Module V – Advanced Fire Modeling
Day 2 – AM Session
Principals of Fire Behavior

Joint EPRI/NRC-RES Fire PRA Workshop
July 31 – August 4, 2017

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Fred Mowrer – Cal. Poly State University
Topics

- Stages / elements of enclosure fires
- Ignition and heat release
  - CHRISTIFIRE
- Fire plumes and ceiling jets
- Heat and smoke detection
- Structural response / damage
- Cable response / damage
  - CAROLFIRE
Fire scenario development / analysis

- To analyze fire scenarios, need to consider:
  - Stage(s) of fire development to include in analysis
  - Elements to include in fire scenario (fuels, targets ...)
  - Data sources for elements (HRRs, properties, damage criteria)
  - Fire modeling tool(s) to be used for the analysis
    - Empirical correlations (Heskestad plume, MQH, FPA ...)
    - Zone model (CFAST, MAGIC)
    - CFD model (FDS)

- This module provides overview of fire modeling concepts
Stages of enclosure fires
Stages of enclosure fires

- NUREG 1805

Figure 2-2 Stages of Compartment Fire
Stages of enclosure fires
Stage 1 - Fire plume / ceiling jet period

- Buoyant gases rise to ceiling in fire plume
- Ceiling jet spreads radially until confined
- Plume entrains surrounding air
- Temperature decays rapidly with height and radial distance
Stages of enclosure fires
Stage 2 - Enclosure smoke filling period

- Period begins when ceiling jet reaches walls
- Period ends when smoke flows through vents
- Smoke layer fills due to entrainment / expansion
Stages of enclosure fires
Stage 3 - Preflashover vented period

- Quasi-steady mass balance develops
- Smoke layer equilibrates at balance point
- Mass balance influenced by sizes, shapes and locations of vents and by mechanical ventilation
- Mass balance influences energy/species balances
Stages of enclosure fires
Stage 4 - Postflashover vented period

- Period begins when secondary fuels begin to ignite from radiant exposure
- Post-flashover fires frequently become ventilation-limited, with flames extending out of vents
- Underventilation affects smoke production
Vent flow stages
Elements of enclosure fires

- Fire source
- Fire plume
- Ceiling jet
- Upper gas layer
- Lower gas layer
- Vents / ventilation
- Boundaries
- Targets
### Elements of enclosure fires

<table>
<thead>
<tr>
<th>DESIGN ELEMENT</th>
<th>EXAMPLE TYPES</th>
<th>PHYSICAL ATTRIBUTES</th>
<th>GEOMETRIC ATTRIBUTES</th>
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<tr>
<td>FUELS</td>
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<td>FURNISHINGS</td>
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<td>NATURAL VENTILATION</td>
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<td>LOCATIONS DIMENSIONS</td>
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<td>MECHANICAL VENTILATION</td>
<td>INJECTION</td>
<td>FLOW RATES</td>
<td>LOCATIONS DIMENSIONS</td>
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<td>EXTRACTION</td>
<td>STATUS</td>
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<td>BALANCED</td>
<td>ACT. PARAMETER</td>
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Design fire

- HRR as \( f(t) \) is termed the *design fire*

- Approaches to determining *design fire*:
  - Knowledge of amount/type of combustibles
    - Object assumed to ignite and burn at known rate
    - HRR history based on experimental data
  - Knowledge of occupancy
    - Little detailed data regarding specific fuels
    - Design fire based on statistics / engineering judgment
The fire source

- First item
  - Ignition
  - Growth rate
  - Peak HRR
  - Burning duration

- Secondary items
  - Time to ignition
  - Burning histories
Factors controlling HRRs

- **Ignition scenarios**
  - Ignition source magnitude
  - Ignition source duration

- **Fuel characteristics**
  - Type
  - Quantity
  - Orientation

- **Enclosure effects**
  - Radiation enhancement
  - Oxygen vitiation
Heat release rate

\[ \dot{Q} = \dot{m}'' A \Delta H_c \]

\( \dot{m}'' \) Mass loss rate per unit area
\( A \) Area of fuel that is burning
\( \Delta H_c \) Fuel heat of combustion

APPROX. HEATS OF COMBUSTION

<table>
<thead>
<tr>
<th>FUEL</th>
<th>( \Delta H_c ) (kJ/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WOOD</td>
<td>15.0</td>
</tr>
<tr>
<td>POLYURETHANE</td>
<td>30.0</td>
</tr>
<tr>
<td>HEPTANE</td>
<td>44.5</td>
</tr>
</tbody>
</table>
Phases of fire development

- Incipient
- Growth
- Fully developed
- Decay / burnout
Burning duration

- Heat released by fire
  \[ Q = \int_o^t \dot{Q}(t) \, dt \]
- Burnout approximation
  \[ t_b = t_{bo} - t_o \approx \frac{Q}{\dot{Q}_{max}} \]
Fire growth characterization

- Power law

\[
\dot{Q} = \dot{Q}_o \left( \frac{t}{t_g} \right)^n
\]

- Exponential

\[
\dot{Q} = \dot{Q}_o \exp \left( \frac{t}{\tau_g} \right)
\]
\[ \dot{Q} = \dot{Q}_o \left( \frac{t}{t_g} \right)^2 ; \quad \dot{Q}_o = 1055 \text{ kW} ; \quad \alpha = \frac{\dot{Q}_o}{t_g^2} \]

