Multi-Unit Risk Assessment Framework Overview

Focus on Internal and External Hazards

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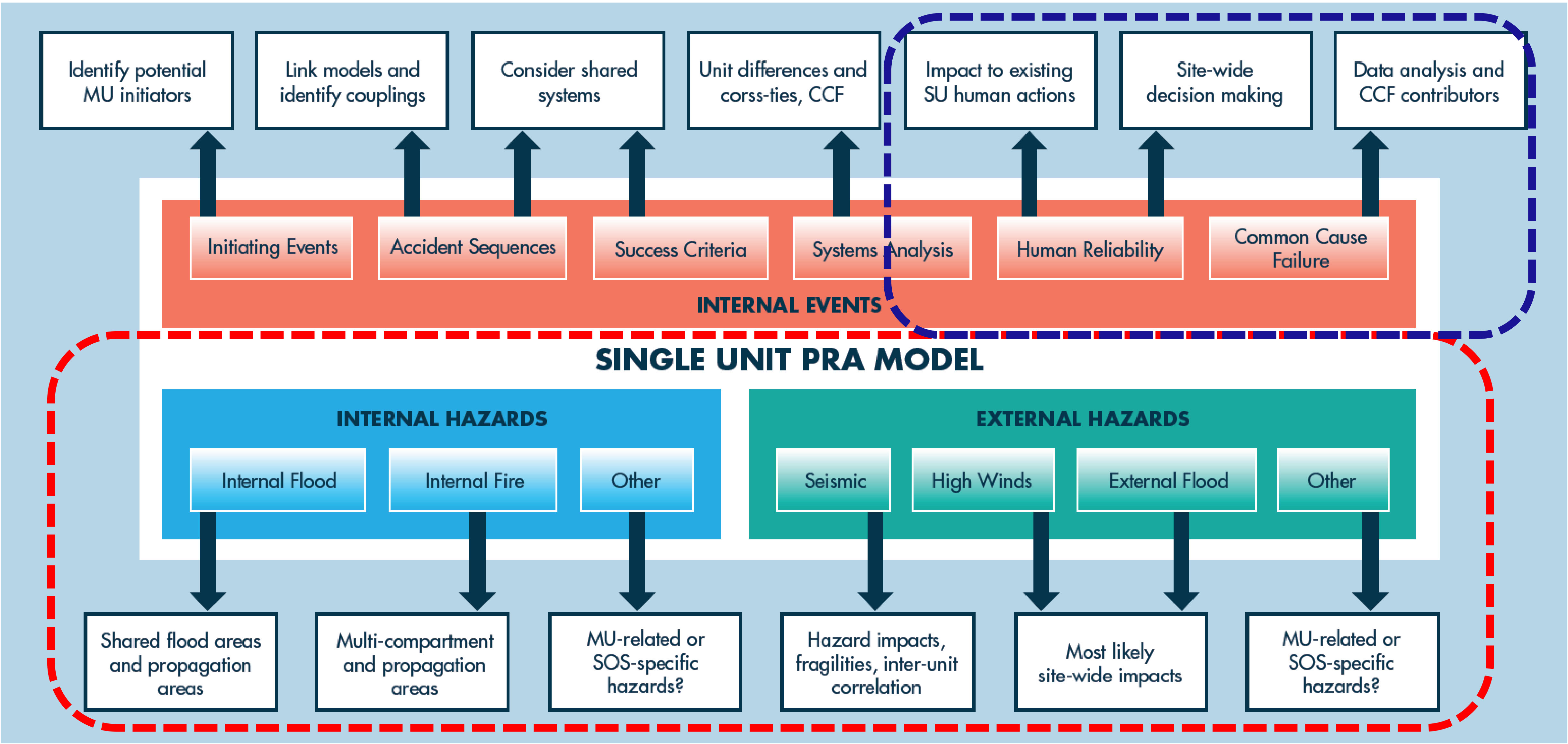
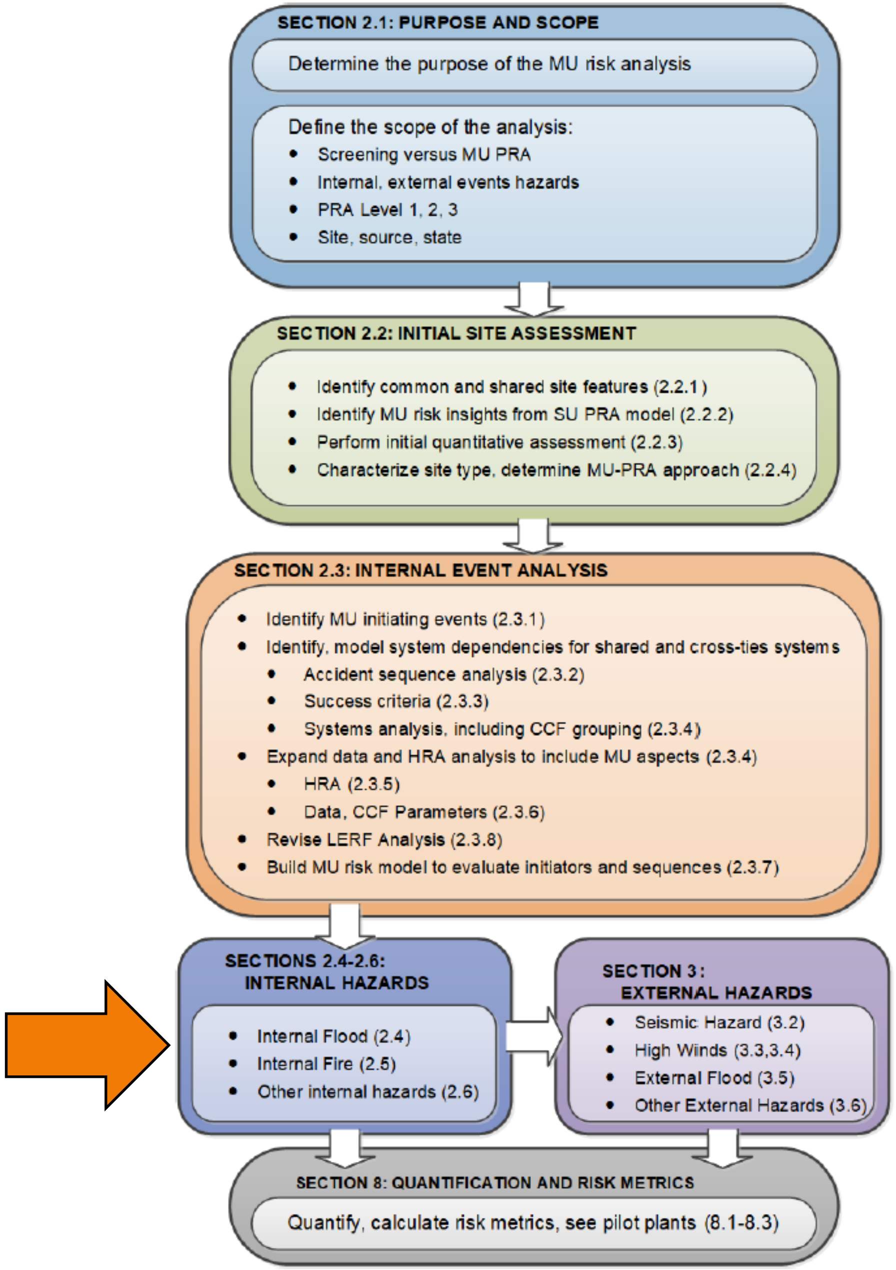
Presentation Focus



Internal Hazards in MU-PSA

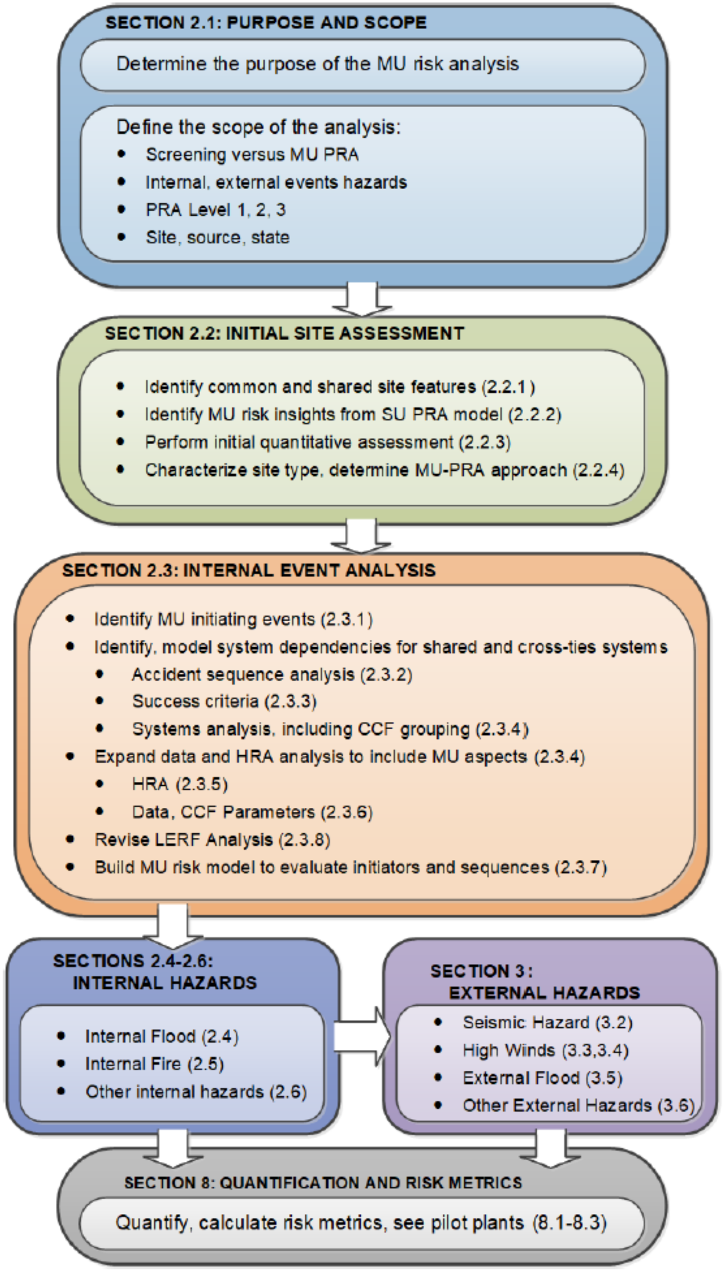
Internal Hazards (Fire and Flooding)

- Use the same single-unit general methodology:
  - Internal Flooding (see EPRI Report 1019194)
  - Internal Fire (see EPRI Report 1011989)
- Focus on the unique aspects caused by multi-unit severe accidents.
- Based on a review of experience, it is rare to find explicit reference to multi-unit fires and floods.
- EPRI focus has been on internal fires and flooding, but considerations could be made for other internal hazards (e.g., heavy load drop event).
- This is a graded approach utilizing both qualitative screening and full fire/flood risk analysis (as needed).



