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Fragility Evaluation and Seismic Probabilistic Safety Assessment

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Fragility Evaluation and Seismic Probabilistic Safety Assessment

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Topics of Discussion

- Overview
- Key elements of SPSA
- Fragility evaluation
  - Seismic response
  - Seismic capacity
  - Plant walkdown
- Standards
- Additional Information
  - References/Bibliography

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Seismic Probabilistic Safety Assessment: High Level End Products

- Develop an appreciation of accident behavior (consequences and role of the operator)
- Understand the most likely accident sequences induced by earthquakes (useful for accident management)
- Gain an understanding of the overall likelihood of core damage induced by earthquakes
- Identify the dominant seismic risk contributors
- Identify the range of earthquakes that contributes significantly to the plant risk (seismic margins) – one measure of conservatism beyond the design basis earthquake
- Compare seismic risk with risks from other events and establish priorities for plant upgrading

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Why perform a SPSA? Existing Facilities/New Facilities – Operational Phase

- Provide input for Risk Informed Safety Assessments – Decision Making
- Seismic margin beyond SSE is needed as part of Severe Accident Policy Implementation – no "cliff edge effect" (i.e., US IPEEE)
- Seismic hazard perception has changed (e.g., new data or newly discovered faults, new seismic hazard methodologies, Charleston Earthquake issue in US, newly recorded data in Japan, DACH in Germany)
- Seismic design and qualification methods have evolved - existing design and qualification procedures are more stringent than original design process
- Earthquake occurs near the plant exceeding the design basis (e.g., NCOE, New Brunswick Earthquake, LeRoy Earthquake, KRSKO)
- Periodic License Review
- Other

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Why perform a SPSA? New Facilities/Design Phase

- Demonstrate seismic margin beyond SSE – High Confidence of Low Probability of Failure (HCLPF) at least 1.67 X SSE in the US; 1.4 X SSE in Europe
- Identify most vulnerable links in systems and operations when subjected to earthquake environment – make design changes if deemed warranted
- Provide basis for future Risk Informed Safety Assessments – Decision Making
  - Inservice Testing
  - Technical Specifications
  - Maintenance
  - QA
  - Others

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SPSAs Performed (To-date 2007) (and Seismic Margin Assessments)

	SPSA	SMA	Comments
US	IPEEE 27 Plants 41 Units	About 30 Plants	All SMA plants where seismic is important are being converted to SPSA s for RISA
Outside US (Europe, Asia, Canada)	About 20 plants	About 15 plants	
Total	About 50 plants	About 45 plants	

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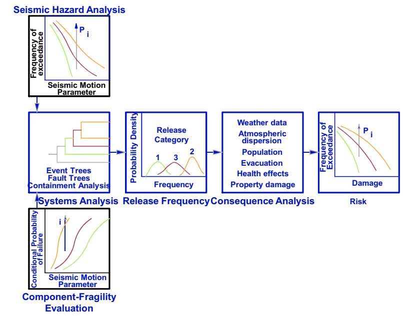
Seismic Probabilistic Safety Assessment



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Key Elements of Seismic PSA Approach

- Probabilistic seismic hazard assessment (PSHA)
- Plant Systems Modeling
  - Modify existing FTs/Ets
  - Incorporate passive failures, low capacity LOSP, etc.
- Seismic fragilities –structures, systems, and components (SSCs)
  - Median seismic response
  - Capacity
- Seismic Risk Convolution
- Enhancements
- Peer Review

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Multi-Disciplinary Problem

- PSHA (Seismology, Geology, Geotechnical Engineering, Probabilistic Modeling)
- Plant Systems Modeling (Engineering –Systems, Civil, Mechanical, Electrical, I & C; and Operations)
- Seismic Fragilities (Engineering – Geotechnical, Civil, Mechanical; Probability knowledge)
- Seismic Risk Convolution (Probabilistic Modeling, Computations)
- Consequence Evaluation (Scientists – Dispersion), Emergency Response

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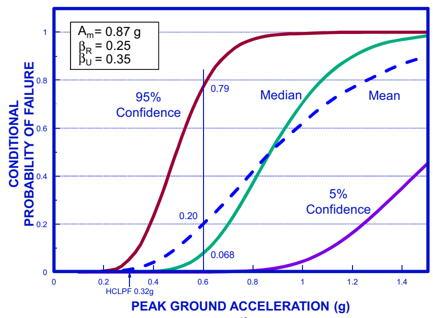
Seismic Fragility Curves



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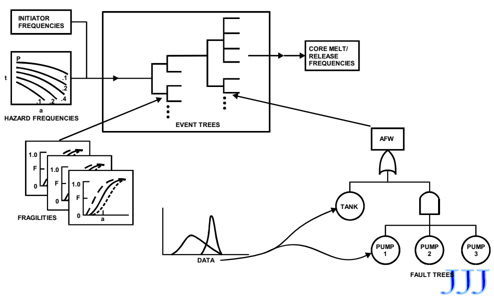
Seismic Probabilistic Safety Assessment (SPSA): Schematic



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Probabilistic Seismic Hazard Assessment (PSHA) for SPSA: End Products

- Family of seismic hazard curves and uniform hazard spectra
- De-aggregate PSHA for incorporation into Seismic PSA
  - Seismic hazard curves and spectral shape
  - Underlying assumptions, e.g., magnitude ranges of contributors for realistic treatment of energy content, including cycles of ground motion
  - Seismic response calculations treat seismic hazard as best estimate, with uncertainties – perform seismic response analyses for de-aggregated portions

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Seismic Fragility

- Fragility is the conditional probability of "failure" of a structure or component for a given peak ground acceleration
- Fragility is used:
  - To estimate the conditional probability of occurrence of initiating events (e.g., LOSP, small LOCA)
  - To quantify the failure of SSCs in fault trees modeling system behavior
  - To quantify accident sequence failure probability leading to probability of core damage frequency (CDF) (Level 1) and large early release frequency (LERF) (Level 2)

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General Procedures for Fragility Evaluation

Seismic fragility of structures and equipment is estimated using a combination of the following:

- Design information
- Qualification test data
- Fragility test data
- Earthquake experience database
- Engineering judgment

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Alternate Fragility Curve Evaluation: Based on HCLPF

- Calculate HCLPF by deterministic methods
- Estimate range for β_C
- Calculate the A_m from HCLPF and β_C
- A_m = HCLPF exp $(2.33^*\beta_C)$
- For approximate risk calculations, often generic β_C are used with deterministic HCLPF to develop fragility
- Quantification is based on mean hazard curve

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Data Sources

- Plant specific
  - Site characteristics
  - Design seismic response analysis
  - Design criteria and reports (need all other loading conditions DL, LL, etc.)
  - Equipment stress reports or qualification test reports
  - Equipment anchorage design data
- Generic
  - Shock test data
  - Past performance
  - Fragility tests
  - Expert opinion

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Seismic Fragility Methodology: General

