A REVIEW OF SELECTED MULTI-UNIT PRA ISSUES

Presentation at the
Probabilistic Safety Assessment 2019 Topical Meeting
Charleston, SC, April 28-May 3, 2019

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Introduction

- This paper presents a partial set of select issues in MUPRAs
- A variation of this paper was presented at the WGRISK International Workshop on Status of Site Level PSA Developments, Munich, Germany, July 18-20, 2018

Calculation and Interpretation of MUPSA Risk Metrics

Sum of Individual Unit Risk Metrics

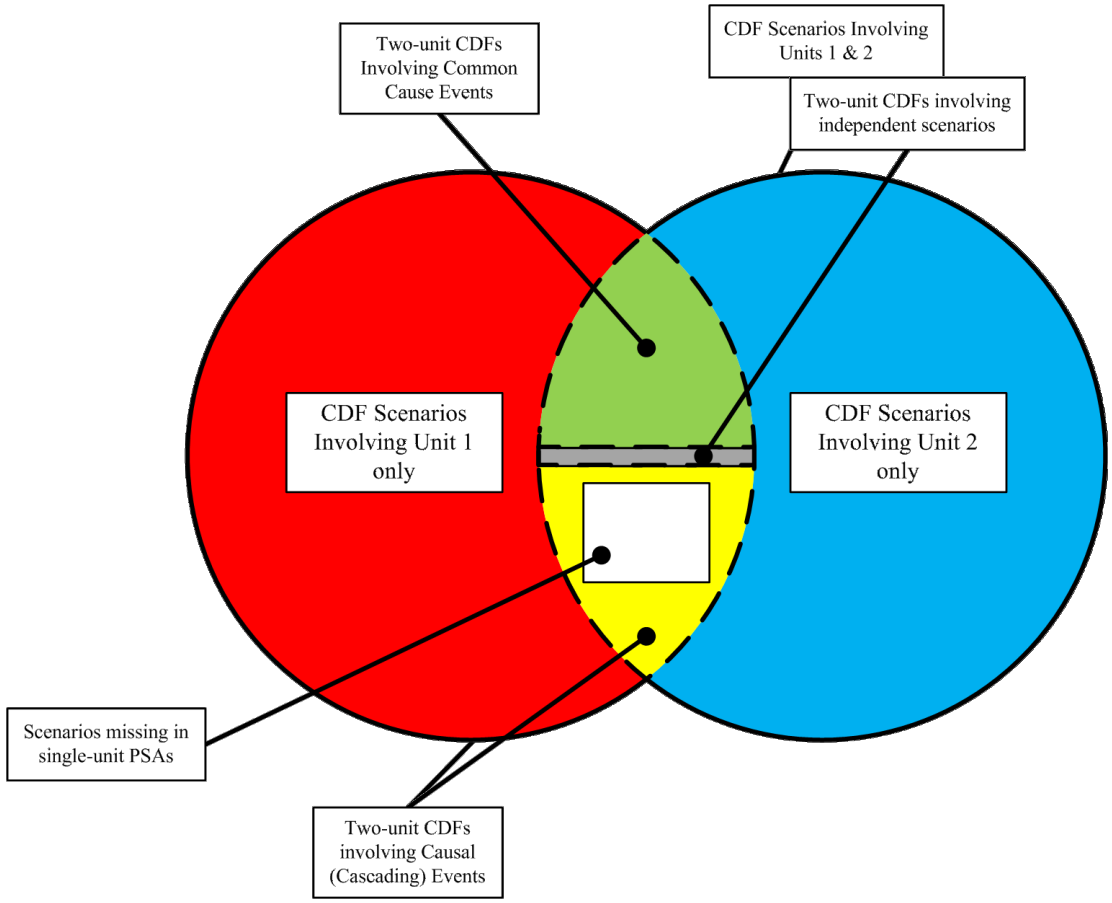
The upper bound of the site risk metric is not necessarily the sum of individual unit risk metrics

- Consider the probability of the union of multiple non-mutually exclusive random events:

$$\Pr(E_1 \cup E_2 \cup \cdots \cup E_n) < \Pr(E_1) + \Pr(E_2) + \cdots + \Pr(En).$$

- True when $\Pr(E_i)$ is the marginal probability of events E_i
- Single-unit PRAs are conditional CDFs not "marginal" CDF
- If certain initiators are not included in the PRA then CDF is conditional
- Single-unit PRAs often lack cascading initiators (e.g., room flooding or missiles generated in one unit evolves to an initiator in another unit)
- In these cases the true multi-unit risk could become larger than the sum of individual (conditional) unit risk metrics

Sum of Individual Unit Risk Metrics (Cont.)

