KNS 2018 SPRING
2018 춘계학술발표회 다수기 리스크 평가 워크샵, 제주

설계초과지진에 대비한 미국원전의 내진안전성 확보 방안

-Seismic Safety of US Plants against Beyond Design Basis Earthquake-

황규호 SGH

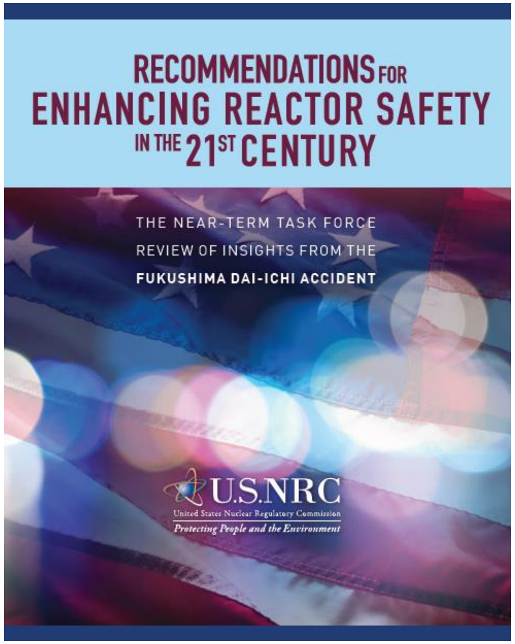
2018. 5. 16

목 차

Post-Fukushima Seismic Risk

Post-Fukushima Seismic Risk

- Post-Fukushima timeline and regulatory documentation
  - Fukushima accident occurs March 2011
  - NTTF Report published July 2011
  - SECY-11-0124 recommends actions w/o delay - issued September 2011
  - SECY-11-0137 establishes prioritization of activities - issued October 2011
  - SECY-12-0025 authorizes 50.54(f)
  - The 50.54(f) letter
    - Issued March 12, 2012
    - To all operating power reactor licensees
    - Establishes a timeline and actions



Post-Fukushima Seismic Risk

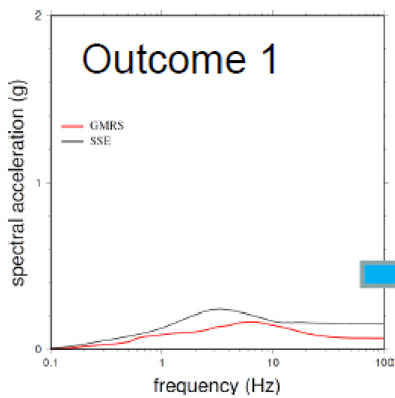
- NTTF Recommendation 2.3 seismic walkdowns
  - 18-month timeline. Reports completed November 2012. Some inaccessible equipment delayed until outages.
  - Industry developed guidance with NRC input, EPRI 1025286.
  - Resident Inspectors observed walkdowns and performed independent verifications.
  - Identified issues entered into NPP's Corrective Action Program (CAP).
  - Objective to confirm compliance with license and look for vulnerabilities.
  - Seismically qualified equipment sampled (approximately 100 items walked down).
  - All spent fuel pool equipment that could lead to rapid drain down is walked down.
  - Area walk-bys performed in rooms with sampled equipment – scope extended.

Post-Fukushima Seismic Risk

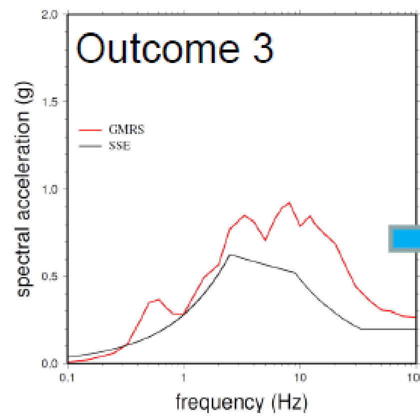
- NTTF Recommendation 2.1 seismic hazard reevaluation
  - PSHA develops plant-specific GMRS (RG1.208)
  - CEUS licensees (96 units / 59 sites)
    - CEUS SSC Source model (NUREG 2115)
    - EPRI Ground Motion model
    - Plant-specific site response analysis
  - WUS licensees (8 units / 4 sites)
    - Site-specific SSHAC level 3 studies for sources and ground motion (NUREG 2117)
    - Plant-specific site response analysis

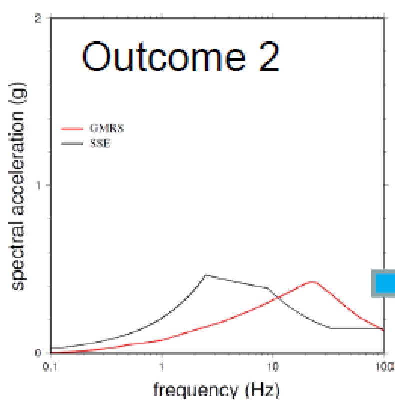
Post-Fukushima Seismic Risk

- NTTF Recommendation 2.1 seismic hazard reevaluation



No Further Analysis





Industry Testing Program for High Frequency Sensitive components

Comparison of SSE vs GMRS

Post-Fukushima Seismic Risk

- Screening, Prioritization, & Implementation Details (SPID)
  - EPRI Report 1025287, November 2012
  - Purpose and Approach
    1. Seismic Hazard Development
    2. GMRS Comparisons and Screening of Plants
    3. Seismic Hazard and Screening Report
    4. Prioritization (Schedule)
    5. Seismic Risk Evaluation
    6. Spent Fuel Pool Evaluation
  - *Four appendices to SPID with detailed guidance on special topics*