- Identification of SSCs of interest to SPSA analysis
  - Seismic Equipment List (SEL) plus Structures
- Conditional probability of failure conditional on ground motion parameter of seismic hazard curves – fragility parameter must be compatible
  - Peak ground acceleration, average spectral acceleration over frequency range of interest, etc.
  - Lognormal distribution
- Two elements comprise fragility
  - Realistic seismic response of or demand on SSC conditional on earthquake occurring over range of seismic hazard
  - Seismic capacity of SSC

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Seismic Response

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Seismic Response as Input to SSC Fragility Evaluation: Three Approaches

- Objective is to calculate best estimate or median-centered seismic response conditional on an earthquake occurring
  - Typically, seismic design calculated values are very conservative
  - Scaling of design values or re-calculation by deterministic or probabilistic methods needed
- Scaling seismic design calculated responses
  - Account for conservatisms in ground motion response spectrum shape, soil-structure interaction, methods of structure and subsystem analysis and parameters – e.g. damping

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Seismic Response as Input to SSC Fragility Evaluation: Three Approaches (cont)

- Probabilistic response analysis -- for each de-aggregated portion of the seismic hazard (PGA range and UHS shape)
  - Ensemble of ground motion time histories, e.g. 30
  - Statistics of important parameters (frequency content, cycles of motion) match PSHA bin
- Deterministic Best Estimate Response
  - De-aggregated seismic hazard (PGA, UHS)
  - Sets of three component earthquake motions which match the UHS at PGA levels
- In-structure response (maximum values, response spectra (ISRS), loads)

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Seismic Response of Risk Important SSCs: Probabilistic Response Analyses

- Termed the SSMRP approach (funded by US NRC, developed and applied in late 1970s through mid 1980s)
- Important structures, components, piping, and equipment re-analyzed
- Modeling, analysis procedures, parameter values treated as best estimate with uncertainty explicitly included
- Re-analysis of large number of systems modeled in the SPSA – time consuming and resource intensive
- One of the SSMRP principle purposes was to benchmark other simpler approaches
- End Product: Seismic responses defined as distributions conditional on an earthquake occurring of a given size
- Current applications – re-analysis selectively performed

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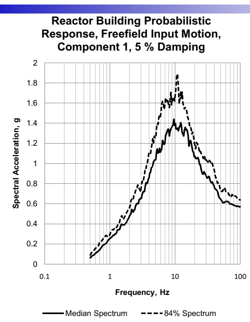
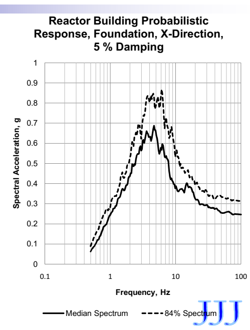
Probabilistic In-Structure Response Spectra: Current Application (2009)





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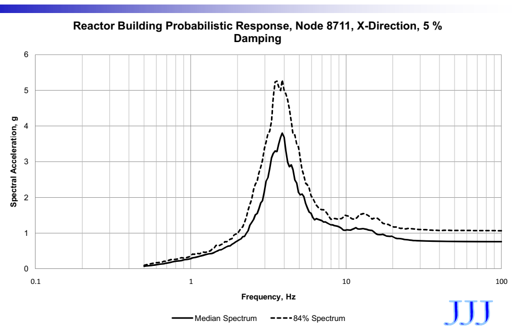

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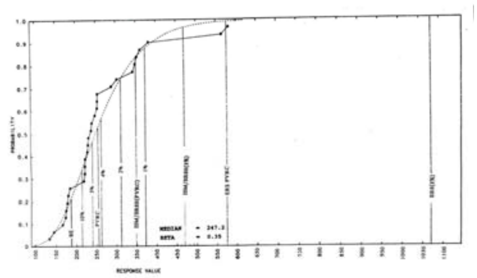
Pipe Stress - Design Conservatism and Median-Centered (Johnson and Benda, 1988)



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Median-Centered Seismic Response Analyses: Lessons Learned

- Extremely important element to realistic seismic risk estimates –
  - Lessons learned from US IPEEE
  - Very significant conservatism in seismic design analyses
- Probabilistic best estimate seismic response analyses
  - World-wide: Over 25 NPP, 100 buildings
  - Applications – SPSA, SMA, other programs

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Best Estimate or Median-Centered Seismic Response: End Product

- In-structure response probability distributions for fragility analyses (loads, in-structure spectra, expected cycles for fatigue evaluation, etc.)
- Response as a function of de-aggregated hazard levels
- Responses described as probability distributions (mean and standard deviation) as a function of seismic hazard levels

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Seismic Capacity

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Seismic Fragility Methodology: Seismic Capacity

- SSCs of interest
- Failure mode identification
- Screening
  - High capacity
  - Low capacity
  - Intermediate – specific fragility calculations performed
- Fragility function derived including seismic response and capacity considerations

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SSCs: Fragility Function Development

- Identify function to be performed during and after earthquake shaking
  - Engineering, Systems, and Operations to determine
  - Structures (Vessels, Tanks, Containment, Buildings, etc.)
    - Pressure boundary, fluid retention, etc.
    - Support of equipment, commodities, etc.
    - Failure of non-safety related structures do not cause failure of SSCs
  - Systems, equipment and components (operability and structural integrity)
    - Emergency power system (Diesel generators, all peripherals)
    - Electrical (switchgear, MCCs, transformers, inverters, etc.) – must function
    - Mechanical (valves, pumps, heat exchangers, etc.)

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SSCs: Fragility Function Development

- Identify failure modes for individual SSCs or groupings of like SSCs, e.g., all MOVs
- Generally, components lose functional capability before pressure boundary fails.
- Components grouped into generic categories and a representative fragility curve developed.

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Seismic Fragility

"FAILURE" is defined as the event when an element reaches a limit state (cannot perform its function)

Element	Limit States
Structures	• Inelastic Deformations Exceeding Operability Limits for Equipment
Piping	• Fracture or Collapse of Pressure Boundary • Failure of Supports • Attachment Failure
Equipment	• Structural - Bending, Buckling of Supports Anchor Bolt Pull-Out, Nozzles, etc. • Functional - Binding of Valve, Excessive Deflection, Relay Chatter

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Seismic Fragility (Cont.)

