Multi-Unit Nuclear Plant Risks and Implications of the Quantitative Health Objectives

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Mohammad Modarres

Nicole Y. Kim Professor and Professor of Nuclear Engineering

Center for Risk and Reliability (CRR)

Department of Mechanical Engineering

University of Maryland, College Park

18 TARVLANO

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Topics Covered

- Implications of Multi-Unit accidents on safety goals
- Assessment of multi-unit / multi-module risk metrics as safety goal surrogates : Core Damage Frequency (CDF), Large Release Frequency (LRF) and Large Early Release Frequency (LERF)
- Significance of Multi-Units Events Observed
- An Approach to Account for Multi-Unit Risks
- Conclusions



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
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Classification of Unit-to-Unit Dependencies

Schroer used a fishbone categorization of multi-unit interdependencies



- Schroer's LER analysis showed 9% of events reported involve two or more units
- Most involving Organizational and Shared Connection types of dependencies

Source: Schroer, S. An Event Classification Schema For Considering Site Risk In A Multi-Unit Nuclear Power Plant Probabilistic Risk Assessment, University of Maryland, Master of Science Thesis in Reliability Engineering, 2012.



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Options for Multi-Unit CDF Measures

- Single-Unit CDF Representations:
 - Conditional CDF of one unit: CDF of one unit given some known states of other units
 - Marginal CDF of one unit: CDF of one unit considering all states of the other units
- Multi-Unit CDF Representations:
 - Frequency of one or more core damages
 - Frequency of multiple core damages (for example exactly two core damages in a three-unit site)



Options for Multi-Unit CDF Measures (Cont.)



A multi-unit PRA (MUPRA) analysis for any of the proposed CDF metric requires assessment of the inter- and intra-unit dependencies



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Options for Multi-Unit CDF Measures (Cont.)

- At least one core damage definition: $(U_{i=1}^{n}CD_{i}) \sim \Sigma_{i \leq n} P(CD_{i})$
 - Conditional and Marginal Definitions:

$$P(CD_i) = \sum_j P(CD_i|C_j)P(C_j)$$

Where for causal conditions,

$$P(C_j) = \sum_m P(C_j | C_{j1}, \dots C_{jm}) P(C_{j1}, \dots C_{jm})$$



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A Depiction of Dependent Failures in Multi-Units



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Accounting for Dependent Failures in MUPRA

- Parametric (identical dependent events)
 - Use of the traditional CCF parametric methods
 - Some preliminary assessment to be discussed
 - Need more research to estimate multi-unit parametric values
- Causal (dissimilar dependent events)
 - Probabilistic Physics-of-Failure
 - Bayesian Networks



Preliminary Assessment of Multi-Unit Parametric Dependencies

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

Event Description	Number of Events, N, for 2- or 3-Unit Sites	Number of Events, N, 3-Unit Sites
Initiating Events	728	134
Component Failure / Degradation	1390	221
Human Error	341	45
Total	2448	400



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Preliminary Assessment of Multi-Unit Parametric Dependencies (Cont.)





Preliminary Assessment of Multi-Unit Parametric Dependencies (Cont.)

Example of results considering LER data of all Multi-unit sites:

Events Categorization, j (identified for either i=2 for events involving 2 units, or i=3 for events involving 3 units)	Number of occurrences of type j events involving i units, n_{ij} , reported by Schroer ³⁰ , and Schroer and Modarres ¹	Point Estimate of the probability of the event, \hat{p}_{ij}	The 95% posterior Bayesian interval within which the true p _{ij} resides
Identical Human Error Event (2 Units)	11	0.032	(1.7E-0.2; 5.5E-02)
Identical Human Error Event (3 Units)	1	0.022	(2.4E-03; 9.9E-02)

- HE SU: Resulted in human error in a single unit
- SSC SU: Resulted in SSC failure(s) in a single unit
- IE SU: Resulted in an initiating event in a single unit
- HP AU: Resulted is the same human error in more than one unit
- SSC AU: Resulted in the same SSC Failure or degradation in more than one unit
- IE AU: Resulted in the same initiating events in more than one unit
- HP DU: Resulted in different human errors in more than one unit
- SSC DU: Resulted in different SSC failures or degradation in more than one unit
- IE DU: Resulted in different initiating events in more than one unit

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 Site-to-Site variations in the above estimates were also evaluated were strates

A Simple Case-Study



Simple Illustration of a Two-Unit Problem

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Preliminary Case Study Results

SINGLE-UNIT

Conditional CDFs

- Frequency of unit1-specific cut sets: 4.64×10⁻⁶/yr.
- Frequency of units1 cut sets involving SCC failures (causally) occurred due to Units2 events: 1.12×10⁻⁷/yr.
- Frequency of Unit1 cut sets involving initiating events (causally) started from Unit2 events: 4.23×10⁻⁸/yr.

Marginal CDF

• Marginal CDF of Unit1: 4.80×10⁻⁶/yr.

DOUBLE-UNIT

 Double-unit CDF accounting (parametrically) for human, initiating event and equipment failure dependencies between units: 1.46×10⁻⁸/yr.



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 than single-unit CDF
- Application to a real multi-unit site PRA is planned



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 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



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
- Site-level level-3 PRA analyses are important
- Societal disruption risks quantitatively monetized would be a critical addition to QHOs



Questions?