Post-Fukushima Seismic Risk

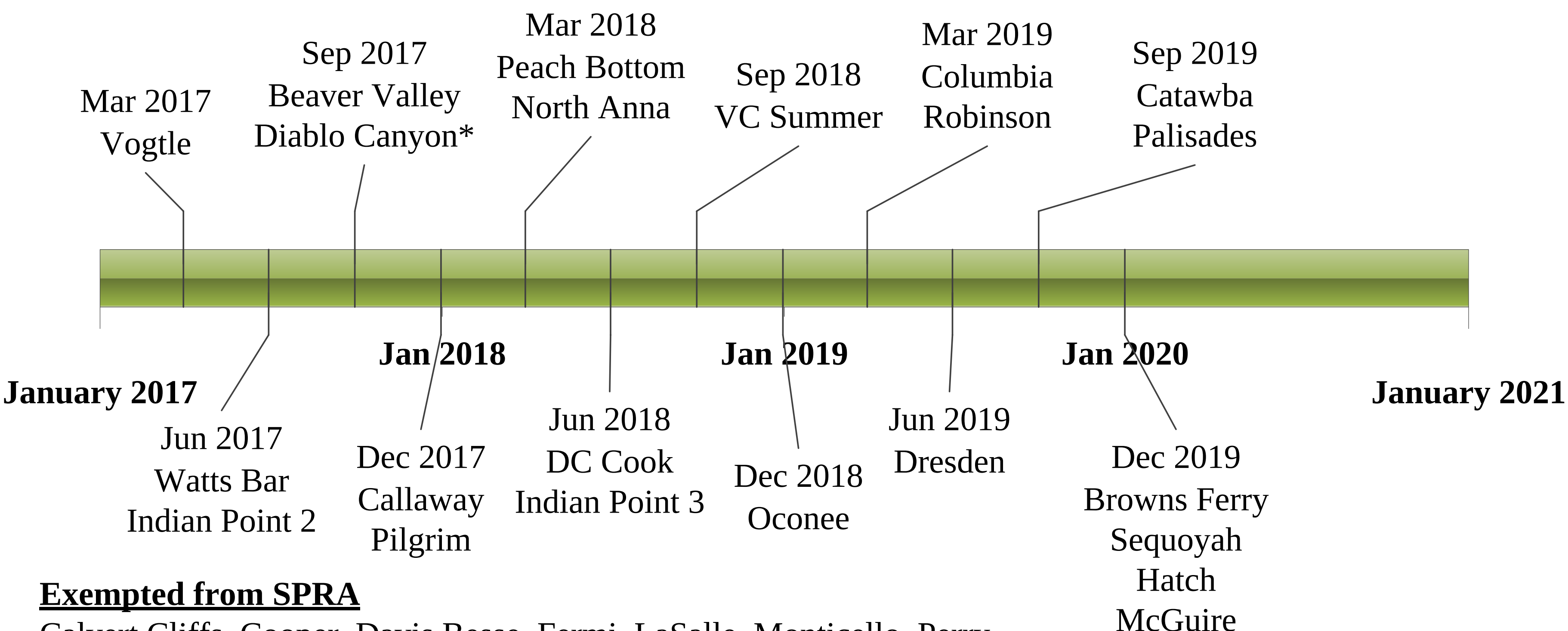
- Key SPID Positions: PSHA/GMRS, screening, high frequency
  - PSHA and GMRS calculations
    - Updated Ground Motion Prediction Equations (GMPEs)
    - Guidance for site amplification methods
    - Clarified positions on the SSE control point
  - SSE to GMRS screening
    - Screening evaluation focused on 1 to 10 Hz range
    - Guidance for special cases (narrow banded exceedances and low frequency exceedances)
  - Separate high frequency “confirmation” based on EPRI research

Post-Fukushima Seismic Risk

- Key SPID Positions: SPRA implementation guidance
  - Structural and SSI Response
    - Structure modeling
    - Seismic response scaling
    - Fixed-based analysis criteria for sites previously defined as “rock”
  - Fragility / Capacity Calculations
    - Hybrid approach for fragility calculations
    - High frequency capacities
    - Capacity-based SSC selection
  - Additional Guidance
    - Large Early Release Frequency (LERF)
    - Comparison to ASME / ANS Standard
    - Peer Review
    - SPRA Documentation

Post-Fukushima Seismic Risk

- SPRA schedule – new staggered schedule



Exempted from SPRA

Calvert Cliffs, Cooper, Davis Besse, Fermi, LaSalle, Monticello, Perry, Point Beach, Seabrook, Three Mile Island, Wolf Creek

* Contingent on NRC acceptance of GMRS by December 2015

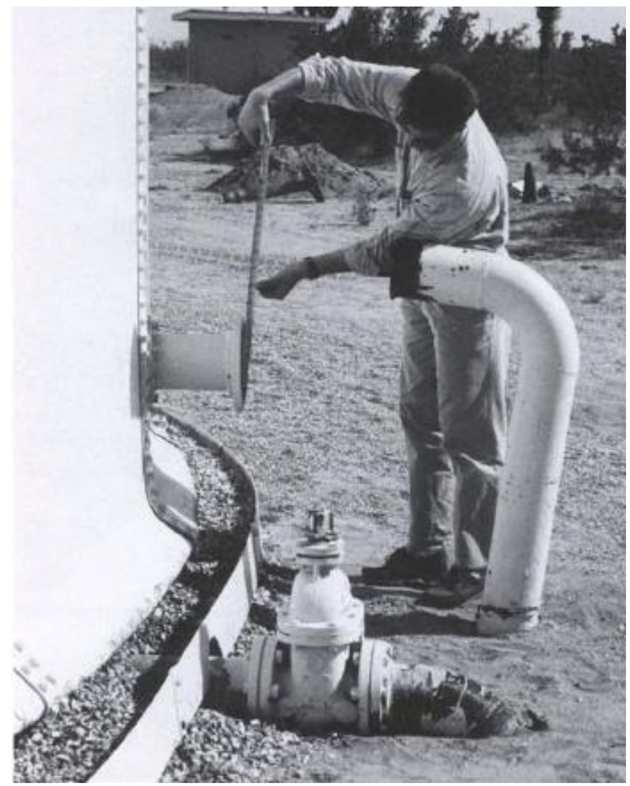
Seismic Walkdown

Seismic Walkdown

- Seismic IPEEE per NUREG-1407
  - Seismic probabilistic risk assessment (SPRA)
    - Address core damage frequency due to earthquake
    - Calculate seismic fragilities by separation of variables (SOV) method per EPRI TR-103959 with updates
  - Seismic margin assessment (SMA)
    - Address plant capability to reach safe shutdown for seismic motions beyond design basis earthquake (BDBE)
    - Calculate seismic fragilities by Hybrid method per conservative deterministic failure margin (CDFM) approach given in EPRI NP-6041-SL Rev. 1 with updates
  - Plant seismic walkdown
    - Seismic walkdown per EPRI NP-6041-SL Rev. 1

