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Resilience of NPPs Considering External Hazards

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Risk-Based Resilience Assessment for Nuclear Power Plants under Seismic Events

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04 Conclusions

Plant risk depends on component states

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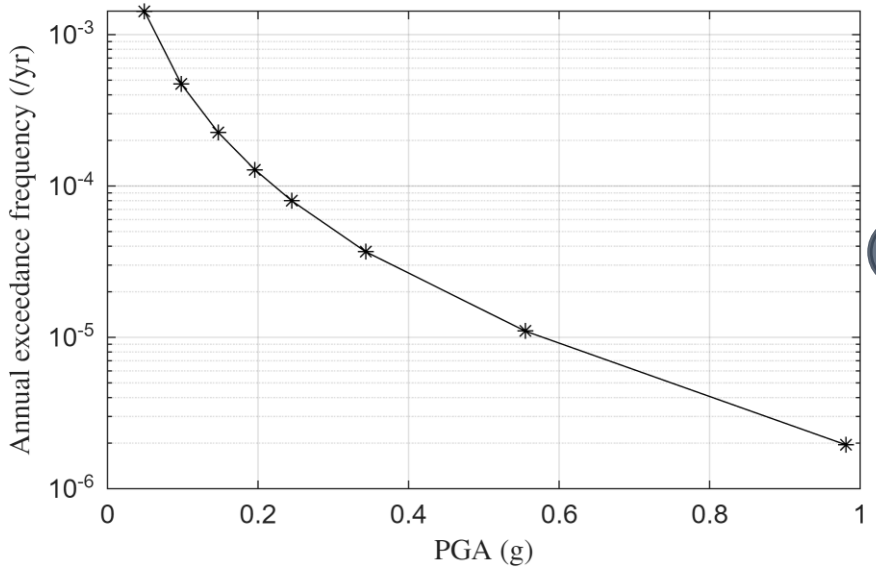
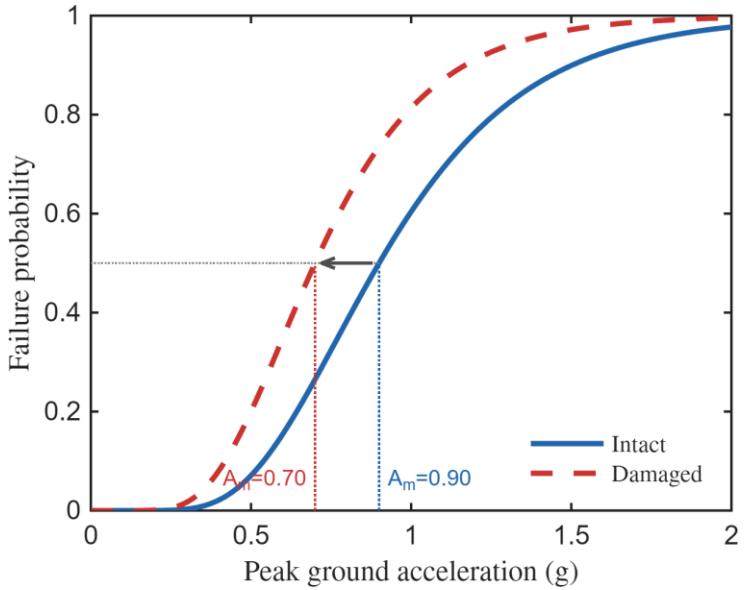
Seismic Probabilistic Safety Assessment (PSA):

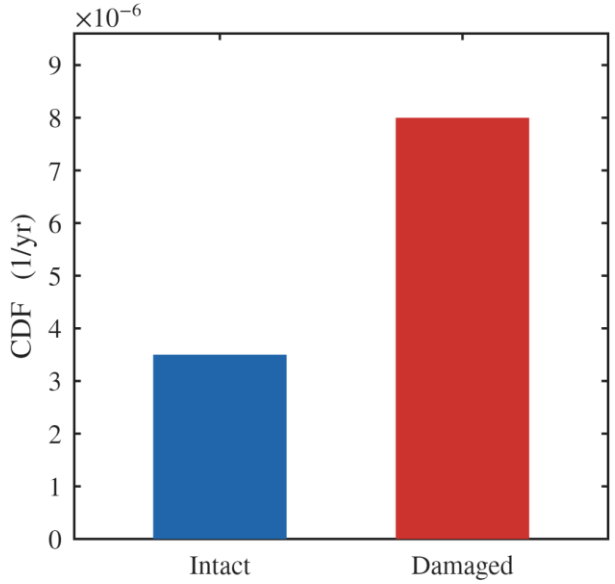
- Plant-level seismic risk combines seismic hazard with system fragility derived from event-tree and fault-tree models
- Component degradation changes fragility parameters and increases plant-level risk
- $Risk = \int_a F(a) \left| \frac{dH(a)}{da} \right| da$



Seismic hazard $H(a)$



System Fragility $F(a)$



Plant-level risk (CDF)

