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

Seminar Presentation

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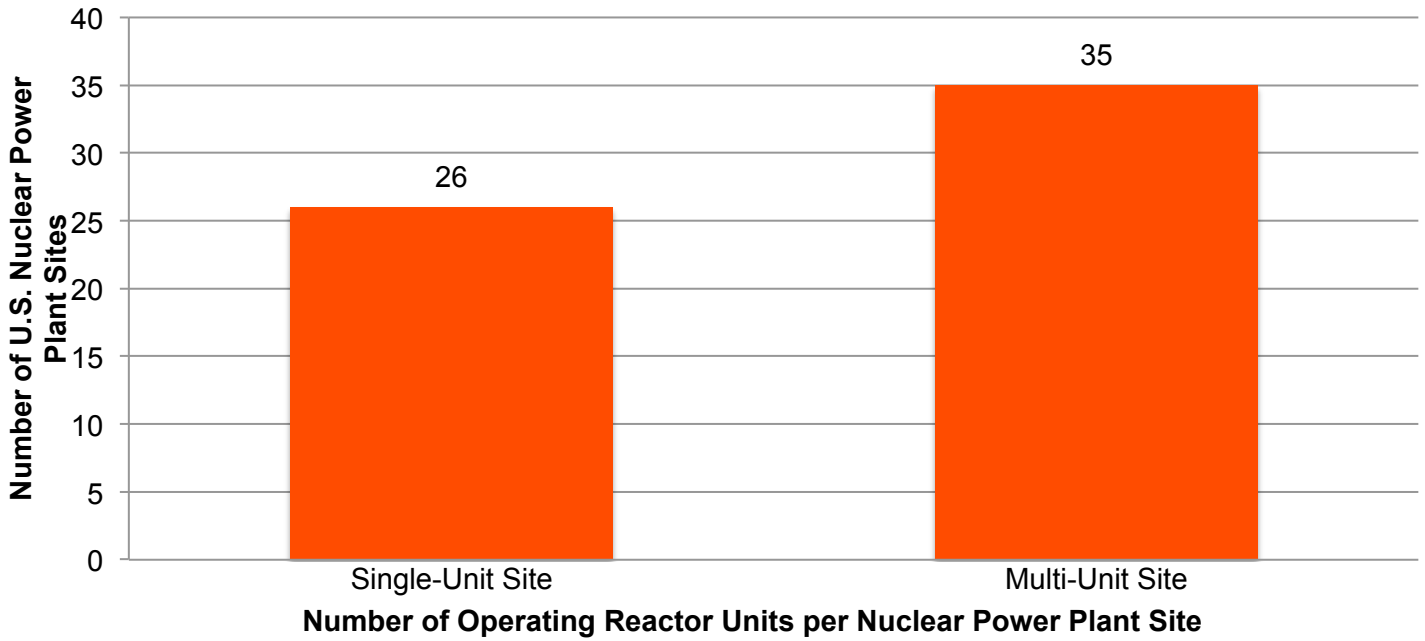
Topics Covered