Ground rule and Assumptions

- A comprehensive single-unit risk model with sufficient documentation is available to serve as the starting point.
- The fire and flooding hazards are modeled using methodologies that represent the current state of practice (e.g., EPRI and NRC guidance).
- Single-unit fire and flooding hazard models meet the requirements ASME/ANS PRA Standard technical elements.



Multi-Unit Flooding: Task #1

Identify multi-unit insights from the single-unit internal flooding risk model:

- identify multi-unit insights from the single-unit analysis.
- If the single-unit risk model meets the ASME/ANS standard requirements, then the same requirements should address multi-unit elements of flooding, for example:

Plant Partitioning	Flood Sources	Flood-induced Initiating Events	Flood Scenario Development

Task #1 Single-Unit to Multi-Unit Considerations

Plant Partitioning	Likely adequate if the single-unit analysis identifies flooding areas for all units at the site.
Flood Sources	The single-unit analysis is expected to identify multi-unit flood sources even if the impacts are different between units.
Flood Scenario Development	It is more likely that unit differences will be subtle and treated in a bounding way. For example, differences in the propagation pathways due to door opening directions, or the identification of applicable operator actions based on the impact to other units at the site.
Flood-induced Initiating Events	The single-unit analysis should already address the possibility of a single-unit flood scenario having different initiator associated with different units. For example, the loss of support system in one unit and the procedure-induced manual trip in another unit.

Multi-Unit Flooding: Task #2

Develop the multi-unit internal flooding accident sequences:

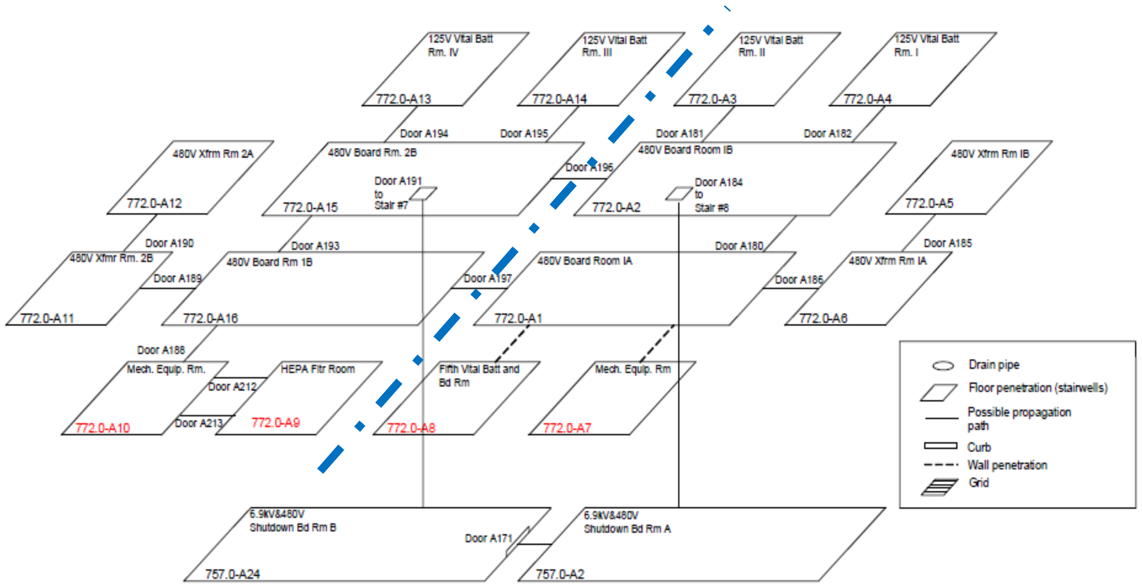
- The development of internal flooding accident sequences follows the **same approach as single-unit** but is associated with the multi-unit end state (multi-unit CDF).
- The single-unit internal flooding analysis should identify which flood scenarios are multi-unit so that a subset of single-unit scenarios can be combined into multi-unit scenarios (e.g., flooding in common structures, or connected structures).
- Multi-unit elements to consider:

Different Initiators
Single-unit and multi-unit initiators may be different and may result in different direct/indirect impacts depending on the floods propagation paths.

Different Timing
Impacts to different units may occur at different times. Depending on how the "primary" unit is impacted, identification and troubleshooting may prevent an initiator in subsequent units – caution when crediting "beneficial" failures.

Insights from the Multi-Unit Internal Flooding Pilot

- Undetected multi-unit internal flooding scenarios (i.e., no flood indicators present in the originating room) lead to the core damage scenarios (also true for single-unit risk).
- For both units, full loss of electrical equipment results in "direct to core damage" scenarios.
- While not credited in the single-unit model, the timing of propagation may allow for the modeling of different impacts on the units (e.g., the first unit that identifies the flood could potentially save the other).
- The multi-unit scenarios are a well know risk contributor to the single-unit model – the pilot plant has been looking into design changes.
- If timing is not considered and sequences are left "timeless" mostly due to phenomenological events in the logic (i.e., fully correlated), the two units will evolve through the exact same accident sequence.



Internal Flooding Areas/Zones at a Multi-Unit Site

Propagation of the exact same accident sequence is unrealistic and suggests that more complex modeling of individual unit behavior (e.g., consideration of unit-specific phenomenological events and breaking correlations in such events) is beneficial.

Multi-Unit Flooding: Task #3

Perform the HRA for multi-unit internal flooding accident sequences by developing flood mitigation human failure events (HFEs).

Feasibility

The feasibility of local actions is addressed consistently with single-unit methods but may be different depending on unit-specific propagation path evolution. Unit differences should already be flagged in the single-unit risk models.

Inter-unit and intra-unit HR dependencies will compound the complexity.

Impact

Multi-unit impacts can be both **detrimental** and **beneficial** to the human response:

- Additional workforce may be needed to address multi-unit scenarios.
- Flood detection in other units could be based on the “primary” unit’s cues.
- Additional timing before reaching critical flood height may be available (i.e., more volume).
- Additional recovery from multiple crews could be beneficial.
- Additional confusion may slow the response.

Multi-Unit Flooding: Task #4

Screen multi-unit internal flooding scenarios (as needed and warranted).

Flood Areas

Qualitatively screen out areas that are not within the multi-unit flood source area or propagation paths.

Flood Scenarios

Screen scenarios where the first significant impact to any unit occurs at least 120 minutes after the flood initiation, the flood provides a clear cue, the mitigation actions are feasible, and isolation is possible (i.e., the area is not impacted by the flood).

Also screen if only one unit trips (auto or manual) due to the multi-unit flooding. This should already be considered within the single-unit analysis.

Flood Sources

Qualitatively screen out internal flooding sources that cannot cause a multi-unit flood scenario.

- ✓ Flooding scenario…
- ✓ Flooding scenario…
- ✓ Flooding scenario…
- ✗ Flooding scenario…
- ✓ Flooding scenario…
- ✗ Flooding scenario…

Multi-Unit Flooding: Task #5 and #6

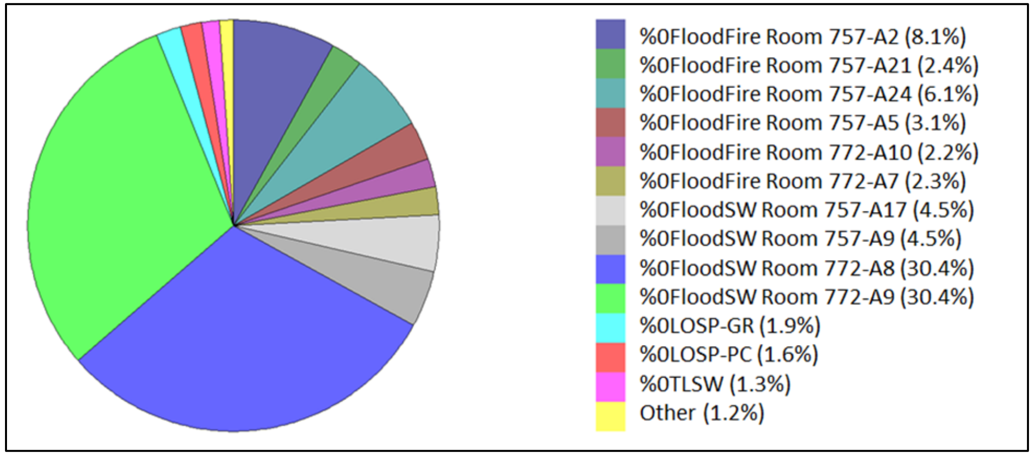
- **Task #5:** Perform multi-unit internal flooding walkdowns and operator interviews:
  - **The ASME/ANS standard provides requirements** for single-unit walkdowns in support of plant partitioning, flood source identification, and scenario development. These requirements also apply to multi-unit walkdowns.
  - Walkdowns should **focus on confirming inputs into important multi-unit internal flooding scenarios** (i.e., not an entire redo of the walkdowns).
  - Dedicated operator interviews should also be performed to review multi-unit considerations.

- **Task #6:** Understand the risk model results and develop multi-unit risk insights.

Multi-Unit Internal Flooding Conclusions

- Multi-unit internal flooding risk is **strongly dependent on the degree of physical coupling** between the units (i.e., have common or connected structures).

- For sites with limited coupling, the multi-unit internal flooding risk assessment may require only screening analysis or limited scenario development.



Pilot Plant Multi-Unit CDF Contributors
(40% Multi-unit/single-unit CDF)

Internal flooding can be a very important contributor to the overall multi-unit risk.

Additional Considerations

Large Sites & Coupling

Multi-unit internal flooding is dependent on the site configuration. For example, a three-unit site with little physical coupling (e.g., three-unit site with fully independent, separated units), the assessment of multi-unit internal flooding risk may be performed using a screening analysis.

For a three-unit site with significant physical coupling (e.g., sharing of safety-related functions such as backup AC power, and alternate safety injection for all three units), the analysis would need to track flood impacts for combinations of two units as well as for all three units.

Plant Operating States

When the site is in different operating states (e.g., Low-power shutdown) their exists an increased potential for maintenance-induced floods. For example, when systems are refilled after extensive maintenance but not all system boundaries are secured. The potential for flood barriers to be breached/removed across units and connected structures (e.g., flood doors that are opened with hoses or power cords running through, so that the door cannot be quickly reclosed) also exists. There is also the potential for immediate (or timelier) cues due to increased maintenance personnel.

Multi-Unit Fire: Task #1

Identify multi-unit insights from the single-unit fire risk model. The starting point is the understanding of how unit differences are addressed in the single-unit fire risk model. Possible outcomes are:

- The single-unit analysis explicitly models all units – **Ideal for a multi-unit analysis.**
- A "lead" unit is explicitly modeled, and other unit differences are captured in ad-hoc scenarios.
- A "bounding" unit explicitly modeled with differences more qualitatively addressed (e.g., sensitivities).

