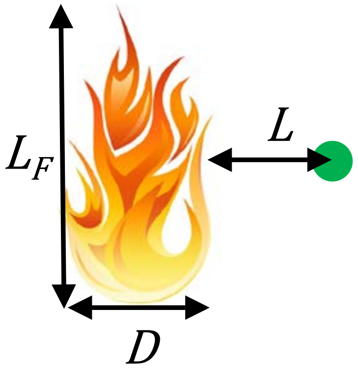
- Revised radiation model
- Obstructed radiation
- Fire spread between adjacent cabinets
- Revised motor and dry-transformer HRR profiles
- Revised wall and corner fire location factors
- Main control board fire scenarios
- Heat soak damage integral

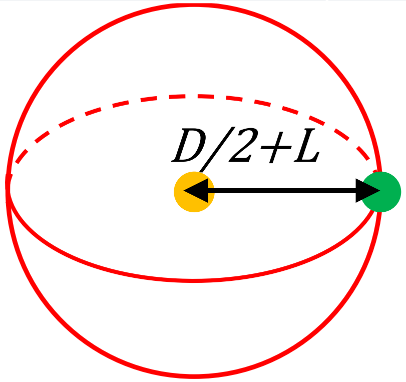
Radiation

Unobstructed Radiation – Point Source Model

- Model assumes:
  - Radiative emissions are isotropic (same in all directions)
  - View factor of fire to target is near zero (target distance must around 2.5 – 3 times larger than either the larger of the flame height or source diameter)
- The larger the fire size, the further the target must be from the source to meet assumptions to justify the application of this model

Source	98th Percentile Fire Size (kW)	Source Dimension (m)		Distance for Heat Flux (m) [ft]		
				Target Flux (kW/m^2)		
		D	L_F	3	6	11
Small cabinet (1 ft^3 cube)	45	0.34	0.73	0.60 [2.0]	0.42 [1.4]	0.31 [1.0]
Medium cabinet (12 ft^3: 2 ft x 2 ft x 3 ft)	325	0.69	1.67	1.61 [5.3]	1.14 [3.7]	0.84 [2.8]
Large cabinet (54 ft^3: 3 ft x 3 ft x 6 ft)	1000	1.03	2.67	2.82 [9.3]	1.99 [6.5]	1.47 [4.8]
Small Motor (1 ft^2 base)	69	0.34	0.92	0.74 [2.4]	0.52 [1.7]	0.39 [1.3]
Transient (Three 41.64 liter [11 gal] bags)	317	0.50	1.84	1.59 [5.2]	1.12 [3.7]	0.83 [2.7]
Lube Oil Spill (3.78 liters [1 gal])	6700	2.6	5.29	7.3 [24]	5.2 [17.1]	3.8 [12.5]
Lube Oil Spill (37.85 liters [10 gal])	67000	8.3	11.6	23 [75.5]	16.3 [53.5]	12.1 [39.7]
Lube Oil Spill (378.5 liters [100 gal])	160000	13	15	36 [118.1]	25 [82]	19 [62.3]





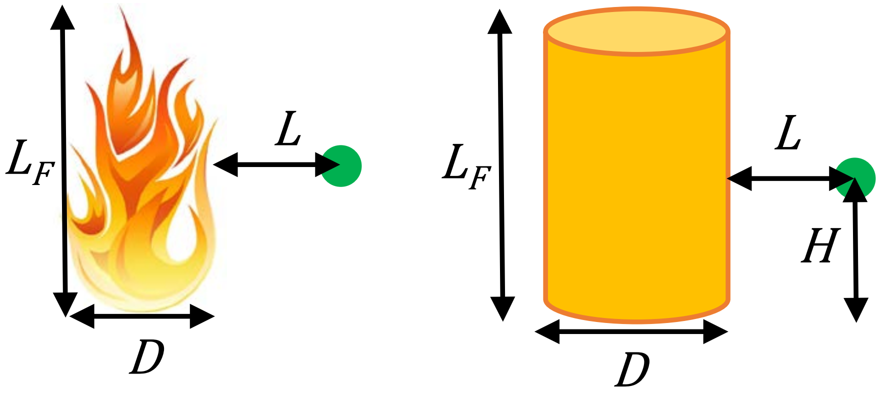
Point Source

$$\dot{q}_r'' = \frac{\chi_r \dot{q}}{4\pi(D/2+L)^2}$$

Unobstructed Radiation – Solid Flame Model

- Model assumes:
  - Fire can be represented by a right, circular cylinder
  - Estimation of emissive power, E, developed from large pool fires.
- Effective radiant fractions, χ_r, estimated using the emissive power for typical NPP HRRs are far larger than experimentally expected 0.3
- Revised estimation of emissive power:

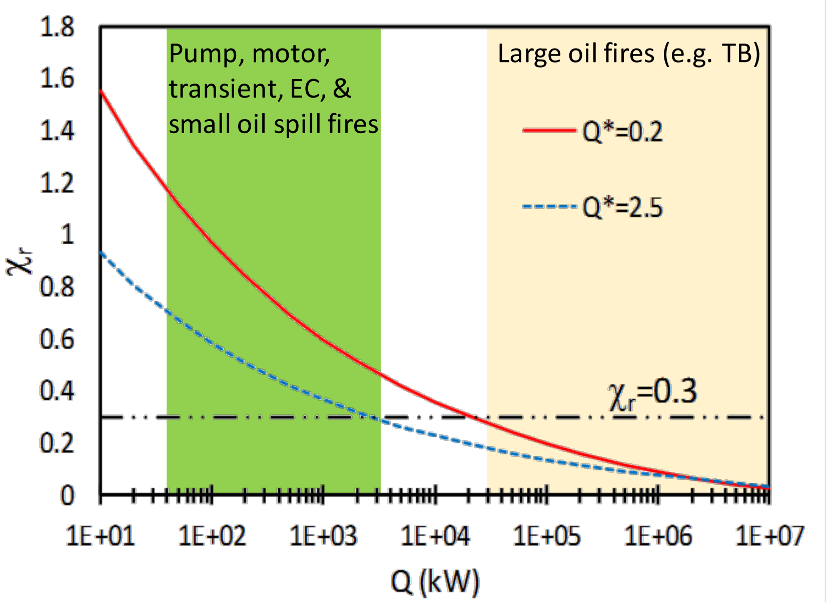
$$E = \mathrm{Min}\left(58 \times 10^{-0.00823D}, \frac{\chi_r \dot{q}}{\pi D L_f}\right)$$



Solid Flame

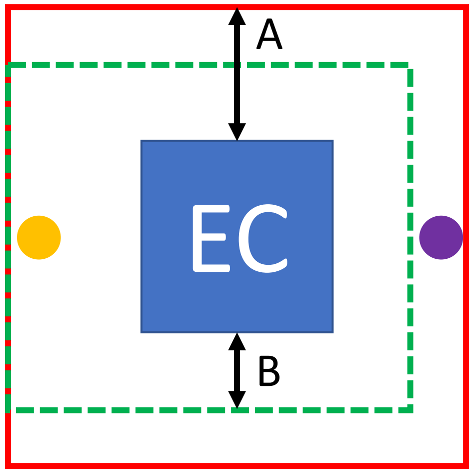
$$\dot{q}_r'' = EF$$

E=emissive power
F=view factor

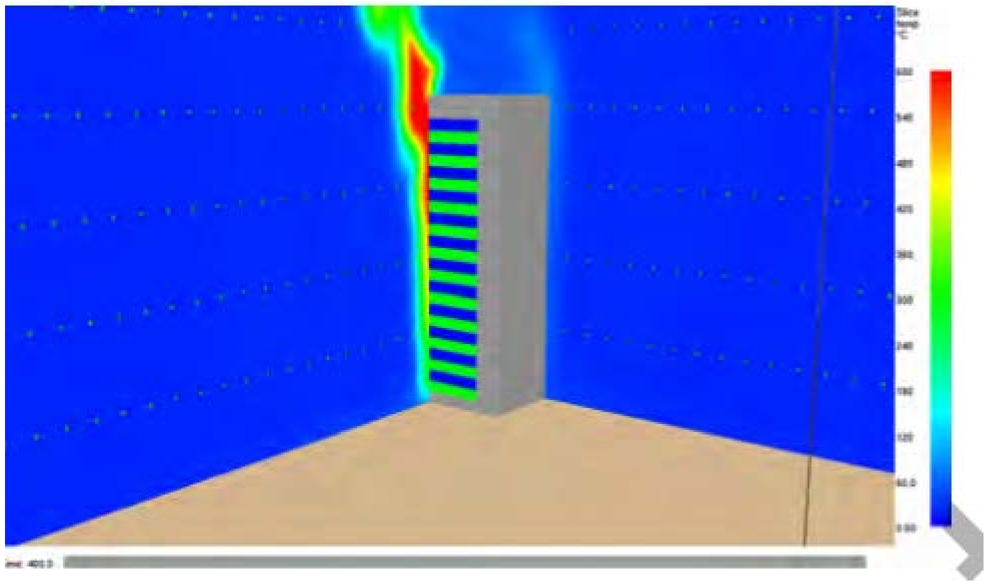


Obstructed Radiation

- CFD (FDS) modeling + NIST fire tests
- Report describes:
  - Screening process for targets
    - Fraction to reduce calculated (FDT^s) ZOI: Obs_Fac
  - Severity factor for closest targets
  - Detailed ‘how to’ in FDS



B= Obs_fac × A



U.S.NRC United States Nuclear Regulatory Commission Protecting People and the Environment
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Obstructed Radiation – Obstructed ZOI Fraction

ZOI Factor (Obs_Fac): Unvented Face

Cabinet Size	Cabinet Ventilaltion[3]	Cable Type	Threshold Approach ZOI Factor[2] (Very Low / Low / Default)	Damage Integral Approach ZOI Factor (Very Low / Low / Default)
Large (>50 ft^3)	Open	TP	0.00 / 0.41 / 0.45	0.00 / 0.44 / 0.53
		TS	0.00 / 0.41 / 0.45	0.00 / 0.27 / 0.45
	Closed	TP	0.00 / 0.43 / 0.68	0.00 / 0.32 / 0.59
		TS	0.00 / 0.32 / 0.52	0.00 / 0.32 / 0.52
Medium (12 ft^3 to 50 ft^3)	Open	TP	0.00 / 0.33 / 0.55	0.00 / 0.33 / 0.48
		TS	0.00 / 0.26 / 0.44	0.00 / 0.26 / 0.44
	Closed	TP	0.00 / 0.39 / 0.63	0.00 / 0.39 / 0.55
		TS	0.00 / 0.30 / 0.61	0.00 / 0.30 / 0.61

