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IAEA-TECDOC-1937

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Probabilistic Safety Assessment for Seismic Events

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PROBABILISTIC SAFETY ASSESSMENT FOR SEISMIC EVENTS

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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 26007 22529
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
www.iaea.org/publications

For further information on this publication, please contact:

External Events Safety Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

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FOREWORD

One of the statutory functions of the IAEA is to establish or adopt standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes. The IAEA is also authorized to provide for the application of these standards to its own operations as well as to assisted operations and, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of nuclear energy.

This publication supports the implementation of IAEA Safety Standards Series No. NS-G-2.13, Evaluation of Seismic Safety for Existing Nuclear Installations, published in 2009. It provides a detailed methodology for seismic probabilistic safety assessment in line with the current international practices for seismic safety assessment of nuclear installations.

The methodology for seismic safety evaluation presented here includes probabilistic and deterministic approaches, as well as a combination of deterministic and probabilistic approaches. Their applications typically address the impact of beyond design basis seismic events.

The IAEA greatly appreciates the contributions of all those involved in the drafting and review of this publication. The contributions to the preparation of this publication provided by Y. Ohtori (Japan), M. Nakajima (Japan), T. Takada (Japan), J.J. Johnson (United States of America), R.D. Campbell (United States of America), D. Serbanescu (Romania), P. Amico (United States of America) and G. Hardy (United States of America) are gratefully acknowledged. The IAEA officer responsible for this publication was O. Coman of the Division of Nuclear Installation Safety.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Probabilistic safety assessment (PSA) is a comprehensive, structured approach to identifying failure scenarios, constituting a conceptual and mathematical tool for deriving numerical estimates of risk. PSA is used to evaluate risks associated with nuclear power plants, from concept definition, through design, construction and operation, and up to removal from service.

For the different types of nuclear power plants currently operating in the world, three levels of PSA are generally recognized:

- *Level 1 PSA* estimates the frequency of core damage;
- *Level 2 PSA* estimates the frequency of radioactive materials releases;
- *Level 3 PSA* estimates the societal consequences such as public health.

Results of the PSA studies worldwide have shown that external hazards in general, and seismic hazards in particular, can significantly contribute to the risk associated with the operation of nuclear power plants.

This TECDOC complements IAEA Safety Standards Series No. SSG-3, Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants [1], and IAEA Safety Standards Series No. NS-G-2.13, Evaluation of Seismic Safety for Existing Nuclear Installations [2], as a technical support publication providing information on consideration of seismic hazards in PSA. Specific terms used in this publication are to be understood as defined in the IAEA Safety Glossary [3] unless otherwise specified in the text.

1.2. OBJECTIVE

The objectives of this publication are:

- To provide details of the technical approaches used for developing Level 1 seismic PSA, consistent with SSG-3 [1] and NS-G-2.13 [2];
- To reflect the current state of practice in the area of seismic PSA, taking into account recommendations provided in IAEA safety standards and information reflected in internationally recognized technical standards (e.g. AMERICAN SOCIETY OF MECHANICAL ENGINEERS / AMERICAN NUCLEAR SOCIETY (ASME/ANS) probabilistic risk assessment standard [4]).

The publication is intended for use by nuclear power plant engineers, designers, consultants and safety analysts.

1.3. SCOPE

The scope of this publication covers the seismic PSA to be performed on nuclear power plants, at full power operation mode, to provide risk insights related to their seismic robustness. This publication provides technical elements and practical approaches on developing seismic PSA on the basis of an existing internal event PSA model.

1.4. STRUCTURE

This TECDOC is organized into ten sections, two appendices and two annexes.

Section 2 presents the general outline of the seismic PSA methodology. Section 3 discusses the probabilistic seismic hazard assessment process and results that have to be understood and used as input in the seismic PSA. Section 4 describes the development of the seismic equipment list, those items important to safety included in the seismic PSA model. Section 5 is devoted to the development of seismic fragility functions for the structures, systems and components, included in the seismic equipment list. Section 6 discusses the human reliability analysis needed to address operator actions, which may be credited to recover seismic induced failures. Section 7 discusses the elements of system analysis dealing with steps and tasks needed to be carried out in order to develop the seismic system analysis model based on the existing internal event PSA model. Section 8 outlines the scope and tasks of the peer review in accordance with Ref. [4]. Section 9 provides a brief description of interfaces with other external events PSA, such as tsunami PSA and multi-unit and multi-hazard safety assessments. Section 10 provides elements of seismic PSA support for the design of new nuclear power plants and/or upgrading of existing nuclear power plants, aimed to assess design robustness (seismic safety margin) consistent with the target safety goals. Appendix I presents examples of enhancements of the probabilistic seismic hazard assessment, using fault rupture modelling in conjunction with empirical approaches. Appendix II provides details of seismic walkdowns supporting fragility analysis tasks. Annex I presents the approach of the Japan Nuclear Energy Safety Organization (JNES) to the evaluation process for fragility capacity of equipment. Annex II presents the example approach for consideration of seismic context in human reliability analysis.

2. OUTLINE OF THE SEISMIC PROBABILISTIC SAFETY ASSESSMENT

The general approach of the seismic probabilistic safety assessment (SPSA) has been well established and practiced in the last decades, and the main principles are documented for example in SSG-3 [1], NS-G-2.13 [2], Ref. [4] and IAEA-TECDOC-1804 [5]. Additionally, these references describe the elements of the multi-disciplinary SPSA methodology. Specific references related to each element of the SPSA methodology, as well as the data requirements for implementation of the SPSA, are presented in this publication.

Seismic PSA differs from an internal event PSA (IEPSA) in the following points:

- Earthquakes could cause initiating events different from those considered in the IEPSA.
- All possible levels of earthquakes, along with their frequencies (or probabilities) of occurrence and their consequential damage to structures, systems and components (SSCs) of the plant, need to be considered.
- Seismic induced ground motions could simultaneously damage multiple redundant components. This major common cause failure effect needs to be appropriately accounted for.

The approaches provided in this section are based on the best practice available in Member States and constitute the example of seismic PSA development. Other quantitative and qualitative approaches, which are out of the scope of this publication, are available for the seismic risk assessment of nuclear power plants.

2.1. SEISMIC PROBABILISTIC SAFETY ASSESSMENT OBJECTIVES

The objectives of a seismic PSA include the following:

(a) To develop an appreciation of accident behaviour (i.e. consequences and role of operator);
(b) To gain understanding of the overall likelihood of core damage induced by earthquakes;
(c) To identify the dominant seismic risk contributors associated with earthquakes;
(d) To identify the range of peak ground acceleration (PGA) that contributes significantly to the plant risk;
(e) To compare seismic risk with risks from other events and establish priorities for addressing identified vulnerabilities.

2.2. OVERVIEW OF SEISMIC PROBABILISTIC SAFETY ASSESSMENT METHODOLOGY

Earthquakes can affect the plant site; the plant's SSCs important to safety; and auxiliary facilities in several ways, not limited to vibratory ground motion, but also resulting in soil liquefaction, landslides and tsunamis, as shown in Fig. 1.

This section provides an introductory overview of the seismic PSA procedure dealing with primarily the vibratory ground motion hazard. However, some secondary or associated effects (other than ground motion) need to be properly considered. Examples are seismic induced fire, flood, explosions, or hazardous material release to the environment; soil failure, such as liquefaction and slope instability; tsunami; and damage to items important to safety due to failure of items not important to safety (e.g. building collapses on items important to safety).

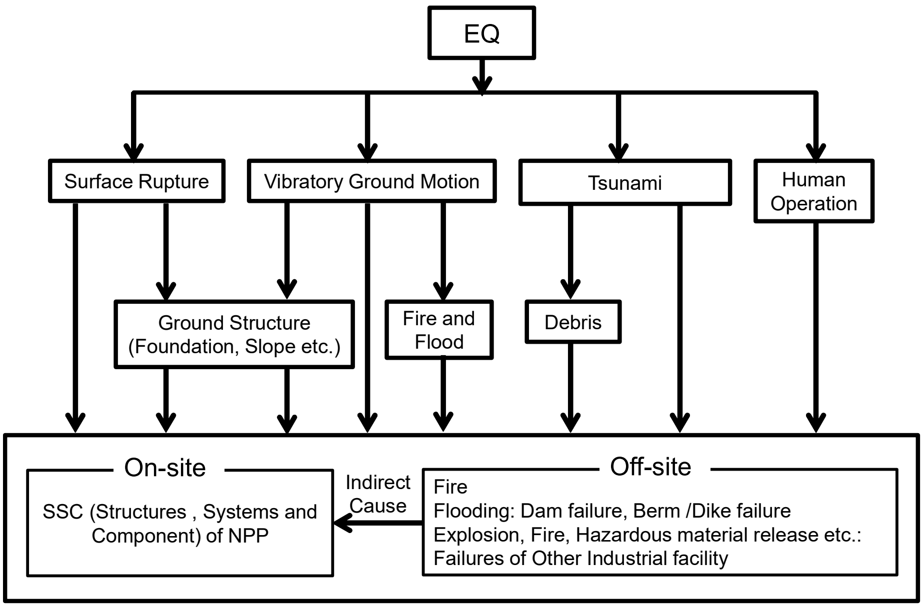

FIG. 1. Block diagram for earthquake (EQ) induced hazards.

This section intends to acquaint the reader with an overview and the various elements of the seismic PSA process, leaving detailed discussion of those elements for later sections. The framework presented in this section will foster the readers' understanding of the nature and purpose of the various features and procedures described in the following sections, permitting the reader to proceed directly to the sections of greater interest.

2.3. KEY ELEMENTS OF SEISMIC PROBABILISTIC SAFETY ASSESSMENT

The major technical elements of a SPSA are:

- Probabilistic seismic hazard assessment;
- Development of the seismic equipment list;
- Seismic fragility analysis;
- Seismic plant response analysis;
- Seismic risk quantification and interpretation of results.

2.3.1. Probabilistic seismic hazard assessment

Probabilistic seismic hazard is usually expressed in terms of the frequency distribution of the ground motion parameters (e.g. PGA or spectral acceleration). The different steps of this analysis are as follows:

- Development of the seismotectonic database;
- Selection of seismotectonic models;
- Characterization of seismic sources;
- Selection of attenuation relationships appropriate for the region, to estimate the earthquake induced ground motion (e.g. PGA) at the site;
- Site response analysis;
- Integration of the above information, using logic tree formalism for propagation of the uncertainties, to estimate the frequency of exceedance for selected ground motion parameters.

The probabilistic seismic hazard assessment (PSHA) results are expressed in terms of annual probabilities of exceedance of ground motion parameters. These results reflect two different classes of uncertainties. First, uncertainties resulting from limited knowledge ('epistemic uncertainties') that can, in principle, be further reduced through acquisition of additional data. Second, random uncertainties ('aleatory uncertainties') are those uncertainties that cannot be reduced.

Typical results of a PSHA include families of seismic hazard curves in terms of PGA and spectral acceleration values and site specific ground motion response spectra. A discussion of the methodology for developing PSHA is given in Section 3. Further recommendations on seismic hazard analysis methods is provided in IAEA Safety Standards Series No. SSG-9, Seismic Hazards in Site Evaluation for Nuclear Installations [6].

2.3.2. Seismic fragility analysis

Seismic fragility deals with the conditional failure probability of SSCs at a given range of values of ground motion. Seismic fragility is expressed as a function of the hazard parameter. The first step in generating fragility functions is to identify the failure modes of the SSCs listed in the seismic equipment list. Several failure modes could be considered for a given SSC, and fragility curves may have to be generated for each of these failure modes. Fragility functions can be defined by lognormal distributions, as described later in Section 5.

2.3.3. Seismic plant response analysis

The response of the plant to seismic induced failures is represented by the plant logic model. This model includes the seismic event trees that define the accident sequences triggered by seismic induced initiating events, and that are linked with the fault trees representing failure of mitigative functions (e.g. SSC failures or human errors). Generally, an SPSA model is developed on the basis of the IEPSA model. These internal events models are modified to include the seismic event trees, and the fault trees are modified to include seismic basic events and associated logic. A combination of event tree and fault tree approach is most commonly applied for seismic PSA in Member States.

2.3.4. Seismic risk quantification and interpretation of results

Seismic risk quantification is performed by integrating seismic hazard curves and families of fragility curves following the Boolean equations defined by the union of minimum cut sets[1]. The integration is conducted along with the non-seismic (or random) failures. In general, the result of the seismic risk quantification is represented as the core damage frequency (CDF) which is reported for all seismic induced initiating events. Seismic risk quantification typically provides the following major outputs:

- Frequency of seismic accident sequence occurrence;
- Impact of non-seismic induced unavailability on seismic risk;
- Contribution of initiating events to CDF;
- Dominant seismic acceleration ranges;
- Risk importance of SSCs and human failure events (considering seismic context);
- Seismic risk insights.

[1] Boolean summation of the cut sets

3. PROBABILISTIC SEISMIC HAZARD ASSESSMENT

The basic concept and methodology for seismic hazard evaluation is described in SSG-9 [6]. The objective of this section is to understand the PSHA results and how the PSHA meets the technical requirements consistent with the objective of the SPSA. The key elements of the PSHA that need to be reviewed against standard technical requirements [4] are presented in this section.

3.1. TECHNICAL ELEMENTS

In performing PSHA, the following technical requirements need to be met as defined in Ref. [4] addressing the technical aspects listed below:

- Scope of the PSHA;
- Data collection and development of seismotectonic models;
- Seismic source characterization;
- Selection of ground motion prediction equations (GMPEs);
- Uncertainties propagated and displayed in the final quantification of hazard estimates for the site;
- Site response;
- Secondary effects, such as fault displacement, landslide, soil liquefaction, or soil settlement, need to be included in the seismic PSA;
- Documentation.

3.2. SCOPE

A basic prerequisite for the conduct of a SPSA for a given facility located at a given site is the development of the site specific PSHA. The PSHA results are expressed in seismic hazard curves representing the annual frequency of exceedance for different values of a selected ground motion parameter (e.g. PGA, response spectral acceleration). A uniform hazard response spectrum (UHRS) (also designated as uniform hazard spectrum) is constructed on the basis of the hazard curves.

The seismic hazard curves and the UHRS are input data to the SPSA.

SSG-9 [6] lists the typical outputs from the PSHA, including the results of the computation of the mean annual rate of exceedance for the selected ground motion parameter and the associated variability of this rate at a particular site. The variability of the rate is due to uncertainty which can be attributed to both randomness (aleatory uncertainty) and to the lack of knowledge about the earthquake phenomenon affecting the site (epistemic uncertainty).

3.3. DATA COLLECTION

In conducting a PSHA, a comprehensive up-to-date database, as described in SSG-9 [6], is to be developed, including geological, geophysical, geotechnical and seismological data at the various geographical layers – region (300 km radius), near region (25 km radius), site vicinity (5 km radius), and plant site. Seismological data is derived from instrumental data, historical earthquake data, and paleoseismic data. Local site topography, surficial geologic data, and geotechnical site properties need to be compiled appropriately. This database is often referred to as the 'geological, geophysical, and geotechnical database'.

3.4. SEISMIC SOURCES AND SOURCE CHARACTERIZATION

To evaluate the exceedance probability (or frequency) of earthquake ground motions at the site, the PSHA examines all potential seismic sources. Each seismic source is characterized by the source type and geometry, seismic recurrence model and associated parameters and by the minimum and maximum magnitude. In performing a PSHA, both aleatory and epistemic uncertainties have to be considered in each process of the PSHA methodology.

3.5. GROUND MOTION PREDICTION EQUATIONS

Given a seismic source, including the definition of all important parameters as probability distributions, GMPEs are selected to represent the most appropriate relationships between the source and the site vicinity. GMPEs were formally referred to as ground motion attenuation relationships. GMPEs are used for earthquakes of certain magnitudes that can occur in specific locations to get realistic estimates of the site specific ground motion. Uncertainties, both aleatory and epistemic, need to be accounted for in the GMPE models.

3.6. LOCAL SITE EFFECTS

The effects of local site response are taken into consideration when conducting the PSHA. This is an extremely important element in defining the local site ground motion.

3.7. AGGREGATION AND QUANTIFICATION

Uncertainties inherent in each step of the PSHA are propagated and displayed when quantifying seismic hazard estimates for the site.

The results of a PSHA are expressed in fractile hazard curves which display median, mean, fractile percentiles, and ultimately a set of UHRS. For certain applications, the dominant seismic sources have to be detected by performing disaggregation of seismic hazards at a site. SSG-9 [6] provides further details in this regard.

3.8. SPECTRAL SHAPE

The UHRS are essential to defining the seismic demand for SSCs or input to the site response analyses. The spectral shapes are based on a site specific evaluation, taking into account the contributions of disaggregated magnitude-distance results of the PSHA. Broad-band, smooth spectral shapes may be also acceptable if they are shown to be appropriate for the site.

4. DEVELOPMENT OF THE SEISMIC EQUIPMENT LIST

In general terms, the SSCs that comprise the seismic equipment list (SEL) are those items that are identified to be modelled in the event trees and fault trees of the SPSA. Failure of one or more of these items may contribute to core damage or large early release (or both). The SEL is developed as a combined effort of the seismic systems analysts and the seismic fragility analysts.

The equipment list for the IEPSA is the starting point in development of the initial list of components that may potentially be important in the accident sequences for seismic events. The final SEL is the list of seismic basic events for which fragility parameters have to be determined. The final SEL will include only those components relevant for SPSA. This is achieved through an iterative process that consists of sequences of screenings and additions or eliminations. Figure 2 illustrates this screening process.

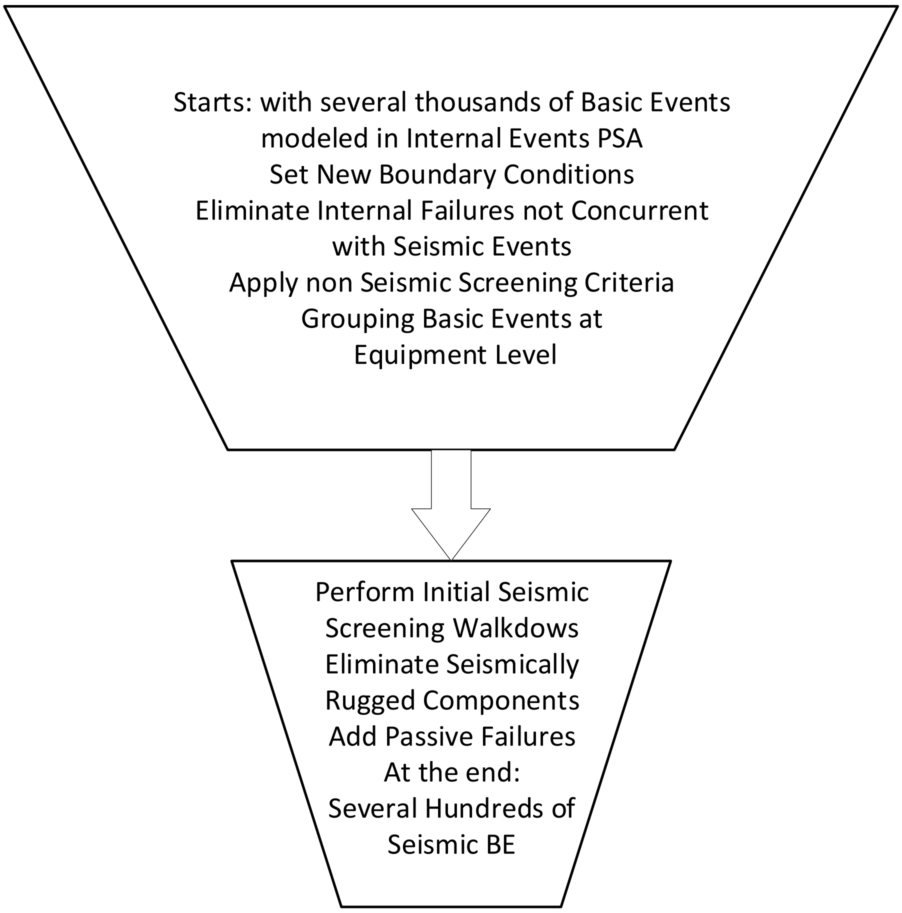

FIG. 2. Initial screening process.

The process of determining those components for which seismic capacity evaluation is described in the following subsections:

4.1. IDENTIFY POTENTIAL RISK SIGNIFICANT COMPONENTS

The process starts with the development of the candidate SEL, which includes all components considered in the IEPSA model, i.e. the list of all basic events in the IEPSA model.

This process is typically done as follows:

- Define the boundary conditions for SPSA.
- Group the internal seismic basic events at equipment/component level based on the defined boundary conditions.
- Add passive components that may have been screened out from the internal events model, but whose failure due to an earthquake could affect the safety functions modelled in the PSA; e.g. tanks, cabinets, cable trays, HVAC (heating, ventilation and air conditioning) ducting.
- Identify structures that house the SEL items and add them to the list.
- Review the emergency procedures for loss of off-site power and small loss of coolant accident, and add any additional equipment and instrumentation that would be needed after an earthquake.
- Add potential failures of unique site or plant equipment or features. These include, but are not limited to:

  - Dams whose failure could lead to flooding of the site;
  - On-site or off-site facilities in which hazardous chemicals or explosives are produced, processed, used or stored;
  - Additional items that may be significant in a seismic event, based on operators' and system engineers' review of the candidate SEL.