Element	Limit States
Soil Failure Modes	Liquefaction Toe Bearing Base Slab Uplift Slope Instability
Dams	Seismically Induced Failure

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Screening of SSCs: Apply Response and Capacity Filters

- Screening is at HCLPF levels and variability must be estimated
- Median-centered seismic response from scaling, deterministic, and probabilistic response analyses provide screening information for SSCs
- Screen components – assign high capacities
  - Seismic responses
  - Based on recent generation SPSA results
  - Generic capacity information (EPRI NP-6041) (when shown applicable)
  - Seismic design criteria
  - Assign low median fragility values (in some cases surrogates)
  - Mechanical components/piping/others
  - Identify these SSCs for verification of no vulnerabilities in the field during the plant walkdown

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Screening of SSCs: Apply Response and Capacity Filters

- Screen out components – assign low capacities or assume failed
- Plant-specific fragilities by the Factor of Safety or other approach
- Generic fragilities
  - Fragilities assigned based on similarity to components of known fragility or from historical performance

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Screening of SSCs: End Product

- Screened-in and –out SSCs based on seismic demand and capacity assessments
- SSC list denoted Seismic Equipment List (SEL) for documentation and further analyses
- Identified structures and components for which detailed fragility assessments are to be performed

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SSCs: Fragility Function Development

- Screened-in components identified for detailed capacity evaluation
  - Plant data (drawings, design calculations, etc.)
  - Plant walkdown (planned, walk-by performed, detailed pre-walkdown data prepared)
  - Detailed plant walkdown performed
  - Fragility analyses performed for SEL items
- End product
  - Probabilistic fragility functions for important SEL items (mean, standard deviation)
  - Seismic hazard bins

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Plant Walkdown In-Plant Evaluation

- Review/verify and perform additional screening
- Confirm functional requirements (SSCs, SEL) during and after event
- Gather all data necessary
  - Resolve capability question
  - In-plant and in-office
  - Easy fixes
- Evaluate seismic spatial interaction issues (falling, impact, spray or flood)
- Documentation

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Examples of Components Typically Needing Specific Capacity Evaluations

- Sensitive relays (function).
- Unreinforced or lightly reinforced masonry and block walls that may impact safety components.
- Flat bottom tanks (buckling).
- Electrical cabinets (anchorage).
- Large heat exchangers and vessels (anchorage).
- Long column pumps (function).

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Factor of Safety Method

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Seismic Fragility Methodology

- Factor of Safety Method (sometimes called Separation-of-Variable method presented in EPRI TR-103959 “Methodology for Developing Seismic Fragilities”and other references)
- Endorsed by ANS-58.21 “External-Events PRA Methodology”
- Identify and quantify conservatism in different parts of seismic design of nuclear power plant structures, systems, and components (SSC)
- Utilize existing seismic design data and qualification documents to the extent possible
- Refine seismic fragility using limited nonlinear analyses

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Fragility Function Development: Factor of Safety Method

- Develop fragility function in terms of ground motion parameter for which the risk quantification will be performed
- Generalized form of the Factor of Safety is:

  $A = F * A_{SSE}$

  where A_{SSE} is a design ground motion parameter, e.g., PGA or average spectral acceleration over a frequency range of interest; A is the ground acceleration capacity; and F is the relationship between the design level response/capacity and the “best estimate” of the seismic capacity;

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Fragility Function Development: Factor of Safety Method

- A and F are assumed to be lognormal distributions with medians described later and logarithmic standard deviations ß. F is expanded to represent the conservatism or Factors of Safety in the capacity and the response of the SSC of interest.

  $F = F_C * F_{RS} * F_{RE}$

  where F_C is the capacity factor, F_{RS} is the structural response factor and F_{RE} is the equipment response factor (for the development of fragilities for items supported by the structures).
- Remaining discussion on Factor of Safety Method

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Fragility Considerations

- Structural Capacity
  - Strength
  - Ductility (Inelastic Energy Absorption Capability)
  - Uncertainty in strength and ductility
- Structural Response
  - Scaling of design analysis results when appropriate
  - Median global structural responses
  - Median factors of safety and associated variability
- Equipment Response
  - Median in-structure response spectra
  - Median factors of safety of other variables associated with equipment response

Fragility Model

- Lognormal model (all properties of variables have lognormal distribution).
- Entire fragility curve and its uncertainty expressed by three parameters A_M, β_R, β_U.

$$A = A_m \, \varepsilon_R \, \varepsilon_U$$

where

A = ground acceleration corresponding to any given frequency of failure.

A_m = median ground acceleration capacity.

ε_R, ε_U = random variables with unit median and logarithmic standard deviation β_R, β_U.

ε_R, ε_U represent inherent randomness about the median and uncertainty in the median value, respectively

Fragility Model

- $A = A_m \, \varepsilon_R \, \varepsilon_U$
  - A_m is median seismic capacity

  ε_R and ε_U are lognormal variables with median value of unity and lognormal standard deviation β_R & β_U

$$\beta_C = \sqrt{\beta_R^2 + \beta_U^2}$$

- HCLPF capacity = $A_m \exp[-1.65 (\beta_R + \beta_U)]$
  = $A_m \exp[-2.33\beta_C]$

Fragility Model

A_m = $F_m \, A_{REF}$ (Median seismic capacity)

F_m = $F_C \, F_{RS} \, F_{RE}$ (Overall factor of safety)

F_C = $F_S \, F_\mu$ (Capacity factor)

F_{RS} = $F_{SS} \, F_{GMTH} F_{SSI} F_{INCOH} F_\delta F_M F_{MCC} F_{ECC} F_{NL}$

F_{RE} = $F_{QM} \, F_\delta \, F_M \, F_{MC}$ (Equipment response factor)

β_F = $(\beta_S^2 + \beta_\mu^2 + \beta_{SS}^2 + \ldots)^{1/2}$

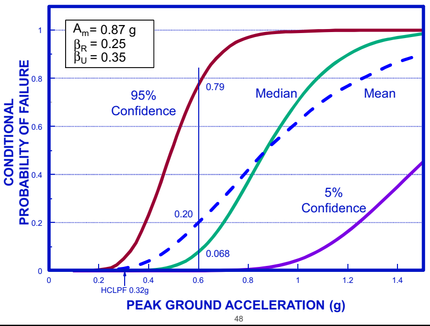
where

A_{REF} = Peak ground acceleration or average spectral acceleration of the reference earthquake

Typical Fragility Evaluation Variables

- Strength
- Inelastic energy absorption
- Spectral shape
- Damping
- Modeling
- Method of analysis/testing
- Combination of modes
- Combination of earthquake components
- Structural response
- Soil-structure interaction
- Ground Motion Incoherence

Seismic Fragility Curves



Lognormal Distribution

- Reasonable since the statistical variation of many material properties and seismic response variables have been shown to be reasonably represented by this distribution
- Central limit theorem states that a distribution consisting of products and quotients of distributions of several variables tends to be lognormal even if the individual distributions are not lognormal

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Variability of Parameters

- Inherent Randomness, aleatory uncertainty, β_R
  - Primarily associated with earthquake characteristics (i.e., response spectra shape and amplification, duration, number and phasing of peaks)
  - Not considered possible to significantly reduce randomness by additional analyses or tests
- Modeling Uncertainty, epistemic uncertainty, β_U
  - Associated with lack of knowledge of model and parameters
  - Generally could be reduced by additional analyses and tests

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Civil Structures

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Conservatisms in Civil Structure Design

- Input ground motion and definition of control point
- Seismic response calculation
- Soil-structure interaction analysis
- Load combinations
- Design capacity
  - Code strength equation with capacity reduction factor
  - Minimum material strengths
- Elastic design – additional capacity after yielding of building structures
- Design margin

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Separation-of-Variable Method - Structures

Capacity Factor
- Strength
- Inelastic energy absorption

Structural Response Factor
- Spectral shape
- Damping
- Soil-structure interaction
- Modeling
- Combination of modes
- Combination of earthquake components

