EPRI/NRC-RES Fire PRA Methodology

Module V: Advanced Fire Modeling

Fire Model Descriptions

Joint RES/EPRI Fire PRA Workshop
Fall 2011
San Diego and Jacksonville

A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)
FIVE (Fire-Induced Vulnerability Evaluation)


- Mostly a collection of hand calculations to estimate fire-generated conditions.

- Capable of estimating smoke layer, height and temperatures.
About FIVE-Rev1

- More than 10 years after the start of FIVE, most of the equations are still used in practice
- A revision of the quantitative fire hazard techniques in FIVE.
- Most of the hand calculations are in the original EPRI publication and some other models available are 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
About FIVE-Rev1

- Excel spreadsheet
  - Graphical interface
  - Excel’s equation library

In FIVE-REV-1, EPRI has automated most of the hand calculations described in FIVE plus some additional models commonly used by fire protection engineers.

Fire models can be accessed in two ways:

1. Click on "Models" to start the interface. Through this interface, users can select a model, provide required inputs and obtain results.

2. Click on "Close" to work in Excel spreadsheet environment. The models are available in the Insert/Functions/User Defined menu. Analysts can take advantage of all Excel built-in capabilities to perform fire modeling analysis.

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Graphical Interface

• Main menu screen: CTRL-m
Graphical Interface

- Additional models screen:
Graphical Interface

- Interface for models
How to User FIVE-Rev1 Excel Function Library

- On a new Worksheet:
  - Click on: Insert/Function/User Defined
  - Use them as any other Excel built in functions
Excel Function Library

• Advantages:
  – Use in the fire modeling analysis all the Excel built-in capabilities
    • Charts, random number generation, statistical analyses
    • Create your own fire modeling templates, forms and reports
  – Uncertainty analysis
    • Propagation of parameter uncertainty
  – Sensitivity analysis

• However,
  – The graphical interface is the typical excel environment
  – Be familiar with Excel and the selected fire models
Technical Details

Uncertainty

\[ f(P_1, P_2, C_i) = R \]

- Some models in the graphical interface can be solved with and without parameter uncertainty.
- If the uncertainty option is selected, the fire intensity is represented the 5th and 95th percentiles of the distribution.
- Both the input distribution and the output result are assumed to be normal.
- Uncertainty propagation is done using the Taylor expansion method.
Fire Dynamic Tools (FDTs)

• FDTs are a series of Microsoft Excel® spreadsheets issued with NUREG-1805, “Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program.”

• The primary goal of FDTs was to be a training tool to teach NRC Fire Protection Inspectors an Introduction to Fire Dynamics.

• The secondary goal of FDTs was to be used in plant inspections and support other programs that required Fire Dynamics knowledge such as, Significance Determination Process (SDP) and NFPA 805.

• NUREG-1805 provides a basic Introduction to Fire Dynamics for NPP applications. Available free download at: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/
Development of NUREG-1805 FDTs

- FDTs are modeled after the Alcohol, Tobacco, Firearms, and Explosives (ATF&E) Fire and Arson Certified Fire Investigation Program

  - Customized for nuclear power plants applications
  - Appropriate physical properties

- New spreadsheets were added as a part of the review.
Features of FDTs

• User-friendly, **Pre-Programmed** Microsoft Excel® based on **Fire Dynamics** equation/correlations.
  
  – Quick application of **Fire Dynamics** principles found in state-of-the-art *Fire Protection Handbooks*
  – Spreadsheets are protected to **Prevent Tampering**
  – **Automatic Unit Conversion**
  – Related **Material Fire Properties Data** for materials commonly found in nuclear power plants listed within each spreadsheet
  – **Reduces Input Errors** from inaccurate manual entries by using **Pull-Down Menus** which allow the user to select material fire property data
  – Provides for quick iterations with easy data entry in the spreadsheets to provide first order Fire Dynamics estimates.

• Spreadsheets are available in English and SI Units.
Features of FDTs
List of FDTs Spreadsheets

- 02.1_Temperature_NV.xls
- 02.2_Temperature_FV.xls
- 02.3_Temperature_CC.xls
- 03_HRR_Flame_Height_Burning_Duration_Calculations.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
- 10_Detector_Activation_Time.xls
- 13_Compartment_Flashover_Calculations.xls
- 14_Compartment_Over_Pressure_Calculations.xls
- 15_Explosion_Calculations.xls
- 16_Battery_Room_Flammable_Gas_Cons.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
New FDTs

THIEF – Cable Failure

• Flammable Liquid Spill Diameter

• Ceiling Jet Temperature & Velocity
## CHAPTER 20. ESTIMATING THE THERMALLY-INDUCED ELECTRICAL FAILURE (THIEF) OF CABLES

Version 1806.0 LOCKED (SI units)

The following calculations estimate the time to failure of cables exposed to a specified hot gas layer.

<table>
<thead>
<tr>
<th>Parameters in YELLOW CELLS</th>
<th>Automatically Selected from the DROP DOWN MENU or SELECT CABLE BUTTON.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters in GREEN CELLS</td>
<td>Entered by the User.</td>
</tr>
</tbody>
</table>

All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secured 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Diameter (mm)</td>
<td>22.05 mm</td>
</tr>
<tr>
<td>Cable Mass per Unit Length (kg/m)</td>
<td>0.80 kg/m</td>
</tr>
<tr>
<td>Cable Jacket Thickness (mm)</td>
<td>2.032 mm</td>
</tr>
<tr>
<td>Ambient Air Temperature (°C)</td>
<td>21°C</td>
</tr>
<tr>
<td>Failure Temperature (°C)</td>
<td>200°C</td>
</tr>
<tr>
<td>Maximum Time (s)</td>
<td>4000 s</td>
</tr>
<tr>
<td>Conduit Thickness (mm)</td>
<td>0.00 mm</td>
</tr>
<tr>
<td>Conduit Outside Diameter (mm)</td>
<td>0.00 mm</td>
</tr>
<tr>
<td>Cable Density (kg/m³)</td>
<td>2063.7 kg/m³</td>
</tr>
</tbody>
</table>

Select Source for Exposure Gas Temperature Profile
- Natural Ventilation - Method of McCarthy, Quintiere, Hanker, and McDuff (MQH)

Click Calculate Button when finished entering data!
Calculate Exposure

<table>
<thead>
<tr>
<th>INPUT PARAMETERS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Diameter (mm)</td>
<td>22.23 mm</td>
</tr>
<tr>
<td>Cable Mass per Unit Length (kg/m)</td>
<td>0.00 kg/m</td>
</tr>
<tr>
<td>Cable Jacket Thickness (mm)</td>
<td>2.03 mm</td>
</tr>
<tr>
<td>Ambient Air Temperature (°C)</td>
<td>21 °C</td>
</tr>
<tr>
<td>Failure Temperature (°C)</td>
<td>290 °C</td>
</tr>
<tr>
<td>Maximum Time (s)</td>
<td>4000 s</td>
</tr>
<tr>
<td>Conduit Thickness (mm)</td>
<td>0.60 mm</td>
</tr>
<tr>
<td>Conduit Outside Diameter (mm)</td>
<td>0.00 mm</td>
</tr>
<tr>
<td>Cable Density (kg/m^3)</td>
<td>2063.76 kg/m^3</td>
</tr>
<tr>
<td>Cable Insulation Type (Thermoplastic, Thermoset)</td>
<td>Thermoplastic</td>
</tr>
</tbody>
</table>

Select Source for Exposure Gas Temperature Profile

- Natural Ventilation - Method of McCaffrey, Quintiere, and Harker (MCH)
- Forced Ventilation - Method of Foote, Pagni, and Alvarez (FPA)
- Forced Ventilation - Method of Deal and Beyler
- Room Fire with Closed Door
- Within Fire Plume
- User Defined

EXPOSURE GAS TEMPERATURE PROFILE

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Gas Temperature (°C)</th>
<th>Gas Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25.00</td>
<td>298.15</td>
</tr>
</tbody>
</table>

RESULTS
Plume-Calculations (Chap. 9)

### CHAPTER 9. ESTIMATING CENTERLINE TEMPERATURE OF A BUOYANT FIRE PLUME

**Version 1805.0 (SI Units)**

The following spreadsheet estimates the centerline temperature of a buoyant fire plume. Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

**INPUT PARAMETERS**

- Heat Release Rate of the Fire (Q)
- Elevation Above the Fire Source (z)
- Area of Combustible Fuel (A)
- Ambient Air Temperature (T)

**AMBIENT CONDITIONS**

- Specific Heat of Air (c)
- Ambient Air Density (ρ)
- Acceleration of Gravity (g)
- Convective Heat Release Fraction (γ)

**ESTIMATING PLUME CENTERLINE TEMPERATURE**


\[
T_{\text{centerline}} = 9.1 \left( \frac{Q}{W^2} \right) \rho_c^3 (c-z)^{0.5}
\]

Where

- \(T_{\text{centerline}}\) = plume centerline temperature (°C)
- \(Q\) = convective portion of the heat release rate (kW)

**SI UNITS**

- 218.06 kW
- 0.55 m
- 1.00 m²
- 26.00°C

**Calculate**

- 2.86.00 °C

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Centerline Plume Temperature Calculation

\[ T_{p(\text{centerline})} - T_a = 9.1 \left( \frac{T_a}{g \ c_p \rho_a} \right)^{2/3} Q_e^{2/3} (z - z_0)^{-5/3} \]

\[ T_{p(\text{centerline})} = T_a - 809.10 \]

\[ T_{p(\text{centerline})} = 1107.10 \text{ K} \]

\[ T_{p(\text{centerline})} = 834.10 \degree \text{C} \quad 1533.37 \degree \text{F} \]
### Temperature-NV (Chap. 2)

#### Input Parameters - SI Units

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compartment Width (m)</td>
<td>4.02</td>
<td>m</td>
</tr>
<tr>
<td>Compartment Length (L)</td>
<td>18.00</td>
<td>m</td>
</tr>
<tr>
<td>Compartment Height (H)</td>
<td>3.10</td>
<td>m</td>
</tr>
<tr>
<td>Vent Width (u_v)</td>
<td>1.00</td>
<td>m</td>
</tr>
<tr>
<td>Vent Height (u_h)</td>
<td>1.00</td>
<td>m</td>
</tr>
<tr>
<td>Top Of Vent from Floor (V)</td>
<td>2.00</td>
<td>m</td>
</tr>
<tr>
<td>Interior Leg Thickness (L)</td>
<td>1.20</td>
<td>m</td>
</tr>
</tbody>
</table>

#### Ambient Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Air Temperature (T)</td>
<td>29.00</td>
<td>°C</td>
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</tbody>
</table>

#### Thermal Properties of Compartment Enclosing Surfaces

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Conductivity (W/m-K)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior Leg (concrete)</td>
<td>0.15</td>
<td>1000</td>
</tr>
</tbody>
</table>

#### Experimental Thermal Properties for Common Interior Lining Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>λ (W/m-K)</th>
<th>ρ (kg/m³)</th>
<th>Select Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium (sheet)</td>
<td>0.206</td>
<td>2716</td>
<td>Select material</td>
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<tr>
<td>Steel (8% Carbon)</td>
<td>0.019</td>
<td>7200</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>0.016</td>
<td>2600</td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>0.018</td>
<td>1000</td>
<td></td>
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</tbody>
</table>

#### Fire Specifications

<table>
<thead>
<tr>
<th>Fire Heat Release Rate (Q)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.00 W</td>
<td></td>
</tr>
</tbody>
</table>
Temperature-NV Results

### Table

<table>
<thead>
<tr>
<th>Time After Ignition (s)</th>
<th>ℏ (W/m²·K)</th>
<th>ΔTg (°C)</th>
<th>Tg (°C)</th>
<th>Tg (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.60</td>
<td>366.84</td>
<td>684.84</td>
<td>733.11</td>
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<tr>
<td>2</td>
<td>1.00</td>
<td>434.21</td>
<td>732.21</td>
<td>1378.98</td>
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<tr>
<td>3</td>
<td>1.40</td>
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<td>762.57</td>
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<td>765.40</td>
<td>1063.40</td>
<td>1760.54</td>
</tr>
</tbody>
</table>

### Graph

- **Hot Gas Layer Temperature**
- Natural Ventilation (MGH Method)

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Fire PRA Workshop, 2011, San Diego, CA
Fire Model Descriptions

A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)
CHAPTER 20. ESTIMATING THE THERMALLY-INDUCED ELECTRICAL FAILURE (THEIF) OF CABLES

**INPUT PARAMETERS**

- Cable Diameter (mm)
- Cable Mass per Unit Length (g/m)
- Cable Jacket Thickness (mm)
- Ambient Air Temperature (°C)
- Failure Temperature (°C)
- Maximum Time (s)
- Conduit Thickness (mm)
- Conduit Outside Diameter (mm)
- Cable Density (g/m²)
- Cable Insulation Type (Thermoplastic, Thermoset)

Select Source for Exposure Gas Temperature Profile: Natural Ventilation - Method of McIntyre, Question: Horizontal (MHG).

