

**Insights from Seismic Risk Analyses of Nuclear
Power Plants and their relevance to Kashiwazaki-
Kariwa Nuclear Power Station**

**M.K. Ravindra Ph.D.
MKRavindra Consulting
Irvine, California, USA**

Outline of Presentation

- Seismic PSA Methodology and Applications
- Development of US National Standard
- Seismic Margin Assessment of KK6
- Recommendation for KK Units

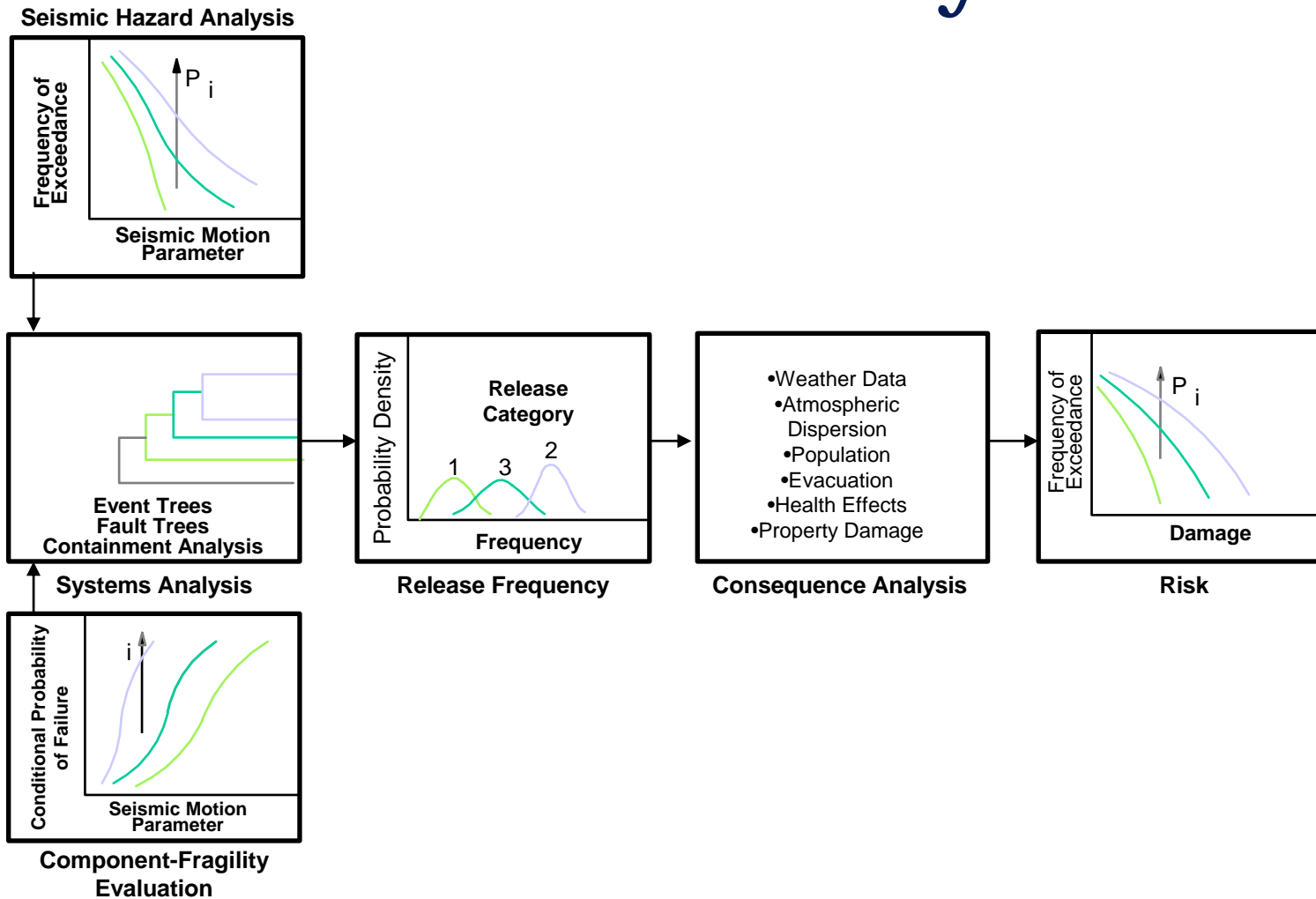
Seismic PSA

- Seismic Probabilistic Safety Assessments have been performed for nuclear power plants in the USA, Europe and Asia since 1980s
- Major Milestones:
 - PRA Procedures Guide NUREG/CR-2300, 1983
 - Development of Seismic Margin Methodology
 - Individual Plant Examination of External Events
 - Risk Informed Decision Making
 - Design Certification of ALWRs