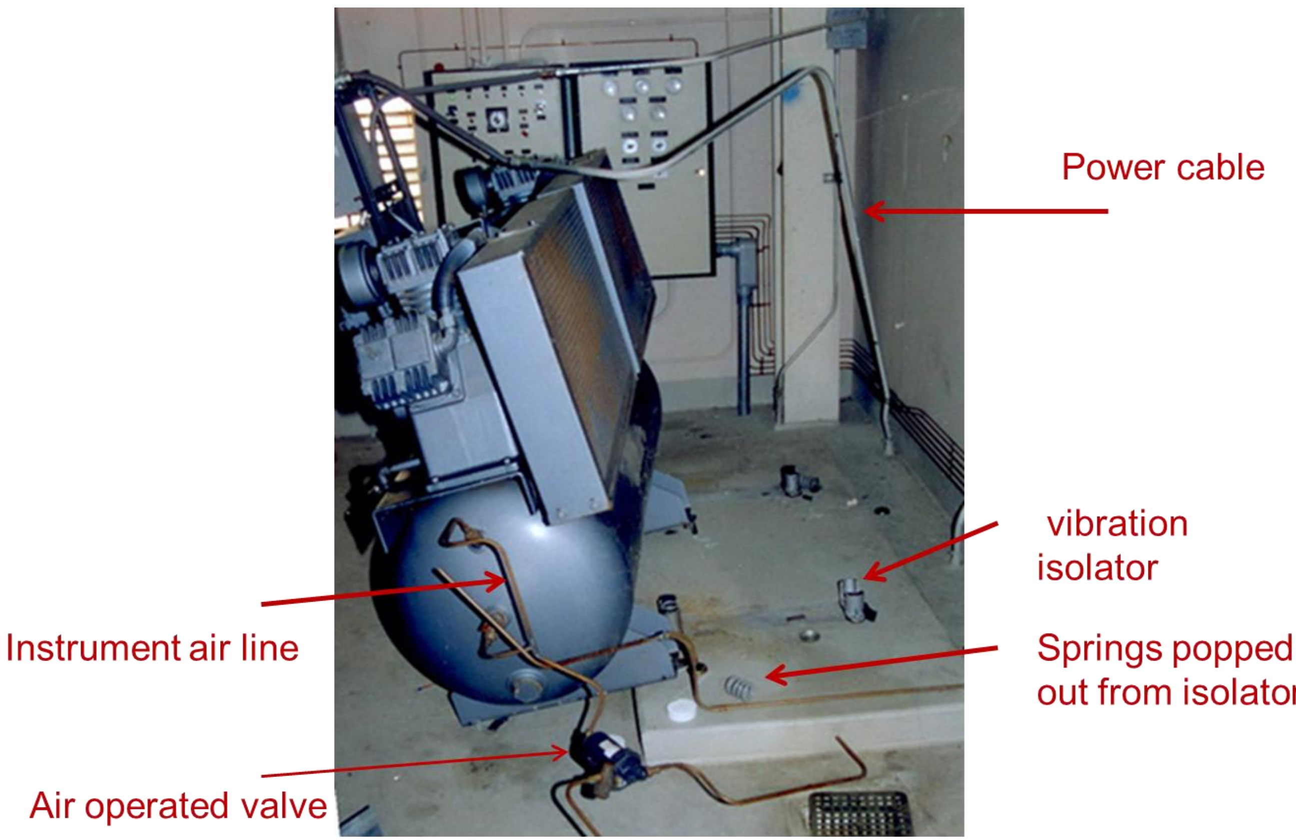
Seismic Walkdown

- Earthquake experience database
  - Atmospheric water storage tanks such as condensate or refueling water storage tanks
  - Pipe rupture due to tank shell buckling



Seismic Walkdown

- Earthquake experience database
  - Vibration isolators supporting air compressor



Seismic Walkdown

- Earthquake experience database
  - Walkdown check lists

Status Y N U

SCREENING AND EVALUATION SHEET (SEWS)

Sheet 1 of ___

Plant Name: Darlington Unit: 014

PART A. DESCRIPTION

Equip. ID No. 0-53290-102CB2 Equipment Class: MCC, LV or MV Switchgear

Equipment Description 4KV BUS BU102 TIE BREAKER TO BU103

Equipment Location Bld Emergency P Floor El. 101 Room, Row/Col: PS103

Manufacturer, model, Etc. ___

Seismic Input Elevation ___

PART B. CABINET EVALUATION

1. Is cabinet of good seismic design?
   - Mounting tab and rolled flange stiffness
   - Internal device mountings
   - Cabinet and attachment weight
   - Load paths
   - Cabinet cutouts
   - Cabinet stiffness
   - General cabinet configuration
   - Door attachment
   - Motor starter panel unit mountings
2. No other cabinet concerns?

Is cabinet itself screened out?

Sheet 2 of ___

SCREENING AND EVALUATION SHEET (SEWS)

Equip. ID No. 0-53290-102CB2 Equipment Class: MCC, LV or MV Switchgear

PART D. ANCHORAGE EVALUATION

1. Is strength assessment based on:
   - Judgement (supported by generic analysis)? ☐
   - Specific analysis? ☐
   - Other? ☐
2. Is strength adequate?
3. Is stiffness adequate?
4. No other anchorage concerns?

Is anchorage adequate?

PART E. SYSTEMS INTERACTION EFFECTS

1. Is cabinet free from influence by adjacent elements?
   - Cabinet contains no soft targets
   - Cabinet contains no essential relays
   - Flexibility of connecting lines
   - Collapse of nearby equipments or structures
   - Masonry block walls
2. No potential sources could flood or spill onto cabinet
3. No other interaction concerns?

Is equipment free from interaction effects?

Seismic Walkdown

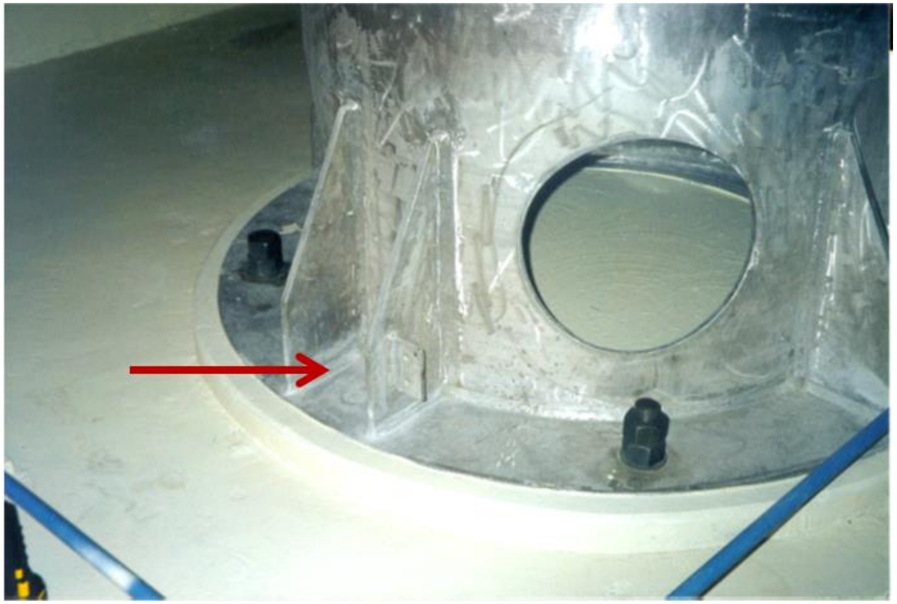
- Earthquake experience database
  - Active components
    - Classified into 20 equipment classes
  - Passive components
    - Pressure vessels, heat exchangers, and atmospheric tanks
    - Piping, cable trays, HVAC ducting, and their supports
  - Equipment out of database
    - Reactor coolant system components: nuclear reactors, coolant pumps, steam generators, and pressurizers

Seismic Walkdown

- Walkdown review
  - Seismic load path
    - Lateral seismic load is resisted by shear walls
    - Loss of function of safety related equipment attached to damaged shear walls

Seismic Walkdown

- Walkdown review
  - Equipment anchorage
    - Vertical pressure vessel supported by skirt
    - Anchor point is off from the seismic load path (stiffened by gusset plates)



