# NRC-RES' Sitewide, All Hazards Level 3 PRA Project: Approach and Results for Multi-Unit Level 1 Risk

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**Abstract:** The U.S. Nuclear Regulatory Commission (NRC) has performed a full-scope, sitewide Level 3 probabilistic risk assessment (PRA) project (L3PRA project) for a two-unit, pressurized-water reactor reference plant. The scope of this project includes all hazards (internal and external) and all radiological sources on the reference site: 1) two, nearly identical reactors; 2) two, hydraulically connected spent fuel pools (SFPs), and 3) a dry cask storage (DCS) facility. The NRC has published a series of reports documenting the results of all of these PRA efforts.

In addition to the single unit PRAs performed for NRC's L3PRA project, a previously, never-performed task was added: integrated site risk. In order to develop integrated site risk results, multi-unit PRA (MUPRA) results were developed first.

The MUPRA results were developed using these high-level steps: 1) perform a systematic, sitewide dependency assessment, 2) assign multi-unit (MU) coupling factors for identified MU dependencies, and 3) perform MU core damage frequency (MUCDF) calculations.

The approach for performing the sitewide dependency assessment was based on previously published reports by the Electric Power Research Institute (EPRI) and the International Atomic Energy Agency (IAEA). The assessment was performed using a phased approach to address multiple categories of potential MU dependencies. Relevant sitewide (or MU) initiating events were identified first. Other categories of potential MU dependencies were addressed only for those MU initiating events (MUIEs). Identified potential MU dependencies were assigned generic coupling factors. Reviews of cutsets for L3PRA project's single unit PRAs informed the assignment of coupling factors. Different types of coupling factors were used in MUCDF calculations (e.g., MU common cause failure coupling factors, MU seismic hazards correlations).

NRC's L3PRA project developed at-power, MUCDF estimates for all hazards, (i.e., internal and external events). Insights have been developed for these results, such as:

- How do the total MUCDF results compare with total single unit CDF?
- Which hazard(s) produced the largest MUCDF results?
- What multi-unit dependencies contribute the most to MUCDF for different hazards?

## 1. INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has performed a full-scope site Level 3 probabilistic risk assessment (PRA) project (L3PRA project) for a two-unit pressurized-water reactor reference plant. The scope of this all-hazards sitewide L3PRA project, includes integrated site risk (ISR), including estimation of multi-unit (MU) risk. This effort was directed by the Commission (see Staff Requirements Memorandum [1] that resulted from SECY-11-0089 [2]) and included the following radiological sources on the reference site:

- two (nearly identical) operating pressurized water reactor units (Unit 1 and Unit 2)
- two hydraulically connected spent fuel pools (SFPs), one for each operating reactor unit (Unit 1 and Unit 2)
- an independent dry cask storage (DCS) facility

Previous NRC PRA efforts, such as NUREG-1150 [3], did not include consideration of risk from the SFPs or DCS, or risk of MU accidents. Consequently, ISR is a new task that has not been previously addressed in NRC PRA efforts. Note, for the L3PRA project, the U.S. nuclear power industry's proposed Diverse and Flexible Coping Strategies (FLEX) were addressed only in a sensitivity study since the project's modeling freeze date is 2012.

In general, PRA has traditionally been performed for single units only, though the Seabrook PRA [4] was an early industry PRA effort that considered two-unit risk.* In response to the 2011 Great Japan Earthquake and the events at the Fukushima Daiichi nuclear power station,† there has been increased interest in MU in both the U.S. and internationally. In addition, there have been multiple responses from the NRC, including lessons learned [10] and implications for PRA [11] with respect to these events. Zhou and Modarres [12] summarize the history and current status of multi-unit PRA (MUPRA) development.

It also should be noted that the American Nuclear Society (ANS)/American Society of Mechanical Engineers (ASME) Joint Committee on Nuclear Risk Management (JCNRM) is currently developing a MUPRA Standard for at-power, existing light water reactors (LWRs).

At present, draft public reports have been published for all of the L3PRA project's all-hazard PRAs - single unit reactor Level 1, 2, and 3 PRAs, SFP and DCS PRAs, and the ISR task. A previous paper [13] previewed some of the ISR task results to provide preliminary MU insights that might be applicable to advanced reactors.

