

Insights from the NRC's Level 3 PRA Project's Multi-Unit Risk Results

2026 RIC Session:
Multi-Unit Risk—Are We Ready for This?

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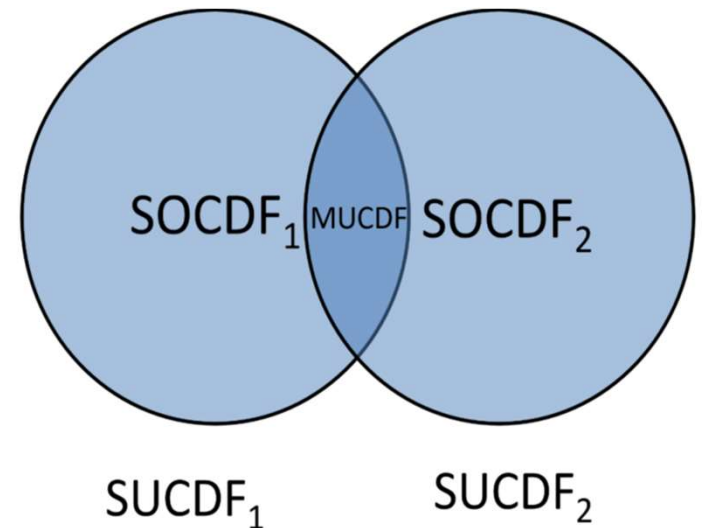
What Are Integrated Site and Multi-Unit Risk?

- Integrated site risk (ISR) is included in the scope of the NRC's Level 3 probabilistic risk assessment (PRA) project. Previous NRC PRA efforts have not addressed ISR.
- 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, considering all hazards and all plant operating states.
- The first step to calculating ISR is to calculate multi-unit (MU) risk—risk from simultaneous accidents for multiple reactors:
 - Level 1 MU risk—MU core damage frequency (MUCDF)
 - Level 2 MU risk—MU release category frequencies (MURCFs)
 - Level 3 MU risk—MU frequency-weighted consequences

How Is MU Risk Calculated?

- Simplistically, we could add the results from each radiological source. But, this—
 - overlooks dependencies between reactors
 - overestimates severe accident frequency
 - does not provide any new PRA insights (i.e., beyond single source PRA results)
- Note that—
 - MUCDF will always be some fraction of the single unit CDF (SUCDF).
 - The sum of MUCDF and single unit only CDF (SOCDF) equals SUCDF.
 - The fraction of SUCDF that represents MUCDF will vary with the strength of the MU dependencies.
 - The timing of the accidents is key to the definitions above.
- MU risk focuses on certain very challenging sitewide accidents; MUPRA results can provide additional insights and identify potential vulnerabilities that the single source PRA results cannot provide.



