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Feasibility Study on a Potential Consequence-Based Seismic Design Approach for Nuclear Facilities

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ABSTRACT

The commercial nuclear power plant industry has initiated the Licensing Modernization Project (LMP) to enhance the risk-informed and performance-based (RIPB) regulatory basis for licensing and regulating the safety of advanced nuclear power reactors. The LMP framework is supported by both the U.S. Department of Energy (DOE) and the Nuclear Energy Institute (NEI). The LMP framework relies heavily on RIPB concepts and approaches that together implement the defense-in-depth philosophy. In Regulatory Guide 1.233, the U.S. Nuclear Regulatory Commission (NRC) adopted, with clarifications, the LMP principles and methodology described in the NEI guidance document NEI 18-04.

Although the LMP framework contains considerable detail about how its concepts should work for many aspects of reactor safety, including external hazards, it does not yet explicitly address how to incorporate seismic performance criteria into the physical design of structures, systems, and components (SSCs). This is particularly true for advanced reactor designs that rely on passive safety controls, have significantly different facility footprints, or use accident-tolerant fuels.

This report documents a study evaluating the state of practice for the seismic design of nuclear facilities, in order to determine whether it is feasible to implement a new, fully RIPB seismic safety approach that integrates existing nuclear industry codes and standards with the LMP framework. The report also seeks to identify any implementation and regulatory hurdles that could inhibit broad application of the LMP framework. Preliminary conclusions are as follows:

- This report discusses an alternative to the current standard review plan approach to seismic design. This alternative integrates RIPB seismic design concepts with the LMP framework; it is referred to herein as the RIPB/LMP Seismic Design Framework. To illustrate the concept, the report describes an example seismic design approach that aligns LMP concepts with the performance targets described in American Society of Civil Engineers (ASCE) standards, such as ASCE 43, for seismic design. This example approach is technology-inclusive and applies to an array of advanced nuclear power reactor designs.

- The example approach and associated stylized risk analyses show that the RIPB/LMP Seismic Design Framework can be used for applications under both Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, “Domestic licensing of production and utilization facilities,” and 10 CFR Part 52, “Licenses, certifications, and approvals for nuclear power plants.” The NRC is currently in the rulemaking process for the new 10 CFR Part 53, “Licensing and regulation of advanced nuclear reactors.” It is anticipated that the RIPB/LMP Seismic Design Framework can also be adjusted to be consistent with 10 CFR Part 53, as this new rule is developed.

- There are no obvious regulatory obstacles to implementing the RIPB/LMP Seismic Design Framework, along with recent updates to several seismic design standards and regulatory guides. However, the detailed evaluations in this report identify several technical, programmatic, and regulatory considerations for implementing the framework.

- The major benefits of the RIPB/LMP Seismic Design Framework come from the flexibility it affords to assign different seismic design categories (i.e., different design-basis ground motion levels) and different design performance limits (i.e., different limit states) to SSCs, based on their risk significance and other risk-informed decision-making factors.

(By contrast, the current approach uses a single design-basis earthquake and a very stringent elastic limit state for all SSCs, irrespective of their risk significance.) Thus, in the RIPB/LMP Seismic Design Framework, the safety margins of individual SSCs are controlled according to their contribution to system-level and plant-level risk, thereby reducing unnecessary conservatism (or increasing margins where needed) and achieving a more risk-balanced design.

- Additional analyses are recommended to fully demonstrate the implementation and to identify pros and cons of the proposed changes in the larger context of seismic design, seismic safety, cost optimization, and existing seismic safety regulations.

TABLE OF CONTENTS

FIGURES

Page

TABLES

EXECUTIVE SUMMARY

Over the past few years, the U.S. commercial nuclear power industry has initiated the Licensing Modernization Project (LMP) to enhance the risk-informed and performance-based (RIPB) regulatory basis for licensing and regulating the safety of advanced nuclear power reactors. The LMP framework[1] includes appropriate risk targets (both for overall plantwide risk and for event sequences with multiple structures, systems, and components (SSCs)), as well as an approach to classifying safety-important SSCs that accounts for the safety role of each SSC more directly than the traditional approach. The LMP framework also emphasizes the understanding of individual event sequences (or groups of them) and provides an updated approach to defense in depth. Finally, it more directly applies probabilistic risk assessment (PRA) as a basis for safety-related decision-making (see, for example, NEI, 2018; INL, 2018). It relies heavily on RIPB concepts and approaches that complement the current defense-in-depth philosophy. Both the U.S. Department of Energy (DOE) and the Nuclear Energy Institute (NEI) support the LMP framework. For its part, the U.S. Nuclear Regulatory Commission (NRC) has adopted the LMP proposals, with clarifications, as described in Regulatory Guide (RG) 1.233 (NRC, 2020b).

While the LMP framework considers external hazards in terms of functional design bases, it does not yet explicitly address how to incorporate seismic performance criteria into the physical design of SSCs. This is particularly true for advanced reactor designs that rely on passive safety features, have significantly different facility footprints, or use accident-tolerant fuels. Although RIPB approaches for seismic design and seismic safety analyses date back to initiatives started in the 1970s,[2] such approaches continue to evolve. This evolution is evidenced by updates to the many standards and RGs that apply to seismic hazards and seismic design, such as RG 1.208 (NRC, 2007), DOE Standard 1020-2016 (DOE, 2016), and the American Society of Civil Engineers (ASCE) standards ASCE 4 (ASCE, 1998) and ASCE 43 (ASCE/SEI, 2005).[3]

Although many applications of seismic probabilistic risk assessment (SPRA) over the years have confirmed that existing seismic design includes significant margins for performing required safety functions,[4] some of the fundamental issues associated with the deterministic design procedures embedded in the NRC's regulatory approach remain. These issues relate to a lack of explicit consideration of the behavior of safety-significant SSCs for beyond-design-basis ground motions and to uneven margins that make inconsistent contributions to plant-level safety and risk significance. In addition, the compartmentalized approach to design (e.g., considering each SSC separately) often leads to excessive conservatism that may not contribute to overall plant safety or provide a consistent way to achieve the desired seismic capability of the plant as a whole. An SPRA reflects a plant's seismic capability in terms of its design, construction, and operations. The increased use of SPRAs, the current movement toward a more RIPB licensing framework, and extensive recent experience with SPRAs create a unique opportunity to

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1 "Framework" in this context means a conceptual structure to support development of the practical components needed to construct and regulate advanced light-water reactors and advanced nonlight-water reactors.

2 The development of probabilistic seismic hazard analysis began in the 1960s with a seminal publication by C. Allin Cornell (Cornell, 1968).

3 The current version of ASCE 43 is ASCE 43-05, published in 2005. A new version is planned to be published soon. Both versions have the same basic philosophy. In this Executive Summary, ASCE 43 is therefore cited without the year of publication.

4 In new license applications under Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, "Licenses, certifications, and approvals for nuclear power plants," SPRAs are used to demonstrate the overall design margin for beyond-design-basis ground motions.

incorporate RIPB concepts in updates to NRC regulations and guidance on seismic design, especially in ways that lead to a more uniform, balanced, and safety- and risk-consistent plant.

Objectives

This report examines ideas and processes for aligning LMP concepts within the current RIPB framework for seismic design and safety and identifies potential future activities to support the NRC's objectives. The NRC staff within the Office of Nuclear Regulatory Research initiated the project governing the work described in this report to identify and evaluate potential improvements to the existing regulatory basis for seismic design. The revised and enhanced RIPB framework will be offered as one of several alternatives to the more deterministic approach that is currently in use.

The objective of this project is to evaluate whether and how to implement the enhanced RIPB concepts of the LMP framework, together with recent improvements to industry codes and standards, in nuclear seismic design. This project also aims to identify any implementation and regulatory hurdles that could inhibit broad adoption and application of the LMP framework. Specifically, the NRC staff seeks to develop a set of preliminary technical and regulatory insights to support the following:

- integration of the LMP concepts with the current NRC regulatory philosophy and regulations
- adoption of appropriate risk metrics
- an understanding of system-level and plant-level performance relative to the performance of individual components
- integration of earthquake-induced failures with nonseismic failures and human errors
- quantification of the risks from earthquakes relative to those from other accident initiators
- consideration of other desirable factors for overall plant safety, such as defense in depth and risk-balanced profiles (i.e., balance between prevention and mitigation, more uniform margins, avoidance of singleton failures that control the risk, etc.)

These insights are intended to be technology-inclusive and explicitly incorporate RIPB evaluation techniques that can be used to license future commercial advanced nuclear reactors.

Any new regulations or guidance for seismic design stemming from this project should be integrated within the broader NRC RIPB framework and should build on existing risk-informed approaches in structural and seismic engineering. Recommendations should be rooted within existing practices (e.g., using existing codes and standards as far as practicable) so that they can be implemented within current NRC regulations (e.g., Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, "Licenses, certifications, and approvals for nuclear power plants," and 10 CFR Part 50, "Domestic licensing of production and utilization facilities") or through reasonable updates to these regulations and associated guidance. The NRC is currently in the rulemaking process for the new 10 CFR Part 53, "Licensing and regulation of advanced nuclear reactors" (NRC, 2020a). It is anticipated that the proposed RIPB framework can also be adapted to be consistent with 10 CFR Part 53.

Overall Approach

This report discusses an alternative to the current approach to seismic design and evaluates the regulatory benefits of the enhanced RIPB concepts within the LMP framework. This alternative is referred to as the RIPB/LMP Seismic Design Framework. To illustrate the concept, the report describes an example approach to seismic design that aligns the LMP concepts with the performance targets described in ASCE standards for seismic design, such as ASCE 43. The report demonstrates implementation through this example, and therefore discusses ASCE 43 and related standards in detail.

ASCE 43 is a logical choice for many designs that use the LMP framework as their regulatory basis for licensing: it is a performance-based code for nuclear facilities; it contains a graded approach that considers the risk significance of each component; it uses well-established design procedures familiar to the nuclear industry. Under ASCE 43, the appropriate selection of design-basis ground motions and design limit states leads to adequate margins and balance in a design. The approach in this report can also accommodate codes other than ASCE 43, such as ASCE 7 (ASCE/SEI, 2010), for the design of low-risk facilities. (Microreactors are special systems of relatively low risk, and the regulatory framework for them is evolving (see, e.g., BNL, 2020). This report does not explicitly consider the application of the RIPB/LMP Seismic Design Framework to microreactors; this topic should be explored in the future.)

The strategy underlying the RIPB/LMP Seismic Design Framework is to consider the performance of individual SSCs and the roles they play in event sequences. In contrast, under current regulations, each safety-related SSC is designed to the same seismic criteria (e.g., the safe shutdown earthquake (SSE)[5]), irrespective of its role in overall system performance. The new strategy embeds risk targets into the acceptability criteria for the seismic design of each SSC, and these risk targets require explicit consideration of the behavior of each important SSC when seismic demands exceed the design-basis ground motion. The strategy explicitly uses SPRA and considerations such as defense in depth and safety margins to tailor the engineering design of the plant, as well as the design of each individual SSC, to the desired performance in the relevant event sequences. The strategy thus achieves the desired safety goals while allowing plant designers and operators greater flexibility in how the overall seismic design can meet system- and plant-level acceptability criteria. It also facilitates the allocation of resources where they matter most to safety.

The LMP framework proposes the use of a frequency-consequence (F-C) target to identify acceptable accident event sequences. The F-C target is a frequency-versus-dose curve delineating ranges of acceptable risk for event sequences. The risk metric incorporates the frequency of occurrence of the event sequences, termed licensing-basis events (LBEs),[6] and the associated radiological dose to the public at the site boundary. In the process proposed in this report, if the design does not meet the F-C metric, the design is modified, and the process is iterated. In addition to recommending that acceptable individual event sequences lie below the F-C target, the LMP framework accounts for aggregate risk by adding up the product of the

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5 The SSE is the design-basis ground motion that is used to determine seismic loads for individual SSCs, and these loads, along with other appropriate load combinations, are used for the design. A nuclear power plant must be designed such that, if the SSE ground motion occurs, critical SSCs will remain functional and within applicable stress, strain, and deformation limits.

6 LBEs are the event sequences considered in the licensing process to derive regulatory requirements. LBEs may include normal plant operational events, events anticipated to occur in the life of the facility, and off-normal events, including infrequent design-basis events (DBEs).

frequency and the dose for each event sequence over all sequences and comparing this total risk with cumulative risk targets. If the cumulative or integrated target is not met, the facility design requires further enhancements to meet it.

It is important to note that in the LMP framework, the safety classification of SSCs already accounts for special treatment, such as differences in maintenance and operating requirements. However, it does not yet explicitly address how to incorporate seismic performance criteria into the physical design of an SSC. Thus, the RIPB/LMP Seismic Design Framework represents a change in the governing design philosophy, in which the design of an individual SSC for seismic safety is tied to the SSC's role in overall safety, as measured by its contribution to the risk of those event sequences in which it participates. Table 1 describes key conceptual differences between the current approach to seismic design of nuclear power plants and the approach proposed in this report, which is based on the LMP and enhanced RIPB concepts in ASCE 43.

Table 1 Comparison of the Current and Proposed Approaches to Seismic Design

Current Seismic Design Approach	LMP/ASCE 43 Approach
Safety Classification: For seismic design purposes, all safety-related SSCs are considered Seismic Category 1 (SC-1) SSCs.	Safety Classification: The LMP framework includes alternate safety classifications that consider risk significance. ASCE 43 allows for alternate seismic design categories (SDCs)[7] based on the desired level of design performance and consistent with risk significance.
Design-Basis Ground Motion: All SC-1 SSCs are designed to the same ground motion level, corresponding to the SSE or design-basis ground motion. The current site-specific design-basis ground motion corresponds to the highest level determined using the RG 1.208 approach; it is based on the hazard exceedance frequency for a performance goal of 1×10^{-5} per year.	Design-Basis Ground Motion: Design-basis ground motions for each SDC are derived based on the performance target and margins associated with the design process. Thus, there is no single design-basis ground motion for all SDCs. The ground motions are based on hazard frequencies for targeted performance goals that depend on the SDC.
Design Performance Criteria: No explicit numerical criteria are defined. The design limits are associated with elastic behavior, resulting in significant safety margins beyond the design-basis ground motion.	Design Performance Criteria: A quantitative design performance criterion is associated with each SDC. Alternate design limit states (LSs) (e.g., those allowing inelastic behavior) are permitted, depending on the desired design performance and margins.
Design Procedures: The design employs deterministic seismic response analyses for the SSE ground motion to establish the seismic demand. The physical design of an SSC uses established construction and engineering standards, such as those published by the American Concrete Institute (ACI), the American Institute of Steel Construction (AISC), the American Society of Mechanical Engineers (ASME), and others.	Design Procedures: The design employs seismic response analyses based on the ground motions that correspond to the assigned SDCs. Seismic demands are adjusted based on the selected LS. The physical design of an SSC uses established construction and engineering standards, such as those of ACI, AISC, ASME and others.

7 Although the initial ASCE concept was to define various SDCs for DOE facilities based on the risk consequences for each facility, this classification can also be used for individual SSCs.

Table 1 highlights important benefits of using enhanced RIPB seismic design concepts. These concepts allow the assignment of different seismic design categories (SDCs) to individual SSCs (providing flexibility in selecting design-basis ground motion levels), and they also permit the selection of alternate design limit states (LSs) to ensure that margins are consistent with each SSC's contribution to overall plant risk. This avoids excess conservatism that does not provide commensurate safety benefits (and also identifies situations that may require additional margins). The strategy is practical, because once the SDC and LS are chosen, the subsequent design processes are essentially the same as those used currently.[8]

This project included the following supporting activities:

- Current NRC regulations and guidance pertinent to implementation of the ASCE 43 seismic design approach were reviewed to identify any changes that might be needed.

- The LMP framework was reviewed to determine how to align the ASCE 43 seismic design approach with this initiative and with the larger RIPB framework. Two crucial factors in this alignment are (1) the use of PRAs in making design decisions and (2) the integration of sequence-level and plant-level risk measures in an iterative design process.

- ASCE 1, ASCE 4, and ASCE 43 were reviewed to identify (2) the differences between the proposed design process and current seismic design methods, (2) the interplay among the different SDCs and LSs in meeting risk metrics (as opposed to the current approach of using only a single SDC/LS combination, namely SDC–5 and LS-D), and (3) practical ways to implement performance targets for individual SSCs in the seismic design process.

- A stylized seven-step design process was formulated, not rigidly, but to illustrate basic concepts and to facilitate discussion of regulatory implementation. This process links the LMP concepts with the ASCE 43 seismic design approach to achieve the project objectives and to illustrate implementation considerations in detail. The process was developed to be integrated within the broader RIPB framework and is referred to as the LMP/ASCE 43 Integration Approach. A fuller description appears in the next section of the Executive Summary and in the body of the report.

- Several implementation issues were assessed, yielding initial insights about the design process. Potential effects of the RIPB/LMP Seismic Design Framework and the LMP/ASCE 43 Integration Approach on the broader regulatory and operational requirements of nuclear plant safety were also identified.

- The LMP/ASCE 43 Integration Approach was evaluated using site-specific ground motions from nine power plant sites in the Central and Eastern United States, representing various site conditions (namely, hard rock, stiff soil, and soft soil) and geographical areas. Ground motions corresponding to the top three SDCs in ASCE 43 were compared to the design ground motions derived from current seismic design requirements to demonstrate the benefits of the enhanced RIPB framework.

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[8] While ASCE 4 does allow some variations for seismic response analysis, the principal response analysis method is basically the same as that currently used with traditional deterministic methods.

- Several simple calculations were performed to demonstrate the feasibility and validity of the process, to clarify implementation issues, and to gauge the level of effort needed for potential future activities in support of the overall LMP/ASCE 43 integration goal. These calculations included the following:

  – calculations of generic fragilities based on underlying assumptions used in ASCE 43 for alternate SDC and LS selections

  – designs for simple shear wall elements using alternate SDC and LS combinations for the same site, to measure the effects of these combinations on physical designs and fragilities

  – a more detailed PRA-based analysis with progressive scope for future activities, including an exploration of approximated adjustments to SSC fragilities to emulate different SDC/LS combinations when a detailed SPRA and supporting information are available

- A workshop was held on September 2–3, 2020, to discuss the RIPB/LMP Seismic Design Framework with stakeholders and to obtain their feedback (see Appendix A).