ZOI Factor (Obs_Fac): Vented Face

Cabinet Size	Cabinet Ventilaltion[3]	Cable Type	Threshold Approach ZOI Factor[2] (Very Low / Low / Default)	Damage Intergral Approach ZOI Factor (Very Low / Low / Default)
Large (>50 ft^3)	Open	TP	0.08 / 0.94 / 1.06	0.08 / 0.80 / 0.99
		TS	0.00 / 0.55 / 0.91	0.00 / 0.55 / 0.91
	Closed	TP	0.26 / 0.43 / 0.76	0.26 / 0.21 / 0.68
		TS	0.00 / 0.32 / 0.78	0.00 / 0.32 / 0.78
Medium (12 ft^3 to 50 ft^3)	Open	TP	0.10 / 0.67 / 0.90	0.10 / 0.59 / 0.83
		TS	0.00 / 0.51 / 0.98	0.00 / 0.51 / 0.98
	Closed	TP	0.34 / 0.39 / 0.79	0.34 / 0.39 / 0.63
		TS	0.31 / 0.30 / 0.73	0.31 / 0.30 / 0.73

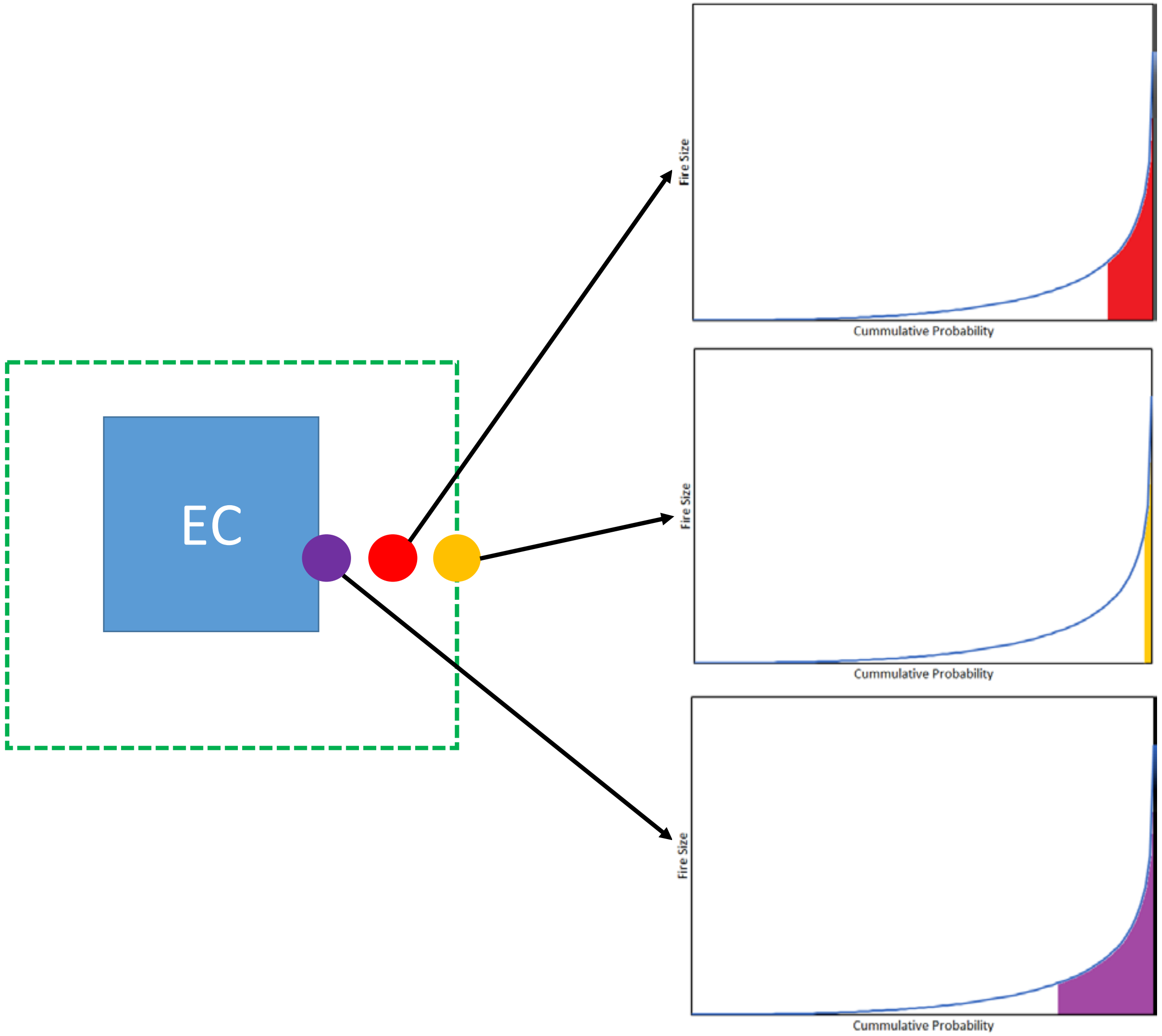
Obstructed Radiation – Severity Factor

Maximum Severity Factor – Unvented Face

Cabinet Size	Cabinet Ventilation[2]	Cable Type	Threshold Approach (Very Low / Low / Default)	Damage Integral Approach (Very Low / Low / Default)
Large (>50 ft^3)	Open	TP	0.00 / 0.16 / 0.30	0.00 / 0.16 / 0.30
		TS	0.00 / 0.04 / 0.11	0.00 / 0.04 / 0.11
	Closed	TP	0.01 / 0.10 / 0.25	0.00 / 0.07 / 0.20
		TS	0.00 / 0.03 / 0.10	0.00 / 0.03 / 0.10
Medium (12 ft^3 to 50 ft^3)	Open	TP	0.00 / 0.08 / 0.25	0.00 / 0.05 / 0.20
		TS	0.00 / 0.03 / 0.10	0.00 / 0.03 / 0.10
	Closed	TP	0.01 / 0.10 / 0.25	0.01 / 0.07 / 0.20
		TS	0.00 / 0.04 / 0.10	0.00 / 0.04 / 0.10

Maximum Severity Factor – Vented Face

Cabinet Size	Cabinet Ventilation[2]	Cable Type	Threshold Approach (Very Low / Low / Default)	Damage Integral Approach (Very Low / Low / Default)
Large (>50 ft^3)	Open	TP	0.06 / 0.37 / 0.50	0.01 / 0.26 / 0.40
		TS	0.01 / 0.16 / 0.26	0.01 / 0.16 / 0.26
	Closed	TP	0.15 / 0.34 / 0.50	0.15 / 0.34 / 0.50
		TS	0.01 / 0.07 / 0.15	0.01 / 0.07 / 0.15
Medium (12 ft^3 to 50 ft^3)	Open	TP	0.08 / 0.23 / 0.50	0.08 / 0.23 / 0.50
		TS	0.02 / 0.12 / 0.24	0.02 / 0.12 / 0.24
	Closed	TP	0.21 / 0.35 / 0.51	0.21 / 0.35 / 0.51
		TS	0.09 / 0.16 / 0.24	0.09 / 0.16 / 0.24



Cabinet to Cabinet Propagation

Flame Spread to Adjacent Cabinets

- Do not postulate fire spread between adjacent cabinets when:
  - Both the exposing and exposed cabinets have solid steel panels on their adjacent sides (double wall)
  - Either cabinet has an open top AND there is an internal wall between the cabinets AND there are no cables running in an upward direction (vertically or diagonally)
  - **The exposing cabinet has a *very low* fuel load**
  - **The exposing cabinet is categorized as a 'small' electrical enclosure**
  - **There is a steel partition between the enclosures AND the exposing cabinet has a *low* fuel load OR the exposed cabinet has a *very low* fuel load**
  - **The exposing cabinet has a *low* fuel load and the exposed cabinet has a *very low* fuel load**
- **Do not postulate fire spread between adjacent MCC and Switchgear vertical sections**

Flame Spread to Adjacent Cabinets

- If the scenario does not screen based on the rules, propagate the fire:
  - For the top 2% of HRR percentiles
  - To one adjacent cabinet (single direction only, based on risk determination)
- Propagation occurs 10 minutes after ignition of the exposing cabinet

Motor and Transformer HRRs

Motors and Indoor Dry-Transformers

- **Revised Motor HRR**

Classification Group	Motor Size (hp)	α	β	75th Percentile (kW)	98th Percentile (kW)
A	>5-30	1.34	3.26	6	15
B	>30-100	1.17	8.69	14	37
C	>100	1.10	24.19	37	100

- **Revised HRR Profile**
  - Growth Duration of 2 minutes
  - Steady Burning Duration of 13 minutes
  - Decay Duration of 2 minutes
- Guidance published in NUREG/CR-6850
  - 69 kW (or 211kW if pump)
  - Electrical cabinet HRR timing profile – total duration: 39 minutes

- **Revised Dry Transformer HRR**

Classification Group	XFMR Power (kVA)	α	β	75th Percentile (kW)	98th Percentile (kW)
A	>45-75	0.38	12.84	6	30
B	>75-750	0.41	28.57	15	70
C	>750	0.46	50.26	30	130