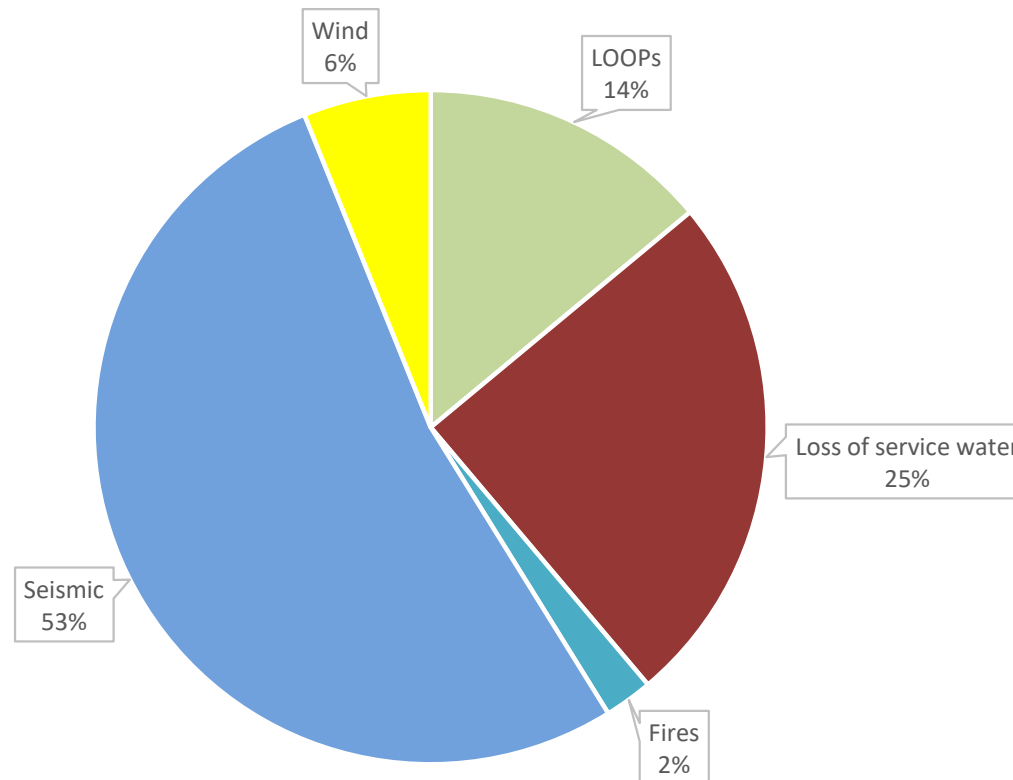
Summary of MU Results

- Sitewide dependency assessment:
 - The two reactors on the reference site are mostly independent (i.e., “loosely coupled”).
 - A subset of the initiating events addressed in the single unit PRAs is relevant to MU risk.
 - There are very few cross-unit dependencies involving operator actions, except for operator actions in the reactor Level 2 PRA model.
 - The sitewide dependencies that have been identified provide important insights by themselves.

Summary of MU Results (continued)

MU Level 1 PRA:

- Total MUCDF ($1.3\text{E-}5$ /reactor-critical year) is approximately 10 percent of total single unit CDF ($1.25\text{E-}4$ /reactor-critical year).
- Seismic events are the biggest contributors to total MUCDF.



Summary of MU Results (continued)

- MU Level 2:
 - It is widely recognized that there are computational challenges for MU Level 2 PRA (i.e., too many MU release category combinations, PRA model too big to solve).
 - Consequently, MURCF calculations were limited to two MU initiating events (weather-related loss-of-offsite power [LOOP] [LOOPWR] and seismic bin 6) and a subset of possible MU release categories.
 - For LOOPWR, containment failure modes depend largely on physical phenomena (e.g., hydrogen combustion) that are not correlated between units.
 - For seismic bin 6, seismic failure of the containment isolation system is coupled between units.
- MU frequency-weighted consequence (MU Level 3) results were developed using MU Level 2 PRA results and the NRC's MELCOR Accident Consequence Code System (MACCS).

Summary of MU Results (continued)

- MU consequences were developed for four risk measures:
 - individual early fatality risk
 - individual latent fatality risk
 - collective total effective dose risk
 - total economic cost risk
- High-level MU Level 3 PRA results show that—
 - Summing the single unit consequences may be sufficient for some of the metrics of interest.
 - May overestimate results for collective doses and health effects
 - This insight is consistent with the observation drawn from the single unit analyses (i.e., many consequences are either linear or sublinear with the magnitude of the release).
- ***Overall, MU releases are not a major contributor to total risk (e.g., smaller than single unit risk by 1 or 2 orders of magnitude).***

Conclusions

- The Level 3 PRA project's MUPRA efforts demonstrated that—
 - MUPRA approaches are adequate to develop useful insights for the existing fleet of light water reactor (LWR) designs, concepts of operations, etc.
 - MUPRA results and insights were developed despite some well-known limitations in MUPRA, for example:
 - MU Level 2 PRA is computationally challenging (e.g., even for just two reactors, the number of MU release categories that could be addressed was limited).
 - There are limited data to support estimation of MU common cause failure [CCF] coupling factors (i.e., the Level 3 PRA project used conservative, generic coupling factors).
 - There is little basis for MU seismic coupling factors.
 - It is expected that similar MUPRA results would be produced for other LWR sites (e.g., limited dependencies between reactors, relatively small MUCDF as compared to SUCDF results).