Multi-Compartment Analysis
Consider how multi-compartment fires are modeled, and the various unit impacts. When adjacent compartments have a different impact, the concept of a "lead" unit can be challenged.

Global Analysis Boundary
The single-unit analysis should consider all areas across the site. As a result, the single-unit plant partitioning is expected to be complete and appropriate for use by the multi-unit analysis.

Multi-Unit Fire: Task #2

Develop the multi-unit fire impacts (i.e., damage vectors):

- Multi-unit fire impacts follow the standard modeling techniques but need to differentiate the impact between units in terms of unit-specific initiators (which may be different) and unit-specific equipment impacts associated with cable routing:
  - The multi-unit analysis starts with fire areas that have cables for both units.
  - Assumptions related to cable routing or component failures may need to be reviewed for multi-unit impact.

- Based on the multi-unit risk significance, fire modeling refinements may be needed beyond what was performed for the single-unit analysis.

Multi-Unit Multi-Compartment Analysis

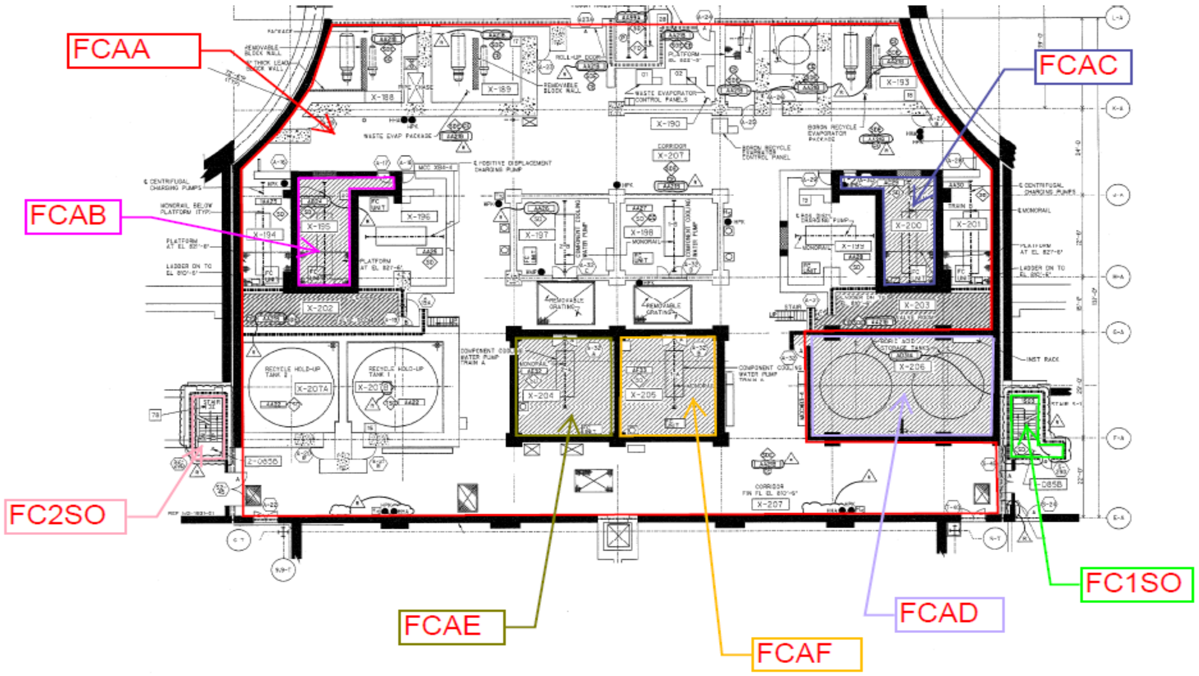
For a multi-unit fire analysis, the multi-compartment analysis (MCA) needs to be extended to:

Adjacent fire areas that were screened from the single-unit MCA based on the lack of equipment or cables in the “exposed” area from the “exposing” unit of interest. Those fire areas need to be included in the multi-unit MCA if cables from other units are present.

Adjacent fire areas that were included in the single-unit MCA, where cables from multiple units are present. Those fire areas need to be included in the multi-unit MCA to address the unique multi-unit impacts.

Insights from the Multi-Unit Fire Pilot

- The reviewed fire compartment did not contain credited equipment or any equipment that would result in an automatic or manual plant trip if damaged by a fire.
- The fire compartment did not contain equipment or cables that if damaged by a fire would result in a controlled manual shutdown.
- Within the common areas, there were a limited number of cables (10 or fewer) belonging to either the opposite unit or the single unit.
- Cables were reasonably separated, and the compartment was not subject to a hot gas layer.



Fire Areas/Zones at a Multi-Unit Site

A limited potential for multi-unit impacts was observed.

Insights from the Multi-Unit Fire Risk Pilot

Unit 1	Screen	Unit 2	Screen
U1 Compartment; Unit 1 Cables	Yes	U2 Compartment; Unit 2 Cables	Yes
U1 Compartment; Common Cables	No	U2 Compartment; Common Cables	No
U1 Compartment; Unit 2 Cables	No	U2 Compartment; Unit 1 Cables	No
U1 Compartment; Off-site power	No	U2 Compartment; Off-site power	No
U1/U2 Compartment; Common Cables	No	U1/U2 Compartment; Common Cables	No
U1/U2 Compartment; Unit 1 Cables	No	U1/U2 Compartment; Unit 2 Cables	No
Shared Main Control Room	No	Shared Main Control Room	No
Shared Turbine Building	No	Shared Turbine Building	No
Shared Service Water Intake Structure	No	Shared Service Water Intake Structure	No
Shared Switchyard	No	Shared Switchyard	No

Multi-Unit Fire: Task #3

Perform the HRA for multi-unit fire accident sequences by developing fire mitigation HFEs:

Local Actions

The consideration of local action feasibility should be performed in a manor that is consistent with the single-unit analysis.

Control and Indication

Fires that damage controls and indications are more likely to have a single-unit impacts and result in single-unit abandonment scenarios (i.e., not a multi-unit concern).

Main Control Room Abandonment

Consideration for multi-unit specific interactions may be required (e.g., main control room (MCR) abandonment in case of a shared control room). Loss of habitability within the control room would be expected to impact multiple units. A multi-unit abandonment should be initially assumed given the loss of habitability.

Remote Shutdown

Modeling of the remote shutdown panels and procedures should be reviewed for unique multi-unit impacts and differences from single-unit evacuation (i.e., the multi-unit scenario is different from multiple independent MRC evacuations).

Inter and intra-unit HRA dependencies compound the complexity.

Multi-Unit Fire: Task #4

Develop multi-unit fire scenarios.

Develop Scenarios

Multi-unit fire scenarios should be built from the information gathered in the single-unit Fire risk model and expanded as needed to include multi-unit fire impacts on equipment and operators.

Screen Scenarios

Screen fire areas based on their potential to contribute to multi-unit fire scenarios. Screen fire areas with low contribution to fire risk based on an understanding of components and cables within the area.

Document & Review

Document the basis and justification for screening fire areas, and for the development of the multi-unit fire scenarios.

Multi-Unit Fire: Task #5

Perform dedicated multi-unit fire walkdowns and interviews:

- Dedicated fire walkdowns are recommended to address unique multi-unit considerations and risk-significant fire areas.
- For sites with shared or connected main control rooms (MRCs), walkdowns of the shared MCR and remote shutdown areas should be performed to support the HRA evaluation of multi-unit MRC evacuation.
- Dedicated operator interviews should also be performed to review multi-unit considerations.

Multi-Unit Fire: Task #6 and #7

- **Task #6:** Understand the risk model results and develop multi-unit risk insights:
  - At a minimum, the multi-unit risk assessment should identify unique risk insights, such as fire sources and scenarios that are of greater importance to multi-unit risk (as compared to single-unit risk).

> ⚠ The multi-unit analysis may conclude that there are no significant multi-unit fire risks.

- **Task #7:** Document the multi-unit fire risk assessment:
  - The multi-unit risk documentation requirements should be similar to the single-unit requirements.

Multi-Unit Internal Hazards Conclusions

- Multi-unit internal flooding and fire risk analysis follow the same general approach used for single-unit analysis.
- Multi-unit scenarios consider direct and indirect impacts:
  - Consider the differences in flooding propagation pathways or multi-compartment fire analysis.
  - Consider the differences in flood or fire propagation timing.
- Large multi-unit models may challenge the quantitative assessment (e.g., building and calculating large models is challenging).
- Analysis is significantly dependent on the plant layout, thus the EPRI framework is graded and generic (one size does not fit all).

External Hazards in MU-PSA

Overview of the Task

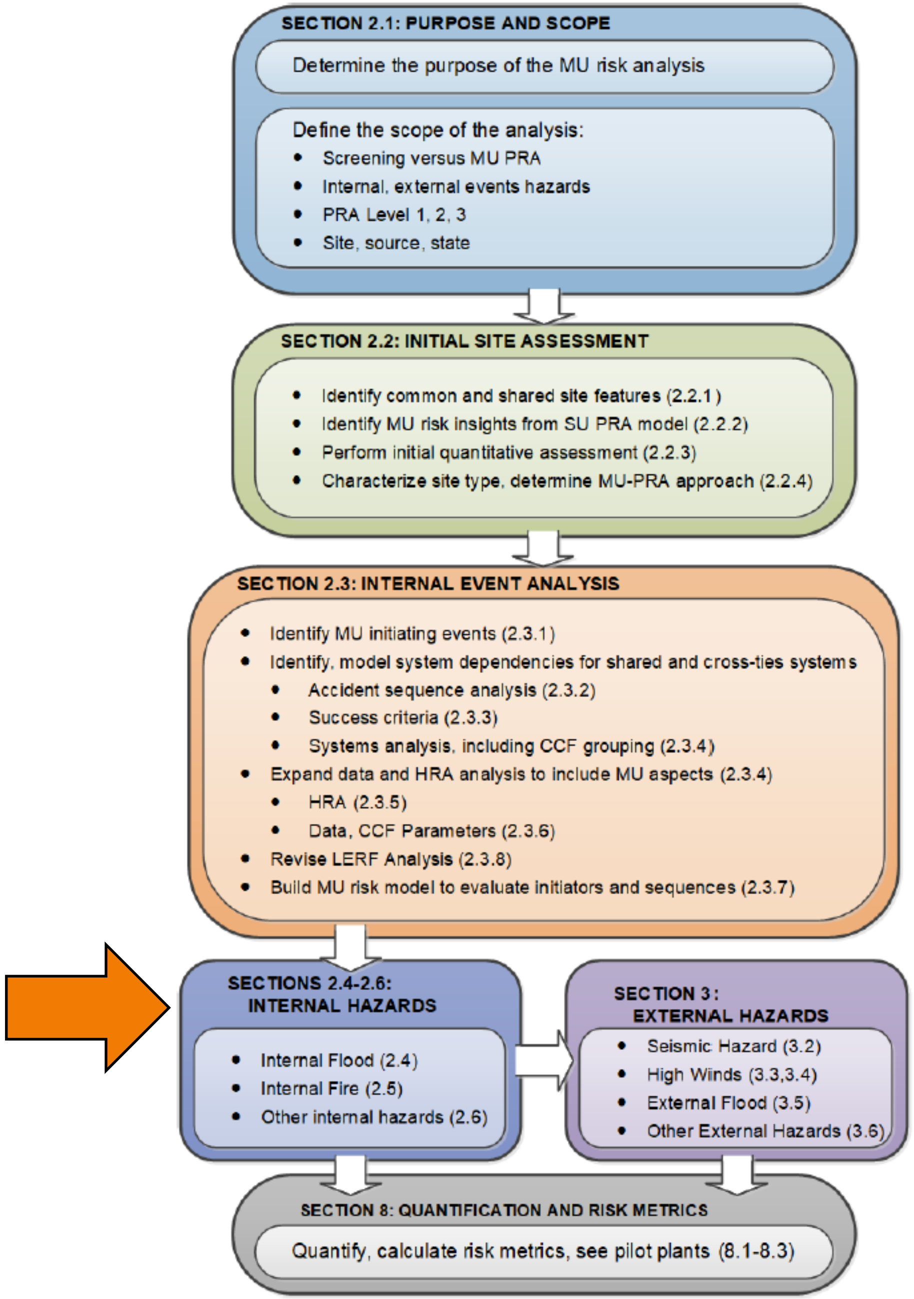
- External hazards may represent the **major sources of multi-unit risk** because they can cause site-level initiators and correlated damage on units across the site.