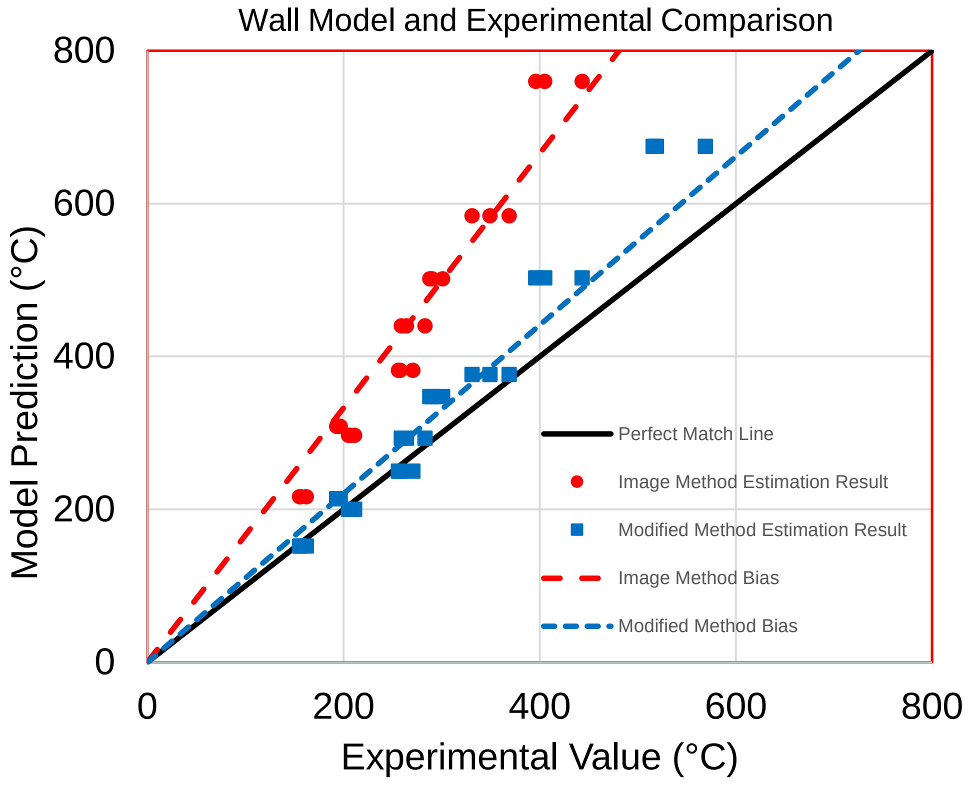
- **Revised HRR Profile**
  - Growth Duration of 0 minutes
  - Steady Burning Duration of 14 minutes
  - Decay Duration of 14 minutes
- Guidance published in NUREG/CR-6850
  - 69 kW
  - Electrical cabinet timing profile – total duration: 39 minutes

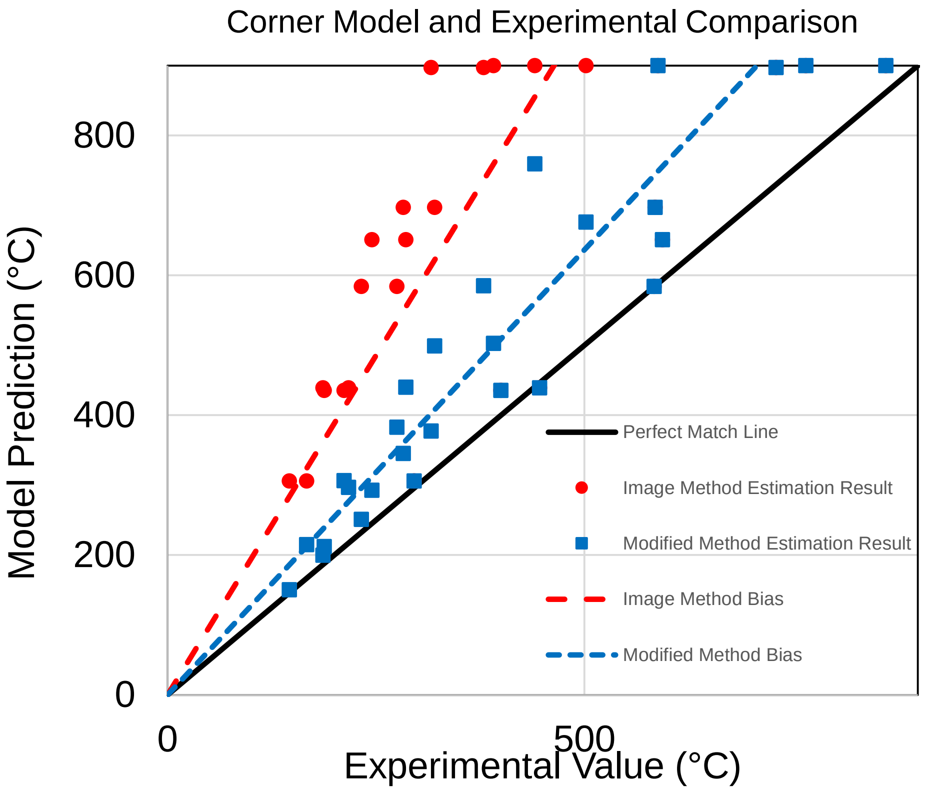
Fire Location Factor

Revised Fire Location Factor

- Based on CFD (FDS) Simulations and NIST Experiments

Configuration	Revised Location Factor		
	0-0.3 m (1 ft)	0.3 – 0.6 m (2 ft)	> 0.6m (2ft)
Corner	4	2	1
Wall	**1**	**1**	**1**

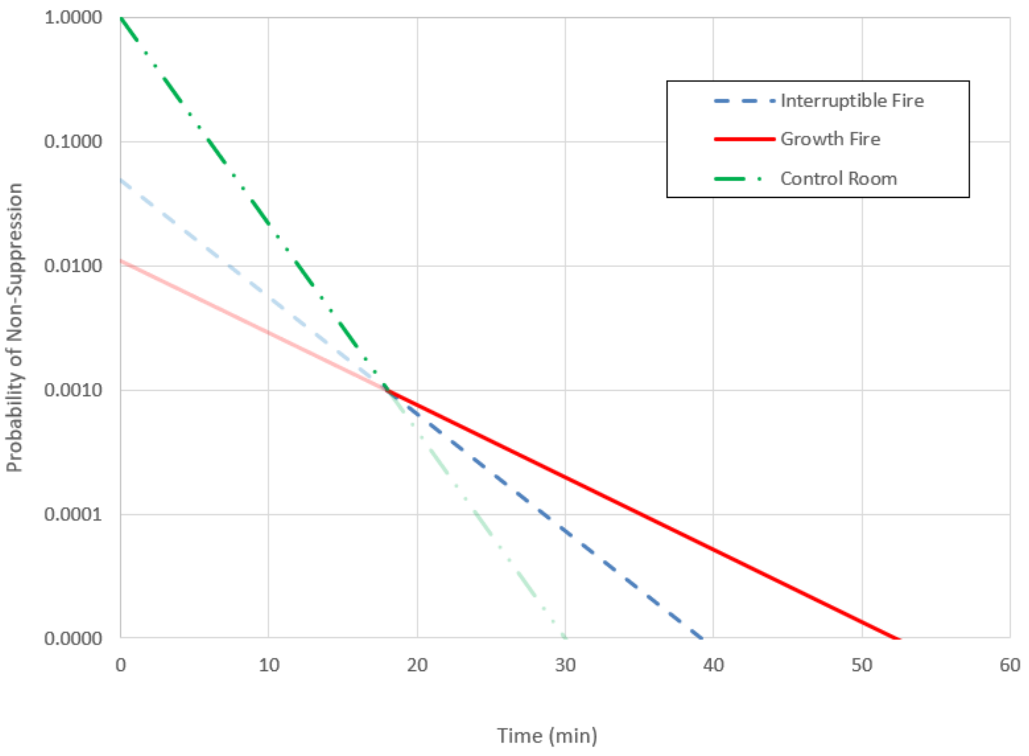




Main Control Board

Main Control Room Manual Non-Suppression Probability Floor

- Revised NSP floor of 2.4E-07 for Control Room fires
  - Split at 1.0E-03 to Non-control Room Suppression Rate(s)



Time (min)	Main Control Room
0	1.00E+00
5	1.46E-01
10	2.14E-02
15	3.12E-03
20	6.40E-04/7.54E-04†
25	2.16E-04/3.86E-04†
30	7.31E-05/1.97E-04†
35	2.47E-05/1.01E-04†
40	8.34E-06/5.17E-05†
45	2.82E-06/2.65E-05†
50	9.53E-07/1.35E-05†
55	3.22E-07/6.93-06†
60	§/3.55E-06†
65	§/1.18E-06†
70	§/9.28E-07†
75	§/4.753E-07†
80	§/2.43E-07†
85	§
90	§
95	§
100	§

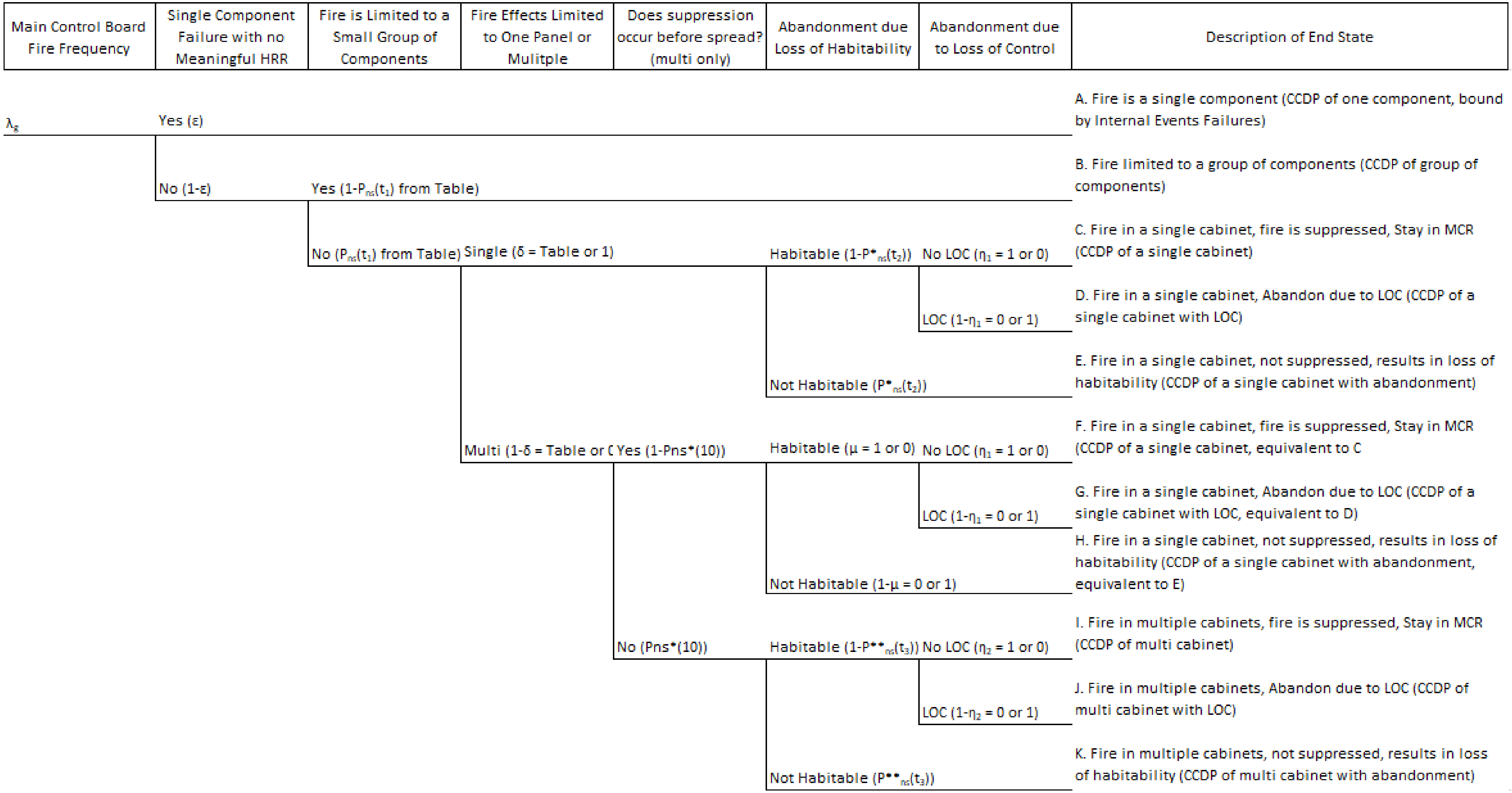
Main Control Board Fires

- Alternate method to Appendix L in NUREG/CR-6850
  - Appendix L limitations:
    - Based on inputs and guidance that has been superseded (NUREG-2169, NUREG-2178)
    - No guidance on how to postulate scenarios and capture the scenario progression
    - No guidance on number of scenarios to postulate
- Revised method follows two general steps:
  1. Calculate a screening CDF for individual MCB panel sections
  2. Outline the detailed fire scenario analysis