The LMP/ASCE 43 Integration Approach

This report presents a seven-step seismic design process to implement the RIPB/LMP Seismic Design Framework. As stated earlier, this is not a rigid process. It was developed to explain basic concepts and to explore the regulatory benefits of the RIPB/LMP Seismic Design Framework. The process builds on existing RIPB approaches in structural/seismic engineering, maintains certain familiar deterministic processes for immediate use, and uses existing codes and standards whenever feasible.

In this seven-step process, SPRAs and seismic design are interrelated: SPRAs (with appropriate risk metrics) are used to inform licensing decisions and help the designer assign alternate SSC design-performance targets and design LSs. (In the existing approach, SPRAs are performed during the 10 CFR Part 52 process to demonstrate plant-level seismic margins for an already-designed plant.) The strategy of the new, iterative design process is to meet risk targets using combinations of variable seismic design requirements for individual SSCs, then examine their contributions to system-level performance using the SPRA. The goal of applying SPRA tools during the design process itself is to arrive at a plant-level design that is both safe and more risk-balanced, with each SSC's margins being consistent with its risk significance in the overall system, with the plant's performance goals, and with component-level performance targets.

The seven steps are presented concretely in the form of the LMP/ASCE 43 Integration Approach to highlight important practical aspects of the RIPB/LMP Seismic Design Framework. Design standards other than ASCE 43 and risk analysis methods other than SPRA may also be suitable for demonstrating compliance with risk criteria, but this report does not evaluate these.

The seven steps of the LMP/ASCE 43 Integration Approach are as follows:

<u>Step 1:</u> Select the initial ASCE 43 SDC and LS for each SSC, considering its safety function and the LBEs identified in the internal-events analysis, including the internal-events-based safety classification of SSCs.

Step 2: Conduct a preliminary design and fragility assessment to determine whether to use more realistic fragilities of important SSCs in Step 3. (This optional step may only be necessary in subsequent iterations to improve the accuracy of Step 5.)

Step 3: Estimate the fragilities of the SCCs.

Step 4: Perform the SPRA.

Step 5: Check the SPRA results against the NEI 18-04 F-C target and cumulative risk criteria, as well as criteria for defense in depth, reliability, and other factors in risk-informed decision-making. Revise the SDC and LS for each SSC as appropriate.

Step 6: Repeat Steps 2 to 5 as needed.

Step 7: Finalize the selection of ASCE 43 SDCs and LSs for the licensing-basis seismic design.

It is important to note that this seven-step process uses ASCE 43 and related standards to determine the SDCs and LSs to be used for the final design. The process relies on available design information to estimate fragilities.

Outcomes of Current Activities Conducted to Support Project Objectives

This report comprehensively explains the seven-step LMP/ASCE 43 Integration Approach. It also describes and evaluates an initial set of practical considerations for implementing LMP concepts and related RIPB enhancements within the existing seismic design framework. These considerations are evaluated in the context of the proposed seven-step process.

To demonstrate the potential benefits of relaxing the requirement that all safety-significant SSCs be designed to the most stringent SDC (namely, SDC–5), the report compares the peak ground acceleration (PGA) and 5-hertz (Hz) ground motions for lower SDCs (namely, SDC–4 and SDC–3) to those for SDC–5 at nine sites in the Central and Eastern United States. These ground motions were derived from the probabilistic seismic hazard analysis (PSHA) results submitted to the NRC by licensees in response to a request based on a recommendation of the NRC's Near-Term Task Force after the accident at Fukushima. (This recommendation required all licensees and certain other permit holders to compute new ground motions, using present practices and guidance and the most recent earthquake data for each site.) To develop the PSHA and associated response spectra, licensees used procedures based on RG 1.208 (NRC, 2007) and ASCE 43 (ASCE/SEI, 2005). This report also uses ASCE 43 to obtain the SDC–3 and SDC–4 ground motions for its comparisons.

In summary, for the nine sites analyzed, the average ratios of the PGA and 5-Hz spectral accelerations for SDC–4 to those for SDC–5 are close to 0.55, and the average ratios of those for SDC–3 to those for SDC–5 are close to 0.35. These results show that choosing alternate SDCs can substantially reduce design ground motions. This report includes comparisons of the entire spectra and derives detailed site-specific insights.

The report also highlights several implications of current regulatory requirements, such as those addressing minimum earthquake design levels and earthquake shutdown and restart criteria. The detailed explanation of the seven-step process includes key management and technical considerations for efficient implementation of the enhanced RIPB concepts.

The report's initial analyses show that existing codes and guidance contain no obvious impediments to a more comprehensive technical evaluation or implementation of the RIPB/LMP Seismic Design Framework and of recent updates to seismic design standards and RGs. The results in this report formed the technical basis for detailed discussions with stakeholders (from industry and other governmental agencies) at a workshop (see Appendix A). The workshop explored the implementation and the pros and cons of the proposed changes to the seismic design process, within the larger context of seismic design, seismic safety, cost optimization, and existing seismic safety regulations.

The analyses and results in this report suggest the following future activities:

- Evaluate the seismic design of a small stylized system (going beyond a single shear wall) to more fully explore the adequacy of guidance in codes such as ASCE 43.
- In cooperation with industry, evaluate the concepts and process further through simplified and more detailed SPRA models, in order to obtain additional technical and regulatory insights into implementation issues and to clarify the enhanced RIPB concepts described in this report. Cooperative activities could include the following:
    - an examination of a simplified and a detailed SPRA of an actual light-water reactor (or advanced light-water reactor), and a practical implementation of the seven-step process, to assess the advantages and limitations of the enhanced LMP approach to seismic safety
    - an examination of a PRA of an advanced reactor (for example, a standard modular high-temperature gas-cooled reactor or a fast-spectrum sodium-cooled small modular reactor), and an implementation of the seven-step process, to identify changes needed in current seismic safety guidance
- Ensure that any proposed approach for seismic safety is also consistent with the 10 CFR Part 53 rulemaking underway.
- Examine how the RIPB/LMP Seismic Design Framework can be used for microreactors and other low-risk facilities.

Summary and Conclusions

The following are the main conclusions of this report:

- An example process for achieving seismic safety has been developed that aligns the LMP concepts, as described in NEI 18-04, with ASCE 43. This example process is technology-inclusive and can be applied under the regulatory requirements in 10 CFR Part 50 and 10 CFR Part 52.
- There are no obvious impediments to implementing the RIPB/LMP Seismic Design Framework and recent updates to seismic design standards and RGs. The report discusses several technical, programmatic, and regulatory considerations for the successful implementation of the framework.
- The major benefits of the LMP/ASCE 43 Integration Approach come from the flexibility it affords to assign different SDCs (i.e., different design-basis ground motion levels) and different design performance limits (i.e., different LSs) to SSCs, based on their risk

significance and other risk-informed decisionmaking factors. (By contrast, the current approach uses a single design-basis earthquake and a very stringent elastic LS for all SSCs, irrespective of their risk significance.) Thus, in the LMP/ASCE 43 Integration Approach, the safety margins of individual SSCs are controlled according to their contributions to system-level and plant-level risk, which reduces unnecessary conservatism (or increases margins where needed) and produces a more risk-balanced design.

- The report contributes to the technical basis for an RG on RIPB seismic design.
- Additional analyses are recommended to fully demonstrate implementation and to identify pros and cons of the proposed changes to the seismic design process, within the larger context of seismic design, seismic safety, cost optimization, and existing seismic safety regulations.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA-generated original data contained in this report meet the quality assurance (QA) requirements described in the CNWRA QA Manual. Computations for simplified systems were used to examine the feasibility of integrating the Licensing Modernization Project initiative with existing codes and standards for seismic safety.

ANALYSES AND CODES: The calculations presented in this report were performed using Excel® and SAP2000 V 21.0.2. The calculations are documented in Scientific Notebook 1331E (Dasgupta, 2020).

Reference

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ABBREVIATIONS/ACRONYMS

10 CFR	Title 10 of the *Code of Federal Regulations*
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
ALWR	advanced light-water reactor
ANS	American Nuclear Society
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
BDBE[1]	beyond-design-basis event
CDF	core damage frequency
CEUS	Central and Eastern United States
CNWRA®	Center for Nuclear Waste Regulatory Analyses
COL	combined license
CSDRS	certified seismic design response spectrum
DBA	design-basis accident
DBE	design-basis event
DC	design certification
DOE	U.S. Department of Energy
DRS	design response spectrum
EPRI	Electric Power Research Institute
F-C	frequency-consequence
GMRS	ground motion response spectrum
HCLPF	high-confidence low probability of failure
HEP	human error probability
Hz	hertz
IEEE	Institute of Electrical and Electronics Engineers
ISG	interim staff guidance
LBE	licensing-basis event
LERF	large early release frequency
LMP	Licensing Modernization Project
LS	limit state
LWR	light-water reactor

1 The acronyms used in this report are based on the terms and definitions in NEI (2018). Several of these acronyms are also used for other seismic terminology with very different meanings. Most notably, BDBE and DBE are commonly used for “beyond-design-basis earthquake” and “design-basis earthquake,” respectively. To prevent confusion, these terms will be spelled out in the document when referring to earthquakes and not events.

NEI	Nuclear Energy Institute
NPH	natural phenomena hazard
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NSRST	Nonsafety Related with Special Treatment
NST	Nonsafety Related with No Special Treatment
OBE	operating-basis earthquake
PGA	peak ground acceleration
PRA	probabilistic risk assessment
PSHA	probabilistic seismic hazard analysis
QA	quality assurance
RG	regulatory guide
RIPB	risk-informed and performance-based
RISC	risk-informed safety class
RRS	required response spectrum
SCDF	seismic core damage frequency
SDC	seismic design category
SDO	standards development organization
SF	scale factor
SLERF	seismic large early release frequency
SOV	separation of variables
SPRA	seismic probabilistic risk assessment
SR	safety-related
SSDRS	site-specific design response spectrum
SSE	safe shutdown earthquake
TRS	test response spectrum
UHRS	uniform hazard response spectrum
U.S.	United States

1 INTRODUCTION

Over the past few years, the U.S. commercial nuclear power industry has initiated the Licensing Modernization Project (LMP) to improve the regulatory basis for licensing and regulating the safety of advanced nuclear power reactors (see, e.g., NEI, 2018; INL, 2018). The LMP framework is supported by both the U.S. Department of Energy (DOE) and the Nuclear Energy Institute (NEI). It includes appropriate risk targets (both for overall plantwide risk and for event sequences with multiple structures, systems, and components (SSCs)), as well as an approach to classifying safety-important SSCs that accounts for the safety role of each SSC more directly than the traditional approach. The LMP framework also emphasizes the understanding of individual event sequences (or groups of them) and provides an updated approach to defense in depth. Finally, it more directly applies probabilistic risk assessment (PRA) modeling as a basis for safety-related decision-making (see, e.g., NEI, 2018; INL, 2018). It relies heavily on risk-informed and performance-based (RIPB) concepts and approaches that complement the current defense-in-depth philosophy. In Regulatory Guide (RG) 1.233, the U.S. Nuclear Regulatory Commission (NRC) adopted, with clarifications, the LMP principles and methodology described in the Nuclear Energy Institute (NEI) guidance document NEI 18-04.

Although the LMP framework contains considerable detail about how its concepts should work for many aspects of reactor safety, including external hazards, it does not yet explicitly address how to incorporate seismic performance criteria into the physical design of SSCs. This is particularly true for advanced reactor designs that rely on passive safety features and controls, have significantly different facility footprints, or use accident-tolerant fuels. Although RIPB approaches for seismic design and seismic safety analyses in nuclear power plants date back to initiatives started in the1970s,[1] such approaches continue to evolve. This evolution is evidenced by updates to the many standards and RGs that apply to seismic hazards and seismic design, such as RG 1.208 (NRC, 2007c), DOE Standard 1020-2016 (DOE, 2016), and the American Society of Civil Engineers (ASCE) standards ASCE 4 (ASCE, 2017) and ASCE 43 (ASCE/SEI, 2005).[2]

RIPB concepts for seismic hazards and seismic design are also beginning to incorporate the lessons learned from recent technical activities, including industry and NRC reassessments of seismic safety at U.S. plants based on updated seismic data, models, and methods, following the 2011 accident at the Fukushima Daiichi Nuclear Power Plant (NRC, 2011). For these reassessments, NRC licensees developed new ground motion response spectra (GMRS)[3] for each plant using present-day NRC requirements and guidance, then compared the GMRS with the plant's safe shutdown earthquake (SSE) ground motion to determine whether further plant risk assessments were warranted. Licensees then used seismic probabilistic risk assessments (SPRAs) to identify potential vulnerabilities given the updated seismic hazards. (The NRC staff and licensees use SPRA results to make and assess risk-informed decisions about seismic safety.) In new license applications under Title 10 of the *Code of Federation Regulations* (10 CFR) Part 52, "Licenses, certifications, and approvals for nuclear power plants," SPRAs are

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1 The development of probabilistic seismic hazard analysis began in the 1960s with a seminal publication by C. Allin Cornell (Cornell, 1968).

2 The current version of ASCE 43 is ASCE 43-05, published in 2005. A new version is planned to be published soon. Both versions have the same basic philosophy. In this report, ASCE 43 is therefore cited without the year of publication.

3 RG 1.208 (NRC, 2007c) describes the procedure for developing the GMRS from the updated probabilistic seismic hazard curves.

also required to demonstrate the overall design margin, taking beyond-design-basis earthquakes into account.

Many applications of SPRA over the years have confirmed that existing seismic design includes significant margins for performing required safety functions. However, some of the fundamental issues associated with the deterministic design procedures embedded in the NRC's regulatory approach remain. For example, these procedures do not explicitly consider the behavior of safety-significant SSCs for beyond-design-basis ground motions, and they impose margins whose contributions to plant-level safety or risk significance are inconsistent. In addition, the compartmentalized approach to design (e.g., considering each SSC separately) often leads to excessive conservatism that may not contribute to overall plant safety or provide a consistent way to achieve the desired seismic capability of the plant as a whole. Many important event sequences in SPRAs involve nonseismic failures and human errors in addition to failures caused by earthquakes, but current regulatory approaches do not explicitly account for these aspects. An SPRA reflects a plant's seismic capability in terms of its design, construction, and operations. The increased use of SPRAs in general, the current movement toward a more RIPB licensing framework, and extensive recent experience with SPRAs create a unique opportunity to incorporate RIPB concepts in updates to NRC regulations and guidance on seismic design and safety, especially in ways that lead to a more uniform, balanced, and safety- and risk-consistent plant.

1.1 Objectives

The NRC staff within the Office of Nuclear Regulatory Research initiated the project governing the work described in this report to identify and evaluate potential enhancements to the existing regulatory basis for seismic design. The project's objective is to evaluate whether and how to implement the enhanced RIPB concepts of the LMP framework, together with recent improvements to industry codes and standards, in nuclear seismic design. The project also aims to identify any implementation and regulatory hurdles that could inhibit broad adoption of the LMP framework. Specifically, the NRC staff seeks to develop a set of preliminary technical and regulatory insights to support the following:

- integration of the LMP concepts with the current NRC regulatory philosophy and regulations
- adoption of appropriate risk metrics
- an understanding of system-level and plant-level performance relative to the performance of individual components
- integration of seismically induced failures with nonseismic failures and human errors
- quantification of the risks from earthquakes relative to those from other accident initiators
- consideration of other desirable factors for overall plant safety, such as defense in depth and risk-balanced profiles (i.e., balance between prevention and mitigation, more uniform margins, avoidance of singleton failures that control the risk, etc.)

These insights are intended to be technology-inclusive and explicitly incorporate RIPB evaluation techniques that can be used to license future commercial advanced nuclear reactors. Any new regulations or guidance for seismic design stemming from the project should be integrated within the broader NRC RIPB framework and should build on existing risk-informed approaches in structural/seismic engineering. Finally, recommendations should be rooted within existing practices (e.g., using existing codes and standards as far as practicable) so that they can be implemented within current regulations (e.g., 10 CFR Part 52 and 10 CFR Part 50, "Domestic licensing of production and utilization facilities") or through reasonable updates to these regulations.

The strategy used to reach these objectives is to consider the performance of individual SSCs and the roles they play in individual event sequences. In contrast, under current regulations, each SSC is designed to the same seismic criteria (e.g., the SSE[4]), irrespective of its role in overall system performance. This new strategy embeds risk targets into the acceptability criteria for the seismic design of each SSC, and these risk targets explicitly account for the behavior of each important SSC when seismic input motions and loads are beyond the design basis. The underlying philosophy explicitly uses SPRA and other considerations such as defense in depth. It allows the tailoring of the overall seismic design and the design of each individual SSC to the desired performance in the relevant event sequences. The strategy thus achieves the desired safety goals while allowing plant designers and operators greater flexibility in meeting system-level acceptability criteria. This represents a change in the governing design philosophy: the design of each SSC for seismic safety is tied to the SSC's role in overall safety, as measured by its contribution to the risk of those event sequences in which it participates. Resources are allocated where they matter the most for safety.

1.2 Scope

The project has two phases:

Phase 1: Develop concepts and a process to align the LMP framework with the RIPB approach to seismic safety. This phase will also identify potential intermediate-term and longer-term activities. The associated analyses will contribute to the technical basis of a future RG on the proposed approach.

Phase 2: Participate in NRC rulemaking for 10 CFR Par 53 by developing regulatory requirements and supporting regulatory guide that are suitable for using the RIPB methodology to address the seismic safety of the advanced non-light water reactor designs

The focus of Phase 1 is to align the LMP concepts with the performance goals in existing codes and standards. The general conceptual process is called the RIPB/LMP Seismic Design Framework. As an example application of the framework, a specific approach is developed, called the LMP/ASCE 43 Integration Approach, which shows how LMP and ASCE principles can be integrated into a consistent and practical regulatory basis for seismic design. At later stages, it may be valuable to collaborate with industry to conduct additional evaluations using more detailed SPRA models, which could clarify the RIPB/LMP Seismic Design Framework and yield further technical and regulatory insights into implementation.