## 2. TERMINOLOGY FOR MULTI-UNIT PROBABILISTIC RISK ASSESSMENT

The L3PRA project's ISR task required terminology not typical for traditional single unit PRAs (SUPRAs). For example, ISR has no formal definition within the PRA community. For the purposes of the L3PRA project, the following definition has been adopted:

> Integrated site risk is the total combined risk of a release from one or more radiological sources on site (i.e., reactors, SFPs, and DCS), considering all hazards and all plant operating states.

If single source (i.e., single reactor, SFP, and DCS facility) PRAs were performed for all hazards and operating states, a simplistic approach for estimating ISR, or total risk, would be to assume that all the radiological sources are independent and, therefore, simply sum the results from all these PRAs. However, a significant limitation of this approach is that it overlooks that there can be dependencies between radiological sources (e.g., there are common initiating events that can cause all reactors on site to trip). In addition, this approach does not provide any useful PRA insights beyond what the single source PRAs have already provided.

The impact of cross-unit dependencies is illustrated in Figure 1. This figure shows a Venn diagram for core damage frequency (CDF) for two identical reactors on a site. In this Venn diagram, the following terms are used:

* Note that the second unit at the Seabrook site was never built.

† See, for example, two reports released by the Government of Japan [5, 6], an IAEA report [7], and two Institute of Nuclear Power Operations (INPO) reports [8, 9].

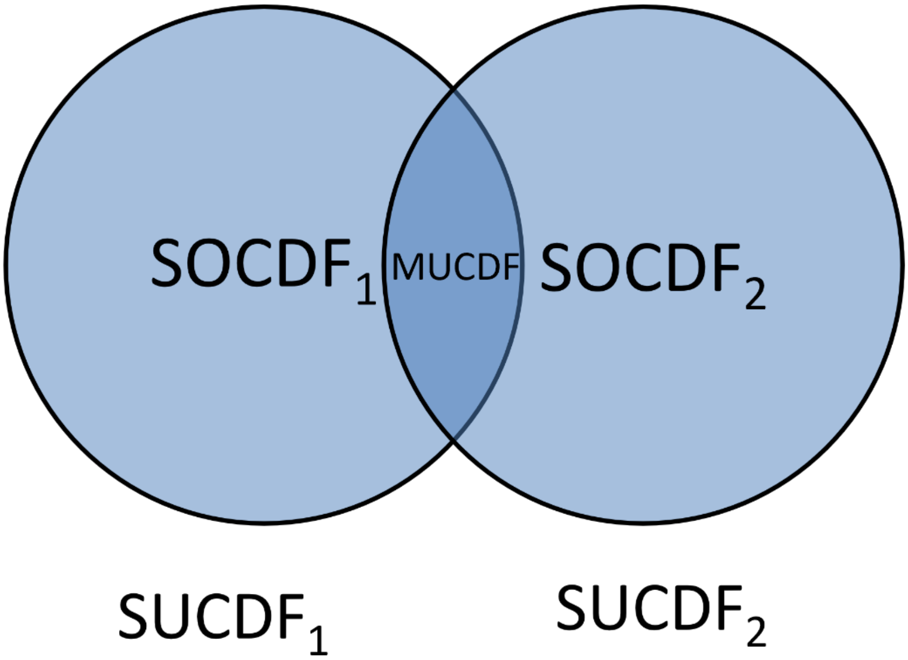


**Figure 1 Venn Diagram Showing Single Unit and Multi-Unit CDF for Two Units**

- Single unit (SU) CDF that is calculated by traditional PRAs (i.e., SUCDF)
- Multi-unit CDF (MUCDF), which is the area of overlap that represents both units experiencing core damage simultaneously
- Single unit only CDF (SOCDF), which represents only one unit experiencing core damage

The fraction of SUCDF that represents MUCDF (i.e., the area of overlap) will vary by the strength of the dependencies between the two reactors. For example, Figure 1 illustrates the case in which the fraction of SUCDF that represents MUCDF is expected to be relatively small.

Similar in concept to Figure 1, the L3PRA project's ISR task is focused on the "overlap" between the two reactors and the SFP (i.e., accidents involving both reactors and the SFP). As for Figure 1, the estimation of ISR for the two reactors and the SFP would be overestimated if the single source risks were simply added (i.e., dependencies between the radiological sources were ignored). A companion paper discusses this work.