MCB – Screening CDF for MCB Panel Sections

- Scenario definition/process
  - Identify each panel section of the MCB
  - Identify FPRA cables associated with each panel
  - Calculate fire ignition frequencies for each panel
    - Product of: MCB generic frequency (Bin 4), ignition source weighting factor, and constant value of 0.22 for fires that propagate past a single sub-component (OPEX derived)
- Identify panels with relatively low risk contribution
  - These panels may not need detailed modeling
- Calculate two CCDPs
  - One for failure of all basic events mapped to the cables associated with each panel
  - One for single worst-case basic event associated with each panel

MCB Detailed Fire Scenario Analysis Event Tree



MCB Detailed Fire Scenario Analysis Event Tree

Events

- Event 1: Ignition (MCB (Bin 4) fire ignition frequency)
- Event 2: Single subcomponent failure with no meaningful HRR
- Event 3: Fire limited to single small group of components
- Event 4: Are fire effects limited to single panel?
- Event 5: Does Suppression occur prior to fire spread?
- Event 6: MCR abandonment due to loss of habitability
- Event 7: MCR abandonment due to loss of control

Branches

Terminal Branch End State	Description
A	A single subcomponent failure. The CCDP of the case can be approximated from Internal Events failures.
B	Fire limited to a small group of subcomponents. The CCDP of the case can be approximated from Internal Events failures.
C	The fire is confined to a single cabinet and suppressed before abandonment due to LOH or LOH. The CCDP of the case is the loss of the MCB panel.
D	The fire is confined to a single MCB panel and suppressed before abandonment due to LOH, but results in LOC. The CCDP of the case is the loss of the MCB panel with alternate shutdown.
E	The fire is confined to a single MCB panel and not suppressed resulting in abandonment due to LOH. The CCDP of the case is the loss of the MCB panel with forced abandonment.
F	The fire is suppressed before the fire spreads to the adjacent cabinet at 10 minutes (see Section 4.4 of this report), which is also before LOH and LOC. The CCDP of the case is the loss of a single MCB panel, equivalent to Branch C.
G	The fire is suppressed before the fire spreads to the adjacent MCB panel at 10 minutes, which is before LOH but LOC occurs. The CCDP of the case is the loss of a single MCB panel with alternate shutdown, equivalent to Branch D.
H	The fire results in LOH before it spreads to the adjacent panel at 10 minutes. The CCDP of the case is the loss of a single MCB panel, with forced abandonment.
I	The fire spreads to an adjacent MCB panel, but is suppressed before LOH and LOC. The CCDP of the case is the loss of two MCB panels.
J	The fire spreads to an adjacent MCB panel and is suppressed before LOH, but LOC occurs. The CCDP of the case is the loss of two MCB panels with alternate shutdown.
K	The fire spreads to an adjacent MCB panel, then results in LOH. The CCDP of the case is the loss of two MCB panels, with forced abandonment.

MCB Fire Ignition Frequency

- Follow guidance presented in FAQs 06-0018 and 14-008 for counting MCB panels
- NUREG-2178 updates the generic ignition frequency

Bin	Location	Ignition Source	Power Modes	PRA Type	Time Period	Mean	Median	5th percent	95th percent
4	Control Room	Main Control Board	AP	FPIE	1990-2014	2.05E-03	2.61E-04	4.27E-07	7.19E-03
4	Control Room	Main Control Board	AL	LPSD	1990-2014	4.36E-03	9.61E-04	2.33E-06	1.36E-02

- Apportion frequency among MCB panels:
  - Identify each MCB section
  - Measure length of each section along its longest horizontal distance
  - Measure length of entire MCB
  - Calculate ratio between each MCB section and the full length of MCB. Use this ratio to apportion the frequency to each MCB section.

Single Subcomponent Failure

- Review of MCB fire OPEX
  – 7 of the 9 events (78%) describe a fire that was not a significant source of heat and the damage was isolated to the initial subcomponent
  – The remaining 2 events (22%) describe fires that caused damage beyond the initial subcomponent
- This ratio will be used as a split fraction for Branch A

Fire Limited to Small Group of Subcomponents

- Fires that progress past the single subcomponent are estimated as a relativity small circular ZOI of 0.092 m^2 (1.0 ft^2)
  - Bounds IEEE 384 design guidelines
- ZOI area may be used as an apportioning factor for each scenario postulated.
- Fires resulting in limited ZOI determined through a Monte Carlo sampling process

Fire Limited to Small Group of Subcomponents

- Monte Carlo Simulation consists of:
  - Generate a fire HRR profile over time (random parameters: time to peak HRR, growth power factor (n), steady time, decay time, and peak HRR).
  - Calculate the time dependent fire exposure at a radial distance of 0.15 m (6 in) (random parameters: HRRPUA; required constant parameters: distance, fire Froude number parameters, radiant fraction).
  - Calculate the time response of an electrical target and determine time to damage, if appropriate (no additional random or constant parameters needed).
  - Calculate NSP for the trial given the time to damage calculation and credit for early detection if appropriate (additional random parameters: manual detection credit; additional constant parameters: in-cabinet detection system credit, system unavailability).
  - Average all NSP results over 20,000 occurrences.

Parameter	Distribution Type	α	B	Average Value	Notes
Distance from fire to target	Constant	N/A	N/A	0.1524 m	Target Separation
Main Control Room Suppression Rate	Constant	N/A	N/A	0.385 min^{-1}	NSP function (See Section 8.5.5)
Non-Suppression probability floor value	Constant	N/A	N/A	0.0001	Minimum value for NSP
Ambient Temperature	Constant	N/A	N/A	25 °C	Typical ambient temperature in MCR
Ambient Pressure	Constant	N/A	N/A	101325 Pa	Typical ambient pressure in MCR
HRR Radiant Fraction	Constant	N/A	N/A	0.3	Typical fire radiant fraction
Duration of the pre-growth and growth phases of the HRR profile	Gamma	2.33	5.59	13.1 min	Total of incipient and growth phase (See Section 8.5.2)
Growth Power Factor (n-1)	Gamma	0.345	5.80	2.98	Add 1.0 such that the distribution is never less than 1.0
Duration of the steady state HRR profile stage	Gamma	0.840	11.2	9.52 min	Steady burning duration (See Section 8.5.2)
Duration of the decay state HRR profile stage	Gamma	0.688	27.1	18.6 min	Decay burning duration (See Section 8.5.2)
Heat Release Rate per Unit Area	Uniform	150 kW/m^2 (min)	500 kW/m^2 (max)	325 kW/m^2	Range to account for cables and electronic subcomponents
Peak HRR	Gamma	Varies	Varies	Varies	See NUREG-2178, Table 4-2

Fire Limited to Small Group of Subcomponents

Results of Monte Carlo Modeling of Non-Severe MCB Fires (no-in cabinet detection)

Enclosure Class/Function Group	Enclosure ventilation	Fuel Type	Probability of non-Suppression, $P_{ns}(t_1)$		
			Default	Low	Very Low
4a - Large Enclosures	Closed	TS/QTP/SIS	0.035	0.021	0.010
	Closed	TP	0.057	0.032	0.015
	Open	TS/QTP/SIS	0.054	0.035	0.010
	Open	TP	0.080	0.056	0.014
4b - Medium Enclosures	Closed	TS/QTP/SIS	0.021	0.012	0.007
	Closed	TP	0.033	0.016	0.006
	Open	TS/QTP/SIS	0.029	0.015	0.006
	Open	TP	0.048	0.019	0.006

Results of Monte Carlo Modeling of Non-Severe MCB Fires (with in cabinet detection)

Enclosure Class/Function Group	Enclosure ventilation	Fuel Type	Probability of non-Suppression, $P_{ns}(t_1)$		
			Default	Low	Very Low
4a - Large Enclosures	Closed	TS/QTP/SIS	0.013	0.008	0.004
	Closed	TP	0.021	0.012	0.005
	Open	TS/QTP/SIS	0.020	0.013	0.004
	Open	TP	0.029	0.020	0.005
4b - Medium Enclosures	Closed	TS/QTP/SIS	0.008	0.004	0.002
	Closed	TP	0.012	0.006	0.002
	Open	TS/QTP/SIS	0.011	0.005	0.002
	Open	TP	0.018	0.007	0.002

Fire Size Limited to a Single Cabinet

- Monte Carlo sampling for fires that grow beyond the small group of sub components:
  - Fires in the top 2% of the HRR distribution,
  - Not initially suppressed in the non-severe Monte Carlo model, and
  - Are not suppressed prior to exposing a second panel.
- The fraction of these fires is captured in this MCB propagation value, $(1 - \delta)$,

Fire Limited to a Single Cabinet

Results of Monte Carlo Modeling MCB for fires that spread to an adjacent panel (no in-cabinet detection)

Enclosure Class/Function Group	Enclosure ventilation	Fuel Type	Fraction of Fires that Spread to an Adjacent Panel $(1-\delta)$		
			Default	Low	Very Low
4a - Large Enclosures	Closed	TS/QTP/SIS	0.114	0.145	0.000
	Closed	TP	0.078	0.113	0.000
	Open	TS/QTP/SIS	0.099	0.106	0.000
	Open	TP	0.065	0.081	0.000
4b - Medium Enclosures	Closed	TS/QTP/SIS	0.162	0.210	0.000
	Closed	TP	0.098	0.152	0.000
	Open	TS/QTP/SIS	0.119	0.227	0.000
	Open	TP	0.084	0.156	0.000