<table>
<thead>
<tr>
<th>Growth rate</th>
<th>t_g (s)</th>
<th>α (kW/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td>600</td>
<td>0.003</td>
</tr>
<tr>
<td>Medium</td>
<td>300</td>
<td>0.012</td>
</tr>
<tr>
<td>Fast</td>
<td>150</td>
<td>0.047</td>
</tr>
<tr>
<td>Ultrafast</td>
<td>75</td>
<td>0.188</td>
</tr>
</tbody>
</table>
Fire growth characterization example

- In the FMSNL fire test series, many of the tests were conducted using a gas burner programmed to grow as a t-squared fire to reach a HRR of 500 kW in 4 minutes, then to maintain a constant HRR of 500 kW for another 6 minutes
  - What does this HRR curve look like?
  - How much energy is released during the growth phase?
  - How much energy is released during the entire test?
Fire growth characterization

- Example

\[ Q_{240s} = \int_{0}^{240} \frac{\dot{Q}_g}{t_g^2} t^2 \, dt = \frac{\dot{Q}_g}{t_g^2} t^3 = \frac{500}{240^2} \frac{240^3}{3} = 40 \text{ MJ} \]

\[ Q_{600s} = \int_{240}^{600} \dot{Q} \, dt = 500 \cdot 360 = 180 \text{ MJ} \]
### Table G-1
Recommended HRR Values for Electrical Fires

<table>
<thead>
<tr>
<th>Ignition Source</th>
<th>HRR kW (Btu/s)</th>
<th>Gamma Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75th</td>
<td>98th</td>
</tr>
<tr>
<td>Vertical cabinets with qualified cable, fire limited to one cable bundle</td>
<td>69 (^1) (65)</td>
<td>211 (^2) (200)</td>
</tr>
<tr>
<td>Vertical cabinets with qualified cable, fire in more than one cable bundle</td>
<td>211 (^2) (200)</td>
<td>702 (^2) (665)</td>
</tr>
<tr>
<td>Vertical cabinets with unqualified cable, fire limited to one cable bundle</td>
<td>90 (^4) (85)</td>
<td>211 (^2) (200)</td>
</tr>
<tr>
<td>Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors</td>
<td>232 (^5) (220)</td>
<td>464 (^6) (440)</td>
</tr>
<tr>
<td>Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors</td>
<td>232 (^5) (220)</td>
<td>1002 (^7) (950)</td>
</tr>
<tr>
<td>Pumps (electrical fires) (^8)</td>
<td>69 (^5) (65)</td>
<td>211 (^2) (200)</td>
</tr>
<tr>
<td>Motors (^9)</td>
<td>32 (^6) (30)</td>
<td>69 (^5) (65)</td>
</tr>
<tr>
<td>Transient Combustibles (^9)</td>
<td>142 (^13) (135)</td>
<td>317 (^13) (300)</td>
</tr>
</tbody>
</table>

HRR taken from Appendix G, NUREG/CR 6850 (EPRI 1011989)
## HRR example – cabinet fire

<table>
<thead>
<tr>
<th>Ignition Source</th>
<th>HRR kW (Btu/s)</th>
<th>Gamma Distribution</th>
<th>75th</th>
<th>98th</th>
<th>α</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical cabinets with qualified cable, fire limited to one cable bundle</td>
<td>69&lt;sup&gt;1&lt;/sup&gt; (65)</td>
<td>211&lt;sup&gt;2&lt;/sup&gt; (200)</td>
<td>0.84 (0.83)</td>
<td>59.3 (56.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical cabinets with qualified cable, fire in more than one cable bundle</td>
<td>211&lt;sup&gt;2&lt;/sup&gt; (200)</td>
<td>702&lt;sup&gt;2&lt;/sup&gt; (665)</td>
<td>0.7 (0.7)</td>
<td>216 (204)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical cabinets with unqualified cable, fire limited to one cable bundle</td>
<td>90&lt;sup&gt;4&lt;/sup&gt; (85)</td>
<td>211&lt;sup&gt;2&lt;/sup&gt; (200)</td>
<td>1.6 (1.6)</td>
<td>41.5 (39.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical cabinets with unqualified cable, fire in more than one cable bundle closed doors</td>
<td>232&lt;sup&gt;5&lt;/sup&gt; (220)</td>
<td>464&lt;sup&gt;6&lt;/sup&gt; (440)</td>
<td>2.6 (2.6)</td>
<td>67.8 (64.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical cabinets with unqualified cable, fire in more than one cable bundle open doors</td>
<td>232&lt;sup&gt;5&lt;/sup&gt; (220)</td>
<td>1002&lt;sup&gt;7&lt;/sup&gt; (950)</td>
<td>0.46 (0.45)</td>
<td>386 (366)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumps (electrical fires)</td>
<td>69 (65)</td>
<td>211&lt;sup&gt;2&lt;/sup&gt; (200)</td>
<td>0.84 (0.83)</td>
<td>59.3 (56.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motors</td>
<td>32 (30)</td>
<td>69 (65)</td>
<td>2.0 (2.0)</td>
<td>11.7 (11.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient Combustibles</td>
<td>142 (135)</td>
<td>317 (300)</td>
<td>1.8 (1.9)</td>
<td>57.4 (53.7)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HRR taken from Appendix G, NUREG/CR 6850 (EPRI 1011989)
Secondary item ignition