Seismic Walkdown

- Walkdown review
  - Seismic interaction
    - High pressure core spray (HPCS) suction line supported by two buildings: reactor building (RB) and auxiliary building (AB)
    - Potential concern for differential displacement between the two buildings

Seismic Walkdown

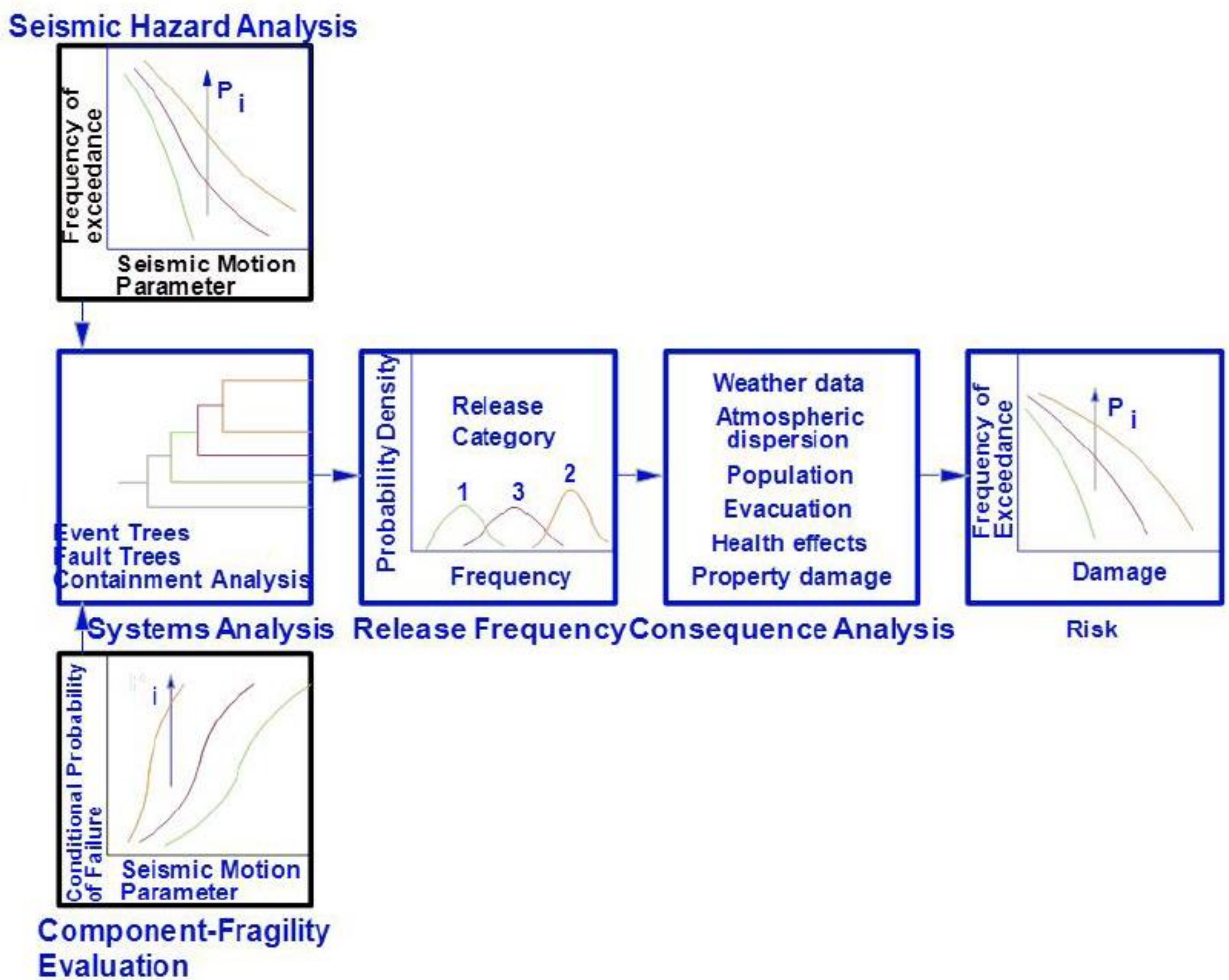
- Walkdown review

  "Risk informed regulation requires that seismic fragilities used in a SPRA be realistic and plant-specific based on actual current conditions of the SSCs in the plant, as confirmed through a detailed walkdown of the plant."

