Fire Modeling Examples From the Nuclear Power Industry

DOE Nuclear Facility Safety Programs Workshop 2014
Las Vegas, Nevada

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Nuclear Power and Fire Protection

- US Nuclear Power Plants were licensed to deterministic fire protection rules (i.e., Appendix R- Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979)
- In July 2004, NRC amended 10 CFR 50.48 to allow licensees to voluntarily adopt NFPA 805 as a risk-informed performance based alternative to the deterministic fire protection requirements.
- Approx. 50% of US NPPs elected to transition to NFPA 805
Why is Fire Modeling Used?

- Fire Modeling can be used to support performance-based fire protection and risk analyses including:
  - NFPA 805 Transition Projects
    - Assess Variances from Deterministic Nuclear Safety Criteria
      - i.e., separation issues, degraded fire protection systems
  - Fire Probabilistic Risk Assessments (FPRA)
    - Estimate Plant CDF/LERF
    - Evaluate Risk Impact of Modifications and Recovery Actions
  - NRC Significance Determination Process (SDP)
Fire Modeling

Benefits of Fire Modeling

- Focused analysis to determine fire compartments/scenarios that have most risk
- Allows for plant specific scenarios to be analyzed
- Reduces unnecessarily high levels of conservatism
- Allows for unique, less expensive solutions when compared to prescriptive requirements (i.e., mods) – without decreasing safety levels
- Provides quantitative results and an adjustable model to aid in decision-making
Why use a risk-based approach?

<table>
<thead>
<tr>
<th>Traditional Engineering Failure Analysis</th>
<th>Risk Approach (Fire Modeling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Deterministic assumption that a consequence will result in the loss of capability of a component to perform its function</td>
<td>• Evaluates the likelihood of consequences of the failure of all components</td>
</tr>
<tr>
<td>• Assumes component is failed/succeeds (1.0)</td>
<td>• Assumes a best estimate failure rate for each component</td>
</tr>
<tr>
<td>• No Common Cause Failures</td>
<td>• Analysis of Common Cause Failures</td>
</tr>
<tr>
<td>• Limited Human Actions</td>
<td>• Significant Human Actions</td>
</tr>
</tbody>
</table>
Available Fire Modeling Tools

- Nuclear Regulatory Commission requires V&V of fire modeling tools
- Available models for use via NUREG-1824:
  - Closed Form Correlations
    - NUREG-1805 FDTs
    - FIVE
  - Zone Models
    - CFAST
    - MAGIC
  - Field Model (CFD)
    - FDS
Zone of Influence (ZOI)
Detailed Fire Modeling Tiered Approach

- 1st Level: Conservative fire modeling
  - Broad brush, “quick and dirty”
  - Closed form correlations
    - Detailed Fire Modeling Workbook
- 2nd Level: Less conservative, more realistic
  - Refine conservatisms, requires additional time
- 3rd Level: Use of zone and field models
  - Most realistic, most time consuming
    - CFAST and FDS
1st Level: Closed Form Correlations

- Examples of closed form correlations
  - Detailed Fire Modeling Workbooks
  - FIVE (Fire Induced Vulnerability Evaluation)
  - NUREG-1805 – Fire Dynamics Tools (FDTs)

- When to use:
  - Generally used as a scoping tool
  - Cost/schedule/budget limitations
  - Resource limitations
  - Conservative inputs required to stay within bounds of V&V
  - Yields conservative bounding results with safety margin
Closed-Form Correlations

NUREG-1805 FDT 9: Plume Temperature Calculations

The following calculations estimate the centerline plume temperature in a compartment fire. Parameters should be specified ONLY IN THE YELLOW INPUT PARAMETER BOXES.

All subsequent output values are calculated by the spreadsheet and based on values specified in the input parameters. This spreadsheet is protected and secure to avoid errors due to a wrong entry in a cell(s).

The chapter in the NUREG should be read before an analysis is made.

INPUT PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Release Rate of the Fire (Q)</td>
<td>18.00 kW</td>
</tr>
<tr>
<td>Elevation Above the Fire Source (z)</td>
<td>1.50 ft</td>
</tr>
<tr>
<td>Area of Combustible Fuel (A_c)</td>
<td>2.78 ft^2</td>
</tr>
<tr>
<td>Ambient Air Temperature (T_a)</td>
<td>72.00 °F</td>
</tr>
</tbody>
</table>

AMBIENT CONDITIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Heat of Air (c_p)</td>
<td>1.00 kJ/kg-K</td>
</tr>
<tr>
<td>Ambient Air Density (ρ_a)</td>
<td>1.29 kg/m^3</td>
</tr>
<tr>
<td>Acceleration of Gravity (g)</td>
<td>9.81 m/sec^2</td>
</tr>
<tr>
<td>Convective Heat Release Fraction (α_C)</td>
<td>0.70</td>
</tr>
</tbody>
</table>