Conclusions (continued)

- Developing MUPRA results for new reactor designs, different concepts of operation, etc., will present some challenges, for example:
 - The lack of available and applicable reliability data is a problem for both single reactor and multi-unit PRAs.
 - More MU dependencies (e.g., sharing of systems, structures, and components) than for existing LWRs are expected for newer reactor designs (i.e., more “tightly coupled” reactors). Consequently, MU risk could represent a greater fraction of single unit risk for newer reactor designs.
 - New or different MU dependencies can be expected (e.g., sharing of operators, more automation, remote control).
 - If there are multiple reactors on site (i.e., more than two), the analysis of MU risk could get complicated very quickly.

BACKUP SLIDES

Level 3 PRA Public Reports

- **Volume 1:** Summary (to be published last)
- **Volume 2:** Background, site and plant description, and technical approach ([ML22067A232](#))
- **Volume 3:** Reactor, at-power, internal event and flood PRA (overview report) ([ML22067A210](#))
 - Volume 3a: Level 1 PRA for internal events (Part 1: [ML22067A211](#); Part 2: [ML22067A212](#))
 - Volume 3b: Level 1 PRA for internal floods ([ML22067A213](#))
 - Volume 3c: Level 2 PRA for internal events and floods ([ML22067A214](#)).
 - Volume 3d: Level 3 PRA for internal events and floods ([ML22067A215](#))
- **Volume 4:** Reactor, at-power, internal fire and external event PRA (overview report) ([ML23194A015](#))
 - Volume 4a: Level 1 PRA for internal fires ([ML23194A016](#))
 - Volume 4b: Level 1 PRA for seismic events ([ML23194A017](#))
 - Volume 4c: Level 1 PRA for high wind events and other hazards evaluation ([ML23194A012](#))
 - Volume 4d: Level 2 PRA for internal fires and seismic and wind-related events ([ML23194A013](#))
 - Volume 4e: Level 3 PRA for internal fires and seismic and wind-related events ([ML23194A014](#))
- **Volume 5:** Reactor, low-power and shutdown, internal event PRA (overview report) ([ML25157A084](#))
 - Volume 5a: Level 1 PRA for internal events ([ML25157A085](#))
 - Volume 5b: Level 2 PRA for internal events ([ML25157A086](#))
 - Volume 5c: Level 3 PRA for internal events ([ML25157A087](#))
- **Volume 6:** Spent fuel pool all hazards PRA (no overview report)
 - Volume 6a: Level 1 and Level 2 PRA ([ML25134A014](#))
 - Volume 6b: Level 3 PRA ([ML25134A015](#))
- **Volume 7:** Dry cask storage, all hazards, Level 1, Level 2, and Level 3 PRA ([ML24164A010](#))
- **Volume 8:** Integrated site risk, all hazards, Level 1, Level 2, and Level 3 PRA ([ML25149A043](#))

ISR Technical Approach

- The ISR task was performed principally using the results of the Level 3 PRA project's PRAs, underlying plant-specific information, and the expertise and experience of the Level 3 PRA project team.
- The technical approach developed to perform the ISR task included multiple steps; at a high level, these are—
 - sitewide dependency assessment (using an expansion of the Electric Power Research Institute's [EPRI's] phased approach)
 - MU dependencies
 - dependencies between spent fuel pools (SFPs) and reactors
 - dependencies between DCS and reactors
 - MU risk estimation
 - MUCDF
 - MURCF
 - MU consequences
 - multi-source risk: aggregation of MU risk results with SFP risk
- At-power conditions for all hazards (internal and external) were addressed for MUCDF.