Multi-Unit Risk

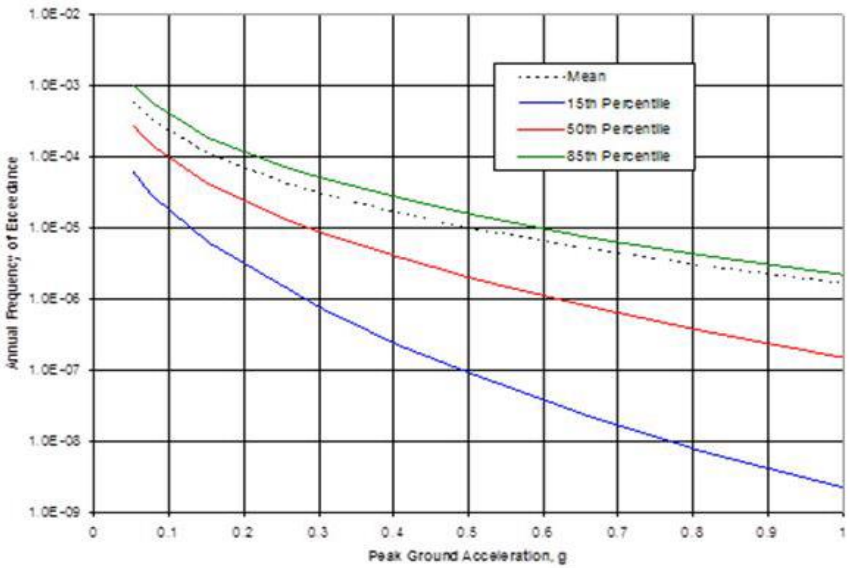
Multi-Unit Risk

- Overview of SPRA

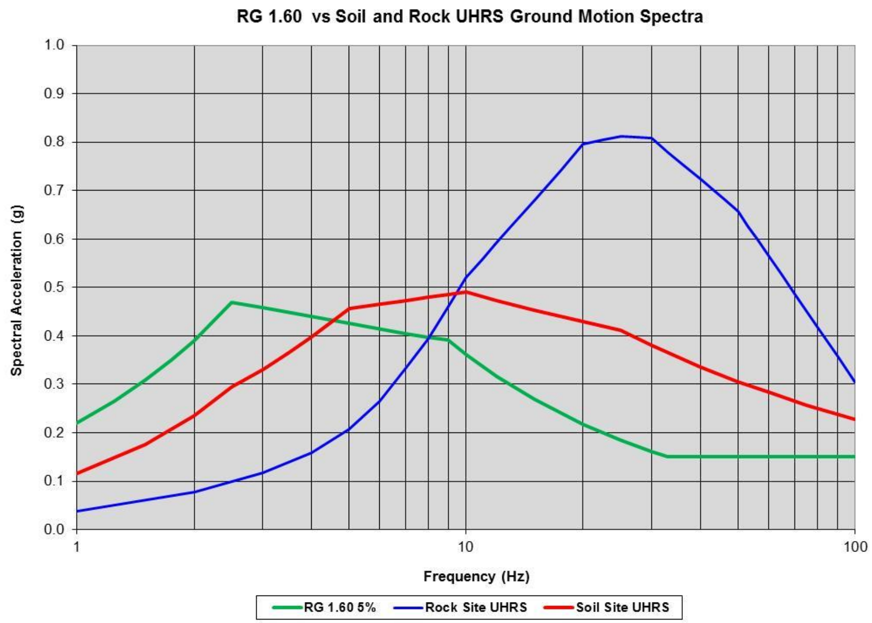


Multi-Unit Risk

- Overview of SPRA
  - Seismic hazard analysis
    - Used to assess the seismic hazard in terms of the frequency of exceedance for selected ground motion parameters during a specified time interval



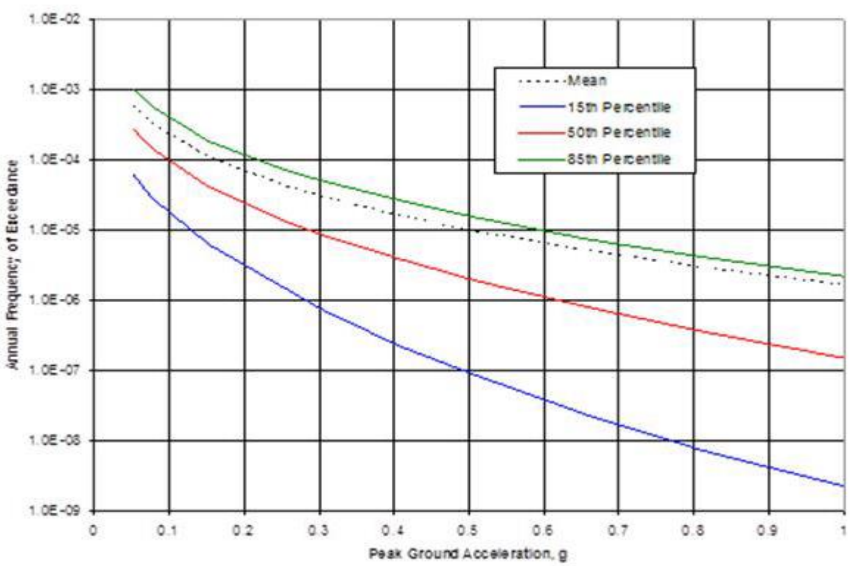
Seismic Hazard Curves



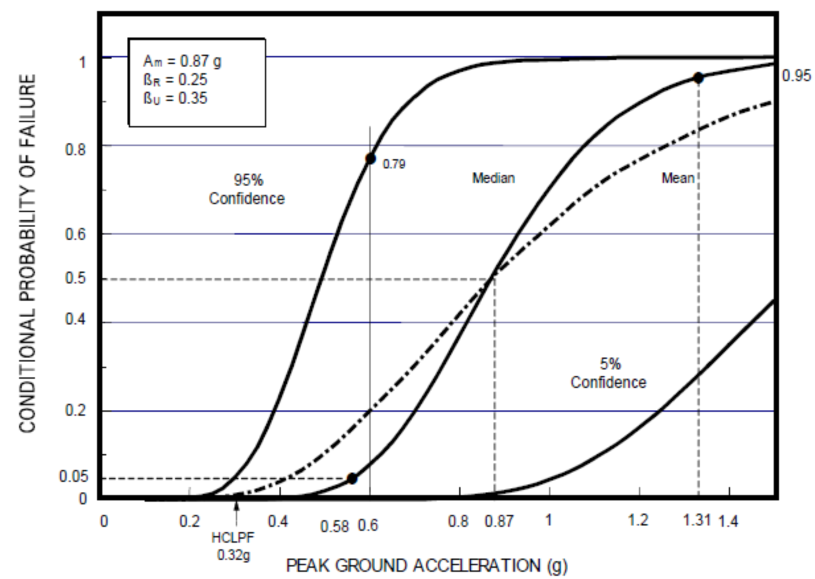
Ground Motion Response Spectra

Multi-Unit Risk

- Overview of SPRA
  - Seismic fragility analysis
    - Estimates the conditional probability of SSC failures at a given value of a seismic motion parameter, commonly peak ground acceleration



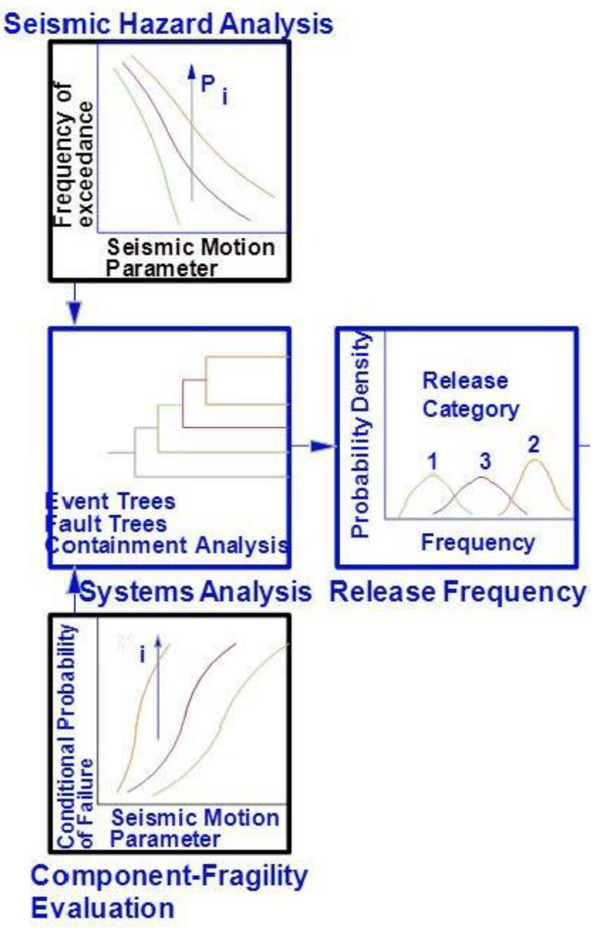
Seismic Hazard Curves



Seismic Fragility Curves

Multi-Unit Risk

- Overview of SPRA
  - Systems analysis and risk quantification
    - Modeling of the various combinations of structural and equipment failures that could initiate and propagate a seismic core damage sequence.
    - Calculates the frequencies of severe core damage and radioactive release to the environment by using the plant logic model and accident sequences for which the SSC fragilities are integrated with the seismic hazard.