**EXPOSURE GAS TEMPERATURE PROFILE**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Use Temperature (°C)</th>
<th>Gas Temperature (°C)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>215.6</td>
<td>215.6</td>
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<td>405.39</td>
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<td>405.51</td>
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</tr>
<tr>
<td>160</td>
<td>408.88</td>
<td>905.07</td>
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</tbody>
</table>

**RESULTS**

- Exposing Temp
- Cable Temp
- Conduit Temp

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### Environment

#### Exposure Gas Temperature Profile

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Gas Temperature (°C)</th>
<th>Gas Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25.00</td>
<td>298.15</td>
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<td>60</td>
<td>411.84</td>
<td>644.99</td>
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<td>732.36</td>
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<td>752.72</td>
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</tr>
<tr>
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</tr>
<tr>
<td>2100</td>
<td>724.54</td>
<td>997.79</td>
</tr>
<tr>
<td>2400</td>
<td>740.39</td>
<td>1013.54</td>
</tr>
<tr>
<td>2700</td>
<td>754.57</td>
<td>1027.72</td>
</tr>
<tr>
<td>3000</td>
<td>767.49</td>
<td>1040.64</td>
</tr>
<tr>
<td>3300</td>
<td>779.38</td>
<td>1052.53</td>
</tr>
<tr>
<td>3600</td>
<td>790.40</td>
<td>1063.55</td>
</tr>
</tbody>
</table>
THIEF Spreadsheet

CHAPTER 20. ESTIMATING THE THERMALLY-INDUCED ELECTRICAL FAILURE (THIEF) OF CABLES
Version 18.05.0 LOCKED (8 units)

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

Cable Selection Options

- Select Cable From List
- User Specified Data
- View Cable Data Sheets

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

Fire PRA Workshop, 2011, San Diego, CA
Fire Model Descriptions
Cable Function & Gauge

Select Cable Function:
- Control
- Instrumentation
- Power

Enter Wire Gauge:

Enter Number of Conductors:

Continue
Characteristics
### Cable List

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Cable Model</th>
<th>Insulation</th>
<th>Jacket</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENERIC</td>
<td>20-10 Control Cable</td>
<td>PE</td>
<td>PVC</td>
</tr>
<tr>
<td>Okonite</td>
<td>P-30</td>
<td>ETFE</td>
<td>CSPE</td>
</tr>
<tr>
<td>Okonite</td>
<td>P-15</td>
<td>PE</td>
<td>PVC</td>
</tr>
<tr>
<td>Okonite</td>
<td>FMR® Okonol®</td>
<td>EPR</td>
<td>CSPE</td>
</tr>
<tr>
<td>Okonite</td>
<td>FMR-LCS® Okonol®</td>
<td>EPR</td>
<td>CSPE</td>
</tr>
<tr>
<td>Okonite</td>
<td>FRM-N8® Okonol®</td>
<td>EPR</td>
<td>CSPE</td>
</tr>
<tr>
<td>Okonite</td>
<td>FRM-N8® Okonol® 1000/2000V</td>
<td>EPR</td>
<td>CSPE</td>
</tr>
</tbody>
</table>

Select one cable from the list above

Continue
Location
Results – Plume, TP

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Gas Temperature (°C)</th>
<th>Gas Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>273.15</td>
</tr>
<tr>
<td>10</td>
<td>364.95</td>
<td>638.10</td>
</tr>
<tr>
<td>2000</td>
<td>364.95</td>
<td>638.10</td>
</tr>
<tr>
<td>4000</td>
<td>364.95</td>
<td>638.10</td>
</tr>
</tbody>
</table>

Click Calculate Button when finished entering data!

Answer: Cable fails at 5.3 minutes
## Results – Plume, TS

### Exposed Gas Temperature Profile

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Gas Temperature (°C)</th>
<th>Gas Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>364.95</td>
<td>630.10</td>
</tr>
<tr>
<td>10</td>
<td>364.95</td>
<td>630.10</td>
</tr>
<tr>
<td>2000</td>
<td>364.95</td>
<td>630.10</td>
</tr>
<tr>
<td>4000</td>
<td>364.95</td>
<td>630.10</td>
</tr>
</tbody>
</table>

### Results

Click Calculate Button when finished entering data!

**Answer:** Cable does not reach failure temperature in 4000.2 seconds
Results – Layer, TP

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Gas Temperature (°C)</th>
<th>Gas Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25.00</td>
<td>298.15</td>
</tr>
<tr>
<td>60</td>
<td>110.95</td>
<td>384.10</td>
</tr>
<tr>
<td>120</td>
<td>121.48</td>
<td>394.83</td>
</tr>
<tr>
<td>180</td>
<td>128.23</td>
<td>401.38</td>
</tr>
<tr>
<td>240</td>
<td>135.30</td>
<td>406.40</td>
</tr>
<tr>
<td>300</td>
<td>137.40</td>
<td>410.55</td>
</tr>
<tr>
<td>600</td>
<td>151.16</td>
<td>424.31</td>
</tr>
<tr>
<td>900</td>
<td>159.99</td>
<td>433.14</td>
</tr>
<tr>
<td>1200</td>
<td>166.62</td>
<td>438.77</td>
</tr>
<tr>
<td>1500</td>
<td>171.98</td>
<td>444.13</td>
</tr>
<tr>
<td>1800</td>
<td>176.52</td>
<td>449.67</td>
</tr>
<tr>
<td>2100</td>
<td>180.45</td>
<td>453.61</td>
</tr>
<tr>
<td>2400</td>
<td>183.96</td>
<td>457.31</td>
</tr>
<tr>
<td>2700</td>
<td>187.11</td>
<td>460.26</td>
</tr>
<tr>
<td>3000</td>
<td>189.98</td>
<td>463.13</td>
</tr>
<tr>
<td>3300</td>
<td>192.62</td>
<td>466.77</td>
</tr>
<tr>
<td>3600</td>
<td>195.67</td>
<td>468.22</td>
</tr>
</tbody>
</table>

Results

Click Calculate Button when finished entering data!

Answer: Cable does not reach failure temperature in 4000.4 seconds
MAGIC is a two zone fire model developed by EDF. The software solves conservation equations for mass and energy in two control volumes. Local values of temperatures and fluxes are accessible with targets (flame, plume, ceiling-jet, relative distance from the fire).
- 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.
Sub-Models

Semi empirical correlations for:

- Plume temperature and entrainment
- Ceiling jet temperature

Vertical openings: hydrostatics

Horizontal opening: Cooper's correlation

Wall and Target conduction: 1-D finite difference

Combustion: global balance – effect of oxygen depletion

Sprinkling system: integrated droplet approach

Ventilation: parabolic fan law (variable), head loss in ducts
An advanced user interface

- Numerical controls, 3D visualization, wide data base (materials, combustible)
- Flexibility: user-friendly interface, PC English version, connection to Excel and Word, etc.
Examples
(EDF)

Fire PRA Workshop, 2011, San Diego, CA
Fire Model Descriptions

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

- CFAST is a two zone fire model developed by NIST
- The software solves conservation equations for mass and energy in two control volumes
- Accounts for the effects of
  - User specified fire(s) in multiple connected compartments
  - Natural flow between compartments through vents
  - Mechanical ventilation
  - Heating and ignition of objects
CFAST Interface

Tabs group model inputs into several categories

Inputs grouped by function with units displayed

Save, view, or run simulation
CFAST: Compartment Geometry

- Compartment name
- Compartment size
- Surface materials
CFAST: Horizontal Flow Vents (Doors, Windows)

- Connects two compartments
- Vent size
- Open or close opening

Fire PRA Workshop, 2011, San Diego, CA
Fire Model Descriptions
CFAST: Mechanical Flow Vents (HVAC)

- Connects two compartments
- Vent size and position
- Flow rate
- Open or close opening
CFAST: Fire Object Definition

Predefined fires

Fire name

Time history of fire size (HRR) and toxic gases

Fire PRA Workshop, 2011, San Diego, CA
Fire Model Descriptions

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

Target position

Normal vector

Target material
Running and Viewing the Simulation
Run: Calculation and Results

<table>
<thead>
<tr>
<th>Compartment</th>
<th>Upper Layer Temperature [°C]</th>
<th>Lower Layer Temperature [°C]</th>
<th>Interface Height [m]</th>
<th>Pyrolysis Rate [kg/s]</th>
<th>Fire Size [kW]</th>
<th>Pressure [Pa]</th>
<th>Ambient Target Flux [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>225.1</td>
<td>83.1</td>
<td>1.2</td>
<td>0.02544</td>
<td>1188</td>
<td>-1.89</td>
<td>2.751</td>
</tr>
<tr>
<td>Outside</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
View: Geometry and Visualization of Results

- CFAST uses Smokeview to visualize scenario geometry, vents, fires, and targets.
- Visualization of model outputs also supported.
FDS (Fire Dynamics Simulator)

• Computational fluid dynamics (CFD) model of fire driven fluid flow
• The software solves a form of the Navier-Stokes equations
  – FDS was designed to study fire dynamics
  – Uses “Low Mach Number” approximation
  – Low speed, thermally driven flows
  – Emphasis on smoke and heat transport
• FDS vs. other CFD codes:
  – Low Mach Number assumptions
  – Large Eddy Simulation (LES) turbulence model
  – Relatively simple gridding
What is Smokeview?