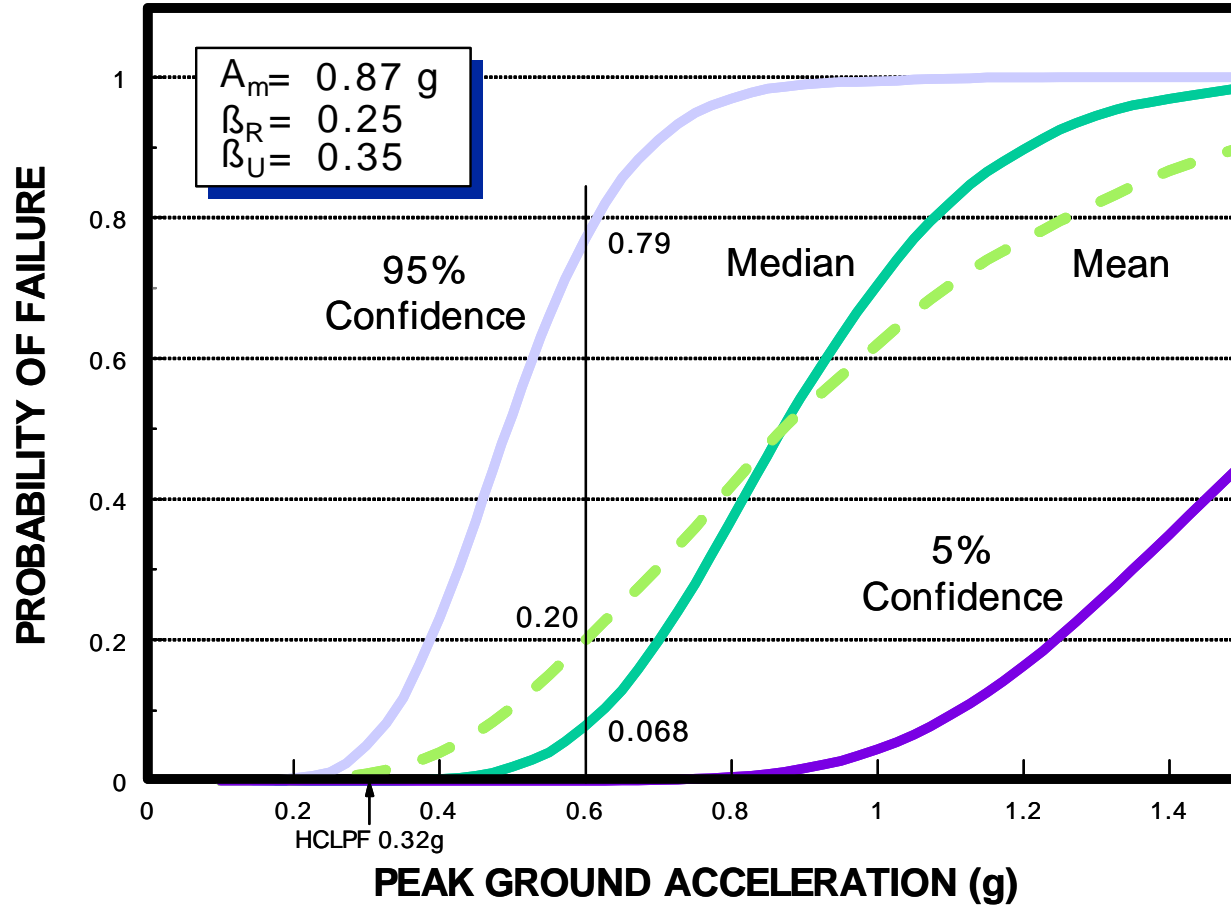
Key Elements of Seismic PSA

- Seismic Hazard Analysis
- Seismic Fragility Evaluation
- Systems Analysis
- Quantification

Seismic Probabilistic Safety Assessment



Seismic Fragility Curves



ASME/ANS Standard on External Event PRA Methodology 58.21-2007

- **Seismic PRA**
- Seismic Margin Assessment
- Screening of “Other” External Events
- PRA for High Winds

