# What's Accomplished and What's Remained in MUPSA Methods and Applications

Keynote Talk

Technical Meeting on Multiunit Probabilistic Safety Assessment
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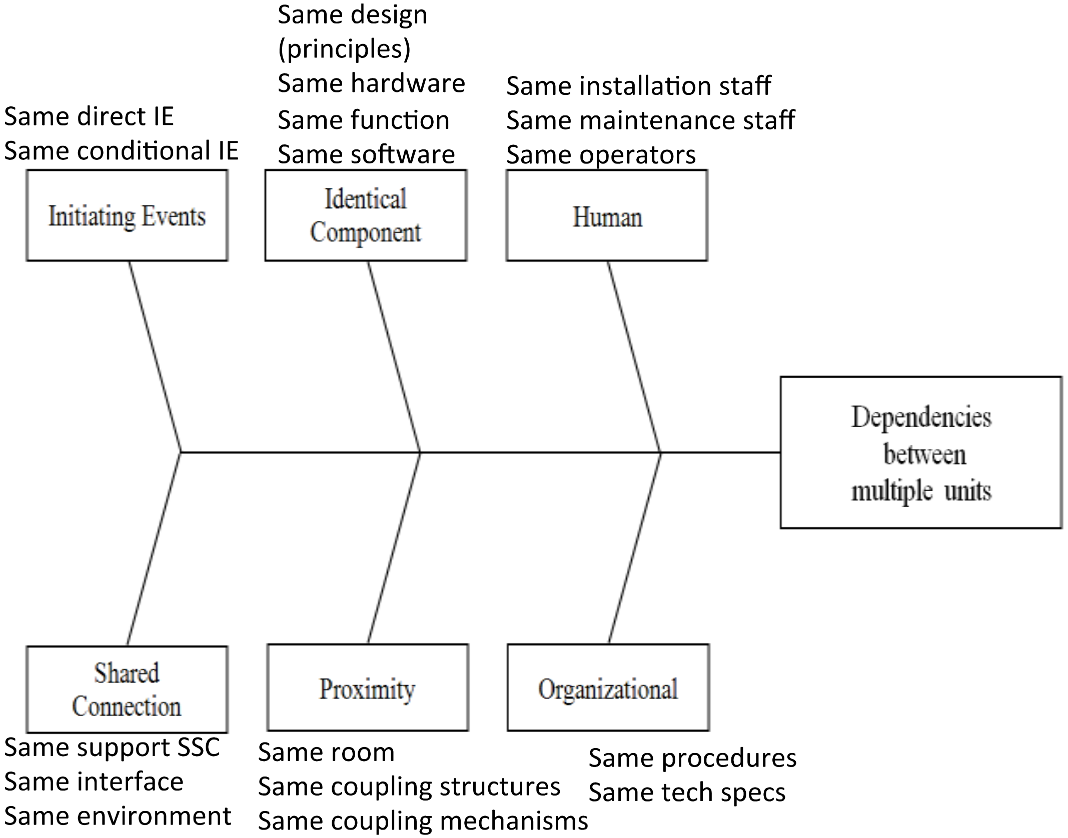
# Progress in MUPSA and Guidance Developments: Milestones

- Mid-1980's: Seabrook Level 3 PRA
- International Workshop on Multi-unit PRA, Ottawa, Canada, November 17-20, 2014
- IAEA Initiatives
  - (2012-2015)Technical Approach to PSA for Multiple Reactor Units, Safety Series # 96
  - (2016-present) Ongoing efforts. Draft TECDOC on MUPSA Guidelines and Case Study
- EPRI Initiative
  - (2018-present) Final MUPSA Framework for MUPSA Phase 1 Internal Events & Case Studies
- OECD /NEA WGRISK meetings
- International Initiatives

# MUPSA is About Identifying and Modeling Dependencies

- Suzanne (Schroer) Dennis dependency categories:

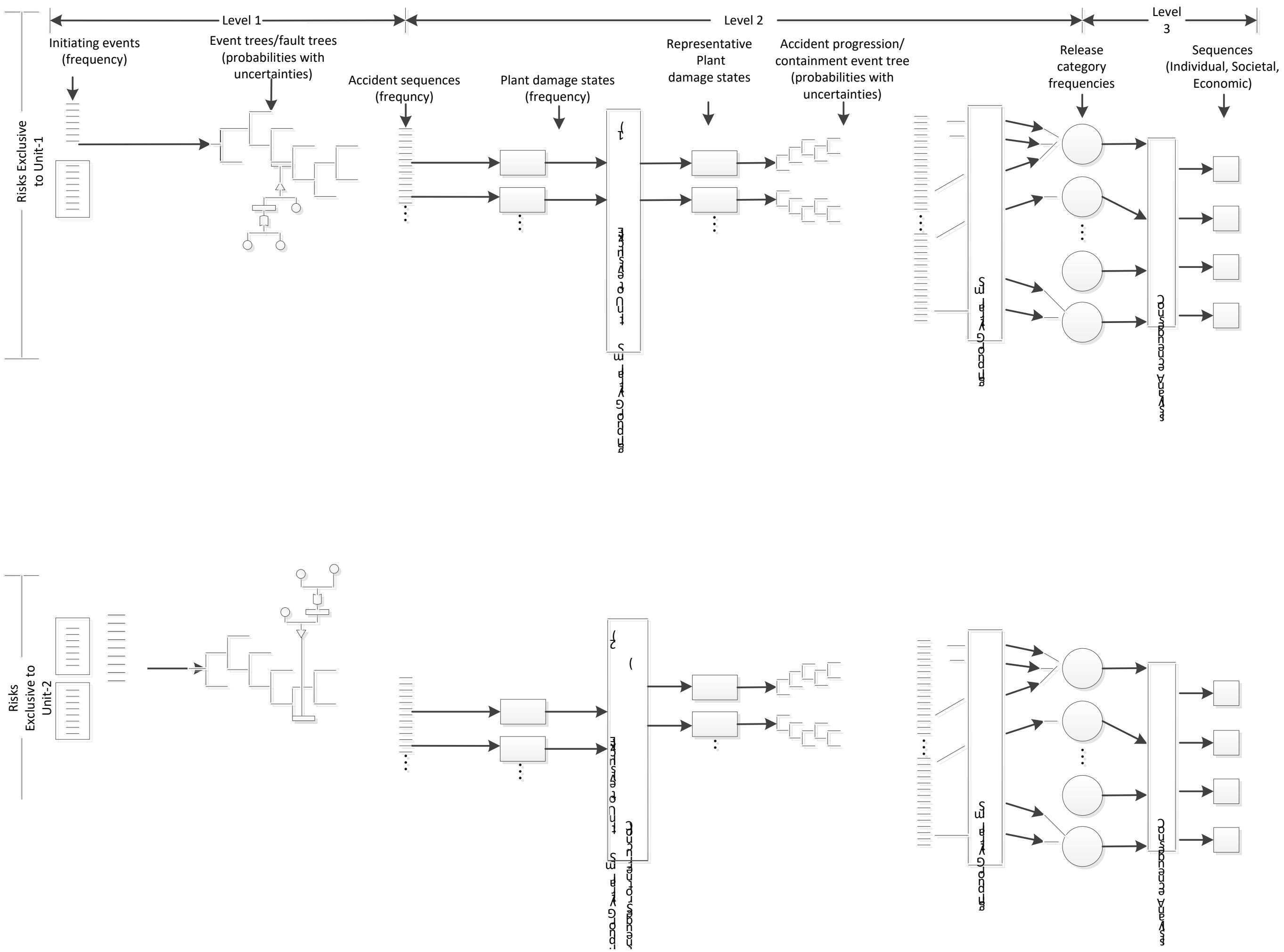



## IMPORTANT FINDINGS

- 17% of LERs in MULTI-UNIT 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.*

# MUPSA: Identifying Dependencies



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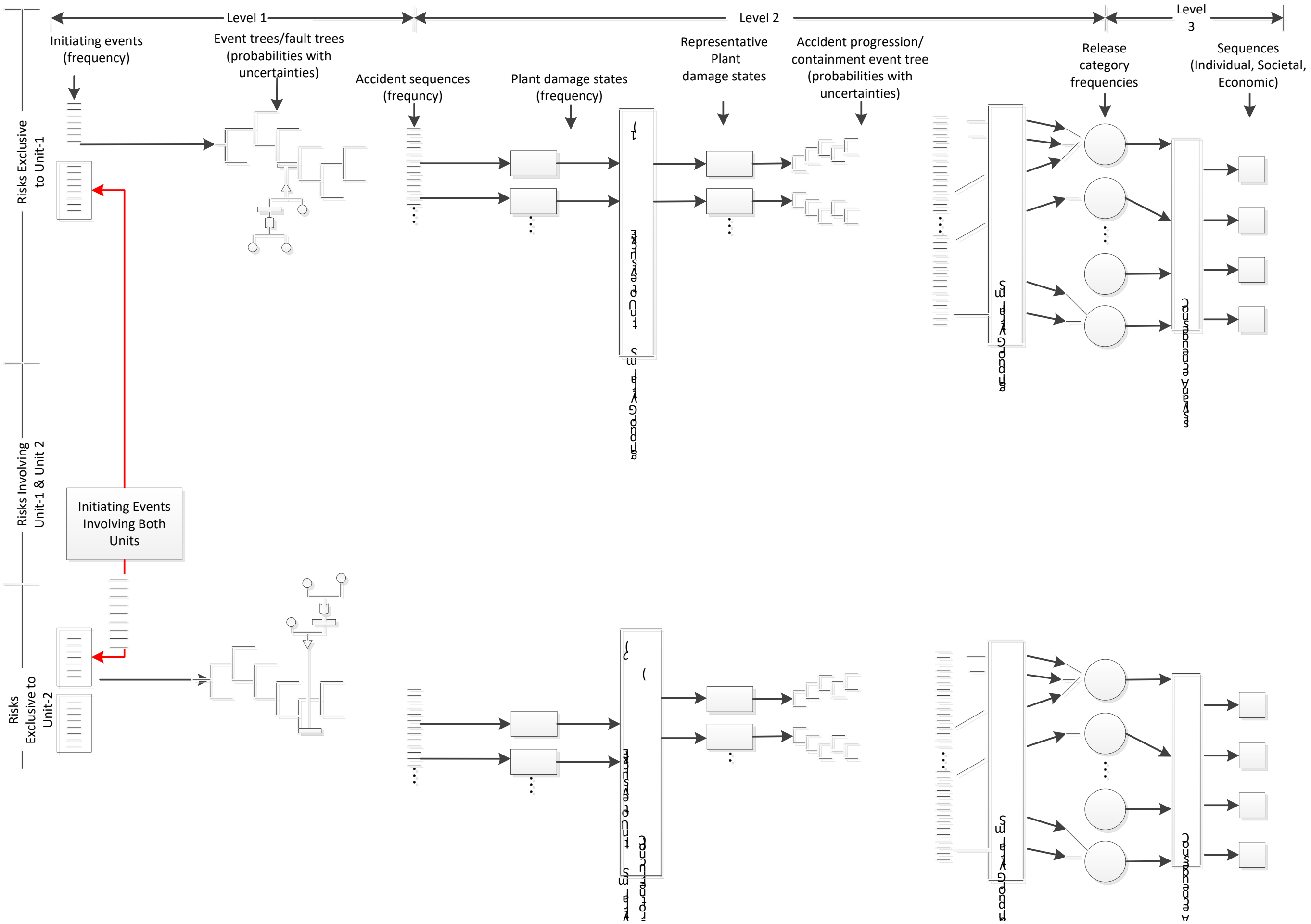