- Software tool designed to visualize numerical predictions generated by FDS
- It is a post processing step after simulation is completed (not a graphical user interface for entering input data)
- Visualizations are performed by:
  - Displaying time dependent tracer particles
  - Animated contour slices of computed gas variables
  - Displaying time dependent surface data
  - Realistic smoke
Basic Fire Physics in FDS
Geometry

• Geometry is defined in FDS with:
  – Obstructions: rectangular solids within the flow domain
  – Vents: planes adjacent to obstructions or external walls
    • Open to the outside, simulating windows, or
    • Model fuel or mechanical ventilation flows
  – For full functionality, obstructions should be specified to be at least one grid cell thick

• Grid Size:
  – Best if grid cells are close to cubes
Geometry

Slide 56
Geometry
Geometry
• Smoke Control in Underground Parking Space

• Mr. Simo Hostikka
  VTT Building and Transport
  Espoo, Finland
• 2006 Olympic Games Ice Hockey Stadium, Turin, Italy
• Davy Leroy
• Ove Arup & Partners Ltd
• Leeds, West Yorkshire, UK
NASA Vehicle Assembly Building
Comparative Venting Scheme Analysis

Rolf Jensen and Associates
Raleigh, NC
Orlando, FL
Smoke Management In A Large Atrium

FDS fire modeling was performed to evaluate the smoke control system of a large atrium

Ervin Cui, PhD, PE
Chen Su, PE
Warren Bonisch, PE
Dan O’Connor, PE
World Trade Center Investigation
Kevin McGrattan, Chuck Bouldin, Glenn Forney
Building and Fire Research Lab, NIST

Upper Layer Temperatures, Floor 97, WTC 1
Inputs

- FDS input is usually conveyed via a text file with .fds extension
- Recommended practice is to copy and sample file and edit it accordingly
Input File Example

```
$HEAD CHID='couch', TITLE='Single Couch Test Case' /
$MESH IJK=24,10,24, XB=1.1,3.5,3.6,4.6,0.0,2.4 /
$TIME T_END=900. /
$MISC SURF_DEFAULT='WALL' /
$SURF ID='BURNER', HRRPUA=1000., PART_ID='smoke' /

$OBJ XE= 1.50, 3.10, 3.80, 4.60, 0.00, 0.40 /
$OBJ XP= 1.50, 3.10, 3.80, 4.60, 0.40, 0.50, SURF_ID='UPHOLSTERY' /
$OBJ XP= 1.50, 3.10, 3.80, 4.60, 0.00, 0.50, SURF_ID='UPHOLSTERY' /

$VENT XE= 2.50, 2.60, 4.30, 4.40, 0.60, 0.60, SURF_ID='BURNER' /
$VENT XP= 'XMIN', SURF_ID='OPEN' /
$VENT XP= 'XMAX', SURF_ID='OPEN' /
$VENT XP= 'TMIN', SURF_ID='OPEN' /
$ENDF QUANTITY='RADIATIVE HEAT FLUX' /
$ENDF QUANTITY='CONVECTIVE HEAT FLUX' /
$SICE PX=2.60, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
$SICE PX=2.60, QUANTITY='HRRPUV' /

$TAIL /
```

Grid & Domain size

Fire

Open door

Outputs
Graphical User Interface (GUI)

- Third Party Software from Thunderhead Engineering
- Their product, PyroSim™, will not be free, but FDS and Smokeview will continue to be
Outputs

• Devices
  – Virtual sensors located in the computational domain
  – Sensors record quantities of interest such as temperature, heat flux, flow velocity, etc.
  – Recorded values are dumped into a comma-delimited text file

• Slice Files
  – Animated contour plots “slicing” through the scene that show quantities of interest such as temperature, species concentration, etc.

• Boundary Files
  – Animated contour plots of surface quantities at all solid boundaries

• IsoSurfaces and Realistic Smoke/Fire
  – Animated 3D contours showing the fire dynamics
Outputs: Thermocouple for temperature

Thermocouple

FDS TC Output File

<table>
<thead>
<tr>
<th>Temp [°C]</th>
<th>Time [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>150</td>
<td>600</td>
</tr>
<tr>
<td>200</td>
<td>800</td>
</tr>
<tr>
<td>250</td>
<td>1000</td>
</tr>
<tr>
<td>300</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>1400</td>
</tr>
</tbody>
</table>
Outputs: Slice files for temp and heat flux
EPRI/NRC-RES Fire PRA Methodology

Module V: Advanced Fire Modeling

Example F: Lube Oil Fire in Turbine Building

Joint RES/EPRI Fire PRA Workshop
Fall 2011
San Diego and Jacksonville

A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)
Step 1. Define Fire Modeling Goals

- Determine the heat flux to and temperature of structural steel columns in a turbine hall due to a lube oil fire.
- Evaluate structural steel response for two potential curb locations.
- This type of analysis may arise when addressing ASME/ANS RA-Sa-2009 supporting requirement FSS-F01.
Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire
Figure F-2. Structural Steel Column in the Turbine Building.
Figure F-3. Main Turbine Lubricating Oil Tanks in the Turbine Building.
### Table 3-1. Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m/K)</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (kJ/kg/K)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>0.8</td>
<td>2600</td>
<td>0.8</td>
<td>NUREG-1805, Table 2-3</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.6</td>
<td>2400</td>
<td>0.75</td>
<td>NUREG-1805, Table 2-3</td>
</tr>
<tr>
<td>Copper</td>
<td>386</td>
<td>8954</td>
<td>0.38</td>
<td>SFPE Handbook, Table B.6</td>
</tr>
<tr>
<td>Gypsum</td>
<td>0.17</td>
<td>960</td>
<td>1.1</td>
<td>NUREG-1805, Table 2-3</td>
</tr>
<tr>
<td>Plywood</td>
<td>0.12</td>
<td>540</td>
<td>2.5</td>
<td>NUREG-1805, Table 2-3</td>
</tr>
<tr>
<td>PVC</td>
<td>0.192</td>
<td>1380</td>
<td>1.289</td>
<td>NUREG/CR-6850, Appendix R</td>
</tr>
<tr>
<td>Steel</td>
<td>54</td>
<td>7850</td>
<td>0.465</td>
<td>NUREG-1805, Table 2-3</td>
</tr>
<tr>
<td>XLP</td>
<td>0.235</td>
<td>1375</td>
<td>1.390</td>
<td>NUREG/CR-6850, Appendix R</td>
</tr>
</tbody>
</table>

### Table F-2. Structural Steel Failure Criteria (ASTM E119-10a)

<table>
<thead>
<tr>
<th>Member</th>
<th>Maximum Cross-Section Temperature (°C)</th>
<th>Maximum Cross-Section Average Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>704</td>
<td>593</td>
</tr>
<tr>
<td>Column</td>
<td>649</td>
<td>538</td>
</tr>
</tbody>
</table>
Ventilation

- Large, open area
- Forced ventilation intentionally shut down at start of fire
- 18 exhaust vents to the outside around the perimeter
## Table F-2. Data for lube oil fire.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Fuel Formula</td>
<td>C_nH_{2n+2}</td>
<td>Assumption (n in range of 12-15)</td>
</tr>
<tr>
<td>Mass burning rate</td>
<td>0.039 kg/s.m²</td>
<td>NUREG-1805 Table 3-4</td>
</tr>
<tr>
<td>Density</td>
<td>760 kg/m³</td>
<td>NUREG-1805 Table 3-4</td>
</tr>
<tr>
<td>Heat of Combustion</td>
<td>46,000 kJ/kg</td>
<td>NUREG-1805 Table 3-4</td>
</tr>
<tr>
<td>CO₂ Yield</td>
<td>2.64 kg/kg</td>
<td>SFPE Handbook, 4th ed., Table 3-4.16*</td>
</tr>
<tr>
<td>Soot Yield</td>
<td>0.059 kg/kg</td>
<td>SFPE Handbook, 4th ed., Table 3-4.16*</td>
</tr>
<tr>
<td>CO Yield</td>
<td>0.019 kg/kg</td>
<td>SFPE Handbook, 4th ed., Table 3-4.16*</td>
</tr>
<tr>
<td>Radiative Fraction</td>
<td>0.33</td>
<td>SFPE Handbook, 4th ed., Table 3-4.16*</td>
</tr>
<tr>
<td>Mass Extinction Coefficient</td>
<td>8700 m²/kg</td>
<td>Mulholland and Croarkin (2000)</td>
</tr>
</tbody>
</table>

*Material identified as “Hydrocarbon” in SFPE Handbook used to derive properties.

The peak heat release rate, $\dot{Q}$, is computed from the fuel mass burning rate, $\dot{m}''$, the heat of combustion, $\Delta H$, and the specified area of the spill, $A$:

$$\dot{Q} = \dot{m}'' \Delta H A = 0.039 \text{ kg/m}^2/\text{s} \times 46,000 \text{ kJ/kg} \times 28.1 \text{ m}^2 \cong 50,400 \text{ kW}$$  \hspace{1cm} (F-1)

The fire duration, $\Delta t$, is determined from the pool depth, $\delta$, density, $\rho$, and burning rate, $\dot{m}''$:

$$\Delta t = \frac{\delta \rho}{\dot{m}''} = \frac{0.11 \text{ m} \times 760 \text{ kg/m}^3}{0.039 \text{ kg/m}^2/\text{s}} \cong 2144 \text{ s} \ (35.7 \text{ min})$$  \hspace{1cm} (F-2)
Step 3. Select Fire Models

• **Algebraic Models**: Fire resistance calculations typically use a pre-defined time-temperature curve, like ASTM E 119. Not appropriate here. However, heat flux calculations are valid.

• **Zone Models**: Challenging case – too many assumptions violated, in particular the ratio of flame height to ceiling height. Zone models not used.

• **CFD**: Near-field or engulfing fire heat flux is a challenge for any model.
## Applicability of Validation

Table F-3. Normalized Parameter Calculations for the Turbine Building Fire Scenario.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Normalized Parameter Calculation</th>
<th>Validation Range</th>
<th>In Range?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Froude Number</td>
<td>$Q^* = \frac{\dot{Q}}{\rho_{\infty} c_p T_{\infty} D^{2.5} \sqrt{g}} = \frac{50,400 \text{ kW}}{(1.1 \text{ kg/m}^3)(1.0 \text{ kJ/kg/K})(309 \text{ K})(6.0^{2.5} \text{ m}^{2.5})\sqrt{9.8 \text{ m/s}^2}} \approx 0.52$</td>
<td>0.4 – 2.4</td>
<td>Yes</td>
</tr>
<tr>
<td>Flame length to ceiling height ratio</td>
<td>$\frac{L_f}{H} = \frac{11.0 \text{ m}}{4.6 \text{ m}} \approx 2.4$</td>
<td>0.2 – 1.0</td>
<td>No</td>
</tr>
<tr>
<td>Ceiling jet radius relative to the ceiling height</td>
<td>$L_f = D \left(3.7 \dot{Q}^{2/5} - 1.02\right) = 6.0 \text{ m} (3.7 \times 0.52^{0.4} - 1.02) \approx 11.0 \text{ m}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equivalence ratio based on opening area</td>
<td>N/A</td>
<td>1.2 – 1.7</td>
<td>N/A</td>
</tr>
<tr>
<td>Compartment aspect ratios</td>
<td>$\frac{L}{H} = \frac{100.3 \text{ m}}{4.6 \text{ m}} \approx 21.8$; $\frac{W}{H} = \frac{99.5 \text{ m}}{4.6 \text{ m}} \approx 21.6$</td>
<td>0.6 – 5.7</td>
<td>No</td>
</tr>
</tbody>
</table>
| Target distance to fire diameter              | $\begin{align*} 
8.5 \text{ m} & \approx 1.4 \\
7.2 \text{ m} & \approx 1.2 \\
18.8 \text{ m} & \approx 3.1 \\
18.3 \text{ m} & \approx 3.1 \\
36.5 \text{ m} & \approx 6.1 \\
78. \text{ m} & \approx 13.1 \\
28.0 \text{ m} & \approx 4.7 \\
26.9 \text{ m} & \approx 4.5 \\
8.8 \text{ m} & \approx 1.5 \\
3.9 \text{ m} & \approx 0.7 \\
43.3 \text{ m} & \approx 7.2 \\
80. \text{ m} & \approx 13.5 \\
\end{align*}$ | 2.2 – 5.7        | Yes/No    |

Notes: (1) The effective area of the fire is determined from the formula, $D = \sqrt{4A/\pi}$, where $A$ is the area of the dike.
To estimate the quantity of oxygen available in the turbine hall, the volume of the turbine hall is calculated to be 209,577 m$^3$ based on the overall dimensions of 100.3 m by 99.5 m by 21.0 m. The volume occupied by solid obstructions is ignored for this calculation. The total mass of oxygen within the turbine building is then calculated as:

$$m_{O_2,\text{tot}} = \rho V Y_{O_2} = 1.1 \text{ kg/m}^3 \times 209,577 \text{ m}^3 \times 0.23 \approx 53,023 \text{ kg}$$  \hspace{1cm} (F-3)

The quantity of oxygen consumed by the specified lube oil fire is calculated as:

$$m_{O_2,\text{req}} = \frac{\dot{Q} \Delta t}{\Delta H_{O_2}} = \frac{50,400 \text{ kW} \times 2,144 \text{ s}}{13,100 \text{ kJ/kg}} = 8,249 \text{ kg}$$  \hspace{1cm} (F-4)

Thus, the specified fire would consume less than 16 % of the oxygen available within the turbine building. Consequently, the fire would not be expected to be ventilation limited, on a global basis, even without ventilation with the outside environment through the roof vents.
Step 4. Calculate Fire-Generated Conditions

Figure F-5. FDS Geometry for the Turbine Building Fire Scenario.
Flame extension beneath turbine deck