Post-earthquake plant states and assessment scope

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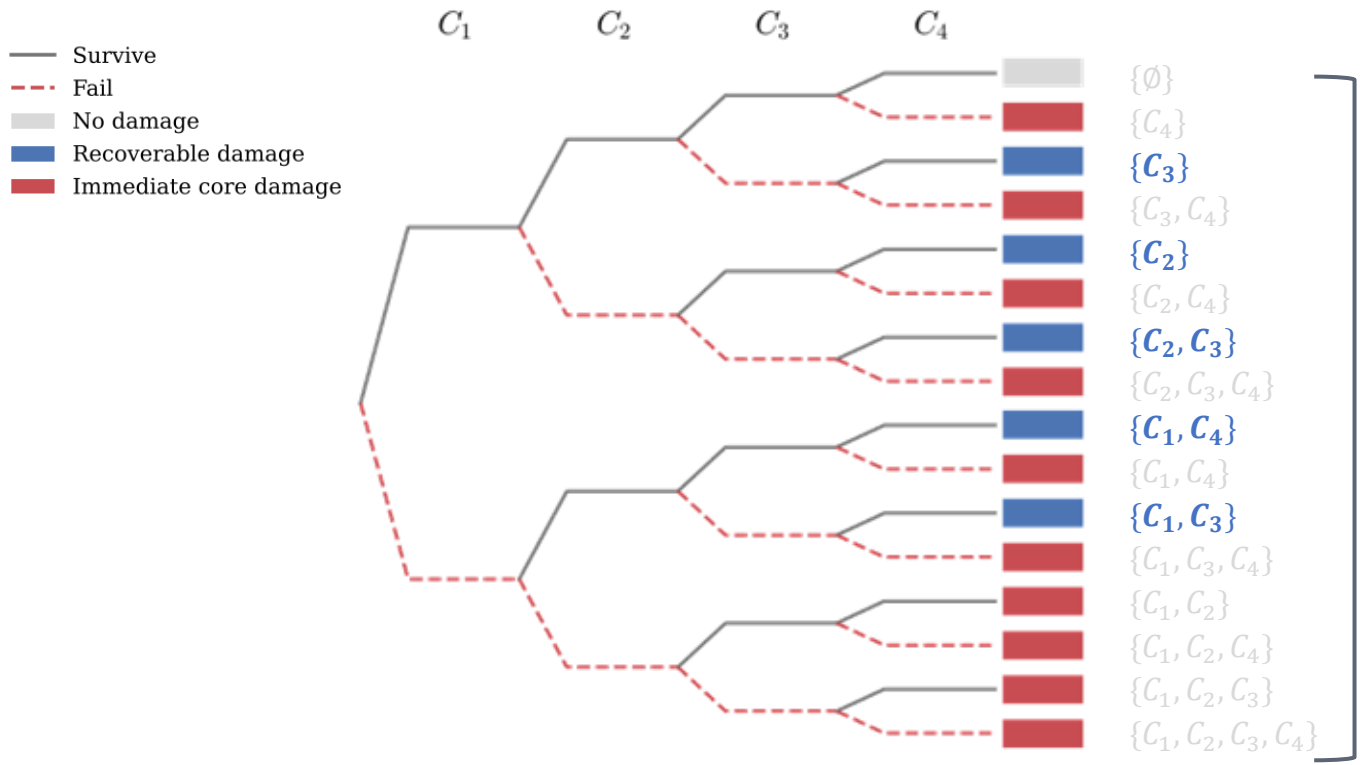
Post-earthquake plant states

- The plant is classified into three states: no damage, recoverable damage, and immediate core damage
- *Resilience analysis* focuses on the **recoverable damage state**
- All 2^n combinations of intact and failed component states are enumerated and classified into the three plant states



Failure scenarios for the resilience analysis

Seismic risk during recovery

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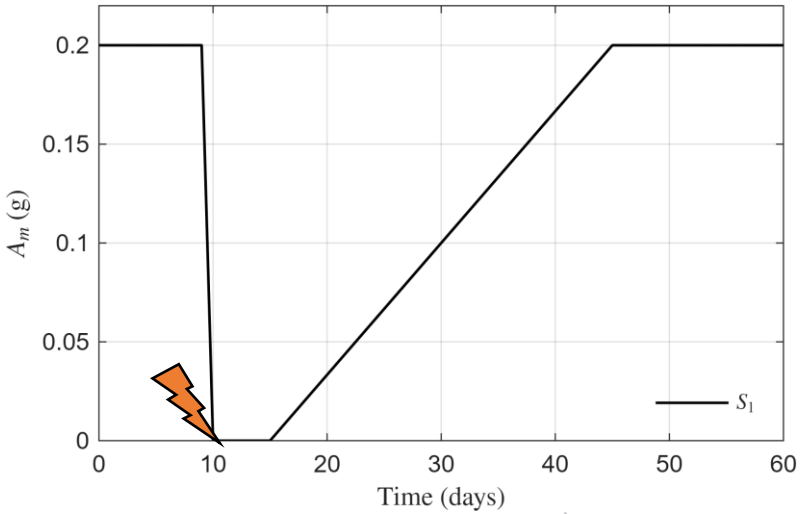
Component damage and recovery

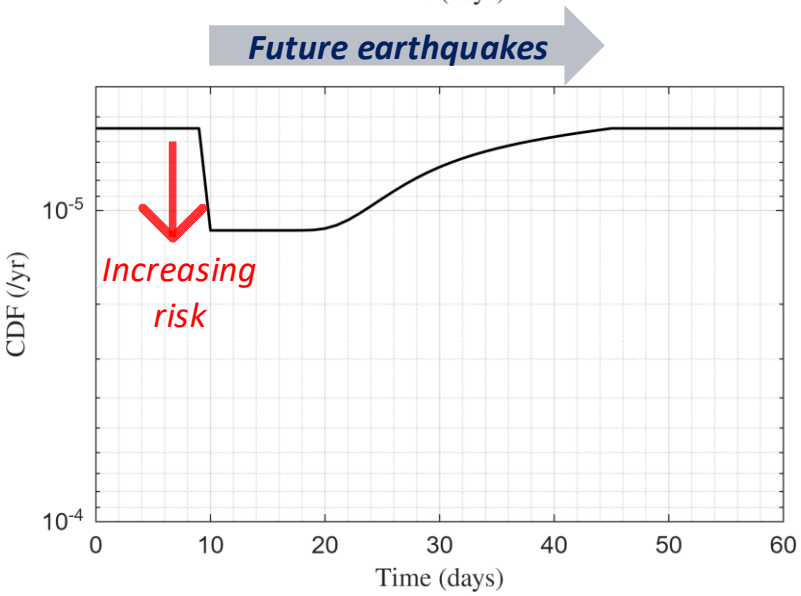
- **An initial earthquake** reduces the median seismic capacity of damaged components: $A_m \rightarrow A_m(t)$
- The degraded capacity is restored through repair, following a prescribed recovery function (shape and duration)



Time-dependent seismic risk

- During recovery, the plant remains exposed to ***future earthquakes***
- $CDF(t)$ is evaluated using **the evolving component capacities** and **an unchanged seismic hazard curve**

$$CDF(t) = \int P(CD|a; A_m(t)) \left|\frac{dH(a)}{da}\right| da$$



Quantification of restoration capability

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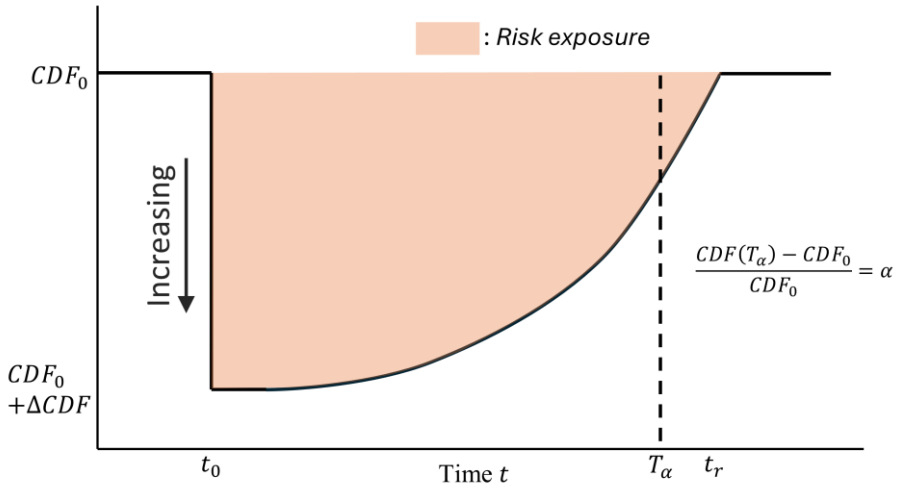
Risk Exposure (RE)