4.2. REVIEW COMPLETENESS AND CONSIDER SEISMIC INTERACTION

The candidate SEL is supported by initial plant walkdowns that focus on the identification of potential system interactions and reviewed by the plant operators and system engineers for completeness.

This review is performed consistent with the development of seismic initiating events and the development of seismic event trees (described in Section 6.4). The candidate SEL include all relevant SSCs involved in the analysis of seismic initiating events and the development of seismic event trees.

4.3. INITIAL SCREENING

There are two aspects of initial screening:

- Removal of SSCs that will be assumed to fail. These low capacity SSCs, and other SSCs that they support, will be set to fail in the SPSA model;
- Removal of SSCs that have very high capacity or are not relevant to the SPSA. These SSCs will not be modelled for seismic failure in the SPSA model, but random failure will be retained in the model if they were included in the IEPSA.

Screening of SSCs Assumed to Fail

If desired, it is reasonable to remove from the SEL those systems modelled in the PSA that are of low capacity or provide a minimum mitigation potential in the SPSA. These systems are usually the balance of plant systems that are not seismically designed (e.g. part of the component cooling system, instrument air, active equipment without backup power). If this is done, these systems are assumed to fail in the PSA model; therefore, care has to be taken because these systems do have some inherent capacity to survive an earthquake. In areas of relatively low seismic hazard, this could result in significant overestimation of risk at low earthquake excitation levels.

However, there are advantages in performing this part of the initial screening for high seismic hazard sites because the resulting initial SEL represents the SSCs for which a detailed walkdown will be performed. It is likely that many of these lower capacity SSCs will not contribute to the prevention of core damage or large early release of radioactive material at high hazard sites. That means that their seismic fragility would have to be evaluated, and this effort is resource intensive. For such sites, the reduction in the scope of the SEL is performed for the following reasons:

- Some non-seismically designed systems have generally low seismic capacity and provide little reduction of the frequency of damage states in the SPSA;
- Off-site power is usually of low capacity. It is a controlling event for the operation of systems without backup power following a seismic event;
- Non-seismically designed support systems that provide little seismic capacity for prevention of damage states or mitigation of their consequences. To assess their potential value in the mitigation of seismic events, several analyses are performed. These model runs are performed on the IEPSA

model and represent the conditional damage state frequencies with the systems assumed failed. This provides the PSA analyst with an order of magnitude estimate of the mitigation potential of these SSCs.

<u>Removal of SSCs with very high seismic capacity</u>

It is assumed that these items perform successfully as required in the systems model. Basic events that do not have an associated seismic failure mode (e.g. human failure events, maintenance) are removed. Multiple basic events for the same component (e.g. pump fails to start, and pump fails to run) are also removed. These failure modes are combined at the component level, i.e. the multiple basis events become a single component entry in the initial SEL. Finally, subcomponents, that are parts of a larger component and are likely to fail together, are subsumed into their larger component; for example, basic events for individual breakers are subsumed into the electrical cabinet (e.g. electrical bus) they are part of and therefore only the bus itself is listed as a component in the initial SEL.

Generic high capacity components are screened out. Both lists developed above are screened, based on generic seismic capacities. Those components which are considered rugged are screened out.

A design review and walkdown of all components, including those which have been screened out, is subsequently performed to verify seismic ruggedness and potential seismic interactions.

The generic screening notes used to obtain the initial SEL and the screened out basic events for the SPSA model are summarized in Table 1.

The subsequent sections will discuss the remainder of this process, covering the detailed walkdown process and the development of the fragility curves.

TABLE 1. EXAMPLE OF GENERIC SCREENING NOTES

Number of Note	Note
Note 1: Inadvertent valve transfer	Inadvertent valve transfer is used to screen those valves that are modelled as inadvertent valve transfers. In the case of manual valves, this includes all basic events that are transfer open and transfer closed failure modes. Manual valves are seismically rugged except for spatial interaction effects. For powered valves (air operated, motor operated or solenoid valves), only those valves that fail in a safe position on loss of supporting systems are screened out.
Note 2: Check valve failures	Check valves are seismically rugged (due to the nature of check valve operation) and are screened from further consideration.
Note 3: Failure of passive components resulting in loss of system integrity	The piping associated with the systems and components of interest are assessed as part of the assessment of the fragility associated with the major component such as pump or heat exchanger.
Note 4: Failure of passive components that results in system blockage	Failures that are the result of heat exchanger blockage, filter blockage, demineralizer and strainer blockage are screened out. Seismic events do not generally result in the failure of filters or strainers. Heat exchangers can be screened only for the blockage failure mode. If no other failure modes are modelled (i.e. rupture), the heat exchanger entry in the SEL is retained.
Note 5: Failure of inactive electronic components	This class of components includes push button switches and temperature elements. With no active parts, these components are considered seismically rugged and screened out. Absence of spatial interactions needs to be confirmed.
Note 6: Other sensors	This class of components includes flow transmitters, level and pressure switches, and level and pressure transmitters. These components are considered seismically rugged and inadvertent actuation is the most probable seismic failure mode. Inadvertent actuation results in initiation of safety systems and, therefore, system success. These components are screened out. It is important to note that, although the individual components can be screened out, the component still needs to be walked down to ensure that the cabinets, instrument racks or other supporting structures are sufficiently seismically rugged.
Note 7: Fail-safe components	This category of components includes only bi-stables, various DC power circuit breakers and turbine stop, and control valves required to trip either the reactor or turbine. A seismic event is assumed to result in a turbine trip and, therefore, stop and control valves are assumed successful. In the case of reactor protection system bi-stable and DC circuit breakers, the most probable failure mode of these fail-safe electronic components is to the actuated position. The actuated position of the reactor protection system results in a reactor trip. These components are screened.
Note 8: Relays and control circuitry, including nuclear instrumentation	Control circuits (solid state) are assumed to be seismically rugged. For relays, this is not a screening for relay chatter, which is a separate assessment.

TABLE 1. EXAMPLE OF GENERIC SCREENING NOTES (cont.)

Number of Note	Note
Note 9: Fuses	Fuses are screened on the basis of a high degree of seismic ruggedness. In general, fuses are located within the panels and buses for which seismic capacities are calculated. They are therefore bounded by the seismic capacity of the respective panel or bus.
Note 10: Circuit breakers	Circuit breakers are contained within switchgear for which seismic capacities are calculated and are bounded by the seismic capacity of the switchgear that are analysed. Therefore, circuit breakers are included in the switchgears.
Note 11: Duplicate entries	Items that appear more than once in the component database can be screened out. For example, components that have multiple random failure modes modelled within the PSA need only be listed once on the SEL. The development of separate fragilities is not necessary.
Note 12: Piece or part components	Items identified in the component list with this seismic note are those that are pieces or parts of a larger component for which a seismic capacity is determined. Since the seismic capacity evaluation is based on the weakest operational piece/part or anchorage of a component, these items are evaluated with the larger component and screened out in this list. To ensure completeness, the 'category' column indicates the larger component designator in which the item is considered for seismic evaluation.
Note 13: Operator action	The impact of seismic failure is subsumed within the hardware failure for these items. That is, the hardware that is used by the operator will be considered for seismic fragility, and in general will be sufficient to cover the seismic effect on the operator action.
Note 14: Test or maintenance, common cause failures and flags	Eliminate the testing, maintenance and common cause failure basic events as well as any house or flag events. The possibility of increase in the human error probability because of an earthquake will also be considered for cases where the operator action is required shortly after the earthquake and the equipment required is seismically rugged. However, this is not considered to be part of the SEL.
Note 15: Related to other hazards	Basic events that were added for analysis of other hazards, such as internal fire, flood impacts, or high winds (these may also fall under the 'duplicate entries' note).
Note 16: Legacy entries	Basic events that represent things such as equipment no longer in the plant, equipment no longer credited in the model, etc.

5. SEISMIC FRAGILITY EVALUATION

5.1. TECHNICAL ELEMENTS

The seismic fragility evaluation of SSCs is one of the key elements of a SPSA. Seismic fragility functions are defined as the conditional probability of failure given a ground motion hazard parameter. The outcome of the seismic fragility evaluation is a family of fragility curves defining conditional probability of failure, function of the ground motion parameter. Most often, fragility functions are defined by lognormal distributions, as described later in this section. Each fragility curve, or family of fragility curves, is defined by a median value and a double lognormal function with variability (aleatory and epistemic uncertainty) defined by lognormal standard deviations.

The following technical elements need to be properly addressed:

- The seismic fragility evaluation needs to include all SSCs whose failure may contribute to core damage or large early release.
- The seismic fragility evaluation needs to be based on a seismic response severity experienced by the SSCs in the vicinity of failure.
- The basis and methodologies used to establish fragilities for SSCs need to be well defined.
- The information and data of plant walkdown(s), to establish or confirm as-built and/or as-operating conditions for SSCs, need to be considered.
- The seismic fragility analysis needs to be performed for relevant failure modes modelled in the plant response analysis.
- The documentation of the seismic fragility analysis needs to ensure traceability of the work.

Considering that a seismic fragility evaluation is resource intensive and time consuming, it is typically carried out in two stages:

1. Screening of seismically rugged SSCs and preliminary fragilities are developed using generic data and available design information.
2. For risk important contributors (resulting from initial seismic risk quantification), a detailed fragility evaluation using the separation of variables approach is performed.

Screening of the number of SSCs for which detailed fragility functions are required needs to be performed. Screening of high capacity (low fragility) is the most useful technique in reducing the number of required detailed fragility functions.

The ASME/ANS probabilistic risk assessment standard [4] provides a set of technical requirements for the seismic fragility methodology and implementation.

5.2. SEISMIC EQUIPMENT LIST AND SEISMIC SCREENING

5.2.1. Screening criteria

Reference [4] states that the seismic risk screening level has to be sufficiently high so that the contribution to CDF and large early release frequency (LERF) from the screened-out components is not significant (less than 5% of total CDF). The basis and methodologies established for implementing the capacity based screening out of SSCs from further fragility analysis needs to be documented.

Two different types of screening levels have been discussed in the technical literature concerning SPSA and seismic margin studies:

- Seismic Risk Screening Level: Seismic fragility levels may be established that are justified to be sufficiently high that the components can be eliminated from the plant logic model on the basis of their low probability of failure having negligible effect on the overall seismic risk.
- Generic Seismic Capacity Screening Level: Generic seismic high confidence of low probability of failure (HCLPF)[2] capacities of many types of SSCs were established within Tables 2-3 and 2-4 of EPRI NP-6041-SL [7]. In some earlier SPSAs, these generic HCLPF capacities were used to screen out SSCs from the risk model without demonstrating that their contribution to seismic risk was not significant. In other cases, these seismic HCLPF capacity levels have been used to develop simplified fragility estimates for use in the risk model, typically by adding the screening level fragility as a surrogate element to each accident sequence to account for SSCs that were not modelled.

Reference [8] recommends that the capacity based screening level be such that the probability of failure is about 5×10^{-7}/y or, alternatively, that the screening level HCLPF be about 2.5 times the design ground motion response spectra.

EPRI NP-6041-SL [7] provides screening tables relative to ground motion. EPRI 1019200 [9] supplements the ground motion screening basis in Ref. [7] to provide HCLPF and median capacity spectral acceleration values for comparison with in-structure

[2] HCLPF is probabilistically defined as the 95% confidence of a 5% probability of failure or, equivalently, a 1% mean probability of failure.

response spectra (ISRS). This procedure requires that ISRS be developed before any screening can be conducted.

Use of the ground motion screening tables in Ref. [7] for nuclear power plants with high seismic design has somewhat limited value in assessing beyond design basis earthquakes in a SPSA; usually, sources of information on higher excitation levels are necessary for development of fragilities.

5.2.2. Screening walkdown

EPRI NP-6041-SL [7] provides seismic capacity criteria based on walkdown observations and screening caveats, a description of the seismic walkdown process, evaluation of anchorage, identification of systems interactions and the qualifications of walkdown personnel. Tables 2-3 for structures and 2-4 for equipment of Ref. [7] provide screening criteria for evaluating SSCs relative to horizontal ground motion spectral acceleration (S_a). The screening levels within these tables are HCLPF values and are intended to cover the entire frequency range of the ground motion spectra. Two seismic capacity review levels are provided in Ref. [7]. The first one is less than 0.8 g S_a, and the second one is from 0.8 g S_a to 1.2 g S_a. The two screening ranges are generally considered to be 0.8 g S_a and 1.2 g S_a, respectively. Any level beyond 1.2 g S_a requires a specific calculation. The caveats for HCLPF capacity of SSCs are almost identical for both levels, and the higher 1.2 g S_a level is typically utilized in developing the HCLPF for most SSCs.

The ground motion screening levels in Ref. [7] are intended for SSCs mounted at or below 40 feet above grade level. EPRI 1019200 [9] provides alternate capacity evaluation criteria based on ISRS demand. These alternative criteria are intended for screening of SSCs that are more than about 40 feet above grade level. Provided that the walkdown screening caveats in Tables 2 to 4 of Ref. [7] are met, the HCLPF level relative to ISRS is 1.5 times the ground motion capacity level in Ref. [7]. The capacity levels given in Ref. [9] can also be applied to SSCs at lower elevations. Clipping of sharp spectral peaks of the ISRS is also applicable.

5.2.3. Screening levels

Candidate HCLPF and associated median capacity values developed from the walkdown screening can be convolved with the seismic hazard curve to determine the probability of failure for the candidate screening level; although, this does not determine the sensitivity of the SSCs relative to the overall plant risk, it does provide useful guidance to the risk analysis team for consideration in the early development of the risk model.

From early parametric studies, the seismic systems analysts who develop the risk model will have some insight on which SSCs are the most governing and may be able to screen out some low contributors even if they have relatively high probability of seismic induced failure. There are also some inherently rugged SSCs that can be screened out by observation. These inherently rugged SSCs may include check and manual valves, pressure transmitters and small wall mounted distribution panels.

This first screening activity only requires that the site specific UHRS and the SEL are available. Generic fragilities and the associated probabilities of failure can be developed and submitted to the risk analysis team for preliminary evaluation of relative contribution to risk. The probability of failure of SSCs that meet the criteria in Ref. [7] may be relatively high compared to an overall seismic risk goal. However, if an SSC is not an important risk contributor, then it may be screened out from further consideration based on this simple approach.

The LERF goal is an order of magnitude lower than the CDF. However, failure of most SSCs evaluated during the walkdown seismic capacity screening will not automatically result in a large early release. Therefore, the initial screening of SSCs by walkdown are usually focused on CDF.

5.3. SEISMIC RESPONSE ANALYSIS

Seismic fragility methodology is comprised of two elements: seismic response of SSCs and seismic capacity of SSCs when subjected to the seismic demand. Seismic response of SSCs is conditional on an earthquake occurring for the range of the seismic hazard at the plant site.

Seismic response of structures serves two purposes: seismic response as input to systems, components, equipment and commodities supported on or within the structure; and seismic response as input to the structure fragility function development.

Seismic response of systems, components, equipment and commodities defines the seismic demand to be imposed on these items for fragility function development.

Currently, the seismic hazard is most often defined by seismic hazard curves specifying the annual probability of exceedance (or occurrence) of a ground motion parameter, such as PGA, peak ground velocity (PGV), spectral acceleration at various natural frequencies, or other ground motion descriptors. Section 3 summarizes the PSHA process. Appendix I presents additional thoughts on current and future approaches to developing the ground motion input for the SPSA.

Stated succinctly, the seismic response element in the SPSA process is to calculate the best estimate or median-centred response of the SEL items conditional on an earthquake producing a probabilistically defined ground motion at the plant site. In addition to median values of seismic response, variability in the seismic response needs to be considered.

5.3.1. Probabilistic response analyses

The methodology is based on analysing SSCs for simulations of earthquakes defined by acceleration time histories at appropriate locations within the plant site. Modelling, analysis procedures, and parameter values are treated as best estimate with uncertainty explicitly introduced. For each simulation, a new set of soil, structure, and subsystem properties are selected and analysed to account for variability in the dynamic properties of the soil/structure/subsystems.

Soil-structure interaction analysis of the plant structures of interest is performed. The outputs from the soil-structure interaction analysis are probability distributions of in-structure responses for fragility analyses (e.g. loads, ISRS, expected cycles for fatigue evaluation) and acceleration time histories for input to subsystems. Multi-supported subsystems, such as piping systems, are analysed by multi-support time history analysis procedures. Probability distributions of stress are generated as the fragility parameters for piping systems. These new seismic response analyses calculate seismic responses as distributions conditional on an earthquake of a given magnitude occurring at the site.

5.3.2. Deterministic response analyses

The objective of determining median-centred seismic response may also be achieved through deterministic analyses.

End products are estimates of the median-centred seismic demand. These median-centred responses will be combined with variabilities assigned to them based on previous probabilistic analyses and engineering judgment.

5.3.3. Scaling seismic design response

An alternative and simpler approach to probabilistic or deterministic response analyses is to apply the so-called ‘factor of safety’ method. The factor of safety method is based on applying safety factors or scale factors which remove excess conservatism (and correct for a lack of conservatism, if necessary) from the calculated seismic response during design. Ground motion distributions are used to formulate seismic response, most commonly in terms of PGA. Furthermore, these distributions (in terms of the same ground motion parameter) are used to define the capacities of SSCs and equipment.

This method has evolved over the last 35 years, adding sophistication and coupling with probabilistic and deterministic reanalyses. In general, scale factors are developed removing conservatism from the calculated responses for the seismic design. The implementation is conditional on a ground motion level defined by the PSHA, i.e. the UHRS.

The generalized form of the factor of safety is:

$$A = F \times A_{DBE} \tag{1}$$

where A represents SSC best estimated seismic capacity expressed function of the ground motion parameter (e.g. PGA), A_{DBE} is a design ground motion parameter, and F represents the factors of safety of the SSC of interest:

$$F = F_C \times F_{RS} \times F_{RE} \tag{2}$$

where F_C is the capacity factor, F_{RS} is the structural response factor, and F_{RE} is the equipment response factor. F_{RE} applies to the seismic demand imposed on subsystems.

The median factor of safety, F_m, is related to the median PGA capacity, A_m, as:

$$F_m = A_m / A_{DBE} \tag{3}$$

Developing new ISRS utilizing median centred parameters is expected to be one of the most beneficial undertakings in identifying seismic capacity for earthquakes above the design basis earthquake. In many cases, the new in-structure spectra will need to be developed using new analyses rather than by scaling. Scaling ISRS is, in general, much more complex than scaling structural loads. Scaling factors are calculated based on ratio of amplification variation due to differences between spectral shape, damping, etc. The following elements need to be considered:

- Change of the ground response spectrum shape;
- Change of the building damping;
- Change of the equipment damping;
- Wave incoherence;
- Limited global structural ductility.

The ISRS scaling methodology is also presented in Section 3.3.3.3 of IAEA-TECDOC-1333 [10], and in Ref. [9].

5.4. SEISMIC FRAGILITY MODEL

The mean PGA at either the 10 000 year or 100 000 year return period is usually used as the reference acceleration parameter, and the structural response analysis is conducted for the reference earthquake. This publication will refer to the use of mean PGA as the reference earthquake parameter, A_{REF}.

The entire fragility family for a structure or component, corresponding to a failure mode, can be expressed in terms of the median PGA capacity, A_m, and two random variables, ε_r and ε_u. The probabilistic PGA capacity, A, is expressed as follows:

$$A = A_m \times \varepsilon_r \times \varepsilon_u \tag{4}$$

The variables ε_r and ε_u represent the aleatory uncertainty (randomness) about the median and the epistemic uncertainty (lack of knowledge) in the median value, respectively. In this model, they are assumed to be lognormally distributed with unit medians and logarithmic standard deviations β_r and β_u, respectively. These aleatory and epistemic uncertainties are generally referred to as randomness and uncertainty and the latter nomenclature is used in this publication.

The lognormal model of the fragility function is defined by:

$$F(a) = \emptyset[\frac{\ln(\frac{a}{A_m} + \beta_u \emptyset^{-1}(Q))}{\beta_r}] \tag{5}$$

$$F(a)mean = \emptyset[\frac{\ln(\frac{a}{A_m})}{\beta_C}] \tag{6}$$

where:

A_m = median capacity

a = hazard parameter (e.g. PGA)

β_u = logarithmic standard deviation for uncertainty

β_r = logarithmic standard deviation for randomness

$\beta c = (\beta_r^2 + \beta_u^2)^{1/2}$

Ø = normal distribution operator (Ø-1 inverse normal distribution operator)

Q = confidence level (e.g. Q = 0.95, 0.5 or 0.05)

Figure 3 shows schematically a family of seismic fragility curves.