The figure above also demonstrates that the key to estimating total or integrated risk is to estimate the risk for the areas of overlap. For the ISR task, these areas of overlap are identified as MU risk and multi-source risk, respectively, and defined as follows:

- MU risk is the risk from concurrent or simultaneous accidents for multiple reactors (i.e., both reactors on the two-unit reference site).
- Multi-source risk is the risk from concurrent or simultaneous accidents for multiple reactors (i.e., both reactors on the reference site) and another radiological source (i.e., either the SFPs or the DCS on the reference site).

Because the definitions for MU and multi-source risk focus on certain very challenging accidents, there is an opportunity for PRA results to provide additional insights and to identify potential vulnerabilities that the single source PRA cannot provide. The remainder of this paper addresses MU risk, specifically, MUCDF.

## 3. MULTI-UNIT LEVEL 1 PRA APPROACH

In addition to the limited experience in performing MUPRAs, there is also limited guidance for developing MUPRAs. Three reports that provide such guidance were used in the L3PRA project's ISR task:

- two International Atomic Energy Agency (IAEA) reports on multi-unit probabilistic safety assessment [14, 15]
- one report on the use of MUPRA to support risk-informed decision-making by the Electric Power Research Institute (EPRI) [16]

The MUPRA results were developed using two high-level steps: 1) perform a systematic, sitewide dependency assessment, and 2) perform multi-unit core damage frequency (MUCDF) calculations. Note that MUPRA results were produced for at-power conditions only.

## 4. SITEWIDE DEPENDENCY ASSESSMENT

A formal approach and associated guidance were developed to support the L3PRA project's technical leads who performed the sitewide dependency assessments. Results of this dependency assessment formed an important basis for the development of multi-unit risk results.

### 4.1. Approach for Performing Sitewide Dependency Assessment

The sitewide dependency assessment approach used by the L3PRA project's ISR task is based upon the previous work by the IAEA [14, 15] and EPRI [16]. In particular, the L3PRA project's sitewide dependency assessment approach used:

- a categorization scheme to identify, characterize, and document the sitewide dependencies for the selected NPP site that was based upon a similar scheme provided in the IAEA [14, 15] and EPRI [16] reports
- a phased approach for the assessment for the different categories of potential sitewide dependencies that is similar to that described in the EPRI report [16]

Eight categories of potential sitewide dependencies were defined. These eight categories were organized into three phases of sitewide dependency assessment as follows:

- Phase 1 Assessment:
  - sitewide and multi-unit initiating events
- Phase 2 Assessment:
  - shared physical resources
  - shared or connected systems, structures, and components (SSCs)
- Phase 3 Assessment:
  - identical components (e.g., expansion of common cause failure (CCF) groups)
  - proximity dependencies
  - human or organizational dependencies
  - accident propagation between units
  - potential hazards correlations

Assessment guidance was provided for each category of potential sitewide dependency in the three phases. The guidance recognized that there could be some overlap in the definition of categories.

### 4.2. Results for Sitewide Dependency Assessment

Results from the L3PRA project's sitewide dependency assessment were developed using the Level 1, 2, and 3 PRA results and insights for the reactors, SFPs, and DCS, as well as other reference plant site information. The L3PRA project team performed these assessments collaboratively.

### 4.2.1 Phase 1 Sitewide Dependency Assessment Results

Phase 1 sitewide dependency assessment identified multi-unit initiating events (MUIEs) to address in later efforts to estimate MUCDF. This identification was based on the screening criteria that have been used in other guidance (e.g., IAEA and EPRI reports). Specifically, a Level 1 PRA initiating event (IE) can be screened out from consideration as an MUIE if all three of these screening criteria are true:

1. The event does not immediately result in a trip of both units.
2. The event does not result in an immediate trip of one unit and a degraded condition at another unit that will eventually lead to a trip (including a required manual trip).
3. The event does not result in a degraded condition at both units that will eventually lead to a trip of the units (including required manual trip(s)).