- The external hazard analysis **begins with an assessment of the single-unit risk**, which is typically either a screening analysis or a detailed hazard evaluation.

- The multi-unit hazard analysis **builds on single-unit risk** and uses the multi-unit internal events model as a foundation.

External Hazards

- Seismic Risk
- High Winds Risk:
  - Tornados
  - Hurricanes
- External Flooding
- Emphasize the unique aspects due to multi-unit severe accidents.
- External hazards (especially seismic) are the most significant contributors to overall risk contribution.



General Assumptions

- Start with a **comprehensive single-unit risk model** and documentation that includes:
  - Seismic, high winds, and external flooding modeled using methodologies that represent the current state of practice.
  - Single-unit risk model meets the requirements provided by the ASME/ANS standard.

> Because external event models rely on internal events for consequential events (e.g., seismic induced fire and flooding) the supporting hazards (e.g., internal fire and flooding) must also be addressed appropriately in the single-unit risk model.

  - It's recognized that the external flooding starting point is closer to a site assessment because of the inherent characteristics of how external floods can impact a site.

Multi-Unit Seismic Risk Analysis

When developing a multi-unit seismic risk model, the main concern is the seismic fragility correlation:

- The multi-unit initiating event screening is changed by fragility correlation and LOCA can also be considered correlated if associated fragilities are correlated

Fragility Grouping

Identifying components that will have the same fragility. For example, two heat exchangers in a common area with the same orientation, general dimensions, and design characteristics.

Failure Correlation

Components within such groups are assumed to fail together. That is to say, when one component within the group fails, all components within the group are assumed to fail. This applies to fragilities for mitigation or initiating events (e.g., LOCA).

✓ When perfect correlation is considered, the terms fragility grouping, and fragility correlation are synonymous.

Single-Unit Refinements

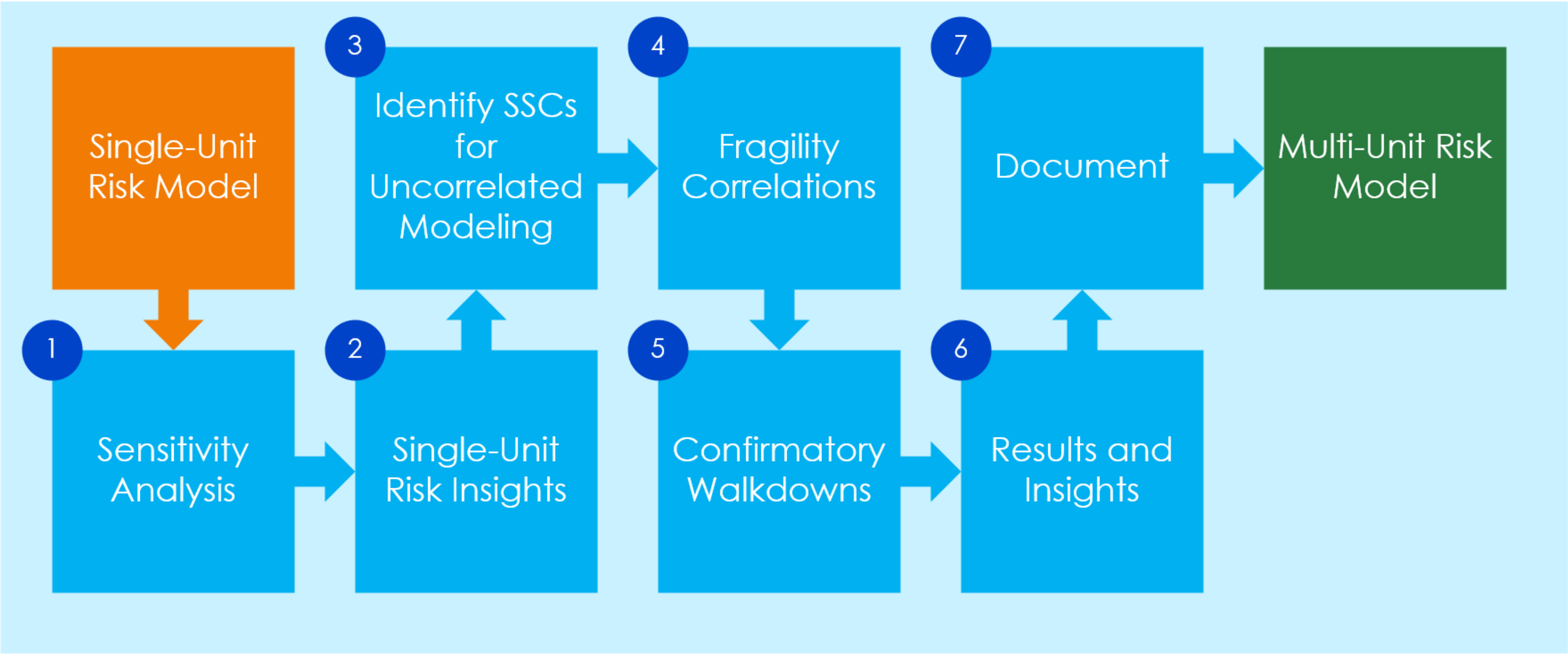
The Single-unit refinement process often starts with conservative fragility group sizes and proceeds to “break fragility groups” based on qualitative or semi-quantitative criteria, including:

- Component Orientation
- Component Size
- Component Anchorage Type
- Component Elevation
- Seismic Demand

The multi-unit analysis approach does not change the process or rationale for “breaking of fragility groups” for fully correlated fragilities - extend this to components that may not have previously been under scrutiny.

Multi-unit analysis does not suggest transitioning to a full partial correlation assessment of all fragilities – this would result in more complex scenarios.

Seismic Framework – From Single-Unit to Multi-Unit



7 Multi-unit insights from single-unit analysis.

Seismic correlations.

Multi-unit risk results and insights.

6 Single-unit vs. multi-unit significant risk contributors.

Unique multi-unit vulnerabilities.

1 Perfectly correlated vs. uncorrelated.

Focus the multi-unit risk analysis.

2 Multi-unit aspects captured in the single-unit analysis.

Close gaps for multi-unit analysis.

3 Shared multi-unit risk significant SSCs.

Generic/bounding fragilities.

4 Simplified vs.rigorous.

5 Verify details used to justify partial correlations.

Assumptions for Multi-Unit Seismic Risk Analysis

- The single-unit risk model is technically adequate, represents the individual units, and includes the following:
  - Realistic modeling of fragilities for significant contributors.
  - Full correlation of modeled equipment based on fragility grouping for single-unit seismic risk.

- The seismic hazard is identical across all units:
  - Dual-unit sites can realistically be modeled using a single hazard that impacts all units.
  - Larger or significantly irregular sites can have significant differences, which can result in a reduced correlation.

Capacity elements for components (including spatial effects and differences) become dominant in fragility correlation considerations

Step #1: Sensitivity Analysis

Commensurate approach to partial correlation of equipment:

- Seismic correlation importance decreases with an increase in input motion (fragilities approach 1.0 independently from correlation assumptions).
- Lower case (i.e., fully uncorrelated) and upper case (i.e., fully correlated) sensitivity identifies the expected importance of correlation assumptions.

The EPRI pilot plant was highly correlated. Partial correlation is not particularly insightful.

HAZARD BIN	U1 CCDP	U1 CDF	TRUNC. LIMIT	U12 CCDP	U12 CDF	TRUNC. LIMIT	CDF12 /CDF1
.09 g-.18 g	1.40E-06	6.33E-10	1E-10	2.73E-08	1.23E-11	1E-11	2%
.18 g-.3 g	1.58E-05	2.10E-09	1E-10	2.58E-07	3.43E-11	1E-11	2%
.3 g-.5 g	4.28E-05	2.45E-09	1E-10	1.24E-05	1.24E-09	1E-10	32%
.5 g-.8 g	1.08E-03	2.32E-08	1E-10	8.50E-04	1.83E-08	1E-10	86%
.8 g-1.2 g	3.13E-02	2.28E-07	1E-10	2.53E-02	1.84E-07	1E-10	88%
1.2 g-2 g	4.56E-01	1.44E-06	1E-10	3.79E-01	1.20E-06	1E-10	91%
2 g-3 g	9.13E-01	6.71E-07	1E-09	8.34E-01	6.12E-07	1E-08	100%
> 3 g	9.14E-01*	2.67E-07	1E-07	8.35E-01	2.44E-07	1E-07	100%
	TOTAL	*2.63E-06*		TOTAL	*2.26E-06*	TOTAL	*86%*

Step #2 and #3: Risk Insights and Correlation

- Single-Unit insights support the following:
  - Help to identify primary targets for uncorrelation effort.
  - Single-unit contributors also rise as significant for multi-unit contributors.
  - It’s possible that fragilities may be relatively refined, and correlation considerations already considered.

The EPRI pilot plant was a dual-unit site with shared equipment.

- Initial multi-unit considerations:
  - Assemble and run the multi-unit model with current correlations to identify good candidates for refinement - use resulting importance measures.
  - Completely separated (i.e., independent) units may show differences in the recommended components.