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Separation-of-Variable Method - Structures

- Code margin
  - Margin of code stress limit over calculated stress

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Civil Structures

- Develop plant specific fragilities from original design analysis
  - Review design analysis
  - Review seismic load paths
  - Identify critical failure modes
  - Perform load distribution to major walls and diaphragms
- Strength Factor
  - Median seismic capacity vs. SSE seismic demand
    - Conservatism in code capacity
    - Use of minimum specified material strengths

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Civil Structures

- Inelastic energy absorption capability
  - NPP structures designed to remain elastic
  - Additional capacity beyond yielding of building (ductile design)
  - The additional capacity is a function of
    - Distribution of nonlinearity
    - Story drift criteria
- Structure response factors
  - Use of scaling approach when appropriate
  - New seismic response analysis for soil sites
- Masonry walls, control room ceiling, plant stack mounted on structure are treated as subsystems

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Major Passive Equipment

- Best to develop plant specific fragilities from original design analysis, if available (require states of stress form other loading conditions)
  - May be able to use generic fragilities – results of other fragility analyses for same equipment
  - New analysis sometimes required
- Typical passive components include:
  - Reactor pressure vessel
  - Steam generator (PWR)
  - Reactor coolant pump (PWR)
  - Recirculation pump (BWR)
  - Pressurizer (PWR)
  - Major vessels (core flood tank, boron

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Major Passive Equipment (Cont.)

- Typical passive components include (cont):
  - Pressurizer (PWR)
  - Major vessels (core flood tank, boron injection tank, etc.)
  - Major heat exchangers (RHR, CCW, etc.)
  - Primary coolant system loop (PWR)
  - Main steam line inside containment
  - Other critical vessels, heat exchangers, piping

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Use Generic Fragilities for Other Passive Equipment

- Large quantities of such equipment
  - Piping and supports
  - Cable trays and supports
  - HVAC ducting and supports
  - Conduits
  - Miscellaneous vessels and heat exchangers
- Requires large β_U to account for uncertainty in actual design stress level and most critical failure mode
  - Typically overdesigned; hence, adequate capacities and uncertainty levels usually result such that contribution to plant risk is low
  - Experience shows a tendency to be conservative when developing generic fragilities as opposed to plant specific fragilities

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Subsystems: Equipment and Components

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Conservatism in Equipment Seismic Qualification: Subsystems

- Seismic demands
  - Enveloping, smoothing, and broadening of floor response spectra
  - Damping values
  - Earthquake components combination
- Seismic capacity
  - Strength equations
  - Minimum material strengths
  - Conservative design criteria
  - Enveloping of test response spectra over required response spectra

Factor of Safety Method – Subsystems

Qualified by Analysis

- Capacity factor
  - Strength
  - Inelastic energy absorption
- Equipment response
  - Qualification method
  - Damping
  - Modeling
  - Modal combination
  - Earthquake component combination
- Building structure response

Factor of Safety Method – Subsystems

Qualified by Testing

- Test capacity
- Equipment factors
  - Response or capacity clipping
  - Capacity increase and demand reduction
  - Cabinet amplification
  - Multi-axis to single-axis conservatism
  - Broad frequency input spectrum device capacity
- Building structure response

Factor of Safety Method – Subsystems

- Subsystem Capacity
  - Strength
  - Ductility
  - Functional limits (deflection, load, etc.)
  - Capacity estimated from achieved test level
  - Uncertainties for all variables affecting capacity

Active Equipment

- A combination of generic and plant specific fragilities is generally required
- Plant specific fragilities developed from design reports including test data on active devices in subsystems
- Generic fragilities developed from data base of varying sources
- Data base includes:
  - Past PRA fragilities
  - Qualification test data (generic & plant specific)
  - Performance in past earthquakes (generic)
  - Military shock test fragility data (generic)
  - Expert opinion (generic)

Current state-of-the-art in equipment design has greater uncertainty than for civil structures and major equipment treated on plant specific basis. Thus, there is need for larger median factors of safety than for civil structures and major equipment in order to achieve a high confidence of low probability of failure above the safe shutdown earthquake level.

Use of Design Information

If it is possible, all seismic fragilities should be developed on a plant-specific basis. This is especially important for components that are judged to be dominant contributors to seismic risk (e.g., weaker components where there is no redundancy).

- Structures, heavy components (e.g., RPV, steam generator, reactor coolant pump and RHR heat exchanger), and yard tanks are generally evaluated on plant-specific basis
- Their critical failure modes (e.g., anchorage failure, support buckling) are structural and seismic capacities can be estimated using theory of mechanics or empirical equations

Use of Design Information (Cont.)

- Sources of design information used in fragility development are
  - Design analysis reports
  - Plant Safety Analysis reports
  - Structural design calculations
  - Structural and equipment support and anchorage drawings
  - Material test reports (e.g., concrete, steel, prestressing tendon, anchor bolt pullout tests)
- Another important phase of fragility development is plant walkdown.

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Use of Qualification Test Data

- Used for mechanical equipment such as active valves and pumps and electrical components such as switchgear, batteries , and motor control centers.
- Component testing is generally employed to demonstrate satisfaction of the functionality (operability) requirements. Demonstration of operability is not related to stress level but to deflection or acceleration limits.
- Both functional and structural failure modes must be evaluated to determine the controlling mode for active components.
- Two sources of data
  - **Plant Specific**
  - **Generic**

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Use of Specific Qualification Test Data

- Typically, the equipment test response spectrum envelopes the required response spectrum by approximately 10 percent or more; it depends on the frequency range.
- This conservatism and the characteristics of testing should be considered in fragility evaluation.
- The variables included are
  - **Qualification method factor**
    - Estimate the overtest median and variability

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Use of Specific Qualification Test Data (Cont.)

- The variables included are (Cont.)
  - Boundary conditions factor

    Differences between component to test table attachment and the actual in-plant condition;
    median = 1 and ß = 0 for reputed testing laboratories
  - Multidirectional effects factor

    Conservatism or unconservatism and variability involved in testing the three different earthquake directional components
    - *Triaxial tests*: median-centered
    - *Biaxial tests*: median centered for functional failures (relay chatter) and unconservative for structural failures
    - *Uniaxial tests*: unconservative for all failure modes

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Use of Generic Qualification Test Data

- EPRI collected seismic qualification test data from nuclear power plant utilities, testing laboratories and vendors
  - 15 classes of electrical and mechanical equipment are included
  - Data was analyzed to develop lower bound spectra called "Generic Seismic Ruggedness Spectra (GERS)"

Reference: EPRI NP-5223-SL "Generic Seismic Ruggedness of Power Plant Equipment (Revision 1)" Prepared by ANCO Engineers, Inc.

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Use of Generic Qualification Test Data (Cont.)

- EPRI report on GERS is a licensable document
- Note that manufacturer's identification and source of test data are intentionally left out of the database.
- Qualification test data was collected for equipment in US nuclear power plants and the test response spectra were for plants with SSE ranging from 0.10g to 0.25g pga.
- Applicability of database and GERS to nuclear power plants with high design earthquakes needs to be examined.