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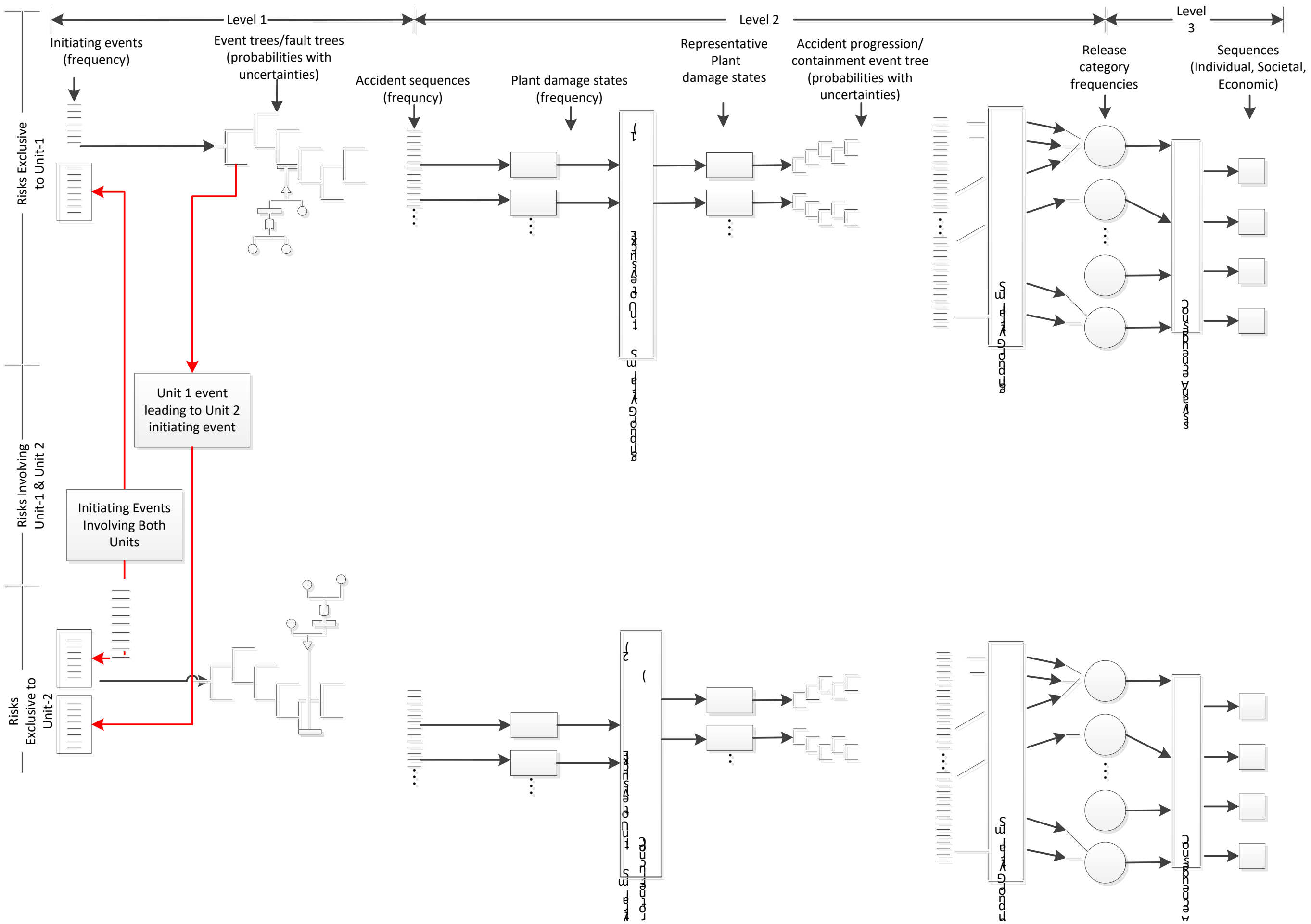

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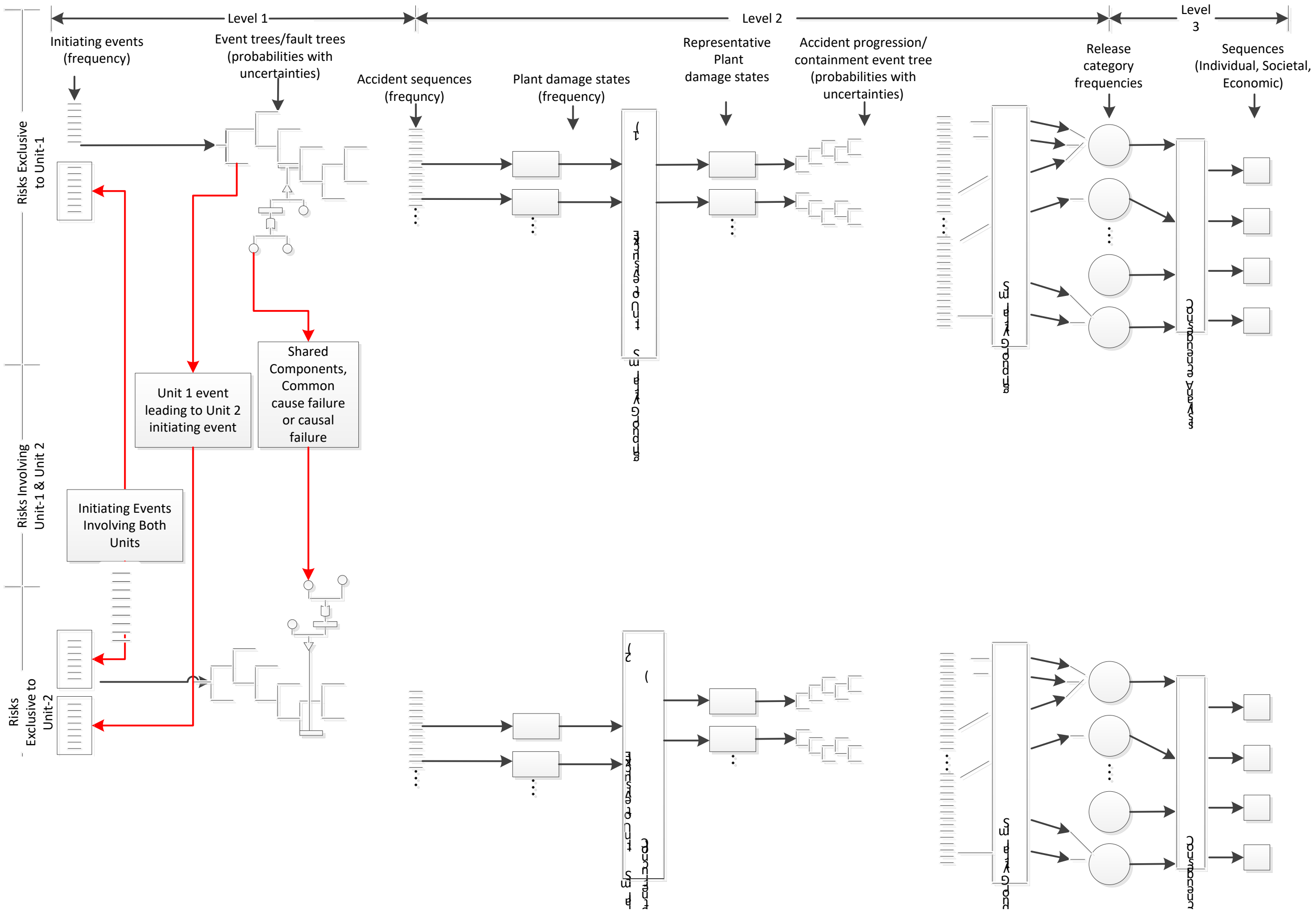