Step #4: Fragility Correlations

Consider the degree of fragility correlation.	Assess Partial Correlations	Fragility Correlation Process
Quantify the effects of partial fragility correlation on combined (union or concurrent) fragilities.	Calculate Partially Correlated Fragilities	
Handoff the fragility results to the systems analysts, and incorporate partially correlated fragilities into the risk quantification software tools.	Perform System Modeling	

Assessment of Partial Correlations

Proposed simplified approach: This approach is based on judgement, and results in a straight-forward application, but may involve more uncertainty, and may require sensitivity analysis to validate and justify the applied judgment.

Existing rigorous approach: Use the current approaches that are resource intensive, require significant computational resources, and can be considered impractical and unnecessary for most applications. This is discussed briefly in the EPRI Technical Report (3002018229).

Hybrid approach: A hybrid approach may also be used. Such an approach uses partial correlation between some fragility variables based on judgment for some variables, and rigorously computed for other variables - based on degree of difficult to perform the calculations.

Simplified Assessment of Partial Correlations

- The fragility correlation coefficient ρ (rho) is calculated as:

$$\rho=(\beta^{*})^{2}/(\beta_{1}\beta_{2})$$

- The two types of fragility correlation coefficients can be defined as follows:

ρ_r
logarithmic standard deviation for randomness.

ρ_u
logarithmic standard deviation for uncertainty.

These variables are not necessarily the same value but can be considered the same as a justifiable simplification in many cases

Simplified Assessment of Partial Correlations

- The fragility correlation coefficient (ρ) varies from zero (perfectly uncorrelated) to one (perfectly correlated).
- Using a qualitative sliding scale, a fragility analyst can assign ρ for the governing fragility variables (e.g., equipment response).
- The variable ρ can be used to compute the shared (correlated) portion (β*) for that variable.
- Square Root of Sum of Squares (SRSS) β* for all governing variables to compute the total β* and the overall ρ value.

Degree of Fragility Correlation	rho
None	0
Weak	0.2
Moderate	0.5
Strong	0.8
Perfect	1

Perfectly Uncorrelated

Perfectly Correlated

Simplified Assessment of Partial Correlations

Example Fragility Correlation Analysis

Fragility Group	Fragility Variable	β_R	β_U	Correlation Coefficient ρ: Judged Value	Correlation Coefficient ρ: Qualitative Basis	β_R^*	β_U^*
Distribution Panels	Equipment Capacity	0.09	0.32	0.8	Both panels are seismically qualified by the same test data, and variability in the capacity is for the range of panels configurations that can be represented by this seismic qualification test. The construction of the individual panels, though not identical, is very similar. The boundary conditions provided by the field anchorage configuration are identical. The capacity variables are therefore judged to be strongly correlated.	0.08	0.29
	Equipment Response	0	0.12	0.2	The associated variability is governed by the spectral clipping variability. Due to the difference in the bandwidth of the input spectra at the locations of the individual cabinets, the associated correlation is judged to be weak.	0	0.05
	Structural Response	0.22	0.30	0.5	The panels are in the same building and at the same elevation, with the same orientation. However, they are in different rooms with significant independence in the governing input spectra such that a strong correlation cannot be justified. The structural response variables are judged to be only moderately correlated.	0.16	0.21
	Total (Square Root of Sum of Squares)	**0.24**	**0.45**			**0.18**	**0.36**

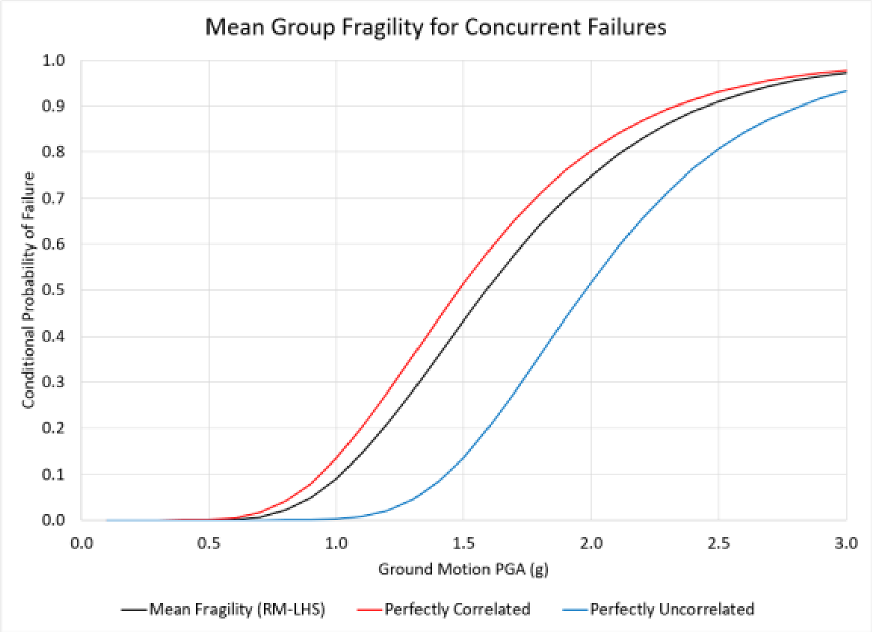
$$\rho_R = \frac{0.18^2}{0.24 \text{ X } 0.24} = 0.6$$

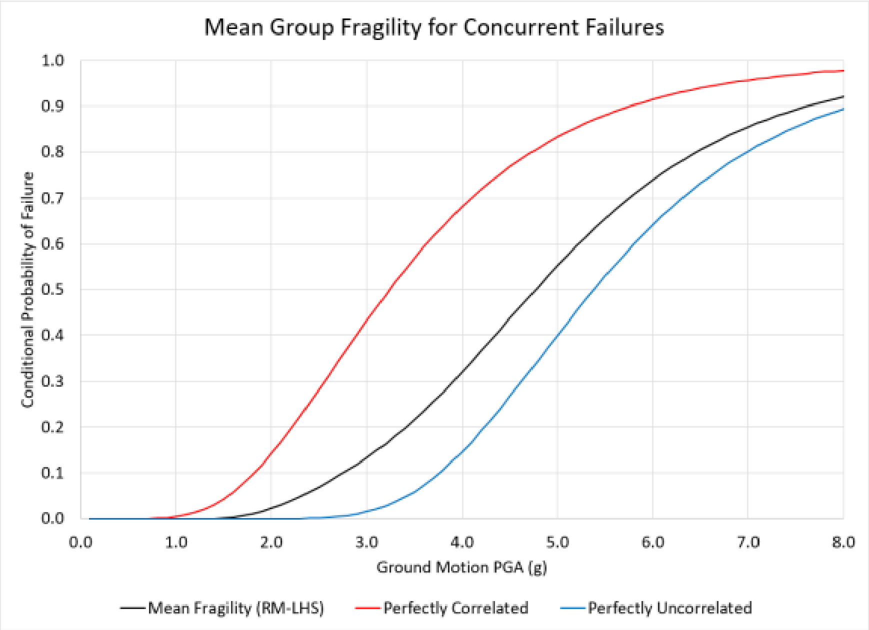
$$\rho_U = \frac{0.36^2}{0.45 \text{ X } 0.45} = 0.6$$

Computation of Partially Correlated Fragilities

With the overall β_R^* and β_U^* values, the partially correlated fragility can be computed using the Separation of Independent and Common Variabilities (SICV) approach recommended in NUREG/CR-7237.

Referred to as Reed-McCann method after the original authors of the approach.





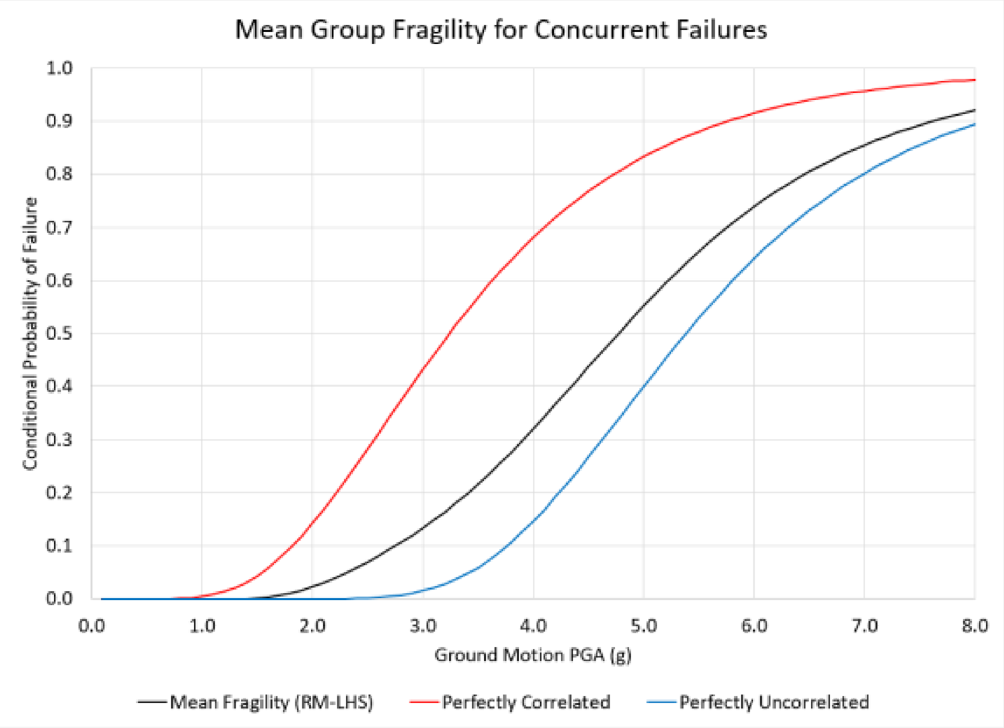
Systems Modeling of Partial Correlations

Handoff of results:

- Fragility correlation coefficients (ρ_R, ρ_U).
- Explicit partially correlated fragilities.
- Split fractions (Beta Factor Method) - **widely supported in current risk quantification software**.

$$SF_\rho = (P_{f,pc} - P_{f,ind}) / (P_{f,cor} - P_{f,ind})$$

$$P_{f,pc} = (SF_\rho)(P_{f,cor}) + (1 - SF_\rho)(P_{f,ind})$$



$P_{f,pc}$
The partially correlated probability of failure for the fragility group (at a given ground motion).

$P_{f,ind}$
The group probability of failure assuming the group component failures are independent.