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Fragility Test Data

- Fragility testing of components has been conducted under the NRC funded research "Component Fragility Program" at Brookhaven National Laboratory (BNL) and Lawrence Livermore National Laboratory (LLNL)
- BNL program consisted of collecting existing test data on 18 nuclear component types (Bandyopadhyay, et al 1991) and developing seismic fragility parameters

Fragility Test Data (Cont.)

- Fragility level (at which the component failed to perform its function) was derived from qualification test data (i.e., the highest qualification level was increased by 10% - 30% to estimate the corresponding fragility level depending on performance of the specimen during the high level test runs
- The Zero Period Acceleration (ZPA) and the Average Spectral Acceleration (ASA) averaged over the 4-16 Hz frequency band of the Test Response Spectrum are used as the fragility indicators

Fragility Test Data (Cont.)

- Table of the fragility parameters for the eighteen components is shown below. The applicability of these results is limited to the equipment types and models that are represented by the database. The data base equipment was manufactured as Class 1E or Seismic Category I after 1975; therefore, the use of these fragility results should be limited for similar equipment manufactured after 1975
- As a minimum, all equipment items should be adequately anchored and all relays should be separately evaluated
- The users of the fragility results presented in this report should confirm that their equipment items belong to these so-called "generic" equipment class

Table of the Fragility Parameters

Equipment	Failure Mode	Acceleration	Median in "g"	β_u	β_r	HCLPF in "g"
MCC	Contact chatter	ZPA ASA	1.3 3.0	0.20 0.20[3]	0.10 0.06	0.8 2.0[3]
	Change of State	ZPA ASA	1.7 4.0	0.17 0.20	0.15 0.18	1.0 2.1
	Structural	ZPA ASA	2.5 5.0	0.20 0.20	0.06 0.06	1.6 3.2
Switchboard	Breaker	ZPA ASA	3.5 7.5	0.30 0.30	0.10 0.10	1.8 3.9
Panelboard	Breaker	ZPA ASA	2.5 6.6	0.45 0.37	0.10 0.07	1.0 3.2
DC Power Supply	Accuracy	ZPA ASA	3.6 9.0	0.15 0.15	0.05 0.05	2.6 6.5
Low Voltage Switchgear[4]	Breaker	ZPA ASA	1.5 6.6	0.30 0.30	0.10 0.10	0.8 3.4
	Structural	ZPA ASA	3.5 8.5	0.15 0.15	0.06 0.06	2.5 6.0
Medium Voltage Switchgear[4]	Internal Damage	ASA	4.0	0.10	0.10	2.9
	Breaker	ZPA ASA	2.0 6.3	0.10 0.10	0.10 0.10	1.4 4.5
	Structural	ZPA ASA	3.5 8.5	0.15 0.15	0.06 0.06	2.5 6.0
NSSS I&C Panels[5]	Electrical	ASA	6.8	0.30	0.10	3.5
	Structural	ASA	9.0	0.30	0.10	4.7
Transmitters[5]	Accuracy	ZPA ASA	4.9 14.5	0.30 0.20	0.10 0.10	2.5 8.9
Indicators	Accuracy	ZPA ASA	5.4 16.3	0.26 0.26	0.10 0.10	3.0 9.0
Switches[6]	Chatter	ZPA ASA	5.0 10.7	0.38 0.38	0.10 0.10	2.3 4.7
Transformers	Coil	ZPA ASA	3.0 6.8	0.27 0.27	0.10 0.10	1.6 3.7
BOP I&C Panels	Electrical	ZPA ASA	2.4 6.3	0.30 0.30	0.10 0.10	1.3 3.3
Misc. Instruments	Accuracy	ZPA ASA	4.5 14.5	0.30 0.30	0.10 0.10	2.3 7.5

Table of the Fragility Parameters (Cont.)

Equipment	Failure Mode	Acceleration	Median in "g"	β_u	β_r	HCLPF in "g"
Batteries on Racks[7]	Discharge	ZPA ASA	3.7 7.3	0.21 0.21	0.10 0.10	2.2 4.4
Battery Chargers	Functional	ZPA ASA	2.4 5.0	0.23 0.23	0.10 0.10	1.4 2.9
Inverters	Functional	ZPA ASA	3.0 5.6	0.23 0.23	0.10 0.10	1.7 3.2
EPA's	Pressure Loss	ASA	12.0	0.30	0.10	6.2
Valve Operators[8]	Functional	ASA	20.5	0.40	0.10	9.0

[1] Acceleration levels are local i.e., they are measured at the base of the equipment. Legend: ZPA - zero period acceleration, ASA - average spectral acceleration at a damping value of 2% (averaged over 4-16Hz).

[2] The equipment type should be enveloped by the data base as described in the text for each equipment class. The most common limitations are as follows:

a) The equipment should be Class 1E or Seismic Category I and manufactured after 1975, unless otherwise mentioned.
b) All relays should be separately evaluated, i.e., the fragility levels presented in this table do not consider the effect of relay malfunction such as chatter.
c) All equipment should be adequately anchored.

[3] Since publication of the MCC Contact Chatter HCLPF value in Reference 3, the data have been further investigated and the results have been revised as shown in this table.

[4] The breakers should be restrained from relative motion and the switchgear should be in the operating (i.e., connected) position.

[5] The data base includes panels and transmitters manufactured after 1971.

[6] Switches operated by mercury are not included in the data base.

[7] The fragility results apply only to lead-calcium batteries not more than 10-12 years old. Electrical discharge of a small number of batteries in a large set up has been considered acceptable.

[8] Includes motor and solenoid operators modified with seismic brackets.

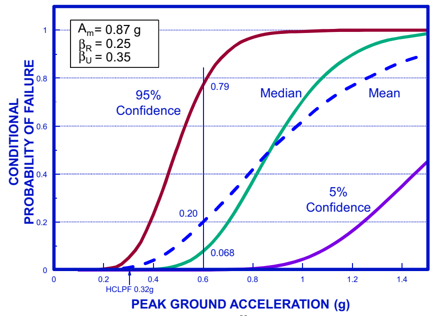
LLNL Component Fragility Research Program

- LLNL performed demonstration fragility tests reported in Holman and Chou (1986a and 1986b)
- Based on the qualification tests conducted on components at Diablo Canyon Nuclear Power Plant, seismic fragility of the following components were developed:
  - Medium voltage (4kV) switchgear
  - Safeguard relay board
  - Emergency light battery rack
  - Potential transformer
  - Station battery and racks
  - Westinghouse Type W motor control center column
  - Fan cooler controller
  - Local starters

Use of Earthquake Experience Database in Seismic PRA

- To establish some generic lower bounds on component seismic capacities
- Earthquake experience data could be used in Bayesian updating of fragilities as described in the paper by Yamaguchi, Campbell and Ravindra (1991)