The following MUIEs were identified for consideration in estimating MUCDF:

- losses of offsite power (LOOPs)
    - plant-centered
    - switchyard-centered
    - grid-related
    - weather-related
- certain fire scenarios (including main control room abandonment scenarios and fires that can spread from one unit to another)
- losses of service water
- seismic events (The L3PRA project used eight seismic bins.)
- wind events

These results for MUIEs are generally consistent with the discussion in the IAEA [14, 15] and EPRI [16] reports, including the associated case studies.

### 4.2.2 Phase 2 Sitewide Dependency Assessment Results

As defined above, Phase 2 sitewide dependency assessment identifies two different types of potential dependencies: shared physical resources and shared or connected SSCs.

For the two reactors, only three physical resources were found to be shared:

1. switchyards
2. an alternate electric power source
3. water supplies used to implement Extensive Damage Mitigation Guidelines (EDMGs) in Level 2 PRA scenarios

The list of shared or connected SSCs for the two reactors is similarly small and consists of:

- portable pumps and associated equipment needed for response to Level 2 PRA scenarios
- the FLEX building
- several buildings that are connected between the two units (e.g., auxiliary buildings, control buildings, cable spreading rooms, turbine buildings)

In addition to the results above, the two reactors on the reference site were assessed for “coupling” per the definition provided in the EPRI report [16]. Based on this guidance, the two reactors were assessed to be “loosely coupled” for all hazards, except certain fire scenarios and seismic events (which are addressed in the Phase 3 sitewide dependency assessment, as discussed below).

### 4.2.3 Phase 3 Sitewide Dependency Assessment

The remaining five categories of potential sitewide dependencies were assessed in Phase 3 (i.e., cross-unit or multi-unit common cause failures (MU CCFs), human and organizational dependencies, proximity dependencies, cascading failures, and hazard correlations). Example results for MU CCFs and human and organizational dependencies are provided below.

Two different types of potential MU CCFs were identified and documented for potential consideration in assessing ISR:

1. CCFs that are already modeled in the L3PRA project's single unit PRA models
2. new MU CCFs involving identical components in each unit

Multiple CCFs from the single unit PRAs were identified to be represented as MU CCFs in MUCDF calculations. Most of these candidate MU CCFs were identified in the single unit, internal events PRA. Only one new CCF group was identified, consisting of the turbine-drive auxiliary feedwater pumps (one in each unit).

The potential human and organizational dependencies that were identified include:

- The main control rooms are connected (but not shared).
- Both units have common training, procedures, human-machine interface, Technical Support Center, and so on. As discussed in EPRI's report [16], both positive and negative dependency impacts are possible, but it is generally believed that commonalities would have a positive effect.

## 5. MULTI-UNIT LEVEL 1 PRA QUANTIFICATION

The section describes how MUCDFs were calculated (with Unit 1 and Unit 2 considered to be identical).

### 5.1 NRC's Approach for Calculating MUCDF

The high-level steps for calculating MUCDF using a traditional PRA logic model and PRA software include:

1. identify MUIEs (discussed in Section 4.2.1 above)
2. determine the MUIE frequencies (MUIEFs)
3. develop an MU event tree for each identified MUIE
4. identify MU dependencies to be addressed (discussed in Section 4.2 above)
5. determine the appropriate values (e.g., coupling factors) to assign to the basic events (BEs) that represent MU dependencies
6. calculate MUCDF for each MUIE

A simplified approach, labeled the "cutset estimation method" (CEM), for generating MUCDFs was used in the L3PRA project for reasons that included the following:

- The NRC's PRA software tool, SAPHIRE [17], is limited in its capabilities for large models.
- At-power, SU cutset results were already available for Level 1 PRAs for all hazards.
- Very few dependencies between the two units on the reference site were identified.
- State-of-the-art limitations (e.g., limited basis for MU CCF and hazard correlations) support the use of simpler, more cost-effective methods.
- In most cases, only a few hundred cutsets were needed to represent 95 percent or more of the SUCDF results for the full range of hazards.

The specific high-level steps for applying the CEM for calculating MUCDFs are the same as those for the traditional PRA approach, with the following exceptions:

- instead of Step 3:
    - identify cutsets that make up 95 percent of the SUCDF for each MUIE
    - review cutsets and identify the different BEs that need to be addressed to account for MU dependencies
- in addition to Step 5, assign cross-unit coupling factors for each relevant cutset during the cutset review

Steps 5 and 6 are discussed further below.