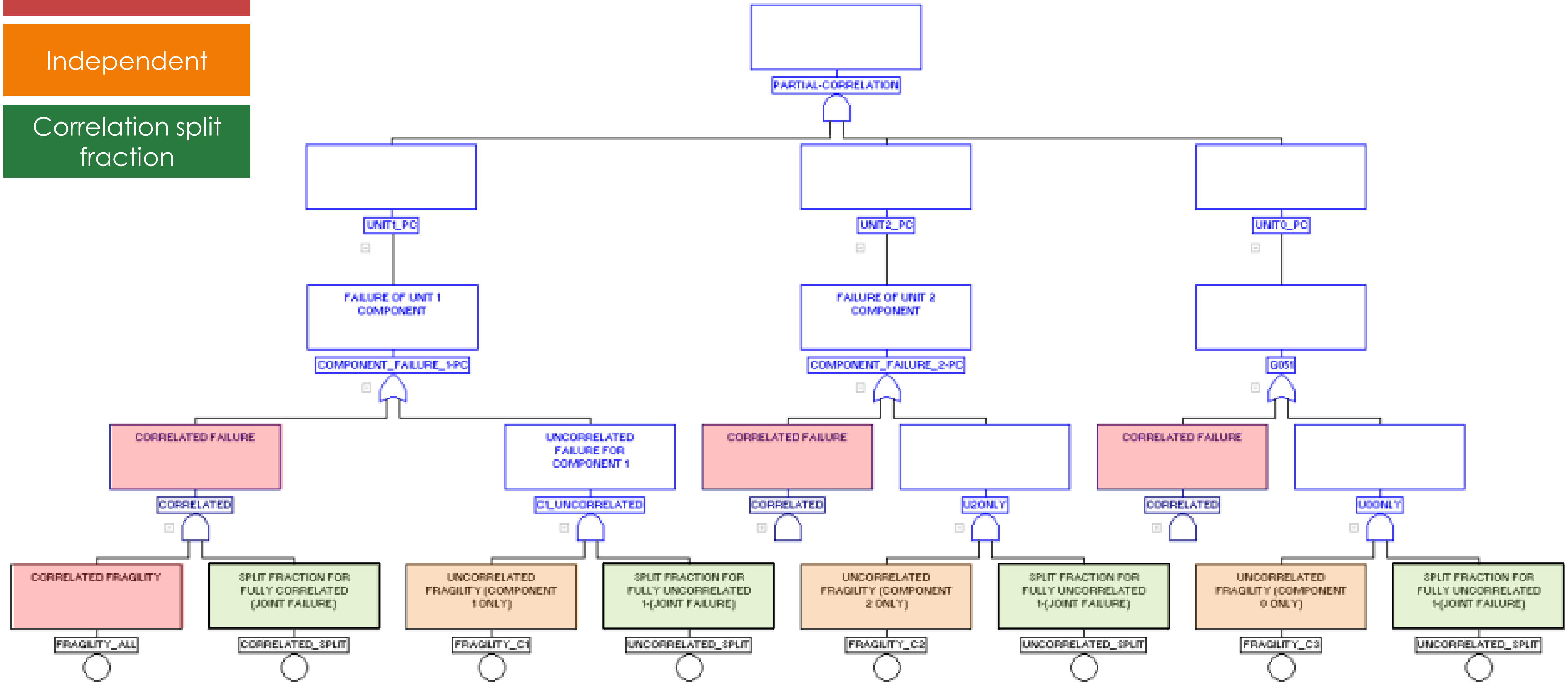
$P_{f,cor}$
The group probability of failure assuming the group component failures are perfectly correlated.

Systems Modeling of Partial Correlations

Shared

Independent

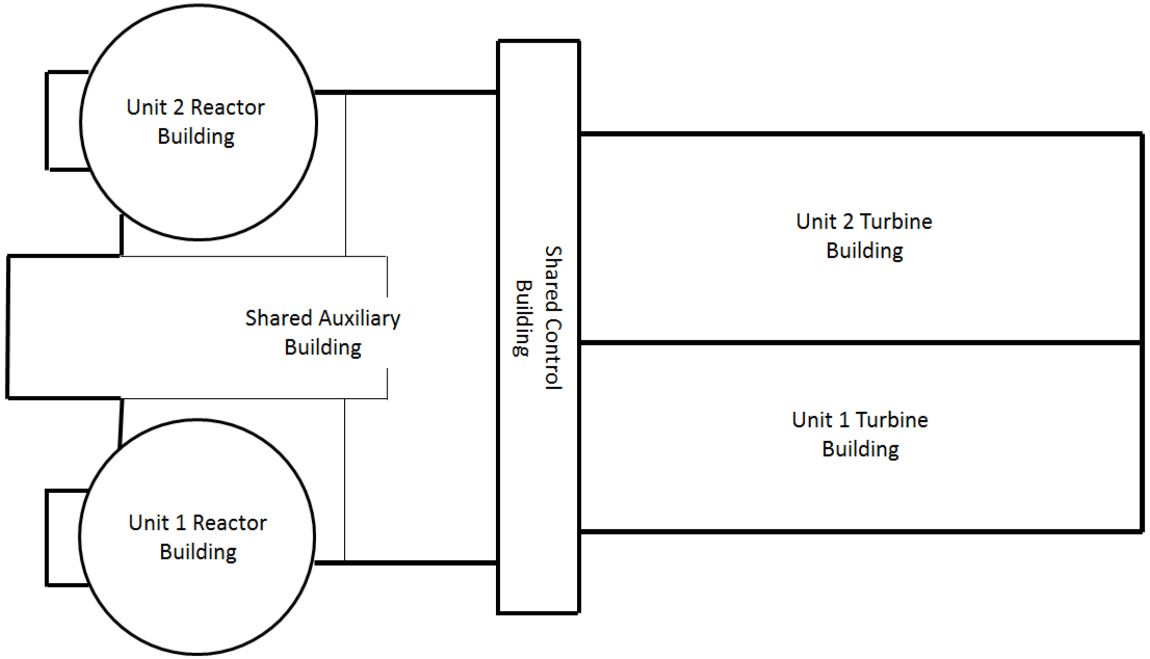
Correlation split fraction

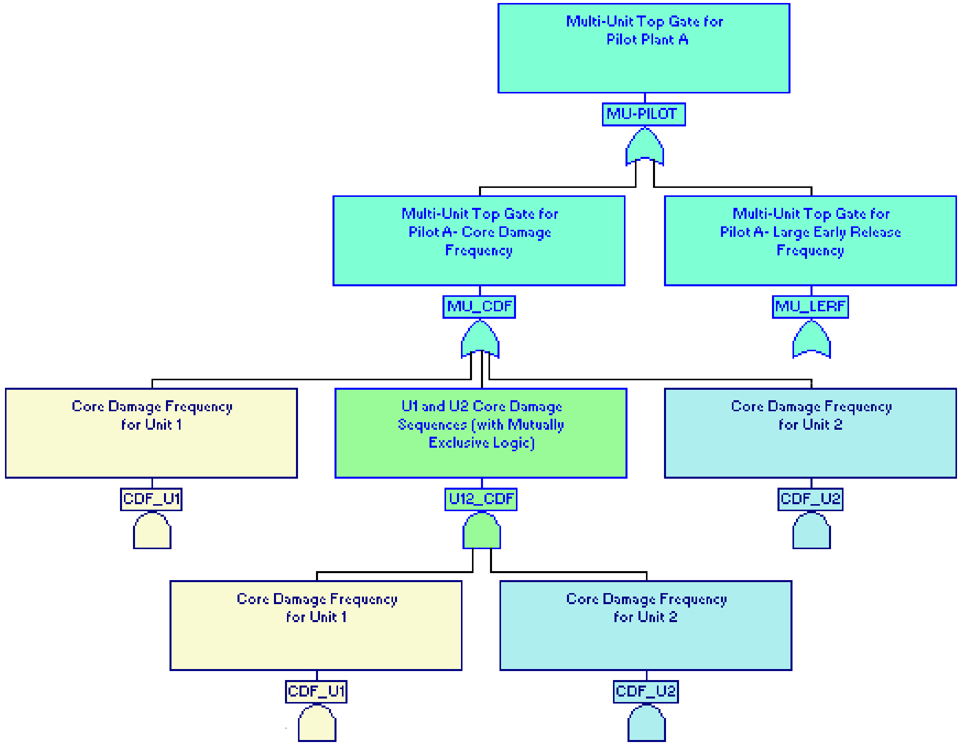


Pilot Plant Application – Overview

The pilot plant had a fully developed single-unit risk model, including:

- Explicit modeling of Unit 1, Unit 2, and shared (Unit "0" SSCs).
- Individual models linked to calculated multi-unit CDF.





Pilot Plant Application

- Initial multi-unit analysis returned fragility candidates for correlation investigation:

Component Cooling Water Heat Exchangers (3 heat exchangers, one per unit and one shared)	Common Walls in the Diesel Generator Building Impacting >1 Unit's Diesels	Unit "0" (common) Relay Panels	Main Control Room Panels (modeled as direct to core damage scenarios)

- None of the important multi-unit scenarios addressed correlated items in different buildings - even if the structures were symmetric and identical.
- Except for the main control room panels, all other fragilities were "triggered" via a seismic-induced Loss of Offsite Power - modeled as fully correlated for both units.

✓ All other correlated initiators screening out based on model truncation.

Pilot Plant Application – Seismic Correlations

Pilot Plant A MU risk-significant fragility groups addressed for partial correlation

Fragility Group	Number of Components in Group	Governing Failure Mode	Am (g)	β_R	β_U	HCLPF (g)
CCW system heat exchangers	3	Anchorage	1.48	0.24	0.26	0.65
Block wall	4	Collapse	2.32	0.24	0.26	1.02
Relay panels	4	Functional	3.27	0.24	0.38	1.15
Relay panels (MCR)	5	Functional	3.24	0.24	0.38	1.14

Pilot Plant A information inputs for the fragility correlation analyses

Fragility	Location of Individual Components	Configuration of Individual Components
CCW system heat exchangers	All heat exchangers are located next to each other in the same room, at the same elevation, and in the same building.	The heat exchangers are very similar in construction, and are anchored in a similar manner. All heat exchangers are oriented along the same direction.
Block wall	The four walls are successively located along the same gridline at the same elevation, in the same building.	The walls are largely the same in terms of design, materials, and configurations, but there are some variations in attached masses and openings.
Relay panels	The individual cabinets are located in the same building and at the same elevation. The four cabinets are located in two adjacent rooms: one pair of Unit 1 and Unit 2 cabinets are in one room, and the other pair of Unit 1 and Unit 2 cabinets are in the adjacent room.	All cabinets are of similar construction, and are oriented along the same direction. Anchorage details are similar.
MCR panels	All panels are located in the main control room, at the same elevation, and in the same building.	The panels have some differences in sizes and configurations.