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4 SSE is the maximum earthquake potential for which certain SSCs important to safety are designed to remain functional.

The following are key aspects of the LMP/ASCE 43 Integration Approach that support the broader goals described in Section 1.1:

- applying the event-sequence-based and risk-target based philosophy of the LMP framework to seismic design, and identifying how to apply the LMP/ASCE 43 Integration Approach with SSC-specific reliability or performance targets

- adopting the probabilistic, performance-goal-based, and graded design philosophy in ASCE 43 and other supporting industry codes and standards, including ASCE 4, ASCE 7, and the American National Standards Institute (ANSI)/American Nuclear Society (ANS) standard ANSI/ANS-2.26

- developing the LMP/ASCE 43 Integration Approach into a consistent and practicable regulatory basis for seismic design (which will be a major focus of future work)

1.3 Purpose

This report aims to describe the Phase 1 activities and to document fragility calculations used in formulating and evaluating a set of practical RIPB steps for implementing the LMP and related concepts. Specifically, the report describes a stylized seven-step seismic design process that combines existing codes and standards with the application of SPRA tools during the design process itself, leading to a plant-level design that is both safe and more risk-balanced. The strategy of this design process is to meet the risk targets using combinations of variable seismic design requirements for individual SSCs, then examine their contributions to system-level performance using the SPRA. The goal is to develop margins consistent with the risk significance of each SSC, while meeting component-level performance targets as well as the plant's overall system risk and performance goals. In the seven-step process, the seismic design and the SPRA are interrelated. (By contrast, in current practice, SPRAs support regulatory decision-making rather than design; they are mostly used to evaluate the performance and seismic risk profiles of existing plants and to quantify the seismic margins of those plants based on deterministic designs.)

To evaluate the feasibility, applicability, and benefits of the seven-step process, a set of fragility and seismic performance calculations were carried out for two simple SSCs (a shear wall and a stylized piece of equipment). Chapters 3 and 4 of this report summarize the results of these exploratory calculations. These results confirm the potential benefits of modifying the current deterministic seismic design requirements. Most importantly, they show that existing codes and guidance contain no obvious impediments to a more comprehensive technical evaluation of seismic design requirements based on the LMP framework, RIPB principles, and recent updates to seismic design standards and RGs.

The report also discusses several other aspects of the NRC's current seismic regulatory basis that can be incorporated into an LMP-consistent approach. These include minimum design requirements; requirements for restart after a large earthquake; practical approaches to classifying SSCs and their tailored special treatment requirements; and the use of seismic-margin-based logic and analysis, particularly for screening or deemphasizing SSCs that are unimportant to risk. The results in this report formed the technical basis for a recent workshop with stakeholders (from industry and other governmental agencies), summarized in Appendix A.

2 REGULATORY BASIS

2.1 Current NRC Approach to Regulating Seismic Safety

The current U.S. Nuclear Regulatory Commission (NRC) approach to regulating commercial nuclear power plants (NPPs) requires applicants and licensees to adhere to a suite of regulations ensuring that NPPs are designed and operated to perform safely during and after an earthquake. These regulations are supported by numerous regulatory guides (RGs), standard review plans, technical positions, and other documents that guide NRC staff in reviewing licensee and applicant submittals and in overseeing plant operations. Many of these NRC documents refer to industry consensus codes and standards, sometimes as requirements that the NRC has adopted by reference directly into its regulations, sometimes as (NRC-endorsed) ways to meet NRC requirements, and sometimes as methodologies (e.g., design or analysis methodologies) that the NRC recognizes as adequate.

NUREG/CR-7193, "Evaluations of NRC Seismic-Structural Regulations and Regulatory Guidance, and Simulation-Evaluation Tools for Applicability to Small Modular Reactors (SMRs)" (Budnitz et al., 2014), gives a comprehensive summary of the existing NRC reactor safety guidance for seismic-structural evaluations, assessing the applicability of the existing regulatory basis to new advanced reactor designs, especially small modular reactors. NUREG/CR-7193 includes a series of tables listing the following:

- the relevant regulations, RGs, interim staff guidance (ISG), standard review plan sections, and consensus codes and standards
- the rationale for the categorization of these table entries
- comments on each entry's relationship to the risk-informed and performance-based (RIPB) framework or to technology-inclusive requirements

The three summary tables in NUREG/CR-7193 classify documents by whether "no changes are needed," "minor changes are needed," or "major changes may be needed" to incorporate an updated RIPB seismic safety framework. Since the publication of NUREG/CR-7193 (Budnitz et al., 2014) in 2014, there have been several new developments, including new Federal legislation and updated NRC and U.S. Department of Energy (DOE) documents. Table 2-1 summarizes these.

Designs for the earliest NPPs, in the early 1960s, followed building codes without special seismic requirements. Later, as sites in California were proposed, the need for seismic considerations was recognized. In 1973, after a significant effort starting in the mid- to late 1960s, the Atomic Energy Commission published the first seismic regulation as Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 100, "Reactor site criteria." Previously, in 1971, it had published General Design Criterion 2, "Design Bases for Protection Against Natural Phenomena," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic licensing of production and utilization facilities," which requires development of a design basis for protection against natural phenomena hazards and thus requires an explicit seismic design. The regulatory basis in Appendix A to 10 CFR Part 100 is deterministic and prescriptive.

Seismic design has historically used a series of consensus codes and standards that are themselves largely prescriptive and deterministic (Stevenson et al., 1984). However, from the beginning, the NRC and its predecessor the Atomic Energy Commission strove to keep a risk perspective in the forefront, even if at first the agency lacked quantitative risk targets and risk analysis methods (see, e.g., NRC, 1986).

Table 2-1 RIPB Developments since Publication of NUREG/CR-7193

Category	Short Descriptor	Name	Observations/Comments
Legislation		Nuclear Energy Innovation and Modernization Act	Directs the NRC and DOE to develop a technology-inclusive, RIPB regulatory basis for commercial advanced nuclear reactors.
NUREG-2213 (NRC, 2018a), NRC Office of Regulatory Research	Updated SSHAC Guidance	Updated Implementation Guidelines for SSHAC Hazard Studies	Provides updated guidance on seismic probabilistic hazard analyses under the SSHAC framework, based on lessons learned from recent applications in the United States and internationally.
DOE guidance	DOE Standard 1020	DOE-STD-1020-2016, “Natural Phenomena Hazard Analysis and Design Criteria for Department of Energy Facilities”	Updated guidance on the use of industry building codes and voluntary consensus standards in meeting natural phenomena hazard (NPH) requirements, particularly the International Building Code for certain NPH-related situations

With experience, it became clear that the deterministic and prescriptive nature of Appendix A to 10 CFR Part 100 created ambiguities and controversies when dealing with the highly uncertain and evolving understanding of seismology. As a result, the NRC undertook several large programs in the late 1970s and 1980s to evaluate probabilistic seismic hazard analysis (PSHA) and seismic probabilistic risk assessment (SPRA). One noteworthy project was the Seismic Safety Margin Research Program (see, e.g., NUREG-1407 (NRC, 1991) and Cummings (1986)), which developed the SPRA methodology in collaboration with the experts who were applying this methodology to other uncertain and complex plant licensing issues. In recent decades, the NRC has been moving towards an RIPB regulatory basis. Early efforts date back to SECY-94-219, “Proposed Agency-wide Implementation Plan for Probabilistic Risk Assessment (PRA),” dated August 19, 1994 (NRC, 1994), which was succeeded by the following documents:

- “Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities; Final Policy Statement,” Volume 60 of the *Federal Register*, page 42622 (August 16, 1995) (NRC, 1995)
- SECY-00-0062 (dated March 15, 2000) and SECY-00-0213 (dated October 26, 2000), both entitled “Risk-Informed Regulation Implementation Plan” (NRC, 2000)
- SECY-07-0074, “Update on the Improvements to the Risk-Informed Regulation Implementation Plan,” dated April 26, 2007 (NRC, 2007b)

With the advent and widening use of both PSHA and SPRA methods in the 1990s, the NRC began to include performance-based elements in its evaluations of plant safety. Insights from both PSHA and SPRA studies formed the technical basis to (1) understand the actual safety levels achieved by plants against earthquakes, (2) determine the main contributors to seismic event sequences, and (3) quantify the principal uncertainties in these situations. Advances in both probabilistic hazard analysis and probabilistic fragility analysis greatly improved understanding of seismic risk. These then-new PSHA and SPRA methods gradually took hold in regulatory requirements, first in certain consensus codes and standards, and later in some of the regulations and regulatory guidance documents themselves. DOE led the way with the publication of DOE Standard 1020-94, “Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities,” (DOE, 1994), a significant advance in the development of RIPB approaches in seismic design. In this standard, DOE evaluated the widely varying seismic risk profiles of its nuclear facilities in terms of a set of categories. Initially, it defined four “performance categories” (PC-1 to PC-4), with the highest-risk facilities, including NPPs, designated as PC-4 facilities. DOE later reclassified its facilities within five “seismic design categories” (SDC–1 to SDC–5). These categories were assigned either to a facility, or to a safety-significant structure, system, or component (SSC) within a facility, based on the potential severity of radiological and toxicological effects of seismically initiated failure on workers, the public, and the environment. These DOE efforts led to the development of several important American Society of Civil Engineers (ASCE) standards, namely ASCE 4-98 (ASCE, 1998) and ASCE 43-05[1], both of which have elements important to the implementation of RIPB approaches for the seismic design of SSCs within each of the DOE seismic design categories.

A major step forward in the application of RIPB regulatory philosophy took place in 1997, when the NRC revised 10 CFR Part 100 to require an evaluation of uncertainties in developing seismic design bases. The principal geologic and seismic considerations for NPP site suitability appear in 10 CFR 100.23, “Geologic and seismic siting criteria.” Reviews for combined license (COL) and early site permit applications have been conducted under Subpart A, “Early Site Permits,” of 10 CFR Part 52, “Licenses, certifications, and approvals for nuclear power plants,” using associated evaluation criteria from 10 CFR 100.23. Specifically, 10 CFR 100.23(d)(1) states that the uncertainties inherent in estimates of the safe shutdown earthquake (SSE) “must be addressed through an appropriate analysis, such as a probabilistic seismic hazard analysis.” RG 1.208 (NRC, 2007c) provides guidance for implementing 10 CFR 100.23 and Appendix S, “Earthquake Engineering Criteria for Nuclear Power Plants,” to 10 CFR Part 50. Figure 2-1 shows a timeline of the development of these key standards and RGs.

[1] The current version of ASCE 43 is ASCE 43-05, published in 2005. A new version is planned to be published soon. Both versions have the same basic philosophy. In this report, ASCE 43 is therefore cited without the year of publication.”

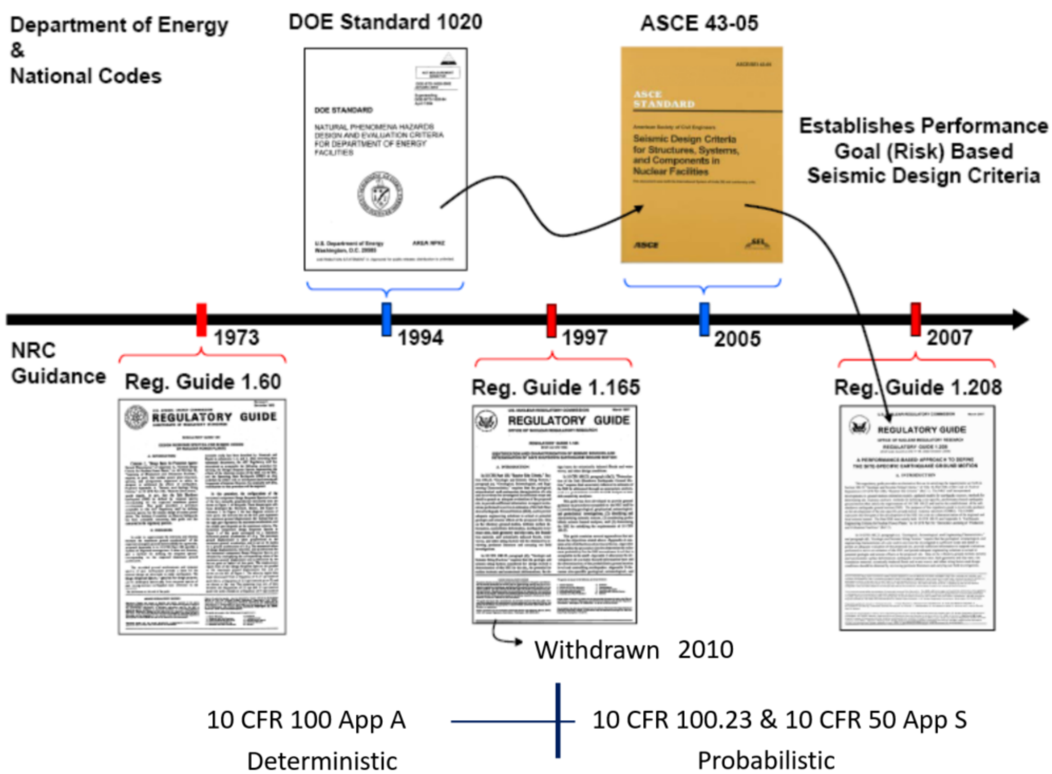

Figure 2-1 Timeline of key RGs and standards for seismic safety

Other NRC-regulated activities on seismic hazards and risks also moved from a deterministic towards a more RIPB philosophy. Among these were the seismic regulations and associated review plans and guidance documents for the proposed high-level radioactive waste repository at Yucca Mountain, NV, which used a risk-graded approach to develop seismic design inputs for the surface and subsurface facilities, per the requirements in 10 CFR Part 63, "Disposal of high-level radioactive wastes in a geologic repository at Yucca Mountain, Nevada." To meet these requirements, the DOE (as an NRC license applicant) developed performance-based criteria using failure probabilities derived from component- and system-level fragility analyses. The methodology for these fragility analyses and the underlying technical bases are summarized, for example, in Dasgupta (2017).

The NRC has initiated rulemaking for 10 CFR Part 53, "Licensing and regulation of advanced nuclear reactors" (NRC, 2020a). There are also several initiatives related to a potential new regulatory framework for microreactors (e.g., BNL, 2020). Seismic safety approaches should be consistent with the 10 CFR Part 53 and microreactor frameworks.

2.2 Summary of Current Codes and Standards for Seismic Design

To implement existing seismic regulations and requirements, the NRC, DOE and industry groups have developed a wide range of guidance documents and design and construction codes, including the American Concrete Institute (ACI) standard ACI 349-13 (ACI, 2013) for reinforced concrete structures and the American National Standards Institute (ANSI)/American Institute of Steel Construction (AISC) standard ANSI/AISC N690-18 (ANSI/AISC, 2018) for structural steel construction. Of the many industry codes and standards for seismic design, the most important to the proposed LMP/ASCE 43 Integration Approach are the ANSI/American Nuclear Society (ANS) code ANSI/ANS-2.26 (ANSI/ANS, 2004), ASCE 4-16 (ASCE/SEI, 2017), and ASCE 43, because they are overarching and incorporate many of the analysis and design requirements spread across RGs and standard review plan sections. They address identification of target "safety levels" for a nuclear facility, define "seismic demands" for the physical design of SSCs, and identify consistent seismic design criteria for specific SSCs.

Two important considerations for seismic design of SSCs in the LMP/ASCE 43 Integration Approach are the selection of the target performance category and the allowable damage state for the SSC, given the demands imposed by the earthquake ground motions corresponding to the target performance category. For DOE facilities, ANSI/ANS-2.26 provides criteria for selecting the seismic design category (SDC) of a facility, as well as criteria and guidelines for selecting the limit states (LSs) of SSCs. ANSI/ANS-2.26 defines five SDCs (SDC–1 through SDC–5), based on the level of unmitigated consequences resulting from failure. These SDCs are assigned to a facility based on the potential severity of the radiological and toxicological effects of any seismically initiated failures at that facility. SDC–1 is for a conventional building whose failure may not result in any radiological or toxicological consequences, while SDC–5 is the most stringent level, applicable, for example, to an NPP or a nuclear material processing facility with a large inventory of radioactive material. Each SDC has a corresponding target performance goal, defined as the mean annual frequency of exceeding a specified LS. Table 2-2 shows the target performance goals for each SDC, as defined in ASCE 43.

Table 2-2 Target Performance Goals

	Seismic Design Category (SDC)			
	1 & 2	3	4	5
Target performance goal (P_F)/reactor-year	4×10^{-4}	1×10^{-4}	4×10^{-5}	1×10^{-5}

ANSI/ANS-2.26 also gives qualitative descriptions of four LSs (A, B, C, and D), which characterize the limiting acceptable deformation, displacement, or stress that an SSC may experience during or after an earthquake while still performing its safety function (Table 2-3).

Table 2-3 ANSI/ANS-2.26 Damage Level for Each LS

Limit State	Expected Deformation	Damage Level
A	Large permanent distortion, short of collapse	Significant damage
B	Moderate permanent distortion	Generally reparable
C	Limited permanent distortion	Minimal damage
D	Essentially elastic behavior	Negligible damage

SSCs designed to LS-A may sustain large permanent distortion (i.e., their integrity is not essential). Acceptable damage levels for LS-B and LS-C are moderate and limited permanent distortion, respectively. LS-D imposes the most stringent design limits, representing deformations that remain essentially elastic (i.e., the SSC is expected to return to the undeformed state after a seismic event). The combination of SDC (SDC–1 through SDC–5) and LS (A, B, C, or D) determines the design-basis earthquake and acceptance criteria for the design of an SSC.

The LS exceedance frequency (the expected frequency with which the LS will be exceeded) is calculated by convolving the design performance[2] fragility curve of the SSC with the control point seismic hazard curve, which plots the annual exceedance frequency (*y*-axis) as a function of ground motion (*x*-axis) at the control point elevation. Because there is a range of spectral acceleration, seismic hazard curves are plotted for several spectral acceleration values, typically 0.5, 1.0, 2.0, 5.0, 10.0, and 20 Hz and peak ground acceleration (PGA). An SSC's design performance fragility is defined as the probability of unacceptable performance of the SSC (i.e.., probability of exceeding a given LS) over a range of ground motions (defined as either PGA or another specified spectral acceleration).

