MU-PRA: Methodology, Safety Goals Implication, Current Research at UMD

Presentation at the IAEA Meeting on Multi-Unit Probabilistic Safety Assessment
Vienna, Austria
December 14-16, 2016

Mohammad Modarres
Center for Risk and Reliability (CRR)
Department of Mechanical Engineering
University of Maryland, College Park
Acknowledgements

Student Contributors

Taotao Zhou
Daniel Hudson
Jonathan DeJesus
Suzanne Schroer (Dennis)
Matthew Dennis

Technical Staff Contributor

Dr. Mahmoud Massoud

Funding and Contributions From the U.S. NRC are Particularly Appreciated
Topics Covered

• Why MU-MUPRA?
• MU-PRA Risk Metrics
• Unit-to-Unit Dependency Modeling
• MU-PRA Methodology
• A Simple Seismic PRA and Impact of MU-PRA
• Implications of MU-PRA on USNRC Safety Goals (QHOs)
• Ongoing Research at UMS
• Observations and Important Directions for IAEA’s Guideline Development
Multi-Unit US and Global NPP Sites

Source: International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) as of August 2015
Why MU-PRA? : Unit-to-Unit Dependencies are significant

- Schroer used a fishbone categorization to group LERs affecting multi-units at the U.S. sites

### IMPORTANT FINDINGS

- **9%** of ALL LERs reported affected two or more units
- **17%** of LERs in MULTI-UNIT sites involved more than one unit
- Most involving Organizational and Shared Connection types of dependencies


COPYRIGHT © 2016, M. Modarres
Multi-Unit CDF Metrics

- Three Possible MU-CDF Definitions:
  - CDF of one unit including consideration of all states of the other units (marginal CDF Definition)*
  - Frequency of at least one or more core damages (total Site CDF Definition)
  - CDF for multiple core damages (concurrent CDF Definition)

* Single unit PRAs include scenarios exclusive to one unit, assuming others will be unaffected
A multi-unit PRA (MUPRA) analysis for any of the proposed CDF metric requires assessment of the inter- and intra-unit dependencies.
Dependent Failures in Multi-Units: The Critical Element of a Successful MU-PRA

Classes of Dependencies:
- Parametric
- Causal
Estimating Dependent Failure Probabilities in MUPRA

Identical and Causal (dissimilar dependent events)

Dependent Failure Methods Proposed or Used:

- Parametric
- Probabilistic Physics-of-Failure
- Bayesian Networks
Parametric Assessment of Conditional Probability of Failures

- Parametric analysis of MU dependencies
- LER Data of 2000-2011 of multi-unit sites 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>
Parametric Assessment of Conditional Probability of Failures (Cont.)

Causal (Different) Effects on Two or Three Units

Double or Triple Unit Effects

IE-D

HE-D

SSC-D

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

Double Unit Effects

Single Unit Effects

Shared Event/ SSC Root Causes

IE

HE

SSC

Shared Event/ SSC Root Causes

EEP

ORG

External/ Environmental/ Organizational Root Causes

Mapping of the multi-unit event: LER5282-001003 showing environmental causes of degradation/aging leading to failure of the same equipment in three units

COPYRIGHT © 2016, M. Modarres
Parametric Assessment of Conditional Probability of Failures (Cont.)

- Site-to-Site variations in estimates also evaluated
- Bayesian estimate of conditional dependent failure probabilities
- LER data used as evidence with uninformative priors

\[ \hat{p}_{ij} = \frac{n_{ij}}{N} \]

where \( n_{ij} \) is the total number of observed events of type j (such as initiating event) involving occurrences in i reactor units (i= 2, or 3 in U.S.) due to the total number of LER events of type-j events observed in N total events that occurred in the MU sites.

<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_i</td>
<td>HE_j) )</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_i</td>
<td>IE_j) )</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_{i}</td>
<td>I_{j}) )</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_{i}</td>
<td>C_{j}) )</td>
<td>24</td>
<td>0.017</td>
</tr>
<tr>
<td>Initiating Event in One Unit Causes Component Failure/Degradation in Other Units: ( (IE_i</td>
<td>C_{j}) )</td>
<td>1</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Case Study:
A Simple MU Seismic PRA of Advanced Reactor Units
Objective and Methodology

- **Objectives**
  - Application to a hypothetical site consisting of two advanced reactor units
  - Common initiating event: seismically induced small LOCA
  - Identify the MU-CD scenarios due to internal events and seismic events.