Results of Monte Carlo Modeling MCB for fires that spread to an adjacent panel (with in cabinet detection)

Enclosure Class/Function Group	Enclosure ventilation	Fuel Type	Fraction of Fires that Spread to an Adjacent Panel $(1-\delta)$		
			Default	Low	Very Low
4a - Large Enclosures	Closed	TS/QTP/SIS	0.116	0.157	0.000
	Closed	TP	0.076	0.113	0.000
	Open	TS/QTP/SIS	0.086	0.128	0.000
	Open	TP	0.061	0.083	0.000
4b - Medium Enclosures	Closed	TS/QTP/SIS	0.161	0.273	0.000
	Closed	TP	0.112	0.124	0.000
	Open	TS/QTP/SIS	0.121	0.215	0.000
	Open	TP	0.094	0.172	0.000

Fire Suppressed Prior Spreading to an Adjacent Cabinet

- For fires that spread to an adjacent cabinet, the probability of suppressing the fire before it propagates is dependent on earlier suppression credit

$$P(B|A) = \frac{P_{ns}(t_B)}{P_{ns}(t_A)}$$

  - $P(B|A)$ is the conditional probability of Event B occurring given that Event A has already occurred,
  - $P_{ns}(t_B)$ is the total probability of non-suppression at the time of the second event (i.e. the current event time, t_B).
  - $P_{ns}(t_A)$ is the probability of non-suppression at the time of the previous event (i.e. the time of Event A, t_A)

MCB Event Tree Branch Summary

Terminal Branch End State	Branch Frequency	Description
A	$\lambda_g \varepsilon$	A single subcomponent failure. The CCDP of the case can be approximated from Internal Events failures.
B	$\lambda_g(1-\varepsilon)\big(1-P_{ns}(t_1)\big)$	Fire limited to a small group of subcomponents. The CCDP of the case can be approximated from Internal Events failures.
C	$\lambda_g(1-\varepsilon)P_{ns}(t_1)\delta\big(1-P_{ns}^*(t_2)\big)\eta_1$	The fire is confined to a single cabinet and suppressed before abandonment due to LOH or LOH. The CCDP of the case is the loss of the MCB panel.
D	$\lambda_g(1-\varepsilon)P_{ns}(t_1)\delta\big(1-P_{ns}^*(t_2)\big)(1-\eta_1)$	The fire is confined to a single MCB panel and suppressed before abandonment due to LOH, but results in LOC. The CCDP of the case is the loss of the MCB panel with alternate shutdown.
E	$\lambda_g(1-\varepsilon)P_{ns}(t_1)\delta P_{ns}^*(t_2)$	The fire is confined to a single MCB panel and not suppressed resulting in abandonment due to LOH. The CCDP of the case is the loss of the MCB panel with forced abandonment.
F	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)\big(1-P_{ns}^*(10)\big)\mu\eta_1$	The fire is suppressed before the fire spreads to the adjacent cabinet at 10 minutes (see Section 4.4 of this report), which is also before LOH and LOC. The CCDP of the case is the loss of a single MCB panel, equivalent to Branch C.
G	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)(1-P_{ns}^*(10)\ \mu(1-\eta_1)$	The fire is suppressed before the fire spreads to the adjacent MCB panel at 10 minutes, which is before LOH but LOC occurs. The CCDP of the case is the loss of a single MCB panel with alternate shutdown, equivalent to Branch D.
H	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)\big(1-P_{ns}^*(10)\big)(1-\mu)$	The fire results in LOH before it spreads to the adjacent panel at 10 minutes. The CCDP of the case is the loss of a single MCB panel, with forced abandonment.
I	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)P_{ns}^*(10)(1-P_{ns}^{**}(t_3))\eta_2$	The fire spreads to an adjacent MCB panel, but is suppressed before LOH and LOC. The CCDP of the case is the loss of two MCB panels.
J	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)P_{ns}^*(10)\big(1-P_{ns}^{**}(t_3)\big)(1-\eta_2)$	The fire spreads to an adjacent MCB panel and is suppressed before LOH, but LOC occurs. The CCDP of the case is the loss of two MCB panels with alternate shutdown.
K	$\lambda_g(1-\varepsilon)P_{ns}(t_1)(1-\delta)P_{ns}^*(10)P_{ns}^{**}(t_3)$	The fire spreads to an adjacent MCB panel, then results in LOH. The CCDP of the case is the loss of two MCB panels, with forced abandonment.

Input Parameters Selected for Evaluation of MCB Event Tree

Parameter	Value	Description
$\boldsymbol{\lambda}$	0.385 min^{-1}	Manual suppression rate constant
$\boldsymbol{\lambda_g}$	2.05E-03 yr^{-1}	Generic Frequency for FPIE
$\boldsymbol{\varepsilon}$	0.78	Fraction of single subcomponent electrical failures counted as fires
$\boldsymbol{\delta}$	Analysis Specific	Fraction of fires effects limited to a single panel
$\boldsymbol{P_{ns}(t_1)}$	Analysis Specific	Split fraction of small fires which are quickly suppressed before spreading to a second electrical subcomponent.
$\boldsymbol{t_2}$	Analysis Specific	This value would be produced by a fire modeling analysis for the time to loss of habitability in the MCR. This value represents an average time to abandonment for simplicity which accounts for the severity factor of all fires below the 98^{th} percentile fire size.
$\boldsymbol{t_3}$	Analysis Specific	This value would be produced by a fire modeling analysis for the time to loss of habitability in the MCR. This value represents the time to abandon given a 98^{th} percentile fire which spreads to an adjacent MCB enclosure.
$\boldsymbol{P^*_{ns}(10)}$	Analysis Specific	This is the conditional probability that a fire is not suppressed at 10 minutes, given the failure to suppress at t_1. The value is calculated using equation: $$P^*_{ns}(10) = \text{MIN}\left(\frac{P_{ns}(10)}{P_{ns}(t_1)}, 1\right)$$
$\boldsymbol{P^*_{ns}(t_2)}$	Analysis Specific	This is the conditional probability that a fire is not suppressed at t_2 (before loss of habitability), given the failure to suppress at t_1. The value is calculated using equation: $$P^*_{ns}(t_2) = \text{MIN}\left(\frac{P_{ns}(t_2)}{P_{ns}(t_1)}, 1\right)$$
$\boldsymbol{P^{**}_{ns}(t_3)}$	Analysis Specific	This is the conditional probability that a fire is not suppressed at t_3 (before loss of habitability for the spreading fire), given the failure to suppress at 10 minutes. The value is calculated using equation: $$P^{**}_{ns}(t_3) = \text{MIN}\left(\frac{P_{ns}(t_3)}{P_{ns}(10)}, 1\right)$$
$\boldsymbol{\mu}$	Analysis Specific	This is the evaluation of whether the MCR is still habitable at 10 minutes for cases in which the fire has been suppressed before spreading to an adjacent enclosure. A value of 1 represents a habitable condition.
$\boldsymbol{\eta_1}$	Analysis Specific	This is the evaluation of whether the failure of the first enclosure fire results in a loss of control event. A value of 1 represents that control has been maintained within the MCR.
$\boldsymbol{\eta_2}$	Analysis Specific	This is the evaluation of whether the failure of the spreading enclosure fire results in a loss of control event once the second enclosure becomes involved. A value of 0 represents that control has been lost and initiation of alternate shutdown is required.

Heat Soak Damage Integral

Heat Soak Damage Integral

- Methods for assessing damage to electrical cables:
  - Exposure threshold (Table H-1, NUREG/CR-6850)
    - Simplest approach, conservative
  - Time-to-damage lookup tables (Tables H-5 through H-8, NUREG/CR-6850)
    - Credit for thermal inertia of cable, not readily lent to application of actual fire scenarios
  - THIEF Model (NUREG/CR-6931 and NUREG-1805)
    - 1D heat transfer to time-varying exposure, not generic
- Desire for generic approach for determining time-to-damage for time-varying conditions

Heat Soak Damage Integral

- Cable damage analogous to potential skin burns

$$\Omega = \int_0^t RR(t)dt$$

  - where Ω is the damage integral and $RR(t)$ is a time dependent reaction rate. Damage occurs when Ω crosses a threshold value. In the case of skin burn modeling, the reaction rate is assumed to be an Arrhenius process.
  - The data in the Appendix H tables contain exposure durations as a function of temperature ranges. This can be modeled in a damage integral by assuming the reaction rate is the inverse of the exposure duration:

$$RR(t) = \frac{1}{t'_{dam}\left(T(t)\right)}$$

  - where $T(t)$ is the exposure temperature at time t and t'_{dam} is the time until damage for that temperature from the tables in Appendix H of NUREG/CR-6850. Cable failure would then occur with a damage integral of 1

$$\Omega = \int_0^{t_{dam}} \frac{1}{t'_{dam}\left(T(t)\right)} dt = 1$$

Heat Soak Damage Integral

- An example cable time history is shown below with the damage integral applied using trapezoidal integration. The cable fails at 4.75 minutes

Time (min)	Temperature (°C)	Appendix H Time to Damage (min)	Damage Rate (min^{-1})	Damage Integral
0	210	30	0.033	0.00
1	320	5	0.20	0.12
2	350	3	0.33	0.38
3	320	5	0.20	0.65
4	320	5	0.20	0.85
5	320	5	0.20	**1.05**

Together…Shaping the Future of Electricity

NUREG-2230 and EPRI 3002016051)

Methodology for Modeling Fire Growth and Suppression for Electrical Cabinet Fire in Nuclear Power Plants

Joint EPRI/NRC-RES Fire PRA Workshop

July 15-19, 2019

What's in NUREG-2230

- Methodology limited to Bin 15, electrical cabinets
  - Updated Bin 15 fire ignition frequency
  - Development of *interruptible fire* definition
    - Interruptible and growing fire split fractions
    - Interruptible and growing fire heat release rate timing profiles
  - Revised detection-suppression event tree
    - Credits fire growth classification, detection by plant personnel, and detection by non-fire trouble alarms
  - Revised NSP curves for electrical cabinets (interruptible and growing)
  - Revised NSP curves for all other electrical fires (motors, pumps, transformers)

Bin 15 Fire Ignition Frequency

- Updated for events up through 2014

Fire Ignition Frequency Distribution for Bin 15									
Bin	**Location**	**Ignition Source**	**Power Modes**	**PRA Type**	**Time Period**	**Mean**	**Median**	**5th percent**	**95th percent**
15	Plant-Wide Components	Electrical cabinets (non-HEAF)	AA	FPIE	2000-2014	3.43E-02	3.19E-02	1.13E-02	6.60E-02

- Increase from NUREG-2169 (3.0E-02)

Interruptible Fire - Criteria

- *Interruptible Fire:* A fire that grew at a rate that is slow enough to allow for plant personnel to be notified of the event, locate the source, and suppress the fire with minimal effort. Such fires are limited to the ignition source and typically suppressed using portable fire extinguishers or by de-energizing the ignition source.
- To determine if an event is an *Interruptible Fire*, there are two criteria that need to be met. These criteria are:
  - *The event describes/provides evidence that some time has passed (from the beginning of the fire, to detection and start of suppression actions against the fire) and the fire has not grown beyond the criteria for a small fire, and,*
  - *The event indicates that minimal suppression effort was required to extinguish the fire.*
- The intent of the first criteria is to ensure the fire had the opportunity to grow – time has passed – but has not grown to a point that prevents responding personnel from attempting a suppression response prior to damage of other targets or damage outside the ignition source.
- The intent of the second criteria is to ensure the fire event could be suppressed by plant personnel with minimal effort. Only events describing fires that were suppressed with minimal effort are counted as interruptible.