ANS Standard Development Team

- Writing Group:
 - Dr.R. Budnitz, Lawrence Berkeley Laboratory
 - Dr. N.Chokshi, USNRC
 - Mr. W. Henries, Maine Yankee
 - Dr. M.K. Ravindra, MK Ravindra Consulting; Current Chairman
 - Dr.J. Stevenson, S&A
 - Mr. T. Yee, Southern California Edison
- Risk Informed Standards Consensus (RISC) Committee
 - Dr Allen Camp, Sandia National Laboratories
- Extensive Review of Drafts by Peers

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”)

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 IPEEE and earlier PRAs.
- Commentary on each supporting requirement suggesting acceptable methods and references – a unique feature of the ANS standard

ANS External Events PRA Methodology

Standard ANSI/ANS 58.21

- Goal is beyond that of IPEEE
 - Risk-informed decisions vs identification of plant vulnerabilities
 - IPEEE corresponds to Capability Category I
 - Higher level requirements for Capability Category II and III
- High Level Requirements and Supplemental Technical Requirements
 - Hazard Analysis
 - Systems Analysis
 - Fragility Evaluation

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.
- **E – LOCAL SITE EFFECTS (HLR-HA-E):** The PSHA SHALL account for the effects of local site response.

High Level Requirements for Seismic Hazard Analysis

- **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.
- **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.
- **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.	
	<p>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.</p>		
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.		

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.
- **C – PLANT FIDELITY (HLR-SA-C):** The seismic-PRA systems models SHALL reflect the as-built and as-operated plant being analyzed.

High Level Requirements for Seismic PRA Systems Analysis

- **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.
- **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.

Example Systems Analysis Requirements

<p>SA-E2</p>	<p>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.</p> <p>Broad groupings MAY be used.</p>	<p>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.</p>
<p>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.</p>		
<p>SA-E3</p>	<p>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.</p> <p>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.</p>	
<p>SA-E4</p>	<p>In the integration/quantification analysis, ACCOUNT for all significant dependencies and correlations that affect the results.</p> <p>The analysis MAY use generic dependency and correlation values if justified.</p>	<p>In the integration/quantification analysis, ACCOUNT for all significant dependencies and correlations that affect the results.</p> <p>USE plant-specific dependency and correlation values throughout.</p>
<p>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.</p>		

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.

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.
- **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.

High Level Requirements for Seismic Fragility Evaluation

- **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.
- **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).		

Status

- Current version ANSI/ANS 58.21 (Revised 2007)
- Major issue was with the use of existing seismic hazard analysis
- Issue of excessive burden of complying with the Standard
- Pilot study on Surry is underway
- Recent applications: Krsko, Columbia Generating Station and Beznau
- Presently combined with Internal Events and Fire PRA Standards in the combined standard under balloting

Issues

- Screening:
 - External Events are screened out if their risk contribution is judged to be acceptably low
 - Seismically rugged components are screened out based on their low risk contribution
- The initiating events from earthquakes do have very low frequencies of occurrence.
- Seismic risk analysis if properly conducted strives to produce realistic estimates of CDF and LERF not conservative estimates
- Although the fragility model has not changed, the procedures and data have benefited from lessons learnt in actual earthquakes, qualification testing and seismic PRAs
- Seismic risk analysis emphasizes full treatment of uncertainties in all stages: hazard, systems and fragilities. Because of the nature of seismic hazard, large uncertainties are inevitable.
- The standard approach of presenting the variabilities in terms of “aleatory” and “epistemic” uncertainties is followed. The final probability distribution on seismic CDF is no “different” animal except it looks somewhat fat and stretched!

Seismic Margin Assessment of KK6

- Conducted as validation of design
- Walkdown performed by Ravindra and GE Nuclear Energy
- Focus on safety systems and components whose failure could lead to core damage and severe release
- High seismic margin (> 1.67 times S_2) demonstrated

Impact of Niigataken Chuetsu Earthquake

- Although S2 earthquake was exceeded, there was no significant damage to safety systems.
- Non-safety systems and components were not expected to survive such a large earthquake
- To gain confidence in the ability of KK units to survive severe accidents beyond design basis, seismic PSAs are recommended.
- Situation is similar to Diablo Canyon Nuclear Power Station in California, USA

Features of Detailed Seismic PSA

- Site specific seismic hazard study
- Seismic fragility analysis using plant specific design data and walkdown
- Systems analysis and quantification
- Conform to Japanese and ANS Standards
 - Documentation
 - Peer review