## 5.2 Assignment of Coupling Factors

As discussed in Section 4.2, the sitewide dependency assessment identified several types of MU dependencies for the two reactors on the reference site. Cross-unit coupling factors were used in the L3PRA project's ISR task to represent cross-unit (or MU) CCFs and seismic hazard correlations, and certain human dependencies.

As noted in Section 2.3.4.3 of EPRI's report on MU risk [16], "[a] well-known challenge for CCF in [risk-informed decision making] is the potentially scarce actual CCF failures in the operating experience databases" to support the development of CCF parameters (e.g., alpha factors) for large CCF group sizes. For this reason, the L3PRA project team selected conservative, generic BE coupling factors[‡] to represent MU dependencies. The BE coupling factors used included the following:

- CCF1: 0.2; used for all SU CCFs except those assigned as CCF2 below
- CCF2: 1.0; used for CCFs associated with very large CCF group sizes (e.g., certain service water (SW) system components)
- HFE: 1.0; used for certain operator actions (e.g., recovery of offsite power[§])

Another challenge for MUCDF calculations is that seismic and wind event hazard correlations for similar SSCs for Units 1 and 2 are not known. Both the IAEA [15] and EPRI [16] reports recommend simplified approaches for considering seismic correlations between SSCs in the two units. MU seismic correlation factors were selected as an extension of those used for the L3PRA project's SU seismic PRA. Two generic coupling factors were used to develop seismic MUCDF results:

- STRUCTURE: Fully correlated (1.0 hazard correlation); used for two-element SU cutsets that result in direct core damage (i.e., cutsets that contain only a seismic IE and a single seismically induced major structural failure that directly results in core damage).
- SEISMIC: Fully correlated (1.0 hazard correlation); used for SU cutsets that contain only one element related to seismic failures.

Assuming full seismic correlation between the two units can be considered a conservative assumption. However, preliminary seismic MUCDF calculations indicated that the extent of conservatism is not very significant and does not justify the level of effort required for a more elaborate analysis.

Note, some MU cutsets involved more than two elements, leading to more complicated MU correlation assignments, as discussed in Section 6.2.3 of the L3PRA project ISR report [18].

## 5.3 Quantification Steps

When traditional PRA software is used, and all cutsets from both units are "ANDed" together, all identified MU dependencies in each cutset need to be addressed. PRA software typically addresses these dependencies automatically using post-processing rules and assigned coupling factors. In addition, any independent BEs in an SU cutset are automatically accounted for when generating and quantifying the MU cutsets (which is important to avoid overestimating the CDF of the MU cutsets). With the CEM approach, identified cross-unit dependencies are addressed on a cutset-by-cutset basis.

The CEM approach uses several simplifications, as compared to traditional CDF calculations. Two of these simplifications are: 1) often, only one dependency within a cutset is addressed, and 2) independent BEs in the cutset are not necessarily addressed for the second unit. Since the CEM approach just applies

[‡] The L3PRA project team also found that generic coupling factors were conservative as compared to coupling factors generated by SAPHIRE.
[§] Although these basic events (BEs) are quantified using statistical data rather than HRA methods, the L3PRA project's PRA models used HFE labels for these events because the reference plant's PRA used this convention.

a coupling factor to the SU cutsets (i.e., it does not carry along the remainder of the cutset from the second unit), both these simplifications can lead to overestimation of MUCDF. If the analyst believes that this overestimation is significant, the CEM approach allows for further refinement in the quantification, as discussed in Section 6.2.3.4 of the L3PRA project ISR report [18].

The basic equation for calculating MUCDF for cutset i is:

$$\text{MUCDFi} = \text{U1-CDFi} \times (\text{MUIEF/U1IEF}) \times [\text{BE-CFi} + \text{U1-CCDP} - (\text{BE-CFi} \times \text{U1-CCDP})] \quad (1)$$

where:

| | |
|---|---|
| MUCDFi: | MU core damage frequency for cutset i of N cutsets |
| U1-CDFi: | Unit 1 SUCDF for cutset i out of N cutsets |
| MUIEF: | Multi-unit initiating event frequency (also sitewide IE frequency) |
| U1IEF: | Unit 1 initiating event frequency |
| BE-CFi: | BE coupling factor for cutset i (assigned) |
| U1-CCDP | Single unit CCDP |