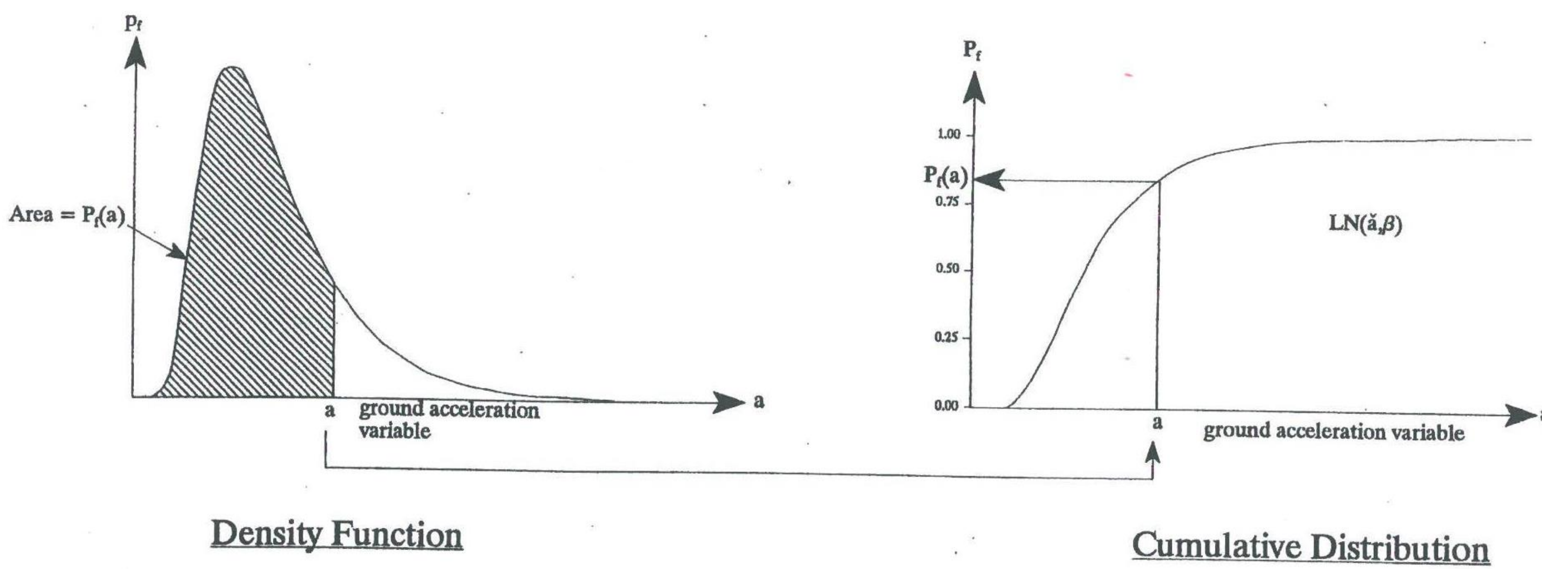


Multi-Unit Risk

- Seismic fragility analysis
  - Fragility methodology has evolved
    - EPRI TR-103959 (1994) Seismic fragility methodology
    - EPRI 1002988 (2002) Seismic Fragility Application Guide
    - EPRI 1019200 (2009) Seismic Fragility Application Guide Update
    - EPRI 1025287 (2013) Seismic Evaluation Guidance
      - Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic
  - Further update (2018) to be published

Multi-Unit Risk

- Seismic fragility analysis
  - Fragility model
    - Lognormal model is typically assumed (all properties of variables have lognormal distributions, e.g. the natural logs of the distributions are normally distributed)
    - Strength and response tend to be lognormally distributed in nature
    - Mathematical treatment is simple



Seismic Fragility Curve

Multi-Unit Risk

- Seismic fragility analysis: fragility model
  - Entire fragility curve and its aleatory and epistemic uncertainty can be expressed by three parameters: A_m , β_R , β_U

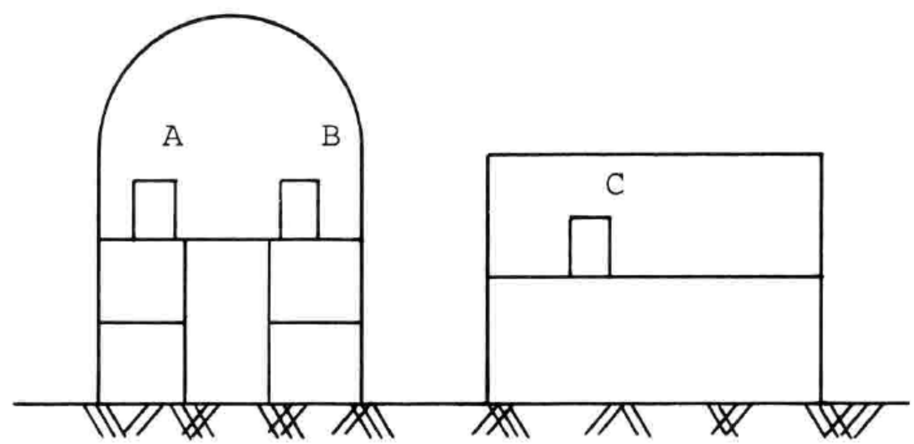
$$HCLPF = A_m \cdot e^{-1.65(\beta_R+\beta_U)}$$

where:

- A_m= median acceleration capacity (PGA or Sa may be used as the reference ground motion parameter)
- β_R = Logarithmic standard deviation of the aleatory uncertainty (randomness) of the variables contributing to the fragility description
- β_U = Logarithmic standard deviation of epistemic uncertainty (incomplete knowledge) of variables contributing to the fragility description
- β_C = Composite uncertainty comprised of SRSS of β_R and β_U

Multi-Unit Risk

- Seismic fragility analysis: variables of a component fragility
  - Equipment capacity
    - Strength
    - Inelastic energy absorption
  - Equipment response
    - Qualification method
    - Damping
    - Modeling
    - Mode combination
    - Earthquake component combination
  - Structure response
    - Ground motion
    - Damping
    - Modeling
    - Mode combination
    - Time history simulation
    - Soil-structure interaction
    - Inelastic structural response



Multi-Unit Risk

- Seismic fragility analysis
  - Variables of a component fragility

Median values

$$A_m = F_m \cdot A_{SSE}$$

$$F_m = F_{EC} \cdot F_{RE} \cdot F_{RS}$$

$$F_{EC} = F_S \cdot F_\mu$$

$$F_{RE} = F_Q \cdot F_D \cdot F_M \cdot F_{MC} \cdot F_{ECC}$$

$$F_{RS} = F_{GM} \cdot F_D \cdot F_M \cdot F_{MC} \cdot F_{TH} \cdot F_{SSI} \cdot F_{IR}$$