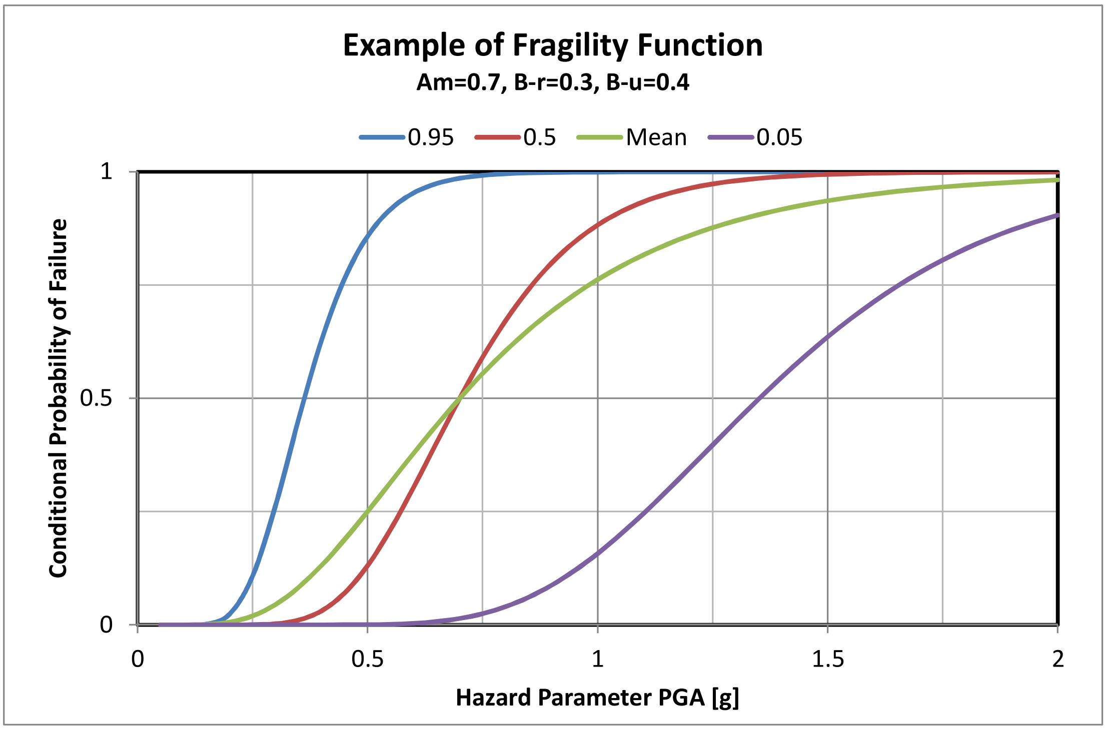

FIG. 3. Schematic illustration of a family of seismic fragility curves.

The HCLPF capacity, is defined as the ground motion at which there is 95% confidence that the probability of failure is less than 5%. The HCLPF capacity is expressed mathematically as:

$$HCLPF = A_m\left[e^{-1.65(\beta_r+\beta_u)}\right] \tag{7}$$

For purposes of calculating a point estimate of probability of core damage, single fragility curves with variability β_C are often used. In this case, the single fragility curve is considered to be a mean fragility curve and the HCLPF value is defined as the 99% confidence value of the single fragility curve:

$$HCLPF = A_m\left[e^{-2.33\beta_C}\right] \tag{8}$$

5.5. SEISMIC CAPACITY WALKDOWN

Plant seismic walkdown is an integral part of a successful seismic PSA project. It is performed by fragility experts in order to document the condition of equipment in the plant and make judgments on whether equipment can be screened out from the risk model based on inherent ruggedness or needs to be considered further for development of fragilities either by simplified methods or by more detailed analysis. Seismic walkdown is typically performed following the walkdown guidance provided in Ref. [7]. The walkdown team consists of seismic experts, one or more members of the seismic PSA modelling team, and plant systems and maintenance personnel as needed. The walkdown is typically conducted for all SSCs on the SEL. The objectives of the seismic walkdown are as follows:

1. Expand or reduce the SEL that is being considered for seismic fragility evaluations.
2. Screen from the SEL those equipment items that have high seismic capacity and, consequently, not significantly contribute to the seismic core damage frequency.
3. Identify equipment or structures that are not included in the SEL but whose structural failure may impact nearby SEL items (i.e. seismic interaction concerns).
4. Define failure modes (e.g. functionality, structural integrity, or anchorage failure) for the SEL items that are not screened out and identify the type of further evaluation required.
5. Review issues related to seismic induced fire, seismic induced flooding, and actuation of fire suppression systems.

Additional details regarding the procedures for seismic capacity walkdowns are presented in Appendix II.

5.6. PRELIMINARY FRAGILITY EVALUATION

Preliminary fragilities can be developed from seismic experience without having to conduct detailed fragility analyses. These preliminary fragilities may be used in the screening process or may be adapted for the final SPSA. These estimates are efficient but may be too conservative for the final risk analysis.

5.6.1. Generic fragilities based on seismic experience and ground motion

Data on the earthquake performance of several generic categories of mechanical and electrical equipment in power plants and heavy industrial facilities demonstrates that they are capable of withstanding significant ground motion levels without functional damage, provided that certain conditions are met.

Earthquake experience data also form (in part) the basis of screening guidelines for seismic margin assessment recommended by EPRI NP-6041-SL [7]. Many categories of equipment may be considered to have a HCLPF capacity up to 1.2 *g* peak 5% damped ground spectral accelerations, provided that the conditions noted in Table 2-3 or 2-4 of Ref. [7] are satisfied. This HCLPF level ground spectral acceleration is determined at a level where the peak ground motion spectral acceleration matches the maximum spectral acceleration capacity of the extended reference spectrum.

This simple method of developing seismic experience based fragilities relative to ground motion is limited, and often fragilities for SSCs developed in this manner are too low for the SSC to be totally screened out from the risk model. However, they can be useful for the seismic systems analysts for use in preliminary risk calculations to determine the relative risk significance of various SSCs.

5.6.2. Generic fragilities based on seismic experience and structure response

The reference EPRI 1019200 [9] provides recommendations for the determination of median spectral acceleration capacities for equipment based on ISRS rather than ground response spectra. These recommendations can be summarized as follows:

- For ground mounted items, the HCLPF capacity for equipment may be taken as C_{HCLPF} = 1.1 × RS and the median capacity for equipment may be taken as C_m = 2.85 × RS. The reference spectrum of the Seismic Qualification Utility Group (SQUG) has a value RS = 1.2 g, which makes the HCLPF capacity C_{HCLPF} = 1.3 g and the median capacity C_m = 3.4 g, to be used for equipment screening and fragility estimates, respectively. These values may be conservatively compared to either free-field demand levels or clipped in-structure demand levels.
- For structure mounted items, the HCLPF capacity for equipment may be taken as C_{HCLPF} = 1.5 × RS and the median capacity for equipment may be taken as C_m = 4.0 × RS. Using the SQUG Reference Spectrum value RS = 1.2 g, the resulting HCLPF capacity is C_{HCLPF} = 1.8 g and the median capacity is C_m = 4.8 g, to be used for equipment screening and fragility estimates, respectively. These values are to be compared to clipped in-structure demand levels.

The median seismic capacity for functional failure of equipment, satisfying the caveats of the SQUG generic implementation procedure (GIP) [11] and the 1.2g HCLPF level of EPRI NP-6041-SL [6] is defined as four times the bounding spectrum. This bounding capacity spectrum has a spectral peak of 4.8 g and is compared to the ISRS at the equipment support location.

The equipment capacity factor (or reference earthquake scale factor), F_{cap}, for equipment functional failure is determined as the scale factor on the clipped median ISRS at which the scaled demand reaches the median capacity represented by the extended capacity spectrum:

$$F_{cap} = 4 \times RS/ISRS_{clip} \tag{9}$$

The recommended variability in Refs [9, 12] for F_{cap} is β_{cap} = 0.42. This includes the randomness and uncertainty in equipment strength and equipment response. Equipment strength and response characteristics are implicit in the extended capacity spectrum; therefore, explicit determination of equipment response and capacity variability is unnecessary.

A breakdown of the randomness and uncertainty in the above variability $\beta_{c\text{-}cap}$ is not provided. Based on Table 3-14 of EPRI TR-103959 [13], the logarithmic standard deviation for randomness, $\beta_{\mathrm{R,cap}}$, of the equipment capacity factor for functional failure is estimated to be 0.09. The logarithmic standard deviation for the uncertainty is determined as follows:

$\beta_{\mathrm{U,cap}}$ = Lognormal standard deviation for uncertainty of the equipment capacity factor for functional failure

$$= (\beta \mathrm{c}^2 - \beta_{\mathrm{R,cap}}{}^2)^{1/2}$$

$$= (0.42^2 - 0.09^2)^{1/2} = 0.41$$

The above approach is appropriate only for earthquake experience based evaluation of failure of the equipment to function after the earthquake. Functional failure during the earthquake of potentially sensitive electro-mechanical devices, such as relays and motor starters, may be lower. In such cases, the functional capacity during the earthquake shaking has to be verified by other means, or the functional failure during the earthquake has to be acceptable based on electrical circuit analysis and/or operator recovery. This approach does not address failure of equipment anchorage. Fragility evaluation of equipment anchorage is usually performed by analysis.

According to EPRI TR-102470 [14], even a very small inelastic deformation in an SSC or its anchorage results in a response that is reduced from the elastic response; thus, the input spectrum for an elastic analysis can effectively be reduced. Appendices B4 and B5 of EPRI 1002988 [11] give an example of a fillet weld and the effective reduction of the input spectrum for evaluation of the fillet weld. The derivation of the reduction in the spectrum that would apply to SSCs and anchorage includes a reduction in the ground motion due to ground motion incoherence and a further effective reduction in ground motion due to high frequency inelastic deformation. Current software for soil-structure interaction analysis can include the ground motion incoherence effects but software used for elastic fixed base analysis of structures does not include ground motion incoherence provisions. The effective reduction of spectra for small inelastic deformations at high frequency requires an analytical effort that is usually not expended in fragility calculations. However, such effort is a viable option for critical cases for which modifications in hardware to reduce seismic risk are not practical.

In summary, potentially brittle anchorage and relay type devices need to be evaluated assuming elastic response. If potentially brittle anchorage failures are dominating the seismic risk, then the more elaborate methods in Appendices B4 and B5 of EPRI 1002988 [11] can be used to effectively reduce the high frequency input motion to account for the limited inelastic response of the SSC. The reduction of spectra for relay evaluation is controversial and use of elastic spectra for comparison with test response spectra (TRS) or generic equipment ruggedness spectra (GERS) is the recommended approach.

If the ISRS were developed for the reference earthquake using damping appropriate for the development of ISRS, the structural response factor is unity. The capacity factor is then multiplied with the structural response factor and the reference earthquake level to obtain the PGA capacity:

$$A_m = F_{cap} \times F_{RS} \times A_{REF} \tag{10}$$

The uncertainties in the structural response factor are then be combined by the square root of sum of squares (SRSS) method with the uncertainties in the extended capacity spectrum:

$$\beta_r = \left({\beta_{r,RS}}^2 + {\beta_{r,SAS}}^2\right)^{1/2} \tag{11}$$

$$\beta_u = \left({\beta_{u,RS}}^2 + {\beta_{u,SAS}}^2\right)^{1/2} \tag{12}$$

5.6.3. Hybrid method of fragility development

If a HCLPF is calculated directly by the updated conservative deterministic failure margin method described in EPRI 1019200 [9], a median capacity can be estimated using an assumed β_C:

$$A_m = HCLPF\left(e^{2.33\beta_C}\right) \tag{13}$$

The current methodology of calculation of HCLPFs is documented in Ref. [9]. Values for β_u, β_R, and β_C are recommended in Ref. [8]. This is a simplified method that can be used for preliminary analyses of risk and if the SSC is not a dominant contributor then it may suffice for the final safety analysis.

5.6.4. Fragility scaling techniques

In some SPSAs, multiple analyses of CDF have been conducted for different UHRS associated with de-aggregation of the earthquake sources. If fragilities are developed by the methods described in Sections 5.6.1 to 5.6.3 or by the more detailed method discussed in Section 5.7, a single fragility calculation is usually conducted for the most dominant UHRS and fragilities for other de-aggregated UHRS are scaled. The scaling is usually based on the expected difference in structural response unless the equipment is ground mounted. Without conducting new structural analyses for the different UHRS, a simple scale factor can be developed by comparing the spectral acceleration of the different UHRS at the fundamental frequency of the soil-structure system. This assumes that all response is in a single mode and is approximate but may be acceptable if the SPSA is conducted accounting for the difference in site UHRS and annual frequency for different earthquake sources. For fixed base structural models, the scaling can be more detailed using the mode shapes, frequencies and participation factors. The use of de-aggregated UHRS is typically not done but is an option for some sites that have significant contribution to site ground motion from more than one dominant seismic source.

5.7. DETAILED FRAGILITY EVALUATION

The development of seismic fragilities follows the separation of variables approach described in EPRI TR-103959 [13]. The fragility model is described herein. The fragility description is represented by a lognormal cumulative distribution function of conditional probability of failure versus a reference ground acceleration parameter. The variability is lognormal and is broken down in aleatory and epistemic uncertainty, represented by lognormal standard deviations β_r and β_u, respectively.

In the separation of variables approach, each variable affecting structural and equipment capacity and structural and equipment response is assigned a factor that represents a scale factor to achieve median capacity or median response associated with the variable. The factors are multiplied together to obtain an overall factor that is then multiplied by the reference earthquake acceleration, A_{REF}, to achieve the median value of the fragility. The β_Rs and β_Us representing the aleatory and epistemic uncertainty are combined by the SRSS method to determine the overall aleatory and epistemic uncertainties. Fragilities for structures are developed by analysis whereas fragilities for equipment can be developed by analysis, from qualification test data or from generic test data. The reference earthquake referred to in this publication is anchored to PGA, although spectral acceleration at a given frequency or averaged over a frequency range can be used as well.

Many of the factors and their variabilities are subject to expert judgment of the seismic fragility analysts. It is impossible to describe in detail the exact value to be used for aleatory and epistemic uncertainties of each important variable. Typical ranges are provided and without doing extensive analysis; instead, seismic response and structural and equipment capacities are defined by expert judgement. Realistic estimates are to be made instead of compounding conservative estimates. The realistic estimates will tend to average out and compensate for any high or low individual estimates. Since the aleatory and epistemic uncertainties are combined by the SRSS method, bias in a few estimates of uncertainty does not have a significant effect on total uncertainty or calculated seismic risk.

5.7.1. Structure fragility evaluation

The median PGA capacity of all structures, components and distribution systems is developed relative to the PGA of the reference earthquake, A_{REF}. In cases where the ground motion input to the different structural models is based on different soil profiles with corresponding UHRS, the fragility is first calculated relative to the UHRS input motion for the applicable profile and then scaled to the reference earthquake PGA. The scaling to the reference earthquake PGA may be conducted using spectral accelerations or PGAs as appropriate. The choice will depend on the spectral shapes of the respective foundation input motions and the dominant structural frequencies. For PGA scaling, the scale factor is the ratio of the reference earthquake PGA divided by the PGA of the input motion. For spectral acceleration scaling, each case is examined individually, and decisions are made on the representative frequency range of the structural response and the amplification of PGA in that frequency range as compared to the UHRS for the reference earthquake.

Following the separation of variables approach, the median PGA capacity, A_m, is related to the PGA for the reference earthquake, A_{REF}, as follows:

$$A_m = F_C \times F_{RS} \times A_{REF} \tag{14}$$

where:

F_C = Median capacity factor

F_{RS} = Median structure response factor

With the properties of the lognormal distribution, the logarithmic standard deviations for randomness and uncertainty, β_r and β_u, are expressed as follows:

$$\beta_r = (\beta_{r\_C}^2 + \beta_{r\_RS}^2)^{1/2}$$

β_u $= (\beta_{u\_C}^2 + \beta_{u\_RS}^2)^{1/2}$

β_{r_C} = Lognormal standard deviation for randomness of the capacity factor

β_{u_C} = Lognormal standard deviation for uncertainty of the capacity factor

β_{r_RS} = Lognormal standard deviation for randomness of the structure response factor

β_{u_RS} = Lognormal standard deviation for uncertainty of the structure response factor

5.7.2. Structural capacity factor

The structural capacity factor F_C is expressed as follows:

$$F_C = F_S \times F_\mu \tag{15}$$

where:

F_S = Median elastic scale factor required to scale the reference earthquake to reach the elastic capacity (also referred to as the 'strength factor' in other references)

F_μ = Median inelastic energy absorption factor

The median capacity factor relative to the median structure seismic demand from the seismic response analysis is based on the best estimate of the capacity at the onset of inelastic deformation. EPRI TR-103959 [13] provides equations for the strength of low rise concrete shear walls which are common in nuclear power plant structures. In Ref. [15], the EPRI equations are shown to be slightly conservative but with higher uncertainty than the test data indicated and are considered representative of concrete shear wall capacity for walls with boundary elements. However, the equations overpredict the strength of walls without boundary elements. Therefore, it is recommended that for walls, such as piers without boundary elements, the equations recommended in Ref. [15] or alternate equations be used for calculating median capacity.

The inelastic energy absorption factor, F_μ, and its uncertainty are developed based on story drift, using the effective frequency / effective damping method and the modified Riddell/Newmark method described in Ref. [13]. The average F_μ value from the two methods is typically used as the median value of F_μ. The variability of F_μ using these methods is also described in Ref. [13]. Depending on the relative risk significance of the structure in the risk model, an approximate F_μ value may be determined from Table 5-1 of ASCE/SEI 43-05 [16] for the structure. Limit States A, B, C, and D as defined by Ref. [16], are based on the amount of damage to the structure or facility and relate to its expected performance level. In SSCs, $F_{\mu,LSA}$ for Limit State A in Table 5-1 is representative of a median F_μ factor, and $F_{\mu,LSC}$ for Limit State C is considered to be a 95% confidence value so that the uncertainty, β_u of F_μ, is calculated as:

$$\beta_{u,F_\mu} = (1/1.65)\ln\left(F_{\mu,LSA}/F_{\mu,LSC}\right) \quad (16)$$

The equations for inelastic energy absorption were primarily derived from analytical and observed response of structures subjected to strong motion low frequency earthquakes. For structures subjected to earthquakes that are predominantly high frequency input motion, they are probably conservative.

5.7.3. Structural response factor

Depending on the method used to develop structural response, the development of the structural factor and its uncertainty will differ. Also, the structural response factor for structural failure, as opposed to the factor appropriate for equipment seismic demand, may differ to some degree. These differences are described further in Sections 5.7.3.1 and 5.7.3.2, respectively.

5.7.3.1. Structural response factor for deterministic structural response analysis

For deterministic structural response analysis, the factors of conservatism and uncertainties in response due to variables associated with structural response are identified in Table 3-1 of EPRI TR-103959 [13].

In the separation of variables approach, the structural response factor F_{RS} is the product of the factors for each important variable:

$$F_{RS} = F_{SS} \times F_{HR} \times F_{VC} \times F_D \times F_F \times F_{MS} \times F_{TC} \times F_{MC} \times F_{TH} \times F_{GMI} \times F_{VSV} \times F_{SSI} \times F_{ECC} \quad (17)$$

where

- F_{SS} = Earthquake response spectral shape
- F_{HR} = Horizontal earthquake peak response
- F_{VC} = Vertical component response
- F_D = Damping
- F_F = Frequency
- F_{MS} = Mode shape
- F_{TC} = Torsional coupling
- F_{MC} = Mode combination
- F_{TH} = Time history simulation

- F_{GMI} = Ground motion incoherence
- F_{VSV} = Vertical spatial variation of ground motion
- F_{SSI} = Soil-structure interaction
- F_{ECC} = Earthquake component combination

The randomness β_R and uncertainty β_U, as applicable, associated with each variable are combined by the SRSS method to form the overall β_R and β_U of the structural response factor:

$$\beta_{r\_RS} = \left[\beta_{r\_SS}{}^2 + \beta_{r\_HR}{}^2 + \cdots\cdots + \beta_{r\_ECC}{}^2\right]^{1/2} \tag{18}$$

$$\beta_{u\_RS} = \left[\beta_{u\_SS}{}^2 + \beta_{u\_HR}{}^2 + \cdots\cdots + \beta_{u\_ECC}{}^2\right]^{1/2} \tag{19}$$

These variables were initially identified on the basis of using generic spectral shapes anchored to PGA. In the case of modern PSHA that result in UHRS for different frequencies of occurrence, some of the variables are no longer applicable. Moreover, some of the variables are also not applicable for fixed base analysis as opposed to soil-structure interaction analysis. And thirdly, the variables and uncertainty may differ for development of ISRS for component fragilities as opposed to development of structural fragilities.

New response analyses are to be based on best estimates of the values for important variables. The base case is established at a response level where the structures are elastic for development of ISRS to define the seismic demand for equipment mounted in the structures. In this case, all factors for the applicable variables are unity. The level of response associated with structural failure may be larger and factors for some variables can be larger than unity if the structural capacity is based on the conservative loads calculated for an elastic structure. Alternatively, a separate structural response analysis can be conducted using properties that are representative of the level of response when the structure is near failure.

The overall structural response factor and randomness and uncertainty are calculated separately for the structural fragility and the equipment fragility by taking the product of the applicable factors and by combining the random variability β_R and uncertainty variability β_U by the SRSS method.