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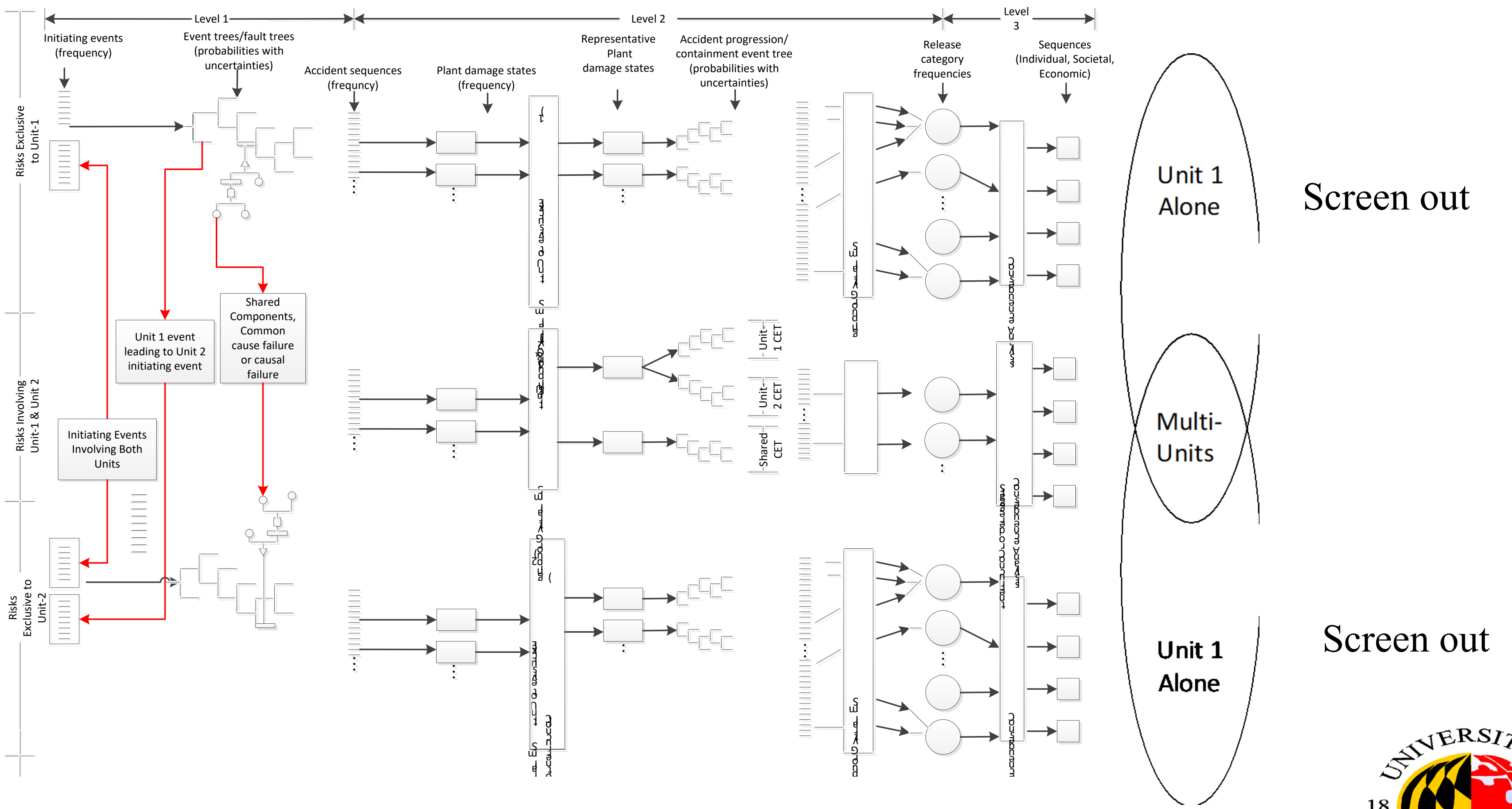

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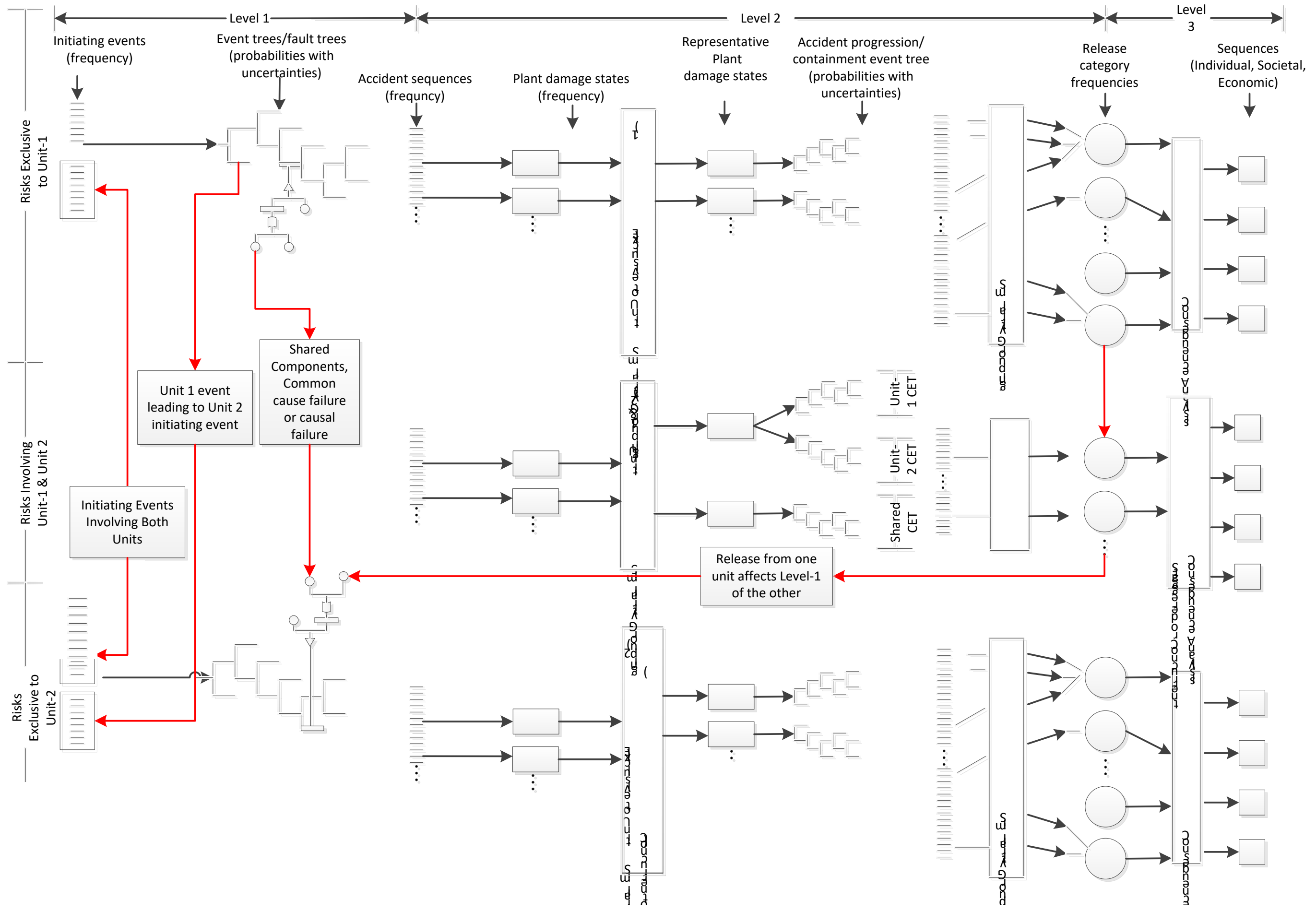