Variability: uncertainty and randomness

$$\beta_U = \sqrt{\beta_{EC}^2 + \beta_{RE}^2 + \beta_{RS}^2} \qquad \beta_R = \sqrt{\beta_{EC}^2 + \beta_{RE}^2 + \beta_{RS}^2}$$

$$\beta_{EC} = \sqrt{\beta_S^2 + \beta_\mu^2}$$

$$\beta_{RE} = \sqrt{\beta_Q^2 + \beta_D^2 + \beta_M^2 + \beta_{MC}^2 + \beta_{ECC}^2}$$

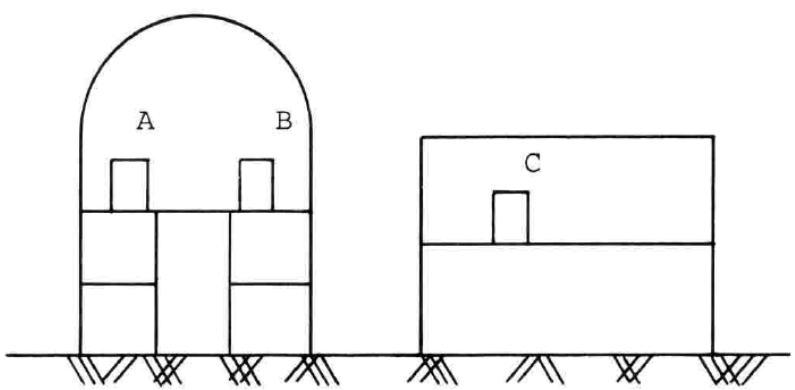
$$\beta_{RE} = \sqrt{\beta_{GM}^2 + \beta_D^2 + \beta_M^2 + \beta_{MC}^2 + \beta_{TH}^2 + \beta_{SSI}^2 + \beta_{IR}^2}$$

Multi-Unit Risk

- Systems fragility curves incorporating dependency: procedure
  - Fragility curves are developed for individual structures, systems, and components (SSCs)
  - Select sets of median capacity values for SSCs using 2-step Latin Hypercube Sampling (LHS) by considering uncertainty
    - Independent step: LHS with reduced uncertainty logarithmic standard deviations(LSDs)
    - Dependent step: LHS with dependent uncertainty LSDs
  - Calculate a systems fragility curve for each of the sets by considering randomness
  - Fragility curves are combined probabilistically according to the Boolean equations for core melt, which leads to a family of system core melt fragility curves
  - System fragility curves are integrated with site ground motion hazard curves, which produces probability distribution on the frequency of core melt

Multi-Unit Risk

- Systems fragility curves incorporating dependency: example problem
  - Components A and B are different components located in the same building: response dependencies.
  - Components A and C are the same component manufactured by the same vendor: high capacity dependence
  - Components B and C are different components located in different buildings: independency



Reference:

Analytical Techniques for Performing Probabilistic Seismic Risk Assessment of Nuclear Power Plants by John Reed and Martin McCann

Multi-Unit Risk

- Systems fragility curves incorporating dependency: example problem
  - Components A and B are different components located in the same building: response dependencies.
  - Components A and C are the same component manufactured by the same vendor: high capacity dependence
  - Components B and C are different components located in different buildings: independency

		Component A			Component B			Component C		
	Variable	Fm	beta R	beta U	Fm	beta R	beta U	Fm	beta R	beta U
Equipment Capacity	Strength	2.10	0.00	0.20	1.50	0.00	0.05	2.10	0.00	0.20
	Inelastic energy absorption	1.00	0.00	0.00	2.20	0.00	0.10	1.00	0.00	0.00
Equipment Response	Damping	1.45	0.00	0.25	1.60	0.00	0.20	1.30	0.00	0.15
	Modeling	1.00	0.00	0.30	1.00	0.00	0.15	1.00	0.00	0.20
	Mode combination	1.00	0.05	0.00	1.00	0.05	0.00	1.00	0.05	0.00
	Earthquake component combination	1.00	0.15	0.00	1.00	0.15	0.00	1.00	0.15	0.00
Structure Response	Ground motion	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00
	Damping	1.00	0.00	0.20	1.00	0.00	0.20	1.00	0.00	0.10
	Modeling	1.00	0.00	0.15	1.00	0.00	0.15	1.00	0.00	0.12
	Mode combination	1.00	0.05	0.00	1.00	0.05	0.00	1.00	0.05	0.00
	Time history simulation	1.00	0.00	0.05	1.00	0.00	0.05	1.00	0.00	0.05
	Soil-structure interaction	1.00	0.00	0.20	1.00	0.00	0.20	1.00	0.00	0.15
Component property		0.91	0.17	**0.55**	1.58	0.17	**0.42**	0.82	0.17	**0.39**

Multi-Unit Risk

- Systems fragility curves incorporating dependency: example problem
  - Dependency between A and B

	Variable	A	B	AB
Equipment Capacity	Strength	**0.20**	**0.05**	
	Inelastic energy absorption	**0.00**	**0.10**	
Equipment Response	Damping	**0.25**	**0.20**	
	Modeling	**0.30**	**0.15**	
	Mode combination	0.00	0.00	0.00
	Earthquake component combination	0.00	0.00	0.00
Structure Response	Ground motion	0.00	0.00	0.00
	Damping	0.20	0.20	0.20
	Modeling	0.15	0.15	0.15
	Mode combination	0.00	0.00	0.00
	Time history simulation	0.05	0.05	0.05
	Soil-structure interaction	0.20	0.20	0.20
Uncerainty		**0.55**	**0.42**	**0.32**

Multi-Unit Risk

- Systems fragility curves incorporating dependency: example problem
  - Dependency between A and C

	Variable	A	C	AC
Equipment Capacity	Strength	0.20	0.20	0.20
	Inelastic energy absorption	0.00	0.00	0.00
Equipment Response	Damping	**0.25**	**0.15**	
	Modeling	**0.30**	**0.20**	
	Mode combination	0.00	0.00	0.00
	Earthquake component combination	0.00	0.00	0.00
Structure Response	Ground motion	0.00	0.00	0.00
	Damping	**0.20**	**0.10**	
	Modeling	**0.15**	**0.12**	
	Mode combination	0.00	0.00	0.00
	Time history simulation	0.05	0.05	0.05
	Soil-structure interaction	0.20	0.15	
Uncerainty		**0.55**	**0.39**	**0.21**

Multi-Unit Risk

- Systems fragility curves incorporating dependency
  - Stage 1: select sets of median capacity values