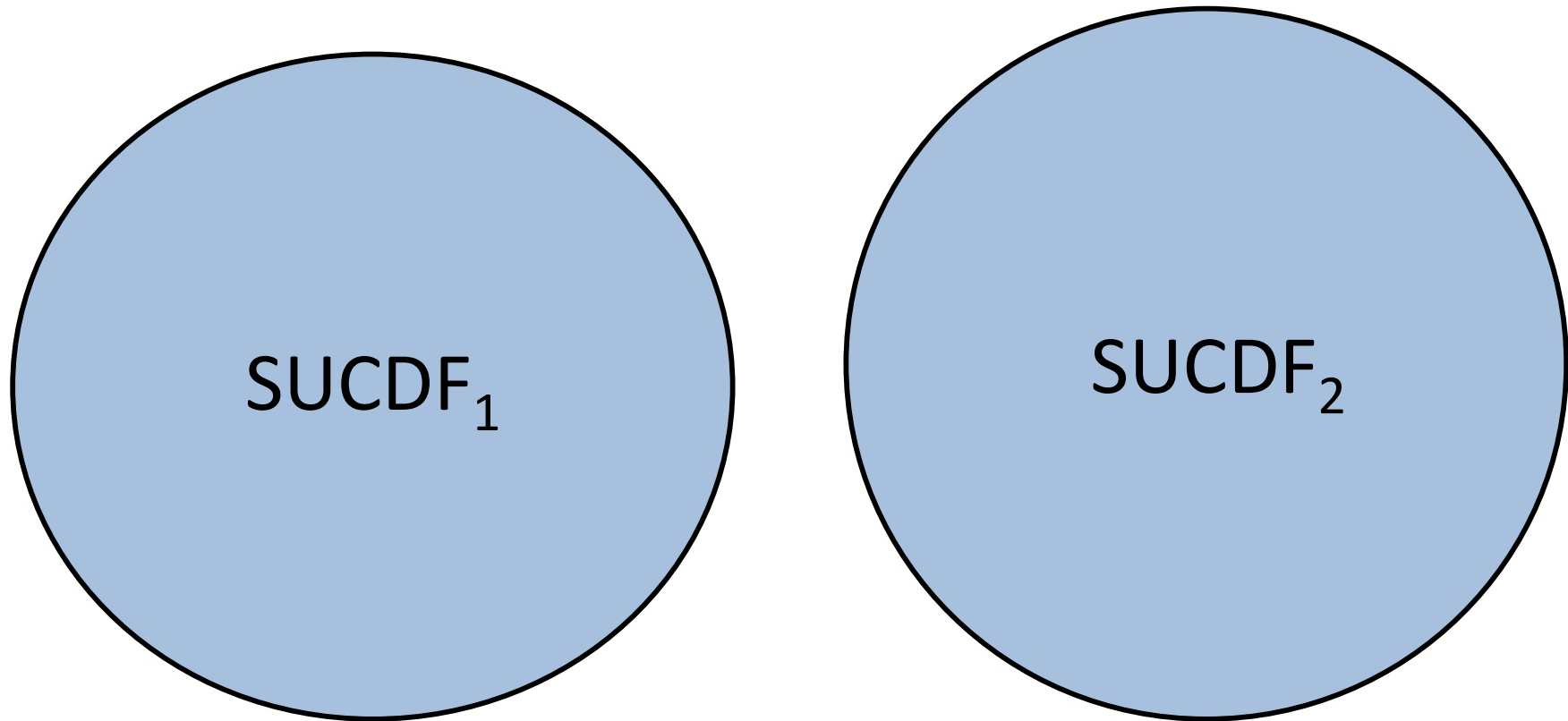
ISR—Sitewide Dependency Assessment

- Used a phased process (expansion of EPRI, 2021)
 - Phase 1: common or multi-unit initiating events
 - Phase 2:
 - shared physical resources
 - shared or connected systems, structures, and components (SSCs)
 - Phase 3:
 - identical components
 - proximity dependencies
 - human and organizational dependencies
 - accident propagation between units
 - hazard correlations
- Developed guidance for all three types of dependency assessments
- Assessment performed by Level 3 PRA project PRA leads using PRA models and results, plant information, and analyst experience and judgment
- Assessed potential dependencies between the two reactors first; then potential dependencies between the SFPs and the reactors next, etc.