Pilot Plant A fragility correlation analysis

Fragility Group	Variable	β_R	β_U	Correlation Coefficient		β_R^*	β_U^*
				Judged Value	Basis		
CCW system heat exchangers	Equipment Capacity	0.04	0.14	0.65	The heat exchanger fragility is governed by anchorage failure. In general, anchors show considerable variation in strengths under testing, even amongst anchors of similar properties (diameter, embedment depth, etc.). This inherent variation is the independent portion of anchor strength variability, which reduces the degree of correlation between the anchor strengths of the individual heat exchangers despite the similarity in anchorage configuration. The capacity variables are therefore judged to be somewhere between moderately to strongly correlated. A fragility correlation value of 0.65 is judged appropriate.	0.03	0.11
	Equipment Response	0.05	0.12	0.8	The individual components are nearly identical, with very similar installation and configuration. Equipment response is judged to be strongly correlated.	0.04	0.11
	Structural Response	0.23	0.19	1.0	All individual components are located next to each other, and are oriented along the same direction. The structural response variables are judged to be nearly perfectly correlated.	0.23	0.19
	Total	**0.24**	**0.26**			**0.24**	**0.25**
Block walls	Equipment Capacity	0.04	0.12	0.5	While the configurations are largely similar, the different masonry walls have some variations in attached masses and openings. The correlation in capacity variables is judged to be moderate.	0.03	0.08
	Equipment Response	0.04	0.16	0.5	For the same reasons as stated for the equipment capacity variables, the equipment response variables are judged to be only moderately correlated.	0.03	0.11
	Structural Response	0.23	0.17	1.0	The walls are located next to each other along the same gridline (and along the same direction). The structural response variables are judged to be nearly perfectly correlated.	0.23	0.17
	Total	**0.24**	**0.26**			**0.23**	**0.22**

Pilot Plant A total fragility correlation coefficients

Fragility	ρ_R	ρ_U
CCW system heat exchangers	1.0	0.9
Block wall	0.9	0.7
Relay panels	0.9	0.9
Relay panels (MCR)	0.5	0.5

Pilot Plant Application – Seismic Correlations

Pilot Plant A total fragility correlation coefficients

Fragility	ρ_R	ρ_U
CCW system heat exchangers	1.0	0.9
Block wall	0.9	0.7
Relay panels	0.9	0.9
Relay panels (MCR)	0.5	0.5

Pilot Plant A correlation split fractions per Hazard Bin

Hazard Bin	Hazard Bin PGA* (g)	Correlation Split Fraction (SF_p)			
		CCW System Heat Exchangers	Masonry Walls	Relay Panels	MCR Panels
0.09g – 0.18g	0.13	0.22	0.11	0.18	0.00
0.18g – 0.3g	0.23	0.22	0.11	0.18	0.00
0.3g – 0.5g	0.39	0.22	0.11	0.18	0.00
0.5g – 0.8g	0.63	0.38	0.11	0.18	0.00
0.8g – 1.2g	0.98	0.66	0.11	0.18	0.00
1.2g – 2g	1.5	0.79	0.41	0.45	0.05
2g – 3g	2.4	0.83	0.61	0.65	0.24
> 3g	3.5	0.86	0.61	0.72	0.31

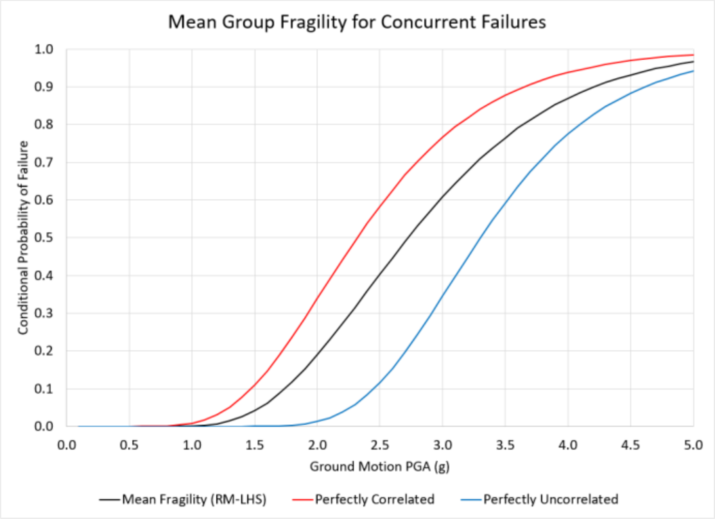


Figure 8-10
Pilot Plant A mean group fragility for concurrent failures of block walls

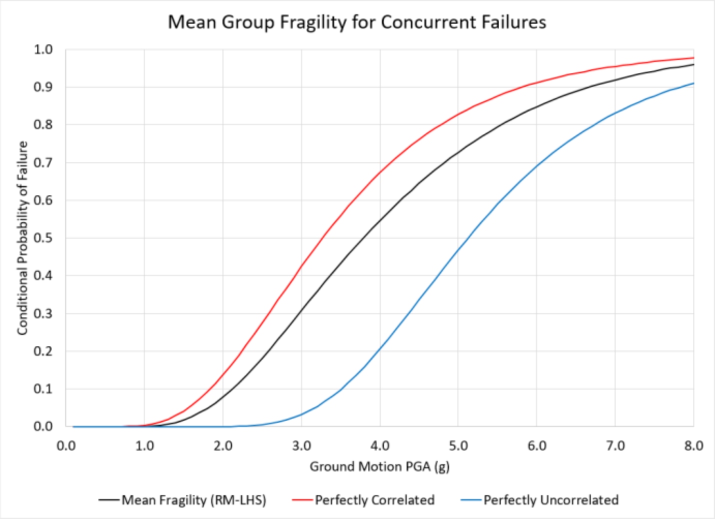


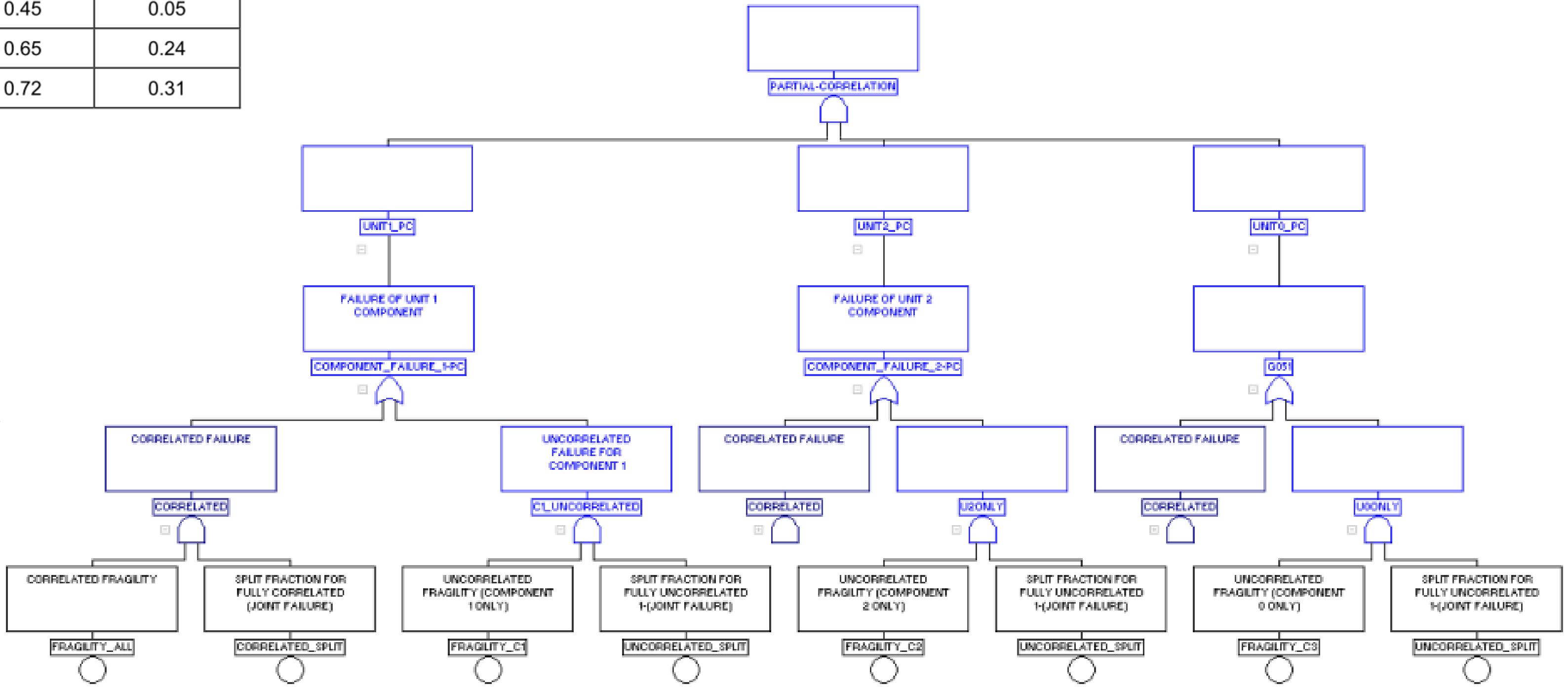
Figure 8-11
Pilot Plant A mean group fragility for concurrent failures of relay panels

Pilot Plant Application – Seismic Correlations

Pilot Plant A correlation split fractions per Hazard Bin

Hazard Bin	Hazard Bin PGA* (g)	Correlation Split Fraction (SF_P)			
		CCW System Heat Exchangers	Masonry Walls	Relay Panels	MCR Panels
0.09g – 0.18g	0.13	0.22	0.11	0.18	0.00
0.18g – 0.3g	0.23	0.22	0.11	0.18	0.00
0.3g – 0.5g	0.39	0.22	0.11	0.18	0.00
0.5g – 0.8g	0.63	0.38	0.11	0.18	0.00
0.8g – 1.2g	0.98	0.66	0.11	0.18	0.00
1.2g – 2g	1.5	0.79	0.41	0.45	0.05
2g – 3g	2.4	0.83	0.61	0.65	0.24
> 3g	3.5	0.86	0.61	0.72	0.31

The split fraction variable with hazard bins required manual modeling beyond the current EPRI tools pre-set.



EPRI

Key Insights from the Pilot Plant Application

Partial vs. Perfect Correlation

Re-quantification of select system models with partially correlated fragilities (instead of perfectly correlated) showed competing effects:

- A limited reduction in multi-unit CDF was observed with partially correlated fragilities.
- A reduction in the importance of the partially correlated fragility groups was observed.
- This reduction was offset by the increase in the number of cutsets due to the partial correlation modeling.

Overall Results

The multi-unit CDF remained unchanged for the pilot plant. However, this insight is plant-specific, and additional refinements to the correlation modeling could result in a reduction in the multi-unit risk results.