Reduced uncertainties LSDs for A, B and C

$$\beta'_U = \sqrt{\beta_U^2 - \sum \beta_C^2}$$

$$\beta_U := 0.55$$

$$\beta_{AB} := 0.32$$

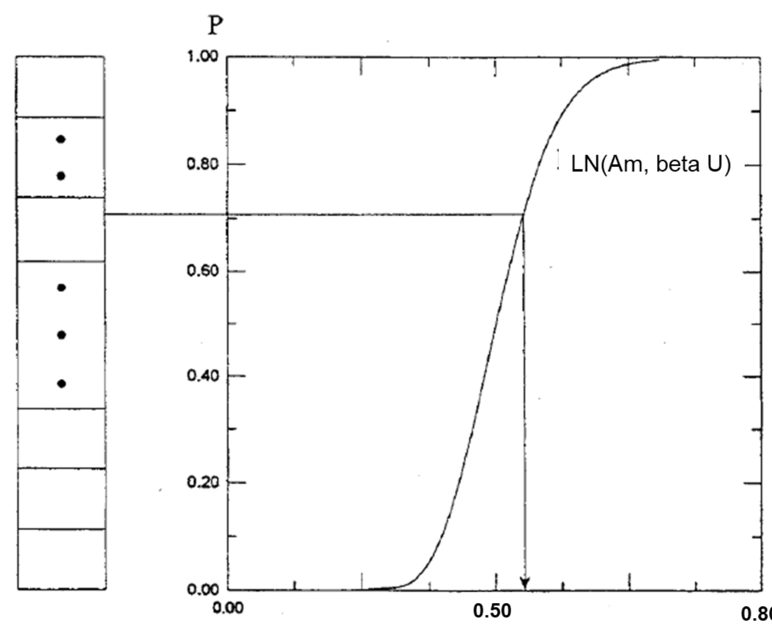
$$\beta_{AC} := 0.42$$

$$\beta'_A := \sqrt{\beta_U^2 - \beta_{AB}^2 - \beta_{AC}^2} = 0.15$$

$$\beta'_B := \sqrt{\beta_U^2 - \beta_{AB}^2} = 0.45$$

$$\beta'_C := \sqrt{\beta_U^2 - \beta_{AC}^2} = 0.36$$

Latin Hypercube Sampling for reduced cases of A, B, and C and cases of AB and AC



Multi-Unit Risk

- Systems fragility curves incorporating dependency
  - Stage 1: select sets of median capacity values

	Independent Step			Dependent Step		Combined Values (g)		
	A	B	C	A, B	A, C	(includes correlation)		
Sample	$\check{a}=0.90g$ $\beta'_U=0.28$	$\check{a}=1.0g$ $\beta'_U=0.30$	$\check{a}=1.1g$ $\beta'_U=0.19$	$a=1.0$ $\beta^*_U=0.40$	$a=1.0$ $\beta^*_U=0.35$	A	B	C
1	0.627	0.758	0.946	0.882	1.973	1.091	0.669	1.867
2	0.849	1.221	0.919	1.206	1.213	1.242	1.473	1.115
3	1.537	1.864	1.725	1.441	0.803	1.779	2.686	1.385
4	0.734	1.313	1.247	0.794	1.158	0.675	1.042	1.444
5	0.680	1.038	1.193	1.862	0.845	1.071	1.933	1.008
6	0.787	0.839	1.313	0.979	0.640	0.493	0.822	0.840
7	0.915	0.981	0.831	0.672	0.568	0.349	0.659	0.472
8	1.076	0.892	1.083	1.244	0.923	1.235	1.109	1.000
9	0.999	0.663	1.005	1.062	1.408	1.493	0.703	1.415
10	1.230	1.151	1.117	0.531	1.037	0.677	0.611	1.159

Multi-Unit Risk

- Systems fragility curves incorporating dependency
  - Stage 2: develop systems fragility curves for sample No. 1

    - Case 1: Union of A, B, and C
      - Failure is assumed to occur if either components A, B, or C fails

$$P_f = \frac{1}{\beta r_{AB} \cdot \beta r_{AC}} \cdot \int \int \left[1 - \left(1 - \Phi\left(\frac{\ln\left(\frac{a}{A_m \cdot x_1 \cdot x_2} \right)}{\beta' r_A} \right) \right) \cdot \left(1 - \Phi\left(\frac{\ln\left(\frac{a}{B_m \cdot x_1} \right)}{\beta' r_B} \right) \right) \cdot \left(1 - \Phi\left(\frac{\ln\left(\frac{a}{C_m \cdot x_2} \right)}{\beta' r_C} \right) \right) \right] \cdot \phi\left(\frac{\ln(x_1)}{\beta r_{AB}} \right) \cdot \phi\left(\frac{\ln(x_2)}{\beta r_{BC}} \right) \cdot \frac{1}{x_1} \cdot \frac{1}{x_2} \, dx_1 \, dx_2$$

    - Case 2: Intersection of A, B, and C
      - Failure is assumed to occur if all components A, B, and C fail

$$P_f = \frac{1}{\beta r_{AB} \cdot \beta r_{AC}} \cdot \int \int \Phi\left(\frac{\ln\left(\frac{a}{A_m \cdot x_1 \cdot x_2} \right)}{\beta' r_A} \right) \cdot \Phi\left(\frac{\ln\left(\frac{a}{B_m \cdot x_1} \right)}{\beta' r_B} \right) \cdot \Phi\left(\frac{\ln\left(\frac{a}{C_m \cdot x_2} \right)}{\beta' r_C} \right) \cdot \phi\left(\frac{\ln(x_1)}{\beta r_{AB}} \right) \cdot \phi\left(\frac{\ln(x_2)}{\beta r_{BC}} \right) \cdot \frac{1}{x_1} \cdot \frac{1}{x_2} \, dx_1 \, dx_2$$

Multi-Unit Risk

- Systems fragility curves incorporating dependency
  - Stage 2: develop systems fragility curves for sample No. 1

	P(A∪B∪C)		P(A∩B∩C)		Correlation Coefficient for A,B	
Acceleration (g)	Dependent	Independent	Dependent	Independent	Capacity[1]	Failure[2]
0.1	4.63-5	4.63-5	3.72-12	1.05-16	0.30	0.002
0.2	7.66-3	7.76-3	2.61-7	7.39-10	0.30	0.026
0.3	5.91-2	6.12-2	3.04-5	6.15-7	0.30	0.070
0.4	1.72-1	1.81-1	4.53-4	2.74-5	0.30	0.113
0.5	3.20-1	3.42-1	2.51-3	3.14-4	0.30	0.142
0.6	4.71-1	5.07-1	8.41-3	1.68-3	0.30	0.161
0.7	6.04-1	6.49-1	1.95-2	5.69-3	0.30	0.168
0.8	7.12-1	7.59-1	3.85-2	1.41-2	0.30	0.173

Multi-Unit Risk

- Systems fragility curves incorporating dependency
  - Recommendations given in NUREG/CR-7237
  - How the analysis will likely proceed
    - Step 1: perform a SPRA using standard methods
    - Step 2: identify cut sets or accident sequences where the correlation analysis makes a difference
    - Step 3: use the proposed methodology to study the identified cut sets or accident sequences one by one
    - Step 4: use the new fragility curves in the SPRA in the usual way
  - Fragility analysts may need further guidance in execution of the proposed correlation methodology
  - Do not use the proposed methodology to address a large number of correlation/dependency problems