Probabilistic Risk Assessment of Multi-Unit Nuclear Power Plant Sites: Advances and Implication on the Safety Goals

Seminar Presentation
Ohio State University
Department of Mechanical and Aerospace Engineering
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Topics Covered

• Why Multi-Unit Accidents are Important
• Multi-unit / multi-module Risk Metrics
• Significance of Multi-Units Events Observed
• An Approach to Account for Multi-Unit Risks
• Implications of Multi-Unit Risks on USNRC Safety Goals
• Conclusions
Multi-Unit U.S. NPP Sites

Number of Operating Reactor Units per Nuclear Power Plant Site

<table>
<thead>
<tr>
<th></th>
<th>Single-Unit Site</th>
<th>Multi-Unit Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of U.S. Nuclear Power Plant Sites</td>
<td>26</td>
<td>35</td>
</tr>
</tbody>
</table>

Number of Operating Reactor Units per Nuclear Power Plant Site
Background

- **NRC:**
  - Requires units to be independent
  - Post Chernobyl control room habitability (quantify site risk)
  - Staff recommended SMRs to account for integrated risk (2005)
  - Current level-3 PRA activities involving multi-units and fuel pool

- **Industry**
  - Station blackout (SBO)
  - Site risk (Seabrook)-early 1980’s
  - Seismic-induced dependencies of units and component fragilities

- **International**
  - IAEA Guidebook
  - Workshops (Ottawa-11/2014)

- **University**
  - Suzanne Schroer (UMD study)
  - UMD’s NRC grant on this subject
Classification of Unit-to-Unit Dependencies

- Schroer used a fishbone categorization of multi-unit interdependencies

![Fishbone Diagram]

- Schroer’s LER analysis showed 9% of events reported involve two or more units
- 17% of LERs in multi-units sites involved more than one unit
- Most involving Organizational and Shared Connection types of dependencies

Options for Multi-Unit CDF Measures

• **Single-Unit CDF Representations:**
  - CDF of one unit implicitly assuming the other units will not melt

• **Multi-Unit CDF (Site) Representations:**
  - *Marginal CDF* of one unit: CDF of one unit considering all states of the other units
  - *Frequency of at least one or more core damages*
  - *Frequency of multiple concurrent core damages*
A multi-unit PRA (MUPRA) analysis for any of the proposed CDF metric requires assessment of the inter- and intra-unit dependencies.
Options for Multi-Unit CDF Measures (Cont.)

• At least one core damage definition:

\[ P(U_{\downarrow i=1} \uparrow n \ CD_{\uparrow (i)}) = \sum_{i \leq n} P(CD_{\uparrow (i)}) - \sum_{i_1 < i_2} P(CD_{\uparrow (i_1)} \cap CD_{\uparrow (i_2)}) + \ldots + (-1)^{n+1} \sum_{i_1 < i_2, \ldots < i(n)} P(CD_{\uparrow (i_1)} \cap CD_{\uparrow (i_2)} \cap \ldots \cap CD_{\uparrow (in)}) \]

• Conditional and Marginal Definitions:

\[ P(CD_{\uparrow (i)}) = \sum_{j} P(CD_{\uparrow (i)} | C_{\downarrow j}) P(C_{\downarrow j}) \]

Where for causal conditions,

\[ P(C_{\downarrow j}) = \sum_{m} P(C_{\downarrow j} | C_{\downarrow j1}, \ldots, C_{\downarrow jm}) P(C_{\downarrow j1}, \ldots, C_{\downarrow jm}) \]
A Depiction of Dependent Failures in Multi-Units

Classes of Dependencies:
- Parametric
- Causal
Accounting for Dependent Failures in MUPRA

• **Identical dependent events**
  • Some preliminary assessments to be discussed
  • Estimate of multi-unit parametric values

• **Causal (dissimilar dependent events)**
  • Parametric
  • Probabilistic Physics-of-Failure
  • Bayesian Networks
Preliminary Assessment of Multi-Unit Parametric Dependencies

- A recent parametric analysis of multi-unit dependencies
- LER Data of 2000-2011 of multi-unit sites were categorized by their root-causes and effects

<table>
<thead>
<tr>
<th>Event Description</th>
<th>Number of Events, N, for 2- or 3-Unit Sites</th>
<th>Number of Events, N, 3-Unit Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiating Events</td>
<td>728</td>
<td>134</td>
</tr>
<tr>
<td>Component Failure / Degradation</td>
<td>1390</td>
<td>221</td>
</tr>
<tr>
<td>Human Error</td>
<td>341</td>
<td>45</td>
</tr>
<tr>
<td>Total</td>
<td>2459</td>
<td>400</td>
</tr>
</tbody>
</table>
Preliminary Assessment of Multi-Unit Parametric Dependencies (Cont.)