ASCE 4-16 provides guidance for evaluating seismic demands on individual SSCs to demonstrate that sufficient conservatism exists so that, when used in conjunction with ASCE 43, the design of each SSC achieves its target performance goal. ASCE 4-16 addresses seismic input, material properties, and modeling and analytical approaches, both for calculating seismic demands for building structures and for developing the in-structure input motions needed to design the systems and components housed within the structure. The explicit goal of ASCE 4-16 is to provide, for each structure to be designed and analyzed, the seismic response (or seismic demand) with an 80-percent probability of nonexceedance for a specific seismic input. In other words, a reasonable level of conservatism is built into the ASCE 4-16 procedures: the probability that the computed seismic response of an SSC will be exceeded, for a given earthquake ground motion, is no more than 20 percent.

ASCE 43 describes the SSC seismic design criteria that are needed to ensure that a facility can withstand the design-basis earthquake ground motion. Individual SSCs are designed to meet target performance goals, which depend on the selected SDC and LS. ASCE 43 uses a graded approach commensurate with tolerable risk. The target performance goal is expressed as an annual frequency of unacceptable performance (e.g., 1×10^{-4} per year, 4×10^{-5} per year, or 1×10^{-5} per year). Unacceptable performance (i.e., a failed state) occurs when the level of structural damage exceeds that defined by the LS (e.g., inelastic behavior of an SSC designed to LS-D).

Seismic engineers consider the seismic design requirements in ASCE 43, in conjunction with other design, detailing, and construction standards, to be sufficient to meet numerical target performance goals. To achieve target performance goals, ASCE 43 relies on consensus codes and standards such as ASCE 4 (ASCE/SEI, 2017), ACI 349-13 (ACI, 2013) for reinforced concrete structures, and ANSI/AISC N690-18 (ANSI/AISC, 2018) for structural steel construction. These codes and standards produce (1) seismic demand at 80-percent nonexceedance probability for the specified input and (2) design strength at 98-percent exceedance probability (i.e., there is a 2-percent probability that the design strength is less than the target). In addition, ASCE 43 aims to achieve two conditional probabilities or fragilities for SSCs, consistent with their target performance goals: (1) less than an approximately 1-percent probability of unacceptable performance for the design-basis ground motion and (2) less than a

2 The term "fragility curve" may describe either of two concepts. The traditional fragility curves that are used in an SPRA relate to SSC failures that prohibit the performance of a required safety function. An LS exceedance or design performance fragility curve represents the conditional probability of exceeding the design LS for a given level of ground motion, without any consideration of functionality. See further discussion in Section 4.4.

10-percent probability of unacceptable performance for ground motion equal to 150 percent of the design-basis earthquake ground motion.

2.3 The Licensing Modernization Project Framework

The diagram in Figure 2-2 summarizes the RIPB seismic design and licensing-basis event (LBE)[3] selection process, which is based on the Licensing Modernization Project (LMP) concepts in the Nuclear Energy Institute (NEI) guidance document NEI 18-04. The main components of the RIPB seismic design process are (1) individual SSC design in accordance with ASCE 43, (2) SPRA, and (3) integrated decision-making, including consideration of adequacy of defense in depth. Within these components, plant operators and designers must (1) select the LBEs, (2) demonstrate compliance with risk criteria, (3) classify safety-related SSCs according to their risk significance, and (4) categorize SSCs for seismic design. Of these four items, the demonstration of compliance with risk criteria is the most novel, because the LMP framework calls for a seismic design evaluation based on new risk metrics incorporating event sequence frequency and public dose estimates; these differ from the traditional risk metrics of core damage frequency and large early release frequency for existing light-water reactors. The iterative process shown in Figure 2-2 explicitly relies on the SPRA, aligning the LMP concepts of NEI 18-04 with the ASCE 43 code for seismic design of SSCs. This process, which this report refers to as the LMP/ASCE 43 Integration Approach, illustrates a way to achieve desired safety goals while allowing greater flexibility in seismic design to meet system-and plant-level acceptability criteria.

Qualitative techniques such as failure modes and effects analysis, hazard and operability studies, and master logic diagrams support the initial selection of operational events and internal hazards, which potentially form the basis for seismically initiated event sequences. The evaluation includes additional seismically induced failure modes (e.g., seismic interaction, seismically induced fire and flooding).

Seismic event sequences include seismically induced initiating events, the plant response to an initiating event (which includes a sequence of successes and failures of mitigating systems), and well-defined end states (Figure 2-3). Each event sequence frequency is a function of the frequencies of the initiating events and of the reliabilities (fragilities) and capabilities of the SSCs that prevent or mitigate the event sequence. Event sequence frequencies are expressed in units of events per plant-year, where a plant may comprise two or more reactor modules and sources of radioactive material. Figure 2-3 depicts a generic event sequence consisting of a seismically initiated event and a combination of failures and successes of a single SSC or a system, represented as an event tree. In this example, fragilities are combined at the event-sequence level, and the sequence-level fragility is convolved with the seismic hazard curve to calculate the event sequence frequency. Each of the event sequences in Figure 2-3 (ES-1, ES-2, and ES-3) has a specific frequency and dose magnitude.

[3] LBEs are events considered in a licensing process to derive regulatory requirements. LBEs may include normal plant operation, events anticipated to occur in the life of the facility, and off-normal events, including infrequent design-basis events (DBEs).

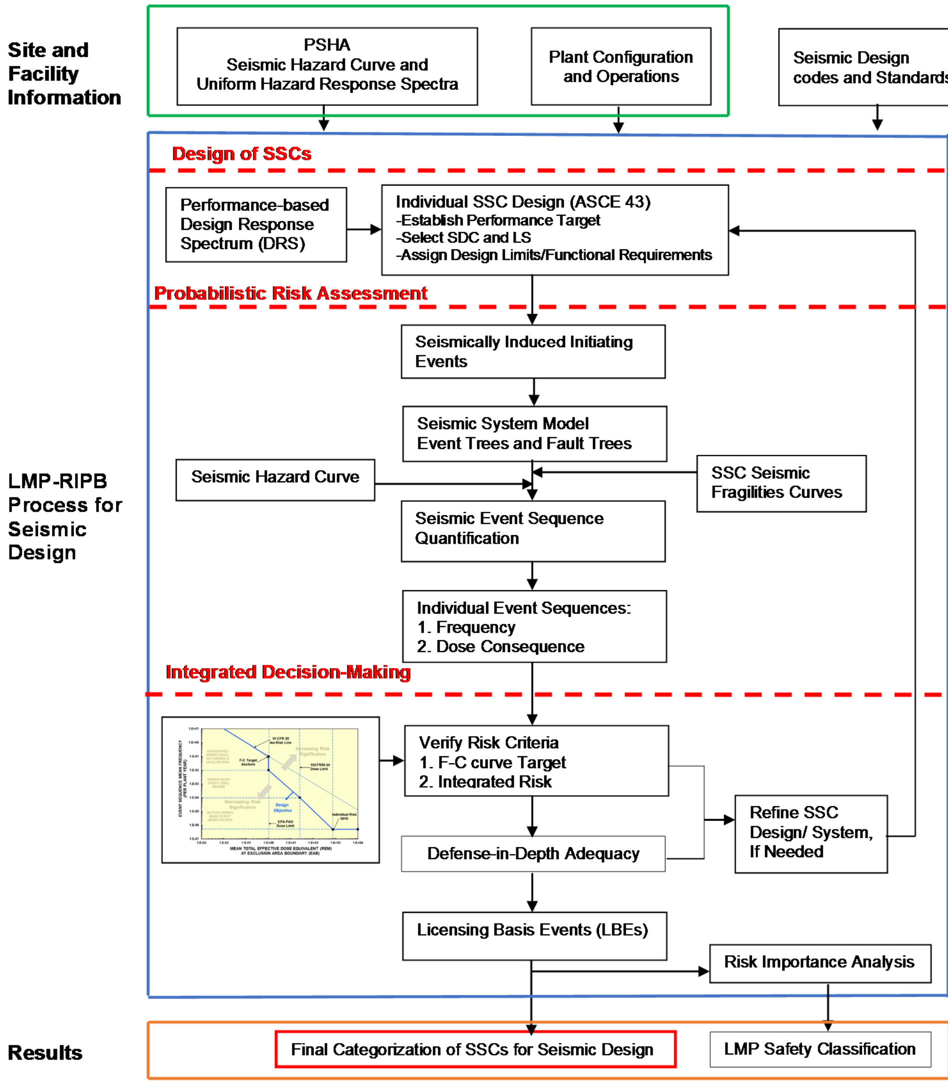

Figure 2-2 RIPB seismic design and LBE selection process, based on NEI 18-04

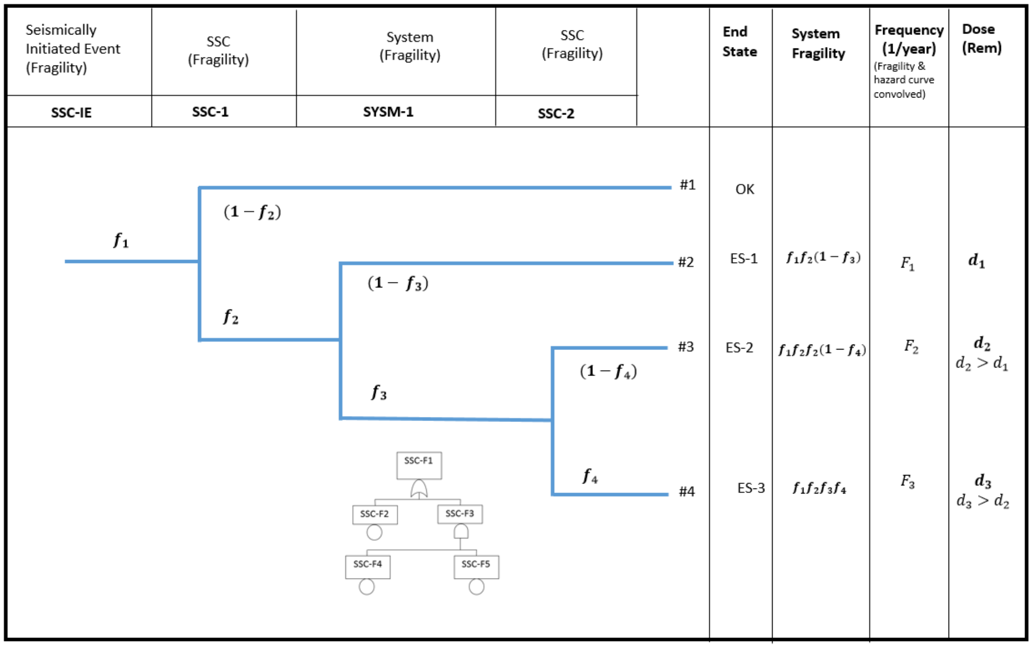

Figure 2-3 Schematic event and fault tree diagram showing seismic LBEs corresponding to an initiating event

2.3.1 The Licensing-Basis Event Selection Process

The LBE selection process is based on a PRA model addressing the following questions (the risk triplet): What can go wrong? How likely is it? What are the consequences? An SPRA evaluation requires five elements:

(1) a site-specific seismic hazard curve
(2) seismic fragility functions for each SSC
(3) delineated seismic event sequences
(4) quantification of each event sequence
(5) estimated radiological consequences at the exclusion area boundary (Figure 2-4)

The seismic hazard curve shows the annual exceedance frequencies of different spectral accelerations of ground motions (including the PGA). The fragility curve of an SSC represents the conditional probability of failure to perform the required safety function over the same range of ground motions. The fragility function for an individual SSC is generally assumed to be a lognormal distribution function, with parameters defined by the median capacity and composite logarithmic standard deviation.

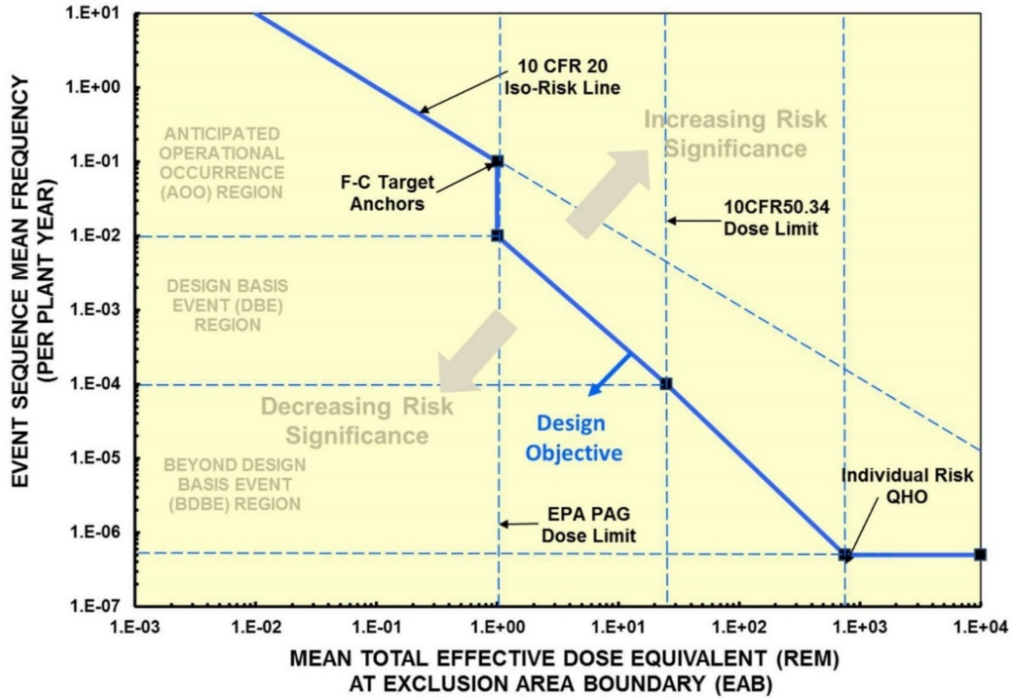

Figure 2-4 Frequency-consequence curve (referred to as F-C target) from NEI 18-04 (NEI, 2018, Figure 3-1)

2.3.2 The Licensing Modernization Project within the NRC's Risk-Informed and Performance-Based Regulatory Construct

RG 1.233 (NRC, 2020b) provides guidance on using a technology-inclusive RIPB methodology to inform the licensing basis and content of applications for nonlight-water reactors, including but not limited to molten salt reactors, high-temperature gas-cooled reactors, and a variety of fast reactors at different thermal capacities. In the RG the NRC staff endorses, with clarifications, the RIPB methodology proposed in NEI 18-04 (NEI, 2018) as one approach that can be used for the evaluation of nonlight-water reactors.

The NRC's approach to licensing future NPPs, first established in NUREG-1860 (NRC, 2007a), is intended to be RIPB, to incorporate defense in depth, and to allow licensees or applicants flexibility to meet safety requirements. It is important to note that in the LMP framework, the safety classification of SSCs already accounts for special treatment, such as differences in maintenance and operating requirements; however, it does not specifically address seismic design. Thus, although the LMP framework represents a change in the governing design philosophy, the implementation of that philosophy for seismic design has not yet been written down or tested. One of the key objectives of this project is to accomplish the latter—that is, to establish an approach in which the design of an individual SSC for seismic safety is tied to the SSC's role in overall safety, as measured by its contribution to the risk of those event sequences in which it participates. Table 2-4 describes crucial conceptual differences between the current approach to seismic design and the proposed approach based on ASCE 43.

Table 2-4 Comparison of the Current and Proposed Approaches to Seismic Design

Current Seismic Design Approach	LMP/ASCE 43 Approach
Safety Classification: For seismic design purposes, all safety-related SSCs are considered Seismic Category 1 (SC-1) SSCs.	Safety Classification: The LMP framework includes alternate safety classifications that consider risk significance. ASCE 43 allows for alternate seismic design categories (SDCs)[4] based on the desired level of design performance and consistent with risk significance.
Design-Basis Ground Motion: All SC-1 SSCs are designed to one ground motion level, corresponding to the SSE or design-basis ground motion. The current site-specific design-basis ground motion corresponds to the highest level determined using the RG 1.208 approach; it is based on the hazard exceedance frequency for a performance goal of 1×10^{-5} per year.	Design-Basis Ground Motion: Design-basis ground motions for each SDC are derived based on the performance target and margins associated with the design process. Thus, there is no single design-basis ground motion for all SDCs. The ground motions are based on hazard frequencies for targeted performance goals that vary with each SDC.
Design Performance Criteria: No explicit numerical criteria are defined. The design limits are associated with elastic behavior, resulting in significant safety margins beyond the design-basis ground motion.	Design Performance Criteria: A quantitative design performance criterion is associated with each SDC. Alternate design limit states (LSs) (e.g., those allowing inelastic behavior) are permitted, depending on the desired design performance and margins.
Design Procedures: The design employs deterministic seismic response analyses for the SSE ground motion to establish the seismic demand. The physical design of an SSC uses established construction and engineering standards, such as those published by ACI, AISC, the American Society of Mechanical Engineers (ASME), and others.	Design Procedures: The design employs seismic response analyses based on the ground motions that correspond to the assigned SDCs. Seismic demands are adjusted based on the selected LS. The physical design of an SSC uses established construction and engineering standards, such as those of ACI, AISC, ASME and others.

Table 2-4 highlights important benefits of using enhanced RIPB seismic design concepts. These concepts allow the assignment of different SDCs to individual SSCs (providing flexibility in selecting design-basis ground motion levels), and they also permit the selection of alternate design LSs, so that the desired margins can be maintained consistent with the SSC's contribution to overall plant risk. This avoids excess conservatism that does not provide commensurate safety benefits (and also identifies situations that may require additional margins). The strategy is practical, because once the SDC and LS are chosen, the design processes are essentially the same as those used currently.[5]

[4] Although the initial ASCE concept was to define various SDCs for DOE facilities based on the risk consequences of each facility, this classification can also be used for individual SSCs.

[5] While ASCE 4 does allow some variations for seismic response analysis, the principal response analysis method is basically the same as that currently used with traditional deterministic methods.