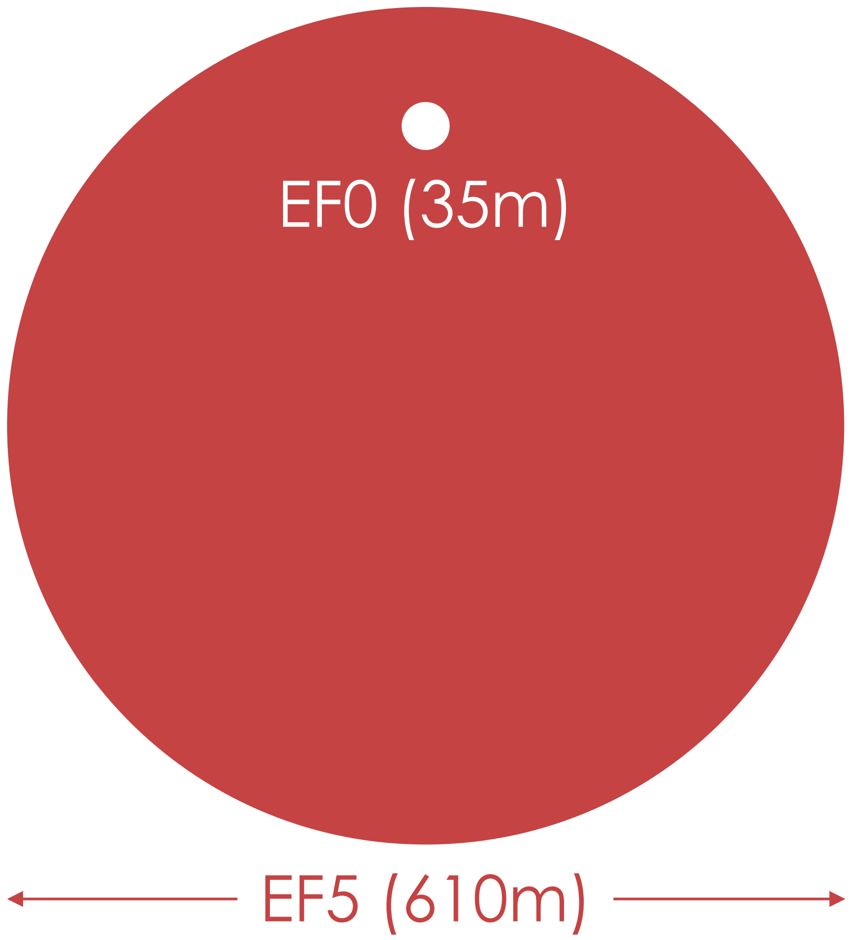
Multi-Unit High Winds Risk – Tornados

Tornado Hazards

Tornados are expected to generate site wide initiators (e.g., loss of offsite power). The site impact and the associated correlation depends on the tornado's size. The larger the tornado, the greater the potential for correlation*.

Multi-unit high winds correlation is beyond the normal state of practice. A conservative first approach starts with assuming the strongest effect over the entire tornado path, and that the tornado's path covers the entire site.

*1,200m to 1,500m is a typical dual-unit site dimension.



Types of High-Wind Impacts

- **Direct wind loading:** Tornadoes have great variability, and it's beyond the current start of art to differentiate this impact between units at a site. To start, assume the same impact for all units.

> Assuming the same impact for all units at a site is conservative but can be partially balanced by a finer discretization of the hazard/fragility, resulting in a less conservative fragility assessment, which is considered constant within each hazard interval.

- **Missile:** Not expected to be any different between single-unit and multi-unit. All buildings at a site should already be included in the analysis as potential sources of, and targets for missiles - same for Atmospheric Pressure Change (APC) scenarios.

Multi-Unit High Winds Risk – Hurricanes

Hazard impacts

For hurricanes, the treatment of direct wind impacts and missile impacts is similar to tornadoes with some variations. For example, missile impacts need to account for the fact that **hurricanes have a much smaller lift component** (smaller than tornadoes), which impacts what could become airborne and undergo significant displacement.

Risk analysis starting point

Multi-unit analysis for the risk of hurricanes is **based on the single-unit risk model**. Like tornados, all units on a site would be expected to have similar impacts.

Hurricane likelihood

Hurricanes are likely to be unit-level, site-level, and even regional hazards (compared to tornados, as hurricanes can span much larger areas).

Warning and preparation

Unlike tornados, hurricanes are typically forecasted hours and days before impact. This **allows the site to consider precautionary measures prior to landfall**. For example, when Hurricane Andrew struck the United States in 1992, nuclear power plants within the path were preemptively shut down based on procedural requirements.

Duration and response actions

Hurricanes have **long durations**, so there is a longer period when operator actions requiring transit outside of buildings may not be feasible. For coastal sites, hurricanes may present additional challenges in terms of equipment access due to the potential for concurrent flooding effects.

High Wind HRA Considerations

Performance Influencing Factor	Basis	SU Modelling	MU considerations
Crew resource availability	• Increased resource demand for field operators • Additional operators and other human resources may be delayed in coming on-site	• Confirm assumptions for staffing prior to and during the tornado event. • Review procedures regarding pre-stationed personnel	Verify that the personnel resource assumptions for local actions account for MU event (resources should be assumed not available from the other unit on-site).
Physical access to SSCs	• Operator travel between buildings will be hindered or impossible due to strong winds and debris (or procedure).	• Fail local actions if access is not feasible • Increase transit time where travel outside protected buildings is required. • Override the dependency analysis if necessary	Review procedures for possibility to credit alternative unit equipment if access to affected unit is hindered.
Cognition and execution actions	• Low frequency practice • Other plant support staff confused and/or distracted • General increased stress • Cognition and execution times may be delayed	• Increase the operator times (t_{cog} and t_{exe}) with increasing hazard levels. • Increase operator execution stress for increasing hazard levels.	Actions related to shared equipment damaged by the tornado may require special treatment

Multi-Unit External Flooding Risk

External floods are typically site-wide events, but impacts may be different for each unit. Site flood characterization needs to consider the following:

Maximum on-site flood elevation

The height the flooding compared to the critical flood height. The critical flood height may be different for various structures within a unit or from unit to unit on a single site.

Concurrent hazards

Generally expected to impact all units at a site, although the specific impacts may vary from unit to unit and will be highly dependent on the hazards.

Warning time

The time interval from when plant staff initiate site response based on forecasted hazard impact to the time the hazard arrives at the site. The warning time is expected to be the same for multiple units at a site, but each unit may need a different amount of time to prepare for the hazard.

Event duration

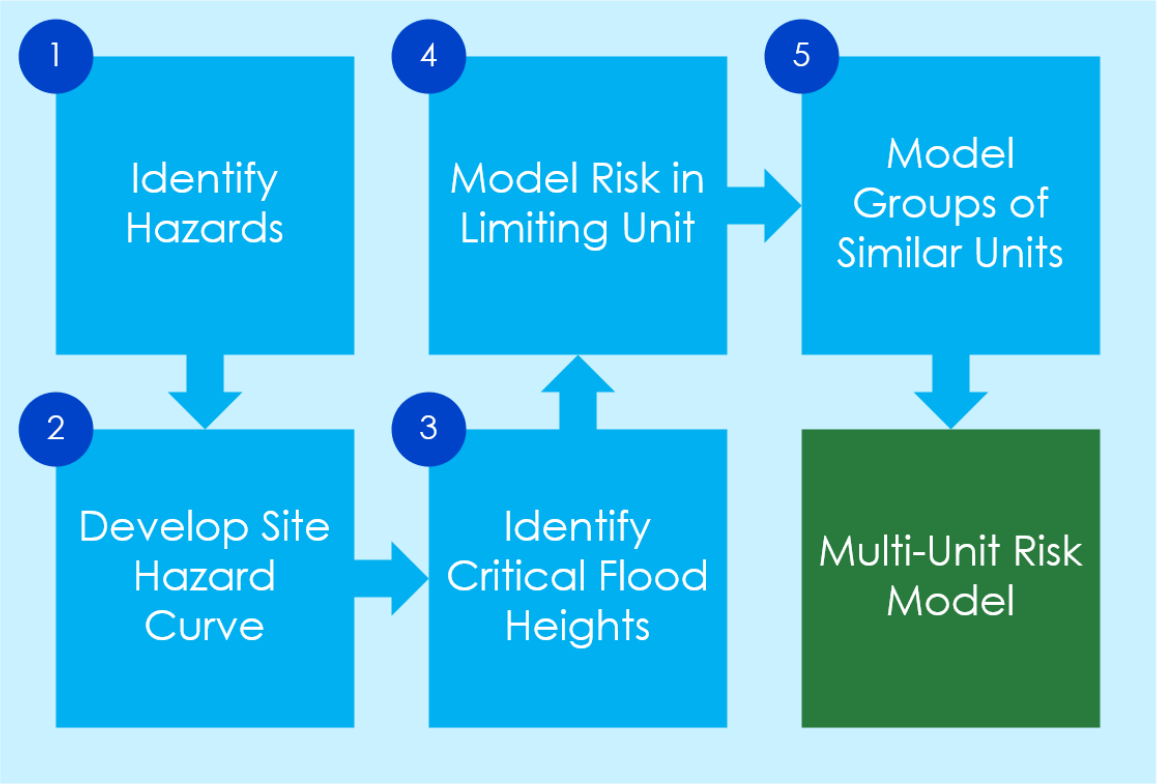
Generally expected to be the same for multiple units at a site. However, units at the same site with significant differences in elevation may experience different flood durations (i.e., some units will see the water recede before others).

The assumed starting point for multi-unit external flooding is not the existence of a single-unit model.

Types of External Flooding

XF Hazard	Warning time	Duration	Concurrent Hazards	MU Impacts	LOOP	LUHS	Structural damage
Local Intense Precipitation	Limited	Short	High winds	Limited correlation between units.	If associated with high winds	Unlikely	Not expected
Storm Surge (hurricane or coastal)	Long	Several hours	High winds	Likely all site. MU impact from water entering cable tunnels. Delay operation outside.	Likely due to hurricane	Potential due to debris	External barrier designed for impacts, possible overtopping
Riverine flood (precipitation)	Short	Day to months	Storm surge	Large MU impact, site is isolated. Debris to intake	Likely impacting switchyard	Potential due to debris	Not expected on short term
Riverine flood (dam)	Based on distance (may be planned)	Days	Rain	Depending on dam inventory. MU sites will be exposed to rising waters creating various flood challenges to equipment in the yard, and equipment within buildings, if no adequate flood protection.	Likely impacting switchyard	Potential due to debris	External barrier designed for impacts, possible overtopping
Riverine flood (dam, seismic)	Based on distance	Condition dependent	Seismic	Potential correlated seismic MU impacts and impact on flood barriers.	Likely impacting switchyard or from EQ	Potential due to debris	External barrier designed for impacts, possible overtopping. Seismic impact.
Tsunami	Hours to a day	Several hours	Seismic	Potential correlated seismic MU impacts and impact on flood barriers.	Likely impacting switchyard or from EQ	Potential due to debris or from drawdown	External barrier designed for impacts, possible overtopping. Seismic impact.

Multi-Unit External Flooding Framework



5 Model the risk of external flooding hazards to groups of similar units at the site.

1 Identify the applicable external flooding hazards.

2 The critical parameter is peak water height. Develop hazard frequency curves that impact the least vulnerable unit at the site.

3 The multi-unit analysis must address how the single-unit model addresses unit differences (e.g., explicit, lead, or bounding analysis).

4 This step allows for a graded approach for adding detail to potentially risk significant multi-unit scenarios.

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