Figure F-4. Schematic diagram of the fire impinging on the ceiling.
Flame extension beneath turbine deck

Figure F-5. Detail from Figure F-1 with estimated flame extension beneath ceiling superimposed.
Column heating – hand calculation

In order to estimate an approximate time for a column to reach the specified failure temperature of 538 °C when subjected to different radiant heat fluxes, a simple energy balance is used to calculate the rate of temperature rise of the steel in response to this imposed heat flux:

\[ \rho_s c_s V_s \frac{dT_s}{dt} = \dot{q}_r'' A_s \]  

(F-6)

The subscript \( s \) refers to steel. For a constant heat flux, this differential equation can be readily integrated to yield the steel temperature as a function of time:

\[ T_s - T_0 = \frac{\dot{q}_r'' t}{\rho_s c_s (V_s/A_s)} \]  

(F-7)

To calculate the time, \( t_{crit} \), when the steel failure temperature is reached, this equation is rearranged, with the critical steel temperature, \( T_{crit} \), inserted for the steel temperature.

\[ t_{crit} = \frac{\rho_s c_s (V_s/A_s)(T_{crit} - T_0)}{\dot{q}_r''} = \frac{c_s (W/D)(T_{crit} - T_0)}{\dot{q}_r''} \]  

(F-8)

The term \( V_s/A_s \) is sometimes called the section factor and is the effective thickness of the steel member; it is calculated as the cross-sectional area of a steel member divided by the heated perimeter of the member. In the US, it is more common to use a parameter referred to as the W/D ratio, which is simply the section factor multiplied by the steel density. For a W14x145 steel column, the W/D ratio has a value of approximately 96.2 kg/m² (1.64 lb/ft²in). With this value used for the W/D ratio, the time to reach the critical steel temperature for the column can be estimated, based on the radiant heat flux estimated in equation F-5, as:

\[ t_{crit} = \frac{(0.465 \text{ kJ/kg}/\text{°C})(96.2 \text{ kg/m}^2)(538 \text{ °C} - 36 \text{ °C})}{75.0 \text{ kW/m}^2} \cong 300 \text{ s} \]  

(F-9)
Column heating – FDS calculation

FDS Results, Curb Location 2

Heat Flux of Column D

Temperature of Column D

Time (s)

Heat Flux (kW/m²)

Temperature (°C)

Time (s)
### Step 5. Sensitivity and Uncertainty Analysis

#### Table F-4. Summary of results for the Turbine Building fire scenarios.

<table>
<thead>
<tr>
<th>Model</th>
<th>Bias Factor, $\delta$</th>
<th>Standard Deviation, $\sigma_M$</th>
<th>Target</th>
<th>Predicted Value</th>
<th>Critical Value</th>
<th>Probability of Exceeding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Curb Location 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column A</td>
<td>270</td>
<td>538</td>
<td>0.000</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column B</td>
<td>260</td>
<td>538</td>
<td>0.000</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column C</td>
<td>170</td>
<td>538</td>
<td>0.000</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column D</td>
<td>150</td>
<td>538</td>
<td>0.000</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column E</td>
<td>90</td>
<td>538</td>
<td>0.000</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column F</td>
<td>50</td>
<td>538</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Curb Location 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column A</td>
<td>130</td>
<td>538</td>
<td>0.000</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column B</td>
<td>120</td>
<td>538</td>
<td>0.000</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column C</td>
<td>400</td>
<td>538</td>
<td>0.001</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column D</td>
<td>620</td>
<td>538</td>
<td>0.828</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column E</td>
<td>75</td>
<td>538</td>
<td>0.000</td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Column F</td>
<td>50</td>
<td>538</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**Surface Temperature (°C), Initial Value = 36 °C**
Step 6. Document the Analysis

• Follow the steps; clearly explain the entire process
• Answer the original question
• Report model predictions with uncertainty and sensitivity included
• Include all references
F.6 Conclusion

Based on the FDS simulation of this scenario, a 50 MW lube oil fire in Curb Location 1, which is the curbed area located between Columns A, B, C, and D, is not predicted to cause the structural steel to exceed a temperature of 538 °C (1,000 °F). This is not the case for the proposed Curb Location 2, which is located closer to Column D and is predicted to cause the structural steel to exceed a temperature of 538 °C (1,000 °F). Consequently, the recommendation for the design package is to install the curbed area at Curb Location 1.

Overall, given the large volume of lubricant involved, it is significant that structural failure is not predicted by the CFD fire model for Curb Location 1. Although it may seem counterintuitive, this is a direct result of the relatively small area in which the lubricant is confined. The curbing restricts the surface area of the lubricant spill, and, correspondingly, the heat release rate of the fire.
EPRI/NRC-RES Fire PRA Methodology

Module V: Advanced Fire Modeling
Example G: Transient Fire in a Corridor

Joint RES/EPRI Fire PRA Workshop
Fall 2011
San Diego and Jacksonville
Step 1. Define Fire Modeling Goals

• Determine if important safe-shutdown equipment will fail due to a fire involving a stack of pallets in a hallway
• Also determine time to smoke detector activation
Step 2. Characterize Fire Scenarios

- General Description
- Geometry
- Materials
- Fire Protection Systems
- Ventilation
- Fire
Notes:
1. Walls are made of Concrete.
2. Doors are made of Steel.
3. Dimensions are in meters, 1 m = 3.28 ft.

Large Trash Bag (x2)
Wood Pallet (x4)
(3.0 x 1.0 x 0.64 overall)

Cable Tray A
Cable Tray B
Cable Tray D
Wall with Open Door
(See Detail D-1)

NCC Cabinet
(See Detail A-A)

Supply Vent
Return Vent

Soffit (See Detail B-B)

+2.1 m x 3

1 m = 3.28 ft

Multi-Corridor
Ventilation and Detection

- 1.67 m$^3$/s air flow
- All doors closed
- 9 smoke detectors with a sensitivity of 4.9 %/m
- No suppression system
Table G-1. Products of combustion for a wood pallet fire.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Fuel Formula</td>
<td>C₆H₁₀O₅</td>
<td>Assumption, Cellulose</td>
</tr>
<tr>
<td>Peak HRR</td>
<td>2500 kW</td>
<td><em>SFPE Handbook, 4th Ed.</em>, Figs. 3-1.65, 3-1.100</td>
</tr>
<tr>
<td>Time to reach peak HRR</td>
<td>420 s</td>
<td><em>SFPE Handbook, 4th Ed.</em>, Figs. 3-1.64</td>
</tr>
<tr>
<td>Heat of Combustion</td>
<td>17,100 kJ/kg</td>
<td><em>SFPE Handbook, 4th Ed.</em>, Table 3-4.16</td>
</tr>
<tr>
<td>Heat of Combustion per unit mass of oxygen consumed</td>
<td>13.2 kJ/g</td>
<td><em>SFPE Handbook, 4th Ed.</em>, Table 3-4.15</td>
</tr>
<tr>
<td>CO₂ Yield</td>
<td>1.27 kg/kg</td>
<td><em>SFPE Handbook, 4th Ed.</em>, Table 3-4.16</td>
</tr>
<tr>
<td>Soot Yield</td>
<td>0.015 kg/kg</td>
<td><em>SFPE Handbook, 4th Ed.</em>, Table 3-4.16</td>
</tr>
<tr>
<td>CO Yield</td>
<td>0.004 kg/kg</td>
<td><em>SFPE Handbook, 4th Ed.</em>, Table 3-4.16</td>
</tr>
<tr>
<td>Radiative Fraction</td>
<td>0.37</td>
<td><em>SFPE Handbook, 4th Ed.</em>, Table 3-4.16</td>
</tr>
</tbody>
</table>
Step 3. Select Fire Models

- **Algebraic Models**: Not designed for multiple compartment scenarios, but can be used to assess room of origin or in this case, the corridor containing the pallets.

- **Zone Models**: Scenario consistent with physical assumptions.

- **CFD**: No need in this case. All questions answered satisfactorily with simpler models.
Table G-2. Normalized parameter calculations for the Multi-Compartment Corridor fire scenario.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Normalized Parameter Calculation</th>
<th>Validation Range</th>
<th>In Range?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Froude Number</td>
<td>( \hat{Q} = \frac{Q}{\rho_{\infty} c_p T_{\infty} D^{2.5} \sqrt{g}} = \frac{2500 \text{ kW}}{(1.2 \text{ kg/m}^3)(1.0 \text{ kJ/kg}) (293 \text{ K})(1.3^{2.5} \text{ m}^2 \text{s}^{-5})\sqrt{9.8 \text{ m/s}^2}} = 1.2 )</td>
<td>0.4 – 2.4</td>
<td>Yes</td>
</tr>
<tr>
<td>Flame Length, ( L_f ), relative to the Ceiling Height, ( H )</td>
<td>( \frac{H_f + L_f}{H} = \frac{0.44 \text{ m} + 3.8 \text{ m}}{6.1 \text{ m}} = 0.7 )</td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Ceiling Jet Horizontal Radial Distance, ( r_{cj} ), relative to the Ceiling Height, ( H )</td>
<td>( r_{cj} = \frac{4.46 \text{ m}}{H - H_f} = \frac{4.46 \text{ m}}{6.1 \text{ m} - 0.44 \text{ m}} = 0.8 )</td>
<td>1.2 – 1.7</td>
<td>No</td>
</tr>
<tr>
<td>Equivalence Ratio, ( \phi ), as an indicator of the Ventilation Rate</td>
<td>( \phi = \frac{\hat{Q}}{\Delta H_{O_2} \dot{m}_{O_2}} = \frac{2500 \text{ kW}}{13,100 \text{ kJ/kg} \times 0.46 \text{ kg/s}} = 0.4 )</td>
<td>0.04 – 0.6</td>
<td>Yes</td>
</tr>
<tr>
<td>( m_{O_2} = 0.23 \rho_{\infty} \dot{W} = 0.23 \times 1.2 \text{ kg/m}^3 \times 1.67 \text{ m}^3 / \text{s} \equiv 0.46 \text{ kg/s} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compartment Aspect Ratios</td>
<td>( \frac{L}{H} = \frac{15.2 \text{ m}}{6.1 \text{ m}} = 2.49 ); ( \frac{W}{H} = \frac{3.0 \text{ m}}{6.1 \text{ m}} = 0.49 )</td>
<td>0.6 – 5.7</td>
<td>No</td>
</tr>
<tr>
<td>Target Distance, ( r ), relative to the Fire Diameter, ( D )</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: (1) The effective diameter of the base of the fire, \( D \), is calculated using \( D = \sqrt{4A/\pi} \), where \( A \) is the area of the pallets.

(2) The “Fire Height”, \( H_f + L_f \), is the sum of the height of the fire off the floor plus the fire’s flame length.
Step 4. Calculate Fire-Generated Conditions

Figure G-4. MAGIC rendering of the Corridor scenario.
Step 4. Calculate Fire-Generated Conditions

Figure G-3. Effective corridor layout for implementation in zone models (not to scale).

Table G-3. Compartment dimensions for Corridor scenario.

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.1</td>
<td>4.1</td>
<td>33.2</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>23.4</td>
<td>46.8</td>
</tr>
<tr>
<td>3</td>
<td>45.1</td>
<td>4.1</td>
<td>184.9</td>
</tr>
<tr>
<td>4</td>
<td>8.1</td>
<td>6.0</td>
<td>48.6</td>
</tr>
<tr>
<td>5</td>
<td>10.3</td>
<td>6.6</td>
<td>66.0</td>
</tr>
<tr>
<td>6</td>
<td>10.3</td>
<td>6.6</td>
<td>66.0</td>
</tr>
<tr>
<td>7</td>
<td>12.2</td>
<td>8.2</td>
<td>100.0</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>15.2</td>
<td>45.6</td>
</tr>
</tbody>
</table>


**Step 4. Calculate Fire-Generated Conditions**

**G.4.1 Algebraic Models**

This scenario concerns the prediction of cable damage at a location outside the compartment of fire origin. The temperature of the hot gas layer in the compartment of fire origin can be modeled as a potential screening tool. If the HGL temperature within the compartment of origin is not likely to cause damage to cables in that compartment, damage to cables outside the fire compartment is even more unlikely. As part of this approach, it is conservatively assumed that the cable surface temperature will match the HGL temperature (i.e., heat-up of the cable is assumed to be immediate).