- 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

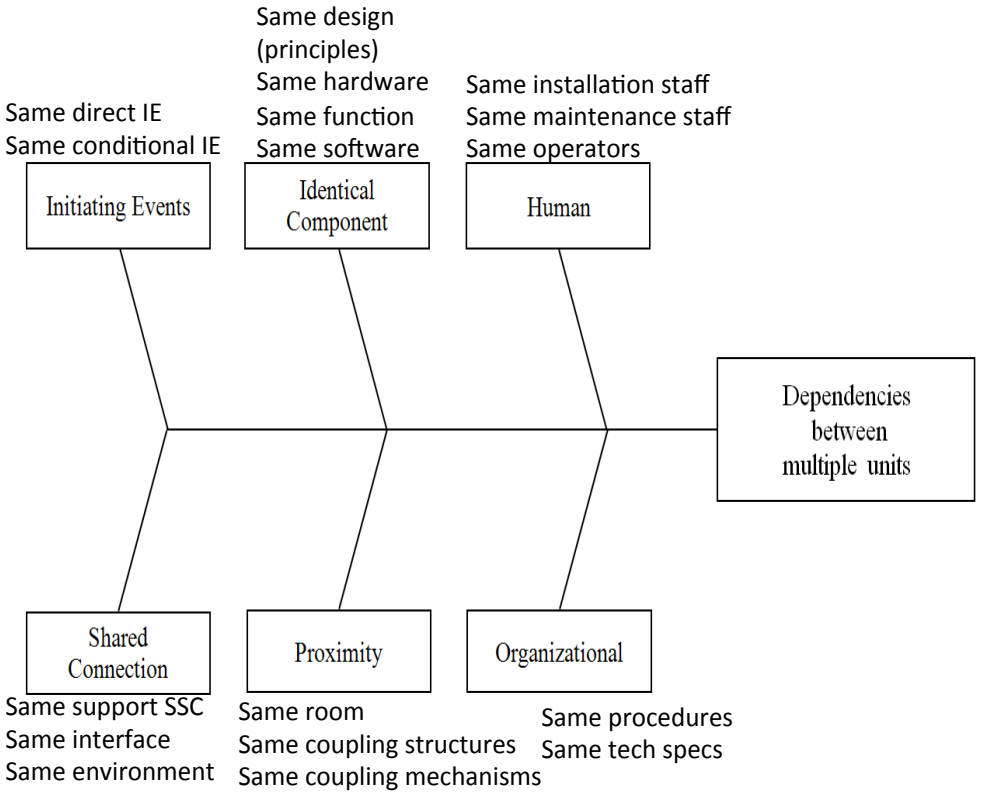


Background

- 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



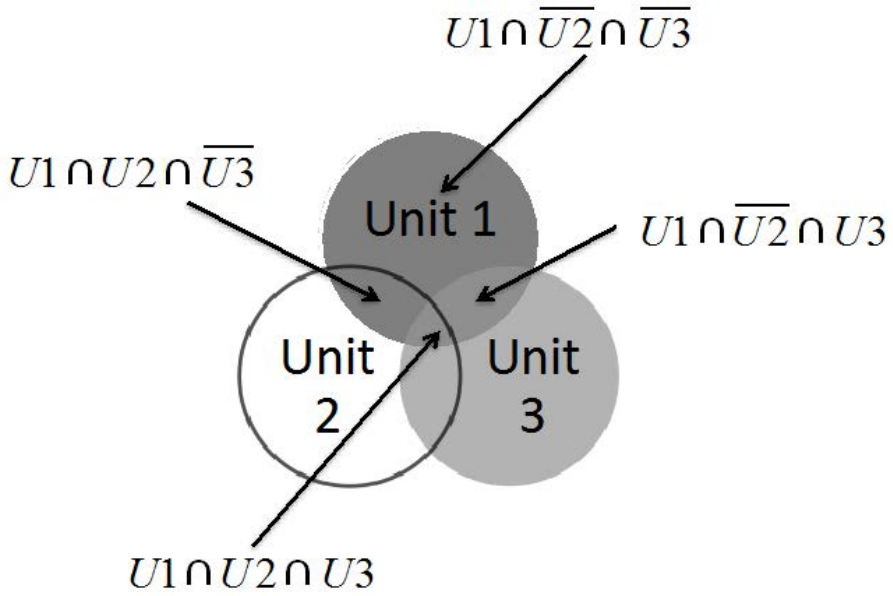
- Schroer's LER analysis showed 9% of events reported involve two or more units
- 17% of LERs in multi-units sites involved more than one unit
- Most involving Organizational and Shared Connection types of dependencies

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.

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*

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

Options for Multi-Unit CDF Measures (Cont.)