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

ESTIMATING PLUME CENTERLINE TEMPERATURE

2nd Level: Modeling Refinements

- Revisit and refine conservative assumptions and modeling inputs:
  - Reduce the zone of influence and subsequent target impacts
    - Reduce assumed heat release rates based on specific ignition source characteristics
    - Credit administrative controls (i.e. transient combustible controlled areas)
  - Refine target set to focus on risk significant target impacts
  - Incorporate possible modifications to limit or prevent target failures (i.e. passive fire protection features)
  - Delay time to target damage to improve suppression probabilities
# Description of Fire Scenario

The fire starts at REAC-TR-SWGR-1A and spreads to its adjacent vertical section (1B) in 10 minutes.

- The fire propagates to ITK154N (approx. 12 inches vertically) and ITK528N (approx. 28 inches horizontally).
- The fire is located 12 inches vertically and 28 inches horizontally resulting in a 1 minute and 12 minute ignition time respectively (per 8850 table H.7).
- The fire spreads along trays approximately 1 foot and ignites unmarked tray at 15 minutes, assuming 3.54 ft/min spread rate.

Section: The fire will be detected by a smoke detector with alarm at MCR within 1 minute. The fire will be manually detected within 15 minutes.

*There is no automatic suppression system in this fire area. The first fire brigade will respond 0 minutes after detection.*

## Time to Damage Calculation

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Source</th>
<th>HRR per Unit [kW]</th>
<th>Unit</th>
<th>Vertical Separation of Tray [in]</th>
<th>Tray Width [in]</th>
<th>Tray Length [in]</th>
<th>Directions of Spread</th>
<th>Number of Units</th>
<th>Ignition Time [min]</th>
<th>Duration [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabinet</td>
<td>SWGR-1A</td>
<td>211</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>1</td>
<td>0</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>1st Tray</td>
<td>ITK154N</td>
<td>20</td>
<td>n/a</td>
<td>24</td>
<td>24</td>
<td>2</td>
<td>1</td>
<td>15</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>2nd Tray</td>
<td>ITK528N</td>
<td>20</td>
<td>n/a</td>
<td>12</td>
<td>12</td>
<td>2</td>
<td>1</td>
<td>15</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>3rd Tray</td>
<td>Unmarked</td>
<td>20</td>
<td>n/a</td>
<td>12</td>
<td>12</td>
<td>1</td>
<td>1</td>
<td>15</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time (minutes)</th>
<th>FDS1</th>
<th>FDS2/3/4/6/8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>24</td>
<td>211</td>
</tr>
<tr>
<td>1</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>12</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>15</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>20</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| Total HRR:     | 24   | 291          | 340          | 484           | 446          | 400           | 460           | 566           | 608           | 648          | 698           | 748          | 800          |

## Zone of Influence

<table>
<thead>
<tr>
<th>Zone of Influence</th>
<th>Flames (ft)</th>
<th>Plume (ft)</th>
<th>Plume Radius (ft)</th>
<th>Ceiling Jet (ft)</th>
<th>Flame Radiation (ft)</th>
<th>Hot Gas Layer Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flames (ft)</td>
<td>0.03</td>
<td>5.54</td>
<td>6.23</td>
<td>6.59</td>
<td>6.93</td>
<td>7.08</td>
</tr>
<tr>
<td>Plume (ft)</td>
<td>1.23</td>
<td>6.90</td>
<td>7.72</td>
<td>8.14</td>
<td>8.54</td>
<td>7.52</td>
</tr>
<tr>
<td>Plume Radius (ft)</td>
<td>0.50</td>
<td>1.35</td>
<td>1.47</td>
<td>1.54</td>
<td>1.60</td>
<td>1.40</td>
</tr>
<tr>
<td>Ceiling Jet (ft)</td>
<td>0.12</td>
<td>1.42</td>
<td>1.77</td>
<td>1.97</td>
<td>2.10</td>
<td>1.95</td>
</tr>
<tr>
<td>Flame Radiation (ft)</td>
<td>0.96</td>
<td>3.91</td>
<td>3.39</td>
<td>3.56</td>
<td>3.73</td>
<td>3.14</td>
</tr>
<tr>
<td>Hot Gas Layer Temperature (°C)</td>
<td>73</td>
<td>100</td>
<td>115</td>
<td>130</td>
<td>144</td>
<td>154</td>
</tr>
<tr>
<td>Hot Gas Layer Temperature (°C)</td>
<td>20</td>
<td>80</td>
<td>60</td>
<td>40</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>
EPM FMWB Fire Event Tree
Single Compartment Fire Modeling