5.7.3.2. Structural response factor for probabilistic response analysis

If a probabilistic structural response analysis is conducted to develop ISRS and structural accelerations and loads, all of the important variables are included in the analysis. Probabilistic structural response analysis is considered to be conducted for a range of variables consistent with elastic structural response that is appropriate for developing median ISRS and variability about this median. Typically, the median and 84th percentile (+1β_C) ISRS are developed. For structural evaluation, the median and +1β_u loads are developed. The median ISRS, loads or peak acceleration values are used as the demand in the median capacity analysis, thus the structural response factor, F_{RS}, is 1.0 for probabilistic spectra.

However, if soil and structural property ranges used in the analysis are appropriate for elastic structural response and a higher structural capacity is achieved, a factor greater than 1.0 can be applied for the structural fragility. This factor will depend on the structural damping and soil properties more appropriate for the structural response beyond the elastic limit and is estimated on the basis of the specific conditions. Alternatively, a separate probabilistic structural response analysis can be conducted using soil properties and structural damping representative of a level of response at structural failure.

The composite uncertainty, β_C, is calculated as:

$$\beta_{C\_pro} \;= \ln(84^{th}/med) \tag{20}$$

For the case of structural fragility and fixed base analysis, the ratio of the 84th percentile load on the governing element to the median load is used to calculate β_C. For soil-structure interaction analysis, the ratio of the 84th percentile peak acceleration to median peak acceleration at the critical element is used. For the case of equipment fragility, the ratio of the 84th percentile spectral acceleration of the ISRS to the median spectral acceleration is used and is taken at the dominant frequency or frequency range of the equipment.

EPRI 1019200 [9] states that the peak to valley random variability is included in the development of the UHRS. Consequently, if there is peak to valley variability in the resulting response spectra from the time histories used in the probabilistic analysis, this needs to be removed from the composite β_C calculated above.

$$\beta_{C\_RS} = \left[{\beta_{C\_prob}}^2 - {\beta_{PV}}^2\right]^{1/2} \tag{21}$$

After removal of peak and valley variability, the structural response random variability, β_{r_RS}, is separated from the composite β_{C_RS}. β_{r_RS} is due to the horizontal and vertical ground motion directional variabilities β_{r_HR} and β_{r_VC}. Typical values are:

$\beta_{r\_HR} = 0.18$
$\beta_{r\_VC} = 0.25$

The uncertainty in probabilistic response is then calculated as:

$$\beta_{u\_RS} = \left[\beta_{C\_RS}{}^2 - \beta_{r\_RS}{}^2\right]^{1/2} \tag{22}$$

where β_{C_RS} and β_{r_RS} are for the horizontal or vertical direction, as appropriate.

5.7.4. Fragility evaluation of equipment and distribution systems

Seismic fragilities of equipment and distribution systems may be based upon analysis, earthquake experience, or test experience. Development of fragility from earthquake experience is discussed in Section 5.6. For a given component, the most appropriate method (or combination of methods) is implemented. The equipment seismic fragility evaluation is also based on the separation of variables approach. Variables considered in the fragility evaluation are associated with equipment capacity, equipment response, and structural response.

$$A_m = F_C \times F_{RE} \times F_{RS} \times A_{REF} \tag{23}$$

The equipment response factor, F_{RE}, is applicable to equipment fragilities developed by analysis. For equipment fragilities developed from earthquake experience and test experience, the equipment response factor and its variability are inherent in the equipment capacity.

Determination of equipment capacity and response for fragility evaluation on the basis of analysis and test experience are discussed in Sections 5.7.5 and 5.7.6.

5.7.5. Equipment fragility evaluation based on analysis

5.7.5.1. Equipment response factor

The variables associated with equipment response are listed in Table 3-6 of EPRI TR-103959 [13]. They are:

- Qualification method, F_{QM}
- Damping, F_D
- Frequency, F_F
- Mode shape, F_{MS}

- Mode combination, F_{MC}
- Earthquake component combination, F_{ECC}

The overall factor for equipment response is the product of the factors developed for each variable. The logarithmic standard deviations for randomness and uncertainty, β_r and β_u, are the square root of sum of squares of the associated betas for each variable.

The capacity factor is then multiplied by the equipment response factor F_{RE}, structural response factor F_{RS} and the reference earthquake level to obtain the PGA capacity A_m.

$$A_m = F_{cap} \times F_{RE} \times F_{RS} \times A_{REF} \tag{24}$$

$$\beta_r = \left[{\beta_{r\_cap}}^2 + {\beta_{r\_RE}}^2 + {\beta_{r\_RS}}^2\right]^{1/2} \tag{25}$$

$$\beta_u = \left[{\beta_{u\_cap}}^2 + {\beta_{u\_RE}}^2 + {\beta_{u\_RS}}^2\right]^{1/2} \tag{26}$$

5.7.5.2. Equipment capacity

Fragility evaluation is primarily applicable to equipment whose fragilities are controlled by anchorage or support failure. In most cases, the inelastic energy absorption factor, F_μ, is not applicable since most equipment failure modes for anchorage or supports are brittle. Some guidance on inelastic energy absorption factors for equipment and supports with ductile failure modes is provided in Table 8-1 of ASCE/SEI 43-05 [16]. Limit State A is considered to be a median inelastic energy absorption factor. Limit State C is considered to be a 95% confidence value for determining the uncertainty on β_U. It is noted that these inelastic energy absorption factors are only applicable to equipment that fails in a structural mode. They do not apply to functional failures such as stem binding in a valve, bearing clearance in rotating equipment or electro-mechanical relays.

Modern PSHA studies are in many cases resulting in UHRS that have their peaks at high frequency. Elastic analysis of structures can result in high frequency peaks of the ISRS. This high frequency input motion can result in large loads on non-ductile equipment elements such as anchor bolts and anchorage welds. The procedure to effectively reduce the high frequency portion of the elastic ISRS is time consuming and is usually not done in fragility analysis unless the contribution to risk is high and modifications to the anchorage are impractical. The general procedure in fragility analysis is to use elastic response and treat the failure modes of welds and anchor bolts as brittle. The reduction of the high frequency portion of the ISRS is not applicable to functional failure modes of active mechanical equipment or electro-mechanical relays and similar devices where the failure modes occur while the SSC is elastic.

The seismic fragility will be developed from design analysis of equipment governed by ASME or similar codes, or by structural type codes which are often used for cable raceways. The development of fragilities for failure modes other than anchorage and supports requires the understanding of the design analysis, the governing codes and the failure modes.

Observations from the review of many design analyses of ASME code components conclude that the fragility analyst is often very conservative by treating secondary bending stress as primary bending and reporting low margins when including bolting preload stresses. Another common conservatism in design analysis is that the fragility analyst inappropriately combines earthquake loads by SRSS which implies that orthogonal earthquake responses are in phase. Therefore, proper combination by SRSS is performed on the end item of interest, such as stress. The fragility analyst needs to identify these conservatisms and develop the fragility based on primary stresses that can directly fail the component.

Functional failure modes evaluated by analysis are difficult to assess. ASME-QME-1 [17] for qualifying function of active mechanical equipment does not require a minimum factor of safety for demonstrating function by analysis. Often the fragility analyst only demonstrates that the component will not exceed some functional limit, such as zero bearing clearance, zero fan blade clearance or conservative elastic deflection limit, and will not have much design basis margin left. In these cases, the fragility analyst typically assumes some reasonable functional failure limit beyond the design limit.

5.7.6. Equipment fragility based on test

There are two types of test experience that may be used for the development of equipment fragilities: GERS and plant specific TRS.

The general form of the fragility equation for test experience is described in EPRI TR-103959 [13].

5.7.6.1. Generic equipment rugged spectra

A large body of data, obtained from shake table testing of nuclear power plant components, demonstrates the seismic ruggedness of certain categories of equipment at levels of in-structure motion that typically exceed the design basis spectra. EPRI NP-5223

[18] reported the results of a study that compiled seismic test data from various sources. The test based seismic capacity was represented by GERS for several classes of equipment. For the GERS to be applicable, it needs to be demonstrated that the equipment satisfies the caveats described in Ref. [18].

Table 3-14 of Ref. [13] provides recommendations for median scale factors (F_D) and their variabilities for components having GERS. The GERS capacity spectrum may be obtained by scaling the non-relay and relay GERS by the median scale factors of 1.45 and 1.07, respectively. The GERS capacity spectrum is for function during and after the earthquake. It is applicable to both horizontal and vertical motions. GERS are broad banded spectra, and the clipping factor as well as the capacity increase factor and their associated variabilities are not applicable to GERS.

5.7.6.2. Seismic qualification tests

In the case of qualification tests for equipment, the TRS is the capacity spectrum with some modifications, depending on the method of testing and the test input motion. Ref. [13] describes the methodology for developing seismic fragilities from the TRS.

As stated in Section 3 of Ref. [13], the median seismic capacity A_m is based on the test response spectrum TRS_C, the required response spectrum RRS_C corresponding to the reference earthquake, the broad frequency input spectrum device capacity factor, response spectrum for the structure factor, and peak ground acceleration as shown in Eq. (27):

$$A_m = \frac{\mathrm{TRS_C}}{RRS_C} \times F_D \times F_{RS} \times PGA \qquad (27)$$

The equipment capacity factor (or reference earthquake scale factor) is determined as the scale factor on the median ISRS at which the median demand reaches the median capacity, represented by the TRS multiplied by its respective median scale factors F_D. The median PGA capacity is then calculated as the product of the equipment capacity factor, the structural response factor and the reference earthquake PGA. In this case, the F_D factors for equipment qualified by test are provided in Table 3-14 of Ref. [13]. For function during the earthquake (no relay chatter or no consequences of chatter, no trip), the F_D factor is 1.4. For function after the earthquake (no significant physical damage), the F_D factor is 1.95. For cases where anomalies are noted (e.g. cracked welds, broken screws, bent hardware), the suggested F_D factor ranges from 1.1 to 1.65. In these cases, the seismic fragility analysts need to judge the significance of the damage and the remaining margin.

Annex I presents the process for seismic fragility testing used in Japan by JNES.

5.8. SOIL FAILURE MODES

Seismically induced ground failure may be required to be addressed in the SPSA. Generally, only a limited number of sites are susceptible to soil related failures; these typically include the youngest geologic deposits (Holocene; less than ~10 000 years old) in areas of active sediment deposition, and human constructed artificial ground along coastlines.

Soil failures can have a significant effect on the SSCs important to safety for those sites where a portion of the site (or its entirety) is susceptible to large seismically induced deformations. In IAEA Safety Standards Series No. NS-G-3.6, Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants [19], seismically induced ground failure is defined as any earthquake generated process that leads to deformations within the soil medium, which in turn results in permanent horizontal or vertical displacements of the ground surface. Four different modes of seismically induced ground failure are of interest: liquefaction, seismically induced land slides, seismic compression, and consolidation settlement.

In general, the identification and evaluation of soil failure is a complex process. From a geotechnical standpoint, numerous issues exist in general and for the site of interest. To date, most evaluations of soil failures, specifically liquefaction related phenomena, are deterministic and rely on methods based on empirical observations. Extensive assessments of empirical data have been performed, leading to the development of methodologies for the assessment of soil liquefaction. Correlations of observational data from past earthquakes with measured soil characteristics have provided the bases for development of the assessment methodology. Limited probabilistic methodologies have been developed and implemented, and are progressively developing for application to evaluate nuclear facilities. New regulatory guides under development that incorporate the probabilistic performance based approach will become available in the coming years.

Liquefaction. Liquefaction is defined as the transformation of a granular soil from a solid state to a liquefied state as a consequence of increased pore pressure and reduced effective stress. Seismically induced liquefaction is a phenomenon that can occur in susceptible soil materials during moderate to large earthquakes, generally exceeding magnitude M6.

Extensive damaging liquefaction has occurred during earthquakes exceeding magnitude M7. This holds particularly true for long duration earthquakes such as subduction zone events and crustal plate margin events.

Seismically induced landslides. Earthquake triggered landslides can occur during relatively small earthquakes for slopes that are already near to failure under static conditions and can be extensive and far reaching during large magnitude earthquakes. Inertial forces generated by strong shaking of earth slopes can cause transient shear stresses to develop along potential slip surfaces. When added to long term static shear stresses, and/or transient pore water pressure increases, these transient shear stresses may cause the strength of the slope materials drop below the static downward forces on a potential failure plane, initiating slope movement. This process leads to permanent shear deformations within the slope materials and is referred to as 'seismically induced land sliding'. Liquefaction induced lateral spreading is one example of land sliding.

Seismic compression. Unsaturated soil subject to large transient shear stresses can experience volumetric strains, which result in ground surface settlements and potential lateral movements (near slopes). This process is termed 'seismic compression' and has been observed during some large earthquakes to be especially prevalent in artificial fill soils that were not properly compacted during initial placement, or unconsolidated geologically young deposits (e.g. recent floodplain sediments) that have not undergone significant natural consolidation. Ground settlement or movement is induced by direct vibrational compaction that shifts and 'ratchets' grains back and forth, temporarily reducing contact and permitting gravity forces to compress grains together.

Consolidation settlement. This failure mode arises from a volume change due to dissipation of excess pore pressure, resulting in expulsion of water from the soil matrix and increased effective stress. The rate of settlement is dependent upon soil properties and the length of the drainage path. The excess pore pressures responsible for consolidation may result from changes in overburden pressure (e.g. fill placement, addition of structural loads) or changes in ground water levels. Earthquake induced consolidation settlement can occur in relatively low density artificial and geologically young natural soil deposits that are saturated and do not trigger full liquefaction.

There is an enormous body of existing and publicly available reference material on soil failures. A major source of technical material and an extensive bibliography on the subject of soil liquefaction can be found in Ref. [20][3].

An overview of the process of design and evaluation of foundations for nuclear power plants is provided in NS-G-3.6 [19].

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[3] This monograph extensively updates the subject area of soil liquefaction covered in the original monograph "Ground Motions and Soil Liquefaction During Earthquakes", published 1982 and authored by H. Bolton Seed and I.M. Idriss.

6. SEISMIC PLANT RESPONSE MODEL

SPSA follows the general principles for the IEPSA, observing the specific impact and plant response to seismic initiating events. Typically, the plant logic model is developed on the basis of the IEPSA model.

The development of seismic induced accident sequences logic (seismic event trees) and modifications to IEPSA fault trees to include seismic basic events, correlations between seismic failures and seismic risk quantification is covered by this task. This effort is supported by the fragility analysis results.

Some specific features of the SPSA tasks related to the seismic plant response can be summarized as follows:

- The performance of the seismic plant response related tasks, starting from the IEPSA model, leads to some detailed specifics in the implementation process, which are described further in this section.
- The existence of a high degree of impact of the epistemic uncertainties necessitates a more detailed evaluation and ranking of the results, iterative re-evaluations of some aspects, and an increased attention allocated to the sensitivity and uncertainty analyses.
- There are also some feedback actions to be considered in IEPSA as a result of the evaluation of SPSA, such as aspects not dealt with in IEPSA (e.g. failures of passive elements).

Each initiating event is described by its frequency and its impact on the plant response. For a seismic PSA, there are some special considerations in this area.

Some seismic events do not challenge normal operation; in such cases, the seismic event itself is not the initiating event. Seismic events could be the cause of an initiating event that occurs due to seismic induced failures; for example, the event may cause loss of main feedwater, loss of off-site power, or another initiating event. The frequency of the initiating event is the product of the frequency of the seismic event and the conditional probability of each possible resulting initiating event which occurs due to the seismic induced failures in plant systems.

The approach described in this section adopted the discrete probability distribution (DPD) method as the basis for seismic risk quantification, which requires discretization in linear steps for the seismic hazard and fragility functions domain. Using the DPD method, the quantification process is similar to the one used for IEPSA and allows integration of SPSA with IEPSA.

Risk importance, sensitivity, ranking analysis and identification of the significant accident sequences are performed based on point estimate results. Propagation of the full fragility and seismic hazard variability to CDF/LERF distribution is performed as post processing of the point estimated results, considering refined fragility for the dominant contributors and significant accident sequences. Furthermore, some quantification enhancements aimed to increase quantification accuracy are presented in this section.

In the evaluation of the results of performing seismic plant response tasks, the evaluation of how the quality requirements are met is very important. In this context, it has to be reiterated that certain technical requirements and recommendations provided by Refs [1, 2, 4] need to be met to provide adequate quality to SPSA results to be used in safety decisions and applications.

The following tasks from the seismic plant response have specific features in the SPSA:

- Review of IEPSA initiating events and their connection with the seismic initiating events;
- Integration of the results from the seismic specific tasks (e.g. hazard analysis, fragility analysis, human reliability analysis) into the SPSA global model;
- Definition of the event trees for the SPSA, starting from the IEPSA model;
- Development of the fault trees for the SPSA, starting from the existing IEPSA model, and based on the SPSA event trees' top events;
- Correlation between seismic induced failures;
- Integration of the fault trees into the event trees for the SPSA;
- Definition of the run cases, quantification of the sequences and end states;
- Evaluation of the results, ranking of contributors and definition of the aspects requiring new iterations;
- Sensitivity analysis for the relevant to address sources of uncertainty, in particular model uncertainty for which propagation of parametric uncertainty is not practical;
- Reporting the results and preparing their use for decision making.

6.1. TECHNICAL ELEMENTS

With regard to system analysis, within the scope of this publication, the following technical attributes are essential [4, 5]:

- Seismically induced initiating events that cause risk-significant accident sequences and/or risk-significant accident progression sequences need to be included.
- Seismic induced SSC failures, non-seismic induced SSC failures, unavailability, human errors and multi-unit effects that can lead to core damage or large early release need to be included.
- The SSCs that contribute to accident sequences in the seismic plant response model need to be included.
- Seismic specific challenges to human performance and common cause failures may be considered.
- The analysis to quantify CDF and LERF needs to integrate the seismic hazard, the seismic fragilities, and the seismic plant response, including uncertainties.

The documentation needs to provide traceability of the work and provide interpretation of the seismic risk profile for the plant.

The specific activities to support tasks of system analysis for seismic PSA are summarized in Table 2.

TABLE 2. SPECIFIC ACTIVITIES TO SUPPORT TASKS OF SYSTEM ANALYSIS FOR SPSA

Item		Code	Step	Short description	Responsibility
1	2	3	4	5	6
1		BEL	Derive the initial list of basic events	Derive the basic events list from the IEPSA model.	IEPSA team
2		SEL	Develop the seismic equipment list	The seismic equipment list represents the seismic basic events after successive screening and additions.	SPSA team
3		IE_FE	Define the interface matrix for each Seismic Event (SE-i) relating it to the initiating event for IEPSA and functional event of IEPSA or new initiating events unique to seismic	Define the list of the IEPSA initiating events and the functional events affected due to each SE-i. Perform an assessment to determine if there are cases where the seismic event can lead to an initiating event not considered in the IEPSA and add the new initiating event as needed.	SPSA team input to IEPSA team and agreed
4			Include seismic part in the PSA database		
	4.1	SIE_IE-IE connect	Include SE-i connections with IEPSA initiating event in the IEPSA	- Develop event tree for SE-i; and - Include the logic connectors between the seismic initiating event and the initiating event of the IEPSA, and new initiating events specific to seismic.	IEPSA team
	4.2	SBE in IEPSA	Include seismic basic events in the functional events	Include seismic basic events in the IEPSA by - Identifying the top closest gate to the internal basic event where a seismic basic event has to be inserted; and - Adding the seismic basic event and associated logic (e.g. switches, using appropriate boundary conditions).	IEPSA team
5		RUN_CASE	Define the case calculation	Define the boundary conditions (list of logic switches to be activated) for the case and assign to the calculation case.	IEPSA team

TABLE 2. SPECIFIC ACTIVITIES TO SUPPORT TASKS OF SYSTEM ANALYSIS FOR SPSA (cont.)

6		RES_REVIEW	Review the results	Review results by ranking based on probability and importance measures. Review the main ranked Monte Carlo simulation, checking its meaning.	IEPSA and SPSA teams
7		S&UA	Perform sensitivity and uncertainty analyses	Perform sensitivity and uncertainty analyses and define the dominant factors and final ranking of the Monte Carlo simulation and contributors.	IEPSA and SPSA
8		REPORT	Develop report and all the documentation	Develop report in accordance with documentation of technical requirements.	IEPSA and SPSA

6.2. DEFINITION OF SUCCESS CRITERIA IN SEISMIC PROBABILISTIC SAFETY ASSESSMENT

Basically, the success criteria are developed and documented for the IEPSA and are used to determine for given initiating events what represents a successful or unsuccessful plant response and to translate this information into detailed success criteria for plant systems and operator actions. However, it is important to note that seismic events may result in plant conditions that were not analysed in the IEPSA. Therefore, additional analyses will be required to address these situations. Thermal hydraulic analyses simulating the course of accident sequence progression and other assessment means are used for this purpose. These analyses and assessments are called in this section supporting analyses for the formulation of success criteria (also assumed to be available from IEPSA). As a first task, core or fuel damage or other unsuccessful accident sequence end states are defined, in order to provide the basis for the derivation of detailed success criteria for safety related functions or human interactions.