- Cumulative excess CDF over the restoration period
- Captures both the magnitude and duration of elevated risk

$$RE = \int_{t_0}^{t_r} (CDF(t) - CDF_0) dt_{yr} = \frac{1}{365} \int_{t_0}^{t_r} (CDF(t) - CDF_0) dt_{day}$$



α-level Restoration Time (T_α)

- The time required for CDF to return to a prescribed level close to its baseline
- Characterizes how quickly plant risk approaches its pre-earthquake risk level

Lower RE and shorter T_α indicate better recovery performance



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Example 1: Limerick Generating Station (LGS)

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LGS NPP (Ellingwood, 1990)

- BWR plant in Pennsylvania, USA
- 13 seismic basic events and 4 random failure events

Selection of recoverable failure scenarios

- 3 of 13 components excluded from the outset
  - S_2: absent from the core damage logic
  - S_4 and S_6: single failure leads directly to core damage
- All $2^{10} - 1 = 1{,}023$ combinations of the remaining 10 components → 509 lead to immediate core damage
- The remaining ***514 scenarios*** are used in the resilience analysis

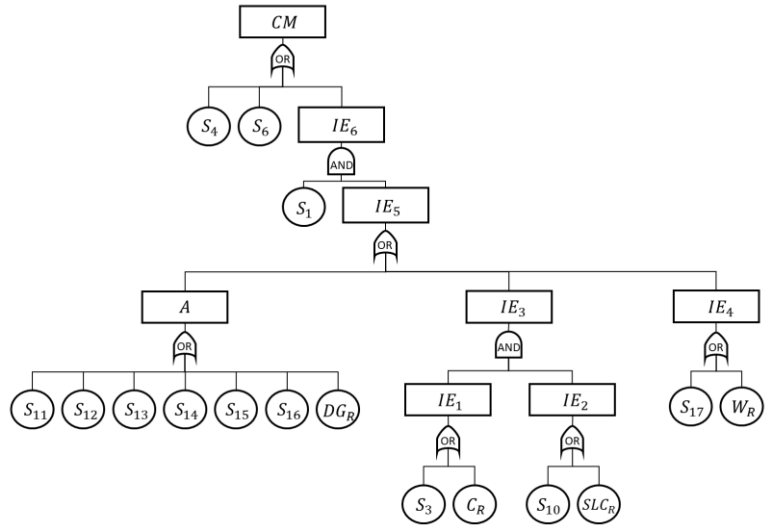


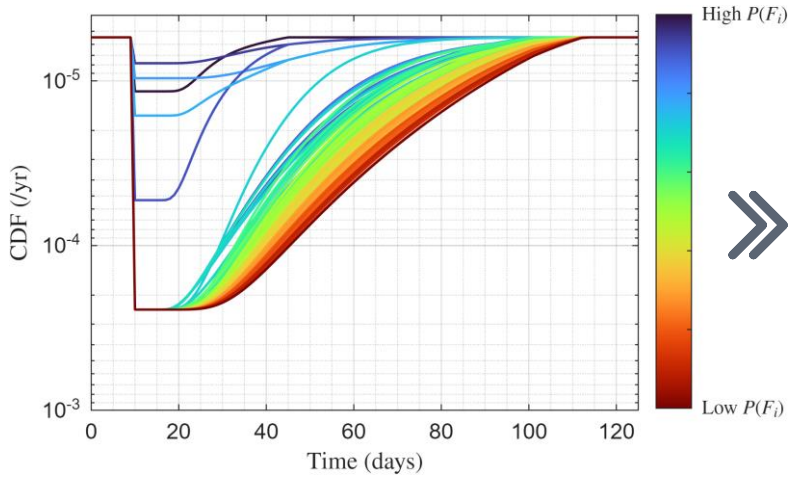
Table 1. Component fragility parameters for the LGS NPP

No.	Event	Description	A_m(g)	β_R	β_U
1	S_1	Offsite power	0.2	0.2	0.25
2	S_2	Condensate storage tank	0.24	0.23	0.31
3	S_3	Reactor internals	0.67	0.28	0.32
4	S_4	Reactor enclosure structure	1.05	0.31	0.25
5	S_6	Reactor pressure vessel	1.25	0.28	0.22
6	S_{10}	SLC tank	1.33	0.27	0.19
7	S_{11}	440-V bus/SG breakers	1.46	0.38	0.44
8	S_{12}	440-V bus transformer breaker	1.49	0.36	0.43
9	S_{13}	125/250-V DC bus	1.49	0.36	0.43
10	S_{14}	4-kV bus/SG	1.49	0.36	0.43
11	S_{15}	Diesel generator circuit	1.56	0.32	0.41
12	S_{16}	Diesel generator heat and vent	1.55	0.28	0.43
13	S_{17}	RHR heat exchangers	1.09	0.32	0.34

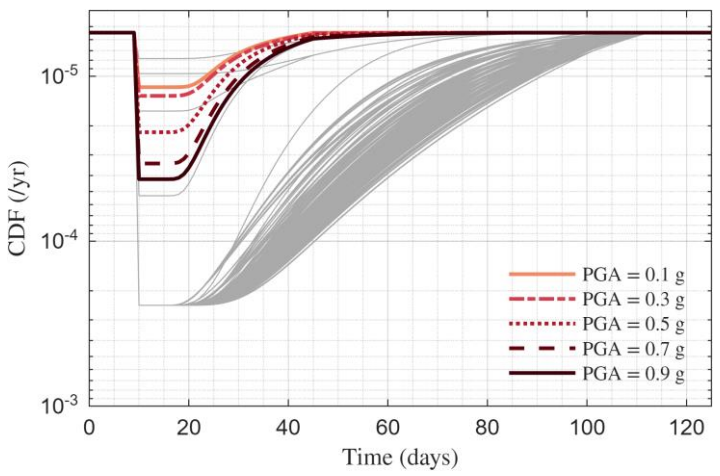
- Ellingwood, B. (1990). Validation studies of seismic PRAs. *Nuclear Engineering and Design*, *123*(2-3), 189-196.