# Progress in MUPSA Modeling

- Identifying and modeling common cause events across units (hardware and human)
- Accounting for shared and cross-ties equipment & assets across units
- Multi-unit initiating events and frequency assessment
- SUPSA model screening & accident sequence analysis involving multiple units
- Identifying and modeling dependent human reliability
- Quantification of MUPSA models
- Internal flood
- Site operating states (SOSs)
- Seismic dependencies
- Useful insights from MUPSA case studies (EPRI's study)
- Level-I Risk Metrics

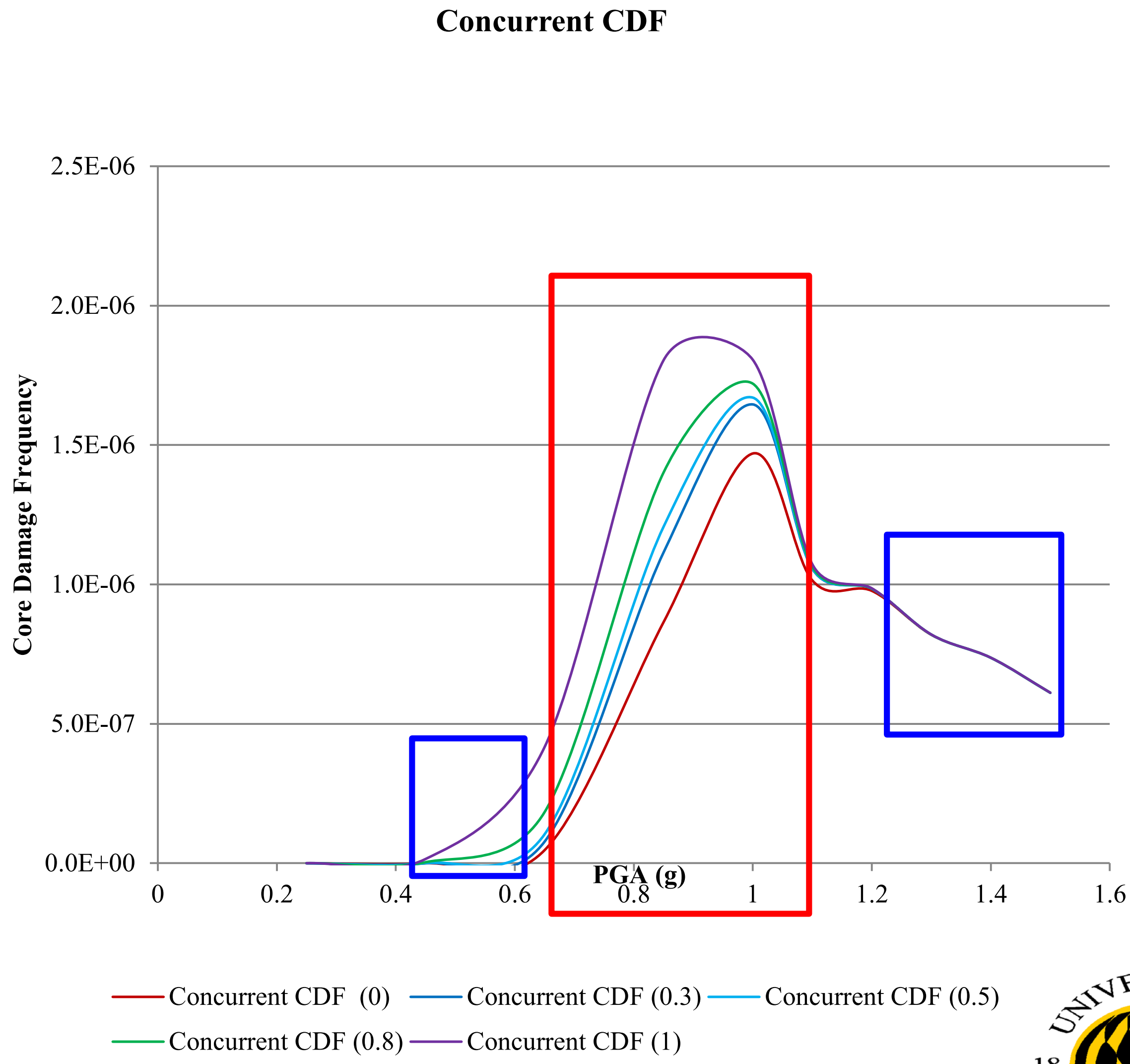
= Good progress = Some progress = Minor progress