- **Factors**
  - Heat flux from primary fire
  - Ease of ignition of target

- **Point source estimate**

\[ \dot{q}_r'' = \frac{\chi_r \dot{Q}_f}{4\pi R^2 \cos(\theta)} \]
Secondary item ignition

- Ignition time estimates (constant heat flux)
  - Thermally thick materials (most materials of interest in NPPs)

\[
t_{ig} = \frac{\pi}{4} k \rho c \left[ \frac{T_{ig} - T_o}{\dot{q}''} \right]^2
\]

- Thermally thin materials

\[
t_{ig} = \frac{T_{ig} - T_o}{\dot{q}'' / \rho c \delta}
\]
Summary

- Engineers need to specify design fires
  - Judgment required
  - Some data available - relatively sparse
  - For NPP applications, data in NUREG CR-6850 typically used

- Design fire specified in terms of HRR(t)
  - Simple case - incipient/growth/steady/decay
  - Complex case - multiple stages pieced together

- Design fire drives consequence analysis
  - Single most important / uncertain factor
Cable Heat Release, Ignition, and Spread in Tray Installations during Fire

(CHRISTIFIRE) Phase I

Kevin McGrattan, Andrew Lock, Nathan Marsh, Marc Nyden
National Institute of Standards and Technology
Gaithersburg, Maryland, USA

David Stroup and Jason Dreisbach
U.S. Nuclear Regulatory Commission
Washington, D.C., USA
What’s the Problem?

Answer: Very little useful information on cables for fire modeling

- Vertical Spread Rate?
- Effectiveness of Wraps?
- Tray to Tray Spread?
- Horizontal Spread Rate?
- Ignition?
Current Guidance for Modeling Cables

Problems going from “bench” to full-scale

Table R-1
Bench Scale HRR Values Under a Heat Flux of 60 kW/m², q_{fs} [R-4]

<table>
<thead>
<tr>
<th>Material</th>
<th>Bench Scale HRR [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>XPE/FRXPE</td>
<td>475</td>
</tr>
<tr>
<td>XPE/Neoprene</td>
<td>354</td>
</tr>
<tr>
<td>XPE/Neoprene</td>
<td>302</td>
</tr>
<tr>
<td>XPE/XPE</td>
<td>178</td>
</tr>
<tr>
<td>PE/PVC</td>
<td>395</td>
</tr>
<tr>
<td>PE/PVC</td>
<td>359</td>
</tr>
<tr>
<td>PE/PVC</td>
<td>312</td>
</tr>
<tr>
<td>PE/PVC, Nylon</td>
<td>589</td>
</tr>
<tr>
<td>PE, Nylon/PVC, Nylon</td>
<td>231</td>
</tr>
<tr>
<td>PE, Nylon/PVC, Nylon</td>
<td>218</td>
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</tbody>
</table>

Which HRR to Use?
Current Guidance on Flame Spread

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

Vague or ill-defined parameters

Based on only one experiment
Cables used in CHRISTIFIRE
Thermoplastic cables tend to melt and drip;
Electrical failure ~200 °C

Thermoset cables tend to char and smolder;
Electrical failure ~400 °C
Multiple Tray Test 8

Heat Release Rate (kW)

Time (s)

Thermoplastic Cable
Thermoset Cable

Heat Release Rate (kW)

Multiple Tray Test 12

Tray 1
Tray 2
Burner Off
Tray 3

HRR (O₂ cal.)
HRR (mass loss)
Comparison of Thermoset and Thermoplastic Cable HRR

![Graph comparing heat release rate of Thermoset and Thermoplastic cables over time.](image-url)
Results of Radiant Panel Experiments

![Graph showing the relationship between external heat flux (kW/m²) and heat release rate per unit area (kW/m²) for different cables labeled as Cable #701, Cable #700, Cable #16, Cable #367, Cable #43, Cable #46, Cable #271, Cable #11, Cable #219, Cable #220, Cable #23, and Cable #270. The graph categorizes cables into Thermoplastics and Thermosets groups.]
Modeling

The Easy Way

Multiple Tray Test 17
Time 45:00

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/m² thermoplastics
150 kW/m² thermosets
Lateral Spread
3.2 m/h thermoplastics
1.1 m/h thermosets
Heat of Combustion
16 MJ/kg for all
Fire Dynamics Simulator (FDS)

Cable 11, Insulator, Test 3
Reaction 1
\[ Y_0 = 0.06 \quad A = 1.32 \times 10^5 \ s^{-1} \]
\[ T_p = 360 \ ^\circ C \quad E = 50.2 \ kcal/mol \]
\[ q_p = 35 \ W/g \]

Reaction 2
\[ Y_0 = 0.91 \quad A = 7.28 \times 10^5 \ s^{-1} \]
\[ T_p = 485 \ ^\circ C \quad E = 76.4 \ kcal/mol \]
\[ q_p = 564 \ W/g \]

Reaction 3
\[ Y_0 = 0.03 \quad A = 5.95 \times 10^4 \ s^{-1} \]
\[ T_p = 425 \ ^\circ C \quad E = 104.6 \ kcal/mol \]
\[ q_p = 30 \ W/g \]
\[ \Delta H = 26774 \ J/g \]
\[ \nu_e = 0.06 \]