CDF trajectories and risk exposure

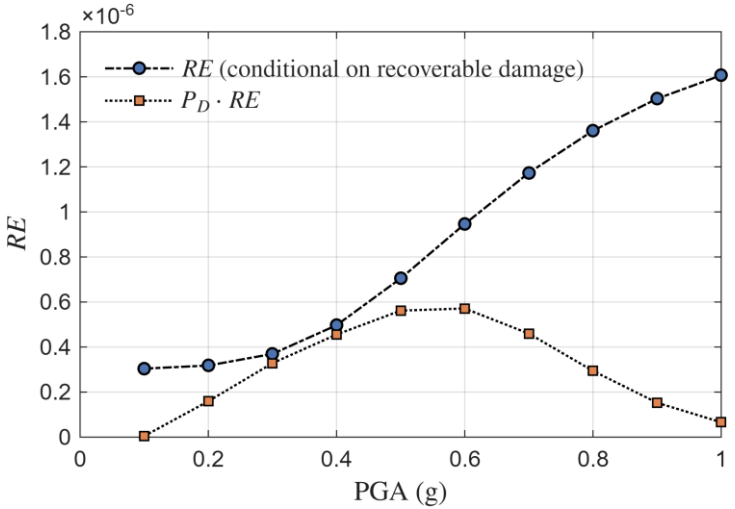
- *Scenario-specific CDF*: a CDF trajectory is evaluated for each of the 514 recoverable failure scenarios
- *Representative CDF*: scenario-specific curves are averaged using occurrence probabilities
- *Risk exposure*: RE increases with PGA, while $P_D \cdot RE$ peaks at approximately 0.5–0.6 g



[Scenario-specific CDF]



[Representative CDF]



[Risk exposure]

$$P(F_i|PGA) = \prod_{C_j \in F_i} P(C_j|PGA) \prod_{C_j \in C_S \setminus F_i} \left(1 - P(C_j|PGA)\right)$$

$$\overline{CDF}(t|PGA) = \frac{\sum_{F_i \in \mathcal{F}} CDF(t|F_i) \times P(F_i|PGA)}{\sum_{F_i \in \mathcal{F}} P(F_i|PGA)}$$

$$P(D) = \sum_{F_i \in \mathcal{F}} P(F_i|PGA)$$

Recovery-phase risk is largest for moderate earthquakes (0.5-0.6 g):
beyond this, immediate core damage dominates and the recovery phase becomes less likely

Baseline risk importance and repair-duration sensitivity

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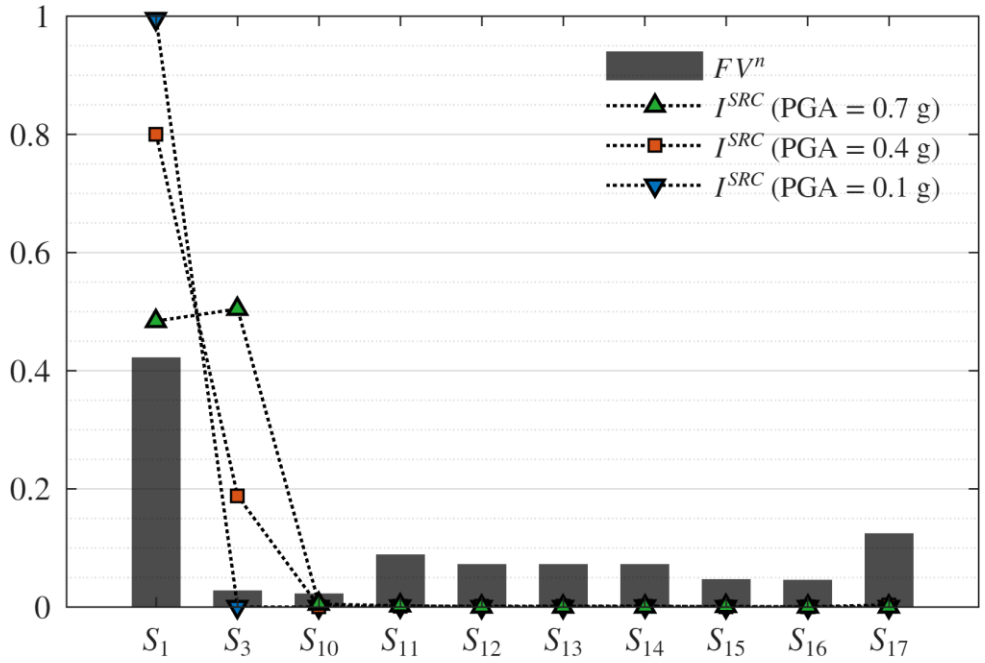
Which components should be prioritized?

Baseline risk importance | FV^n *(conventional seismic PSA)*

- Relative contribution of each component to seismic CDF under the intact plant configuration

Repair-duration sensitivity | I^{SRC} *(this study)*

- Influence of each component's repair duration on RE
- Repair durations: $U(30,110)$ days; 1,000 LHS points
- Sensitivity by normalized standardized regression coefficients



- S_{11}–S_{17}: noticeable FV^n, but negligible I^{SRC}
- S_3: ranks ninth by FV^n, but has the greatest influence on RE through its repair duration at $PGA \geq 0.7$ g

Components important to baseline risk may differ from those whose repair durations govern recovery-phase risk

Which failure scenarios govern risk exposure?

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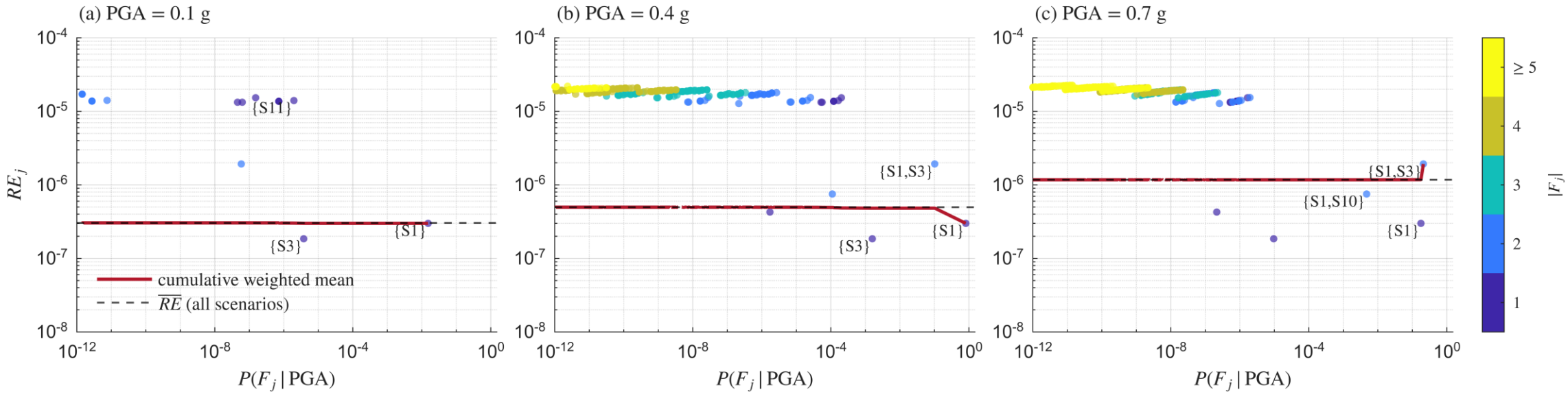
- Each point represents one failure scenario
- X-axis: scenario probability; Y-axis: scenario-specific RE
- The solid line shows the cumulative weighted mean, adding scenarios from highest to lowest probability (from right to left)