# Examples of LER-based CCFs across multiple units

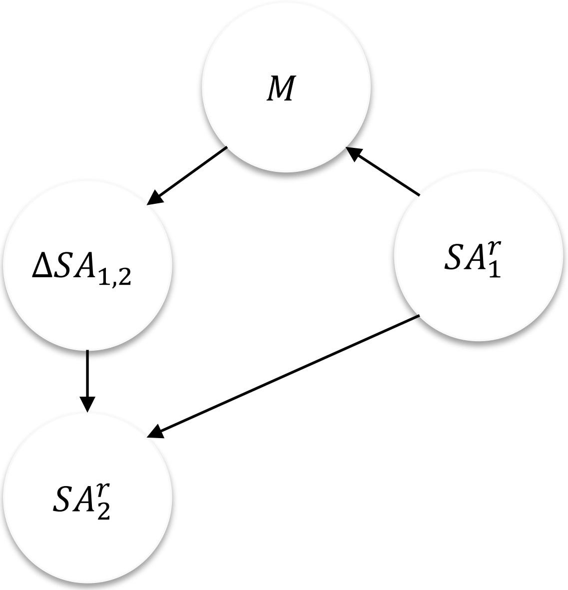
| Events Categorization, j (identified for either i=2 for events involving 2 units, or i=3 for events involving 3 units) | Number of occurrences of type j events involving i units, $n_{ij}$, reported by Schroer[20] | Point estimate of the probability of the event, $\hat{p}_{ij}$ | The 95% posterior Bayesian 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) $(HE_x\|HE_y)$ | 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) $(IE_x\|IE_y)$ | 7 | 0.010 | (4.3E-03; 1.9E-02) |
| Component Failure/Degradation in One Unit Causes Initiating Event in Other Unit(s): $(C_x\|I_y)$ | 8 | 0.011 | (5.2E-03; 2.1E-02) |
| Component Failure/Degradation in One Unit Causes Different Component Failure/Degradation in Other Unit(s): $(C_x\|C_y)$ | 24 | 0.017 | (1.1E-02; 2.5E-02) |
| Initiating Event in One Unit Causes Component Failure/Degradation in Other Units: $(IE_x\|C_y)$ | 1 | 0.001 | (1.5E-04; 6.4E-03) |

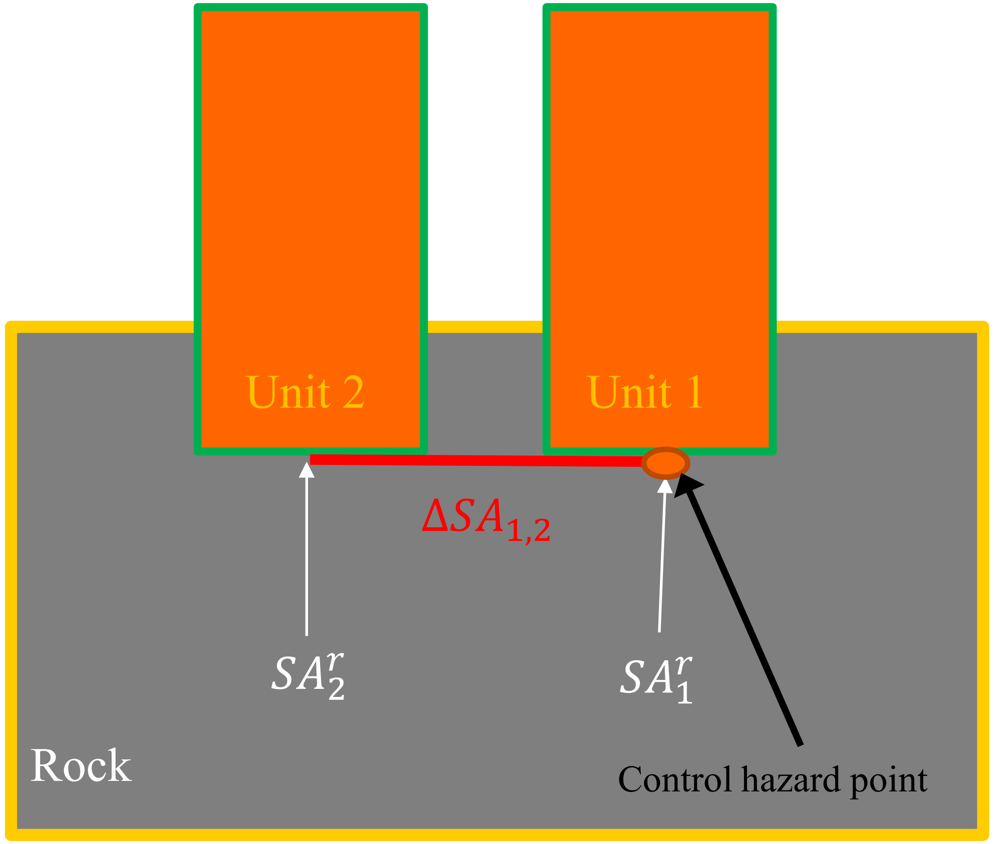
# Multi-Unit CDF vs. PGA

- Hypothetical site consisting of two advanced reactor units at power.
- Seismically induced small loss of coolant accident (SLOCA) concurrently.
- Sensitivity study.: independent (i.e., 0), partial (i.e., 0.3, 0.5, 0.8) and full dependency (i.e., 1.0).
- Total Site CDF (i.e., at least one CD); Multi-Unit CDF (i.e., concurrent CDs); Marginal CDF.