- At least one core damage definition:

$$P(U_{i=1}^{n} CD(i)) = \sum_{i \le n} P(CD(i)) - \sum_{i1<i2} P(CD(i1) \cap CD(i2)) + \ldots$$
$$+(-1)^{n+1} \sum_{i1<i2,\ldots<i(n)} P(CD(i1) \cap CD(i2) \cap \ldots \cap CD(in))$$

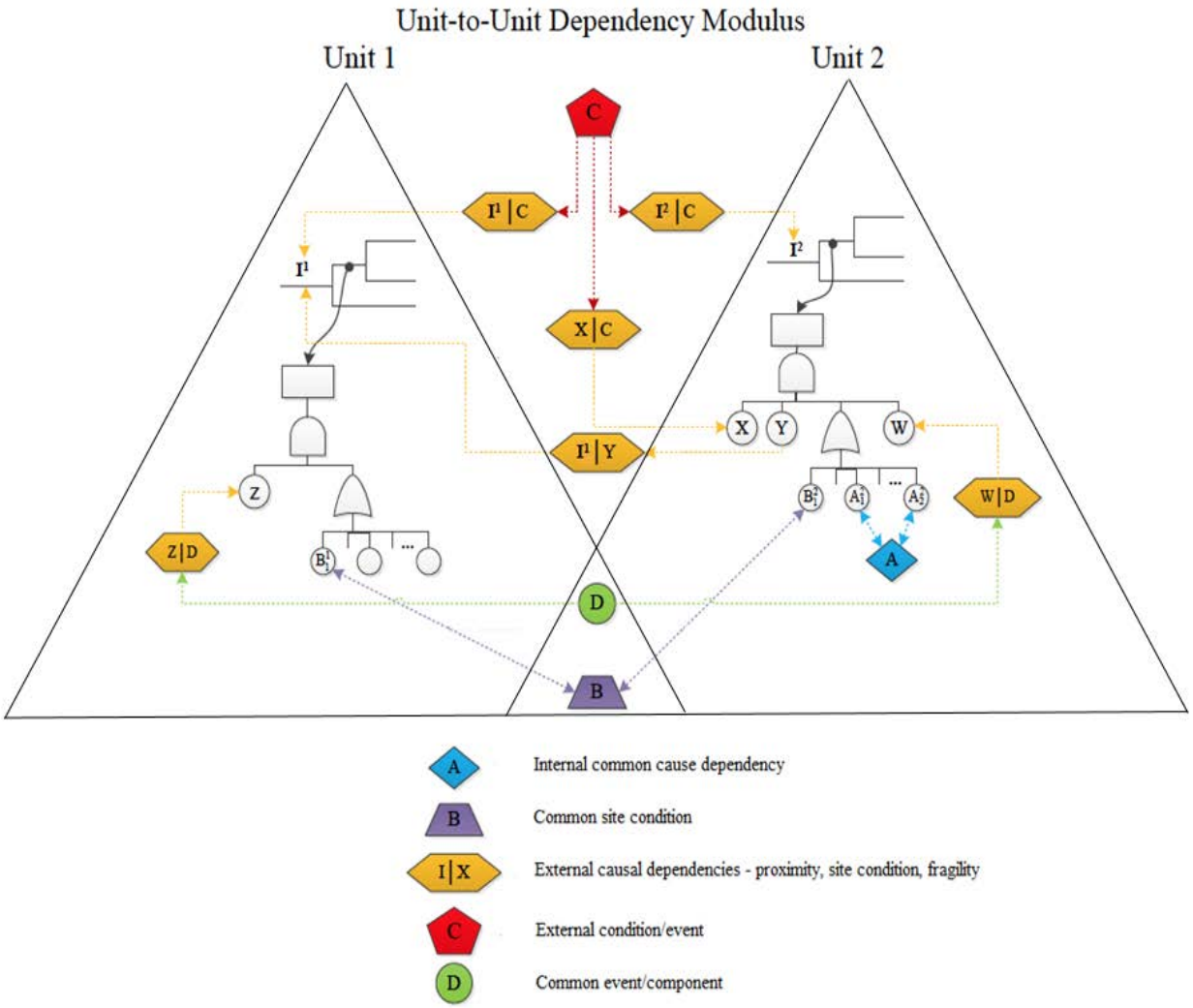
- Conditional and Marginal Definitions:

$$P(CD(i)) = \sum_{j} P(CD(i) \mid C_j) P(C_j)$$

Where for causal conditions,

$$P(C_j) = \sum_{m} P(C_j \mid C_{j1}, \ldots C_{jm}) P(C_{j1}, \ldots C_{jm})$$

A Depiction of Dependent Failures in Multi-Units



Classes of Dependencies:

- **Parametric**
- **Causal**

Accounting for Dependent Failures in MUPRA

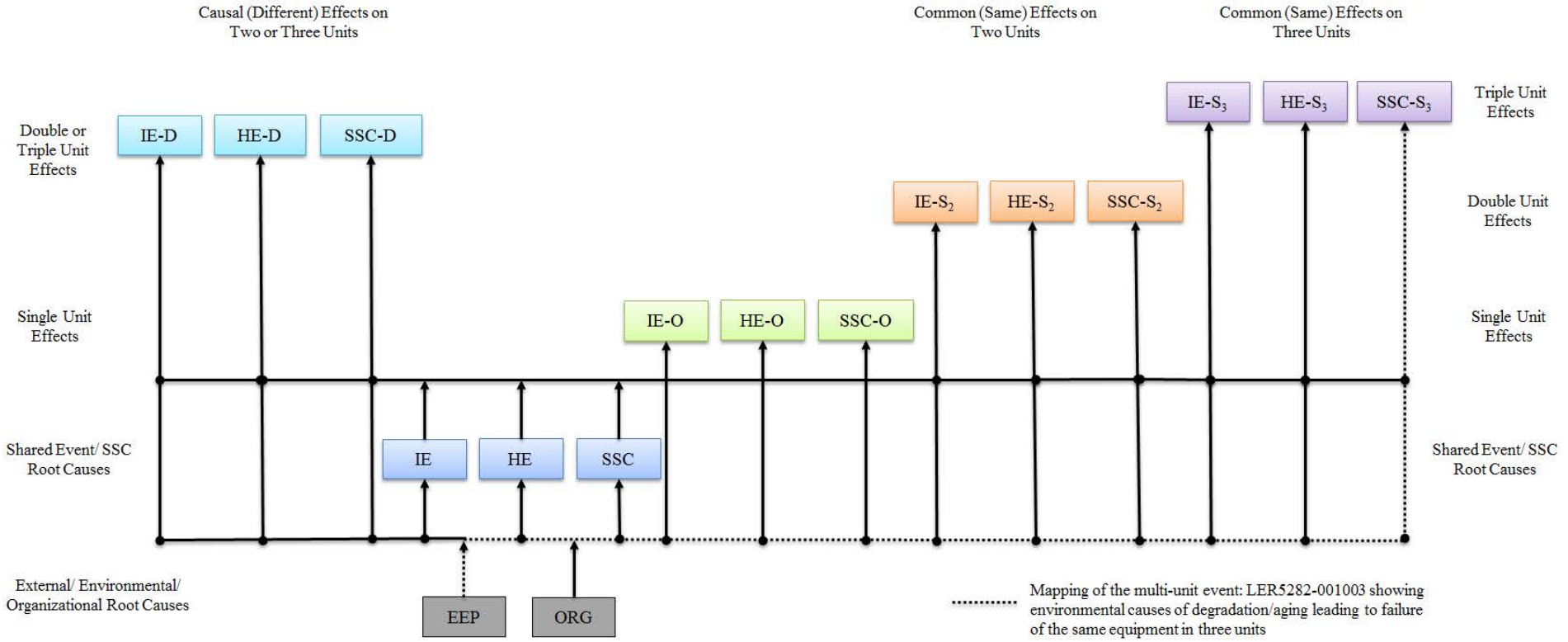
- Identical dependent events
  - Some preliminary assessments to be discussed
  - Estimate of multi-unit parametric values
- Causal (dissimilar dependent events)
  - Parametric
  - Probabilistic Physics-of-Failure
  - Bayesian Networks