Identify and Characterize

- Secondary Combustibles
- Targets with Fire Protection Features
- Targets
- Ignition Sources
- Detection & Suppression
- Compartment
Example where simple fire modeling was successful
Example where fire modeling suppression was successful
Suppression Example

_target A_

_target B_

_ignition source_
3rd Level: Zone and Field Models

- Can provide greater detail for model analysis using differential equations instead of algebraic correlations.
  - Increased cost due time and preparation
  - May require dedicated computational resources

- When to use:
  - For refined analysis or complicated configurations/building features
  - When closed form correlations do not provide enough detail or accuracy for model analysis
  - High value or risk significant areas need analysis
  - Detailed input information is available within the bounds of V&V
  - Detailed, realistic inputs will yield more realistic results and can still be within the safety margin
Single Compartment Fire Modeling

- Comprised of fire scenarios damaging target sets located within the *same compartment*,
- Does not include scenarios within or impacting the MCR
- The majority of fire scenarios analyzed generally fall into this category

Smokeview screenshot of FDS simulation
In some cases the HGL/Plume interaction can cause increased plume temperatures.
HGL/Plume Interaction Study

Category I:
- Room dimensions preclude HGL/plume interaction because HGL is unlikely to form
- Room volume > 25,000 cubic ft, ceiling height > 15ft

Category II:
- Room dimensions require HGL/plume interaction analysis
- FDT may underestimate plume temperatures
- Room volume < 25,000 cubic ft, ceiling height > 10ft

Category III:
- HGL/plume interaction bounded by plume calculations in FDT9
- Ceiling height < 10 ft
Damage Time Calculations

Computer Fire Modeling:

- Consolidated Model of Fire Growth and Smoke Transport (CFAST)
  - 2-zone model approximation

- Fire Dynamics Simulator (FDS)
  - 3-D computational fluid dynamics (CFD) model
  - Numerically solves a form of the Navier-Stokes equations associated with low-speed, thermally driven flow
  - Allows for results which show an approximation of the temperature (or other parameter) at any location in the simulation
  - Allows more complex scenarios to be modeled

Smokeview screenshot of CFAST fire model results (Electrical Cabinet Fire)

Smokeview screenshot of FDS fire model results (transient fire spreading to cable trays)
Multi Compartment Analysis

- Model the spread of hot gases and smoke from one compartment to another.
- Analysis predicts the flow of gases through open doors and failed penetrations.
- Results determine if smoke and hot gases can accumulate and cause damage to targets in adjacent compartments.
Temperature Sensitive Equipment Zone of Influence (ZOI) Study

- Subject of NFPA 805 Task Force FAQ 13-0004

- Evaluated the shielding effects of the electrical cabinet housing on the temperature sensitive components inside.
Main Control Room Fire Modeling

- This analysis considers fires that could occur within the MCR. Also considers scenarios from fires in other compartments that may force MCR abandonment.
Main Control Room (MCR) Forced Abandonment Example

- **Problem**: The shared ventilation system between the subject MCR and Cable Spreading Room (CSR) allows air flows to be recycled between the two compartments.
- Openings in the floor of the MCR to the CSR below, protected via fire dampers
- MCR habitability impacted by a fire in the MCR and in the CSR below
MCR and CSR Shared HVAC System

- A smoke-purge mode was not provided for the MCR
  - Normal HVAC system could only be credited until shutdown
  - Duct smoke detection interlock provided in the CSR
  - Upon activation of the smoke detector HVAC stops
Modeling the HVAC System in FDS

- HVAC ducts modeled as hollow obstructions
- Recycled air flows modeled using fans within the ductwork which induced flows between the compartments
- Fresh ambient air was introduced into the HVAC system via volume fluxes flowing in and out of the computational domain
- Interlock smoke detector modeled in the CSR to shutdown flows at set obscuration point
Benefits of Using FDS for the MCR Analysis

- Able to predict the effects of a fire in either compartment on the adjacent volume
- Allowed the actual duct configurations and HVAC flows to be modeled
- Simultaneously able to evaluate the impact of recycled air flows between the compartments as well as the introduction of fresh ambient air into the HVAC system
- Allowed normal HVAC flows until interlock activation and system shutdown
Summary

- Models vary by complexity directly in relation to the level of detail and accuracy they provide.
  - Closed form correlations are limited to the applications they were developed for, but are the most cost effective.
  - CFAST allows for additional accuracy and detail with moderate resources.
  - FDS serves as a versatile, refined tool to accurately model complex fire modeling scenarios.

- Documented success using fire models in the nuclear power industry within the regulatory process to reduce plant risk and cost.
Questions?

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