2.3.3 The Frequency-Consequence Target

NEI 18-04 (NEI, 2018) proposes the use of a frequency-consequence (F-C) target to identify acceptable accident event sequences (Figure 2-4). The F-C target is a frequency-versus-dose curve delineating ranges of acceptable risk for LBEs. The NEI 18-04 risk metric includes both the frequency of occurrence of the LBE sequence and the associated radiological dose to the public at the site boundary. The NEI 18-04 dose limits are consistent with the NRC's Quantitative Health Objectives. In RG 1.233 (NRC, 2020b), the NRC staff endorses the F-C target as a reasonable approach for determining risk significance, classifying SSCs, and incorporating defense in depth. However, the NRC staff recognizes that the F-C target alone does not define strict acceptance criteria or regulatory limits. Consistent with the NRC risk-informed philosophy, including the philosophy described in RG 1.174 (NRC, 2018b), risk insights are used along with other factors in an integrated decisionmaking process. The F-C target provides a general reference for assessing events, SSCs, and programmatic controls in terms of sensitivities and available margins.

In addition to recommending that acceptable individual event sequences lie below the F-C target, NEI 18-04 accounts for aggregate risk by adding up the product of the frequency and the dose for each LBE sequence over all LBE sequences and comparing this total risk with cumulative risk targets. If the cumulative or integrated target is not met, the facility design may require further enhancements to meet it (Figure 2-2). A small set of LBEs may be identified, based on risk information, and used to select SSCs for design enhancements. After these adjustments, the complete calculation process is iterated until the cumulative risk target is met.

2.3.4 Determination of Risk Significance and Classification of Structures, Systems, and Components in the Licensing Modernization Project Framework

The F-C target allows direct evaluation of the relative risk contributions of risk-significant SSCs. The frequency and consequence of each LBE is compared to the F-C target, as shown in Figure 2-5. LBEs whose frequency and consequence fall within 1 percent of the F-C target, and whose site boundary doses exceed 2.5 mrem, are considered to be risk-significant. NEI 18-04 recommends using 95th-percentile estimates of both frequency and dose to rank LBEs. In Figure 2-5, the event sequences represented by the orange dots (i.e., those in the shaded region) are considered risk-significant. The designer may further refine the design of selected SSCs to improve prevention and mitigation capabilities and increase the LBE margin.

The safety classification of SSCs in NEI 18-04 depends on their specific safety functions for each LBE sequence in which they appear. Risk insights gained from the PRA model when identifying and selecting LBEs can be used to classify SSCs. SSCs are classified as safety-related (SR), nonsafety-related with special treatment (NSRST), or nonsafety-related with no special treatment (NST). Safety-significant SSCs are those classified as SR or NSRST. Commonly used risk-significance measures in PRA models also support risk ranking of basic events.

NEI 18-04 describes a framework that includes an integrated decisionmaking process, where design and risk-informed decisions are used to ensure adequacy of design and defense in depth. Through examination of plant LBEs and of SSCs relied on to prevent and mitigate events, the evaluation identifies SSC capabilities and programmatic controls to support defense in depth. In RG 1.233 (NRC, 2020b), the NRC staff stated that the NEI 18-04 approach was acceptable for assessing adequacy of defense in depth.

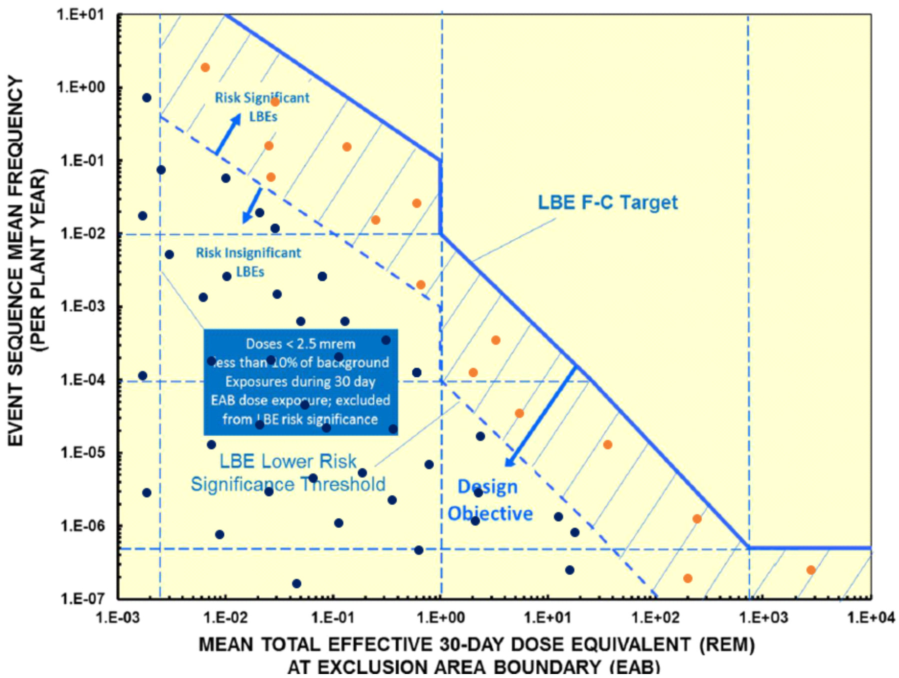

Figure 2-5 LBE F-C target proposed by NEI 18-04, showing distribution of risk-insignificant LBEs (black dots) and risk-significant LBEs (orange dots)

2.4 Opportunities To Enhance the Current Seismic Regulatory Construct

As described earlier, the LMP framework establishes the conceptual foundation needed to apply the existing RIPB philosophy to the seismic design of an NPP. Moreover, existing codes and standards already contain many of the tools needed to realize these concepts in practice. Finally, SPRAs have now been developed to the point where they can be incorporated into the design process itself. These factors lead to several opportunities to enhance the current seismic regulatory construct, six of which are described below. Implementing all six of these enhancements is a long-term goal; this report, while it is a starting point towards that goal, does not address all six in detail. In particular, issues related to code committees (under items 5 and 6 below) are outside the scope of this project.

The six opportunities to enhance the current seismic regulatory construct are as follows:

(1) Account adequately for the roles of individual SSCs in the event sequences of most concern.

The revolution that occurred with the advent of PRA showed the safety community that achieving safety requires concentrating on individual event sequences one by one, and examining (one by one) the roles of individual SSCs and human errors in each event sequence. However, the NRC's seismic regulatory philosophy concentrates almost entirely on ensuring that each SSC is designed "correctly." It does consider the role of an individual SSC in various seismic event sequences to address some operational issues, but not at the design stage and not in a consistent way.

(2) Explicitly account for the role of nonseismic failures and human errors in seismically initiated event sequences.

In SPRAs, many important event sequences involve a combination of seismic failures (beyond-design-basis failures) and nonseismic failures, such as random failures of equipment to start or to run, or human errors. However, the NRC's regulatory scheme does not distinguish between human errors (in the control room, out in the plant, etc.) that occur in a normal environment and those that occur during or shortly after a strong-motion earthquake. The NRC's approach to postarthquake human performance at existing plants effectively disregards issues that might arise from a large earthquake, such as extra stress, limited time for action, or impeded access. (This situation has been improving: recent NRC design reviews and audits for new plants have regularly addressed these issues.) Neither the training nor the licensing examinations emphasize these issues appropriately, and the human-machine interfaces in plant designs are not generally optimized for seismic failures, except in a few cases.

(3) Provide a mechanism for relaxing regulatory requirements for an SSC whose seismic capacity significantly exceeds what is needed to maintain system-level and plant-level safety.

Because every safety-related SSC in a plant is designed to the same criteria, no mechanism has traditionally existed to relax regulatory requirements for a safety-related SSC whose seismic capacity significantly exceeds what is needed. The NRC's recently established regulation in 10 CFR 50.69, "Risk-informed categorization and treatment of structures, systems and components for nuclear power reactors," does address such SSCs; however, it focuses on operational requirements, not on redesigning the SSCs. Under 10 CFR 50.69, for specified SSCs, a licensee may be exempt from certain requirements, such as maintenance and inspections, to reduce operational burden. However, as the regulation applies to plants that are already built, the licensee makes no changes to designs, and the plant retains the original seismic margins. For example, in this one-size-fits-all approach, there is no opportunity to redesign an SSC with lesser safety importance (but still some safety importance) to allow some modest inelastic behavior for earthquake motions at the design basis. Nor is there an opportunity to reduce the seismic input load that the design requires for such SSCs. In some situations, relaxations such as these might greatly decrease facility cost, maintenance, or cost of regulatory review without compromising safety.

Of course, this issue is partly due to the need for deterministic design criteria that apply to a variety of design situations and site conditions. Also, some "excess" margins may be needed in the future if the understanding of seismic hazards changes or if new loads are discovered.

(4) Recognize the need to upgrade the seismic capacity of an SSC that meets current regulations but, in light of its risk significance, has inadequate margins in case of failure beyond the design-basis ground motion.

The traditional NRC regulatory review does not distinguish between an SSC with large additional seismic margins above the design basis and one with only modest additional margins. With no way to know that, nor to know how that seismic margin "plays out" in terms of affecting overall plant risk, requiring additional margins for some SSCs is not an available option. The current one-size-fits-all approach is an impediment to achieving an overall balanced seismic risk profile. Although use of SPRAs as a part of the design process helps to address this issue, the overall regulatory basis would benefit if this concept was explicitly incorporated in guidance and regulation.

(5) Acknowledge and account for the fact that design codes for various categories of SSCs embed very different margins to failure (above the design basis).

The NRC's regulatory requirements for the seismic design of SSCs have always relied heavily on design codes produced by standards development organizations (SDOs), most of which are sponsored by professional societies. These SDOs include ANS, ASME, ASCE, ACI, the Institute of Electrical and Electronics Engineers (IEEE), AISC, and a few others; furthermore, a given SDO may comprise multiple code committees. All codes embed extra margins in the seismic design requirements, so that an SSC designed using the code will continue to function under seismic loads in excess of the design basis. However, different code committees may use different embedded margins, based on industry practice in their respective fields. The result is that within a single NPP, the added seismic margins above the design basis will differ from one type of SSC to another.

This situation has improved somewhat as civil engineering has adopted probability-based design, in the form of load and resistance factor design, which began to supplement or replace allowable-stress design years ago. For example, the material codes for concrete, steel, cold-formed steel, and aluminum now follow the same probability model to determine strength factors. (They may appear to differ, because they properly consider the variability and uncertainty in the strength predictions specific to each material.) The load factors and load combinations in these codes have been developed using a combination of probabilistic and deterministic bases, generated through years of interactions between code committees (including ACI, AISC, ASCE and ASME committees) and the NRC staff; they apply to all materials (steel, concrete, etc.) used in constructing NPPs.

Nevertheless, because different groups developed the original codes, and because the NRC's regulatory philosophy historically did not explicitly consider the details of the seismic behavior of SSCs well beyond their design basis (although the NRC has recently begun to explicitly evaluate beyond-design-basis behavior), the embedded seismic margins vary more than they would if more coordination had occurred. In practice this means that the seismic design process does not sufficiently allow for the relaxing (or enhancing) of seismic margins to produce a design with more "balanced" margins.

It is important to note that the recommendations in this report do not rely on any changes to industry consensus codes and standards. However, as experience is gained with the proposed enhanced RIPB approach, commensurate changes to some of those codes and standards will likely be identified, which may then further enhance the benefits described in this report.

(6) Account for how the differing margins in various codes affect the likelihoods or consequences of individual SSC failures at the accident-sequence level.

The NRC's current approach gives only limited consideration to the accident-sequence-level implications of the varying design margins for different SSCs—that is, to their effects on the likelihoods or consequences of event sequences involving individual SSC seismic failures (beyond-design-basis failures). For example, containment design has always incorporated large margins (including large seismic margins) because of its role in preventing large releases. However, to judge whether those large seismic margins are appropriate, insufficient, or overly conservative, it is necessary to understand the role of the containment in various important seismic release sequences. While this is an inevitable consequence of designing individual SSCs separately rather than in view of their role in the plant as a whole, SPRAs can address the problem within an iterative design process. This philosophy is becoming the norm for the design of new plants, but it needs to be recognized more fully from the outset in any proposed revision to the seismic regulatory construct.

These six opportunities for enhancement indicate that, although the fleet as a whole is adequately safe against earthquakes, there is room for improvement in the following areas:

- The NRC's current seismic regulatory construct can be made consistent with the broader RIPB regulatory basis.
- The current regulatory construct generally produces plants with very unbalanced seismic risk profiles.
- The current regulatory construct neglects some important methods for analyzing seismic safety that could improve understanding.
- The current regulatory construct also misses some opportunities to improve seismic safety and balance cost against safety.

It is important to note that, although addressing these areas will take some time, there are no known impediments to doing so except the usual (and important) difficulties of obtaining consensus among all interested parties and ensuring that new approaches preserve the consistency and usefulness of the system now in place.

3 INCORPORATING THE ENHANCED RISK-INFORMED AND PERFORMANCE-BASED CONCEPTS IN THE SEISMIC DESIGN PROCESS

3.1 Background

As discussed in Chapter 1, several applications in operating reactors and other nuclear facilities already use risk-informed and performance-based (RIPB) approaches. These applications include the development of site-specific seismic ground motions for design, using probabilistic seismic hazard analysis (PSHA) in conjunction with probabilistic criteria; seismic probabilistic risk assessments (SPRAs) for both plant-specific and generic issues; and currently accepted alternative RIPB regulatory approaches, such as those in Title 10 of the *Code of Federal Regulations* (10 CFR) 50.69, "Risk-informed categorization and treatment of structures, systems and components for nuclear power reactors." At various stages during licensing, such as design certification, application for a combined license to build and operate a nuclear power plant (NPP), and verification of seismic margin capacity before fuel loading, new plant designs require probabilistic risk assessment (PRA) margin analyses or SPRAs to demonstrate that they meet performance targets (NRC, 2010b).

Many of these applications focus on the overall plant response to emerging issues, such as those related to updated seismic ground motions or operating experience. What distinguishes the RIPB/LMP Seismic Design Framework and the example seven-step Licensing Modernization Project (LMP)/American Society of Civil Engineers (ASCE) 43 (ASCE/SEI, 2005)[1] Integration Approach proposed in this report is the incorporation of these RIPB concepts in the seismic design itself, to choose the seismic hazard levels for each safety-related structure, system, or component (SSC), commensurate with its contribution to risk. For example, the LMP/ASCE 43 Integration Approach aims for seismic margins consistent with the risk significance of each SSC within the plant's overall risk and performance goals and within component-level performance targets. This approach contrasts with current practice, which applies a single hazard level to the design of all safety-related SSCs (and of the entire facility), and which uses PRA methods primarily for existing plants, to evaluate their performance and risk profiles and to quantify their seismic margins based on their original design.

The goal of the LMP/ASCE 43 Integration Approach is to evaluate the applicability of enhanced RIPB concepts within the design process, integrating the existing RIPB seismic safety philosophy with principles from the LMP (see Chapter 2) to increase safety and decrease costs. It is important to note that the LMP/ASCE 43 Integration Approach is not rigid and can be simplified as appropriate for any specific design. For example, designs for microreactors or other reactors with very low risk profiles may use codes other than ASCE 43 and may use risk analysis methods other than SPRA to demonstrate compliance with applicable risk criteria. (This report does not explicitly consider the application of the RIPB/LMP Seismic Design Framework to the seismic design of microreactors; this topic should be explored in the future.)

[1] The current version of ASCE 43 is ASCE 43-05, published in 2005. A new version is planned to be published soon. Both versions have the same basic philosophy. In this report, ASCE 43 is therefore cited without the year of publication.

3.1.1 Guiding Principles

The development of the seven-step LMP/ASCE 43 Integration Approach was guided by the following principles:

(1) integrating seismic RIPB concepts with the LMP framework
(2) building on existing RIPB approaches in structural/seismic engineering
(3) recognizing that the actual design process is still fundamentally "deterministic"
(4) using existing codes and standards wherever feasible
(5) identifying and suggesting updates to the regulatory basis and guidance, as necessary

Chapter 2 described the general LMP framework, as well as some considerations for integrating external hazards when defining licensing-basis events (LBEs) and SSC safety classifications. Initially, LBEs and SSC safety classifications are likely to be based on a PRA that covers only internal events. For external hazards amenable to PRA methods, including seismic hazards, new LBEs may be created to represent event sequences initiated by earthquake ground motions and other external-hazard loads. These would include design-basis events and beyond-design-basis events induced by external hazards modeled in the PRA; they would be subject to evaluation using frequency-consequence (F-C) and cumulative risk targets. For some SSCs, the initial safety classifications may change; a few iterations may be necessary[2] to establish their seismic design categories (SDCs). The proposed integration in this chapter is to have a process that defines performance targets for individual SSCs such that the overall performance targets, both F-C dose and cumulative targets, are met. As described in Chapter 2, considerable infrastructure and experience exist in the fields of seismic design, evaluations, and PRA. The intent is to build on this experience.

There are several technical reasons for selecting ASCE 43 (ASCE/SEI, 2005) to link with the LMP framework. ASCE 43 is a performance-based code with numerical design performance goals. It has a risk-graded approach that allows SSCs to be categorized according to their risk significance. It was written specifically for nuclear facilities and contains methods and practices familiar to the nuclear industry. The seven-step process described in this report could, however, accommodate the use of codes other than ASCE 43, such ASCE 7 (ASCE/SEI, 2010), to design low-risk systems such as microreactors (for which the regulatory framework is still evolving; see, e.g., BNL 2020).

ASCE 43 incorporates RIPB principles by developing a design-basis ground motion from a PSHA to meet a specified annual exceedance frequency (in accordance with the chosen SDC), a specified probabilistic performance target, and the selected design limit state (LS). It uses an SPRA to demonstrate that the overall design complies with broader performance targets. Once the design-basis ground motion is established, the seismic response analysis and design procedures are basically "deterministic," employing well-established practices. Although ASCE 4 (ASCE/SEI, 2017) and ASCE 43 allow alternative approaches, including more explicitly probabilistic approaches, there is no substantial experience of using these approaches in design; therefore, discussion in this report is limited to the deterministic option. The use of the deterministic framework and the existing construction codes (such as American Concrete Institute codes) for component design is, at this stage, the only practical approach for designing

[2] This is a reasonable expectation, as all design processes are iterative to some extent, but the process proposed here includes explicitly iterative steps to establish SSC seismic design categories.

complex facilities such as NPPs, which require large teams spanning various engineering disciplines.