- Two scenarios dominate mean risk exposure: offsite power loss alone $\{S_1\}$, and its joint failure with reactor internals $\{S_1, S_3\}$
- The contribution of $\{S_1, S_3\}$ increases with PGA, reaching approximately 88% of the mean RE at 0.7 g

This concentration explains why the repair durations of S_1 and S_3 dominate RE sensitivity



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Example 2: Korean NPP (OPR1000)

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Korean NPP Model (Kwag and Hahm, 2020)

- Seismic PSA model with six initiating events
- 22 SSCs and an operator error event (C_r)
- Design basis earthquake (DBE): 0.2 g

Damage assumption (two groups)

- Complete loss ($A_m \rightarrow 0$): structures, tanks, piping, electrical & instrumentation interfaces — $C_2, C_3, C_{11}-C_{13}, C_{18}-C_{20}, C_{22}$
- Partial degradation ($A_m \rightarrow 0.5A_m$): DG, HVAC, electrical distribution, cooling water systems — $C_1, C_4-C_{10}, C_{14}-C_{17}, C_{21}$

Failure scenario set

- 13 SSCs (12 partial + C_{20}): 22 SSCs – 7 (failure along -> CD) – 2 (GTRN prerequisites, C_{21}, C_{22})
- $2^{13} - 1 = 8{,}191$ scenarios are used for the resilience analysis

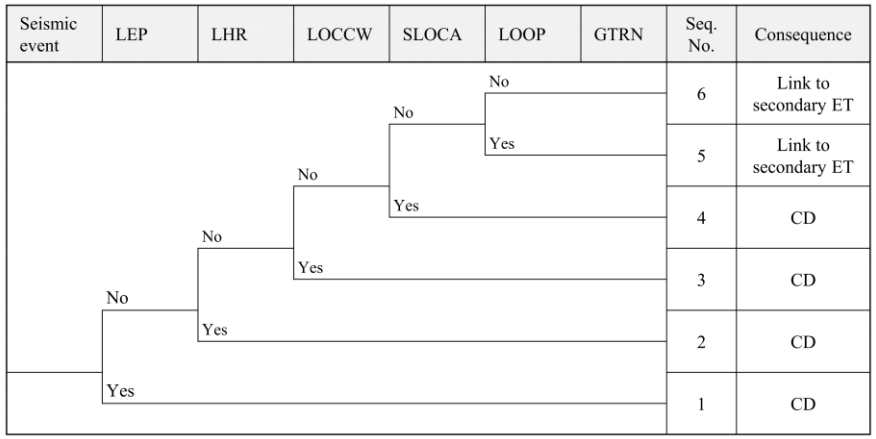
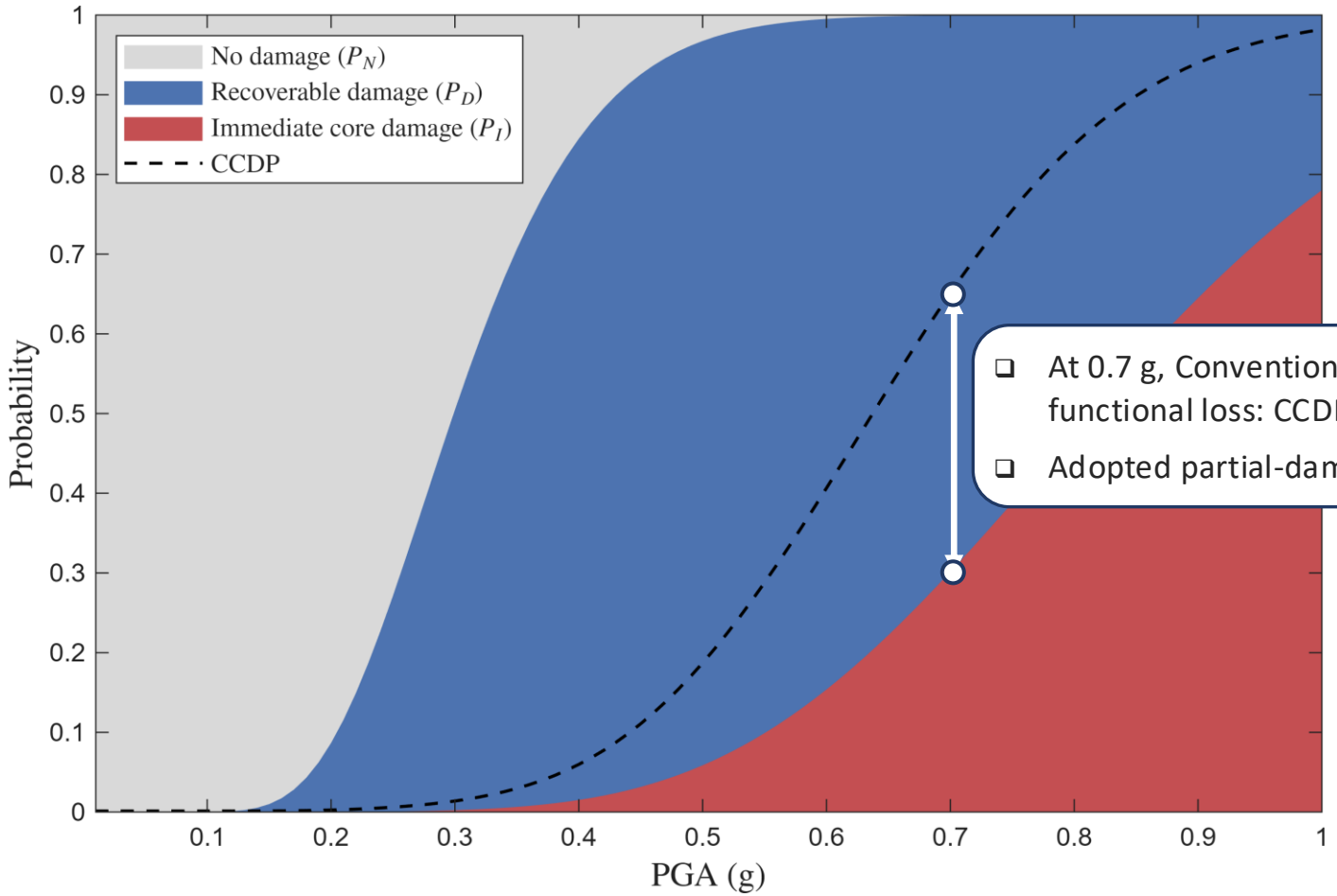


Table 4. Descriptions of SSCs and their seismic fragility parameters.