Cable 701, Jacket, Test 3
Reaction 1
\[ Y_0 = 0.66 \quad A = 1.88 \times 10^6 \ s^{-1} \]
\[ T_p = 310 \ ^\circ C \quad E = 31.0 \ kcal/mol \]
\[ q_p = 156 \ W/g \]

Reaction 2
\[ Y_0 = 0.34 \quad A = 9.29 \times 10^6 \ s^{-1} \]
\[ T_p = 460 \ ^\circ C \quad E = 28.6 \ kcal/mol \]
\[ q_p = 47 \ W/g \]
\[ \Delta H = 17959 \ J/g \]
\[ \nu_e = 0.22 \]
Vertical cable fire spread experiments at NIST
Corridor Fire Spread Experiments at NIST
Cable fire spread in a corridor, courtesy NIST.
The spread rate of a fire can be estimated from:

\[
v \propto \frac{(\dot{q}_f^\prime\prime)^2 \delta_f}{\pi (k\rho c) \left(T_{\text{ign}} - T_\infty \right)^2}
\]

If the cables are located within the Hot Gas Layer (HGL), the spread rate could increase by a factor of 10.

\[
\frac{v_2}{v_1} = \left(\frac{T_{\text{ign}} - T_\infty}{T_{\text{ign}} - T_{\text{HGL}}}\right)^2 = \left(\frac{400 - 20}{400 - 280}\right)^2 \approx 10
\]
FLASH-CAT

Flame Spread over Horizontal Cable Trays

Results of Hallway Experiments
FLASH-CAT

Vertical Tray Results
Results of CHRISTIFIRE Phase 2

Average heat release rates for thermoplastic and thermoset cables are consistent with Phase 1 experiments and FLASH-CAT modeling.

Fire spread rates are roughly a factor of 10 greater for multiple vertical trays or horizontal trays close to ceilings (or within the hot gas layer).
CHRISTIFIRE Report, NUREG/CR-7010

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david.stroup@nrc.gov
Fire plumes and ceiling jets

- Describe fire plume and ceiling jet phenomena
- Discuss the theory behind fire plume correlations
- Appreciate the role of plume entrainment on fire conditions within an enclosure
- Calculate fire plume and ceiling jet conditions, including temperatures and velocities, for different correlations
References – fire plumes

- *Enclosure Fire Dynamics*
  - Chapter 4 - Fire plumes and flame heights

- *SFPE Handbook*
  - Chapter on Flame Height
  - Chapter on Fire Plumes
Fire plume issues

- Transports combustion products / entrained air vertically to ceiling
- Causes formation and descent of smoke layer
- Elevated temperatures and velocities expose targets located in plume
Fire plume topics

- Types of plumes
- Flame heights
- Flame/plume temperatures
- Entrainment in fire plumes
- Gas velocities in fire plumes
Types of fire plumes

- Axisymmetric plumes
- Line plumes
- Window plumes
- Balcony spill plumes
- Other ...
Axisymmetric fire plumes

- **Correlations**
  - Morton-Taylor-Turner (ideal)
  - Zukoski
  - Heskestad
  - McCaffrey
  - Alpert
  - Alpert & Ward
  - Thomas

- **Typically use Heskestad correlation**
Heskestad flame height correlation

\[ Z_f = 0.23 \dot{Q}^{2/5} - 1.02D \]

\[ \frac{Z_f}{D} = 3.7Q^{2/5} - 1.02 \]
The Heskestad plume

- **Plume entrainment**
  - Effective flame height

\[ z_L = z_o + 0.166\dot{Q}_c^{2/5} \]

- Flame region \((z < z_L)\)

\[ \dot{m}_{pl} = 0.0054\dot{Q}_c z / z_L \]

- Plume region \((z > z_L)\)

\[ \dot{m}_{pl} = 0.071\dot{Q}_c^{1/3} (z - z_o)^{5/3} + 0.0018\dot{Q}_c \]
The Heskestad plume

- Plume centerline temperature
  
  - Continuous flame region
  \[ \Delta T \approx 900^\circ C \]
  
  - Plume region

\[
\frac{\Delta T_o}{T_\infty} = 9.1 \left( \frac{\dot{Q}_c}{\sqrt{g \rho_\infty c_p T_\infty}} \right)^{2/3} (z - z_o)^{-5/3} \approx 0.085 \frac{\dot{Q}_c^{2/3}}{(z - z_o)^{5/3}}
\]

\[
\Delta T_o \approx 25 \frac{\dot{Q}_c^{2/3}}{(z - z_o)^{5/3}}
\]
Fire location factors

- Multiply HRR by fire location factor
  - Fires in the open: $k_{lf} = 1$
  - Fires along walls: $k_{lf} = 2$
  - Fires in corners: $k_{lf} = 4$
Fire plume - example

- In the FM/SNL fire test series, the room height was 6.1 m and the burner was 0.1 m above the floor.
- For many tests, the fire HRR was 500 kW and the burner diameter was 0.9 m.
- What would be the plume centerline temperature rise and velocity at the ceiling based on the Heskestad plume correlation?
Fire plume - example