The development of the seven-step LMP/ASCE 43 Integration Approach took into consideration possible deviations from the existing guidance, practice, and regulatory construct. No impediment to implementing the process has been identified. Section 3.3 discusses several situations that require consideration during implementation.

3.1.2 Key Assumptions and Considerations

Under current U.S. Nuclear Regulatory Commission (NRC) regulations, all safety-related SSCs and certain safety-important equipment (e.g., spent fuel pool racks) are designated as Seismic Category 1 SSCs; these are all designed to the same design-basis earthquake ground motions. Some of these SSCs are not related to the reactor accident risk; for example, in the LMP framework, risks associated with potential accidents in spent fuel pools are analyzed through a separate PRA, which also includes seismically initiated event sequences. SSCs related to nonreactor radiological sources, such as radiological waste holdup tanks, are designed to less stringent requirements, but they are within the scope of NRC reviews and safety evaluations. Similarly, NRC reviews also consider how failures of nonsafety-related SSCs may adversely affect safety-related SSCs.

The description of the seven-step LMP/ASCE 43 Integration Approach in this report makes the following four assumptions:

- For risks resulting from reactor operations, two LMP safety classifications—namely, safety-related (SR) and nonsafety-related with special treatment (NSRST)—are assumed to be within the scope of the NRC review. The corresponding designs will therefore comply with NRC regulations, accepted guidance, and industry codes and standards.

- SSCs such as waste holding tanks and spent fuel pools are also assumed to be designed using the process described here, as the LMP framework considers the risk arising from all sources of radiological hazards and all plant operating modes.

- Although many combinations of SDC and LS are possible (e.g., SDC–5 with LS-A, SDC–5 with LS-B, SDC–5 with LS-C), it is assumed that only a limited number occur in practice, for technical and regulatory reasons that are discussed in detail in Section 3.3. The analyses in this report use only combinations of SDC–3, SDC–4, and SDC–5 with LS-C and LS-D. However, in low-risk facilities, such as microreactors (which this report does not consider explicitly), other combinations may be possible and practical.

- Licensing under 10 CFR Part 52, “Licenses, certifications, and approvals for nuclear power plants,” has three stages: (1) design certification, (2) a combined license application to build and operate at a site, and (3) NRC approval before fuel loading. Reactor design and licensing within the LMP framework may use a similar three-stage structure. The LMP/ASCE 43 Integration Approach assumes such a structure and identifies several specific licensing considerations, which are discussed in this report. However, the proposed seven-step process is equally applicable to other regulatory structures and to site-specific design and licensing processes under 10 CFR Part 50, “Domestic licensing of production and utilization facilities.” Its applicability should also be evaluated with respect to the forthcoming 10 CFR Part 53, “Licensing and regulation of advanced nuclear reactors" (NRC 2020), and with respect to the evolving regulatory framework for microreactors.

The following are key considerations for applying the LMP/ASCE 43 Integration Approach (Sections 3.2 and 3.3 and the examples in Chapter 4 expand upon these):

- The seven-step LMP/ASCE 43 Integration Approach is intended to be applied before the production of the detailed and final seismic design; its implementation is not expected to require significant resources or a long time. Its outcome is a categorization of the SSCs in the appropriate SDCs, in accordance with LMP risk criteria.

- The seven-step process may be applied at various design stages. In preliminary stages (particularly for certified designs under 10 CFR Part 52), only limited information may be available, so that engineering judgment will be needed to complement the available information and to estimate fragilities. As the design matures, the fragility analyst may be able to use more sophisticated analysis techniques and experimental data, depending on the stage of the design (e.g., design certification, site-specific design, or constructed plant before fuel loading). The seven-step process does not require precise fragility values, only a realistic range of estimated fragilities for components designed to different SDCs.

- The level of detail is an important consideration in the LMP framework in general. American Society of Mechanical Engineers (ASME)/American Nuclear Society (ANS) standard ASME/ANS RA-S-1.4, "Probabilistic Risk Assessment Standard for Advanced Non-Light Water Reactor Nuclear Power Plants" (ASME/ANS, 2020), discusses the graded requirements for different stages of the design life cycle.

- The LMP/ASCE 43 Integration Approach requires design engineers and risk analysts to interact in order to make robust[3] decisions about the categorization of SSCs. The detailed design can proceed as usual once the final categorization is established.

3.1.3 Nomenclature

Several design-basis ground motions are possible under the LMP/ASCE 43 Integration Approach. Under 10 CFR Part 52, there is the design-basis ground motion for the certified design, as well as a site-specific design-basis ground motion to account for site-specific hazards. For advanced reactors, the term "safe shutdown earthquake" (SSE) may be confusing as the required safety functions discussed in Chapter 2 do not explicitly include reactor shutdown. ASCE 43 uses both the terms "design-basis earthquake" and "design response spectra" (DRS), stating that "the design-basis earthquake ground motion shall be defined in terms of the Design Response Spectra (DRS)." In addition, the current terminology may be counterintuitive compared to the use of "Seismic Category 1" for safety-related structures. For consistency with LMP framework terminology and with the safety functions of advanced reactors, this report uses the nomenclature in Table 3-1. To prevent confusion, the report explicitly identifies all cases where the terminology differs from that of the LMP framework.

[3] The term "robust" indicates that when the final designs and SPRAs are completed, the categorization produced by the seven-step process yields a design having the desired margins against the F-C criteria of the Nuclear Energy Institute (NEI) guidance document NEI 18-04, with no further changes needed.

Table 3-1 Seismic Design Nomenclature

ASCE Seismic Design Category	Certified Seismic Design Response Spectra (CSDRS)	Site-Specific Design Response Spectra (SSDRS)
SDC–5	CSDRS-5	SSDRS-5
SDC–4	CSDRS-4	SSDRS-4
SDC–3	CSDRS-3	SSDRS-3

3.2 Overview of the Seven-Step Seismic Design Process

To facilitate discussion of the regulatory concepts in the RIPB/LMP Seismic Design Framework and to demonstrate its regulatory benefits, the LMP/ASCE 43 Integration Approach was developed as an example application. This seven-step process was developed in the context of current NRC guidance and existing seismic design codes, especially ASCE 43. However, it is flexible enough to accommodate seismic codes and standards other than ASCE 43.

Although ASCE 43 has been used to evaluate the seismic safety of existing nuclear facilities, it has never been used in the actual design of an NPP. However, the ASCE 43 design response analysis and strength design process for SDC–5 and LS-D reflect many of the design practices currently used for light-water reactors (LWRs), and ASCE 43 is consistent with the current staff positions in Regulatory Guide (RG) 1.208 (NRC, 2007c). The LMP/ASCE 43 Integration Approach builds on insights gained from the application of ASCE 43 to safety evaluations of existing facilities and from current LWR design practices.

The graded approach to SDCs and LSs in ASCE 43 requires the definition of performance goals for different SSCs, which cannot be derived solely from the F-C plot of NEI 18-04 (NEI, 2018). Since each event sequence involves a multitude of SSCs, many different combinations of performance goals for individual SSCs may yield the same overall performance for the event sequence. Therefore, one potential approach is to assign predetermined categories and performance goals to the SSCs, then use the PRA to calculate how close the resulting F-C pairs are to the F-C target and whether the design meets the F-C limits for the individual event sequences and the cumulative risk metrics. If it does not, the risk target may be achieved by altering safety classifications, selectively hardening or relaxing the design, introducing redundancy, improving random failure rates, improving human-error probabilities, or some combination of these. This is an inherently iterative process that could lead to the identification of additional LBEs and the recategorization of SSCs.

Figure 3-1 illustrates the seven-step seismic design process. A related integrated process is shown in Figure 2-2, which also illustrates how this process fits into the overall LMP framework.

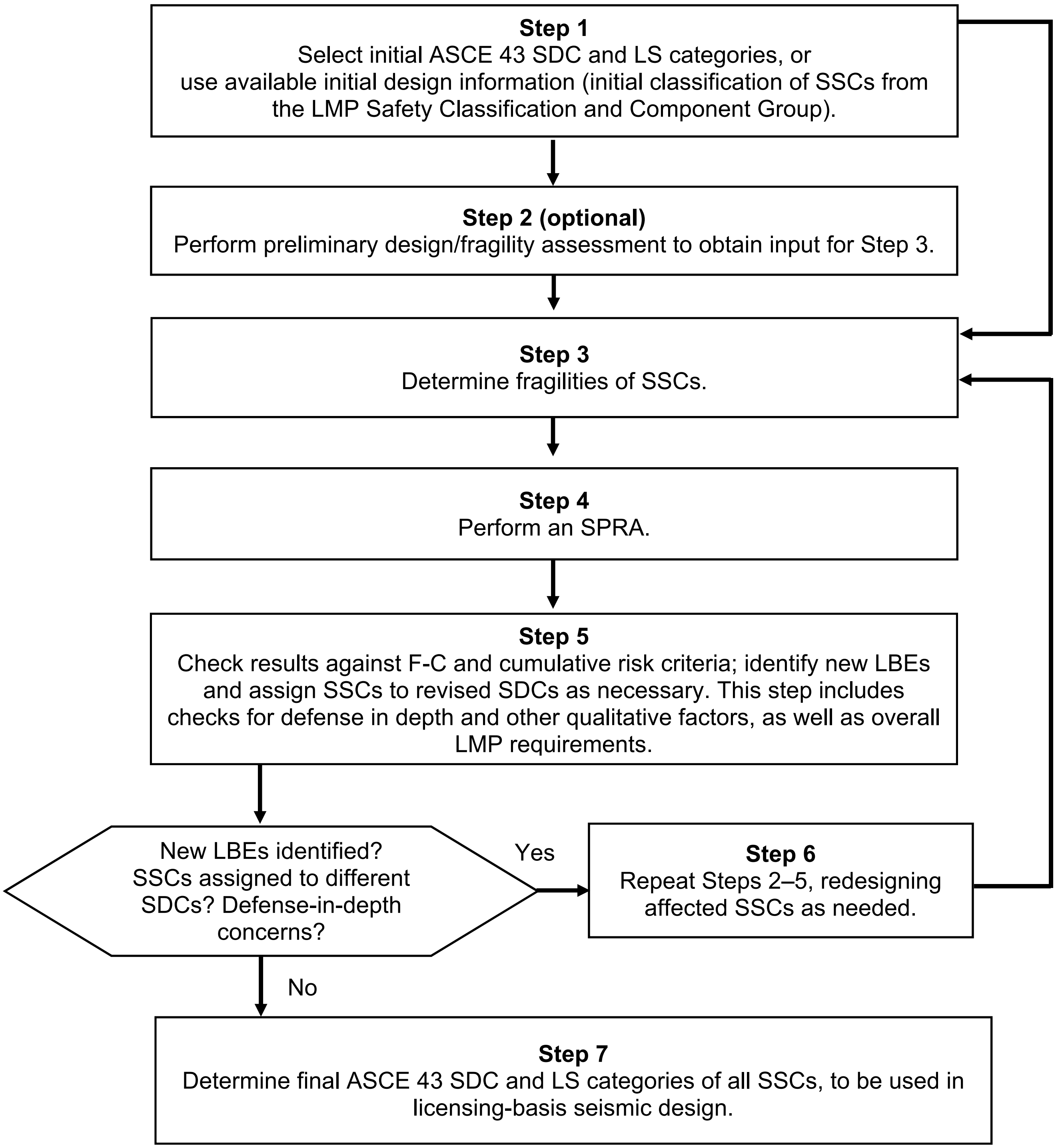

Figure 3-1 Proposed seven-step seismic design process (LMP/ASCE 43 Integration Approach)

Section 3.3 describes all seven steps in detail and notes technical considerations for implementing them. While the proposed seven-step process is for advanced reactors, the concepts also apply to advanced light-water reactor (ALWR) and LWR designs, with certain modifications and the appropriate risk metrics. Section 3.5 describes a modified process for LWRs (or ALWRs).

The seven steps of the LMP/ASCE 43 Integration Approach are as follows:

- Step 1: Select initial ASCE 43 SDCs and LSs.

  In this step, the LMP Safety Classification and Component Group (LMP Component Group)[4] establishes an initial classification of SSCs based on an internal-events PRA. For LWRs, this step may be relatively straightforward because of existing designs and past design experience.

  For advanced reactors whose designs are already in progress or have been completed, the seismic design is based on an approach akin to that of ASCE 4 and ASCE 43, using SDC–5 and LS-D requirements. Newer advanced reactor designs have the option of using combinations of SDCs and LSs (such as SDC–5 and LS-D, SDC–5 and LS-C, or SDC–4 and LS-D), which are selected at the onset.

  This step should also consider regulatory requirements, design stability, and available information. The choice of LS for an SSC is related to its intended safety function. Section 3.3 provides additional details on the technical and regulatory considerations necessary during the initial selection of SDCs and LSs.

- Step 2 (optional): Perform preliminary design/fragility assessment.

  This optional step provides an opportunity to conduct preliminary design and fragility assessments to determine whether certain important SSCs require more precise fragility estimates. This may only be necessary in the second and subsequent iterations of the process, to improve accuracy in Step 5. In most cases, once the SDCs and LSs are chosen (Step 1), one can proceed to Step 3. However, in some cases, a better understanding of the design and/or a better estimate of the fragility of certain components may allow for more informed and robust decisions.

- Step 3: Determine fragilities.

  Based on the assignment of SDCs and LSs in Step 1, and based on available details, fragilities can be either calculated in accordance with accepted procedures or determined using generic information, engineering judgment, or experimental data. The selection of SDCs and LSs does not require precise fragility values, only estimates within a realistic range. The current generic database reflects the current practice of designing safety-related SSCs using SDC–5 and LS-D. Chapter 4 discusses the adjustment of these fragilities for different combinations of SDC and LS.

[4] The LMP Component Group for a given design has overall responsibility for establishing LBEs and classifying SSCs, using the integrated decisionmaking process of the LMP framework. It is a multidisciplinary group having pertinent technical and regulatory expertise.

- Step 4: Perform an SPRA.

  In this step, the analyst performs an SPRA using the fragilities determined in Step 3 and the SPRA models developed in accordance with the applicable codes. The LMP approach requires an SPRA at the stage of design certification. As noted earlier, ASME/ANS RA-S-1.4 discusses graded PRA constraints for different design life-cycle stages. This is a departure from the approach currently used in the design certification of ALWRs. As described in SECY-93-087 (NRC, 1993) and ISG-020 (NRC, 2010b), the current approach uses a PRA-based margin analysis, which does not require a PSHA, to demonstrate whether the proposed design meets a plant-level performance target of high-confidence low probability of failure (HCLPF) level of 1 percent at 1.67 times the design-basis ground motion. (The plant-level HCLPF in this context is with respect to the PRA's core damage frequency (CDF) and large early release frequency (LERF). In other words, this performance target ensures that seismically induced core damage and large early releases are unlikely at ground motion levels that are 1.67 times the design-basis ground motion.)

  In contrast, the LMP framework requires an SPRA to establish LBEs, and the performance targets are in terms of frequencies and consequences. Further methods are needed to select seismic hazard information that can be used for a design certification SPRA.

  The SPRA results from Step 4 are provided to the LMP Component Group, which checks, in Step 5, whether the results meet the various risk metrics, including the cumulative risk metric.

- Step 5: Check proposed classifications against risk, defense-in-depth, reliability, and other qualitative criteria.

  In this step, the LMP Component Group evaluates the results of the initial SPRA to determine whether the individual event sequence risks are within F-C target limits, whether the integrated risk criteria are met, and which risk-significant LBEs fall within a 1-percent margin on the F-C curves. The group also evaluates defense-in-depth adequacy, reliability, and other qualitative factors related to risk-informed decision-making (e.g., balance between prevention and mitigation, avoidance of singleton failures that control the risk), as well as other LMP guidelines. The group may identify opportunities to design SSCs to less stringent SDCs or LSs. It provides this feedback as needed to the seismic design and SPRA teams to recalculate the SSC fragilities.

- Step 6: Iterate.

  Steps 2–5 are repeated to optimize the design so as to meet all safety goals, cost goals, and regulatory requirements. The SDC and LS classifications of the SSCs in the final design may differ from the initial classifications chosen in Step 1.

- Step 7: Determine final SSC categorization for seismic design.

  This step produces a final SSC categorization, which becomes the basis for the plant's final seismic design and for the licensing of the certified design. The final SPRA will use this categorization and the associated fragilities.

3.3 Detailed Discussion of the Seven-Step Seismic Design Process

This section discusses additional considerations for effective implementation of each step in the seven-step design process. These considerations promote a stable design process, one that produces a seismic design (at the design certification stage) that is robust enough to be placed at multiple sites with minimal site-specific changes. However, at the same time, they help maximize the benefits of the RIPB approach through optimal selection of SDCs and LSs.

In the following discussion, it is important to note that the certified seismic design response spectra (CSDRS) are site parameters assumed for the design certification (DC) design under 10 CFR Part 52. The design vendor selects CSDRS and associated generic site profiles for seismic safety analyses. The purpose of this section is to show that the RIPB approach can be implemented in the context of the 10 CFR Part 52 process.

3.3.1 Step 1—Select Initial ASCE 43 Seismic Design Category and Limit States

Ground rules for choosing SDCs and LSs should be established early in the process. For example, an SSC that provides structural support to several other SSCs could be analyzed and designed to a hazard level (seismic input) higher than that of the supported SSCs (e.g., the former might be SDC–5 while the latter are SDC–4). This would require seismic loads for supported SSCs to be based on the SDC–4 category.

Two example options are presented for selecting initial SDCs and LSs. In Option 1, SSCs under all four LMP safety categories are designated as SDC–5 and LS-D. Option 2 allows less stringent SDCs and LSs. To illustrate this, Table 3-2 shows selections of SDC/LS pairs under both options. (The table also shows two other safety-related categories, encompassing nonreactor radiological sources and other SSCs that may not be part of any risk assessment.) For reasons discussed later in this section, the initial selection is limited to SDC–4, SDC–5, LS-C, and LS-D. The table also includes the name of the design-basis ground motion corresponding to each SDC, as discussed in Section 3.1.3.

