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

Presented at the
International Workshop on Multi-Unit Probabilistic Safety Assessment
November 17 – 20, 2014, Ottawa, Canada

Mohammad Modarres

Center for Risk and Reliability (CRR)
Department of Mechanical Engineering
University of Maryland, College Park
Topics Covered

• Implications of the current NRC safety goals and 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)

• This talk focuses on
  • Expanding single-unit PRAs into a multi-unit one by superimposing the effects of the unit-to-unit dependencies
  • Alternative approach using a dynamic probabilistic risk assessment (DPRA) is being studied at CRR to be presented later by Mr. Matt Dennis in this Workshop
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

• **University**
  - Suzanne Schroer’s MS thesis
  - UMD’s current grant on this subject
Classification of Unit-to-Unit Dependencies

- Schroer uses a fishbone representation of categorization of inter-unit dependencies

Schroer’s LER analysis showed 9% of events reported involve two or more units

Most involving Organizational and Shared Connection types of dependencies

CDF Measures

- **Single-Unit CDF Representations:**
  - Conditional CDF of one unit: CDF of one unit given the know states of other units
  - Marginal CDF of one unit: CDF of one unit regardless of the state of other units

- **Multi-Unit CDF Representations:**
  - Frequency of one or more CD events
  - Frequency of multiple CD events (for example exactly two core damages in a three unit site)
The core element of a multi-unit PRA analysis for any of the proposed CDF measures is assessment of the inter- and intra- dependencies.
CDF Measures (Cont.)

At least one core damage and multiple core damage events:

\[ P(U_{i=1}^n CD_i) = \sum_{i \leq n} P(CD_i) - \sum_{i_1 < i_2} P(CD_{i_1} \cap CD_{i_2}) + \cdots + (-1)^{n+1} \sum_{i_1 < i_2 < \cdots < i(n-1)} P(CD_{i_1} \cap CD_{i_2} \cap \cdots \cap CD_{i_n}) \]

Where,

\[ P(\bigcap_{i=1}^k CD_i) = \sum_j P(\bigcap_{i=1}^k CD_i | C_j) P(C_j) \]

Marginal CDF

\[ P(CD_i) = \sum_j P(CD_i | C_j) P(C_j) \]

Where for causal conditions, \( P(C_j) = \sum_m P(C_j | C_{j_1}, \ldots, C_{j_m}) P(C_{j_1}, \ldots, C_{j_m}) \)
Dependent Failures in Multi-Units

Classes of Dependencies:
- Parametric
- Causal
Dependent Failures in Multi-Units (Cont.)

Same IE- Different SSC Dependent Events
Semi-Complete Symmetry

Different IE- Different SSC Dependent Events
Complete Asymmetry

Same IE- Same SSC Dependent Events
Complete Symmetry

Different IE- Same SSC Dependent Events
Non-Symmetry
Possible Dependent Failures Methods

- **Parametric (identical events)**
  - Use of the traditional intra-unit CCF parametric methods
  - Need more research for parametric values for inter-unit CCFs

- **Causal (identical or dissimilar events)**
  - Probabilistic Physics of Failure
  - Bayesian Networks
Research on Dependent Failures Methods

Failure Mechanism
- System-Level
- Component-Level
- Sub-component or Part-Level
- Failure Mode Level
- Failure Mechanism level

Intra- & Inter-environmental Factors

Fig 6. Common Cause Failure Modeling Using Probabilistic Physics-Of-Failure

Probabilistic Physics of Failure

Bayesian Belief Network

Fig 7 Causal modeling approach for a physics-based CCF modeling
Simple Case-Study
Preliminary Case Study Results

SINGLE-UNIT FREQUENCIES

• Frequency of unit1-specific internal and external cut sets: $3.72 \times 10^{-4}$/yr.

• Frequency of units1 cut sets involving SCC failures (causally) occurred due to Units2 events: $2.86 \times 10^{-5}$/yr.

• Frequency of Unit1 cut sets involving initiating events (causally) started from Unit2 events: $1.66 \times 10^{-3}$/yr.

• Marginal CDF of Unit1: $3.72 \times 10^{-4} + 2.86 \times 10^{-5} + 1.66 \times 10^{-3} = 2.06 \times 10^{-3}$/yr.

DOUBLE-UNIT FREQUENCIES

• Double-unit frequency with causal dependencies, but without common cause failures between units: $4.99 \times 10^{-6}$/yr.

• Double-unit frequency with CCF parametric correction across units, but without causal dependency correction: $7.95 \times 10^{-4}$/yr.
Observations from this Simple Example

- Contribution from CCF dependencies to the total “site” frequency is likely to be significant
- Contribution to the single-unit marginal frequency from causal events is likely to be significant
- Contributions from causal dependencies to multi-unit frequency would not be significant
- Contribution from multi-unit frequency to the total “site” frequency is likely to be significant
- “Site” frequency will only be marginally smaller than than a single-unit marginal frequency

Results are not generic to multi-units but anecdotally reasonable
Quantitative Health Objectives (QHO)

• NRC qualitative safety goals and QHOs should remain unchanged for 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 (should the limits of $10^{-4}$, $10^{-6}$, and $10^{-5}$ for these surrogates in the context of site risk change?)
Quantitative Health Objectives (QHO) (Cont.)

• Important factors, which influence the prompt fatality risk relate to source term parameters: radionuclide activity, rate and timing of release, chemical and physical form of radionuclides, thermal energy, release fractions, etc.

• Level 3 consequence analysis would be needed assuming a “generic” site and applying multi-unit PRA scenarios to quantify and evaluate the implications of the NRC’s QHOs
Surrogate Multi-Unit LRF and LERF Metrics

• Three Options for Measuring LRF (surrogate for prompt fatality goal--NRC has not defined LRF yet)

  1. Frequency of rapid, unmitigated release of airborne fission products that would result in at least one early fatality from the sites (NUREG/CR-6094 suggests a stationary individual one mile from plant)

  2. Frequency of site-level absolute or relative quantities of radionuclides released (absolute expressed in terms of activity released, relative in terms of the percent of available inventory—usually of I-131 or Cs-137)

  3. Frequency of pre-set site-level plant states: physical condition of systems, states of pressure boundaries and radionuclide barriers at the time release begins

  • The prompt fatality in the safety goals applies to an average individual living in the region between the site boundary and 1 mile beyond.
  • The latent cancer fatality in the safety goals applies to an average individual living in the region between the site boundary and 10 miles beyond.
Surrogate Multi-Unit LRF and LERF Metrics (Cont.)

- LERF (proposed by EPRI and adopted in RG 1.174 as the surrogate for prompt fatality goal)
  - U.S. NRC’s definition: “the frequency of significant, unmitigated releases in a time frame prior to effective evacuation of the close-in population such that there is a potential for early health effects.” The use of system states to define magnitudes of release has been discussed in NUREG/CR-6596 for calculating LERF.
  - Note that the Commission rejected the recommendation to use LERF ($10^{-5}$/year) in place of LRF ($10^{-6}$/year) in the Safety Goal Policy statement.

LRF appears to be a more appropriate surrogate for sequences involving multi-unit site-specific
Conclusions

• Multi-unit events are important contributors to site risks
• Parametric CCF methods for multi-unit CDF assessment are useful but limited data are available
• Causal dependence methods need further research beyond external event fragility methods currently practiced
• Unit-to-unit causal events could be significant contributors to marginal CDFs of single units, but not as much in multiple CDFs
• Site-level CDF and LRF as surrogates to latent cancer and prompt fatality QHOs are appropriate but should be clearly defined
• Site-level level-3 PRA analyses would be useful
Questions?