- Solution – plume temperature
  - First calculate the virtual origin elevation

\[ z_o = 0.083 \dot{Q}^{2/5} - 1.02D = 0.083(500)^{2/5} - 1.02(0.9) \]
\[ = 0.08 \]
  - Then calculate the plume centerline temp rise

\[ \Delta T_o \approx 25 \frac{\dot{Q}_c^{2/3}}{(z - z_o)^{5/3}} = 25 \frac{(350)^{2/3}}{(6 - 0.08)^{5/3}} \]
\[ = 64K \]
Fire plume - example

- Solution – plume velocity

\[ u_o = 1.03 \left( \frac{\dot{Q}_c}{z - z_o} \right)^{1/3} = 1.03 \left( \frac{350}{6 - 0.08} \right)^{1/3} \]

\[ = 4.0 \text{ m/s} \]
Enclosure smoke filling

- The ASET model

\[ \frac{dV_u}{dt} = A \frac{dz_u}{dt} = \dot{V}_{pl} + \dot{V}_{exp} \]

- Analytical solutions
  - Expansion negligible
  - Leak at ceiling only

\[ \frac{dV_u}{dt} = A \frac{dz_u}{dt} = \dot{V}_{pl} \]
Summary – fire plumes

- Plume important for number of reasons
  - Temperatures/velocities/heat fluxes at targets
  - Smoke layer filling / exhaust rates
  - Smoke concentrations

- Correlations available for some scenarios
  - Axisymmetric / line plumes
  - Windows / balconies (limited theory / data)

  - For NPP applications, generally use Heskestad correlations
Summary – fire plumes

- Limited/no correlations for other scenarios
  - 3D fuel sources (e.g., racks, sprays …)
  - Obstructions in plume / flow field
  - Sloped / stepped ceilings
  - Wind / mechanical ventilation

- CFD models can address scenarios where correlations are inappropriate
Ceiling jet topics

- Unconfined ceiling jets
- Confined ceiling jets
- Ceiling jet correlations
  - Temperature
  - Velocity
References – ceiling jets

- SFPE Handbook
  - Chapter on Ceiling Jet Flows
Unconfined ceiling jets
Confined ceiling jets
Unconfined ceiling jet

- Temperature correlations
  - Alpert
    \[
    \frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.32}{(R / H)^{2/3}}
    \]
  - Alpert and Ward
    \[
    \frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.31}{(R / H)^{2/3}}
    \]
    \[
    \Delta T_{pl} = 16.9 \frac{\dot{Q}^{2/3}}{H^{5/3}}
    \]
    \[
    \Delta T_{pl} = 22.0 \frac{\dot{Q}_c^{2/3}}{H^{5/3}}
    \]
Temperature correlations

Unconfined ceiling jet

$\frac{\Delta T_{cj}}{\Delta T_{pl}}$ vs. $R/H$

- Alpert
- A & W
- H & D
- Cooper
Confined ceiling jet

- Temperature correlation
  - Delichatsios

\[
\frac{\Delta T_{cj}}{\Delta T_{pl}} = 0.37 \left[ \frac{H}{W} \right]^{1/3} \exp \left[ -0.16 \left( \frac{L}{H} \left( \frac{W}{H} \right)^{1/3} \right) \right]
\]
Ceiling jet temperatures

Confined ceiling jet

\[ \frac{\Delta T_{cj}}{\Delta T_{pl}} \]

L/H

H/W = 0.5
H/W = 1.0
H/W = 1.5
H/W = 2.0
H/W = 2.5
Unconfined
Unconfined ceiling jet

- Velocity correlation
  - Alpert

\[
\frac{u}{u_o} = \frac{0.2}{(R / H)^{5/6}}
\]

- Note that according to this correlation the velocity decreases as the flow moves away from the source
Confined ceiling jet

- Velocity correlation
  - Delichatsios

\[
\frac{u}{u_o} = \frac{0.27}{(W / H)^{1/3}}
\]

- Note that according to this correlation the velocity does not change as the flow moves down the corridor
Ceiling jet velocities

Ceiling jet velocity correlations

\[ \frac{u}{u_0} \]

R/H or W/H

Alpert
H & D
Delichatsios
Ceiling jet - example

- In the FM/SNL enclosure, what would be the ceiling jet temperature and velocity at a radial distance of 3.0 m (10 ft) from the plume centerline for a HRR of 500 kW?
Ceiling jet - example

- **Solution**
  - \( \frac{\Delta T_{cj}}{\Delta T_{pl}} = \frac{0.31}{(R/H)^{2/3}} = 0.49 \)
  - Temperature rise
  - \( \Delta T_{cj} = 0.49 \Delta T_{pl} \)
    \( = 0.49(64) = 32 \)
  - Velocity
  - \( \frac{u}{u_o} = \frac{0.2}{(R/H)^{5/6}} = 0.36 \)
    \( u = 0.36u_o \)
    \( = 0.36(4) = 1.44 \text{ m/s} \)
Summary – ceiling jets

- Ceiling jets form when buoyant plume gases are trapped beneath ceiling
- Temperature / velocity correlations exist for some conditions
  - Unconfined, horizontal, smooth ceiling
  - Confined, horizontal, smooth ceiling
- For other conditions, such as obstructed or sloped ceilings, CFD model needed
  - In many NPP applications, the ceiling is highly obstructed (“cluttered”), so CFD modeling may be necessary
Fire plume / ceiling jet summary