Seismic Fragility Curves



Questions and Discussion

Additional Information

Interfaces Between Fragility and System Analysts

- Fragility Parameter (Spectral Acceleration or pga)
- Definition of failure
  - Structural integrity failure
  - Functional
  - Relay chatter
- Screen high seismic capacity components
- Treatment of dependence between component fragilities

Typical Approach to Past SPSAs

- Use existing design information for first round of fragility development
- Interface closely with systems analysts to channel resources to the most critical components
- Re-analyze components only if improvement in uncertainty and best estimate capacity would significantly alter risk results (may be determined from sensitivity studies)
- High seismic zone plants have required more detailed extrapolation of design information and more detailed re-analysis

Scope of Typical Studies

- Emphasis on safety-related components and non-safety event initiators. Only components related to shutdown and accident mitigation are included
- Systems interaction effects are also included

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Seismic PSA Standards: Examples

- US ANS External Events PRA Methodology Standard ANSI/ANS 58.21, 2007
- Germany: “Methoden zur Probabilistichen Sicherheitsanalyse für Kernkraftwerke” August 2005
- Finland: Radiation and Nuclear Safety Authority (STUK) “Probabilistic Safety Analysis in Safety Management of Nuclear Power Plants”, Guide YVL 2.8, May 2003
- Japan: “Seismic PSA Implementation Standards” by the Atomic Energy Society of Japan, to be published.

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ANS External Events PRA Methodology Standard ANSI/ANS 58.21

- Objective is to set forth requirements for external-event PRA used to support risk-informed decisions for commercial NPPs
- Includes Seismic Probabilistic Risk Assessment (SPRA), Seismic Margin Assessment (SMA), High Winds, External Flooding and “Other” External Events
- Seismic PRA format similar to ASME-RA-S-02 for Internal Event PRA
- Three Capability Categories for graded approach to risk assessment (based on “scope and level of detail”, “plant-specificity” and “realism”)

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ANS External Events PRA Methodology Standard ANSI/ANS 58.2: Capability Categories

ANS External Events PRA Methodology Standard ANSI/ANS 58.21: Capability Categories

- US IPEEE and previous SPSAs meet Category I with some aspects of Category II
- Newly designed nuclear power plants and many current SPSA implementations will likely meet the majority of the Category II requirements
- Category III is beyond the current state of the art

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ANS External Events PRA Methodology Standard ANSI/ANS 58.21

- Limited to Level 1 analysis of CDF during full power operation and limited Level 2 analysis of LERF.
- **Requirements, not procedures.**
- Requirements based primarily on state-of-the-art in external event PRA as practiced in US IPEEE and earlier PRAs.
- Commentary on each supporting requirement suggesting acceptable methods and references – a unique feature of the ANS standard
- High Level Requirements and Supplemental Technical Requirements

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High Level Requirements for Seismic Hazard Analysis

- **A – SCOPE (HLR-HA-A):** The frequency of earthquakes at the site SHALL be based on a site-specific probabilistic seismic hazard analysis (PSHA) (existing or new) that reflects the composite distribution of the informed technical community. The level of analysis SHALL be determined based on the intended application and on site-specific complexity.
- **B – DATA COLLECTION (HLR-HA-B):** To provide inputs to the PSHA, a comprehensive up-to-date data base including: geological, seismological, and geophysical data; local site topography; and surficial geologic and geotechnical site properties, SHALL be compiled. A catalog of historical, instrumental, and paleoseismicity information SHALL also be compiled.

High Level Requirements for Seismic Hazard Analysis

- **C – SEISMIC SOURCES AND SOURCE CHARACTERIZATION (HLR-HA-C):** To account for the frequency of occurrence of earthquakes in the site region, the PSHA SHALL consider all credible sources of potentially damaging earthquakes. Both the aleatory and epistemic uncertainties SHALL be considered in characterizing the seismic sources.
- **D – GROUND MOTION CHARACTERIZATION (HLR-HA-D):** The PSHA SHALL account for all credible mechanisms influencing estimates of vibratory ground motion that can occur at a site given the occurrence of an earthquake of a certain magnitude at a certain location. Both the aleatory and epistemic uncertainties SHALL be considered in characterizing the ground motion propagation.

High Level Requirements for Seismic Hazard Analysis

- **E – LOCAL SITE EFFECTS (HLR-HA-E):** The PSHA SHALL account for the effects of local site response.
- **F – AGGREGATION AND QUANTIFICATION (HLR-HA-F):** Uncertainties in each step of the hazard analysis SHALL be propagated and displayed in the final quantification of hazard estimates for the site. The results SHALL include fractile hazard curves, median and mean hazard curves, and uniform hazard response spectra (UHS). For certain applications, the PSHA SHALL include seismic source deaggregation and magnitude-distance deaggregation.

High Level Requirements for Seismic Hazard Analysis

- **G – SPECTRAL SHAPE (HLR-HA-G):** For further use in the SPRA, the spectral shape SHALL be based on a site-specific evaluation taking into account the contributions of deaggregated magnitude-distance results of the PSHA. Broad-band, smooth spectral shapes, such as those presented in NUREG/CR-0098 (Newmark and Hall, 1978) (for lower-seismicity sites such as most of those east of the U.S. Rocky Mountains) may also be used taking into account the site conditions. The use of UHS may also be appropriate if it reflects the site-specific shape.

High Level Requirements for Seismic Hazard Analysis

- **H – USE OF EXISTING STUDIES (HLR-HA-H):** When use is made of an existing study for PSHA purposes, it SHALL be confirmed that the basic data and interpretations are still valid in light of current information, the study meets the requirements outlined in A through G above, and the study is suitable for the intended application.
- **I – OTHER SEISMIC HAZARDS (HLR-HA-I):** A screening analysis SHALL be performed to assess whether, in addition to the vibratory ground motion, other seismic hazards, such as fault displacement, landslide, soil liquefaction, or soil settlement need to be included in the SPRA for the specific application. If so, the SPRA SHALL address the effect of these hazards through assessment of the frequency of hazard occurrence and/or the magnitude of hazard consequences.

High Level Requirements for Seismic Hazard Analysis

- **J – DOCUMENTATION (HLR-HA-J):** The PSHA SHALL be documented in a manner that facilitates applying the PRA and updating it, and that enables peer review.

Example Seismic Hazard Requirements

SEISMIC HAZARD ANALYSIS HIGH-LEVEL REQUIREMENT F: AGGREGATION AND QUANTIFICATION

(HLR-HA-F): Uncertainties in each step of the hazard analysis SHALL be propagated and displayed in the final quantification of hazard estimates for the site. The results SHALL include fractile hazard curves, median and mean hazard curves, and uniform hazard response spectra (UHS). For certain applications, the PSHA SHALL include seismic source deaggregation and magnitude-distance deaggregation.