Interruptible Fire - Conditions

- In review of the events, a number of conditions have been consistently observed for fires that did not show appreciable fire growth and may be used to determine if the *Interruptible Fire* criteria have been met. These conditions can be generally classified based on the detection and personnel response to a cue and the fire size/burning characteristics. Specifically, the following conditions are evaluated:
  1. Notification of an event,
  2. Indication of the passage of time, often recorded or logged as:
     a) Time for personnel traveling to the ignition source,
     b) Time for confirmation of fire detection,
     c) Time for notification to MCR (for both fire and non-fire related initial notifications), and
     d) Time for the dispatch and arrival of the appropriate suppression capabilities, and
  3. Fire size (i.e., small fire observed), and
  4. Suppression of the fire with minimal effort.
- While these conditions may be used to identify the two *Interruptible Fire* criteria, observing these conditions should be used to justify the *Interruptible Fire* **criteria**, and not to directly classify an event as an *Interruptible Fire.*

Interruptible - Notification

- Potential methods of detection
  - Automatic notification to the MCR
    - Non-fire trouble alarm (loss of function, malfunction alarm) to the MCR
  - Automatic smoke alarm
  - Notification by plant personnel
- Excluded methods of detection:
  - Automatic suppression actuation alarms
  - Automatic heat (thermal) alarms
  - Personnel conducting testing and maintenance on equipment of origin

Interruptible – Passage of Time

- The passage of time condition captures the intent of the *Interruptible Fire* criteria that some time has passed allowing the fire an opportunity to grow.
- In most cases, travel (passage of) time is included in the event description as an indication that an operator was dispatched to a location following a notification or alarm in the MCR. In addition,
  - If a fire is discovered while on roving fire watch or routine walkdown it is assumed that the fire started prior to the discovery and had an opportunity to grow.
  - An event where plant personnel discover a fire while working in the same vicinity as the ignition source should not be immediately excluded. While there may not be clear indication of travel, the passage of time may still take place as in these cases personnel would likely have to search for this fire. Examples of the passage of time would include an indication of an odor of smoke or a noise (notification) and words and phrases in the event description like *investigated*, *determined*, *discovered*, or *looking for indication of (a) fire*.

Interruptible – Small Fire

- The small fire condition of an *Interruptible Fire* event means the fire has not grown larger than could be suppressed by the initial responding plant personnel.
  - In many cases an event report includes descriptions of *small* flame lengths, *small* flame heights, or even simply as a *small* fire. This qualitative description does not mean that this condition has been met. While the qualifier *small* is often observed for events that should be classified as *Interruptible Fire*, it must be judged against the context of the entire event description. That is, a propagating or fully involved fire discovered late in the progression does not constitute a small fire.
- In order to meet the *small* fire condition, one of the following indications should be present in the event description:
  - Plant personnel or an operator describes the fire as "small"
  - The fire is limited to a sub-component within the ignition source when discovered
  - The fire is suppressed with minimal effort
- Potential indications that should <u>not</u> be used as evidence of a small fire:
  - A fully involved fire
  - A fire not limited to the ignition source, damaging targets other than the ignition source

Interruptible – Minimal Suppression Effort

- Potential suppression methods
  – De-energization of the ignition source and/or
  – Discharge of a single portable extinguisher
    - Or parts of multiple extinguishers as long as there is an indication that the fire was successfully controlled by the initial attempt.
  – This condition also requires the suppression actions to be performed by the first responding personnel (may be either plant personnel or fire brigade).
- Excluded suppression types:
  – Fixed automatic suppression system
  – Use of multiple extinguishers in quick succession
  – Suppression by hose stream
  – Suppression by off-site assistance

Interruptible Fire – Split Fraction

- Split Fraction

Interruptible and Growing Split Fractions		
Growth Profile	**Count**	**Split Fraction**
Interruptible	34	0.723
Growing	13	0.277

- NSP

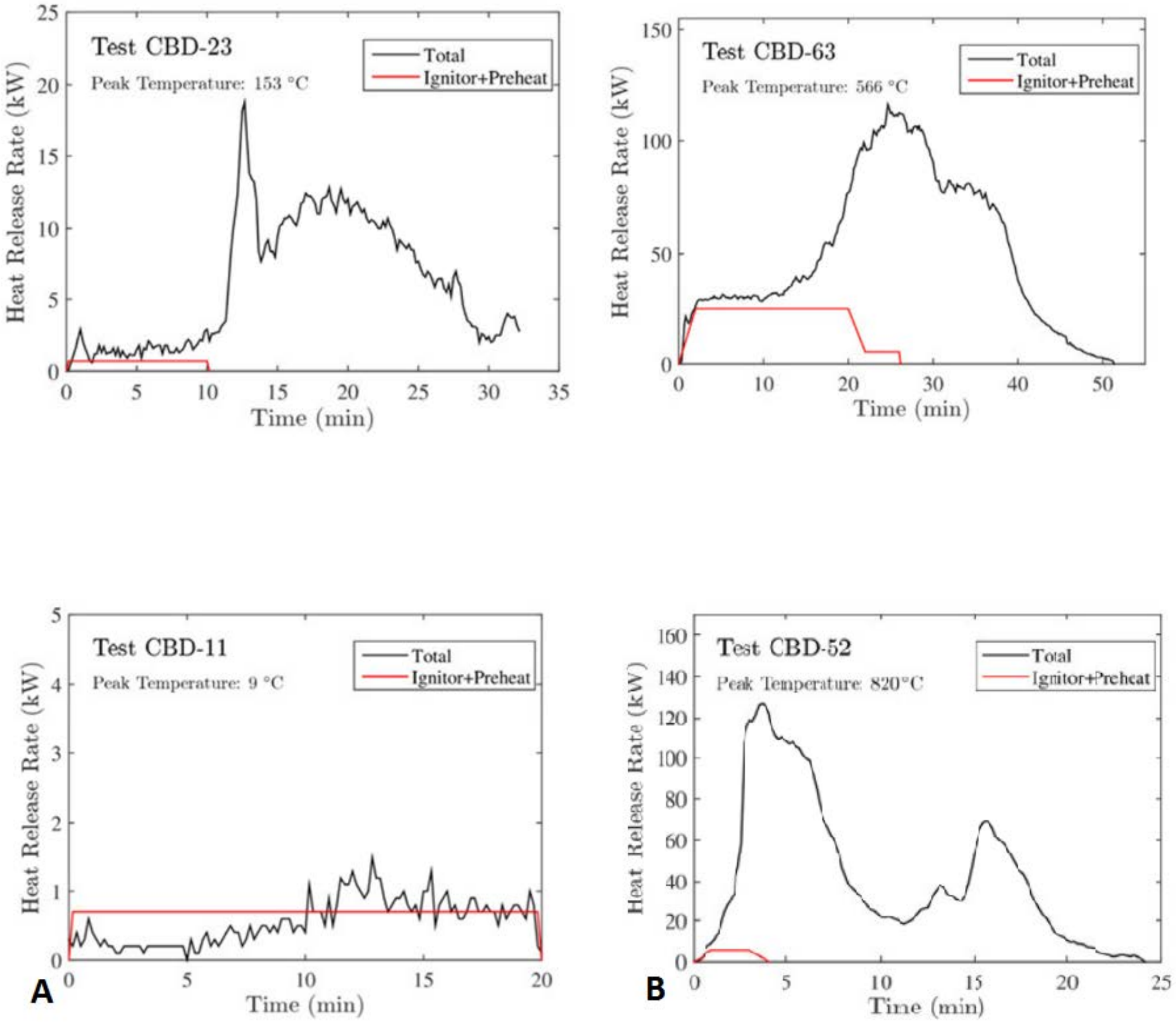
Electrical Ignition Source Probability Distribution for Rate of Fires Suppressed per Unit Time (1990-2014†)						
Suppression Curve	Number of Events	Total Duration	Rate of Fire Suppressed (λ)			
			Mean	5th Percent	50th Percent	95th Percent
Interruptible	43	310	0.139	0.106	0.138	0.175
Growing	19	191	0.099	0.065	0.098	0.140
Electrical Fires*	74	653	0.113	0.093	0.113	0.136
Main Control Room (MCR)†	10	26	0.385	0.209	0.372	0.604

*Electrical fires include non-cabinet electrical sources, such as electrical motors, indoor dry transformers, and junction boxes among other electrical equipment

†Due to the limited number of events in the MCR, the development of the suppression rate includes data from the 1980s. For detailed information on the control room suppression rate, see NUREG-2178 Volume 2 EPRI 3002016052