- Fire plumes and ceiling jets are important aspects of enclosure fire dynamics.
- Temperature, velocity and entrainment correlations exist for a few idealized geometries.
  - These correlations are used for hand calculations and in zone models.
- Fire plume / ceiling jet flows are calculated directly in CFD models such as FDS.
Heat and smoke detection

- Understand terminology used to describe the activation of fire detection devices
- Appreciate the role of different variables in estimating fire detector activation and structural damage times
- Calculate the response of fire detectors to fire plume and ceiling jet conditions
References - detection

- *Enclosure Fire Dynamics*
  - Chapter 4 - Fire plumes and ceiling jets
- *SFPE Handbook*
  - Chapter on Fire plumes
  - Chapter on Ceiling jet flows
  - Chapter on Design of detection systems
Overview of methods to predict heat / smoke detector activation

- Idealized geometry – smooth flat ceiling
Overview of methods to predict heat / smoke detector activation

- Realistic geometry – obstructed ceiling
Overview of methods to predict heat / smoke detector activation

- Step 1. Specify heat/smoke release rates
Overview of methods to predict heat / smoke detector activation

- Step 2. Calculate temperature / smoke concentration outside detector
Overview of methods to predict heat / smoke detector activation

- Step 3. Calculate detector response to local environmental conditions

![Diagram showing the overview of methods to predict heat / smoke detector activation.](image)
The DETACT model

- A first order response model for predicting fire detector activation based on convective heating and a lumped capacity analysis
Bases

- Heat balance at detector
- Convective heating only
- Lumped capacity analysis
- Negligible losses (basic model)

\[
\dot{q}_{abs} = \dot{q}_{in} - \dot{q}_{out}
\]

\[
\dot{q}_{in} = h_c A_s (T_g - T_d)
\]

\[
\dot{q}_{abs} = m c_p \frac{dT_d}{dt}
\]

\[
\dot{q}_{out} \approx 0
\]
Solution

- Predictive equation for temperature rise

\[
\frac{dT_d}{dt} = \frac{h_c A_s}{mc_p} (T_g - T_d) = \frac{(T_g - T_d)}{\tau}
\]

- Definition of detector time constant

\[
\tau \equiv \frac{mc_p}{h_c A_s}
\]

- Time constant not really constant because it depends on heat transfer coefficient, which depends on gas velocity
Response Time Index

- For cylinders in cross flow
  
  \[ h_c \sim \sqrt{u_g} \]

- Implications
  
  \[ \tau \sim \frac{1}{\sqrt{u_g}}, \quad \tau \sqrt{u_g} = \text{const} \]

- Definition of RTI
  
  \[ RTI \equiv \tau \sqrt{u_g} \]

- Predictive equation
  
  \[ \frac{dT_d}{dt} = \frac{\sqrt{u_g}}{RTI} \left( T_g - T_d \right) \]
RTI determination (1)

- **Plunge test**
  - $T_g = \text{constant}$
  - $u_g = \text{constant}$
  - $T_{\text{act}} = \text{known}$

- **Analytical solution**

\[
\frac{\Delta T_d}{\Delta T_g} = 1 - e^{-t/\tau_o}
\]
\[
\frac{\Delta T_{\text{act}}}{\Delta T_g} = 1 - e^{-t_{\text{act}} \sqrt{u_o} / \text{RTI}}
\]
Plunge test

\[
\frac{\Delta T_d}{\Delta T_g} = 1 - e^{-t/\tau}
\]
**DETACT formulation**

- *Euler equation for* $T_d$

\[ T_d^{(t+\Delta t)} = T_d^{(t)} + \frac{dT_d}{dt} \Delta t \]

- Substitute equation for $dT_d/dt$

\[ T_d^{(t+\Delta t)} = T_d^{(t)} + \sqrt{\frac{u_g^{(t)}}{RTI}} \left( T_g^{(t)} - T_d^{(t)} \right) \Delta t \]

- Evaluation requires RTI, $T_g(t)$ and $u_g(t)$
Detector activation

- Fixed temperature devices
- Rate-of-rise devices

- Typical value of $\frac{dT_{act}}{dt}$: 8.3°C (15 °F) /min
## Sprinkler activation

- **Generic sprinkler temperature ratings**
  - From NUREG 1805

### Table 10-2. Generic Sprinkler Temperature Rating ($T_{activation}$)

<table>
<thead>
<tr>
<th>Temperature Classification</th>
<th>Range of Temperature Ratings °C (°F)</th>
<th>Generic Temperature Ratings °C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary</td>
<td>57–77 (135–170)</td>
<td>74 (165)</td>
</tr>
<tr>
<td>Intermediate</td>
<td>79–107 (175–225)</td>
<td>100 (212)</td>
</tr>
<tr>
<td>High</td>
<td>121–149 (250–300)</td>
<td>135 (275)</td>
</tr>
<tr>
<td>Extra high</td>
<td>163–191 (325–375)</td>
<td>177 (350)</td>
</tr>
<tr>
<td>Very extra high</td>
<td>204–246 (400–475)</td>
<td>232 (450)</td>
</tr>
<tr>
<td>Ultra high</td>
<td>260–302 (500–575)</td>
<td>288 (550)</td>
</tr>
<tr>
<td>Ultra high</td>
<td>343 (650)</td>
<td>288 (550)</td>
</tr>
</tbody>
</table>
Sprinkler activation