# Spatial Variability of Ground Motion—Rock Site

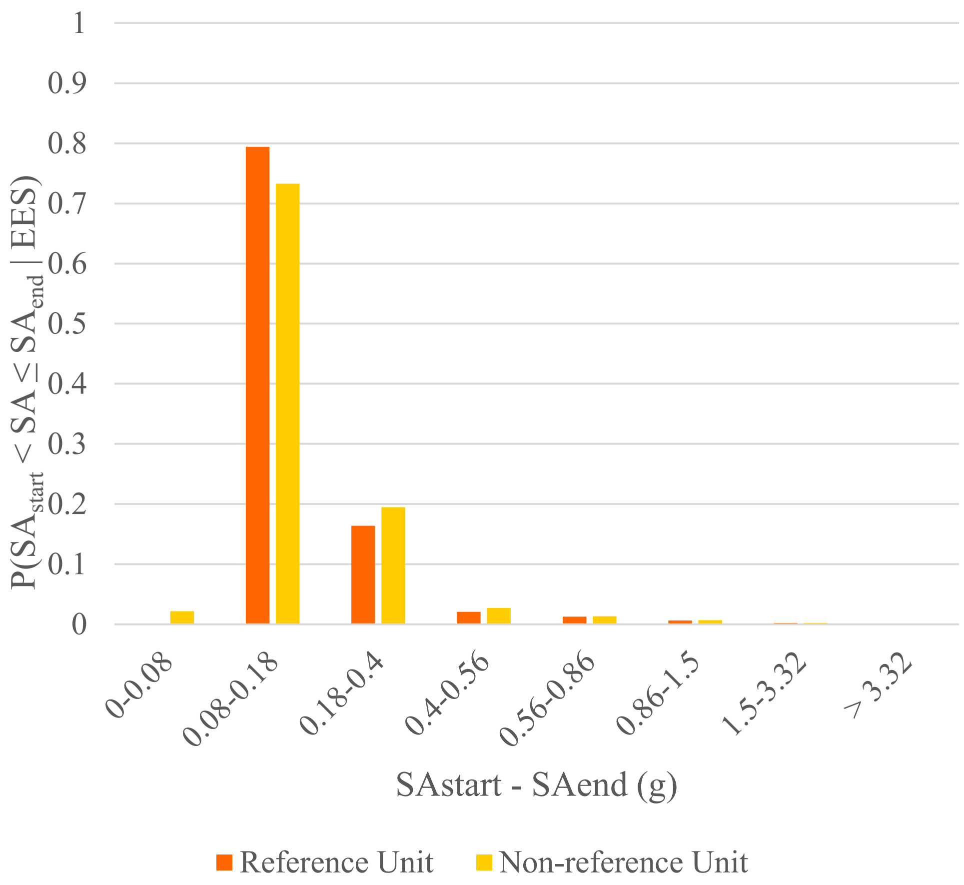


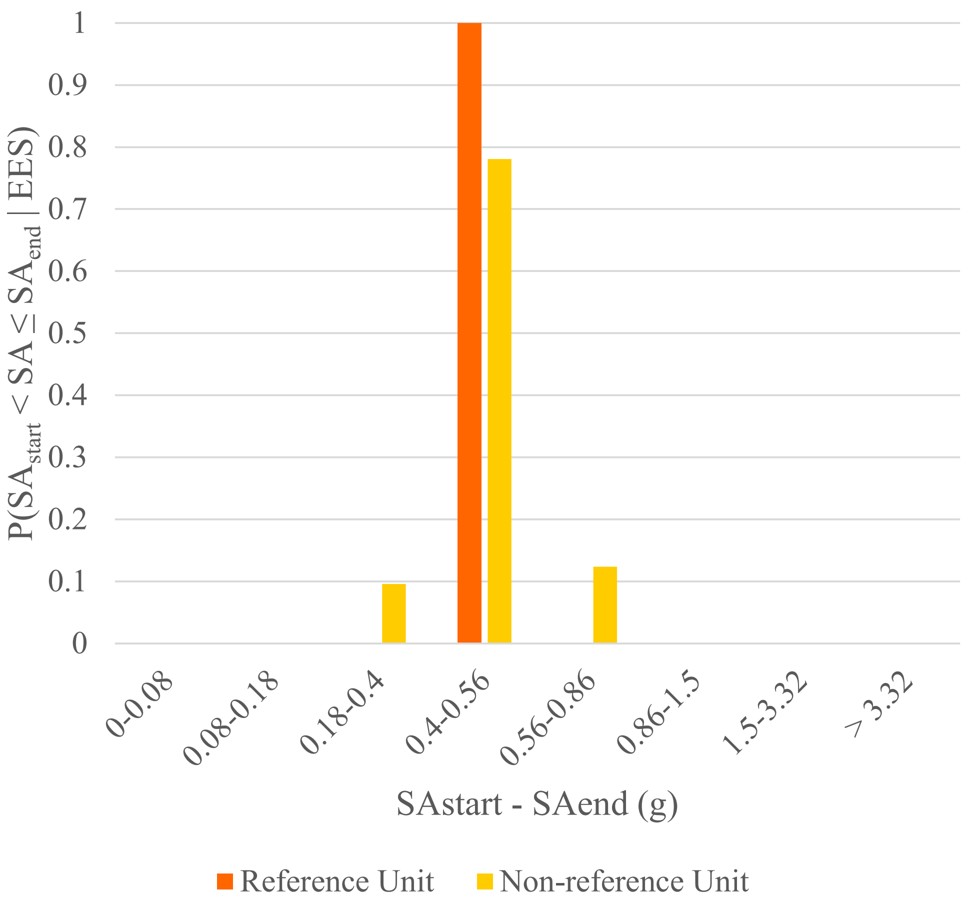




Unit 1 = reference unit (location)
Unit 2 = non-reference unit (location)
$SA_1^r$ = ground motion experienced by Unit 1
$SA_2^r$ = ground motion experienced by Unit 2
$M$ = earthquake magnitude
$\Delta SA_{1,2}$ = ground motion variability model

DeJesus Segarra, J., Bensi, M., Weaver, T., and Modarres, M. "Extension of Probabilistic Seismic Hazard Analysis to Account for the Spatial Variability of Ground Motions at a Multi-Unit Nuclear Power Plant Site," *Structural Safety* (under review).