In Table 3-2, SDCs and LSs are assigned to groups or classes of components. Although it is theoretically possible to assign an SDC and LS individually to each SSC, it can be cumbersome to do so in practice. However, some major components may be assigned independent SDCs and LSs to realize cost and safety benefits.

Table 3-2 Initial Selection of SDC and LS Categories

Safety Category	Option 1 ASCE 43 SDC and LS	Option 2 ASCE 43 SDC and LS
SSCs selected by the designer to perform required safety functions to mitigate the consequences of DBEs to within the F-C target, and to mitigate DBEs to meet the dose limits of 10 CFR 50.34, “Contents of applications; technical information,” using conservative assumptions.	SDC–5, LS-D CSDRS-5 (or SSDRS-5)	SDC–5, LS-D CSDRS-5 (or SSDRS-5)
SSCs selected by the designer to perform required safety functions to prevent the frequency of BDBEs with consequences exceeding 10 CFR 50.34 dose limits from increasing into the DBE region and beyond the F-C target.	SDC–5, LS-D CSDRS-5 (or SSDRS-5)	SDC–5, LS-D CSDRS-5 (or SSDRS-5)
Nonsafety-related SSCs relied on to perform risk-significant functions, which are those that keep LBEs from exceeding the F-C target or that contribute significantly to the cumulative risk metrics selected for evaluating the total risk from all analyzed LBEs.	SDC–5, LS-D CSDRS-5 (or SSDRS-5)	SDC–5, LS-C (or SDC–4, LS-D) CSDRS-5 or CSDRS-4 (SSDRS-5 or SSDRS-4)
Nonsafety-related SSCs relied on to perform functions requiring special treatment for defense-in-depth adequacy.	SDC–5, LS-D CSDRS-5 (or SSDRS-5)	Use current approaches. Allow applicant to choose SDC and LS (with SDC at least 4).
All other SSCs, except those covered by the row below.	Use current approaches. Allow applicant to choose.	Use current approaches. Allow applicant to choose.
SSCs not included in SPRA models, but related to radiological sources (e.g., spent fuel pool).	Use current approaches as follows: SFP SDC–5, LS-D for spent fuel pool	Use current approaches as follows: SFP SDC–5, LS-D for spent fuel pool

3.3.1.1 Considerations for Choosing SDCs

As discussed in Chapter 2, ASCE 43 refers to the annual frequency of exceeding the acceptable performance level as the target performance goal; this quantity decreases with increasing SDC level (Table 3-1). The decrease in the target performance goal is achieved by decreasing the annual exceedance frequency of the design-basis earthquake ground motion (i.e., by going from SSDRS-4 to SSDRS-5). When selecting an SDC, it is important to understand the relative differences among the design-basis earthquake ground motions. For reference, the DRS[5] associated with SDC–3, SDC–4, and SDC–5 are derived from the uniform hazard response spectra (UHRS) with annual exceedance frequencies of 1×10^{-3}, 4×10^{-4}, 1×10^{-4}, and 1×10^{-5}, respectively.

To illustrate the differences among the SDCs, Table 3-3 summarizes the PGA and the 5-hertz (Hz) spectral frequency values from several recent site-specific PSHA. The ground motions were derived from recent licensee submittals in response to Near-Term Task Force Recommendation 2.1. Figure 3-2 shows mean PGA hazard curves for the sites at the SSE control point locations. These sites are Central and Eastern United States (CEUS) NPP locations in different physiographic regions with different site characteristics.

Table 3-3 Ground Motion Data from Nine CEUS Sites

Plant Site	General Site Characteristics	1×10^{-4}		1×10^{-5}		GMRS
		PGA (g)	5 Hz (g)	PGA (g)	5 Hz (g)	PGA (g)
A	Rock	0.325	0.313	1.05	0.983	0.499
B	Rock	0.378	0.328	1.201	1.01	0.572
C	Soil over rock	0.436	0.876	0.814	1.77	0.436
D	Soil over rock	0.153	0.223	0.389	0.559	0.194
E	Soil over rock	0.207	0.49	0.521	1.13	0.26
F	Till over rock	0.34	0.351	1.06	1.32	0.505
G	Soil	0.12	0.242	0.352	0.737	0.17
H	Soil	0.069	0.165	0.182	0.394	0.090
I	Soil	0.089	0.161	0.219	0.372	0.11

Current NRC guidance uses the ASCE 43 SDC–5 approach to develop the ground motion response spectra (GMRS), as described in RG 1.208 (NRC, 2007c). The comparisons in this section show how the ground motions differ among varying SDCs and how they relate to those used in current practice.

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[5] The site-specific design response spectra (SSDRS) are derived from the newer procedure for developing the DRS that will appear in the new version of ASCE 43. However, the results are very similar to those of the procedure in ASCE 43-05, which is illustrated in Section 4.2.2 of this report. The annual exceedance frequency of 4×10^{-4} is included here because ASCE 43-05 uses this UHRS to derive DRS for SDC–4. Similarly, the annual exceedance frequency of 1×10^{-5} is included because the revised procedure to develop DRS for SDC–5 uses this UHRS.

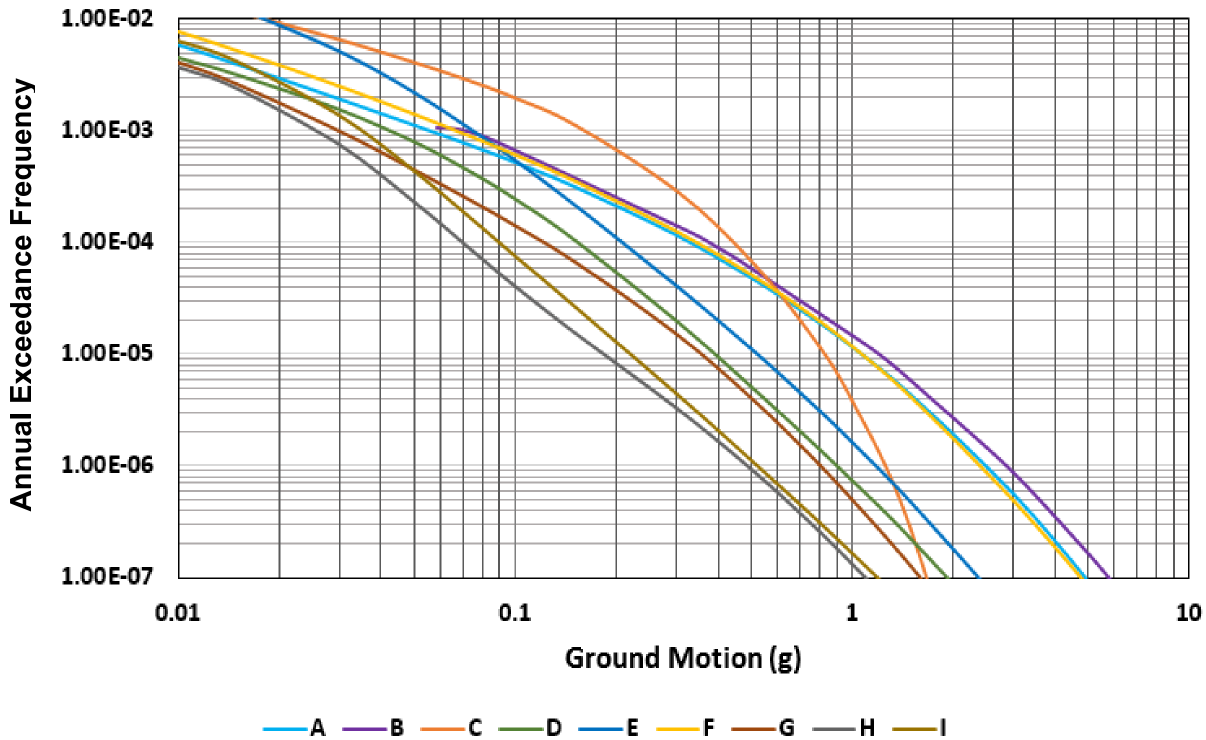

Figure 3-2 Mean hazard curves (PGA) at the control points for the nine CEUS sites described in Table 3-3

Because ASCE 43 establishes the DRS by modifying the underlying UHRS, it is instructive to compare the UHRS for different exceedance frequencies and site conditions. Figure 3-3 through Figure **3-6** show UHRS for all sites at exceedance frequencies of 1×10^{-3}, 4×10^{-4}, 1×10^{-4}, and 1×10^{-5}. Figure 3-6 is included because the revised process in the upcoming edition of ASCE 43 uses UHRS associated with 1×10^{-5} annual exceedance frequency to derive the DRS for SDC–5.

These figures also include a plot of the RG 1.60 (NRC, 2014) spectrum anchored at 0.1g PGA, to compare the design-basis ground motions for various SDCs to the current regulatory requirements for a minimum earthquake level. Appendix S, "Earthquake Engineering Criteria for Nuclear Power Plants," to 10 CFR Part 50 states, "The horizontal component of the Safe Shutdown Earthquake Ground Motion in the free-field at the foundation level of the structures must be an appropriate response spectrum with a peak ground acceleration of at least 0.1g." ISG-017 (NRC, 2010a) further states that the RG 1.60 spectra are considered appropriate for meeting this part of the regulation. ASCE 43 includes similar statements: "If required, the DRS shall be amplitude scaled up by one factor across the entire frequency range such that the zero period acceleration is not less than 0.04 g for SDC–2, 0.06 g for SDC–3, 0.08 g for SDC–4, or 0.10 g for SDC–5."

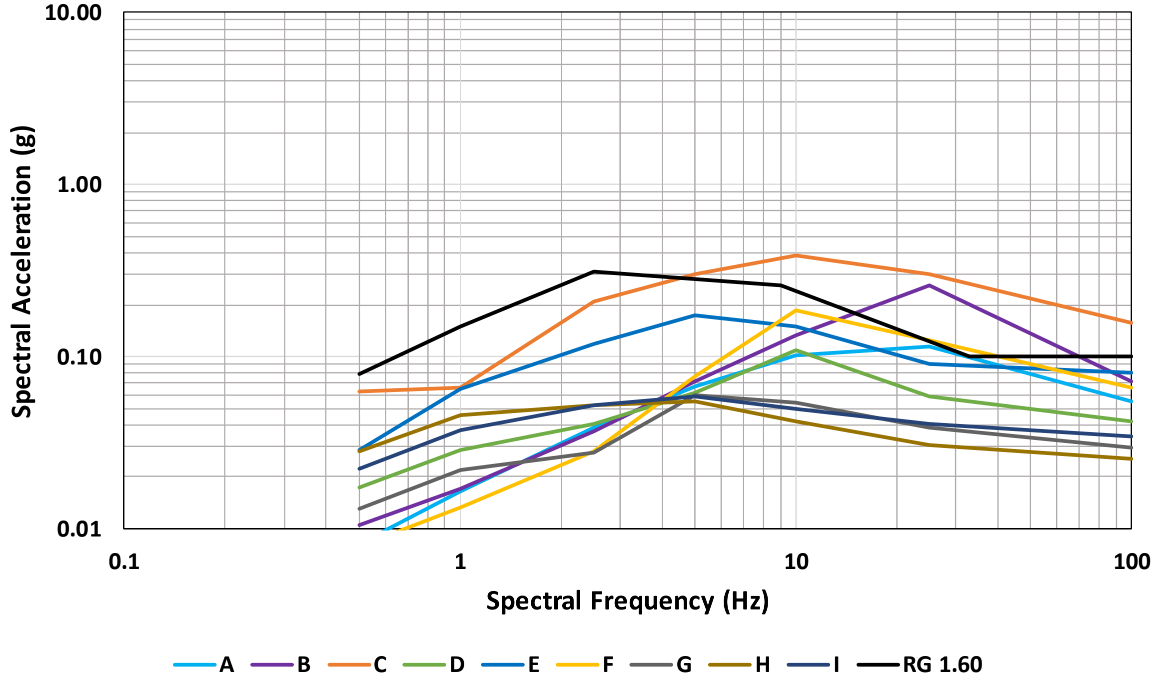

Figure 3-3 UHRS for nine CEUS sites corresponding to the 1×10^{-3} exceedance frequency

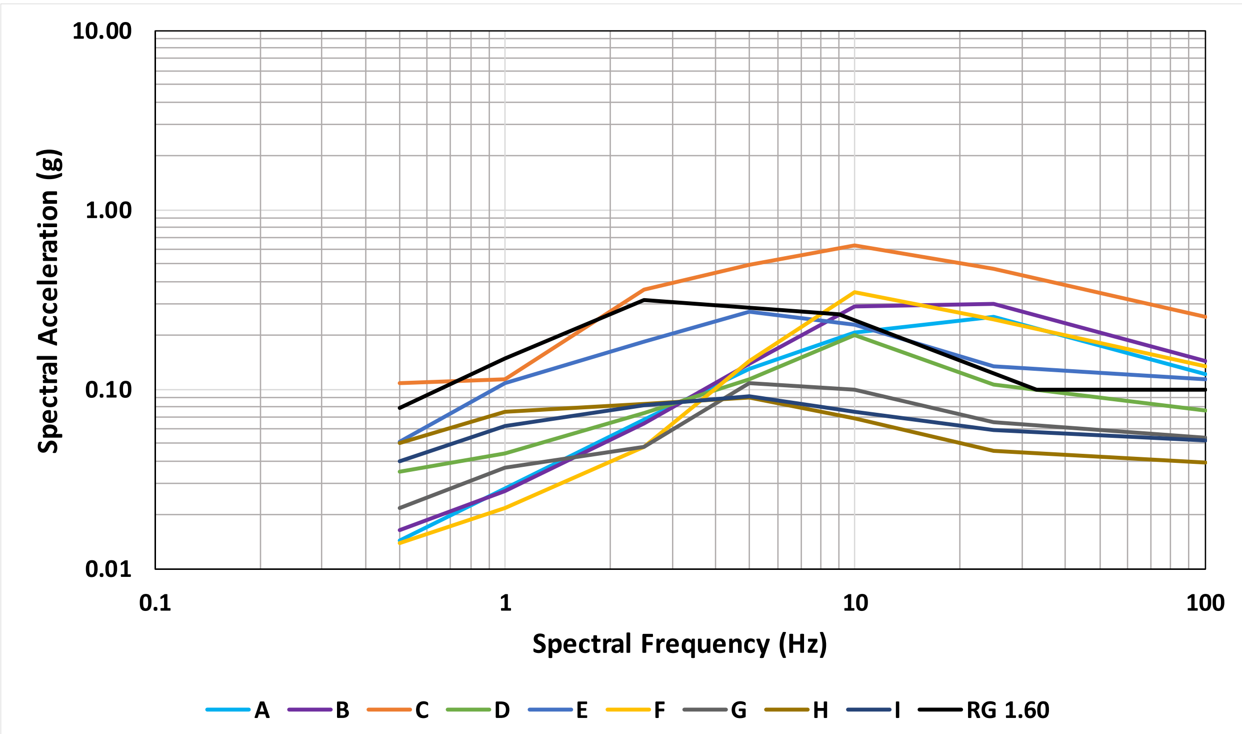

Figure 3-4 UHRS for nine CEUS sites corresponding to the 4×10^{-4} exceedance frequency

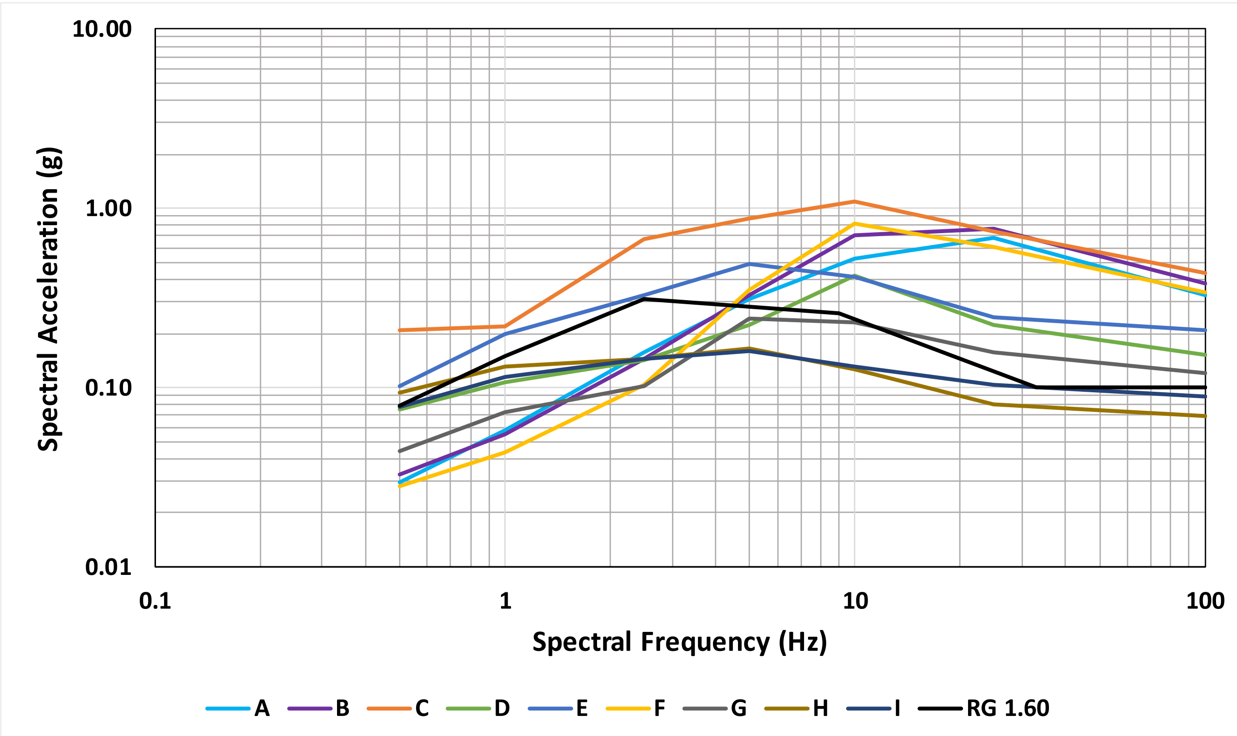

Figure 3-5 UHRS for nine CEUS sites corresponding to the 1×10^{-4} exceedance frequency