- Generic sprinkler RTIs
  - From NUREG 1805

<table>
<thead>
<tr>
<th>Common Sprinkler Type</th>
<th>Generic Response Time Index (RTI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard response bulb</td>
<td>235</td>
</tr>
<tr>
<td>Standard response link</td>
<td>130</td>
</tr>
<tr>
<td>Quick response bulb</td>
<td>42</td>
</tr>
<tr>
<td>Quick response link</td>
<td>34</td>
</tr>
</tbody>
</table>
Heat detector activation

- Generic heat detector RTIs
  - From NFPA 72

<table>
<thead>
<tr>
<th>UL Listed Spacing (ft/m)</th>
<th>UL Listed Activation Temperature</th>
<th>All FM Listed Temps.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>128°F (53°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>135°F (57°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>145°F (63°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160°F (71°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>170°F (77°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>196°F (91°C)</td>
<td></td>
</tr>
<tr>
<td>10/3.1</td>
<td>894/494</td>
<td>217/120</td>
</tr>
<tr>
<td></td>
<td>738/408</td>
<td>436/241</td>
</tr>
<tr>
<td></td>
<td>586/324</td>
<td></td>
</tr>
<tr>
<td></td>
<td>358/198</td>
<td></td>
</tr>
<tr>
<td>15/4.6</td>
<td>559/309</td>
<td>246/136</td>
</tr>
<tr>
<td></td>
<td>425/235</td>
<td></td>
</tr>
<tr>
<td></td>
<td>349/193</td>
<td></td>
</tr>
<tr>
<td></td>
<td>199/110</td>
<td></td>
</tr>
<tr>
<td>20/6.1</td>
<td>369/204</td>
<td>38/21</td>
</tr>
<tr>
<td></td>
<td>302/167</td>
<td>157/87</td>
</tr>
<tr>
<td></td>
<td>235/130</td>
<td></td>
</tr>
<tr>
<td></td>
<td>116/64</td>
<td></td>
</tr>
<tr>
<td>25/7.6</td>
<td>277/153</td>
<td>107/59</td>
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<td>174/96</td>
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<td></td>
<td>72/40</td>
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</tr>
<tr>
<td>30/9.2</td>
<td>212/117</td>
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<tr>
<td></td>
<td>179/99</td>
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<td>136/75</td>
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<td></td>
<td>81/45</td>
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<tr>
<td>40/12.2</td>
<td>159/88</td>
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</tr>
<tr>
<td></td>
<td>128/71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>92/51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40/22</td>
<td></td>
</tr>
<tr>
<td>50/15.3</td>
<td>132/73</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>98/54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>67/37</td>
<td></td>
</tr>
<tr>
<td>70/21.4</td>
<td>81/45</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>54/30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20/11</td>
<td></td>
</tr>
</tbody>
</table>

Notes: 1. RTIs are shown in (ft-s)½/(m-s)½
Gas parameters - $T_g$, $u_g$

- Alpert correlation used in DETACT model (unconfined ceiling jet)
  - Temperature
  \[
  \Delta T_{g,pl} = 16.9 \frac{\dot{Q}^{2/3}}{H^{5/3}}
  \]
  - Velocity
  \[
  u_{g,pl} = 1.0 \left( \frac{\dot{Q}}{H} \right)^{1/3}
  \]
  \[
  \frac{\Delta T_{g,cj}}{\Delta T_{g,pl}} = \frac{0.3}{(r/H)^{2/3}}
  \]
  \[
  \frac{u_{g,cj}}{u_{g,pl}} = \frac{0.2}{(r/H)^{5/6}}
  \]
Sprinkler activation example

- Assume sprinklers are installed on a 3m x 3m (10 ft x 10 ft) spacing in the FMSNL test room.
- The FM/SNL test room is 18 m (60 ft) long x 12 m (40 ft) wide x 6 m (20 ft) high.
- For a quasi-steady fire with a HRR of 500 kW, estimate the activation time for a sprinkler with
  - \( T_{act} = 74 \, ^\circ C \)
  - \( RTI = 130 \, \text{(m-s)}^{1/2} \)
Sprinkler activation example

Solution

– Step 1 – determine radial position of sprinkler

\[ R = \frac{\sqrt{S^2 + S^2}}{2} = \frac{S}{\sqrt{2}} = \frac{3}{\sqrt{2}} = 2.1 \text{ m} \]

\[ \frac{R}{H} = \frac{2.1}{6.0} = 0.35 \]

– Step 2 – calculate gas temperature / velocity at sprinkler

\[ \Delta T_{g,pl} = 16.9 \frac{\dot{Q}^{2/3}}{H^{5/3}} = 54 \text{ C} \]

\[ u_{g,pl} = 1.0 \left( \frac{\dot{Q}}{H} \right)^{1/3} = 4.4 \text{ m/s} \]

\[ \Delta T_{g,cj} = \frac{0.3}{(r/H)^{2/3}} \Delta T_{g,pl} = 33 \text{ C} \]

\[ u_{g,cj} = \frac{0.2}{(r/H)^{5/6}} u_{g,pl} = 2.1 \text{ m/s} \]
Sprinkler activation example

Solution

- Step 3 – Calculate sprinkler response
- The next step would normally be to calculate the activation time of the sprinkler
- But note that the gas temperature at the sprinkler is only 53°C \((20+33)\) for this example, while the sprinkler activation temperature is 74°C
- So the 500 kW fire would not activate the sprinkler until the hot gas layer forms and the ceiling jet temperature exceeds the activation temperature
Smoke detector activation (temperature model)