Specific issues that have to be considered for SPSA include:

- Success criteria regarding the plant response to IEPSA initiating events triggered by seismic initiating events need prior in-depth knowledge based on previous experience, results from similar studies and specific plant features performed as per the seismic standards during plant walkdowns.
- The definition of the safety related functions in terms of a PSA may be functions not only of front-line safety systems, but also of the operator actions, instrumentation and control, support systems and passive elements of the structures and components.
- Success criteria for operator actions are characterized by specific models that need to be adapted to the plant and the operator action during or following a seismic event.
- Success criteria are used to construct the logic PSA model, including the determination of event tree branch point probabilities and probabilities for other events in the logic model. It is expected that the plant reaction is in accordance with the IEPSA model as a very important precondition of a good quality SPSA.
- The transformation of the success criteria for the top-level safety related function for the SPSA, starting from the IEPSA model, needs to be done. The approach has to be able to transform the IEPSA model into a SPSA model.

The mission time for the model is very important. Consideration of a longer impact implies the development of a series of PSA for the relevant intermediate stages up to the moment when the plant is in a stable state from a risk metrics perspective.

6.3. DEVELOPMENT OF SEISMICALLY INDUCED INITIATING EVENTS

The seismic initiating events are defined using the hazard and fragility analyses results. However, the seismic initiating events induce IEPSA initiating events in the plant. The IEPSA initiating events triggered by the seismic initiating events are described in a matrix type. A sample list of initiating events from IEPSA is compiled in Table 3.

TABLE 3. SAMPLE LIST OF INITIATING EVENTS FROM IEPSA

No	Identifier	Description
1	IE_ATWS	Initiating event: Anticipated transient without scram
2	IE_LLOCA_FP	Initiating event: Large loss of coolant accident at full power
3	IE_LOAC_FP	Initiating event: Loss of vital AC bus at full power
4	IE_LOCCP_FP	Initiating event: Loss of core coolant pressure at full power
5	IE_LODC_FP	Initiating event: Loss of vital DC bus at full power
7	IE_LOOP_FP	Initiating event: Loss of off-site power at full power
8	IE_LOSW_FP	Initiating event: Loss of service water at full power
9	IE_MLOCA_FP	Initiating event: Medium loss of coolant accident at full power
10	IE_SLOCA_FP	Initiating event: Small loss of coolant accident in design basis at full power
11	IE_TRAN	Initiating event: General transient
12	IE_IORV	Initiating event: Inadvertent open relief valve at full power

The initiating events from IEPSA (a sample is represented in Tables 4 and 5) which are called by each seismic initiating event may be shown in a matrix format. This task is solved by starting from a list of existing event trees in the IEPSA part. The purpose of the SPSA is to define the changes to this list and to the event trees themselves. The list of existing event trees in the model shows a solution adopted (not the only possible approach for this task) to perform this implementation. This is based on the fact that two categories of event trees are being developed:

- One event tree, having as input the initiating events calculated in the initiating event fault trees and defined by hazard evaluations, and as an output a consequence labelled with the same name of the initiator and another one.

- The event trees for the SPSA itself, having as input the defined hazard event and as output the connectors to the internal event or new seismic-unique initiating event tree with appropriate boundary conditions. The connections are defined by a set of interdependencies between the seismic event and the initiating event from the IEPSA.

TABLE 4. SAMPLE LIST OF CONDITIONAL PROBABILITIES OF FAILURE FOR SEISMIC INITIATING EVENTS

Seismic Event	Freq	Mean Acc	Conditional Probability of Failure for the Seismic Initiating Event					
			IE_LODC_FP	IE_LOAC_FP	IE_LOSP_SDE	IE_LOSW_FP	IE_SLOCA_FP	IE_TRAN_
SE1(0.1-0.3)	9.92E-02	0.2	1.83E-04	2.53E-05	2.79E-01	6.39E-04	6.89E-06	4.88E-01
SE2(0.3-0.6)	2.65E-03	0.45	3.91E-02	2.14E-02	9.25E-01	7.80E-02	1.02E-02	9.77E-01
SE3(0.6-0.9)	1.14E-04	0.75	2.66E-01	2.27E-01	9.97E-01	3.88E-01	1.48E-01	9.99E-01
SE4(0.9-1.2)	1.69E-05	1.05	5.48E-01	5.37E-01	1.00E+00	6.79E-01	4.20E-01	1.00E+00
SE5(1.2-1.5)	4.22E-06	1.35	7.52E-01	7.65E-01	1.00E+00	8.47E-01	6.65E-01	1.00E+00

TABLE 5. SAMPLE LIST OF FREQUENCIES OF SEISMIC INITIATING EVENTS

Seismic Events	Freq	Mean Acc	Frequency of the Seismic Initiating Event					
			IE_LODC_FP	IE_LOAC_FP	IE_LOSP_SDE	IE_LOSW_FP	IE_SLOCA_FP	IE_TRAN_
SE1(0.1-0.3)	9.92E-02	0.2	1.81E-05	2.51E-06	2.76E-02	6.34E-05	6.84E-07	4.84E-02
SE2(0.3-0.6)	2.65E-03	0.45	1.04E-04	5.67E-05	2.45E-03	2.07E-04	2.69E-05	2.59E-03
SE3(0.6-0.9)	1.14E-04	0.75	3.03E-05	2.59E-05	1.14E-04	4.43E-05	1.69E-05	1.14E-04
SE4(0.9-1.2)	1.69E-05	1.05	9.27E-06	9.07E-06	1.69E-05	1.15E-05	7.10E-06	1.69E-05
SE5(1.2-1.5)	4.22E-06	1.35	3.17E-06	3.23E-06	4.22E-06	3.57E-06	2.81E-06	4.22E-06

Depending on the software used, the IEPSA initiating events triggered are connected using logic conditions called ‘switches’. These switches are included in the fault trees that define the IEPSA initiating events, or by allowing the seismic events to propagate through seismic event tree to the transfer end states linking seismic event tree with IEPSA event trees.

Examples of seismic event trees developed on the basis of Tables 4 and 5 are presented in Fig. 4.

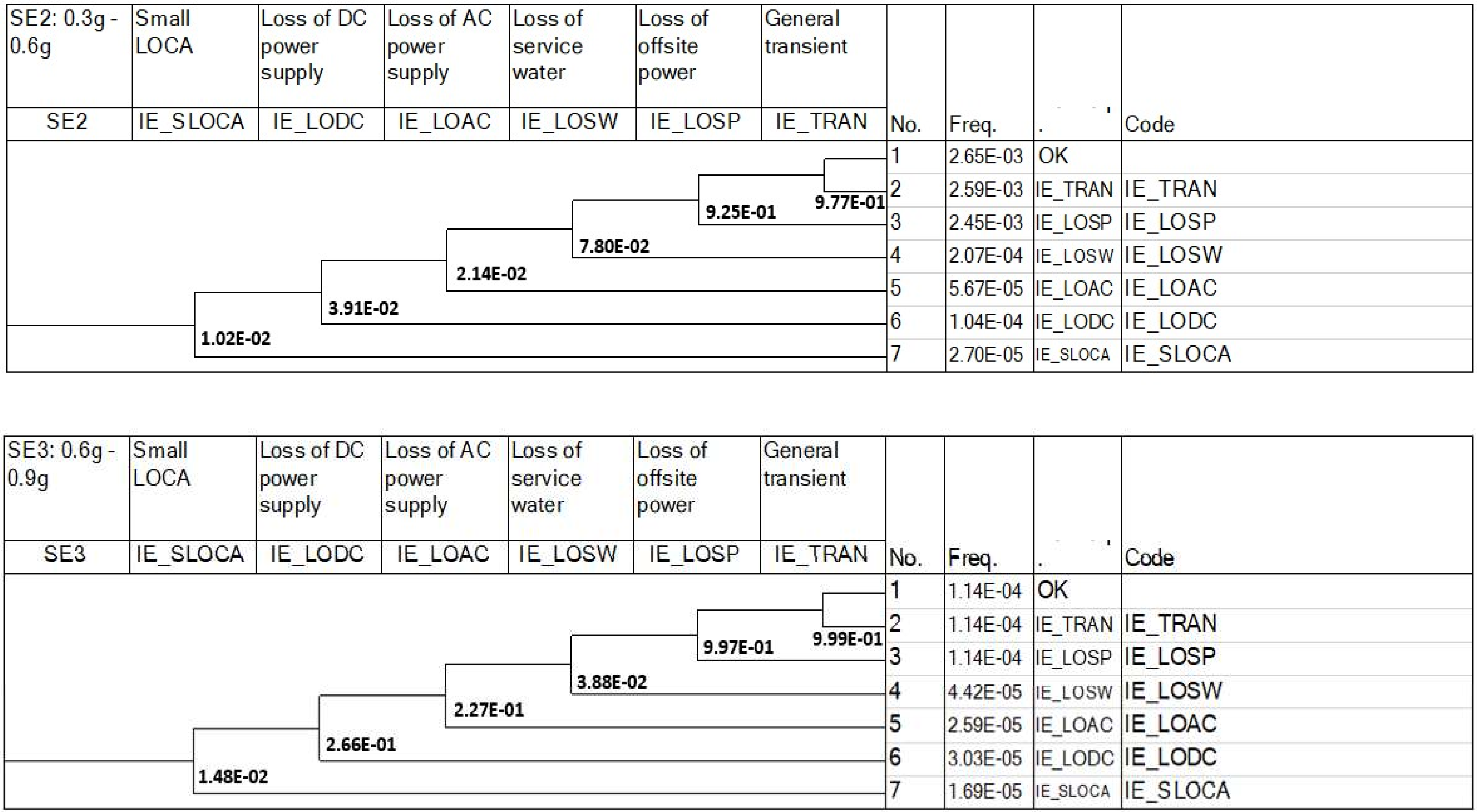

FIG. 4. Examples of seismic event trees for various seismic acceleration ranges.

6.4. DEVELOPMENT OF SEISMIC EVENT TREES

The tasks developed to build the plant model in the event tree part have general features fully applicable in SPSA according to existing standards technical requirements. However, there are specific issues to be considered to perform those tasks for the support of SPSA.

For each heading event (i.e. functional event) of the event tree, the conditions need to be determined on the basis of the success criteria in the given event tree for the corresponding system; thereby, the top event in the fault tree called by the functional event has to be specified. The top event of the fault tree is defined by focusing on the following aspects:

- For each given accident sequence, the effect of the functional and phenomenological dependency caused by the success and failure of the previous top events in the event tree;
- The effect of the specific basic event success and failures in the cut sets of the branches defined in the event tree in systems (success cases and failure cases of e.g. support systems);
- Attributes of damage leading to loss of system function, and the status of system operation;
- Time conditions related to damage (e.g. mission time).

In SPSA, the objective of the accident sequence analysis is, as in IEPSA, to ensure that the response of the plant systems and operators to a seismic initiating event is reflected in the assessment of the risk metric in such a way that:

- Significant mitigation systems, operator actions and phenomena that influence or determine the course of sequences are appropriately included in the accident sequence model and sequence definition;
- Plant specific dependencies due to initiating events from the IEPSA, or those seismic-unique initiating events added to the PSA, triggered by the seismic initiating event, human interfaces, functional dependencies, environmental and spatial impact, as well as common cause failures, are reflected in the accident sequence;
- The individual function successes, mission times, and time windows for operator actions for each critical safety function modelled in the accident sequences reflect the success criteria evaluated in accordance with the PSA;
- End states are clearly defined to be either a core damage or successful prevention with the capability to support the interface between Level 1 PSA and Level 2 PSA.

There are two important aspects related to the development of the SPSA model from the IEPSA model:

- It is necessary to develop a set of connecting rules (preferably in a matrix format) to describe the connection between the SPSA seismic events and the IEPSA initiating events;
- It is necessary to develop a set of dependencies between the functional event called in each event tree.

6.5. MODIFICATION OF FAULT TREES TO INCLUDE SEISMIC BASIC EVENTS

The first important step in the quantification process is to define the necessary changes for the event trees and fault trees developed in the IEPSA.

A set of logical connectors and equations establishes the link between the initiating events for SPSA and the parts that have to be switched off or on the functional events at the system modelling level. The connectors are illustrated in the sample from Fig. 5.

Figure 6 shows that the initial switch action starts considering only one basic event (ALTHEAT_N). In order to introduce a logical combination of the internal basic event and the seismic basic event (S1\ALTHEAT_N) in case that the initiating event is triggered by seismic event 1 (IE-SE-1), the following steps are required:

- The place of the first highest OR gate above the internal basic event for which a seismic basic event has to be introduced (see Fig. 5).
- Under this gate, two logic constructions are introduced as shown in the figure.
    - One for the internal basic event;
    - One for the seismic initiator SE-1.

The events coded as ‘switch…’ are events with only logic values (i.e. TRUE or FALSE).

In Fig. 5, the status is FALSE for both switches and the effect is:

- The event ALTHEAT_N will be enabled (since a NOR gate of a FALSE event will lead to a TRUE one, and the gate FRAMFT1-2 will be valid and true and calculated); and
- The gate FRAMFT 1-7 will be false and not calculated and the seismic basic event S1\ALTHEAT_N will be excluded. The result of the top (the OR gate FRAME CASE 1) will be only the internal basic event ALTHEAT_N.

If the switches are set so that:

- SWITCH_E is FALSE, and
- SWITCH_S1 is turned TRUE,

then both internal and seismic basic events are calculated.

Combinations of more than one switch can be used and defined as a logic rule called 'Boundary Condition'. The boundary conditions will then be used for the input description to the top event trees and run cases, allowing performing runs with various combinations. However, attention has to be paid to the fact that a boundary condition is valid for one event tree, so it has to be introduced everywhere in the event tree where required. This is the manner to transform an IEPSA event tree type into a SPSA event tree type without making modifications in the event tree itself, except imposing the applicable boundary conditions.

Figure 6 shows how to build the fault tree for the initiating events for seismic and internal events combination. The manner in which the switches are connected or disconnected is similar to the previous explanations, except that the logic construction represents more than one seismic initiating event. The result is that, for a seismic case, the internal part of the initiating event is disconnected and all the other seismic events are not called in that run.

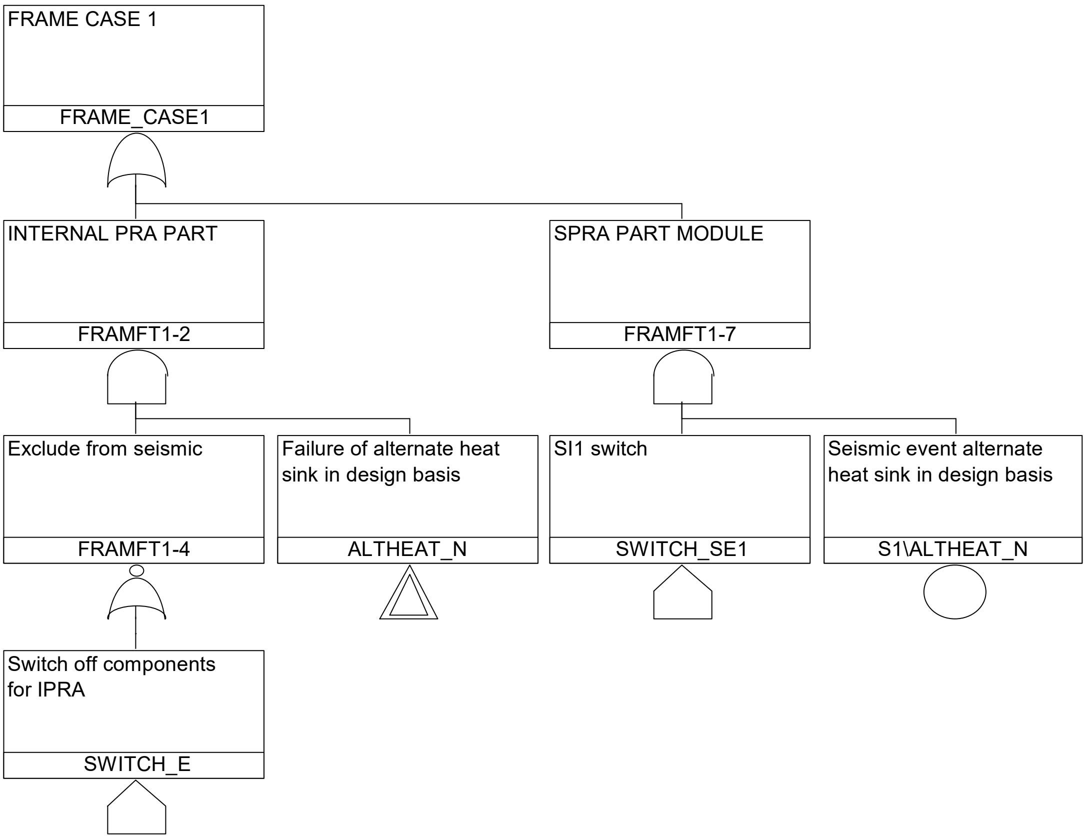

FIG. 5. Sample of basic use of switches for one seismic initiating event.

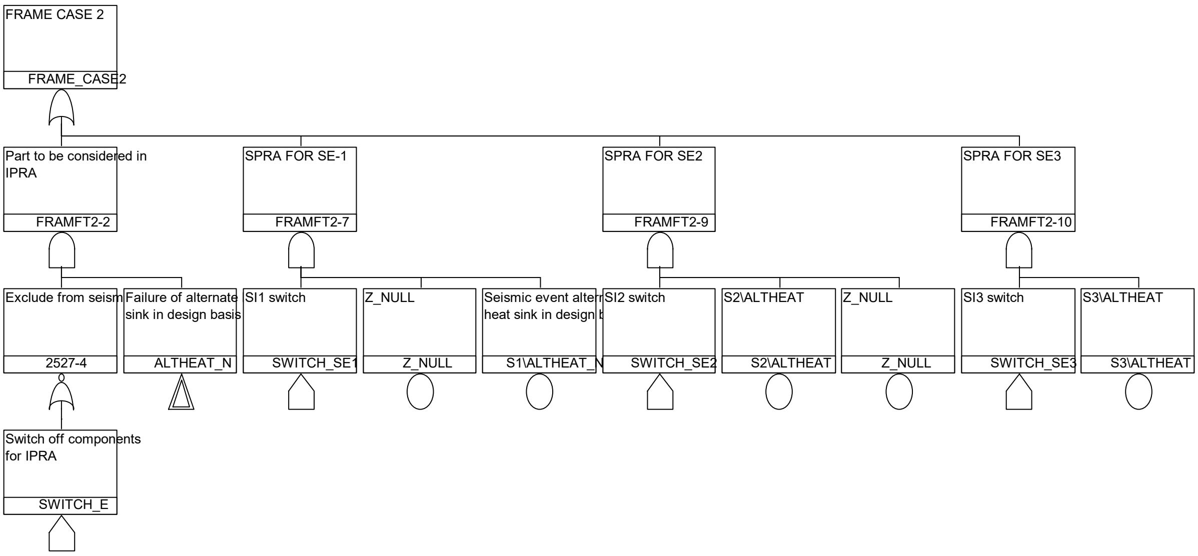

FIG. 6. Sample of basic use of switches for multiple seismic initiating events.

6.6. CORRELATIONS AMONG FAILURES

Seismic PSA normally assumes complete response correlation for similar and nearby equipment subjected to the same floor excitation. Nearby equipment of different types is usually assigned only minor response correlation. Even when there is a high response correlation, the capacity correlation may not be proportional.

A simplified theoretical methodology for correlations is developed in Ref. [11], which addresses the very limited testing and experimental data available on the topic. The determination of complete correlation, as implied above, is accomplished by the application of three simple rules. A set of components is completely correlated if:

- They are essentially identical, AND
- They are located on the same level of the same building, AND
- They are oriented in the same direction (axis).

Sets of components that meet all of these conditions would be considered completely correlated (i.e. they would all fail together and can be represented by a single basic event in the model). If any condition is not met, they are considered uncorrelated (i.e. they would fail independently). There is a lot of engineering judgement required as to what are 'essentially identical' components. For example:

- A 480 V AC bus and a 4 kV AC bus could be considered essentially identical, but a 480 V AC motor control centre would not be.
- A low flow, high pressure pump is not essentially identical to a high flow, low pressure pump.

As noted, this simplification is not necessarily realistic, but currently there is no technical basis for any other approach, and so this is universally accepted as being the state of the art. To overcome the problem that this simplification causes, the usual approach is to perform a sensitivity analysis, for example assuming complete correlation between component sets that do not meet all three conditions, and then complete independence of component sets that meet all three conditions, and finally ascertaining what difference these two assumptions make.

Sensitivity analyses can also use an approach to variability in response and correlations developed on the basis of the results of the Seismic Safety Margin Research Program [21], a multi-year, multi-phase programme funded by the U.S. Nuclear Regulatory Commission and carried out by the Lawrence Livermore National Laboratory. The results of this programme do not have a general technical acceptance in the SPSA community, so they are typically used for sensitivity. The rules for assigning response correlation for this sensitivity analysis are established in NUREG/CR-4840 [22] and are based on NUREG/CR-4482 [21]. The same approach has been further developed and re-affirmed in a more recent USNRC publication [23]. These rules are listed below:

- Components on the same floor slab and sensitive to the same spectral frequency range will be assigned response correlation of 1.0.
- Components on the same floor slab and sensitive to different ranges of spectral frequencies will be assigned response correlation of 0.5.
- Components on different floor slabs (but the same building) and sensitive to the same spectral frequency range will be assigned response correlation of 0.75.
- Components on the ground surface can be treated as if they were on the grade floor of an adjacent building.
- Ganged valve configuration (either parallel or series) will have response correlation equal to 1.0.
- All other configurations will have response correlation equal to zero.