FIVE was used for the MQH room temperature analysis. The inputs to the model are found in Table 3-1, Table G-1, and Table G-3. The calculation is applied to the fire room only, with the opening to the next compartment treated as an opening with an area (height x width) equal to 6.1 x 3 = 18.3 m². To correct the MQH temperature correlation for a fire in the corner, a factor of 1.7 is multiplied by the results in FIVE, as suggested by Karlsson and Quintiere 2000 (Equation 6.23).

For the time to detection, the Alpert Ceiling jet temperature calculation is used. The approach is to calculate the time at which the ceiling jet temperature at the heat detector is 30°C. The additional inputs for this correlation are the horizontal radial distance from the centerline of the fire plume to the detector, which is 4.5 m, and the fire location factor of 4, due to fire in the corner. Because the fire room is a corridor shape, the flow is likely to be confined; therefore, the confined flow correlation by Delichatsios is also used. The additional input is the corridor half-width of 1.5 m.
Step 4. Calculate Fire-Generated Conditions

Figure G-9. Hot Gas Layer Temperature Predictions by MAGIC for the Corridor Scenario.
Step 4. Calculate Fire-Generated Conditions

G.5.2 Smoke Detection

The smoke detector activation time in the corridor containing the fire is based on the time for the ceiling jet temperature to reach 30°C at the detector location. The results, plotted in Figure G-11, show that the two correlations from FIVE produce identical results of 50 s. MAGIC predicts 40 s.

Figure G-11. Detector temperature prediction by MAGIC for fire corridor.
Step 5. Sensitivity and Uncertainty Analysis

Table G-2. Summary of the model predictions of the Corridor scenario.

<table>
<thead>
<tr>
<th>Model</th>
<th>Bias Factor, $\delta$</th>
<th>Standard Deviation, $\sigma_M$</th>
<th>Ventilation</th>
<th>Predicted Value</th>
<th>Critical Value</th>
<th>Probability of Exceeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIVE (MQH)</td>
<td>1.56</td>
<td>0.32</td>
<td>Natural</td>
<td>256</td>
<td>330</td>
<td>0.001</td>
</tr>
<tr>
<td>MAGIC</td>
<td>1.01</td>
<td>0.07</td>
<td>Mechanical</td>
<td>240</td>
<td>330</td>
<td>0.000</td>
</tr>
</tbody>
</table>

HGL Temperature ($^\circ$C), Initial Value = 20 $^\circ$C
Step 5. Sensitivity and Uncertainty Analysis

What happens if the room height is reduced?

Figure G 10. Hot Gas Layer Temperature for Reduced Ceiling Height by MAGIC.
Step 6. Document the Analysis

• Follow the steps; clearly explain the entire process
• Answer the original question
• Report model predictions with uncertainty and sensitivity included
• Include all references
G.6 Conclusion

Both FIVE and the zone model MAGIC predict that HGL temperatures will not reach high enough to cause cable damage in any compartment or corridor, including the corridor containing the burning pallets, while accounting for uncertainty in the temperature predictions of MAGIC and the sensitivity of the predictions to variations in the heat release rate. Based on a simplified method for smoke detector activation, smoke detector operation occurs at 40 to 50 seconds.
EPRI/NRC-RES Fire PRA Methodology

Module V:
Advanced Fire Modeling
Example H: Cable Tray Fire in Annulus

Joint RES/EPRI Fire PRA Workshop
Fall 2011
San Diego and Jacksonville

A Collaboration of U.S. NRC Office of Nuclear Regulatory Research (RES) & Electric Power Research Institute (EPRI)
Step 1. Define Fire Modeling Goals

- Determine potential for damage to redundant safe-shutdown cables due to a fire in an adjacent tray in annulus region of the containment building.
- Follow guidance provided in Chapter 11 of NUREG/CR-6850 (EPRI 1011989), Volume 2, Appendix R, “Cable Fires”
Notes:
1. Dimensions are in meters, 1 m = 3.28 ft.

SECTION E-E, ISO VIEW

Ground Level
Concrete Shield Building
Stainless Containment Liner
Annulus Space

1 m = 3.28 ft
Fire

HRR taken from Appendix R, NUREG/CR 6850 (EPRI 10111989)

R.4.1.2 Recommended Values for Flame Spread in Horizontal Cable Trays

Consider a single vertical cable tray ignited at the bottom. Assume a heating distance of 2 mm and an incident heat flux of 70 kW/m².

- Flame spread for PVC cable = 0.9 mm/sec
- Flame spread for XPLE cable = 0.3 mm/sec

Table R-4
Flame Spread Estimates for PVC Cable

<table>
<thead>
<tr>
<th>Material</th>
<th>Bench Scale HRR [kW/m²]</th>
<th>Flame Spread Rate [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE/PVC</td>
<td>395</td>
<td>156</td>
</tr>
<tr>
<td>PE/PVC</td>
<td>359</td>
<td>137</td>
</tr>
<tr>
<td>PE/PVC</td>
<td>312</td>
<td>112</td>
</tr>
<tr>
<td>PE/PVC</td>
<td>589</td>
<td>258</td>
</tr>
</tbody>
</table>

Figure H-1. Heat release rate for a cable fire in the annulus.
What is burning?

Cables made of polyethylene ($\text{C}_2\text{H}_4$) and polyvinylchloride ($\text{C}_2\text{H}_3\text{Cl}$).

Assume effective fuel: $\text{C}_2\text{H}_{3.5}\text{Cl}_{0.5}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat of Combustion</td>
<td>20,900 kJ/kg</td>
<td><em>SFPE Handbook, 4th ed.</em>, Table 3-4.16</td>
</tr>
<tr>
<td>CO$_2$ Yield</td>
<td>1.29 kg/kg</td>
<td><em>SFPE Handbook, 4th ed.</em>, Table 3-4.16</td>
</tr>
<tr>
<td>Soot Yield</td>
<td>0.136 kg/kg</td>
<td><em>SFPE Handbook, 4th ed.</em>, Table 3-4.16</td>
</tr>
<tr>
<td>CO Yield</td>
<td>0.147 kg/kg</td>
<td><em>SFPE Handbook, 4th ed.</em>, Table 3-4.16</td>
</tr>
<tr>
<td>Radiative Fraction</td>
<td>0.49</td>
<td><em>SFPE Handbook, 4th ed.</em>, Table 3-4.16</td>
</tr>
</tbody>
</table>
Material Properties

Cables: The cable trays are filled with PE-insulated, PVC-jacketed control cables. These cables have a diameter of approximately 1.5 cm (0.6 in), a jacket thickness of approximately 1.5 mm (0.06 in), and 7 conductors. There are approximately 120 cables in each tray. The mass of each cable is 0.4 kg/m. The mass fraction of copper is 0.67. These cables fail when the internal temperature just underneath the jacket reaches approximately 205 °C (400 °F) or the exposure heat flux exceeds 6 kW/m² (NUREG-1805, Appendix A).

\[
m_c'' = \frac{n Y_p (1 - \nu)m'}{W} = \frac{120 \times 0.33 \times (1 - 0) \times 0.4 \text{kg/m}}{0.6 \text{m}} \approx 26.4 \text{kg/m}^2 \quad (H-1)
\]

\[
\Delta t = \frac{m_c'' \Delta H}{5 \dot{q}_{avg}/6} = \frac{26.4 \text{kg/m}^2 \times 20,900 \text{kJ/kg}}{5/6 \times 250 \text{kW/m}^2} \approx 2648 \text{s} \quad (H-2)
\]
Figure 9-1. Idealized time history of the local heat release rate per unit area.
Step 3. Select Fire Models

- **Algebraic Models**: Point source heat flux
- **Zone Models**: Typically not used outside of a compartment.
- **CFD**: FDS assumes rectangular geometry, but it can approximate the curved wall using a series of “stair steps”
Applicability of Validation

- Diameter of the fire is not well-defined
- Compartment parameters not appropriate
CHRISTIFIRE 2, Vertical Tests

Two trays of PVC Instrument Cable separated by 6 inches

October 2011, NIST Large Fire Lab
Step 4. Calculate Fire-Generated Conditions

Two forms of the point source radiation model

\[ q'_{ps} = \frac{X_r \dot{Q}}{4\pi r^2} = \frac{0.49 \times 945 \text{ kW}}{4\pi \times 2.0^2 \text{ m}^2} \approx 9.2 \text{ kW/m}^2 \]  \hspace{1cm} (H-3)

\[ q''_{dps} = \frac{X_r}{4\pi} \sum \frac{\dot{Q}_i}{r_i^2} = \frac{0.49}{4\pi} \left( \frac{255}{2.9^2} + \frac{172.5}{2.4^2} + \frac{172.5}{2.0^2} + \frac{172.5}{2.2^2} + \frac{172.5}{2.9^2} \right) \frac{\text{kW}}{\text{m}^2} \approx 6.2 \text{ kW/m}^2 \]  \hspace{1cm} (H-4)
FDS simulation.
Step 5. Sensitivity and Uncertainty Analysis

### Table H-2. Summary of model predictions for the annulus fire scenario.

<table>
<thead>
<tr>
<th>Model</th>
<th>Bias Factor, $\delta$</th>
<th>Standard Deviation, $\sigma_M$</th>
<th>Target</th>
<th>Predicted Value</th>
<th>Critical Value</th>
<th>Probability of Exceeding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat Flux (kW/m²)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point Source</td>
<td>1.42</td>
<td>0.55</td>
<td>Cables</td>
<td>9.2</td>
<td>6.0</td>
<td>0.553</td>
</tr>
<tr>
<td>Distributed Point Source</td>
<td>1.42</td>
<td>0.55</td>
<td>Cables</td>
<td>6.2</td>
<td>6.0</td>
<td>0.248</td>
</tr>
<tr>
<td>FDS</td>
<td>1.10</td>
<td>0.17</td>
<td>Cables</td>
<td>2.5</td>
<td>6.0</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Target Temperature (°C)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDS</td>
<td>1.02</td>
<td>0.13</td>
<td>Cables</td>
<td>120.0</td>
<td>205.0</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Plume Temperature (°C)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FDS</td>
<td>1.15</td>
<td>0.11</td>
<td>Sprinkler</td>
<td>90.0</td>
<td>100.0</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Sensitivity Analysis – how do changes in the input parameters affect the outcome?

\[
\text{Output Quantity} = \text{Constant} \times (\text{Input Parameter})^\text{Power}
\]

\[
(\text{Relative Change in Output}) = \text{Power} \times (\text{Relative Change in Input})
\]

Relative Change in Plume Temperature = \( \frac{2}{3} \times \text{Relative Change in HRR} \)

![Sprinkler Link Temperature Graph](image)

Figure H-6. Predicted sprinkler link temperature for the annulus fire scenario.

\[
\Delta \dot{Q} = \frac{3}{2} \dot{Q} \frac{\Delta T}{T - T_0} = \frac{3}{2} \times 945 \text{ kW} \times \frac{10 \text{ °C}}{90 \text{ °C} - 35 \text{ °C}} \approx 258 \text{ kW}
\]

Table 4-3. Sensitivity of model outputs from Volume 2 of NUREG-1824 (EPRI 1011999).