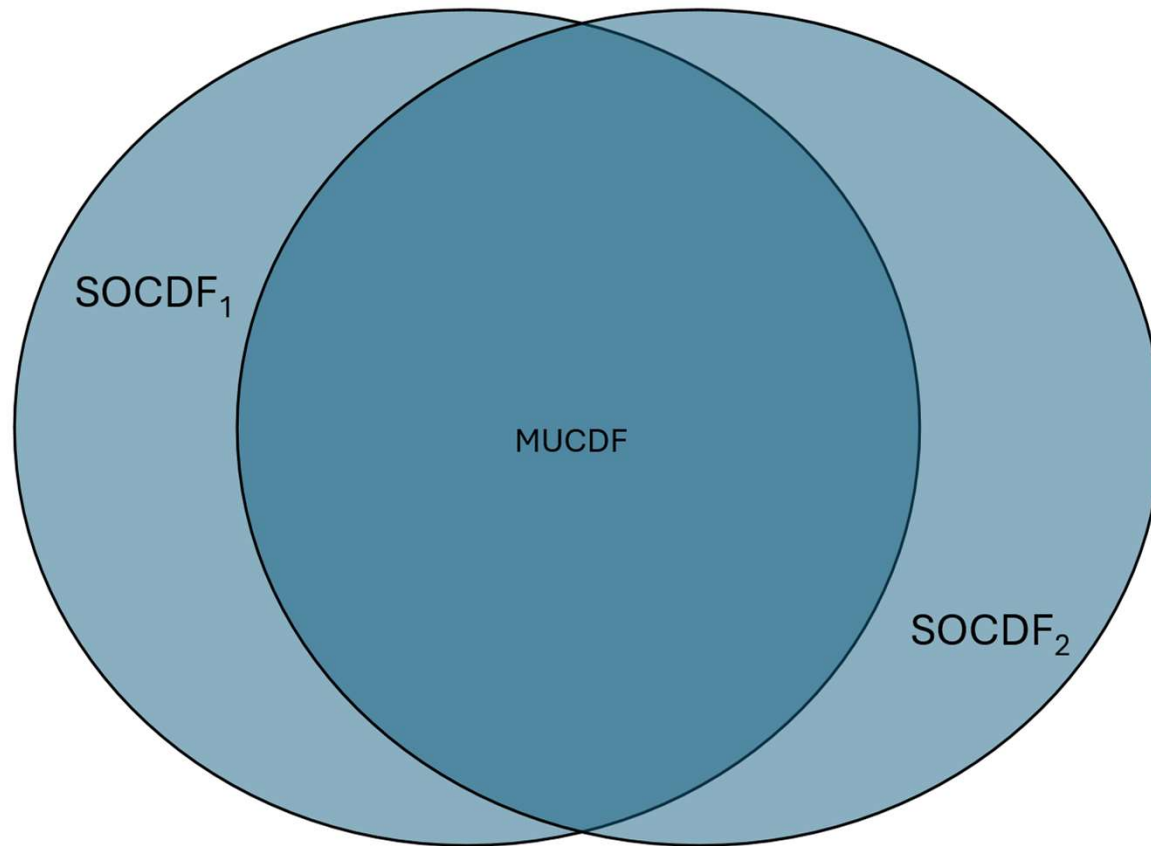
ISR—Sitewide Dependency Assessment (continued)

- Definition of human and organizational dependencies:
 - dependencies among operator actions across multiple radiological sources that can result from multiple causes, including sharing of staff and shared organizational factors
- Categories of human and organizational dependencies:
 - shared human resources between units
 - shared control rooms
 - common procedures (e.g., emergency operation plans, abnormal operating procedures, severe accident management guidelines, procedures for diverse and flexible coping strategies [FLEX])
 - common operator training
 - common human–machine interface
 - common command and control structure
 - common Technical Support Center
 - common emergency response organization
 - common offsite support
 - increased stress due to MU accident conditions
 - accessibility concerns due to the other unit’s degraded condition
 - common environmental concerns for operators of both units (e.g., field operators taking actions at local control stations, at locations shared by both units, or outside the plant(s))
- Additional, typical HRA concerns are relevant, such as:
 - timing of the action (especially with respect to when conditions from one reactor can affect another reactor)
 - cues and indications to prompt and/or support operator actions
 - feasibility (see NUREG-1921 [original and Supplements 1 and 2])

Venn Diagram: Visual Representation of Boolean Algebra for Core Damage Frequencies for Two Independent Reactors