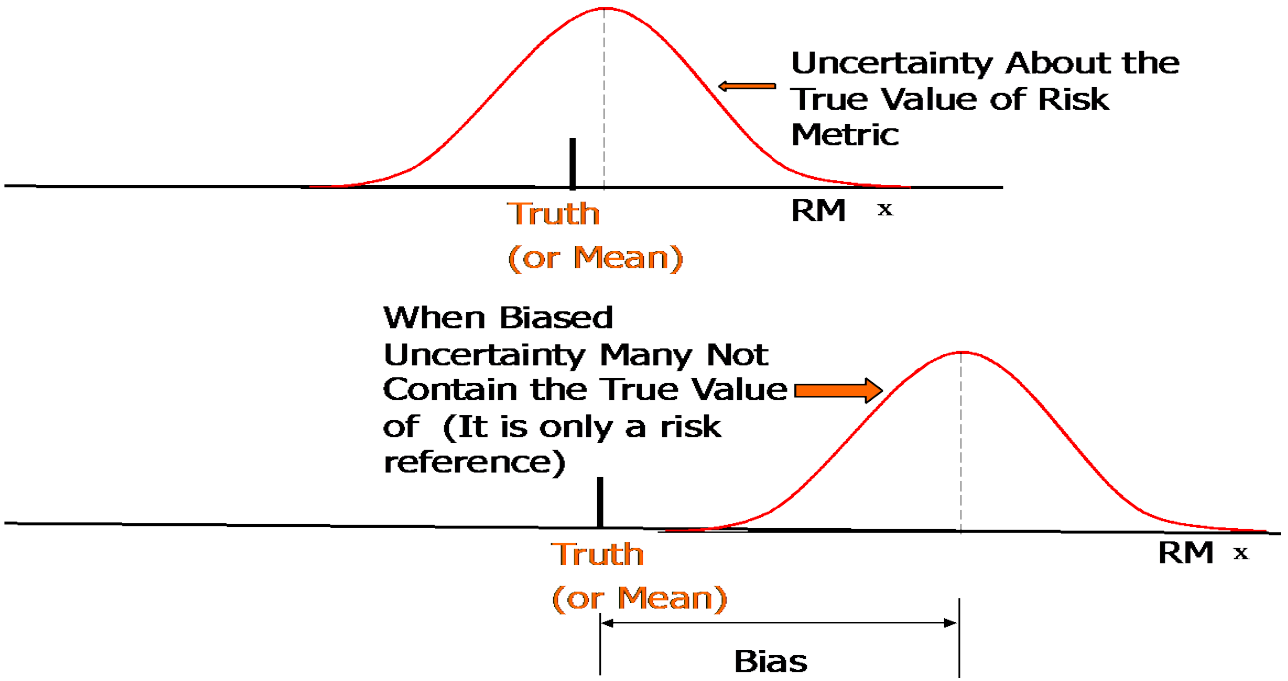


Bias in Risk Metrics

Bias is not an uncertainty and usually exists in risk metrics that complicates risk aggregation

- The amount (or degree) of bias in PRA results is uncertain
- Bias is a deliberate skewness in the risk results whereas uncertainty results from lack of knowledge and information
- Bias is risk metric of PRAs originates from sources below:
  - Conservatism
  - Approximation
  - Scope
  - Simplification
  - Quality

Bias in Risk Metrics (Cont.)

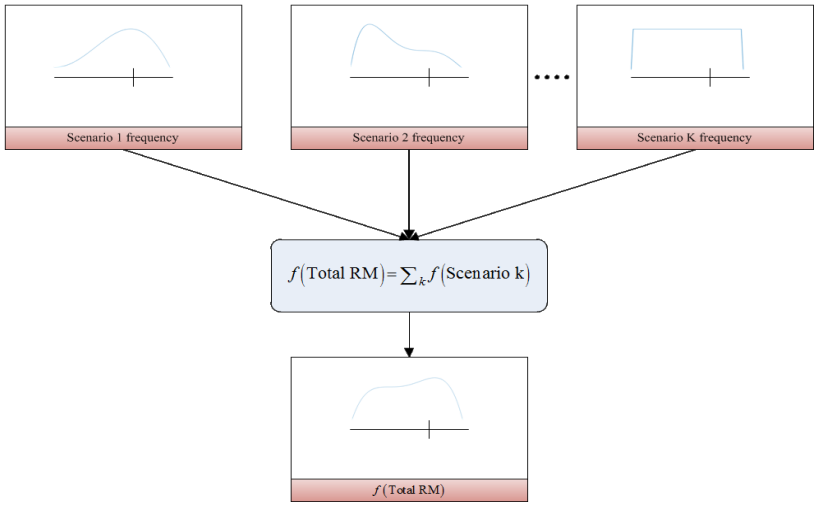


- Biased risk metric should be corrected to envelope the true risk metric
- Corrections needed for proper risk aggregation
- Biased risk metric in risk-informed applications could mask risk contributors!