<table>
<thead>
<tr>
<th>Output Quantity</th>
<th>Important Input Parameters</th>
<th>Power Dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRR</td>
<td>Surface Area</td>
<td>2/3</td>
</tr>
<tr>
<td></td>
<td>Well Conductivity</td>
<td>-1/3</td>
</tr>
<tr>
<td></td>
<td>Ventilation Rate</td>
<td>-1/3</td>
</tr>
<tr>
<td></td>
<td>Door Height</td>
<td>-1/6</td>
</tr>
<tr>
<td>HGL Temperature</td>
<td>HRR</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td>Production Rate</td>
<td>1</td>
</tr>
<tr>
<td>HGL Depth</td>
<td>Door Height</td>
<td>1</td>
</tr>
<tr>
<td>Gas Concentration</td>
<td>HRR</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Soot Yield</td>
<td>1</td>
</tr>
<tr>
<td>Smoke Concentration</td>
<td>HRR</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Soot Yield</td>
<td>1</td>
</tr>
<tr>
<td>Pressure</td>
<td>HRR</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Leakage Rate</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Ventilation Rate</td>
<td>2</td>
</tr>
<tr>
<td>Heat Flux</td>
<td>HRR</td>
<td>4/3</td>
</tr>
<tr>
<td>Surface/Target</td>
<td>HRR</td>
<td>2/3</td>
</tr>
<tr>
<td>Temperature</td>
<td>HRR</td>
<td>2/3</td>
</tr>
</tbody>
</table>
Step 6. Document the Analysis

• Follow the steps; clearly explain the entire process
• Answer the original question
• Report model predictions with uncertainty and sensitivity included
• Include all references
H.6 Conclusion

Simple point source heat flux calculations indicate that a fire in one of the cable trays within the annulus region of the containment building might damage the cables in an adjacent tray. However, an additional analysis using FDS indicates that cable damage is unlikely due to the orientation of the target cables and the blockage of thermal radiation by the cable tray itself. This suggests that the details of the cable tray location, orientation, and configuration can significantly impact potential for damage.

FDS predicts that sprinkler activation above the fire is unlikely. However, its prediction is sensitive to the exact location of the sprinkler relative to a fire plume that may be subject to unpredictable air movements throughout the entire facility. Alternative protection strategies, such as shielding between trays or other thermal barriers, should be considered to ensure the protection of the redundant cables.
EPRI/NRC-RES FIRE PRA METHODOLOGY

Module 5 – Advanced Fire Modeling
Part 1 – Principles of fire modeling

Joint RES/EPRI Fire PRA Workshop
August and November 2011
San Diego, CA and Jacksonville, FL

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

• Course Objectives
  – Provide guidance on applying fire models to NPP fire protection issues
  – Provide guidance on estimating the quantitative confidence in the predictive capability of fire models

• Approach
  – Evaluate fire scenarios relevant to NPPs
  – Use fire models evaluated in V&V study
  – Demonstrate of capability and limitations each model type
  – Quantify uncertainty as part of the fire modeling analysis
  – Identify relevant sensitivity analyses to support use of results
Background

- NFPA issued the first edition of NFPA 805 in 2001
- NRC amended 10 CFR 50.48(c) in 2004 to employ NFPA 805 as alternative to existing deterministic requirements
- NFPA 805 requires that
  - Fire models shall be verified and validated (section 2.4.1.2.3)
  - Only fire models that are acceptable to the authority having jurisdiction (AHJ) shall be used in fire modeling calculations (section 2.4.1.2.1)
- NRC/RES and EPRI completed V&V project for five fire modeling tools in 2007
- Results documented in NUREG-1824, EPRI 1011999
The objective is to describe the process of conducting fire modeling analyses for commercial nuclear power plant applications.

The process addresses the following technical elements:
- Selection and definition of fire scenarios
- Determination and implementation of input values
- Sensitivity analysis
- Uncertainty quantification
- Documentation

The document provides generic guidance, recommended best practices, and example applications.
• Users with following expertise will benefit the most:
  – General knowledge of the behavior of compartment fires
  – General knowledge of basic engineering principles, specifically thermodynamics, heat transfer, and fluid mechanics
  – Ability to understanding the basis of mathematical models involving algebraic and differential equations
• Further training resources in Section 1.3.2
  – Academic courses
  – Short courses
  – Written materials
Figure 1-1. Characteristics of compartment fires.
Fire Modeling Theory

- Parameters of interest in fire modeling analyses:
  - Rate of smoke production
  - Rate of smoke filling
    - HGL interface position
  - Properties of the fire plume and ceiling jet
    - Temperatures / velocities
  - Properties of the HGL
    - Temperature / smoke concentration / visibility
  - Target response to incident heat flux
    - Nuclear safety targets (cables, equipment, operators …)
    - Fire protection targets (sprinklers, detectors …)
Fire Models In NUREG 1934 / EPRI 1023259

- **Algebraic models (1.4.1)**
  - FDTs
  - FIVE-rev1

- **Zone models (1.4.2)**
  - CFAST
  - MAGIC

- **CFD models (1.4.3)**
  - FDS
Fire Model V&V

• Fire models shall only be applied within the limitations of the given model and shall be verified and validated.

• Validation
  – Is the physics right?
  – Are the right equations being solved?

• Verification
  – Is the math right?
  – Are the selected equations being solved correctly?

• NUREG-1824, EPRI 1011999 - Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications
NFPA 805 Fire Modeling Applications

- NFPA 805 requirements associated with fire modeling are organized in two sections
  - NFPA 805 Section 4.2.4.1 describes requirements for the implementation of a performance-based fire modeling analysis.
  - NFPA 805 Section 2.4.1.4 describes the requirements associated with the analytical fire modeling tools selected for the analysis.
NFPA 805 Fire Modeling Applications

- NFPA 805 Section 4.2.4.1 describes the process to follow when using fire modeling to address variances from deterministic requirements (VFDRs):
  - Identify Targets (NFPA 805 § 4.2.4.1.1)
  - Establish Damage Thresholds (NFPA 805 § 4.2.4.1.2)
  - Determine Limiting Conditions (NFPA 805 § 4.2.4.1.3)
  - Establish Fire Scenarios (NFPA 805 § 4.2.4.1.4)
  - Protection of Required Nuclear Safety Success Paths (NFPA 805 § 4.2.4.1.5)
  - Operations Guidance (NFPA 805 § 4.2.4.1.6)
NFPA 805 Fire Modeling Applications

• NFPA 805 Section 2.4.1.2 describes the requirements for the use of fire models, which include:
  – The use of fire models acceptable to the AHJ
  – The application of fire models within their range and limitations
  – Section 2 of NUREG 1934, EPRI 1023259 provides guidance on
    • Ensuring the model is within the range of limitations
    • Ensuring specific fire model applications are within the scope of existing V&V studies
    • What steps should be taken if they are not
Fire Modeling in Support of Fire PRA

- Fire PRA applies fire modeling in the fire scenario development and analysis process
  - A fire scenario in a Fire PRA is often modeled as a progression of damage states over time
  - It is initiated by a postulated fire involving an ignition source
  - Each damage state is characterized by a time and a set of targets damaged within that time
  - Fire modeling is used to determine the targets affected in each damage state and the associated time at which this occurs
Fire Modeling in Support of Fire PRA

<table>
<thead>
<tr>
<th>Ignition</th>
<th>Damage State 1 (Ignition Source Only)</th>
<th>Damage State 2</th>
<th>Damage State 3</th>
<th>Damage State 4 (Hot Gas Layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No additional damage outside the ignition source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>t = t₁</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t = t₂</td>
<td>No damage outside target set 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t = t₃</td>
<td>No damage outside target set 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t = t₄</td>
<td>No damage outside target set 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1-4: Event tree depicting scenario progression modeled in a Fire PRA
Fire Modeling Process

- **Step 1**
  - Define modeling goals
- **Step 2**
  - Characterize fire scenarios
- **Step 3**
  - Select fire models
- **Step 4**
  - Calculate fire conditions
- **Step 5**
  - Sensitivity / uncertainty analyses
- **Step 6**
  - Document the analysis
Step 1 - Define Modeling Goals

- Establishment of general goals and performance objectives specific to the fire modeling application

- Example of a general goal
  - Demonstrate that targets required for safe shutdown remain free from fire damage (deterministic goal) … to a specified level of probability (probabilistic goal)

- Example of a specific performance objective
  - Evaluate if a fire in Fire Area “X” involving Panel “Y” could cause the surface temperature of Cable “Z” to exceed 330 °C (625 °F)
Step 1 - Define Modeling Goals

- Maximum acceptable surface temperature for a cable, component, secondary combustible, structural element, or fire-rated construction
- Maximum acceptable incident heat flux for a cable, component, structural element, or secondary combustible
- Maximum acceptable exposure temperature for a cable, component, structural element, or secondary combustible
- Maximum acceptable enclosure temperature
- Maximum smoke concentration or minimum visibility
- Maximum or minimum concentration of one or more gas constituents, such as carbon monoxide, oxygen, hydrogen cyanide
Step 2 - Characterize Fire Scenarios

• A fire scenario is defined as a set of elements needed to describe a fire incident
• These elements are typically specified in fire models
• These elements include the following:
  – Enclosure details
  – Fire location within the enclosure
  – Fire protection features that will be credited
  – Ventilation conditions
  – Target location(s)
  – Secondary combustibles
  – Source fire
Step 2 - Characterize Fire Scenarios

- Enclosure details
- Enclosure details include
  - The identity of the enclosures included in the fire model analysis
  - The physical dimensions of these enclosures
  - The boundary materials of each enclosure
Step 2 - Characterize Fire Scenarios

• Fire location
  • The location depends on the fire modeling goal, the target location, and the fire modeling tool selected
• Examples:
  – Targets in the fire plume or ceiling jet
  – Targets affected by flame radiation
  – Targets engulfed in flames
  – Targets immersed in the Hot Gas Layer
Step 2 - Characterize Fire Scenarios

• Credited fire protection
• Fire protection features to be credited in a fire modeling analysis usually require a fire protection engineering evaluation of the system’s effectiveness
  – Assessment of the system compliance with applicable codes, including maintenance and inspection
  – Assessment of the system performance against particular fire scenarios being considered.
• Fire modeling tools within this course may not be able to model the impact of some of the fire protection features credited in a given scenario.
Step 2 - Characterize Fire Scenarios

• Ventilation conditions

• Ventilation conditions include:
  – Mechanical ventilation
    • Normal HVAC / purge mode
  – Natural ventilation
    • Door / window / damper / vent positions

• Target location(s)

• The physical dimensions of the target relative to the source fire or the fire model coordinate system.
Step 2 - Characterize Fire Scenarios

- Secondary combustibles
  - Any combustible materials that, if ignited, could affect the exposure conditions to the target set considered.
    - Intervening combustibles, which are those combustibles located between the source fire and the target, are examples of secondary combustibles
  - Secondary combustibles include both fixed and transient materials
  - Secondary combustibles take on the characteristics of a target prior to their ignition
Step 2 - Characterize Fire Scenarios

• Source fire

• The source fire is the forcing function for the fire scenario

• Common fuel packages include electrical panels and transformers, cables, transient combustible material, lubricant reservoirs, and motors

• The source fire is typically characterized by a heat release rate history

• Other important aspects include the physical dimensions of the burning object, its composition, and its behavior when burning
Step 3 - Select Fire Models

• Fire models can be classified into three groups:
  – Algebraic models
  – Zone models
  – CFD models

• The level of effort required to describe a scenario and the computational time consumed by each group increase in the order in which they are listed.
  – Combination of all three types of models may be useful for analyzing a specific problem.
Step 3 - Select Fire Models

### Table 2-1. Summary of Common Fire Model Tools

<table>
<thead>
<tr>
<th>Fire Model Class</th>
<th>Examples</th>
<th>Typical Applications</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algebraic models</td>
<td>FDT&lt;sup&gt;5&lt;/sup&gt;</td>
<td>Screening calculations; zone of influence; target damage by thermal radiation, Hot Gas Layer, or thermal plume acting in isolation.</td>
<td>Simple to use; minimal inputs; quick results; ability to do multiple parameter sensitivity studies.</td>
<td>Limited application range; treats phenomena in isolation; typically applicable only to steady state or simply defined transient fires (e.g., proportional to the square of time or t^2 fires).</td>
</tr>
</tbody>
</table>
Step 3 - Select Fire Models