The correlation between any two component failures is computed from the following expression:

$$\rho_{12} = \frac{\beta_{R1}\beta_{R2}}{\sqrt{\beta_{R1}^2+\beta_{F1}^2}\sqrt{\beta_{R2}^2+\beta_{F2}^2}}\rho_{R1R2} + \frac{\beta_{F1}\beta_{F2}}{\sqrt{\beta_{R1}^2+\beta_{F1}^2}\sqrt{\beta_{R2}^2+\beta_{F2}^2}}\rho_{F1F2} \tag{28}$$

where:

ρ_{12} = correlation coefficient between the failure of components 1 and 2

$\beta_{R1}\,\beta_{R2}$ = standard deviation of the logarithms of the response of components 1 and 2

$\beta_{F1}\,\beta_{F2}$ = standard deviation of the logarithms of the fragilities (capacities) of components 1 and 2

ρ_{R1R2} = correlation coefficient between the response of components 1 and 2

ρ_{F1F2} = correlation coefficient between the capacities of components 1 and 2

6.7. HUMAN RELIABILITY ANALYSIS

Each seismic event introduces new accident contextual factors and dependencies beyond those typically treated in IEPSA, which could potentially increase the probability of human failure events (HFEs) already available in IEPSA model.

According to SSG-3 [1], HFEs need to be integrated into the seismic PSA model regardless of whether the context characterisation for a specific HFE is affected by the seismic event or not.

In seismic PSA, the human reliability analysis (HRA) is performed using the same principles that are applied for IEPSA, taking into consideration the specific context created by seismic event. Recommendations on HRA in general, and seismic context characterisation in particular, are provided in SSG-3 [1]. The quality attributes on HRA implementation can be found in Refs [4, 5, 24]. For use in seismic context, IAEA Safety Reports Series No. 66 [25] defines four plant damage levels, depending on the damage to SSCs important to safety and those not important to safety, as follows:

- Damage level 1: No significant damage or malfunction to SSCs important to safety and those not important to safety.
- Damage level 2: No significant damage or malfunction to SSCs important to safety. Significant damage or malfunction to SSCs not important to safety (not required for power generation).
- Damage level 3: No significant damage or malfunction to SSCs important to safety. Significant damage to or malfunction of SSCs not important to safety (required for power generation).
- Damage level 4: Significant damage to or malfunction of SSCs important to safety (it is highly likely that SSCs not important to safety will experience significant damage at this damage level).

There are three different groups of HFEs in seismic HRA:

- HFEs already included in IEPSA, which need to be re-assessed considering the seismic context;
- HFEs not included in IEPSA and to be added specifically for the seismic PSA (need to be assessed using principles of HRA used for IEPSA considering the seismic context);
- HFEs related to undesired operator responses to spurious alarms and indications (errors of commissions).

The seismic context is characterized by various factors, such as:

- Time availability;
- Complexity of an action;
- Human resources requirements;
- Availability of cues;

- Procedures and training;
- Accessible location and environmental factors;
- Equipment accessibility, availability and operability;
- Workload, pressure and stress;
- Human-machine interface;
- Special fitness needs (e.g. respiratory protection equipment, physical exertion);
- Crew communications.

Above mentioned factors need to be properly taken into consideration in HRA within SPSA study. This is typically implemented using relevant performance shaping factors[4].

In general, HRA consists of four steps, which have the following specifics in seismic context:

- **Identification and Definition of Human Failure Events.** In SPSA, this step is aimed to identify the HFEs that will be credited in response to seismic events, and to define them in sufficient detail to support modelling and quantification. In this step, those HFEs that are already modelled in IEPSA are reviewed for applicability to the seismic context. This is done with consideration of the SEL, which may result in the elimination or modification of some HFEs. Therefore, the HRA process needs to be integrated with the fragility analysis and systems modelling tasks, in particular the SEL development and walkdown results.
- **Qualitative Assessment.** The purpose of this step is to fully characterize the context induced by seismic events and to determine the feasibility of each HFE in the seismic context. Feasibility needs to be demonstrated separately for each of the plant damage bins, considering the extent of potential damage.
- **Quantitative Assessment.** The purpose of this step is to estimate the probabilities for the considered HFEs. Considering the adverse effects of seismic events, it is typically expected to have an increase in human error probabilities (HEPs) for certain HFEs already modeled in IEPSA.
- **Integration into PSA.** The purpose of this step is to reflect the results of HRA in the seismic PSA model, by including the results of the quantitative assessment in the event trees and fault trees.

The example approach for considering seismic context in HRA is presented in Annex II.

[4] In many HRA models, the human error probability is estimated on the basis of a set of performance shaping factors. The term encompasses the various individual, organizational and environmental factors that affect human performance and that can change the likelihood of a human error.

7. SEISMIC RISK QUANTIFICATION

7.1. SEISMIC RISK QUANTIFICATION

The seismic risk quantification for the SPSA sequence model requires the following inputs:

- PSHA results represented by seismic hazard curves;
- Component fragilities represented by fragility functions for each seismic basic event;
- Complete seismic PSA model and seismic sequences generated for each seismic initiating event.

Seismic risk quantification requires solving the convolution integral using discrete acceleration bins that cover the acceleration domain of interest. The acceleration range of interest is bounded by the no failure zone and the screening limit.

Quantification methods include:

- Utilization of simulation techniques, such as latin hypercube sampling or Monte Carlo simulation, involving random sampling from a number of continuous probability density functions (PDFs). The conditional probability of plant failure at each ground motion level is computed. The sampling process continues where the plant fragility curves are sampled along with the confidence level of the hazard curve.

- Discretization of analytical PDFs into DPDs (referred to in Section 6 as the DPD method).

In a discretization scheme, a continuous lognormal density function is approximated by a finite number of {<pi, xi>} doublets. The quantification steps then proceed along the lines outlined above to determine the plant fragility curves and finally the CDF (or LERF) with uncertainties.

The difference in this approach is that just two probability distributions are combined at a time, and that the process is repeated for each summation required.

The above two methods provide plant state fragility functions and the seismic CDF distribution.

Point estimate quantification based on the DPD method is used in any SPSA (capability category 2) for the following reasons:

- To maintain compatibility with the IEPSA quantification technique and allow the use of standard PSA software;
- To perform risk importance and sensitivity analysis needed to identify significant risk contributors and dominant accident sequences;
- To run selected cases and generate a basis for developing seismic risk insights.

Quantification considering hazard and fragility variability is done after a refined fragility analysis has been performed, the system model is updated and the dominant accident sequences are identified. Quantification is typically done as a post processing step using the following input:

- Seismic hazard curves for different fractiles;
- List of dominant sequences that built up 80-90% of the seismic CDF/LERF;
- Fragility parameters table describing fragility functions associated to the seismic basic events.

This section describes point estimate quantification where only the mean seismic hazard curve, mean fragility parameters and accident sequences are needed.

Assuming the seismic initiating events SI_1, SI_2, SI_3 … SI_n, the convolution integral (Eq. (29)) can be approximated using discrete intervals as follows:

$$P_F = \int_{a1}^{a2} \frac{dH(a)}{da} F(a) da \tag{29}$$

$$P_F = \sum (F(a_{SIi}) \times da) \times \frac{H_{i+1}(a) - H_i(a)}{da} \tag{30}$$

where:

$F(a_i)$ represents conditional probability of failure corresponding to SI_1, SI_2 … SI_n.

$H_{i+1}(a) - H_i(a)$ represents seismic initiating event frequency for SI_1, SI_2 …. SI_n.

7.2. INTERPRETATION OF RESULTS

7.2.1. Importance analysis

The risk importance measures are used in order to:

- Identify common contributors that appear in many sequences or cut sets;
- Rank plant features by risk significance (e.g. for focused testing or maintenance);
- Evaluate risk achievement worth for estimating the risk significance of equipment that is removed from service;

- Evaluate risk reduction worth for bounding the risk benefits from proposed improvements/upgrades;
- Evaluate impacts from some precursor events by examination of importance measures; and
- Examine groups to provide insights about compound impacts and dependencies not evident from single-component analyses.

Their use is an important step in the whole verification and validation groups of tasks for a PSA model, including SPSA.

The following importance measures are usually used:

- Fussell-Vesely – measures the overall percent contribution of cut sets containing a basic event of interest to the total risk;
- Risk Reduction Worth – measures the amount that the total risk would decrease if a basic event's failure probability is 0 (i.e. never fails);
- Risk Achievement Worth – measures the amount that the total risk would increase if a basic event's failure probability is 1 (i.e. component is taken out of service or fails);
- Birnbaum – measures the rate of change in total risk as a result of changes to the probability of an individual basic event.

Some specifics of using the importance analysis in the review of results are as follows:

- By using the combined evaluation of both minimal cut sets and the importance factors identify the hierarchy of events having an impact on the results and potentially to be reviewed during the sensitivity analysis.
- There are various possible approaches to be used in the evaluation of the results by using not only the values of the probabilities of a dominating minimal cut sets for a given metric, but also importance analysis for basic events.
- One possible approach could be, for example, to evaluate the combined ranking of the basic events based on the probabilities and importance and then to consider sequences in which one or more high ranked basic events appear. That approach or similar ones will give a more refined view on the ranking of the sequences to be considered for further analysis.

7.2.2. Sensitivity analysis

The quantification process and the propagation of uncertainty address to a large extent uncertainty in risk estimates. However, it does not address model (or epistemic) uncertainty. The specific goal of the sensitivity analysis for SPSA, which has a high degree of epistemic uncertainties, is to perform a parametric type of evaluation to assess the extent of potential impact of these uncertainties on the risk results.

This is possible by considering any of the initial assumptions and other dominant contributors as possible sensitivity cases in an integrated PSA internal–external model. Extended sensitivity analysis is crucial for SPSA where the epistemic uncertainties are very high and the accuracy of results and indications of how to use them for decision making is extremely important. Sensitivity analysis is conducted to evaluate the impact of the assumptions on the results, so that the degree of confidence in the result will be acceptable for the decision makers. Sensitivity analysis is related to the degree of confidence in SPSA results.

In order to perform the sensitivity analyses, the following aspects are to be considered at the level of implementation actions:

The list of all assumptions and sources of uncertainty need to be reviewed to determine which ones will be subject to sensitivity analysis. There are certain ones that are typical in a seismic PSA.

- Correlated failure groups. Certain definitions of what constitutes ‘similar’ components, ‘same’ location, and ‘same’ orientation are used in the PSA. Sensitivity analysis is performed using alternate definitions that result in larger or smaller correlated failure groups;
- Correlated failure probability. As noted previously, it is generally accepted practice to use either complete or zero correlation. An approach to this was discussed previously;
- Human error probabilities. The methods of adjusting HEPs for the effects of seismic damage are not as well proven as for internal events. Even though the HEPs carry a distribution that is used in the uncertainty analysis, sensitivity analysis needs to be performed; and
- Hazard event frequency. Again, even though the hazard carries its own uncertainty distribution, these are very large and may not capture all the epistemic uncertainty.

It is likely that there will be plant specific model uncertainties that need to be evaluated using sensitivity analysis.

7.3. DEVELOPMENT OF THE SEISMIC PROBABILISTIC SAFETY ASSESSMENT REPORT

The main principles of the development of the SPSA report are provided in SSG-3 [1], NS-G-2.13 [2] and in the ASME/ANS probabilistic risk assessment standard (Ref. [4]).

However, the most important aspect to be mentioned as a specific feature for SPSA is that the report has to consider the goals of the study and the needs of the user. If the use of the study is intended for risk informed decision making, then the need to comply with certain quality requirements is mandatory, as mentioned in Ref. [4].

Seismic PSA needs to be documented in a manner that facilitates peer review, as well as future upgrades and applications of the SPSA. Detailed recommendations on the documentation and presentation of results for seismic PSA are provided in SSG-3 [1]. Additional information on the quality attributes and technical requirements for documentation can be found in Refs [4, 26].

8. PEER REVIEW

Peer review is an essential element of the seismic evaluation of existing installations.

The purpose of the peer review is to provide an independent review of the SPSA, to ensure concurrence with the applicable state of practice in the nuclear industry. As discussed below, the composition and qualifications of the peer review team are important. The specific number of reviewers is dependent on the skill set of the individuals selected. In some cases, individuals may cover many of the elements of the SPSA based on their expertise. For example, systems expertise is commonly coupled with risk quantification expertise, especially for licensees with active PSA groups. A peer review may take 5 to 10% of the programme execution resources. Performance of the peer review may be based on an overall review of the end results of each element and a review of a sample of the detailed analyses/calculations – the sample being large enough to provide confidence to the peer reviewer that methodologies and parameters are being appropriately implemented.

Peer review aspects for seismic PSAs are as follows:

- The peer review team needs to have combined experience in the areas of systems engineering, seismic hazard, seismic fragility, and seismic PSAs. The team members need to have demonstrated experience in seismic walkdowns.
- The peer review team will evaluate whether the seismic hazard study used in the SPSA is appropriately specific to the site and has met the relevant technical requirements and complies with [4] or other pertinent guidelines.
- The peer review team needs to evaluate whether the seismic initiating events are properly identified, the accident sequences are properly quantified, and seismic induced failures are properly modelled.
- The peer review team needs to evaluate whether the seismic response analysis used in the development of seismic fragilities appropriately represents the median-centred response conditional on the ground motion occurring.
- The peer review team needs to review the seismic walkdown of the plant. This review is typically performed on a sampling basis by selecting a sample of components to review and perform the review in the plant.
- The peer review team needs to evaluate whether the methods and data used in the fragility analysis of SSCs or a combination thereof, are adequate for the purpose. The review team needs to perform independent fragility calculations of a selected sample of components, covering different categories and contributions to CDF and LERF.

- The peer review team evaluates if the seismic risk quantification method used in the seismic PSA is suitable and if the seismic PSA provides all the necessary results and insights for risk informed decisions. The review typically focuses on the CDF and LERF estimates and uncertainty bounds and on the dominant risk contributors.

In addition, comprehensive guidance on the activities of the peer review team can be found in Ref. [4].

9. COMBINATION OF SEISMIC HAZARDS AND TSUNAMI HAZARDS

This section introduces the concept of the combination of seismic hazards and tsunami hazards and the extension to multi-unit and multiple hazards. Seismic hazards could be the cause of large tsunamis (correlated hazards) that may impact a nuclear site (multiple units).

The Fukushima Daiichi nuclear power plant accident in 2011 has provided several important lessons [27]. One of these lessons is that the assessment of natural hazards needs to consider the potential for their occurrence in combination, either simultaneously or sequentially, and their combined effects on a nuclear power plant. The assessment of natural hazards also needs to consider their effects on multiple units at a nuclear power plant [27].

9.1. SCREENING FOR CORRELATION OF EXTERNAL HAZARDS

9.1.1. Screening process

Based on design basis hazard event frequency

Correlated hazards can be screened out if (a) the plant has a design basis for both hazards; (b) the plant will not directly suffer core damage if all SSCs that are not designed to either design basis hazard event fail; and (c) the frequency of the correlated design basis hazard event is less than 1% of the internal events CDF for a single reactor unit. If the hazard can affect multiple units on the site, it can be screened out if the frequency of the correlated design basis hazard events is less than 1% of seismic CDF.

Based on design basis hazard event core damage frequency

Correlated hazards can be screened out if (a) the plant has a design basis for both hazards; (b) the plant conditional core damage probability is calculated assuming all SSCs that are not designed to either design basis hazard event fail; and (c) the frequency of the correlated design basis hazard events multiplied by the conditional core damage probability is less than 1% of the internal events CDF.

Based on overall hazard frequency

Correlated hazards can be screened out if either (1) a bounding or demonstrably conservative estimate of the hazard frequency (over the full range of hazard event severity) is less than 1% of the internal events CDF, or (2) a realistic estimate of the hazard frequency (over the full range of hazard event severity) is less than 0.1% of the internal events CDF.

Based on overall core damage frequency

Correlated hazards can be screened out if a bounding or demonstrably conservative estimate of CDF (over the full range of hazard event severity) is less than 1% of the internal events CDF.

It is assumed that earthquake and tsunami are identified as dominant hazards at a target site after external hazards are screened out from all potential hazards, based on a criterion established in IAEA Safety Reports Series No. 92 [28].

9.2. METHOD FOR COMBINING SEISMIC PROBABILISTIC SAFETY ASSESSMENT AND TSUNAMI PROBABILISTIC SAFETY ASSESSMENT

The framework and guidance for the combination of external hazards in PSA for nuclear power plants are presented in IAEA Safety Reports Series No. 92 [28].

PSA methodology is typically applied to individual external hazards to evaluate their contribution to risk metrics such as CDF and LERF. The methodology consists of the identification of external hazards, screening of hazards based on some defined qualitative and quantitative criteria, bounding analysis for certain hazards, and detailed PSA for the remaining screened-in external hazards.

The external hazard PSA methodology allows the analyst to treat correlated or induced hazards by properly modelling the joint occurrence of these hazards in the event tree and fault trees. However, there are not many examples of the treatment of correlated hazards in the public domain. The combination of seismic hazards and tsunami hazards in the PSA is characterized by the following points:

1. There exists a causality between earthquake and seismic induced tsunami as natural phenomena.
2. It is necessary to identify scenarios and their probabilities or frequencies from potential seismic sources where an earthquake could occur and cause a seismically induced tsunami to occur.

Correlation between the peak ground motion caused by an earthquake and the maximum height of a tsunami strongly depends upon source mechanism, geometrical location relationship of site to source, site conditions, etc.

The above scenario can be classified into four quadrants as shown in Fig. 7. Combination of seismic PSA and tsunami PSA is required when the dominant seismic source is located near the site and the tsunami hazard is high.

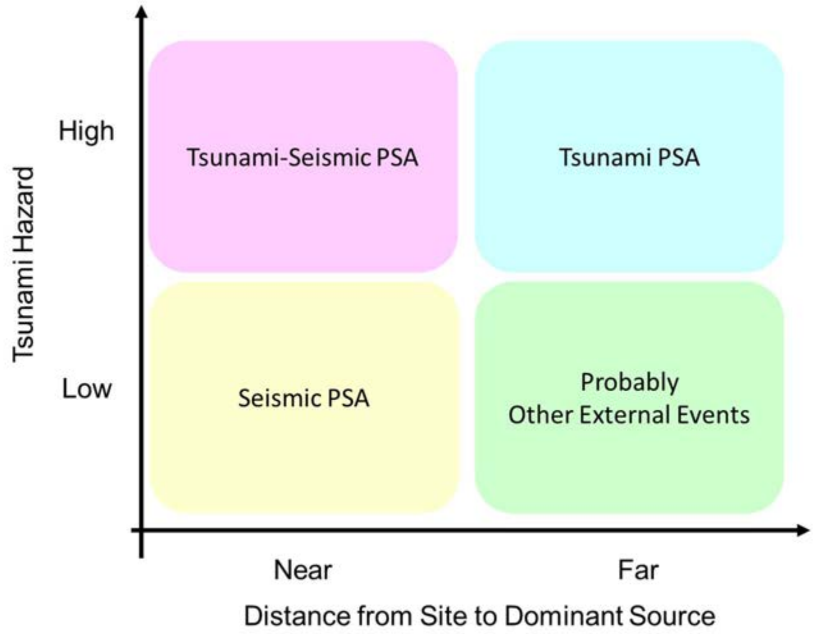

FIG. 7. Identification of scenarios of seismic hazards and tsunami hazards.

10. CONSIDERATION OF SEISMIC PROBABILISTIC SAFETY ASSESSMENT APPLICATION AT THE DESIGN STAGE

Seismic PSA can be used in the development and/or optimization of a new nuclear power plant design. PSA can be used as a design tool with the following objectives:

- Check if sufficient seismic margin was achieved by design (at the plant level) to avoid cliff edge effects;
- Provide a systematic means to find and eliminate seismic severe accident vulnerabilities.

Design stage seismic PSA is limited to information availability in the design phases; however, it is much easier to make corrections and modifications during the design process than after construction. Seismic PSA can be used to address and eliminate seismic vulnerabilities identified in the past, to check the effectiveness of the defence in depth provisions, to provide insights for setting performance targets consistent with the with seismic safety goals, and to optimize the robustness of seismic design based on relative contribution to risk. The protective strategies address both the prevention of accidents and the mitigation of their consequences, and consist of the following:

- Maintaining stable operation (provides measures to reduce the likelihood of challenges to safety systems);
- Protective systems (provide highly reliable equipment to respond to challenges to safety); and
- Maintaining barrier integrity.

Following the above mentioned objectives and strategies, seismic PSA during design development can be used to properly balance seismic margin for SSCs based on their relative contribution to overall seismic risk.