Venn Diagram for Two Units that Have More Cross-Unit Dependencies

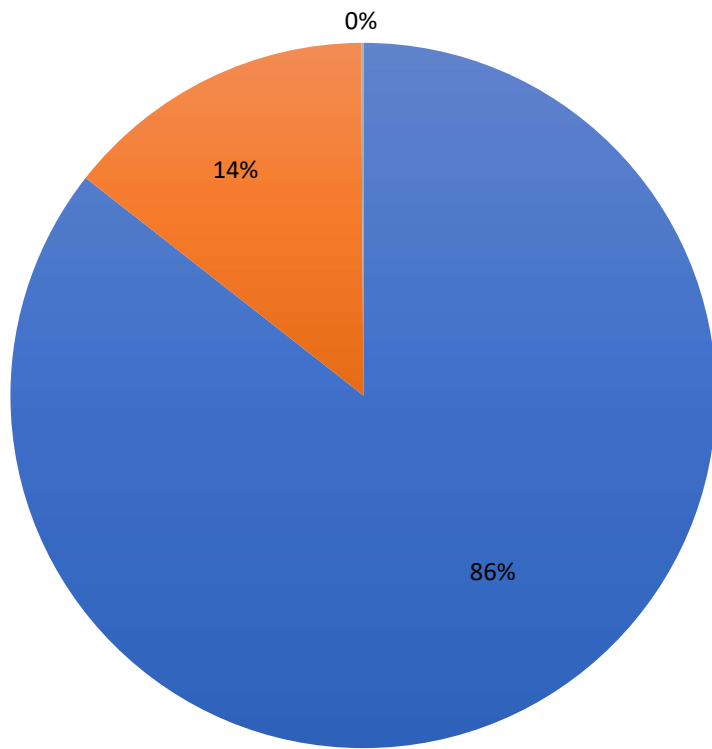


ISR—MUCDF Results

	Scenario Name	Scenario Description	U1IEF (/rcy)	MUIEF (/rcy)	MUIEF/ U1IEF	U1CDF (/rcy)	MUCDF (/rcy)	MUCDF/ U1CDF
1	MU-IE-LOOPGR	Grid-related LOOP	1.23E-02	6.15E-03	0.500	1.83E-05	1.00E-06	0.055
2	MU-IE-LOOPPC	Plant-centered LOOP	1.93E-03	1.07E-04	0.056	1.91E-06	1.43E-08	0.007
3	MU-IE-LOOPSC	Switchyard-centered LOOP	1.04E-02	2.80E-03	0.269	1.04E-05	3.56E-07	0.036
4	MU-IE-LOOPWR	Weather-related LOOP	3.91E-03	2.44E-03	0.625	9.02E-06	4.47E-07	0.049
5	MU-LONSCW	Loss of nuclear service cooling water	3.47E-05	3.47E-05		8.76E-06	3.23E-06	0.369
6	MU-IE-FRI-1	Main control room abandonment due to fire	1.50E-07	1.47E-07	1.0	1.47E-07	1.47E-07	1.0
7	MU-IE-FRI-2	Shared (A+Y) area fires by U1 and U2	3.40E-02	3.42E-02	1.0	1.00E-05	2.28E-08	0.023
8	MU-IE-FRI-3	U1 to U2 (U1 fires affecting U2)		9.08E-03	1.0		6.59E-08	-
9	MU-IE-FRI-4	U2 to U1 (U2 fires affecting U1)	9.08E-03	9.08E-03	1.0	4.23E-05	6.59E-08	0.002
10	MU-IE-EQK-1	Seismic event in bin 1 (0.1–0.3g) occurs (bin pga 0.17g)	1.64E-03	1.64E-03	1.0	1.30E-06	8.03E-08	0.062
11	MU-IE-EQK-2	Seismic event in bin 2 (0.3–0.5g) occurs (bin pga 0.39g)	2.19E-04	2.19E-04	1.0	1.22E-06	1.24E-07	0.102
12	MU-IE-EQK-3	Seismic event in bin 3 (0.5–0.7g) occurs (bin pga 0.59g)	4.79E-05	4.79E-05	1.0	1.62E-06	8.24E-07	0.509
13	MU-IE-EQK-4	Seismic event in bin 4 (0.7–0.9g) occurs (bin pga 0.79g)	1.34E-05	1.34E-05	1.0	2.43E-06	1.85E-06	0.761
14	MU-IE-EQK-5	Seismic event in bin 5 LOOP (0.9–1.1g) occurs (bin pga 1.0g)	4.26E-06	4.26E-06	1.0	2.24E-06	2.02E-06	0.902
15	MU-IE-EQK-6	Seismic event in bin 6 LOOP (1.1–1.5g) occurs (bin pga 1.29g)	1.92E-06	1.92E-06	1.0	1.75E-06	1.72E-06	0.983
16	MU-IE-EQK-7	Seismic event in bin 7 LOOP (1.5–2.5g) occurs (bin pga 1.94g)	2.48E-07	2.48E-07	1.0	2.34E-07	2.34E-07	1.000
17	MU-IE-EQK-8	Seismic event in bin 8 LOOP (2.5g and above) occurs (bin pga 2.5g)	2.32E-09	2.32E-09	1.0	2.32E-09	2.32E-09	1.000
18	MU-IE-WIND-1	Station blackout and SSC wind damage	8.89E-03	8.89E-03	1.0	1.38E-05	7.93E-07	0.006
	Total		8.24E-2	7.47E-02		1.25E-4	1.30E-05	0.104