# Probability Distribution of Ground Motions

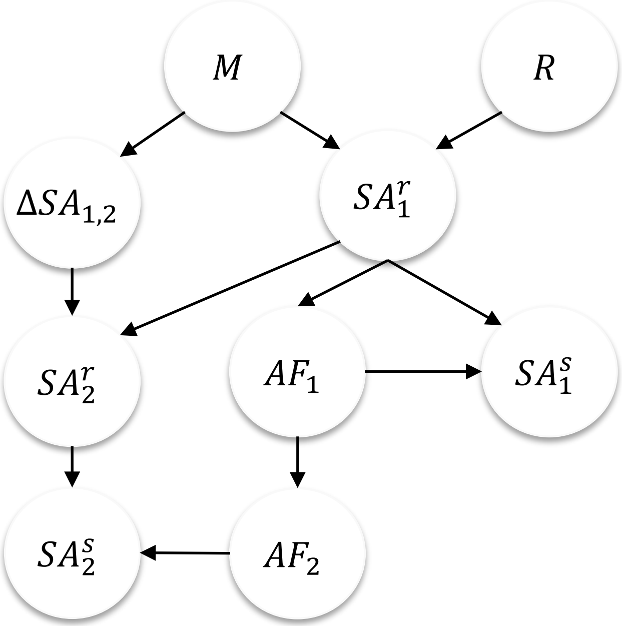


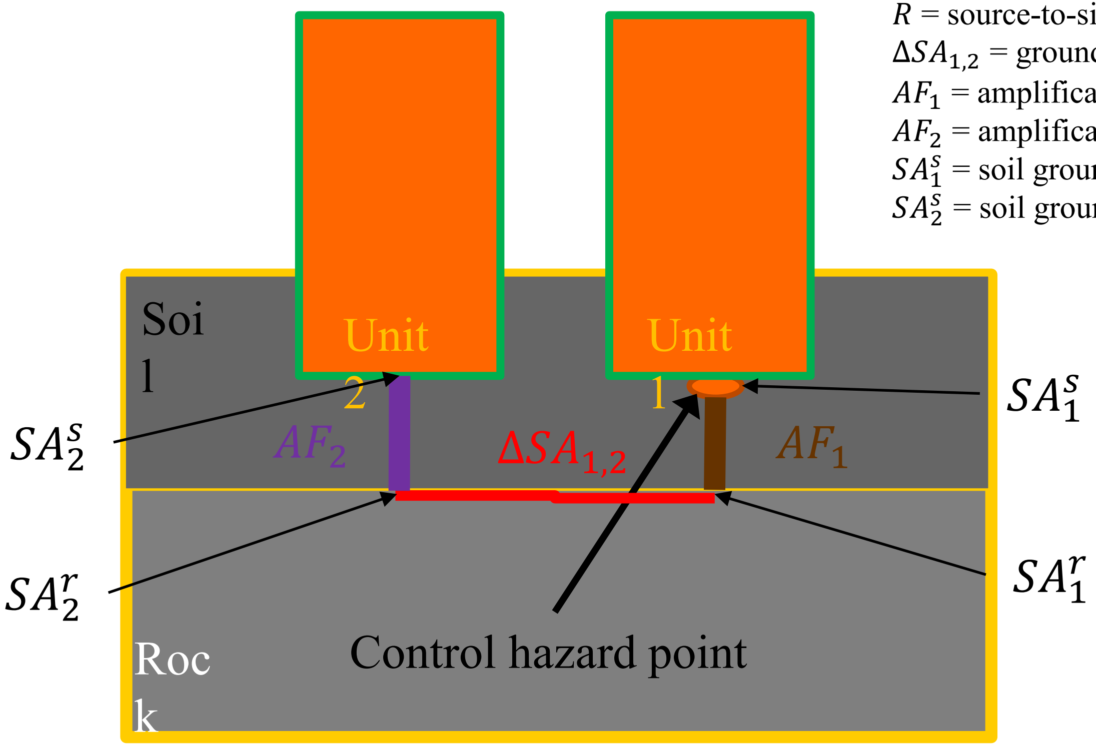




EES = earthquake of engineering significance

$SA_{start}$ and $SA_{end}$ = value of ground motion at the start and end of ground motion bin, respectively

# Backup Slide—Ground Motion Variability Model for Soil Site




Unit 1 = reference unit (location)
Unit 2 = non-reference unit (location)
$SA_1^r$ = bedrock ground motion experienced underneath Unit 1
$SA_2^r$ = bedrock ground motion experienced underneath Unit 2
$M$ = earthquake magnitude
$R$ = source-to-site distance
$\Delta SA_{1,2}$ = ground motion variability model
$AF_1$ = amplification factor for Unit 1
$AF_2$ = amplification factor for Unit 2
$SA_1^s$ = soil ground motion experienced by Unit 1
$SA_2^s$ = soil ground motion experienced by Unit 2

# My Views on Remaining MU Inter-dependency Identification and Modeling: Level I

- ➢ Definition of site and risk metrics
- ➢ Quantification of CCFs across reactor units
- ➢ Data and models for dependent HRA across reactor units
- ➢ Seismic and other external event correlations
  - ➢ Fragility correlations
  - ➢ Spatial spectral acceleration dependencies
  - ➢ Regional sites
- ➢ Causal (cascading) dependent events
- ➢ Large sites with many different interacting units (SOS )
- ❖ Low power and shutdown integration into MUPSA
- ❖ Identifying and modeling dependencies between reactor units & spent fuel pool
- ❖ Shared resources (emergency response, Flex equipment,…)
- ❑ Adjacent sites (Regional dependencies)

➢ = High Priority
❖ = Medium Priority
❑ = Low Priority

# My Views on Remaining MU Inter-dependency Identification and Modeling: Level II & Level III

- Guidance development
- Definition of MU and site LRF and LERF
- Case studies
- Unit-to-unit & unit-to-spent fuel storage dependencies (CCF and cascading)
- Site-level source-term, release magnitudes, energies and timing offsets, multiple release points
- Risk metric aggregation across reactor units, hazard groups, operating states including consideration of biases
- Interpretation of risk and safety significance in MUPSA results
- Comparing aggregated risks against safety goals
- Risk-informed and DiD applications

# MU Risk Metrics

- Progress
  - Number of core damage-based metrics: MUCDF, Site-MUCDF
  - CMUCDP ranges from 0.03 to 0.7 depending in the degree of separation and independence and consideration of seismic, internal flood and fire
- Remaining
  - Core damage-weighted metrics: MUCDF, Site-MUCDF
  - Site measure of damage (CDF + Spent fuel damage)
  - Site LERF and LRF
  - Characterization of site release (concurrent release may not always be the worst)
  - Risk metric uncertainties, biases and site risk aggregation across units and hazard
  - Level 2 & 3  metrics, sequence delineation, analysis and mission times

# Other (Lofty) Remaining Tasks

- Standards (ASME/ANS and IAEA)
- SAMGs in the context of MU accidents
- Safety goals in the context of site and regional risks
- International consensus.
- Use of MUPSA results to enhance DiD implementation

# Conclusion

- Good Progress since the Ottawa workshop of 5 years ago
- No need for integrated MUPSA, single-unit PSAs screening works
- International interest and contribution with varied accomplishments
- External events drive the multi-unit and site risks
- Cascading (causal) events should be further developed
- Site-level risks aggregation in early stages of development
- Level II and Level III MUPSAs are important and not a lot done
- Relevance and interpretation of existing safety goals for site events

# Thank you

# Examples of More Specific Dependencies: Partial

**Examples of Human Dependency Subclasses**

| Pre-Initiating Event | Post-Initiating Event |
|---|---|
| Missing Surveillances | Misalignment Of Breakers After Loop Or SBO |
| Maintenance Cleaning | Misalignment Of Valves After Transient |
| Identical Installations | Mental Slip Because Of Lack Of Attention To Other Units After An Event |
| Transposition Errors | |
| Identical Maintenance Actions | |

**Examples of Organizational Dependencies**

Incorrect Procedure That Has Been Mirrored For Multiple Units

Latent Design Issue That Affects Multiple Units

Incorrect Calculation That Is Used On Multiple Units

Incorrect Technical Specifications That Have Been Mirrored For Multiple Units

Incorrect Vendor Guidance That Has Been Applied To Multiple Units.

Incorrect Engineering Judgment That Has Been Applied To Multiple Units

A Misinterpretation Of Guidance Or Requirements That Affects Multiple Units

A Misunderstanding Of System Configuration Or Function That Affects Multiple Units

Poor Safety Culture, Which Leads To Errors Of Judgment And Execution Across The Organization

Lack Of Adequate Training And Skills For Events That Affect Multiple Units