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

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	2459	400

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

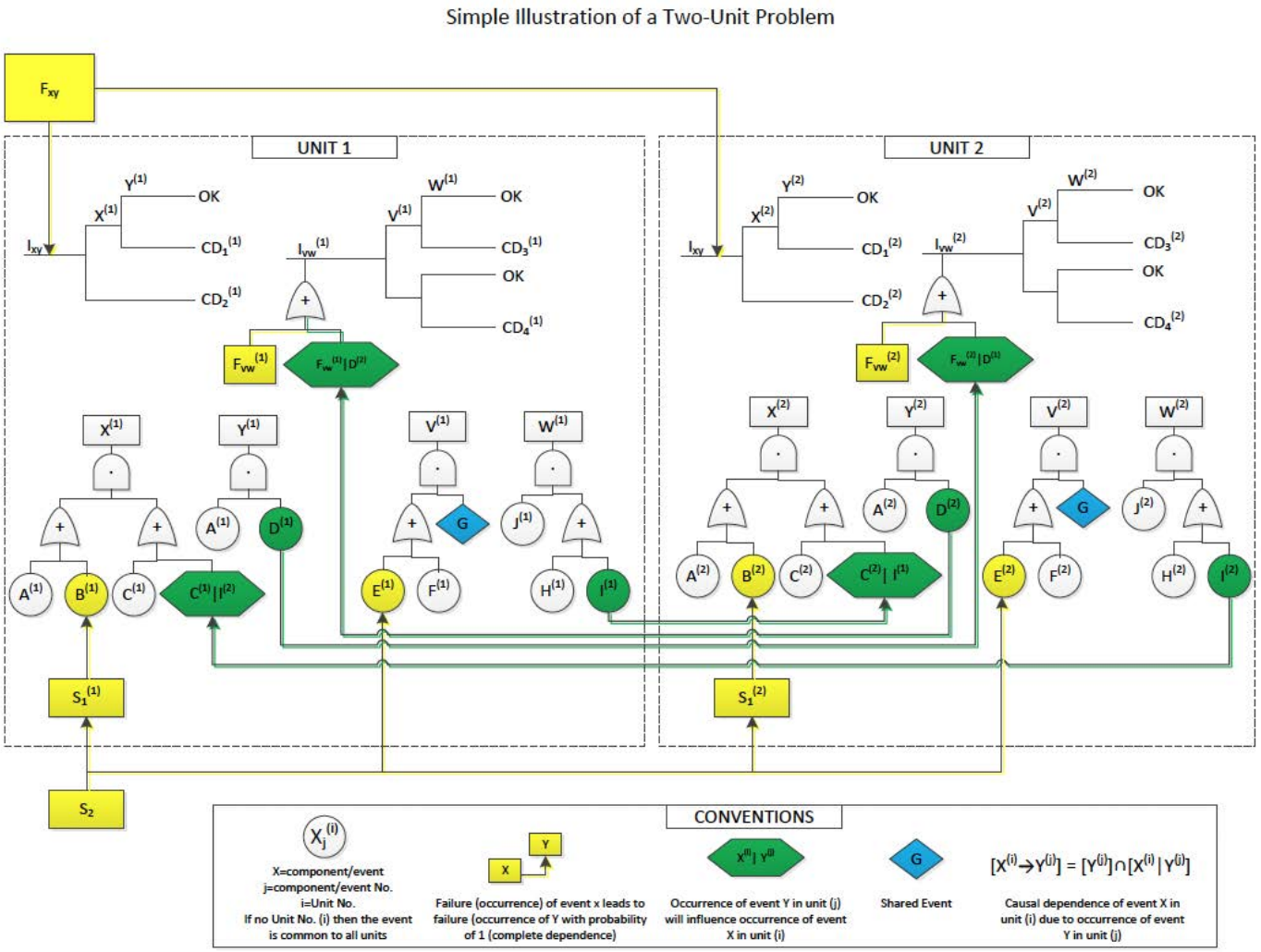


Preliminary Assessment of Multi-Unit Parametric Dependencies (Cont.)