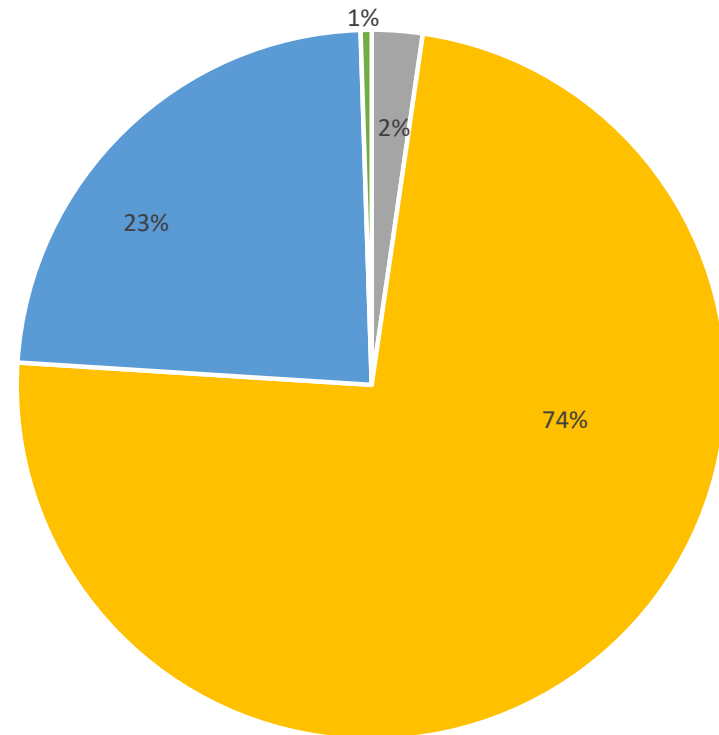
MUCDF Results (continued)

Grid-Related LOOPs



■ % CCF1 ■ % CCF2 ■ % Random

Seismic Bin 6



■ % CCF1 ■ % CCF2 ■ % Random
■ % Seismic ■ % Structure ■ % Other

Sitewide Consequences: Single-Source, MU, and Multi-Source

Scope Piece	Release Freq. (/yr)	Individual Latent Fatality Risk, 0–10 miles (/yr) ¹	Collective Total Effective Dose Risk (person-rem/yr), 0–50 miles ¹	Total Economic Cost Risk, 0–50 miles (2015\$/yr) ¹
At-power (internal events and internal floods) for a single unit	6.9E-05	2.5E-08	9.9	80,000
At-power (all hazards ²) for a single unit	1.6E-04	6.4E-08	27	230,000
Low power and shutdown (internal events) for a single unit	1.2E-05	4.5E-09	3.6	72,000
SFP (all hazards)	5.8E-07	6.3E-10	0.52	8,400
All MU LOOPWR ³	5.52E-07	3.35E-10	0.14	1,220
All MU EQK-BIN-6 ⁴	2.47E-06	1.84E-09	0.94	9,630
Multi-source (i.e., simultaneous accidents for both reactors and SFP) for seismic bin 6	3.10E-08	5.55E-11	0.041	589