Causal (Different) Effects on Two or Three Units

Double or Triple Unit Effects
- IE-D
- HE-D
- SSC-D

Single Unit Effects
- IE
- HE
- SSC

Shared Event/SSC Root Causes
- EEP
- ORG

Common (Same) Effects on Two Units
- IE-S₁
- HE-S₁
- SSC-S₁

Common (Same) Effects on Three Units
- IE-S₂
- HE-S₂
- SSC-S₂

Triple Unit Effects
- IE-S₃
- HE-S₃
- SSC-S₃

Mapping of the multi-unit event: LER5262-001003 showing environmental causes of degradation/aging leading to failure of the same equipment in three units.
**Preliminary Assessment of Multi-Unit Parametric Dependencies (Cont.)**

<table>
<thead>
<tr>
<th>Events Categorization, j (identified for either i=2 for events involving 2 units, or i=3 for events involving 3 units)</th>
<th>Number of occurrences of type j events involving i units, n_{ij}, reported by Schroer^{20}</th>
<th>Point estimate of the probability of the event, ( \hat{p}_{ij} )</th>
<th>The 95% posterior Bayesian interval within which the true ( p_{ij} ) resides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identical Human Error Event (2 Units)</td>
<td>11</td>
<td>0.032</td>
<td>(1.7E-02; 5.5E-02)</td>
</tr>
<tr>
<td>Identical Human Error Event (3 Units)</td>
<td>1</td>
<td>0.022</td>
<td>(2.4E-03; 9.9E-02)</td>
</tr>
<tr>
<td>Human Error Event in One Unit Causes Different Human Errors in Other Unit(s) ( (HE_X</td>
<td>HE_Y) )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Identical Component Failure/Degradation Event (2 Units)</td>
<td>39</td>
<td>0.028</td>
<td>(2.0E-02; 3.8E-02)</td>
</tr>
<tr>
<td>Identical Component Failure/Degradation Event (3 Units)</td>
<td>2</td>
<td>0.009</td>
<td>(1.9E-03; 2.9E-02)</td>
</tr>
<tr>
<td>Identical Initiating Event (2 Units)</td>
<td>23</td>
<td>0.032</td>
<td>(2.1E-02; 4.6E-02)</td>
</tr>
<tr>
<td>Identical Initiating Event (3 Units)</td>
<td>2</td>
<td>0.015</td>
<td>(3.1E-03; 4.7E-02)</td>
</tr>
<tr>
<td>Initiating Events in One Unit Causes Different Initiating Event in Other Unit(s) ( (IE_X</td>
<td>IE_Y) )</td>
<td>7</td>
<td>0.010</td>
</tr>
<tr>
<td>Component Failure/Degradation in One Unit Causes Initiating Event in Other Unit(s): ( (C_x</td>
<td>IE_Y) )</td>
<td>8</td>
<td>0.011</td>
</tr>
<tr>
<td>Component Failure/Degradation in One Unit Causes Different Component Failure/Degradation in Other Unit(s): ( (C_x</td>
<td>C_y) )</td>
<td>24</td>
<td>0.017</td>
</tr>
<tr>
<td>Initiating Event in One Unit Causes Component Failure/Degradation in Other Units: ( (IE_X</td>
<td>C_Y) )</td>
<td>1</td>
<td>0.001</td>
</tr>
</tbody>
</table>

- Site-to-Site variations in the above estimates were also evaluated
A Simple Case-Study

Simple Illustration of a Two-Unit Problem

CONVENTIONS

- $X_i$: component/event
- $Y_i$: component/event No. $i$
- $H_i$: Unit No.
- If no Unit No. $(i)$ then the event is common to all units
- Failure (occurrence) of event $X$ leads to failure (occurrence) of $Y$ with probability $p$ (complete dependence)
- Occurrence of event $Y$ in unit $(i)$ will influence occurrence of event $X$ in unit $(i)$
- Shared Event
- Casual dependence of event $X$ in unit $(i)$ due to occurrence of event $Y$ in unit $(i)$
Preliminary Case Study Results

- **Single Unit CDFs**
  - Frequency of unit-1-specific cut sets: $4.64 \times 10^{-6}/yr.$
  - Frequency of units-1 cut sets involving SCC failures (causally) occurred due to Units-2 events: $2.09 \times 10^{-7}/yr.$
  - Frequency of Unit-1 cut sets involving initiating events (causally) started from Unit-2 events: $4.23 \times 10^{-8}/yr.$

- **Marginal CDF**
  - Marginal CDF of Unit-1: $5.16 \times 10^{-6}/yr.$
Preliminary Case Study Results (Cont.)