APPENDIX I

FAULT RUPTURE MODEL

I.1. EXAMPLE OF SEISMIC HAZARD EVALUATION USING A FAULT MODEL

This appendix provides an example of a method to perform a probabilistic seismic hazard evaluation based on a fault rupture model that used a semi-empirical waveform synthesis method.

I.1.1. Evaluation conditions

The procedure for earthquake ground motion prediction using a semi-empirical waveform synthesis method is explained in available technical literature. The procedure consists of six steps, which are described below. The evaluation conditions were established according to these steps.

Step 1) Identification of seismic sources and rupture zones

The seismogenic faults that can dominate the seismic hazard are the faults that are located close to the site and that have a significant magnitude.

Large magnitude earthquakes that occur in active faults and in the subduction zone can be the subject in this seismic hazard evaluation because it would be relatively easy to identify the seismogenic sources and rupture areas and to estimate their magnitude.

Therefore, the focus is placed on earthquake faults for which it would be easy to identify the seismic source region and for which it would be comparatively easy to identify the scale. This applies in particular to large scale earthquakes that occur in active faults or plate boundaries.

Step 2) Calculation of the earthquake occurrence probability

The time series for earthquake occurrence can be modelled on the basis of either a Poisson process or a renewal process.

Step 3) Establishing the fault rupture model

3a) Setting of the medium constants near the seismic source

The medium constants near the seismic source that will be required when using a fault rupture model to evaluate the seismic ground motion are the shear wave velocity β, the density ρ, the modulus of rigidity μ, and the Q value. Furthermore, these constants can be used to predict earthquake ground motions using fault rupture models.

3b) Establishment of the fault rupture model (seismic source characteristics)

The macroscopic fault parameters are set as follows by using a modified strong motion prediction recipe or the like:

- Fault plane area ($S = L \times W$): based on estimation;
- Fault position: travel, dip, slip angle;
- Starting point of fault rupture: latitude, longitude, depth;
- Rupture propagation mode: radial, etc.;
- Static stress drop ($\Delta\sigma$): the average value for subduction earthquakes (30 bar), etc.;
- Seismic moment (M_0): $M_0 = (16 / (7 \times \pi^{1.5})) \times \Delta\sigma \times S^{1.5}$;
- Mean slippage (D): $D = M_0 / (\mu S)$;
- Rupture propagation velocity (V_r): $V_r = 0.72 \times \beta$, etc.;
- Build-up time (τ): $\tau = W / (2 \times V_r)$, etc.;
- Establishment of the microscopic fault parameters.

Here, a macroscopic fault model is built that can be determined on the basis of the asperity area. The following microscopic fault parameters can be established in the asperities and background region:

- Number and location of the asperities: based on estimation;
- Total asperity area (Sa): Sa/S mean 0.248, standard deviation 0.076;
- Displacement (Dm asp) in individual asperities (radius ri): Estimated using active fault surveys or the mean convergence rate for the plate, etc.;
- Seismic moment in individual asperity (M0 asp): M0 asp = μ Dm asp Sm asp;
- Stress drop in individual asperity (Δσm asp): Δσm asp = (7 × 16) × (M0 / (Rr2));
- Fault parameters in the background source region (area, average slippage, seismic moment, stress drop);

where R represents the equivalent radius when converting the area of the whole fault to a circle, and r represents the equivalent radius when converting the total asperity area to a circle.

Step 4) Establishment of the element earthquake (propagation characteristics)

The element earthquake is modelled in a case where the observed waveforms with keeping sufficient quality and quantity have been obtained at the target site. The following fault parameters for the element earthquake can be established when using waveforms observed for small and medium scale earthquakes at the site:

- Setting of the seismic moment M_0;
- Setting of the critical circle frequency ω_c;
- Calculation of the fault area, average slippage, effective stress;
- Setting of rising time.

Step 5) Seismic ground motion evaluation

The seismic ground motion can be calculated using the fault rupture model established in Step 3 and using the element earthquake established in Step 4.

A group of seismic ground motions can be obtained as a result after seismic ground motions are calculated corresponding to each scenario based on the fault rupture model.

In order to consider the uncertainties related to fault rupture models, a logic tree method can be used to represent a combination of parameters such as the starting point of fault rupture, the number and location of asperities in each segment, the stress drop of asperities, the type of seismic wave generated from element earthquake, and the high frequency cut-off property.

Step 6) Seismic hazard evaluation

The seismic hazard curves can be calculated using the earthquake occurrence probability established in Step 2, and the peak acceleration of the seismic ground motion calculated in Step 5. A table can be prepared showing the maximum acceleration of the seismic ground motion that was calculated or the response spectrum and the number of earthquake events per year. The cumulative number of events per year can be determined through accumulation of the number of events per year, and the hazard curve can be calculated through Poisson approximation.

PSHA procedure considering fault rupture models

The scheme in Fig. 8 illustrates the procedure for a method combining a seismic hazard evaluation method using GMPEs and a seismic hazard evaluation method using a fault rupture model.

First, the seismic environment near the site is surveyed, and the earthquakes are broadly classified into earthquakes to be evaluated in the fault model, and all other earthquakes. Next, the annual incidence ν of events is determined. This value is one for which the response spectrum or maximum acceleration of ground motion at the site resulting from each earthquake exceeds a certain value y. Then, the seismic ground motion is calculated using a GMPE according to the conventional method for earthquakes that will not be evaluated in the fault model, as is indicated in the left flow in the figure.

On the other hand, the seismic hazard is evaluated according to the right flow in the figure in a case where seismic sources based on the fault rupture models need to be considered.

Finally, integrate the seismic hazard based GMPE and that based on fault rupture models by adding the annual incidence v, resulting from each earthquake, together.

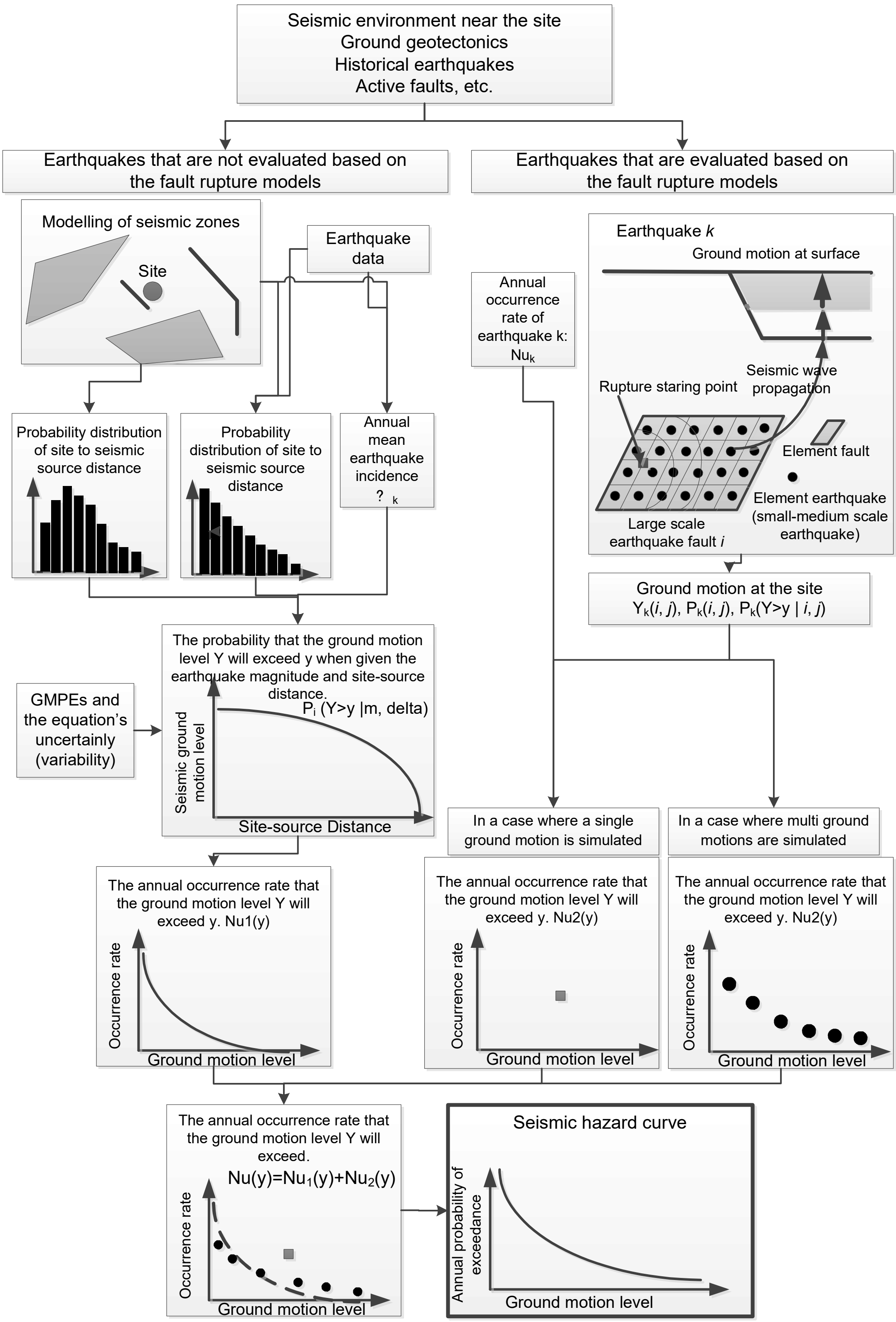

FIG. 8. Procedure of combining the seismic hazards obtained using an attenuation equation and a wave propagation model.

APPENDIX II

SEISMIC CAPABILITY WALKDOWN

This appendix presents the necessary organizational and procedural aspects of performing seismic capability walkdowns.

II.1 SEISMIC REVIEW TEAM

The seismic review team (SRT) performing the seismic walkdown includes the following members:

1. Seismic fragility engineers who are responsible for review and screening of items on the SEL and subsequently performing the fragility calculations;
2. Plant operations personnel who are knowledgeable about operations procedures, operator responses to abnormal situations, and equipment locations;
3. Systems engineers who are responsible for identification of the means necessary to bring the plant to and maintain in a controlled state, and systems and components required to achieve this condition;
4. Other plant personnel as necessary to open electrical cabinets, arrange for area access, provide safety equipment, etc.

II.2 PRE-WALKDOWN PREPARATION

Prior to the walkdown, available plant design documentation needs to be reviewed by the SRT members to gain understanding of the seismic design requirements for the plant, plant configuration and design features. The equipment layout drawings need to be marked to denote locations of equipment to be reviewed. Some preliminary generic calculations of fragility based on the experience based fragility methods discussed in Section 5.4 are performed to determine if some SSCs can be screened out on the basis of these simplified methods. Support to be provided by plant personnel needs to be identified in advance. Such support may include having a plant guide who can locate SEL items in the field, open panel doors for anchorage inspection, and de-energize electrical equipment for internal inspection.

II.3 WALKDOWN PROCEDURES

The SRT needs to review all equipment in the scope of work that is reasonably accessible and in non-radioactive or moderately radioactive environments. For components in highly radioactive environments or contaminated areas, a smaller team and briefer review may be employed. For components that are inaccessible, alternate means of examination, such as drawing review, review of construction records, construction photos, remotely taken photos, etc. may be necessary.

When the SRT has a reasonable basis for assuming that a group of components is similar in configuration and anchorage, a single lead item component of this group may be selected for detailed inspection and documentation. The similarity of a group of SEL items can be established based on equipment construction, dimensions, locations, seismic qualification requirement, anchorage type, and configurations. The 'similarity basis' needs to be confirmed during the walkdown.

The SRT needs to review the SEL items for equipment caveats defined in Ref. [7], screening guidelines, potential seismic interaction effects and anchorage. Depending on the seismicity at the site and generic earthquake experience based fragility calculations, some equipment may be screened from further evaluation based upon the walkdown findings.

II.4 WALKDOWN DOCUMENTATION

The walkdown findings for each lead equipment item are typically documented on a screening evaluation worksheet (SEWS). Examples of SEWS are provided by Refs [7, 12] with suitable modifications to incorporate in-structure seismic demand used in fragility methodology. The SEWS contains specific caveats to be verified during the walkdown or alternatively, details sufficient to perform a subsequent seismic capacity evaluation, if necessary, are noted. The SEWS are similar for different classes of equipment but have some specific equipment class differences. Entries in the SEWS denoting the walkdown status conform to the following conventions:

- 'Yes' signifies that the specific criterion is satisfied.
- 'No' signifies that the specific criterion is not satisfied.
- 'U' signifies that it is unknown if the criterion is satisfied and has to be resolved by further analysis or review.
- 'N/A' signifies that the criterion is not applicable to the specific item of equipment.

Current industrial practice is to document the review findings in an electronic database. Walkdown photos of the equipment may be hyperlinked to the database for easy retrieval of information and for creation of a permanent electronic record.

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ANNEX I

FRAGILITY TEST OF EQUIPMENT IN JNES AND ITS PROGRESS AND POSITIONING OF THE REPORT

Evaluation of JNES Equipment Fragility Tests for Use in Seismic Probabilistic Risk Assessments for U.S. Nuclear Power Plants was published in NUREG/CR-7040 [I-1]. Figure I-1 illustrates the evaluation process for fragility capacity of equipment. The tests are carried out for the selected equipment, and it is examined whether structural damage and/or loss of active function occur. In the case that an abnormality does occur, a detailed analysis is performed. Various types of abnormality can be expected as abnormality of function, and some of the fragility capacity could be improved by relatively simple measures, depending on such abnormality. Therefore, limits for maintaining function (e.g. acceleration, load, displacement) are evaluated, confirming how much fragility capacity could be improved by reinforcement measures if necessary.

References to Annex I

[I-1] UNITED STATES NUCLEAR REGULATORY COMMISSION, Evaluation of JNES Equipment Fragility Tests for Use in Seismic Probabilistic Risk Assessments for U.S. Nuclear Power Plants, NUREG/CR-7040, USNRC, Washington, DC (2011).

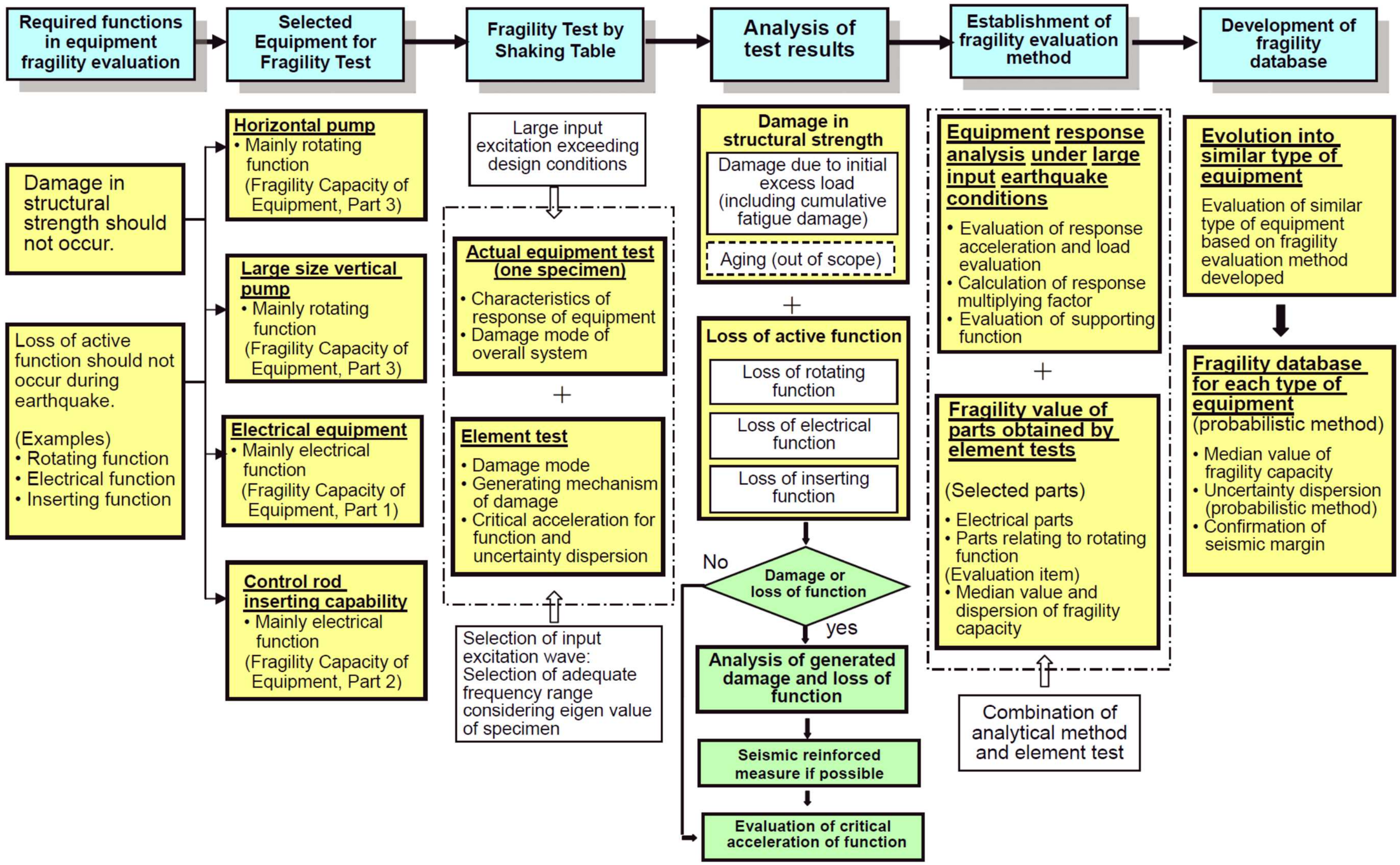

FIG. I-1. Evaluation process for fragility capacity of equipment.

ANNEX II

EXAMPLE OF THE APPROACH CONSIDERATION OF THE SEISMIC CONTEXT IN HUMAN RELIABILITY ANALYSES

This Annex presents the example of the HRA approach used for seismic PSA purposes. This approach is based on commonly used HRA concepts that were tailored specifically for internal and external hazards by the US Nuclear Regulatory Commission and the Electric Power Research Institute [II-1] as well as in other recent seismic PSA studies. The approach, which is briefly described in Section 6.7, covers the following HRA:

- Identification and Definition of Human Failure Events;
- Qualitative Assessment;
- Quantitative Assessment;
- Integration into PSA.

II-1. IDENTIFICATION AND DEFINITION OF HUMAN FAILURE EVENTS

As mentioned in Section 6.7, this step allows analyst to identify the HFEs to be considered in seismic PSA model. This is done taking into account the results of the fragility analysis and systems modelling, considering the SEL and the results of the walkdown. At this stage, some of the HFEs previously included in IEPSA might be eliminated or modified for different reasons:

- If the condition for particular human action has been screened out during the development of SEL;
- If the SEL task has determined that certain equipment could not be credited (assumed to be failed).

Note that care needs to be taken to consider each internal HFE carefully in the context of the SEL. Depending on the definition of the HFE in the IEPSA, it may be that the HFE is not eliminated, but is also not fully applicable and needs to be re-defined for the seismic PSA.

New HFEs that may not have been modelled in the IEPSA will also be identified through review of plant procedures and consideration of the seismic failures that will be in the seismic PSA model. The main reason for that is that certain condition that the seismic procedure calls for may not have been modelled in the IEPSA because it did not have a credible internal event failure mode. Examples for such kind of HFEs are following:

- HFEs related to seismic specific procedures and training;
- Seismic related control room actions as well as local manual actions (e.g. recovery of relay chatter);

- Undesired operator responses to false alarms and indications (triggered by relay chatter due to a seismic event).

II-2. QUALITATIVE ASSESSMENT

As mentioned in Section 6.7, this step allows analyst to characterize the seismic context and to determine the HFEs feasibility. The qualitative assessment performed at this step is directly supporting the next step - quantification. There are two levels of qualitative assessment: screening and detailed.

Screening qualitative assessment. At the screening stage, the feasibility assessment will evaluate each HFE to determine if there are sufficient time and resources to implement required action. The following factors are typically considered in this assessment:

- **Time:** Assessment whether the available time is sufficient to perform the action under seismic context. This includes the entire process of performing the action (i.e. cognitive and execution). The initial assessment is typically starting from the expected timing for the action under nominal conditions (i.e. internal initiating event), so the timing margin for a seismic event needs to be established and justified.
- **Human resources:** Assessment whether the available human resources are sufficient to perform the action under seismic context. A key consideration is that plant procedures often require that a damage assessment begin immediately following a seismic event. The people required to perform that assessment would not be available to perform other actions. For longer term actions, credit could be given for the arrival of additional support staff as called for by plant procedures, while for short term actions unavailability of staff could result in deeming the action to be not feasible under seismic context.
- **Cues:** Assessment whether the necessary cues are available to perform the action under seismic context. It is expected that this would be the case for the minimal damage bin, but for each subsequent damage bin this needs to be evaluated. In general, a good screening rule would be that no credit is taken for any cues whose limiting HCLPF value is below the lower PGA limit for the damage bin.
- **Procedures and training:** Assessment whether procedures and training for the operators are in place to perform the action. If the action is unique to seismic events or if seismic failures can modify the conduct of the action, then the procedures and training need to contain ‘warnings’ or ‘alternatives’ relevant to seismic events. If the action is one that is expected to be performed ‘from memory’, then the existence of a procedure is not required in order to demonstrate feasibility, but there still needs to be relevant training.