Index No. HA-F	CAPABILITY CATEGORY I	CAPABILITY CATEGORY II	CAPABILITY CATEGORY III
HA-F1	In the final quantification of the seismic hazard, INCLUDE mean estimates. ADDRESS how this accounts for uncertainties.	In the final quantification of the seismic hazard, INCLUDE and DISPLAY the propagation of both aleatory and epistemic uncertainties.	
	NOTE HA-F1: The seismic hazard quantification involves the combination of seismic source and ground motion inputs to compute the frequency of exceedance of ground motions at a site (i.e., the seismic hazard). Thus, the principal result of the PSHA is a set of seismic hazard curves that quantify the aleatory and epistemic uncertainties in the site hazard. This is typically presented in terms of a set of fractile seismic hazard curves, defined at specified fractile levels, and the mean hazard. Two acceptable approaches have been used to propagate epistemic uncertainties: logic tree enumeration and Monte Carlo simulation (EPRI, 1989 and Bernreuter et.al., 1989). For Capability Category I applications, use of a single mean curve may be appropriate.		
HA-F2	In the PSHA, INCLUDE appropriate sensitivity studies and intermediate results to identify factors that are important to the site hazard and that make the analysis traceable.		

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High Level Requirements for Seismic PRA Systems Analysis

- **A – COMPLETENESS (HLR-SA-A):** The seismic-PRA systems models SHALL include all important seismic-caused initiating events that can lead to core damage or large early release, and SHALL include all other important failures that can contribute significantly to CDF or LERF, including seismic-induced SSC failures, non-seismic-induced unavailabilities, and human errors.
- **B – ADAPTATIONS BASED ON THE INTERNAL-EVENTS PRA SYSTEMS MODEL (HLR-SA-B):** The seismic-PRA systems model SHALL be adapted to incorporate seismic-analysis aspects that are different from corresponding aspects found in the full-power, internal-events PRA systems model.

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High Level Requirements for Seismic PRA Systems Analysis

- **C – PLANT FIDELITY (HLR-SA-C):** The seismic-PRA systems models SHALL reflect the as-built and as-operated plant being analyzed.
- **D – SEISMIC EQUIPMENT LIST (HLR-SA-D):** The list of SSCs selected for seismic-fragility analysis SHALL include all SSCs that participate in accident sequences included in the seismic-PRA systems model.
- **F – DOCUMENTATION (HLR-SA-F):** The seismic-PRA analysis SHALL be documented in a manner that facilitates applying the PRA and updating it, and that enables peer review.

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High Level Requirements for Seismic PRA Systems Analysis (Risk Quantification)

- **E – INTEGRATION AND QUANTIFICATION (HLR-SA-E):** The analysis to quantify CDF and LERF frequencies SHALL appropriately INTEGRATE the seismic hazard, the seismic fragilities, and the systems-analysis aspects.
- **F – DOCUMENTATION (HLR-SA-F):** The seismic-PRA analysis SHALL be documented in a manner that facilitates applying the PRA and updating it, and that enables peer review.

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Example Systems Analysis Requirements

SA-E2	In quantifying CDF and LERF frequencies, PERFORM the quantification on a cut-set-by-cut-set or accident-sequence-by-accident-sequence basis (or for defined groups of these), as well as on a comprehensive/integrated basis. Broad groupings MAY be used.	In quantifying CDF and LERF frequencies, PERFORM the quantification on a cut-set-by-cut-set or accident-sequence-by-accident-sequence basis (or for defined groups of these), as well as on a comprehensive/integrated basis.	
	NOTE SA-E2: The intent of this requirement is to ensure that key information about each accident sequence (or cut set) is retained, rather than simply "lost" in the production of overall integrated values for CDF and LERF. Of course, it is common to group cut-sets of accident sequences when they are so similar that phenomenologically they cannot be distinguished very well; such grouping is entirely acceptable, if its basis is defined.		
SA-E3	In the analysis, USE the quantification process to ensure that any screening of SSCs does not affect the results, taking into account the various uncertainties.		
	NOTE SA-E3: SSC screening – the elimination from the model of SSCs – is done throughout the process of performing any PRA. A defined set of criteria must be developed and used to ensure that this screening does not eliminate elements of the model that should have been retained. The intent of this requirement is to ensure that the quantification process is used to check that the screening has not erroneously eliminated important SSCs. It is recognized that this type of work is an iterative process, in which approximate interim quantifications are done during which the screening decisions are checked, and only then is a final quantification done. There are many different approaches in current use among seismic-PRA analysts to accomplish this step. (Bohn and Lambright, 1988) contains a useful discussion on this aspect.		
SA-E4	In the integration/quantification analysis, ACCOUNT for all significant dependencies and correlations that affect the results. The analysis MAY use generic dependency and correlation values if justified.		In the integration/quantification analysis, ACCOUNT for all significant dependencies and correlations that affect the results. USE plant-specific dependency and correlation values throughout.
	NOTE SA-E4: As discussed earlier, treating earthquake-specific correlations and dependencies properly is vital to achieving a successful seismic-PRA. This requirement is intended to ensure that this issue is covered. A discussion of this type of correlation/dependency analysis is found in (Bohn and Lambright, 1988). See (REQ. SA-B3) where the requirement to deal with dependencies and correlations in initial screening is covered, and (REQ. SA-E7) where appropriate sensitivity analyses are required to explore these issues.		

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High Level Requirements for Seismic Fragility Evaluation

- **A – REALISM (HLR-FR-A):** The seismic fragility evaluation SHALL be performed to estimate plant-specific, realistic seismic fragilities of structures, systems and components whose failure may contribute to core damage and/or large early release.
- **B – SCREENING (HLR-FR-B):** If screening of high-seismic-capacity components is performed, the basis for the screening SHALL be fully described.
- **C – RESPONSE (HLR-FR-C):** The seismic fragility evaluation SHALL be based on realistic seismic response that the SSCs experience at their failure levels. Depending on the site conditions and response analysis methods used in the plant design, realistic seismic response MAY be obtained by an appropriate combination of scaling, new analysis and new structural models.

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High Level Requirements for Seismic Fragility Evaluation

- **D – FAILURE MODES (HLR-FR-D):** The seismic fragility evaluation SHALL be performed for critical failure modes of structures, systems and components such as structural failure modes and functional failure modes identified through the review of plant design documents, supplemented as needed by earthquake experience data, fragility test data, generic qualification test data, and a walkdown.

High Level Requirements for Seismic Fragility Evaluation

- **E – WALKDOWN (HLR-FR-E):** The seismic fragility evaluation SHALL incorporate the findings of a detailed walkdown of the plant focusing on the anchorage, lateral seismic support, and potential systems interactions.
- **F – DATA SOURCES (HLR-FR-F):** The calculation of seismic fragility parameters such as median capacity and variabilities SHALL be based on plant specific data supplemented as needed by earthquake experience data, fragility test data and generic qualification test data. Use of such generic data SHALL be justified.

High Level Requirements for Seismic Fragility Evaluation

- **G – DOCUMENTATION (HLR-FR-G):** The seismic fragility evaluation SHALL be documented in a manner that facilitates applying the PRA and updating it, and that enables peer review.

Example Seismic Fragility Requirements

SEISMIC FRAGILITY EVALUATION HIGH LEVEL REQUIREMENT D: FAILURE MODES

(HLR-FR-D): The seismic fragility evaluation SHALL be performed for critical failure modes of structures, systems and components such as structural failure modes and functional failure modes identified through the review of plant design documents, supplemented as needed by earthquake experience data, fragility test data, generic qualification test data, and a walkdown.