DOUBLE (Concurrent)-Event

• The frequency of double-unit CD frequency (total independence) without consideration and correction for causal or common cause dependencies: \(2.4 \times 10^{-11}/\text{yr.}\)
• Double-unit CD frequency with causal dependency correction, but without common cause parametric correction: \(1.97 \times 10^{-10}/\text{yr.}\)
• Double-unit CD frequency with common cause parametric correction, but without causal dependency correction: \(1.45 \times 10^{-8}/\text{yr.}\)
• Double-unit CD frequency with causal dependency correction and common cause parametric correction: \(1.47 \times 10^{-8}/\text{yr.}\)
• Contribution from CCF dependencies to the total double-unit CD frequency: \(98.66\%\)
• Contributions from causal dependencies to the total double-unit CD frequency: \(1.18\%\)
• Contribution from independent double-unit CD cut sets to the total double-unit CD cut set frequency: \(0.16\%\)
• Double-unit CDF accounting (parametrically) for human, initiating event and equipment failure dependencies between units: \(1.47 \times 10^{-8}/\text{yr.}\)
• Site-CD frequency (i.e., frequency of at least a CD): \(1.03 \times 10^{-5}/\text{yr.}\)
• Factors by which site CD frequency events are smaller than the double-unit CD frequency events: \(703\)
Observations From the Simple Example

- Contribution from dependencies to the total “site” CDF is significant
- Contributions from causal dependencies to multi-unit CDF is not significant
- Contribution from multi-unit (simultaneous) CDF to the total “site” CDF is small, but not insignificant
- “Site” CDF not significantly smaller than single-unit CDF
- Application to a real multi-unit site seismic PRA of an advanced reactor site is completed and under review with similar conclusions
Quantitative Health Objectives (QHO)

• NRC qualitative safety goals and QHOs still applicable to multi-unit sites.
  ➢ Prompt fatality goal remains more restrictive than the latent cancer fatality goal in multi-unit releases

• Multi-unit risk should be below the QHOs for both prompt and latent fatalities

• For multi-unit releases, surrogates for QHOs (CDF, LRF and LERF) for site risk should be assessed and compared to goals
  ➢ Would limits of $10^{-4}$, $10^{-6}$, and $10^{-5}$ for these surrogates remain the same?
Quantitative Health Objectives (QHO) (Cont.)

• Important factors for prompt fatality risk relate to source-term parameters become more critical in multi-unit releases
  ➢ radionuclide activity, frequency and release timing, chemical and physical forms, thermal energy, etc.

• Level 3 consequence analysis would be needed assuming a “generic” site along with MUPRA scenarios to evaluate implications of the QHOs
Multi-Unit Accident Contributions to QHOs

• To evaluate the implications of the QHOs, Level 3 consequence analyses was performed at two representative U.S. NPP sites using SORCA study.
  - Peach Bottom Atomic Power Station Unit 2 and 3
  - Surry Power Station Unit 1 and 2

• Specific Research Aims
  - Base Case Analysis
  - One-Way Sensitivity Analyses
    - Variation in assumed inter-unit dependence
    - Variation in assumed timing offset between multiple releases
Policy Alternatives

• **Option 1: Status Quo**
  - Only single-unit accident contributions included in estimating risk metrics for comparison to QHOs

• **Option 2: Expansion in Scope of Safety Goal Policy**
  - Contribution from both single-unit and multi-unit accident scenarios (marginal risk) included in estimating risk metrics for comparison to QHOs

• **Option 3: Expansion in Scope of Safety Goal Policy**
  - Besides the ones in Option 1 and 2, single-unit exclusive accident scenarios from other units included
Figures of Merit

- Figures of Merit 1 (FOM₁):
  - The percentage change in the mean value of QHO risk metrics, comparing Option 2 relative to Option 1