Aggregation of MURPA Risk Metrics

Biased risk metrics from multiple hazards, reactor units, and radiological sources can't be aggregated

- The mean of unbiased identical risk metrics (e.g., CDFs from internal and external initiators) can be simply summed (aggregated).
- Similarly, risk metric distributions can be summed through Monte Carlo simulation



Aggregation of MURPA Risk Metrics (Cont.)

- If risk metrics are biased one method proposed is to elicit k experts for the amount of bias in metric i (see Multi-Unit Risk Aggregation with Consideration of Uncertainty and Bias in Risk Metrics, Zhou, Modarres, Droguett, Reliability Engineering and System Safety, 2019.)

$$\frac{f_i^{ub}}{f_i^b} = F_i$$

$$F_i = \left(\prod_{k=1}^{n} F_i^k\right)^{1/n} \Rightarrow \quad f_i^{ub} = F_i \times f_i^b$$

$$L(F_i|m_i, s_i) = \prod_{k=1}^{n} \frac{1}{\sqrt{2\pi}} \frac{1}{F_i^k s_i} e^{-\frac{\left[\ln\left(F_i^k\right) - m_i\right]^2}{2s_i^2}}$$ For equally qualified experts

$$L(F_i|m_i, s_i) = \frac{1}{\tau} \prod_{k=1}^{n} \frac{1}{\sqrt{2\pi}} \frac{1}{F_i^k s_i} e^{-\frac{\left[\left(ln\left(F_i^k\right)\right)^{w_k} - m_i\right]^2}{2s_i^2}}, where, \sum_{k=1}^{n} w_k = 1$$ For unequal experts

$$\pi_1\left(m_i, s_i | \text{ all } F_i^k\right) = \frac{L(F_i|m_i, s_i)\pi_0(m_i, s_i)}{\iint_{m_i, s_i} L(F_i|m_i, s_i)\pi_0(m_i, s_i) dm_i ds_i} \Rightarrow \quad f_i^{ub} = F_i \times f_i^b$$

Issues Related to MUPRA Dependencies

Applicability of Single-unit CCF to MURPAs

Application of single-unit parametric CCF values may not apply to multi-unit common cause events

- While parametric CCF models apply, inter-unit dependencies are weaker than intra-unit dependencies because of weaker coupling factors
- Our earlier works show inter-unit hardware dependencies have a mean conditional failure probability of 0.028, whereas the β factor intra-unit dependencies for hardware (NUREG/CR-6268) range: 0.03-0.22
- Use of intra-unit CCF parametric estimates adds bias into the results with possible masking of site-based critical events
- More analysis would be needed in this direction

HRA Dependence in MUPRAs

Human errors across multiple units/radiological sources are not independent

- Pre-initiator actions and post-initiator recovery actions rely on similarly developed procedures, training and sometimes shared personnel
- Control rooms of multiple units shared contiguous area
- Our analysis of the U.S. LER data showed that the mean conditional probability that an operator will make a similar pre-initiator error in a second unit is 0.032 (even larger than hardware inter-unit dependencies!)
- Prevailing common socio-economic, political and safety culture also affect human dependencies

Casual Dependencies Across Multiple Units

Causal (cascading) dependencies among dissimilar units in MUPRAs should be considered

- A mishap (e.g., pipe break or fire) in a shared area between multiple units could cascade into diverse failures or initiating events in other units
- An external event may cause different responses in terms of SSC failures, initiating events and human actions in the other units
- Deficient spent fuel cooling resulted in overheating, rapid oxidation and generation of large amounts of hydrogen, led to the explosion/destruction of the adjacent reactor buildings at the Fukushima units 1 and 3

Dependencies in Probabilistic Seismic Hazard Frequencies of Multiple Units

Same probabilistic seismic hazard frequency fully dependent or fully independent seismic fragilities are improper for seismic-MUPRA