No.	Event	Description of structures, components, and equipment	Seismic fragility parameters A_m (g)	β_R	β_U
1	C_1	Diesel generator	1.13	0.36	0.03
2	C_2	Auxiliary building	2.00	0.32	0.37
3	C_3	Switches	2.33	0.41	0.45
4	C_4	HVAC ducting and supports	2.06	0.32	0.41
5	C_5	4.16 kV switchgear	1.33	0.33	0.30
6	C_6	480V load center	1.50	0.32	0.29
7	C_7	Battery charger and relay chatter (480 V related)	1.03	0.28	0.28
8	C_8	Inverter	1.37	0.33	0.30
9	C_9	Regulating transformer	1.30	0.33	0.30
10	C_{10}	125V DC control center	1.58	0.33	0.30
11	C_{11}	Battery charger (125 V related)	1.54	0.33	0.33
12	C_{12}	Battery rack	1.46	0.33	0.31
13	C_{13}	Condensate storage tank	1.04	0.25	0.24
14	C_{14}	Essential chilled water compression tank	1.00	0.35	0.20
15	C_{15}	Essential chilled water chiller	1.08	0.28	0.27
16	C_{16}	Essential chilled water pump	1.85	0.36	0.27
17	C_{17}	Essential service water pump	1.20	0.29	0.28
18	C_{18}	Component cooling water surge tank	2.00	0.41	0.47
19	C_{19}	Instrumentation tube (primary system)	1.50	0.30	0.30
20	C_{20}	Offsite power (154 kV Switchyard)	0.30	0.22	0.20
21	C_{21}	Motor center functional failure	1.33	0.33	0.30
22	C_{22}	Motor center structure failure	1.99	0.33	0.33

- Kwag, S., & Hahm, D. (2020). Multi-objective-based seismic fragility relocation for a Korean nuclear power plant. *Natural Hazards*, *103*(3), 3633-3659.

Damage assumptions change the plant-state probabilities



- Shaded areas: no damage, recoverable damage, and immediate core damage
- Dashed line: conventional SPSA assuming complete functional loss

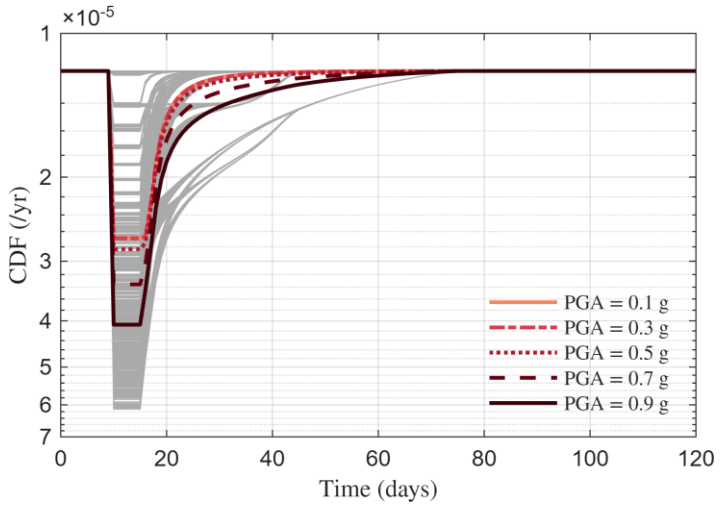
- At 0.7 g, Conventional SPSA with complete functional loss: CCDP ≈ 0.65
- Adopted partial-damage assumptions: $P_I \approx 0.30$

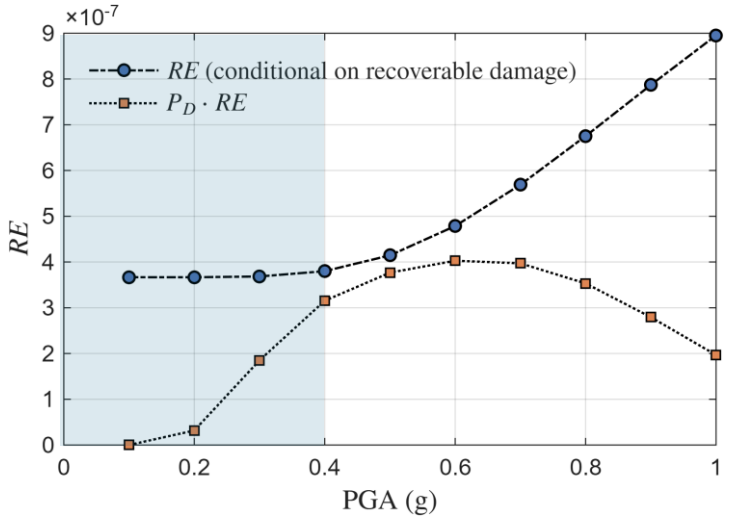
- Recoverable damage is the most likely state over 0.3–0.8 g, with its probability reaching approximately 0.91 at 0.5 g

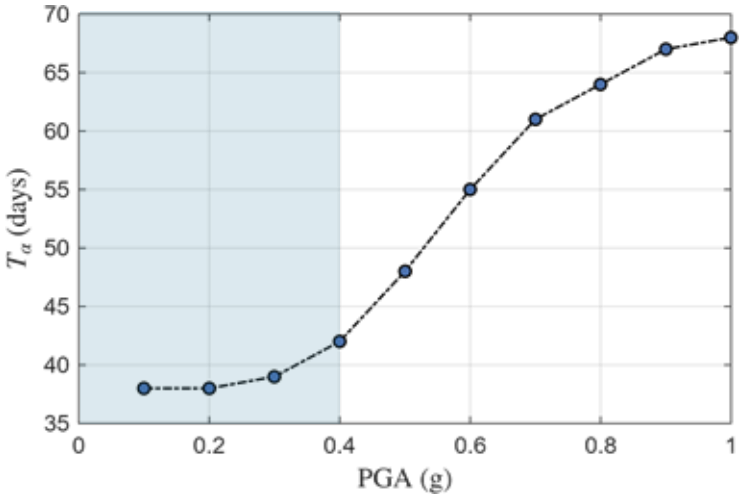
Under the partial-damage assumption, recoverable damage states dominate up to about 0.8 g