Table 2-1. Summary of Common Fire Model Tools

<table>
<thead>
<tr>
<th>Fire Model Class</th>
<th>Examples</th>
<th>Typical Applications</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone Model</td>
<td>CFAST MAGIC</td>
<td>Detailed fire modeling in simple geometries; often used to compute hot gas temperatures and target heat fluxes.</td>
<td>Simple to use; couples Hot Gas Layer and localized effects; quick results; ability to do multiple parameter sensitivity studies.</td>
<td>Error increases with increasing deviation from a rectangular enclosure; large horizontal flow paths not well treated.</td>
</tr>
</tbody>
</table>
### Table 2-1. Summary of Common Fire Model Tools

<table>
<thead>
<tr>
<th>Fire Model Class</th>
<th>Examples</th>
<th>Typical Applications</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computation Fluid Dynamics</td>
<td>FDS</td>
<td>Detailed fire modeling in complex geometries, including computing time to target damage and habitability (MCR abandonment or manual action feasibility).</td>
<td>Ability to simulate fire conditions in complex geometries and with complex vent conditions.</td>
<td>Significant effort to create input files and post-process the results; long simulation times; difficult to model curved geometry, smoke detector performance, and conditions after sprinkler actuation.</td>
</tr>
</tbody>
</table>
Step 3 - Select Fire Models

- Fire Dynamics Tools (FDTs)
- FDTs is a set of algebraic models preprogrammed into spreadsheets
- The FDTs library is documented in NUREG-1805 and Supplement 1 (2011)
- The NRC maintains a website where both new and updated spreadsheets are posted:
- See NUREG-1934, EPRI 1011999 Table 2-2 for complete list of FDTs routines
Step 3 - Select Fire Models

• Fire-Induced Vulnerability Evaluation (FIVE)-Rev1
  • Five-Rev 1 is a set of algebraic models preprogrammed into spreadsheets
  • The FIVE-Rev 1 library is documented in EPRI 1002981
  • See NUREG-1934, EPRI 1011999 Table 2-3 for complete list of FIVE-Rev 1 routines
Step 3 - Select Fire Models

- Consolidated Fire Growth and Smoke Transport (CFAST)
- CFAST is a multi-room two-zone computer fire model
- The model subdivides a compartment into two control volumes
  - A relatively hot upper layer (i.e., the HGL)
  - A relatively cool lower layer
  - Conditions within each control volume are considered as uniform at any time, with no spatial variations within a control volume
- For some application the two-zone assumption may not be appropriate
  - Long hallways
  - Tall shafts
Step 3 - Select Fire Models

• MAGIC
• MAGIC is a two-zone computer fire model, developed and maintained by EdF specifically for use in NPP analysis
• MAGIC is fundamentally similar to CFAST and solves the same basic set of predictive differential equations
Step 3 - Select Fire Models

- Fire Dynamics Simulator (FDS)
- FDS is a CFD model of fire-driven fluid flow
- The model numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow, with an emphasis on smoke and heat transport from fires
- FDS computes the temperature, density, pressure, velocity, and chemical composition within each grid cell at each time step
  - There are typically hundreds of thousands to several million grid cells, and thousands to hundreds of thousands of time steps in a FDS simulation
### Step 3 - Select Fire Models

#### Table 2.5. Selected Normalized Parameters for Application of the Validation Results to NPP Fire Scenarios (NUREG-1824/EPRI 1011999, 2007)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Normalized Parameter</th>
<th>General Guidance</th>
<th>Validation Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Froude Number</td>
<td>$Q^* = \frac{Q}{\rho_{\infty}c_{p}T_{\infty}D^2 \sqrt{gD}}$</td>
<td>Ratio of characteristic velocities. A typical accidental fire has a Froude number of order 1. Momentum-driven fire plumes, like jet flares, have relatively high values. Buoyancy-driven fire plumes have relatively low values.</td>
<td>0.4 – 2.4</td>
</tr>
<tr>
<td>Flame Length, $L_f$, relative to Ceiling Height, $H$</td>
<td>$\frac{L_f}{H}$</td>
<td>A convenient parameter for expressing the “size” of the fire relative to the height of the compartment. A value of 1 means that the flames reach the ceiling.</td>
<td>0.2 – 1.0</td>
</tr>
<tr>
<td>Ceiling Jet Radial Distance, $r_{cij}$, relative to the Ceiling Height, $H$</td>
<td>$\frac{r_{cij}}{H}$</td>
<td>Ceiling jet temperature and velocity correlations use this ratio to express the horizontal distance from target to plume.</td>
<td>1.2 – 1.7</td>
</tr>
</tbody>
</table>
Step 3 - Select Fire Models

### Table 2-5. Selected Normalized Parameters for Application of the Validation Results to NPP Fire Scenarios (NUREG-1824/EPRI 1011999, 2007)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Normalized Parameter</th>
<th>General Guidance</th>
<th>Validation Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalence Ratio, $\varphi$, as an indicator of the Ventilation Rate</td>
<td>$\varphi = \frac{m_F}{m_{O_2}}$</td>
<td>The equivalence ratio relates the mass loss rate of fuel, $m_F$, to the mass flow rate of oxygen into the compartment, $m_{O_2}$. The fire is considered over or underventilated based on whether $\varphi$ is less than or greater than 1, respectively. The parameter, $r$, is the stoichiometric ratio.</td>
<td>0.04 – 0.6</td>
</tr>
<tr>
<td></td>
<td>$m_F = \dot{Q}/\Delta H$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$m_{O_2} = \begin{cases} 0.23 \times \frac{1}{2} \sqrt{A_0 H_0} &amp; \text{(Natural)} \ 0.23 \rho_\infty \nu &amp; \text{(Mechanical)} \end{cases}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compartment Aspect Ratio</td>
<td>L/H or W/H, where L is the Length, W is the Width, and H is the Height of the compartment.</td>
<td>This parameter indicates the general shape of the compartment.</td>
<td>0.6 – 5.7</td>
</tr>
<tr>
<td>Radial Distance, $r$, relative to the Fire Diameter, $D$</td>
<td>$\frac{r}{D}$</td>
<td>This ratio is the relative distance from a target to the fire. It is important when calculating the radiative heat flux.</td>
<td>2.2 – 5.7</td>
</tr>
</tbody>
</table>
Step 3 - Select Fire Models

- Fire parameters may fall outside their validation range defined in NUREG-1824, EPRI 1011999
- The predictive capabilities of the fire models in many scenarios can extend beyond the range
- Analyst is required to address these situations
- Sensitivity analyses can be used to address these scenarios
Step 3 - Select Fire Models

- Sensitivity analysis examples
  - Fire Froude number
  - Flame length relative to ceiling height
  - Ceiling jet radial distance relative to ceiling height
  - Equivalence ratio
  - Compartment aspect ratio
  - Radial distance relative to fire diameter
Step 4 - Calculate Fire Conditions

- This step involves running the model(s) and interpreting the results.
- The process includes
  - Determine the output parameters of interest
  - Prepare the input file
  - Run the computer model
  - Interpret the model results
  - Arrange output data in a form that is suitable for the goal
Step 5 - Sensitivity And Uncertainty Analyses

• A comprehensive treatment of uncertainty and sensitivity analyses are an integral part of a fire modeling analysis

• Model uncertainty
  – Models are developed based on idealizations of the physical phenomena and simplifying assumptions

• Parameter uncertainty
  – Many input parameters are based on available generic data or on fire protection engineering judgment
Step 6 - Document The Analysis

- Information needed to document fire scenario selection will be gathered from a combination of observations made during engineering walkdowns and a review of existing plant documents and/or drawings
  - Marked up plant drawings.
  - Design basis documents (DBDs).
  - Sketches.
  - Write-ups and input tables.
  - Software versions, descriptions, and input files.
- A reviewer should be able to reproduce the results of a fire scenario analysis from the information contained within the documentation.
Fire Modeling Elements – Heat Release Rate

• Three questions usually have to be answered to adequately assess the heat release rate of a fire:
  – How fast does the fire grow?
  – What is the peak intensity of the fire?
  – How long does the fire burn?

• Other factors:
  – Fire elevation
  – Fire location relative to targets or obstructions
  – Soot yield
  – Radiative fraction
  – Yield factors
Fire Modeling Elements – Area Configuration

- Compartment geometry
- Compartment Boundary materials

Table 3-1. Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m/K)</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (kJ/kg/K)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>0.8</td>
<td>2600</td>
<td>0.8</td>
<td>NUREG-1805, Table 2-3</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.6</td>
<td>2400</td>
<td>0.75</td>
<td>NUREG-1805, Table 2-3</td>
</tr>
<tr>
<td>Copper</td>
<td>386</td>
<td>8954</td>
<td>0.38</td>
<td>SFPE Handbook, Table B.6</td>
</tr>
<tr>
<td>Gypsum</td>
<td>0.17</td>
<td>960</td>
<td>1.1</td>
<td>NUREG-1805, Table 2-3</td>
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<tr>
<td>Plywood</td>
<td>0.12</td>
<td>540</td>
<td>2.5</td>
<td>NUREG-1805, Table 2-3</td>
</tr>
<tr>
<td>PVC</td>
<td>0.192</td>
<td>1380</td>
<td>1.289</td>
<td>NUREG/CR-6850, Appendix R</td>
</tr>
<tr>
<td>Steel</td>
<td>54</td>
<td>7850</td>
<td>0.465</td>
<td>NUREG-1805, Table 2-3</td>
</tr>
<tr>
<td>XLP</td>
<td>0.235</td>
<td>1375</td>
<td>1.390</td>
<td>NUREG/CR-6850, Appendix R</td>
</tr>
</tbody>
</table>
Fire Modeling Elements – Ventilation Effects

- Ventilation openings
  - Vertical (doors / windows)
  - Horizontal (ceiling / floor vents)
- Leakage paths
- Mechanical ventilation
  - Injection
  - Extraction
  - Recirculation
Fire Modeling Elements – Targets

• Targets are objects of interest than can be affected by the fire-generated conditions

• Targets typically consist of
  – Cables in conduits
  – Cables in raceways
  – Plant equipment or
  – Plant personnel

• Targets are characterized by
  – Location,
  – Damage criteria and
  – Thermophysical properties
• Intervening combustibles should be described in terms of their locations as well as in terms of their relevant thermophysical and flammability properties.

• Representing intervening combustibles in fire models presents technical challenges that the analyst should consider:
  – Obtaining the necessary geometric and thermophysical properties representing the intervening combustible and
  – The ability of the computer tools to model the fire phenomena (e.g., fire propagation).
Representative Fire Scenarios

Figure 3-1. Pictorial representation of the fire scenario and corresponding technical elements described in this section.
Scenario 1 - Targets in the Flames or Plume

- This scenario consists of a target (electrical cable in a raceway) immediately above an ignition source (electrical cabinet)
- Objective: Calculate the time to damage for a target immediately above a fire
- Examples B and E
Scenario 2 - Targets Inside or Outside the Hot Gas Layer

- This scenario consists of a target, ignition source, and perhaps a secondary fuel source
- Objective: Calculate the time to damage for the target if it is inside or outside the Hot Gas Layer
- Examples C and E

Figure 3-4 Pictorial representation of scenario 2
Scenario 3 - Targets Located in Adjacent Rooms

- This scenario consists of a target in a room adjacent to the room of fire origin.
- Objective: Calculate the time to damage for a target in a room next to the room of fire origin.
- Example G

Figure 3-5. Pictorial representation of scenario 3
Scenario 4 - Targets in Rooms with Complex Geometries

- This scenario involves a room with an irregular ceiling height
- Objective: Calculate the time to damage for a target in a room with a complex geometry
- Examples D and H
Scenario 5 - Main Control Room Abandonment

• This scenario consists of a fire (electrical cabinet fire within the main control board) that may force operators out of the control room.

• Objective: Determine when control room operators will need to abandon the control room due to fire-generated conditions.

• Example A

Figure 3-7. Pictorial representation of scenario 5.
Scenario 6 - Smoke Detection and Sprinkler Activation

• This scenario addresses smoke/heat detector or sprinkler activation

• Objective: Calculate the response time of a smoke or heat detector that may be obstructed by ceiling beams, ventilation ducts, etc.