- **Accessibility and environmental factors:** Assessment whether the required location is accessible after a seismic event and whether the environmental factors are allowing operators to perform the action. Both the location of the action and the path to the action need to be accessible and free from hazards (e.g. flooding, debris, radiation). Key considerations would include seismic failure of unanchored equipment and block walls. If SSCs that could affect accessibility have a HCLPF below the lower bound of the damage bin, the screening typically assumes they are failed and render the action infeasible.
- **Tools and equipment accessibility and operability:** Assessment whether the tools and equipment are accessible and operable after a seismic event. This refers both to any special tools required to perform the action as well as the equipment required to be operated. Accessibility to special tools would be considered in the same way as discussed above. Operability may also pertain to the special tools if they could be damaged in a seismic event. If either the special tools or the equipment has a HCLPF below the lower bound of the damage bin, the screening can assume the action is infeasible.

HFEs determined to be not feasible are not to be credited, whereas the rest of the HFEs initially are to be quantified using a screening quantification approach (see discussion of quantification below). As mentioned in Section 6.7, the feasibility assessment is done for each plant damage bin defined for the screening analysis. Typically, this implies conservative consideration of the extent of damage that may have occurred at the plant. For example, an action determined to be feasible for a damage state with no damage expected may not be feasible for another damage state where safety related equipment damage can be expected.

Detailed qualitative assessment. A more detailed qualitative analysis will be performed for HFEs whose risk contribution is significant when a screening value is used. The key aspect of this activity is the development of the HFE narrative. This provides the necessary detail to perform a detailed quantification of the HFE (see 'Quantitative assessment' below). The detailed qualitative analysis will document the following:

- **Seismic induced initiating event:** There could be more than one initiating event that would result in the action being performed. While all of these initiating events need to be included in the documentation, it would be necessary to assess the action only for the specific initiating event(s) where a detailed HRA is desired.
- **Accident sequence** (preceding functional failures and successes): Similar to the above, the action may appear in multiple accident sequences, and only those for which the HFE is a significant risk contributor will need to be addressed. In defining each sequence, it is important that the sequence involves a given HFE in terms of

the functional failures and successes as well as the seismic damage that has accompanied the sequence. This calls for examining the cut sets that contain the HFE, and extracting from them the seismic damage context. It is not necessary to consider every unique combination of seismic failures in the cut sets, but rather to define a series of seismic contexts, each of which envelopes the damage for a group of cut sets. Since it is necessary to develop a HEP for each defined context under which the action is performed, the idea is to keep the number of 'context bins' as small as possible while obtaining a realistic assessment of the seismic risk.

- **Timing information**: This includes the traditional timing parameters, as follows:
  - $\boldsymbol{T_{sw}}$ – System time window. This is also often referred to as the available time. It is the time from T=0 (the occurrence of the seismic event or plant trip) until the time when the action is no longer effective. That is, if the action is not complete within this time, irreversible damage will occur. The system time window is usually based on thermal-hydraulic calculations.
  - $\boldsymbol{T_d}$ – Delay time. This is the time from T=0 until the operators have sufficient cues to diagnose that the given actions need to be taken. Prior to this time, the operators will not be able to determine that the conditions exist that would cause them to take the action. The delay time may also be based on thermal-hydraulic calculations when the action is taken in direct response to a parameter. There may be cases where the delay time relates to how long it takes to get to a step in the procedure where the operators are directed to check for a given condition. In the latter case, it is likely that this estimate will be based on observations under non-seismic conditions, so it is typical to adjust this value to account for distractions and complications related to the seismic effects.
  - $\boldsymbol{T_{1/2}}$ – Median response time. This is the time taken from the point at which the operators have the cues (i.e. from the end of the delay time) until the point at which the operators make the correct diagnosis. Since it is the median, it represents the time by which 50% of the crews will have made the correct diagnosis and 50% will not. It is likely that this estimate will be based on observations under non-seismic conditions, so it is typical to adjust this value to account for distractions and complications related to the seismic effects.
  - $\boldsymbol{T_m}$ – Manipulation (or execution) time. This is the time that it takes to perform the actions once the decision has correctly been made on what actions to perform. This time is usually based on walk-throughs of the actions, which would likely reflect non-seismic conditions. Adjustments may apply to this time for actions outside the main control room to account for complications from

seismic damage. It is not generally necessary to adjust this for actions in the main control room.

- **Accident specific procedural guidance:** This refers to procedures that may direct certain actions to be performed in the event of an earthquake. Such guidance can affect an HFE in different ways.
  - It may improve the performance of the action because it gets the operators to the decision more quickly than would otherwise occur if the normal diagnosis process was followed.
  - It may help the operator to diagnose the situation by providing alternate direction or alternate cues to compensate for seismic damage.
  - It may degrade performance of the action by diverting resources and attention away from the performance of other actions in response to the seismic event.
- **Availability of cues**: This refers to the necessary cues and other associated indications that may be needed to identify necessary actions, as well as those that might subsequently enable the operators to detect the need for a correct action that has been omitted or performed incorrectly. This includes considerations whether the operators have alternate cues that could compensate if primary cues are compromised due to the seismic event.
- **Preceding operator errors or successes in sequence.** This effects the dependency between HFEs, since preceding errors indicate the operators are on an erroneous path. Intervening successes (between two HFEs that might appear in cut sets) will 'de-couple' the dependency between the two failures.
- **Operator action success criteria.** The operator needs to respond to alarms and confirmed malfunctions with certain actions in a given time window established based on thermohydraulic analyses.
- **Physical environment.** The physical environment will have been assessed initially under non-seismic conditions. Seismic induced failures can alter the physical environment by causing debris or dust, loss of lighting, increased heat or cold, humidity, etc.

A key aspect of this task is a review with plant operations, including talk-throughs and walk-throughs. Maximum use will be made of the plant operations review for the internal events HRA, but it will still be necessary to augment this with consideration of the unique aspects of the seismic event context.

II-3. QUANTITATIVE ASSESSMENT

As mentioned in Section 6.7, this step allows analyst to estimate the HEPs for identified HFEs based on the results of qualitative assessment.

There are two levels of quantitative assessment: screening and detailed.

Screening quantification: The key to screening quantification is defining plant damage levels related to the severity of the earthquake. Earthquake severity, while a convenient measure that allows each HFE to be treated in a manner similar to a fragility, is a very imperfect parameter for measuring human performance. It has in the past been promoted as the primary parameter affecting human performance following an earthquake through the use of the 'shock model'. This model supposes that the HEP increases as the severity of the earthquake (i.e. the PGA) increases, due to the 'shock' felt by the operators as they experience the ground motion.

Variations of this approach add a time factor to allow for the effect 'wearing off', but do not address the other issues. Again, while convenient, more recent research in human performance indicates that the total context needs to be considered (e.g. EPRI 1025294 [II-1]). For screening, the idea is to determine the HEP for the HFE under 'normal' (i.e. non-seismic, internal events initiators) and to adjust it for seismic events in a way that conservatively bounds the HEP for each HFE by defining plant damage levels that establish a context for the action.

IAEA Safety Reports Series No. 66 [II-2] defines four plant damage levels. While the way these damage levels are defined therein is by no means the only one to approach the analysis, it is instructive and illustrates the required conservatism. The damage levels based on [II-2] are defined as shown in Table II-1.

TABLE II-1. EXAMPLE OF PLANT DAMAGE LEVELS FOR SCREENING QUANTIFICATION

Damage Level (DL)	Description of DL	Earthquake Exceedance Level (EL)[5]	HRA Bin
DL 1	No significant damage to SSCs important to safety. No significant damage to SSCs not important to safety.	SL-1 < EL < SL-2 EL < HCLPF for NSQ items	1
DL 2	No significant damage to SSCs important to safety. Significant damage to SSCs not important to safety, not required for power generation.	SL-1 < EL < SL-2 EL < HCLPF for SQ items	2
DL 3	No significant damage to SSCs important to safety. Significant damage to SSCs not important to safety, required for power generation.	EL > SL-2 EL < HCLPF for SQ items (or marginal exceedance for some SQ items)	3
DL 4	Significant damage to SSCs important to safety.	EL > SL-2 EL > HCLPF for SQ items	4

Note the conservative nature of the definitions. Damage level 1, which is associated with no change to the HEP for any HFE, applies only up to the SL-2 or the HCLPF of the weakest non-seismically qualified SSC, when it is expected that there would be a very low probability of any significant failures at all. Once the HCLPF for non-seismically qualified items is exceeded, the HEPs begin to increase. Damage level 2 applies up to the HCLPF of the weakest safety related SSCs, but it does not account for whether the failure of the weakest non-seismically qualified SSC would actually affect human performance. Since the HCLPF represents the 0.01 failure probability for an SSC, the HEP is increased even though there is only a 1% expectation of failure of a single safety related SSC – which would not be expected to be a particularly difficult context for the operators to respond to even if there were some non-safety related SSC failures.

There is also the issue of how to adjust the HEPs for each damage bin. The EPRI approach in [II-1]) uses a decision tree (essentially an event tree) that asks a series of questions about the action, such as the timing, where the action is, and how difficult it is. The answers to those questions lead to a multiplication factor on the baseline internal events HEP or a set value (e.g. 0.5, 1.0) to use for the seismic HEP. Such value or multiplication factor does not actually adjust the performance shaping factors for the context, because in this damage state approach the definition of the damage bin is somewhat subjective (e.g. it is 'significant damage to SSCs not

[5] NSQ = non-seismically qualified, SL-1 = seismic level 1, SL-2 = seismic level 2, SQ = seismically qualified.

important to safety' rather than some specific set of SSCs to assume damaged). Whatever adjustments are made to the HEPs, the outcome is that they are likely to be very conservative versus the actual impact of the damage.

For screening purposes, PGA is used as a surrogate for the extent of plant damage for development of conservative HEPs for screening analysis. That is, each damage bin is defined as a HCLPF range, starting at the HCLPF of a representative SSC in the bin and ending at the HCLPF of the representative SSC for the next highest bin. Note that the representative SSC may not be the one with the lowest HCLPF, since that SSC may not on its own be a significant part of the context. Keeping in mind that using a HCLPF is already a quite conservative trigger point for the bin, the representative SSC will be the one where the damage really would begin to define a 'jump' to a more adverse context than the previous bin (or the base internal events context). It is then possible to map the HRA bins to the seismic event levels used in the model. For example, if there are ten seismic events in the model, it may be determined that the first three apply to HRA damage bin 1, the next four to damage bin 2, etc. In most cases, the HEP applied using this method will not be a significant risk contributor, and the screening value can stay.

Detailed quantification. Detailed quantification is performed for all the HFEs that are shown to be risk significant when the screening values are used. It is implemented by making HFE specific and damage specific adjustments to the HEPs. This requires that the HEP be adjusted on a cut set by cut set basis that considers the actual damage that has occurred in the cut set. The detailed qualitative analysis will provide the information required to make adjustments to the parameters considered (such as timing, stress, accessibility) that were discussed in Section II-2 of this Annex. That section discussed the concept of defining "context bins" for each action, and the detailed quantification would be performed for each of the context bins by adjusting the baseline parameters used in the model to account for the context. In the detailed quantification of these HFEs, they may no longer simply relate to a bin, but to a combination of SSC failures represented in the model and appearing in cut sets. The specific parameter adjustments will depend on the HRA quantification model that is being used. Some examples are provided below:

- **Time increase:** Increase the values of T_d, $T_{1/2}$, and/or T_m to account for the seismic effects (e.g. 1-5 minutes). Increases with the lower end being used for minimal damage and working upwards as the damage context increases.
- **Stress increase:** Increase the stress level for cognition and/or execution.
- **Quality of procedures:** It implies questioning whether the procedures adequately cover the response under the damage context and whether there are seismic specific procedures that would be in effect in parallel to abnormal operating procedures or

emergency operating procedures (multiple procedures in effect in parallel). Note that a belief by the operators that the procedures are incomplete or inadequate for the situation they are facing could bias them towards deliberately violating them in the false belief that they are doing what is better for the plant.

- **Quality of cues:** It implies questioning the availability of the primary cues, whether the operators are experienced in use of alternate cues, and whether the procedures provide warnings/alternates to the operators.
- **Training applicability:** It implies questioning whether the operators are specifically trained for the particular scenario and/or to what extent the context is covered by the general training.
- **Environment degradation:** It implies questioning whether the environmental conditions (e.g. light, temperature, humidity, dust/debris) degraded due to seismic damage.
- **Workload increase:** It implies questioning whether the damage increased the workload for the operators performing the action (in comparison with the IEPSA context).
- **Recovery credit:** It implies questioning whether the extra crew credit is still valid, and whether the shift technical advisor review and technical support centre are available. The earthquake may delay the availability of these people to provide review and recovery support to the primary operator because they may be required to perform inspections of earthquake damage or be involved in other coordination efforts. An estimate of when they would become available needs to be made (given the context), and no credit is given if the action needs to be completed before that time.

II-4. INTEGRATION INTO PSA

As mentioned in Section 6.7, the purpose of this step is to incorporate basic events associated with HFEs into the seismic PSA model. The integration consists of the following substeps:

- **Cut set review and HEP reasonableness check:** This includes a check of the consistency of the HEP quantification by reviewing the final HEPs relative to each other and relative to the given 'scenario context, plant history, procedures, operational practices and experience'. The reasonableness check is done at three levels: (1) consistency within the HFE, (2) consistency between HFEs (relative risk ranking), and (3) cut set review [II-1]. The cut set review is typically performed as part of the quantification task.
- **Recovery analysis:** This is a review to determine whether the recoveries credited in the IEPSA are still valid for the seismic context, and whether additional recovery actions are needed to get a realistic estimate of the seismic risk. The recovery actions

are defined, evaluated, quantified, and integrated into the SPSA in the same manner as other HFEs.

- **Dependency:** As with internal event HRA, dependency between HFEs will be evaluated. In this case, however, it considers the context of the seismic event. The dependency analysis typically takes into account the following aspects:
  - The time necessary to complete all actions in relation to the time available to perform the actions;
  - Factors that could lead to dependency (e.g. common instrumentation or procedures, an inappropriate understanding or mindset as reflected by the failure of a preceding HFE, and increased stress; spatial and environmental dependencies needs to be considered for external events);
  - The availability of resources (e.g. crew members and other plant personnel to support the alignment of the portable equipment).

EPRI 1025294 [II-1] provides guidance on selecting dependency levels by means of a decision tree adapted from practice in IEPSA.

As shown in Fig. II-1, seismic versions of the affected HFEs can be explicitly modelled in the seismic PSA model when screened HEPs are used, since the screening approach uses PGA as a surrogate for the extent of plant damage. The seismic logic will be mapped to existing HFE basic events in the IEPSA model. The rule based recovery file and the mutually exclusive event combination file or logic will be updated to reflect the seismic HFEs.

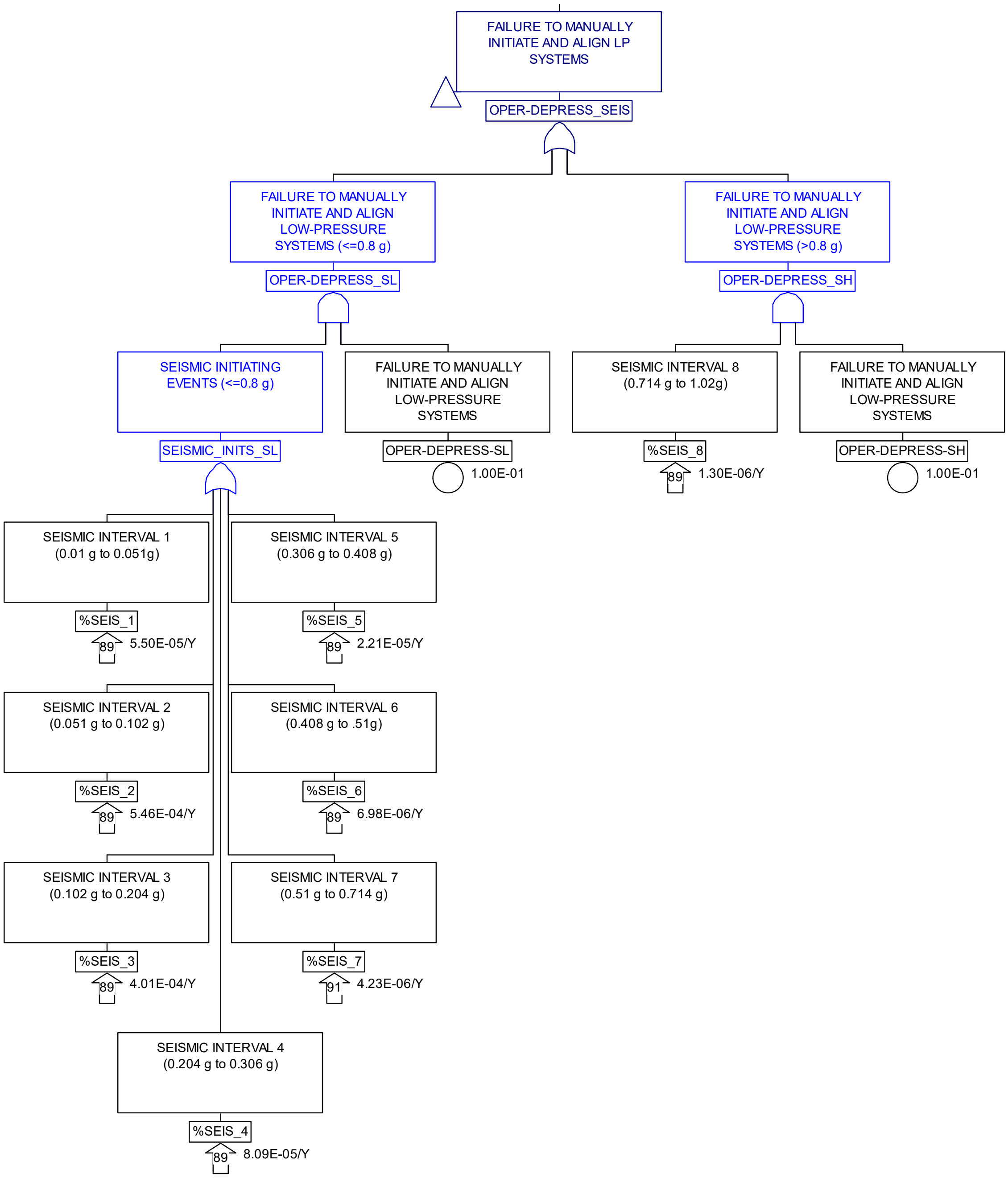

FIG. II-1. Example logic for seismic HFEs using screening quantification.

For those HFEs that will need to be evaluated in detail, the HEPs will be related to actual plant damage as represented by the failures in each cut set. In this case, the normal approach would be to create recovery rules that will apply a HEP appropriate to the SSC damage that has occurred in the cut set. That is, each cut set would be searched for combinations of the HFE with failures that were selected as representing the seismic damage context. Where these combinations are found, the recovery rule would apply the correct HEP for the context.

References to Annex II

[II-1] ELECTRIC POWER RESEARCH INSTITUTE, A Preliminary Approach to Human Reliability Analysis for External Events with a Focus on Seismic, EPRI 1025294, EPRI, Palo Alto, CA (2012).
[II-2] INTERNATIONAL ATOMIC ENERGY AGENCY, Earthquake Preparedness and Response for Nuclear Power Plants, Safety Reports Series No. 66, IAEA, Vienna (2011).

ABBREVIATIONS

CDF	core damage frequency
GMPE	ground motion prediction equation
HCLPF	high confidence of low probability of failure
ISRS	in-structure response spectra
LERF	large early release frequency
PGA	peak ground acceleration
PSA	probabilistic safety assessment
PSHA	probabilistic seismic hazard assessment
SEL	seismic equipment list
SPSA	seismic probabilistic safety assessment
SSCs	structures, systems and components
UHRS	uniform hazard response spectrum

CONTRIBUTORS TO DRAFTING AND REVIEW

Abe, H.	Japan Nuclear Energy Safety Organization, Japan
Amico, P.	Jensen Hughes, United States of America
Campbell, R.	Consultant, United States of America
Chokshi, N.	US Nuclear Regulatory Commission, United States of America
Coman, O.	International Atomic Energy Agency
Ebisawa, K.	Japan Nuclear Energy Safety Organization, Japan
Hardy, G.	Simpson Gumpertz and Heger, United States of America
Johnson, J.	Consultant, United States of America
Kammerer, A.	US Nuclear Regulatory Commission, United States of America
Nakajima, M.	Central Research Institute of Electric Power Industry, Japan
Ohtori, Y.	Central Research Institute of Electric Power Industry, Japan
Poghosyan, S.	International Atomic Energy Agency
Serbanescu, D.	Consultant, Romania
Stoeva, N.	International Atomic Energy Agency
Suzuki, K.	Japan Nuclear Energy Safety Organization, Japan
Takada, T.	University of Tokyo, Japan

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