- **Heat detector analogy**
  - Treat smoke detector as low RTI device
    - Cannot use zero - Divide by zero error
    - Hand calculations - use $T_d = T_g$
  - Assume $\Delta T_{act} \sim 15 ^\circ C$ (or less)
  - Questions regarding validity
    - Relies on optical density analogy
    - Smoke detectors don’t always respond to optical density
Smoke detector activation (Heskestad model)

Smoke concentration in detector chamber, $Y_c$

$$\frac{dY_c}{dt} = \frac{Y_s(t) - Y_c(t)}{\delta t_c}$$

$\delta t_c = L / u$

- $u$ is the local gas velocity outside the detector
- $L$ is the characteristic entry length of the detector
- $Y_s$ is the smoke concentration outside the detector
- $Y_c$ is the smoke concentration in the detection chamber

Need to know $Y_c$ that causes detector activation
Structural steel damage

- Same concept as DETACT for steel

\[ \frac{dT_s}{dt} = \frac{\dot{q}'' A_s}{\rho V c_p} = \frac{\dot{q}''}{\rho c_p \left( \frac{V}{A_s} \right)} = \frac{\dot{q}''}{c_p \left( \frac{W}{D} \right)} \]

- Steel properties

\[ \rho c_p \approx 3,666 \text{ kJ/(m}^3 \cdot \text{K)} \]

\[ \frac{V}{A_s} = \text{cross-section} \]

\[ \frac{W}{D} = \text{Weight/length} \]
Structural steel damage

- Steel critical temperature, $T_c \approx 550 \, ^\circ C$
- Evaluation of heat fluxes
  - Flame radiant heat flux
    - Applies in flame only
  - Plume convective heat flux
    - Applies in flame and plume
  - Radiant flux outside flame
    - Point source estimate
  - Based on Alpert & Ward FSJ article

\[
\dot{q}_r'' = 160 \, \text{kW/m}^2
\]
\[
\dot{q}_c'' = 0.3 \frac{(k_f \dot{Q})}{H^2}
\]
\[
\dot{q}_r'' = \frac{\chi_r \dot{Q}}{4\pi R^2}
\]
EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5
Advanced Fire Modeling
Development of a Cable Response Model and Fire Model Verification and Validation

Kevin McGrattan
National Institute of Standards and Technology

Joint RES/EPRI Fire PRA Workshop
August 2015
Rockville, Maryland
CAROLFIRE
(Cable Response to Live Fire)

- **Penlight** heats target cables via grey-body radiation from a heated shroud

- Well controlled, well instrumented tests

- Allows for many experiments in a short time

- Thermal response and failure for single cables and small cable bundles (up to six cables)

- Cable trays, air drops, conduits
Typical Penlight setup
Intermediate-Scale Experiments

• Less controlled, but a more realistic scale
• Hood is roughly the size of a typical ASTM E 603 type room fire test facility
• Propene (Propylene) burner fire (200 kW to 350 kW)
• Cables in trays, conduits and air drop
Simple Response Models in Fire

Solve for link temperature using velocity $u$ and gas temperature from Fire Model. The RTI (Response Time Index) is unique to each sprinkler.

Source: Gunnar Heskestad, Factory Mutual

\[
\frac{dT_l}{dt} = \frac{\sqrt{|u|}}{\text{RTI}} (T_g - T_l)
\]

Solve for smoke chamber concentration using external smoke concentration and velocity $u$ from Fire Model. $L$ is a length scale unique to each detector.

\[
\frac{dY_c}{dt} = \frac{Y_e(t) - Y_c(t)}{L/u}
\]
Cable Failure Model

\[ \rho_s c_s \frac{\partial T_s}{\partial t} = \frac{k_s}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T_s}{\partial r} \right) \]

\[ -k_s \frac{\partial T_s}{\partial r} = \dot{q}_c'' + \dot{q}_r'' \]

1-D heat conduction into homogenous cylinder. Thermal conductivity \( k \) and specific heat \( c \) assumed constant for all cables. Density \( \rho \) obtained from cable diameter and mass per unit length. Failure temperature obtained experimentally.

The Fire Model provides the convective and radiative heat flux at the cable surface.

Source: Andersson and Van Hees, SP Fire, Sweden.
Single Cable

Courtesy Steve Nowlen and Frank Wyant
Sandia National Laboratory
Cable in a Conduit

 Courtesy Steve Nowlen and Frank Wyant
 Sandia National Laboratory
Intermediate-Scale Experiments

- Single Cable in Tray
- Loose Fill Cables in Tray
- 6 Cable Bundle in Tray
- 12 Cable Bundle in Tray
- 3 Cable Bundle in Conduit
- Air Drop Cable(s)

Predicted Failure Time (s)

Measured or Inferred Failure Time (s)
Summary

- Methods to calculate fire detector response and structural/cable damage have been discussed
  - First-order response characteristics
  - Lumped capacity analysis (Low Biot No.)
- Methods require estimates for:
  - Heat flux or gas temperature at target
  - Thermal response properties of target
- Basic models use fire plume/ceiling jet correlations
  - Same predictive equations used in computer fire models, but temperatures/velocities calculated by models rather than specified by empirical correlations