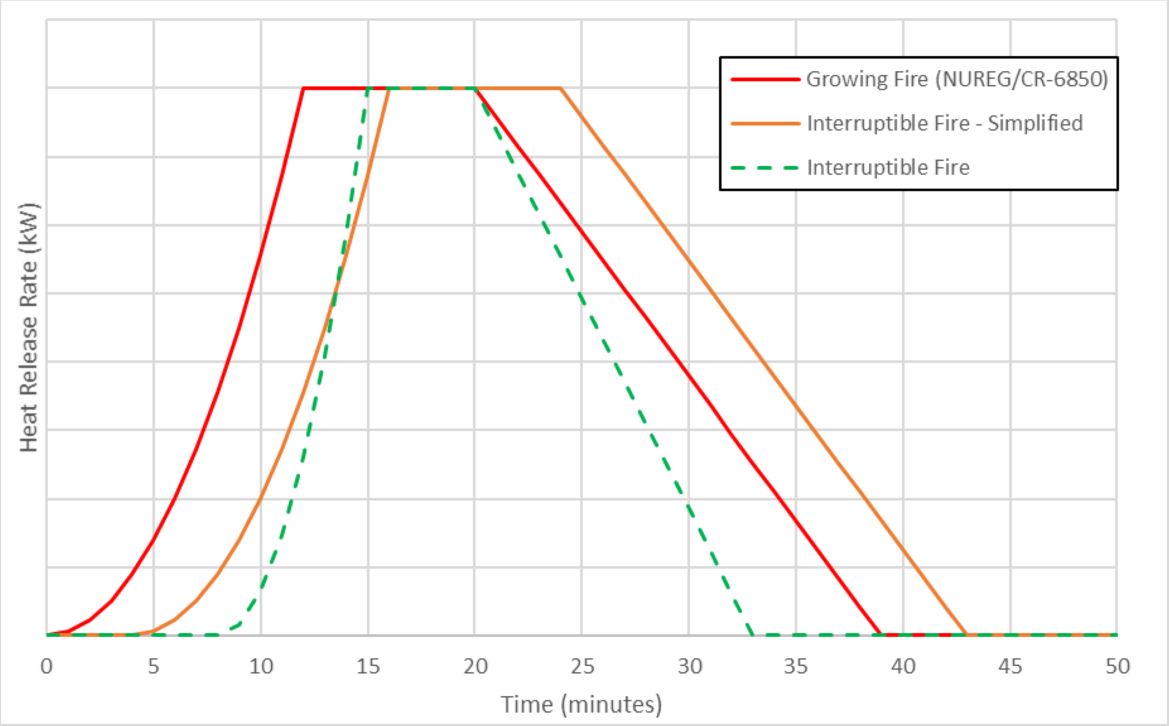
Interruptible and Growing Fire HRR Timing Profiles

- Update to include new test data developed since the publication of NUREG/CR-6850
  - Top: Pre-growth period observed in experimental testing
  - Bottom:
    - A. No growth
    - B. No pre-growth period



Interruptible and Growing Fire

- The resulting HRR profile for interruptible electrical cabinet fires is as follows:
  - A period **of up to 8 minutes*** with no measurable HRR may be included prior to the period of fire growth
  - Following this period, the fire will grow to its peak HRR in seven minutes
  - The fire burns at its peak HRR for five additional minutes
  - The fire decays linearly over 13 minutes
- Alternatively, a simplified modeling of an interruptible fire may use the NUREG/CR-6850 profile with a period **of up to 8 minutes*** with no measurable HRR
- Growing fires may be modeled using the NUREG/CR-6850 profile



***Half of the average experimental pre-growth period, four minutes, is recommended for the Interruptible the HRR profile for Interruptible Fires. This allows for:

1) Uncertainty in the time separating the ignition (start) of the fire and the detection (notification) of the fire in the recorded fire events.

2) The time between ignition (start) of the fire and observed appreciable growth in experimental results.

Interruptible and Growing Fire Detection and Suppression Event Tree

- Probability of detection
  - Smoke detection effectiveness
    - Not all fires are large enough to create a detectable fire
    - **Introduces a probability of failure to detect for automatic smoke detection**
    - Ignored for scenarios that result in ignition of secondary combustibles
    - Allows for a time of detection = 0 (interruptible only)
  - Ability to credit MCR indication
    - Credit for equipment monitored and alarmed in MCR
    - 1.0E-03, general value
    - Time of detection = 0
  - Credit for general plant personnel detection
    - **Introduces a probability of personnel present in compartment**
    - Tied to previously determined transient influencing factor ratings
    - Time of detection = 0

Sequence	Detection	Suppression
A-IF/GF	First Detection (Zero Time of Detection)	Fire Suppression by an Automatically Actuated Fixed System
B-IF/GF		Fire Suppression by a Manually Actuated Fixed System
C-IF/GF		Fire Suppression by the Fire Brigade
D-IF/GF		Fire Damage to Target Items
E-IF/GF	Second Detection (Modeled Time to Detection)	Fire Suppression by an Automatically Actuated Fixed System
F-IF/GF		Fire Suppression by a Manually Actuated Fixed System
G-IF/GF		Fire Suppression by the Fire Brigade
H-IF/GF		Fire Damage to Target Items
I-IF/GF	Manual/Delayed Detection	Fire Suppression by an Automatically Actuated Fixed System
J-IF/GF		Fire Suppression by a Manually Actuated Fixed System
K-IF/GF		Fire Suppression by the Fire Brigade
L-IF/GF		Fire Damage to Target Items

Interruptible and Growing Fire Detection and Suppression Event Tree

- Detection-Suppression event tree is analyzed twice, once for an Interruptible Fire and again for a Growth Fire.
  - Each iteration uses specific fire model times (per-growth and detection for Interruptible) and specific suppression rate
- Failed suppression end sequences for both fire profiles (weighted by the interruptible and growing fire split fractions) summed together

Fire	Interruptible Fire	Event Tree	Pr (Non-Suppression)
FI	Yes 0.72	Interruptible	
	No 0.28	Growth	
		Total	

Fire	First Detection	Second Detection	Automatic Suppression	Manual Fixed	Fire Brigade	Sequence	End State	Pr (Non-Suppression)
FI	DET		AS	MF	FB			
						A-IF/GF	OK	
						B-IF/GF	OK	
						C-IF/GF	OK	
						D-IF/GF	NS	
						E-IF/GF	OK	
						F-IF/GF	OK	
						G-IF/GF	OK	
						H-IF/GF	NS	
						I-IF/GF	OK	
						J-IF/GF	OK	
						K-IF/GF	OK	
						L-IF/GF	NS	
							Total	

Probability of Detection of Electrical Cabinet Fires: Automatic Smoke Detection

- In the NSP calculations in NUREG/CR-6850, the probability of failure associated with automatic detection is characterized with the unreliability and unavailability of the detection system
- Given the revised treatment for detection, an effectiveness parameter is added to explicitly capture fires that are too small to activate an automatic smoke detection system.
- To capture the potential for smoke detectors failing to activate due to fire size, a Monte Carlo sampling process was performed to calculate the average probability of detection for both *Interruptible* and *Growing fires*. The effectiveness term refers to the probability that a fire will be large enough to be detectable.
- The effectiveness terms should be used for fire scenarios limited to a single electrical cabinet where relatively small fires may not activate automatic systems. When the HRR includes propagation to secondary combustibles it is assumed the fire is large enough to be detected. Therefore, the resulting probability of failure would be determined only by the unreliability and unavailability of the automatic smoke detection system.

Probability of Detection of Electrical Cabinet Fires: Automatic Smoke Detection

Automatic Smoke Detection Probability of No Detection					
Enclosure Class/ Function Group	**Enclosure Ventilation**	**Fuel Type**	**Default Fuel Loading Probability of Detection**	**Low Fuel Loading Probability of Detection**	**Very Low Fuel Loading Probability of Detection**
1 – Switchgears and Load Centers	Closed	TS/QTP/SIS	0.6	N/A	N/A
1 – Switchgears and Load Centers	Closed	TP	0.32	N/A	N/A
2 – Motor Control Centers and Battery Chargers	Closed	TS/QTP/SIS	0.62	N/A	N/A
2 – Motor Control Centers and Battery Chargers	Closed	TP	0.33	N/A	N/A
3 – Power Inverters	Closed	TS/QTP/SIS	0.64	N/A	N/A
3 – Power Inverters	Closed	TP	0.45	N/A	N/A
4a - Large Enclosures	Closed	TS/QTP/SIS	0.56	0.65	0.69
4a - Large Enclosures	Closed	TP	0.34	0.45	0.53
4a - Large Enclosures	Open	TS/QTP/SIS	0.47	0.55	0.69
4a - Large Enclosures	Open	TP	0.31	0.4	0.53
4b - Medium Enclosures	Closed	TS/QTP/SIS	0.65	0.7	0.64
4b - Medium Enclosures	Closed	TP	0.45	0.58	0.64
4b - Medium Enclosures	Open	TS/QTP/SIS	0.6	0.72	0.64
4b - Medium Enclosures	Open	TP	0.37	0.63	0.64
4c – Small Enclosures	N/A	All	0.65	N/A	N/A

Probability of Detection of Electrical Cabinet Fires: Main Control Room Indication

- Many Bin 15 events describe notification via trouble alarms or indications in the MCR, such as a loss of power, reduced output alarms, etc.
- For ignition sources that are specifically monitored and/or annunciated in the MCR a value of 0.99 may be used as an option for detection
  - Developed from sensor/transmitter fail to operate data in NUREG/CR-6928

Probability of Detection of Electrical Cabinet Fires: Main Control Room Operator Response

- When an alarm (e.g., automatic fire detection or equipment trouble) occurs, operators must react and appropriately perform actions to ensure a timely response to a potential fire
- Reviewed multiple HRA methods to determine appropriate screening level HEP:
  - SPAR-H
  - CBDTM
  - THERP
- Screening value of 1E-03 may be used for failing to appropriately respond to a non-fire equipment trouble alarm

Probability of Detection of Electrical Cabinet Fires: Detection by Plant Personnel

- Most electrical cabinet fires have been detected by plant personnel
- Probability tied to transient influencing factors for occupancy and maintenance
  - These rating levels are used to make an estimation of the probability that personnel would be present in a compartment and therefore capable of detecting a fire.
    - Note, the changes described only apply to estimating the numerical probability that personnel are expected to be in a compartment. The influencing factors assigned for the purposes of apportioning the transient ignition frequency should be maintained for estimating the probability of personnel detection.