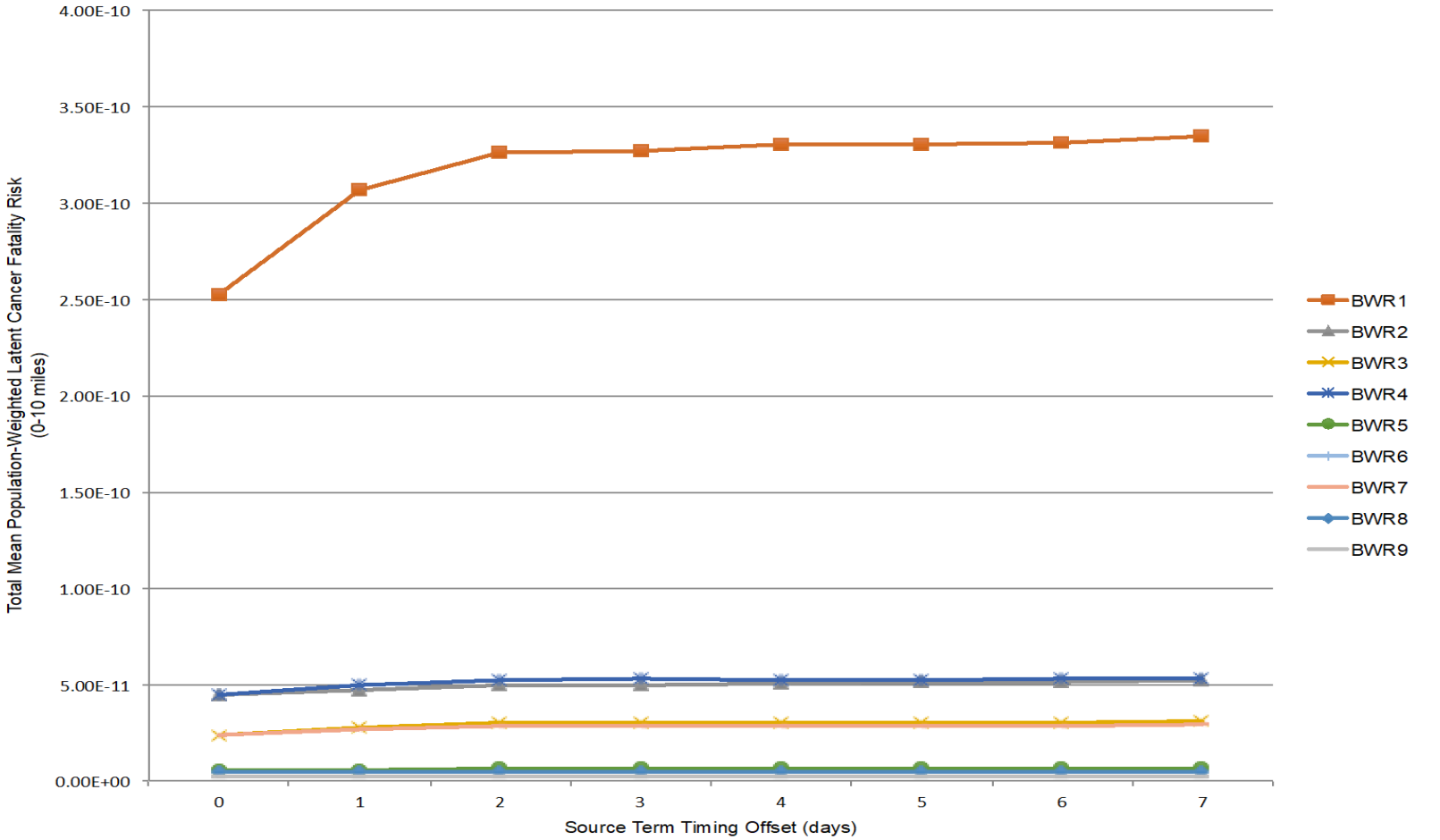
- Various factors such as geological differences spatial variability affect ground motion and site response at different points of the site (we have a paper on this topic in this PSA2019 meeting)
- Soil deposits tend to act as "filters" to seismic waves by attenuating (or de-amplifying) motion at certain spectral frequencies and amplifying it at others
- Soil conditions often vary over short distances, so ground motion can vary within a small area

Worst Site's Radiological Releases

The worst site risk may not necessarily correspond to simultaneous releases from all the units

- This assumption is mostly true but not always
- Timing of the release, evacuation and weather conditions, including nonlinear dose-consequence play a role
- Counter-intuitively, a mild increasing trend was observed and attributed to the latent cancers arising from long-term exposures during the recovery

Worst Site's Radiological Releases (Cont.)



Source: Hudson, D. W., & Modarres, M. (2017). Multiunit Accident Contributions to Quantitative Health Objectives: A Safety Goal Policy Analysis. Nuclear Technology, 197(3), 227-247

Conclusions

- MUPRA is an important consideration to identify and risk-inform site-level contributors and risk-informed decisions:
  - It is important to model all dependencies among the site's units and other radiological sources
  - There are differences between dependencies at the single-unit, multi-unit, site-level and multi-site (regional-level)
  - This paper only addresses a select set of issues and there are more not covered in this paper

Thank you

A Quick Overview of MUPRA