Other terms or contributions in the above equation that also need explanation include:

$\text{U1CDF}_i = \text{U2CDF}_i = \text{U1IEF} \times \text{U1-CCDP}_i = \text{U1IEF} \times \text{U2-CCDP}_i$

$\text{U1CDF}_i \times \text{MUIEF/U1IEF} = \text{MUIEF} \times \text{U1-CCDP}_i$

$\text{U1CDF}_i \times (\text{MUIEF/U1IEF}) \times \text{BE-CF}_i$: Dependent contribution to $\text{MUCDF}_i$

$\text{U1CDF}_i \times (\text{MUIEF/U1IEF}) \times [\text{U1-CCDP}]$: Independent contribution to $\text{MUCDF}_i$

$\text{BE-CF}_i \times \text{U1-CCDP}$: Term needed for rare events approximation in Boolean algebra

The above process was aided by the ability to export SAPHIRE cutsets into Excel.

## 6. MULTI-UNIT CORE DAMAGE FREQUENCY RESULTS

Table 1 provides the L3PRA project's MUCDF results. These results for the L3PRA project's "base case" correspond to how the reference plant was designed and operated as of 2012. The L3PRA project's ISR task produced some "FLEX[**] sensitivity case" results that represent the impact of several plant updates (e.g., implementation of FLEX and improved reactor coolant pump seals).

In summary, the MUCDF results for the reference site consisting of two essentially identical PWRs, show that:

- Total MUCDF (1.3E-5/rcy) is between 10 and 15 percent of the total SUCDF developed in the traditional, single unit PRA (1.25E-4/rcy)
- MUCDF contributions from LOOPs are relatively small (e.g., the MUCDF of each LOOP category represents about 5 percent or less of LOOP SUCDF)
- MUCDF contributions from seismic events drive the overall percentage of MUCDF as compared to SUCDF, for example:
    - MUCDF is 75 percent of SUCDF for seismic bin 4
    - MUCDF is 100 percent of SUCDF for seismic bins 7 and 8
- Contributions to total MUCDF are approximately:
    - 2 percent from selected fire scenarios
    - 6 percent from wind events
    - 14 percent from LOOPs (with the largest contribution from grid-related LOOPs)
    - 25 percent from loss of service water
    - 53 percent from seismic events

[**] FLEX refers to the U.S. nuclear power industry's Diverse and Flexible Coping Strategies. FLEX is intended to maintain long-term core and spent fuel cooling and containment integrity using installed plant equipment that is protected from natural hazards, as well as backup portable onsite equipment. If necessary, similar equipment can be brought from offsite facilities.

**Table 1 L3PRA Project's MUCDF Estimates – Base Case**

| Scenario Name | Scenario Description | MUIEF (/rcy) | MUCDF (/rcy) | % MUCDF (/rcy) |
|---|---|---|---|---|
| MUIE-LOOPGR | Grid-related LOOP | 6.15E-03 | 1.00E-06 | 7.7% |
| MUIE-LOOPPC | Plant-centered LOOP | 1.07E-04 | 1.43E-08 | 0.1% |
| MUIE-LOOPSC | Switchyard-centered LOOP | 2.80E-03 | 3.56E-07 | 2.7% |
| MUIE-LOOPWR | Weather-related LOOP | 2.44E-03 | 4.47E-07 | 3.4% |
| MU-LOSW | Loss of SW | 3.47E-05 | 3.23E-06 | 24.8% |
| MUIE-FRI-1 | MCR abandonment due to fire | 1.47E-07 | 1.47E-07 | 1.1% |
| MUIE-FRI-2 | Shared area fires by U1 and U2 | 3.42E-02 | 2.28E-08 | 0.2% |
| MUIE-FRI-3 | U1 to U2 (U1 fires affecting U2) | 9.08E-03 | 6.59E-08 | 0.5% |
| MUIE-FRI-4 | U2 to U1 (U2 fires affecting U1) | 9.08E-03 | 6.59E-08 | 0.5% |
| MUIE-EQK-1 | Seismic event in bin 1 (0.1–0.3g) | 1.64E-03 | 8.08E-08 | 0.6% |
| MUIE-EQK-2 | Seismic event in bin 2 (0.3–0.5g) | 2.19E-04 | 1.24E-07 | 1.0% |
| MUIE-EQK-3 | Seismic event in bin 3 (0.5–0.7g) | 4.79E-05 | 8.24E-07 | 6.3% |
| MUIE-EQK-4 | Seismic event in bin 4 (0.7–0.9g) | 1.34E-05 | 1.85E-06 | 14.2% |
| MUIE-EQK-5 | Seismic event in bin 5 LOOP (0.9–1.1g) | 4.26E-06 | 2.02E-06 | 15.6% |
| MUIE-EQK-6 | Seismic event in bin 6 LOOP (1.1–1.5g) | 1.92E-06 | 1.72E-06 | 13.3% |
| MUIE-EQK-7 | Seismic event in bin 7 LOOP (1.5–2.5g) | 2.48E-07 | 2.34E-07 | 1.8% |
| MUIE-EQK-8 | Seismic event in bin 8 LOOP (2.5g and above) | 2.32E-09 | 2.32E-09 | <0.1% |
| MUIE-WIND-1 | SBO and SSC wind damage | 8.89E-03 | 7.93E-07 | 6.0% |
| **Total** | | 7.47E-02 | 1.30E-05 | 100.0% |