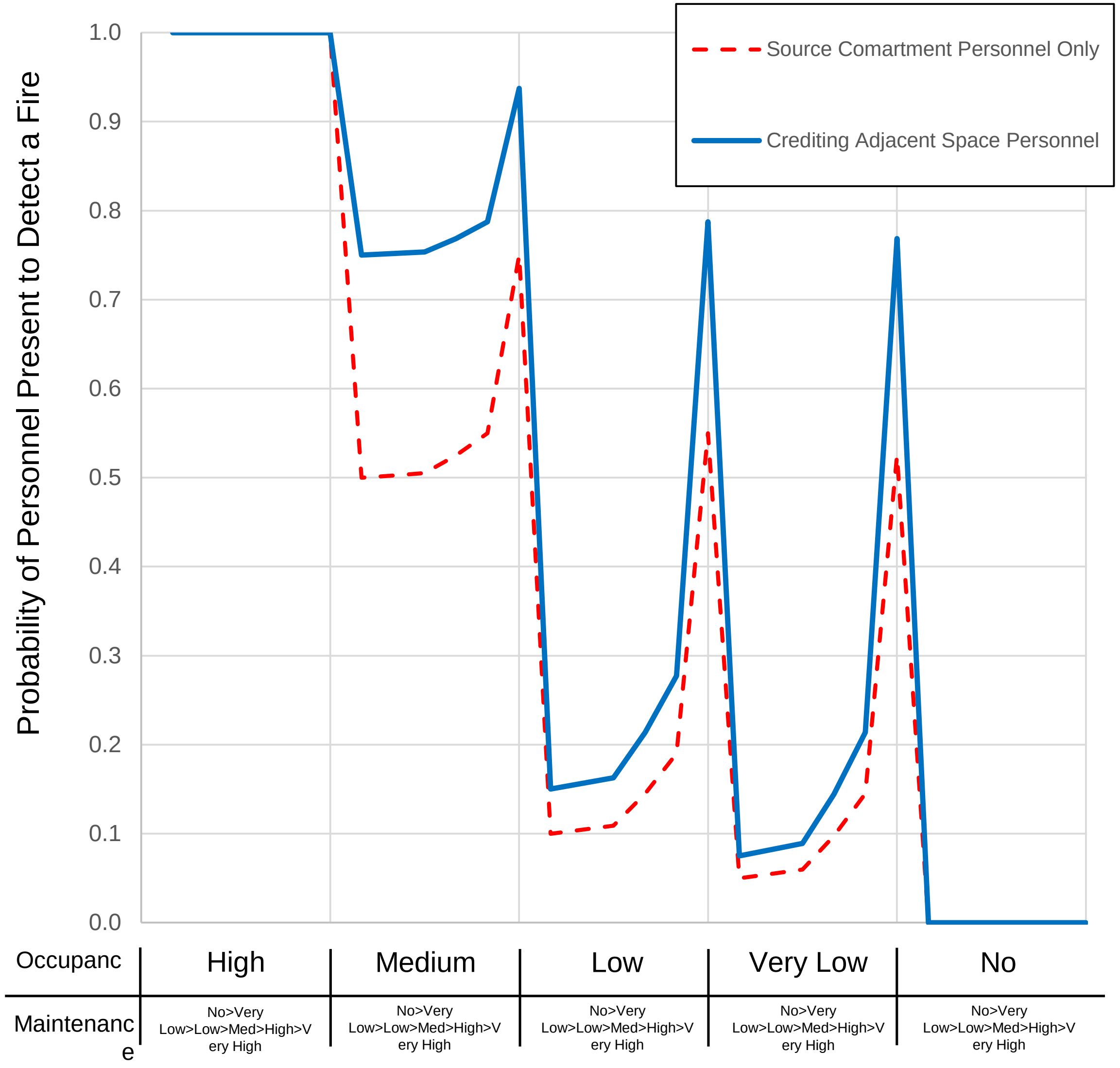
Probability of Detection of Electrical Cabinet Fires: Detection by Plant Personnel

Influencing Factor	No (0)	Very Low (0.5)	Low (1)	Medium (5)	High (10)	Very High (50)
$Pr(n_O) = \frac{Occupancy\ Rating}{Maximum\ Occupancy\ Rating}$	0/10 = 0	0.5/10 = 0.05	1/10 = 0.1	5/10 = 0.5	10/10 = 1.0	N/A
Occupancy	Entrance not possible	Normally un-occupied during plant operations. • Not used as an access pathway for any other plant location. • Entrance is strictly controlled / not accessible to general plant personnel. • Access requires prior approval and notification to on-shift operators in the MCR.	Low foot traffic or out of the general traffic path (e.g. a roving fire watch or security rounds).	Not continuously occupied, but with regular foot traffic.	Continuously occupied compartment.	
$Pr(n_O) = \frac{Maintenance\ Rating/2}{Maximum\ Maintenace\ Rating}$	0/50 = 0	(0.5/2)/50 = 0.005	(1/2)/50 =0.01	(5/2)/50 = 0.05	(10/2)/50 = 0.1	(50/2)/50 = 0.5
Maintenance*	Maintenance activities during power operation are precluded by design.	Access is strictly controlled, contains only cables, fire detectors and junction boxes, hot working during operation is prohibited, and plant records confirm no violations of these procedures over some reasonable time.	Small number of work orders compared to the average number of work orders for a typical compartment.	Average number of work orders for a typical compartment.	A large number of work orders for a typical compartment.	Area experiences significantly more work orders compared to the average number of work orders for a typical compartment.

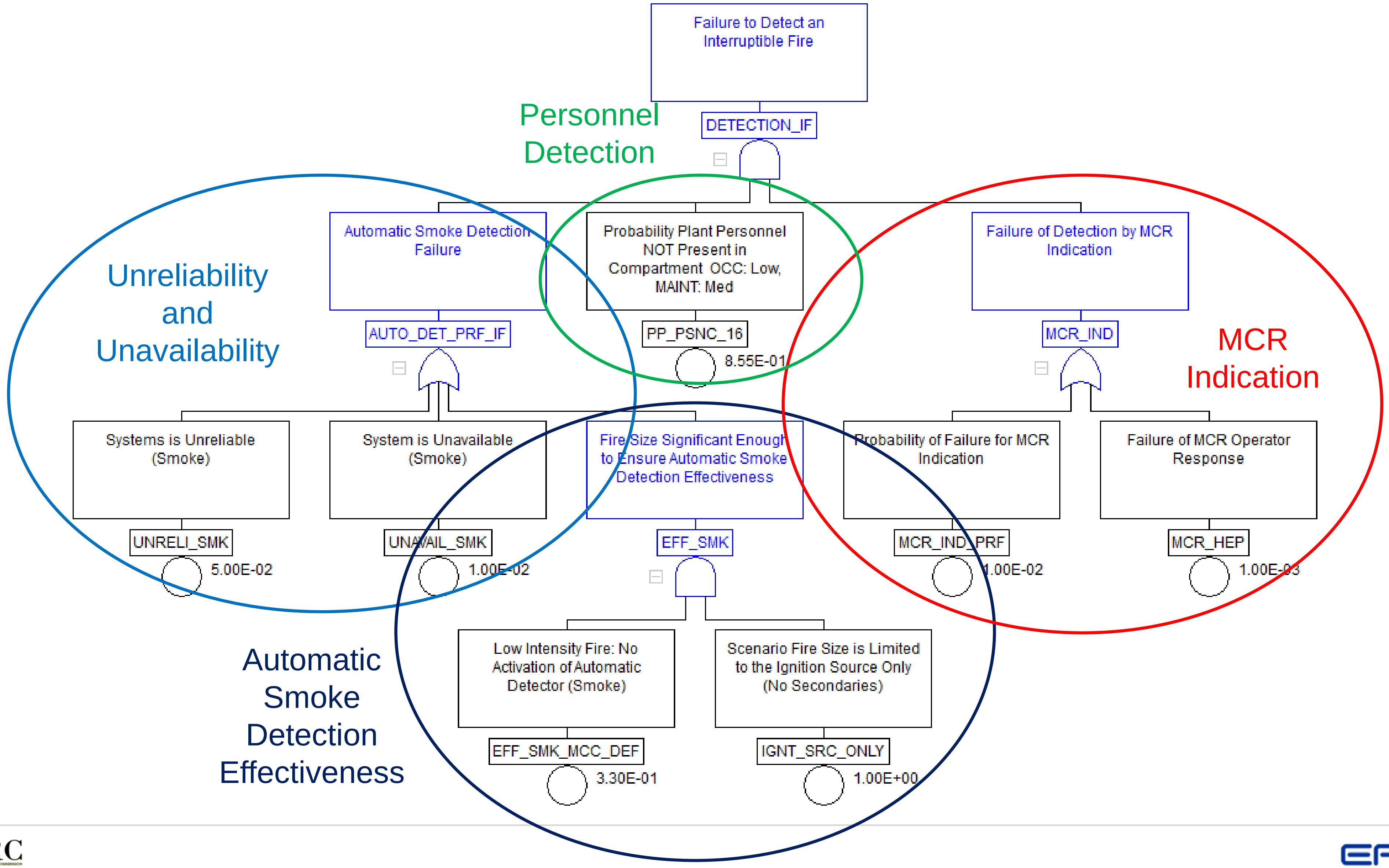
*Note: Understanding that maintenance activities are not as strong an indication of personnel presence as the occupancy factor, all maintenance rating levels were reduced by 50%

Probability of Detection of Electrical Cabinet Fires: Detection by Plant Personnel

- The following rules are applied independent of the personnel probability calculation:
- A high occupancy in the source compartment results in a 100% chance of personnel being present – regardless of maintenance and adjacent compartment ratings,
- A no occupancy in the source compartment results in a 0% chance of personnel being present – regardless of maintenance and adjacent compartment ratings,
- Credit for maintenance is reduced by 50% to recognize that maintenance activities are not as strong an indication of personnel presence as the occupancy factor,
- Credit for adjacent spaces may only be taken for adjacent spaces:
  - with an influencing factor rating equal to or greater than that of the source compartment,
  - within the same building, and
  - located on the same floor/elevation as the compartment containing the ignition source.
  - Allowance may be taken for adjacent compartments with documented open barriers to allow the smoke and other products of combustion to be shared between compartments. Examples include:
    - Open stairways between floors,
    - Un-sealed barrier penetrations, and
    - Doors or dampers.
- Credit for adjacent spaces may only be taken for a maximum of half of the rating of the source compartment.
- Rooms with controlled ventilation and designated airflow directionality should be considering when considering adjacent space influencing factors.
  - Example: A control room with a high occupancy may not necessarily be credited as the adjacent room with a higher influencing factor rating given that the differences in pressure will limit the ability for occupants to detect a fire outside the control room.



Probability of Detection of Electrical Cabinet Fires



Time of Detection of Electrical Cabinet Fires

- Detection by MCR indication and plant personnel occurs at t = 0 for both interruptible and growing fires.
- For interruptible fires, automatic smoke detection occurs at t=0
- For interruptible fires that cause target damage after the inclusion of secondary combustibles, automatic smoke detection is determined by detailed fire modeling
- For growing fires, automatic detection (smoke and thermal) is determined by detailed fire modeling

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