Index No. FR-D	CAPABILITY CATEGORY I	CAPABILITY CATEGORY II	CAPABILITY CATEGORY III
FR-D1	IDENTIFY realistic failure modes of structures and equipment that interfere with the operability of equipment during or after the earthquake through a review of the plant design documents and the walkdown.		
	NOTE FR-D1: Note that sometimes failure modes such as drift and yielding MAY be more relevant for the functionality of attached equipment, than gross structural failures (i.e., partial collapse or complete collapse).		
FR-D2	CONSIDER all relevant failure modes of structures (e.g., sliding, overturning, yielding, and excessive drift), equipment (e.g., anchorage failure, impact with adjacent equipment or structures, bracing failure, and functional failure) and soil (i.e., liquefaction, slope instability, excessive differential settlement), and EVALUATE fragilities for critical failure modes.		
	NOTE FR-D2: Published references and past seismic PRAs MAY be used as guidance. Examples include (Reed and Kennedy, 1994); (EPRI, 1991); (PG&E, 1988).		

IAEA References Relevant to SPSA

- [1] INTERNATIONAL ATOMIC ENERGY AGENCY, Fundamental Safety Principles: Safety Standard Series No. SF-1, IAEA, Vienna (2006).
- [2] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, Safety Standards Series No. NS-R-1, IAEA, Vienna (2000).
- [3] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Operation, Safety Standards Series No. NS-R-2, IAEA, Vienna (2000).
- [4] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Evaluation for Nuclear Installations, Safety Standards Series No. NS-R-3, IAEA, Vienna (2003).
- [5] INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluation of Seismic Hazards for Nuclear Power Plants, Safety Guide No. NS-G-3.7, IAEA, Vienna (in print 2009).
- [6] INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic Design and Qualification for Nuclear Power Plants, Safety Guide No. NS-G-1.6, IAEA, Vienna (2003).
- [7] INTERNATIONAL ATOMIC ENERGY AGENCY, Periodic Safety Review of Nuclear Power Plants, Safety Standards Series No. NS-G-2.10, IAEA, Vienna (2003).
- [8] INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic Evaluation of Existing Nuclear Power Plants, Safety Report Series No. 28, IAEA, Vienna (2003).

IAEA References Relevant to SPSA

- [9] INTERNATIONAL ATOMIC ENERGY AGENCY, Probabilistic Safety Assessment for Seismic Events, IAEA-TECDOC-724, Vienna (1993).
- [10] INTERNATIONAL ATOMIC ENERGY AGENCY, Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants, Safety Guide No. NS-G-3.6, IAEA, Vienna (2004).
- [11] INTERNATIONAL ATOMIC ENERGY AGENCY, Quality Assurance for Safety in Nuclear Power Plants and Other Nuclear Installations, Safety Series No. 50-C/SG-Q, IAEA, Vienna (2001).
- [12] INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic Safety Evaluation of Existing Nuclear Installations, Safety Guide No. NS-G-2.13, IAEA, Vienna (2009).

Bibliography of Historical and Procedural Documents for SPSA

- BUDNITZ, R.J.,AMICO, P.J., CORNELL, C.A., HALL, W.J., KENNEDY, R.P., REED, J.W., SHINOZUKA, M., An Approach to the Quantification of Seismic Margins in Nuclear Power Plants, Report NUREG/CR-4334, US Nuclear Regulatory Commission, Office of Standards Development, Washington, DC (1985).
- ELECTRIC POWER RESEARCH INSTITUTE, A Methodology for Assessment of Nuclear Power Plant Seismic Margin, Report EPRI-NP-6041-SL, Rev. 1, Electric Power Research Institute, Palo Alto, CA (1991).
- US NUCLEAR REGULATORY COMMISSION, Individual Plant Examination for External Events (IPEEE) for Severe accident Vulnerabilities – 10 CFR 50.54 (f), Generic Letter No. 88-20 Supplement 4, US Nuclear Regulatory Commission, Washington, DC (1991).
- US NUCLEAR REGULATORY COMMISSION, Perspectives Gained from the Individual Plant Examination of External Events (IPEEE) Program, Report NUREG-1742 Vols. 1 and 2, US Nuclear Regulatory Commission, Washington, DC (2001).
- ELECTRIC POWER RESEARCH INSTITUTE, Individual Plant Examination for External Events (IPEEE) Seismic Insights: Revision to EPRI Report TR-112932, Electric Power Research Institute, Palo Alto, CA (2000).
- AMERICAN NUCLEAR SOCIETY, External-Events PRA Methodology, Report ANSI/ANS-58.21-2003, American Nuclear Society, La Grange Park, IL (2003).
- NEWMARK, N.M., HALL, W.J., Development of Criteria for Seismic Review of Selected Nuclear Power Plants, Report NUREG/CR-0098, US Nuclear Regulatory Commission, Washington, DC (1978).

Bibliography of Historical and Procedural Documents for SPSA

- JOHNSON, J.J., GOUDREAU, G.L., BUMPUS, S.E., MASLENIKOV, O.R., Seismic Safety Margins Research Programme – Phase I Final Report, Seismic Methodology Analysis Chain with Statistics (SMACS) (Project VIII), Report NUREG/CR-2015, Vol. 9, US Nuclear Regulatory Commission/Lawrence Livermore National Laboratory, Washington DC (1981).
- SEISMIC QUALIFICATION UTILITIES GROUP, Generic Implementation Procedure for Seismic Verification of Nuclear Power Plant Equipment, Rev. 2, Office of Standards Development, Washington, DC (1992).
- ELECTRIC POWER RESEARCH INSTITUTE, Seismic Probabilistic Risk Assessment Implementation Guide, Report No. 1002989, Electric Power Research Institute, Palo Alto, CA (2003).
- RAVINDRA, M.K., “Seismic Risk Assessment,” Probabilistic Structural Mechanics Handbook – Theory and Industrial Applications, Chap. 19, C. Sundararajan, Ed., Chapman and Hall, New York (1995).
- BUDNITZ, R.J., “Current Status of Probabilistic Seismic Probabilistic Safety Analysis,” Reliability Engineering and Systems Safety, Vol. 62, pp. 71-88 (1998).
- KENNEDY, R.P, “Overview of Methods for Seismic PRA and Margins Methods Including Recent Innovations,” Proceedings of the Organization for the Economic Cooperation and Development/Nuclear Energy Agency Workshop on Seismic Risk, August 10-12, 1999, Tokyo, Japan.
- KENNEDY, R.P., RAVINDRA, M.K., “Seismic Fragilities for Nuclear Power Plant Risk Studies,” Nuclear Engineering and Design, Vol. 79, No. 1, pp. 47-68 (1984).
- ELECTRIC POWER RESEARCH INSTITUTE, Methodology for Developing Seismic Fragilities, Report TR-103959, Electric Power Research Institute, Palo Alto, CA (1994).