• Examples B and E
Scenario 7 - Fire Impacting Structural Elements

• This scenario consists of fire impacting exposed structural elements
• Objective: Characterize the temperature of structural elements exposed to a nearby fire source
• Example F

Figure 3-9. Pictorial representation of scenario 7
Summary

• The purpose of this module has been to introduce the following concepts relevant to NPP applications:
  – The fire modeling process
  – The fire modeling tools
  – Representative fire modeling scenarios
  – Uncertainty / sensitivity analyses

• Over the next 2 days we will consider these representative fire modeling scenarios in more detail

• On Friday, you will perform your own analyses
EPRI/NRC-RES Fire PRA Methodology

Module V: Advanced Fire Modeling
Model Uncertainty

Joint RES/EPRI Fire PRA Workshop
Fall 2011
San Diego and Jacksonville

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

- **Parameter Uncertainty** – refers to the contribution of the uncertainty in the input parameters to the total uncertainty of the simulation.

- **Model Uncertainty** – refers to the effect of the model assumptions, simplified physics, numerics, etc.

- **Completeness Uncertainty** – refers to physics that are left out of the model. For most, this is a form of Model Uncertainty.
Fire Model Validation Study, NUREG-1824

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

Model Uncertainty
Table 4-1. Results of the V&V study, NUREG-1824 (EPRI 1011999).

<table>
<thead>
<tr>
<th>Output Quantity</th>
<th>FDTs</th>
<th>FIVE</th>
<th>CFAST</th>
<th>MAGIC</th>
<th>FDS</th>
<th>Exp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta$</td>
<td>$\sigma_M$</td>
<td>$\delta$</td>
<td>$\sigma_M$</td>
<td>$\delta$</td>
<td>$\sigma_M$</td>
</tr>
<tr>
<td>HGL Temperature Rise*</td>
<td>1.44</td>
<td>0.25</td>
<td>1.56</td>
<td>0.32</td>
<td>1.06</td>
<td>0.12</td>
</tr>
<tr>
<td>HGL Depth*</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td>1.04</td>
<td>0.14</td>
<td>1.12</td>
</tr>
<tr>
<td>Ceiling Jet Temp. Rise</td>
<td>N/A</td>
<td></td>
<td>1.84</td>
<td>0.29</td>
<td>1.15</td>
<td>0.24</td>
</tr>
<tr>
<td>Plume Temperature Rise</td>
<td>0.73</td>
<td>0.24</td>
<td>0.94</td>
<td>0.49</td>
<td>1.25</td>
<td>0.28</td>
</tr>
<tr>
<td>Oxygen Concentration</td>
<td>N/A</td>
<td>N/A</td>
<td>0.91</td>
<td>0.15</td>
<td>0.90</td>
<td>0.18</td>
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<tr>
<td>Smoke Concentration</td>
<td>N/A</td>
<td>N/A</td>
<td>2.65</td>
<td>0.63</td>
<td>2.06</td>
<td>0.53</td>
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<tr>
<td>Room Pressure Rise</td>
<td>N/A</td>
<td>N/A</td>
<td>1.13</td>
<td>0.37</td>
<td>0.94</td>
<td>0.39</td>
</tr>
<tr>
<td>Target Temperature Rise</td>
<td>N/A</td>
<td>N/A</td>
<td>1.00</td>
<td>0.27</td>
<td>1.19</td>
<td>0.27</td>
</tr>
<tr>
<td>Radiant Heat Flux</td>
<td>2.02</td>
<td>0.59</td>
<td>1.42</td>
<td>0.55</td>
<td>1.32</td>
<td>0.54</td>
</tr>
<tr>
<td>Total Heat Flux</td>
<td>N/A</td>
<td>N/A</td>
<td>0.81</td>
<td>0.47</td>
<td>1.18</td>
<td>0.35</td>
</tr>
<tr>
<td>Wall Temperature Rise</td>
<td>N/A</td>
<td>N/A</td>
<td>1.25</td>
<td>0.48</td>
<td>1.38</td>
<td>0.45</td>
</tr>
<tr>
<td>Wall Heat Flux</td>
<td>N/A</td>
<td>N/A</td>
<td>1.05</td>
<td>0.43</td>
<td>1.09</td>
<td>0.34</td>
</tr>
</tbody>
</table>

I.D. indicates insufficient data for the statistical analysis.
N/A indicates that the model does not have an algorithm to compute the given Output Quantity.
Underlined values indicate that the data failed a normality test because of the relatively small sample size.
* The algorithm used to compute the layer temperature and depth for the model FDS is described in NUREG-1824.
** All of the models except FDS use the Heskestad Flame Height Correlation (Heskestad, SFPE Handbook). These models were shown to be in qualitative agreement with the experimental observations, but there was not enough data to further quantify this assessment.
1. Express the predicted value in terms of a rise above ambient. For example, subtract the ambient temperature from the predicted temperature. Call this value $M$.

2. Find the values of model bias and relative standard deviation from table on previous slide. Compute the mean and standard deviation of normal distribution:

$$
\mu = \frac{M}{\delta} \quad \sigma = \frac{\delta}{\sqrt{2}}
$$

3. Compute the probability of exceeding the critical value:

$$
P(x > x_c) = \frac{1}{2} \text{erfc}\left(\frac{x_c - \mu}{\sigma \sqrt{2}}\right)
$$
4.3.1 Example 1: Target Temperature

Suppose that cables within a compartment are assumed to fail if their surface temperature reaches 330 °C (625 °F). The model FDS predicts that the maximum cable temperature due to a fire in an electrical cabinet is 300 °C (570 °F). What is the probability that the cables could fail?

Step 1: Subtract the ambient value of the cable temperature, 20 °C (68 °F) to determine the predicted temperature rise. Refer to this value as the model prediction:

\[ M = 300 - 20 = 280^\circ C \]  

(4-6)

Step 2: Refer to Table 4-1, which indicates that, on average, FDS overpredicts Target Temperatures with a bias factor, \( \delta \), of 1.02. Calculate the adjusted model prediction:

\[ \mu = \frac{M}{\delta} = \frac{280}{1.02} = 275^\circ C \]  

(4-7)

Referring again to Table 4-1, calculate the standard deviation of the distribution:

\[ \sigma = \delta M \left( \frac{M}{\delta} \right) = 0.13 \left( \frac{280}{1.02} \right) = 36^\circ C \]  

(4-8)

Step 3: Calculate the probability that the actual cable temperature would exceed 330°C:

\[ P(T > 330) = \frac{1}{2} \text{erfc} \left( \frac{T - T_0 - \mu}{\sigma \sqrt{2}} \right) = \frac{1}{2} \text{erfc} \left( \frac{330 - 20 - 275}{36 \sqrt{2}} \right) = 0.16 \]  

(4-9)

The process is shown graphically in Figure 4-3. The area under the “bell curve” for temperatures higher than 330 °C (625 °F) represents the probability that the actual cable temperature would exceed that value. Note that this estimate is based only on the model uncertainty.
4.3.2 Example 2: Critical Heat Flux

As part of a screening analysis, the model MAGIC is used to predict the radiant heat flux from a fire to a nearby group of thermoplastic cables. According to NUREG/CR-6850 (EPRI 1011989), Appendix H, one of the damage criteria for thermoplastic cables is a radiant heat flux to the target cable that exceeds 6 kW/m². The model, by coincidence, predicts a heat flux of 6 kW/m². What is the probability that the actual heat flux from a fire will be 6 kW/m² or greater? Assume for this exercise that the model input parameters are not subject to uncertainty, only the model itself.

Step 1: Unlike in the previous example, there is no need to subtract an ambient value of the heat flux (it is zero). Thus, the model prediction is:

\[ M = 6 \text{ kW/m}^2 \]  \hspace{1cm} (4-10)

Step 2: Refer to Table 4-1, which indicates that, on average, MAGIC overpredicts Radiant Heat Flux with a bias factor, \( \delta \), of 1.15. Calculate the adjusted model prediction:

\[ \mu = \frac{M}{\delta} = \frac{6}{1.15} \approx 5.2 \text{ kW/m}^2 \]  \hspace{1cm} (4-11)

Referring again to Table 4-1, calculate the standard deviation of the distribution:

\[ \sigma = \bar{\sigma}_M \left( \frac{M}{\delta} \right) = 0.36 \left( \frac{6}{1.15} \right) \approx 1.9 \text{ kW/m}^2 \]  \hspace{1cm} (4-12)

Step 3: Calculate the probability that the actual heat flux, \( \dot{q}'' \), will exceed the critical value of the heat flux, \( \dot{q}_c'' = 6 \text{ kW/m}^2 \):

\[ P(\dot{q}'' > \dot{q}_c) = \frac{1}{2} \text{erfc} \left( \frac{\dot{q}_c'' - \mu}{\sigma \sqrt{2}} \right) = \frac{1}{2} \text{erfc} \left( \frac{6 - 5.2}{1.9 \sqrt{2}} \right) \approx 0.34 \]  \hspace{1cm} (4-13)

This is a somewhat surprising result. Even though the model predicts a peak radiant heat flux equal to the critical value, there is only a one in three chance that the actual heat flux would exceed this value. This is mainly due to the fact that MAGIC has been shown to over-predict the heat flux by about 15%.
Sensitivity Analysis to Address Parameter Uncertainty

Output Quantity $- Constant \times (Input\ Parameter)^{Power}$

Example: MQH correlation states that the HGL temperature rise is proportional to the HRR to the $2/3$ power:

$$T - T_0 = C \dot{Q}^{2/3}$$

$$\frac{\Delta T}{T - T_0} \approx \frac{2 \Delta \dot{Q}}{3 \dot{Q}}$$
Table 4-3. Sensitivity of model outputs from Volume 2 of NUREG-1824 (EPRI 1011999).

<table>
<thead>
<tr>
<th>Output Quantity</th>
<th>Important Input Parameters</th>
<th>Power Dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGL Temperature</td>
<td>HRR, Surface Area, Wall Conductivity, Ventilation Rate, Door Height</td>
<td>2/3, -1/3, -1/3, -1/6</td>
</tr>
<tr>
<td>HGL Depth</td>
<td>Door Height</td>
<td>1</td>
</tr>
<tr>
<td>Gas Concentration</td>
<td>HRR, Production Rate</td>
<td>1/2, 1</td>
</tr>
<tr>
<td>Smoke Concentration</td>
<td>HRR, Soot Yield</td>
<td>1, 1</td>
</tr>
<tr>
<td>Pressure</td>
<td>HRR, Leakage Rate, Ventilation Rate</td>
<td>2, 2</td>
</tr>
<tr>
<td>Heat Flux</td>
<td>HRR</td>
<td>4/3</td>
</tr>
<tr>
<td>Surface/Target Temperature</td>
<td>HRR</td>
<td>2/3</td>
</tr>
</tbody>
</table>
Suppose, for example, that as part of an NFPA 805 analysis the problem is to determine the Limiting Fire Scenario for a particular compartment whose HGL temperature is not to exceed 500 °C (930 °F). Assume that the geometrical complexity of the compartment rules out the use of the empirical and zone models, and that FDS has been selected for the simulation.

Step 1: Determine an appropriate maximum expected fire heat release rate. For this example, suppose that a 98th percentile HRR for the electrical cabinet fire, 702 kW, has been determined to be the MEFS. Choose a model and calculate the peak HGL temperature.

Step 2: Assume that FDS predicts 450 °C (840 °F) for the selected fire scenario. Adjust the prediction to account for the model bias, $\delta$ (See Table 4-1):

$$T_{\text{adj}} = T_0 + \frac{T - T_0}{\delta} = 20 + \frac{450 - 20}{1.03} \approx 437^\circ C$$ (4-17)

Step 3: Calculate the change in HRR required to increase the HGL temperature to 500 °C (930 °F):

$$\Delta \dot{Q} \approx \frac{3}{2} \dot{Q} \frac{\Delta T}{T_{\text{adj}} - T_0} = \frac{3}{2} 702 \frac{500 - 437}{417} = 159 \text{ kW}$$ (4-18)

This calculation suggests that adding an additional 159 kW to the original 702 kW will produce an HGL temperature in the vicinity of 500 °C (930 °F). This result can be double-checked by re-running the model with the modified input parameters.