- **Methodology: parametrical-based using SAPHIRE.**
  - Using internal events MU dependent events from the 2000-2011 LERs
  - The seismic events are derived from a general copula-based simulation approach with equally-correlated assumption between the capacity of SSCs. (the specific correlation could be derived via “separation of variable” method)

- **Risk Metrics**
  - Site CDF (i.e., at least a core damage (CD))
  - Multi-Unit CDF (i.e., concurrent CDs)
  - Marginal Single-Unit CDF
Seismic Hazard Curve and Initiating Event Frequency

The Frequency of Seismically induced SLOCA

- Annual frequency exceedance (e.g., \(4.78\times10^{-5}\) for PGA=0.5g)
- Conditional probability of SLOCA (e.g., 0.089 for PGA=0.5g)
- Frequency of seismic-induce SLOCA (e.g., \(4.25\times10^{-6}\) for PGA=0.5g)
Preliminary Case Study Results (Seismic Event) – Site CDF

**Site CCDP/Fragility**

- Conditional Core Damage Probability vs Acceleration (g)
- Contribution of Dependence to Site CCDP/Fragility
- Site CDF

- Site CCDP (0)
- Site CCDP (0.3)
- Site CCDP (0.5)
- Site CCDP (0.8)
- Site CCDP (1)

- Dependence Contribution (0.3)
- Dependence Contribution (0.5)
- Dependence Contribution (0.8)
- Dependence Contribution (1)

COPYRIGHT © 2016, M. Modarres
Preliminary Case Study Results (Seismic Event) – Concurrent CDF

Contribution of Dependence to Multi-Unit CCDP/Fragility

Multi-Unit CCDP/Fragility

Multi-Unit CDF

Preliminary Case Study Results (Seismic Event) – Marginal CDF

Marginal Single-Unit CCDP/Fragility

Contribution of Dependence to Single-Unit CCDP/Fragility

Marginal Single-Unit CDF
Preliminary Case Study Results (Seismic Event) – Contribution of Concurrent CDF to Site CDF

![Graph showing the contribution of concurrent CDF to site CDF for different correlation values. The graph plots the percentage of contribution against acceleration (g). The legend indicates different colors representing correlation values: 0, 0.3, 0.5, 0.8, and 1.]
Observations From the Seismic Event

• The seismic-induced dependencies are significant in “site” risk, and show extremely high contributions to “concurrent” risk too.
• With increasing ground motions, the probability of concurrent CDs would approach “site” CDs.
• The middle region of site fragility curve is the most sensitive to the potential dependencies, while it is less sensitive to both the low end and high end of site fragility curve.
• The sensitivity studies of correlations show that the main sensitive region would be shifted to the lower end of site fragility curve with potentially higher dependencies.
• The impact of perfect dependency assumption is too conservative for “site” risk and marginal CD risk, but not for assessing concurrent risk.
**MU Risk Implications on Safety Goals**

**Quantitative Health Objectives (QHOs)**

- 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?
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
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 included in estimating risk metrics for comparison to QHOs. That is considering “Marginal” Risk

• **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. That is considering “site” risk
MU Risk QHO Results

- **Figures of Merit 1**: Change in the mean value of QHO risk metrics, comparing Option 2 relative to Option 1
- **Figures of Merit 2**: Change in the mean value of QHO risk metrics, comparing Option 3 relative to Option 1
- **The contribution from the two-unit accident scenarios (assuming 10% unit-to-unit dependency) results in**
  - The QHO risk metrics 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$_2$</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>
Results of Sensitivity Analysis

- Variation of the assumed inter-unit dependence from 0% to 100% reinforced conclusions from base case analysis. Including the contributions from multi-unit accidents to safety goal QHO metrics increase risk estimates, but still meet the safety goals with wide margins.

- Variation of the timing offset between releases from multiple units assuming 10% inter-unit dependence reinforced conclusions from base case analysis. Also,
  - Early fatality risk is more sensitive to release timing.
  - 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 site can lead to significant reductions in multi-unit early fatality risk.
Research in Dependent MU Seismic Hazard

• **Objective**
  - Obtain the seismic response of different units at a nuclear power plant site and their correlation

• **Method**
  - Machine learning – supervised regression
    - Available data: NGA-East*
    - Used K-Nearest Neighbors regression model
      - Features: (1) earthquake magnitude, (2) earthquake recording station elevation, (3) epicenter and recording station distance, (4) time-average shear wave velocity in upper 30 meters of a site ($V_{s30}$), and (5) geology type (text)
      - Response: Peak ground acceleration

* NGA-East is developing a new ground motion characterization model for the Central and Eastern North-American (CENA) region.
Preliminary Findings of Dependent Seismic Hazard Research

- Able to predict the peak ground acceleration (PGA) for each units at a site
- Model produces point estimates (no uncertainty associated with results yet)
- Peak ground acceleration could noticeably be different leading to varied SSC responses and fragilities, although PGAs are small due to the low seismic events in the data base.
Conclusions

• Multi-unit accidents are important contributors to site risks
• Parametric MUPRA are 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 in MUPRA
• Contribution from multi-unit accident scenarios reduce margin to QHO.
• Seismic event hazard dependency research a possible path to developing dependencies in unit response and fragilities
• Societal and disruption risks quantitatively monetized would be a critical addition to the QHOs
Questions?