Recovery-phase risk

- Plateau up to 0.4 g: offsite power alone, $\{C_{20}\}$, governs
- Above 0.4 g, additional component failures become more influential
- $P_D \times RE$ peaks at 0.6–0.7 g and decreases as immediate CD takes over







shaded: plateau ($\{C_{20}\}$ alone)

Expected recovery-phase risk ($P_D \cdot RE$) peaks at 0.6–0.7 g, where recoverable damage is still the likely outcome

Concentrated vs. distributed recovery-phase risk

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LGS NPP: concentrated in two scenarios
$\{S_1\}$, $\{S_1, S_3\}$, dominate RE at all PGA

Korean NPP: increasingly distributed across scenarios
$\{C_{20}\}$ alone at low PGA → multi-component scenarios at high PGA

1 scenario for 99% of RE
$\{C_{20}\}$ alone

›

10 scenarios for 99% of RE
$\{C_{20}\}, \{C_1, C_{20}\}, \{C_{14}, C_{20}\}, \ldots$

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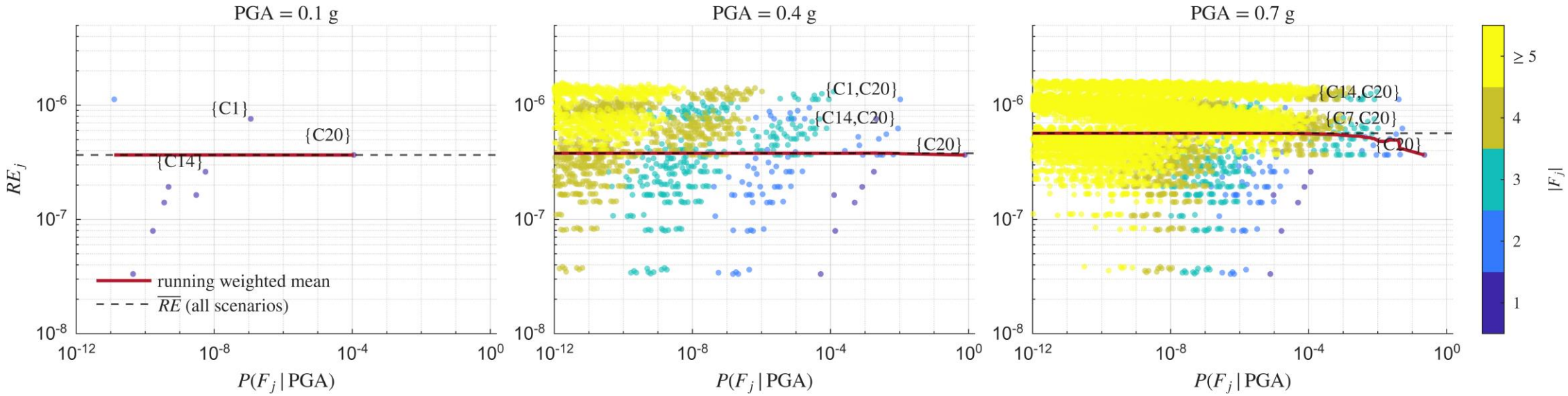
385 scenarios for 99% of RE
mostly multi-component



Recovery assessment should consider both dominant individual scenarios and the combined influence of many scenarios

Resilience-based component importance measure (RCIM)

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RCIM

Expected RE (or T_α) of scenarios **containing** C_j, relative to all scenarios

RCIM > 1: scenarios with C_j are worse than average

C_1 (diesel generator): highest at all PGA

A_m = 1.13 g, critical role in LEP

C_{14}–C_{17} > C_5–C_{10}

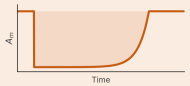
Operators (C_r = 0.01) can back up C_5–C_{10}, but not C_{14}–C_{17}