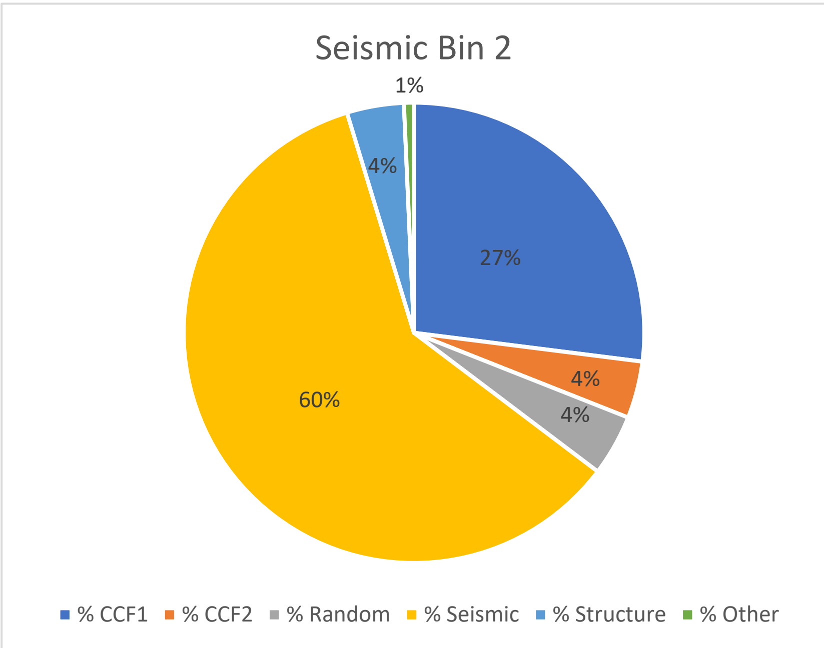


**Figure 2 Sitewide Dependency Contributions to Seismic Bin 2**

The MU dependencies that underlie the results in Table 1 are different for different MUIEs. For example, MUCDF for LOOPs, loss of service water, wind events, and seismic bin 1 is dominated by MU CCFs. MUCDF results for all other seismic events are dominated by assigned seismic correlations. Figure 2 shows such MUCDF results for seismic bin 2 for which seismic correlations and correlations associated with structural failures dominate. The MUCDF contribution from seismic correlations is even more pronounced for higher bins.

## 7. CONCLUSIONS

In summary, the at-power, MUCDF results for the L3PRA project's ISR task show the following:

- Total MUCDF is relatively small (i.e., about 10 percent) compared to total SUCDF
- Seismic events contribute the most to MUCDF results (i.e., more than 50 percent of total MUCDF)
- Seismic events (especially those for Bins 4 through 8) are more likely to involve MU core damage than other MU events
- Different types of MU dependencies are important for different hazards (e.g., MU CCFs are the most important contributors for LOOPs, while MU hazard correlations are most important for most of the seismic events)

Another PSAM 18 paper describes the multi-source risk results from the ISR task in NRC's L3PRA project.


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