- Figures of Merit 2 (FOM₂):
  - The percentage change in the mean value for QHO margins, comparing Option 2 relative to Option 1

- Figures of Merit 3 (FOM₃):
  - The percentage change in the mean value of QHO risk metrics, comparing Option 3 relative to Option 1

- Figures of Merit 4 (FOM₄):
  - The percentage change in the mean value for QHO margins, comparing Option 3 relative to Option 1
### Results of Base Case Analysis

- The contribution from the two-unit accident scenarios results in
  - **Non-negligible increases in QHO risk metric.** The QHO risk metrics are increased by 15% to 77% comparing Option 2 to Option 1, and by 115% to 177% comparing Option 3 to Option 1.

<table>
<thead>
<tr>
<th>Safety Goal QHO Risk Metric</th>
<th>FOM$_1$</th>
<th>FOM$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Representative BWR (Peach Bottom) Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Individual Early Fatality Risk (1 mi)</td>
<td>77%</td>
<td>177%</td>
</tr>
<tr>
<td>Population-Weighted Latent Cancer Fatality Risk (0-10 mi)</td>
<td>15%</td>
<td>115%</td>
</tr>
<tr>
<td><strong>Representative PWR (Surry) Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Individual Early Fatality Risk (1 mi)</td>
<td>20%</td>
<td>120%</td>
</tr>
<tr>
<td>Population-Weighted Latent Cancer Fatality Risk (0-10 mi)</td>
<td>18%</td>
<td>118%</td>
</tr>
</tbody>
</table>
The contribution from the two-unit accident scenarios results in

- **Non-negligible reductions in QHO margin.** The mean margins to QHO are reduced by 13% to 43% comparing Option 2 to Option 1, and by 53% to 64% comparing Option 3 to Option 1.

<table>
<thead>
<tr>
<th>Safety Goal QHO Risk Metric</th>
<th>FOM$_2$</th>
<th>FOM$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Representative BWR (Peach Bottom) Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Individual Early Fatality Risk (1 mi)</td>
<td>-43%</td>
<td>-64%</td>
</tr>
<tr>
<td>Population-Weighted Latent Cancer Fatality Risk (0-10 mi)</td>
<td>-13%</td>
<td>-53%</td>
</tr>
<tr>
<td><strong>Representative PWR (Surry) Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Individual Early Fatality Risk (1 mi)</td>
<td>-17%</td>
<td>-55%</td>
</tr>
<tr>
<td>Population-Weighted Latent Cancer Fatality Risk (0-10 mi)</td>
<td>-16%</td>
<td>-54%</td>
</tr>
</tbody>
</table>
Results of Sensitivity Analysis 1

• Variation of the assumed inter-unit dependence from 0% to 100% for simultaneous releases reinforced conclusions from base case analysis.

• Two additional conclusions were drawn:
  ➢ Percent change in risk is more sensitive to assumptions about inter-unit dependence than percent change in QHO margin.
  ➢ Several orders of magnitude in margin to both QHOs exist even for worst-case assumption of complete dependence.

Including the contribution from multi-unit accidents to safety goal QHO metrics may result in non-negligible changes in risk estimates but no change in conclusions from safety goal evaluation.
Results of Sensitivity Analysis 2

• Variation of the timing offset between concurrent releases from co-located units with assumed 10% inter-unit dependence reinforced conclusions from base case analysis.

• Two additional conclusions were drawn:
  ➢ Early fatality risk is more sensitive to assumptions about differences in timing for multi-unit accident scenarios in which the co-located unit experiences a more rapidly progressing accident.
  ➢ Increasing the delay between concurrent accidents may cause latent cancer fatality risk to increase for some scenarios.

Severe accident mitigation measures that serve to delay more rapidly progressing concurrent accident scenarios in a co-located unit can lead to significant reductions in multi-unit early fatality risk.
Conclusions

- Multi-unit events important contributors to site risks
- Parametric methods for MUPRA useful—LER a starting point
- Causal dependence modeling needs further research
- Unit-to-unit causal events are significant in external events
- Site-level CDF and LRF as surrogates to latent cancer and prompt fatality QHOs need better definition
- Contribution from multi-unit accident scenarios results in non-negligible increases in QHO risk metrics, and reductions in QHO margins.
- Societal disruption risks quantitatively monetized would be a critical addition to QHOs.
Questions?