≥ 0.4 g: values converge toward 1

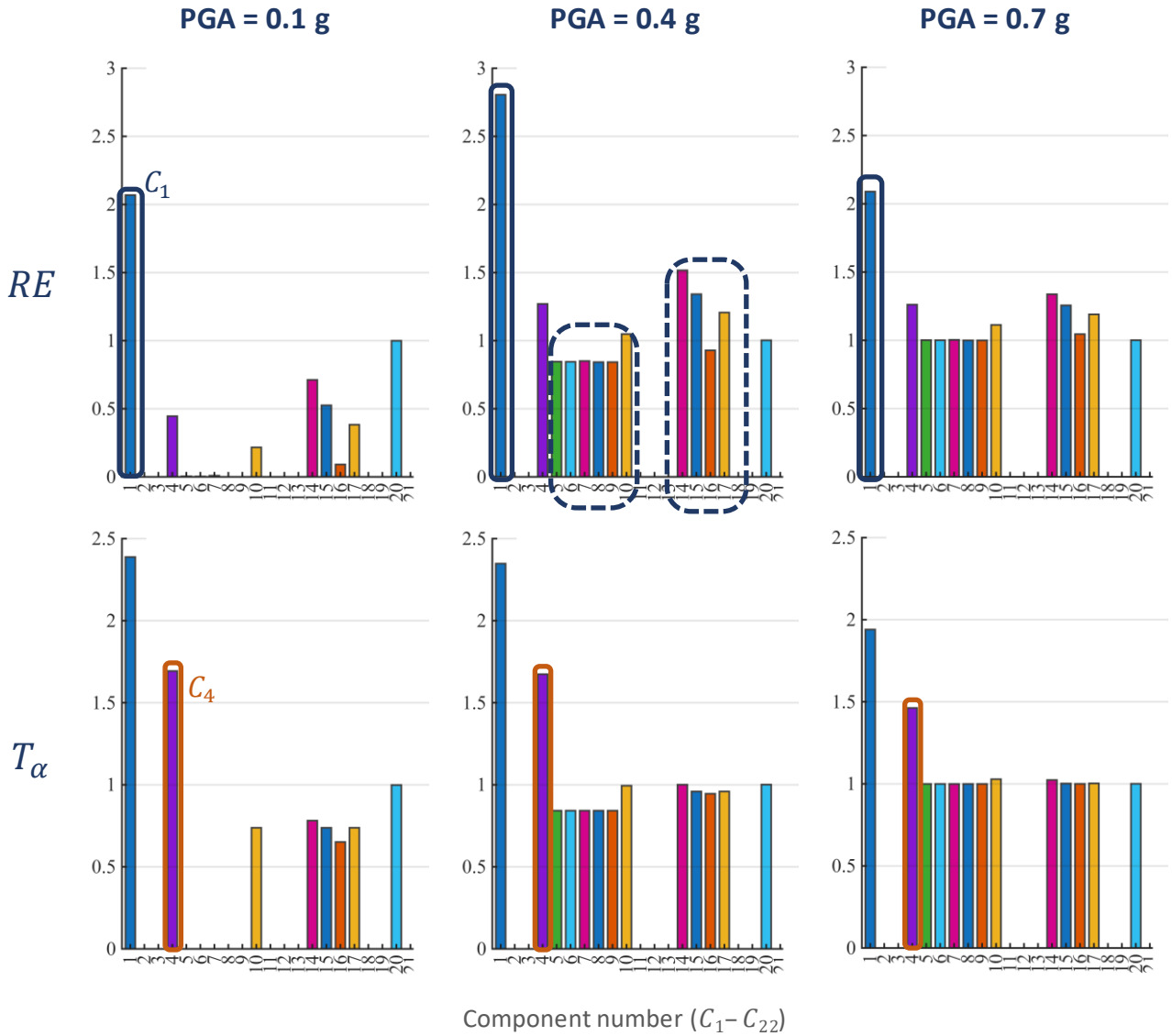
Importance becomes distributed

C_4 (HVAC ducting): high for T_α only

The only negative-exponential recovery



Component importance during recovery reflects seismic capacity, system logic, and recovery characteristics



Two plants, contrasting recovery-phase risk patterns

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	Example 1 · LGS	Example 2 · Korean NPP
System model	BWR, 13 SSCs + 4 random events	PWR (OPR1000), 22 SSCs, 6 IEs
Damage model	Complete loss only	Complete loss + **partial degradation**
Failure scenarios	**514**	**8,191**
Recovery-phase risk	**Concentrated**: $\{S_1\}, \{S_1, S_3\}$ at all PGA	**Concentrated → distributed** (1 → 385 scenarios for 99% of RE)
Importance measure	I^{SRC} (repair-duration sensitivity)	RCIM (scenarios containing C_j vs. all)
Key component(s)	$S_1 \rightarrow S_3$ (shift with PGA)	C_1 (all PGA); C_4 for T_α; many at high PGA
Recovery strategy	Focus on **a few SSCs** (S_1, S_3)	**Collective recovery capability** of multiple systems

Whether recovery-phase risk is concentrated or distributed depends on plant characteristics and modeling assumptions

Conclusions

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Risk-based resilience framework

Time-dependent CDF during recovery, consistent with SPRA; plant states (P_N, P_D, P_I) and indices RE, T_α

Few probable scenarios govern the risk

Severe scenarios: high RE_j, negligible probability; the pattern is plant-specific (concentrated vs. distributed)

Prevention ≠ recovery importance

High $FV \neq$ high recovery importance (S_3); recovery importance also reflects recovery shape (C_4) and operator backup $(C_{14}–C_{17})$

Damage modeling matters

Partial degradation turns conditional core damage probabilities into a recoverable state (Korean NPP)

Future work

Repair sequencing
under limited repair resources

Aftershock hazard
time-dependent, during recovery

Damage and repair models
damage states, repair uncertainty

Recovery planning should target SSCs that govern probable recoverable states, not only those ranked high by conventional importance measures

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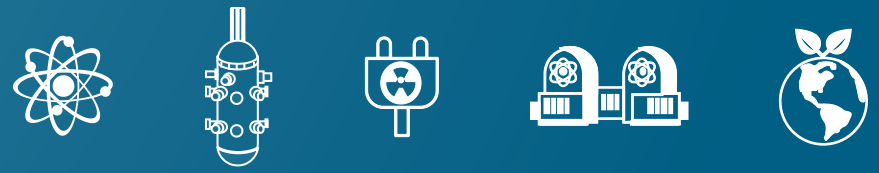

THANK YOU

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Recovery Modeling

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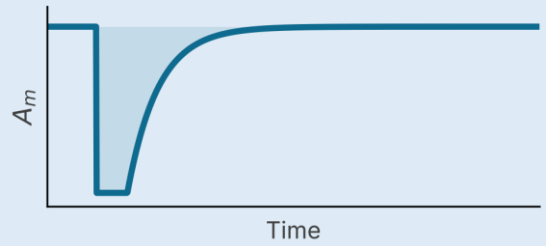
Recovery of the 13 scenario components

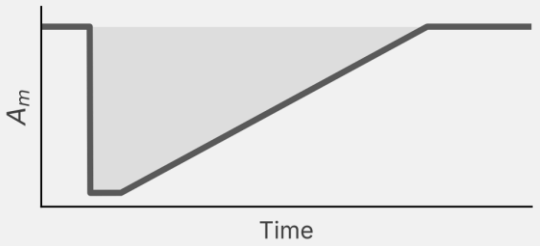
recovery types and repair durations from Singhal et al. (2021)



Positive-exponential

Fast early recovery · **11 of 13**

C_5 60 d	C_6 90 d	C_7 90 d
C_8 60 d	C_9 60 d	C_{10} 90 d
C_{14} 30 d	C_{15} 30 d	C_{16} 30 d
C_{17} 30 d	C_{20} 90 d	



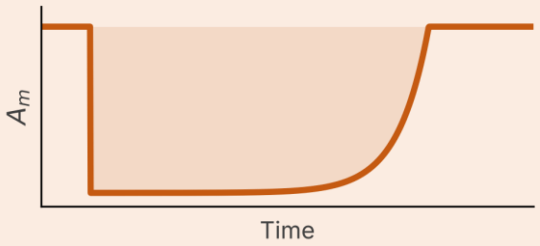
Linear

Constant recovery rate

C_1 60 d

Diesel generator

$A_m = 1.13$ g, critical role in the LEP sequence



Negative-exponential

Degraded until late in repair

C_4 30 d

Only NE component

Short repair (30 d), but stays degraded for most of it → watch T_α in RCIM

Recovery shape matters: most SSCs recover early (PE); C_4 stays degraded for most of its repair (NE)

- Singhal, T. K., et al. (2021). Development of a civil infrastructure resilience assessment framework and its application to a nuclear power plant. Struct. Infrastruct. Eng., 18(1), 1-14.