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[20]	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)
Human Error Event in One Unit Causes Different Human Errors in Other Unit(s) $(HE_x \mid HE_y)$	0	0	(1.4E-06; 7.3E-03)
Identical Component Failure/Degradation Event (2 Units)	39	0.028	(2.0E-02; 3.8E-02)
Identical Component Failure/Degradation Event (3 Units)	2	0.009	(1.9E-03; 2.9E-02)
Identical Initiating Event (2 Units)	23	0.032	(2.1E-02; 4.6E-02)
Identical Initiating Event (3 Units)	2	0.015	(3.1E-03; 4.7E-02)
Initiating Events in One Unit Causes Different Initiating Event in Other Unit(s) $(IE_x \mid IE_y)$	7	0.010	(4.3E-03; 1.9E-02)
Component Failure/Degradation in One Unit Causes Initiating Event in Other Unit(s): $(C_x \mid I_y)$	8	0.011	(5.2E-03; 2.1E-02)
Component Failure/Degradation in One Unit Causes Different Component Failure/Degradation in Other Unit(s): $(C_x \mid C_y)$	24	0.017	(1.1E-02; 2.5E-02)
Initiating Event in One Unit Causes Component Failure/Degradation in Other Units: $(IE_x \mid C_y)$	1	0.001	(1.5E-04; 6.4E-03)

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

A Simple Case-Study



Preliminary Case Study Results

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

- **Marginal CDF**
  - Marginal CDF of Unit-1: 5.16×10^{-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: 2.4×10^{-11}/yr.
- Double-unit CD frequency with causal dependency correction, but without common cause parametric correction: 1.97×10^{-10}/yr.
- Double-unit CD frequency with common cause parametric correction, but without causal dependency correction: 1.45×10^{-8}/yr.
- Double-unit CD frequency with causal dependency correction and common cause parametric correction: 1.47×10^{-8}/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: 1.47×10^{-8}/yr.
- Site-CD frequency (i.e., frequency of *at least a CD*): 1.03×10^{-5}/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 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 (FOM_1):
  - The percentage change in the mean value of QHO risk metrics, comparing Option 2 relative to Option 1
- Figures of Merit 2 (FOM_2):
  - The percentage change in the mean value for QHO margins, comparing Option 2 relative to Option 1
- Figures of Merit 3 (FOM_3):
  - The percentage change in the mean value of QHO risk metrics, comparing Option 3 relative to Option 1
- Figures of Merit 4 (FOM_4):
  - 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.

Safety Goal QHO Risk Metric	FOM_1	FOM_3
Representative BWR (Peach Bottom) Analysis		
Average Individual Early Fatality Risk (1 mi)	77%	177%
Population-Weighted Latent Cancer Fatality Risk (0-10 mi)	15%	115%
Representative PWR (Surry) Analysis		
Average Individual Early Fatality Risk (1 mi)	20%	120%
Population-Weighted Latent Cancer Fatality Risk (0-10 mi)	18%	118%

Results of Base Case Analysis (cont.)

- 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.

Safety Goal QHO Risk Metric	FOM_2	FOM_4
Representative BWR (Peach Bottom) Analysis		
Average Individual Early Fatality Risk (1 mi)	-43%	-64%
Population-Weighted Latent Cancer Fatality Risk (0-10 mi)	-13%	-53%
Representative PWR (Surry) Analysis		
Average Individual Early Fatality Risk (1 mi)	-17%	-55%
Population-Weighted Latent Cancer Fatality Risk (0-10 mi)	-16%	-54%

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?