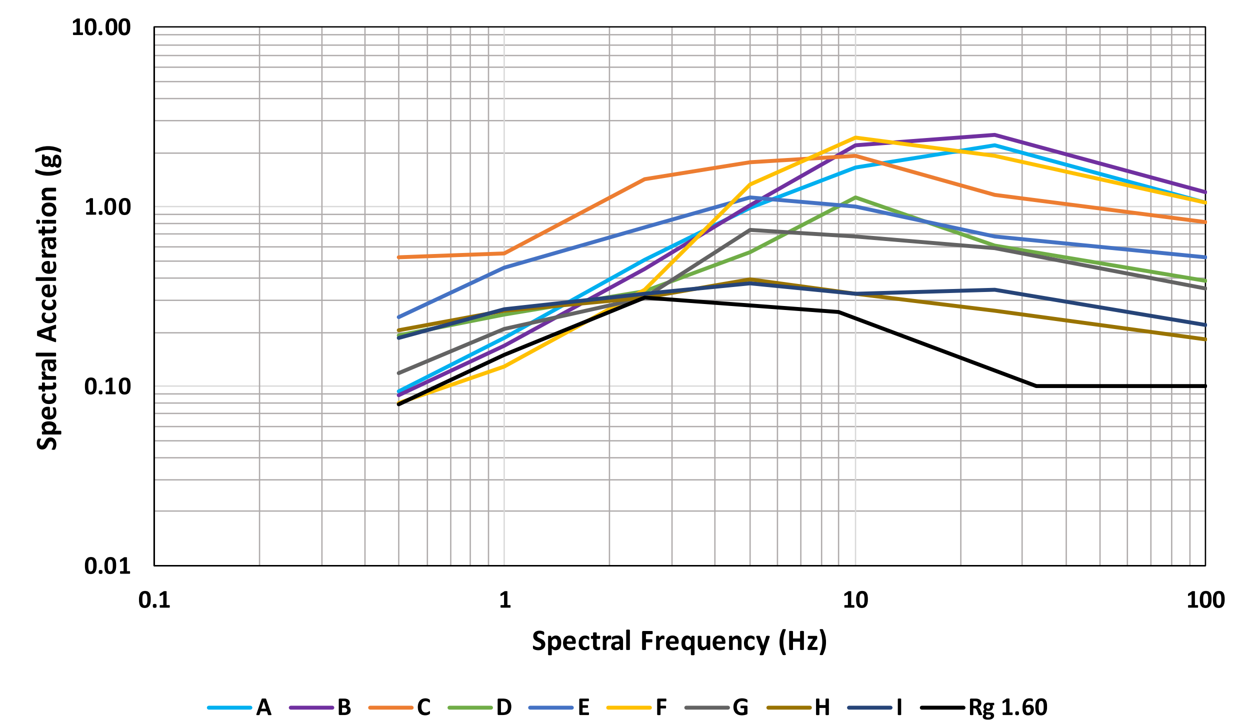

Figure 3-6 UHRS for nine CEUS sites corresponding to the 1×10^{-5} exceedance frequency

ASCE 43 has minimum PGA values smaller than 0.1g, because its SDCs were developed for DOE facilities, including nonreactor nuclear facilities not requiring the same levels of seismic design as NPPs. Because this report considers only NPP designs, the following discussion assumes a minimum PGA of 0.1g.

Using the above UHRS, the site-specific design response spectra (SSDRS[6]) associated with SDC–3, SDC–4, and SDC–5 are computed for three site conditions: (1) hard rock, (2) soil over rock, and (3) deep soil. Figure 3-7 shows DRS for the rock site. Figure 3-8 and Figure 3-9 show results for a selected soil-over-rock site and a selected deep soil site, respectively.

As is typical at many CEUS sites, site-specific PSHA results indicate stronger ground motions at higher spectral frequencies and weaker ground motions at lower frequencies than the RG 1.60 spectrum anchored at PGA. The RG 1.60 spectrum, first developed in the 1970s, was based on a limited set of earthquake records from California. For a rock site (Figure 3-7), the RG 1.60 ground motion exceeds the SSDRS-5 motions for spectral frequencies of 2 Hz and lower. At 10 Hz, the RG 1.60 ground motion is considerably stronger than the SSDRS-3 ground motion at frequencies below 10 Hz. For the soil-over-rock site (Figure 3-8), the differences are less pronounced. For the deep soil site (Figure 3-9), the SSDRS ground motions are, in general, weaker than the RG 1.60 spectrum. However, it should be noted that the deep soil site is located near the Gulf of Mexico, in a region of low seismicity. The differences among the SSDRS ground motions and the RG 1.60 spectra anchored at PGA affect many site-specific design activities and decisions, and they may also be important in the context of a certified design, which needs to be feasible across a variety of site conditions.

Table 3-4 lists ground motions at the nine CEUS sites (PGA and 5 Hz) for SSDRS-3, SSDRS-4, and SSDRS-5. Table 3-5 gives the ratios of the SSDRS-3 and SSDRS-4 ground motions to the SSDRS-5 ground motions. These ratios indicate the potential reduction in seismic demand if an SSC design uses a lower SDC, assuming the design maintains a consistent LS for all SDCs. As discussed in Chapter 4, the reduction in seismic demand alone may not control the design of an SSC, since there are many other complex design factors. One should also note that each SDC has a different performance target for exceeding the LS.

As Table 3-5 shows, the PGA and 5-Hz values are 30 to 50 percent lower for SDC–4 than for SDC–5 ground motions, and 50 to 70 percent lower for SDC–3 than for SDC–5. As the current design approach uses LS-D, the above reductions also suggest how the fragilities (i.e., median capacity) could change if the designs were anchored to categories other than SDC–5, but for the same LS-D (with different performance targets). This is an important insight, explicitly demonstrating the relationship between the capacity and the risk significance of an SSC .

[6] Section 4.2.2 describes the procedure for computing SSDRS.

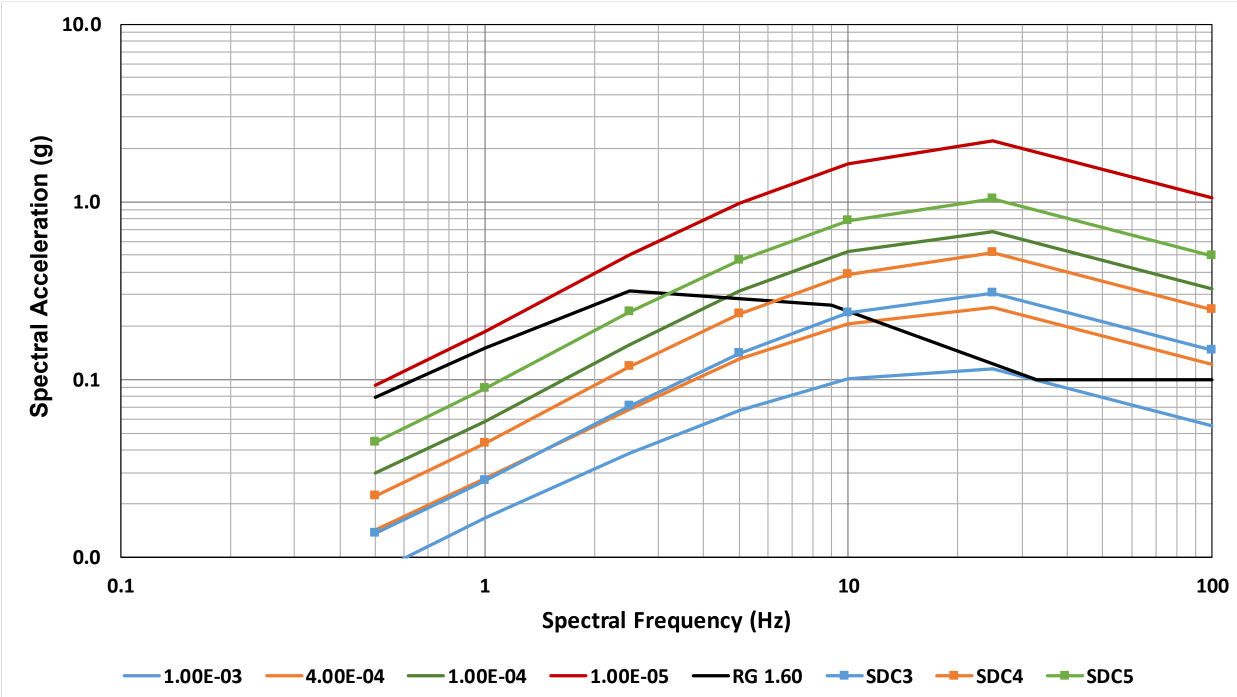

Figure 3-7 SSDRS for three SDCs and four UHRS for Site A, compared to an RG 1.60 spectrum anchored at 0.1g

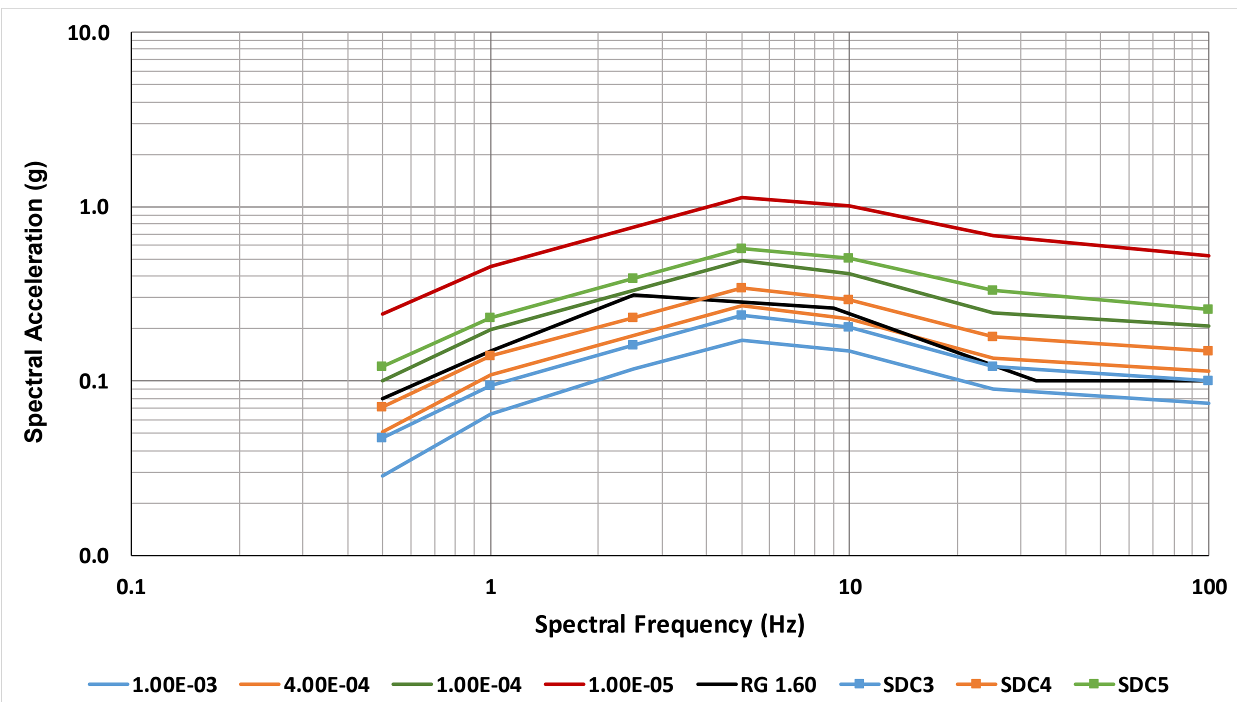

Figure 3-8 SSDRS for three SDCs and four UHRS for Site E, compared to an RG 1.60 spectrum anchored at 0.1g

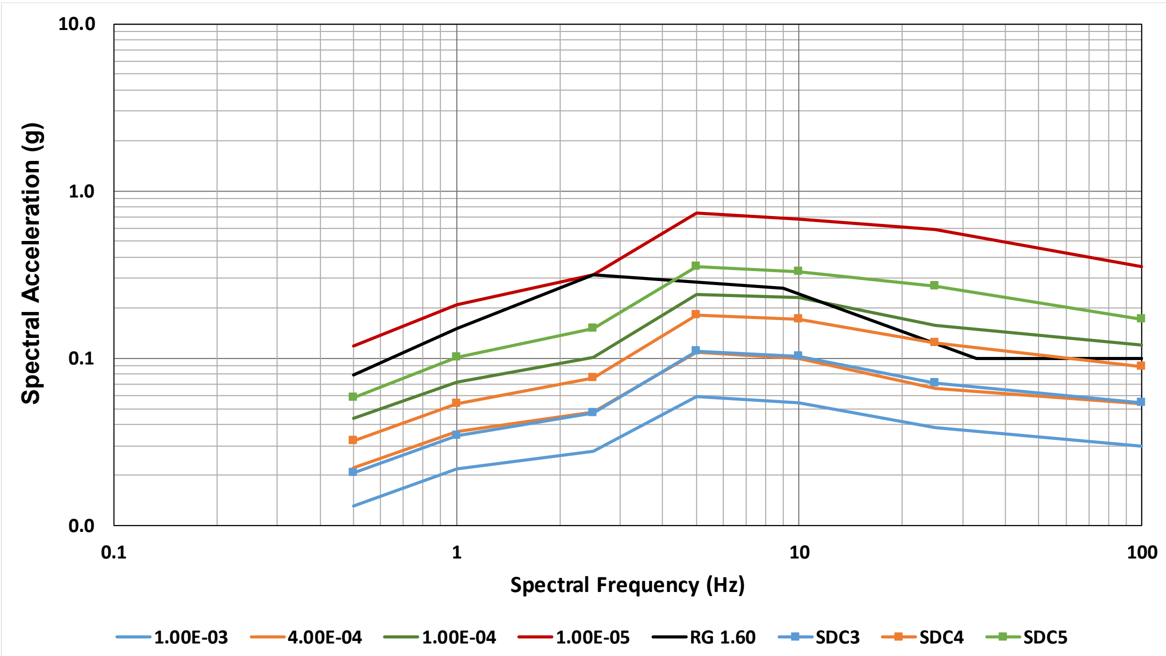

Figure 3-9 SSDRS for three SDCs and four UHRS for Site G, compared to an RG 1.60 spectrum anchored at 0.1g

Table 3-4 PGA and 5-Hz Spectral Acceleration Ground Motions for SDC–3, SDC–4, and SDC–5 at the Nine CEUS Sites

Site	ASCE 43 DRS—PGA (g)			ASCE 43 DRS—5 Hz (g)		
	SSDRS-5	SSDRS-4	SSDRS-3	SSDRS-5	SSDRS-4	SSDRS-3
A	0.50	0.25	0.15	0.47	0.23	0.14
B	0.57	0.27	0.17	0.49	0.24	0.15
C	0.44	0.29	0.21	0.92	0.60	0.42
D	0.19	0.11	0.07	0.28	0.16	0.10
E	0.26	0.15	0.10	0.57	0.34	0.24
F	0.51	0.25	0.15	0.61	0.28	0.16
G	0.17	0.09	0.05	0.35	0.18	0.11
H	0.09	0.05	0.03	0.20	0.12	0.08
I	0.11	0.06	0.04	0.19	0.11	0.08

Table 3-5 Ratios of SSDRS-3 and SSDRS-4 Ground Motions to the SSDRS-5 Ground Motions for All Nine CEUS Sites

Site	Ratios of PGA Values		Ratios of 5-Hz Values	
	SSDRS-4 /SSDRS-5	SSDRS-3 /SSDRS-5	SSDRS-4 /SSDRS-5	SSDRS-3 /SSDRS-5
A	0.49	0.29	0.50	0.30
B	0.48	0.30	0.50	0.30
C	0.67	0.49	0.65	0.46
D	0.56	0.37	0.57	0.37
E	0.57	0.39	0.60	0.42
F	0.50	0.30	0.45	0.26
G	0.52	0.32	0.51	0.31
H	0.55	0.38	0.58	0.40
I	0.58	0.40	0.60	0.42

Figure 3-10 through Figure 3-12 plot the SSDRS-5, SSDRS-4, and SSDRS-3 for all nine sites. These plots also include CSDRS-5, CSDRS-4, and CSDRS-3 curves, which envelop the SSDRS-5, SSDRS-4, and SSDRS-3 curves, respectively. These CSDRS curves represent examples of design certification motions for the three SDCs. In current practice, the CSDRS ground motion spectrum is developed to be generic, enveloping ground motions at all 69 CEUS sites. One crucial difference in the enhanced RIPB approach of this report is that there may be more than one CSDRS, depending on how many SDCs are selected for the various SSCs in the seismic design. In addition, design vendors can opt to use alternative criteria to develop certified design spectra; they are not required to follow the bounding approach shown here. This conservative bounding approach was developed to demonstrate that the use of alternate combinations of SDCs, rather than SDC–5 across the board, can yield significant design benefits because of the potential for reduced ground motions.

Because it envelops multiple site conditions, the CSDRS for all SDCs will exceed the NRC's current minimum ground motion requirement of 0.1g PGA. The annual exceedance frequencies of the CSDRS ground motions are lower than those of the corresponding underlying SSDRS motions.

As shown in Figure 3-13 and Table 3-6, LS-D corresponds to essentially elastic response. LS-C, LS-B, and LS-A permit progressively increasing permanent deformations and excursions into the inelastic regime. Because inelastic behavior leads to additional energy losses, a component or a structural element designed to LS-C, LS-B, or LS-A is subjected to lower seismic demands than the elastic demand for the same design-basis ground motion. Table 3-7 shows how, in accordance with ASCE 43, forces for a shear-controlled reinforced concrete shear wall are lower for LS-A, LS-B, and LS-C than for LS-D. Chapter 4 includes a discussion of a shear wall design for different SDC and LS combinations to clarify the design process and implications.

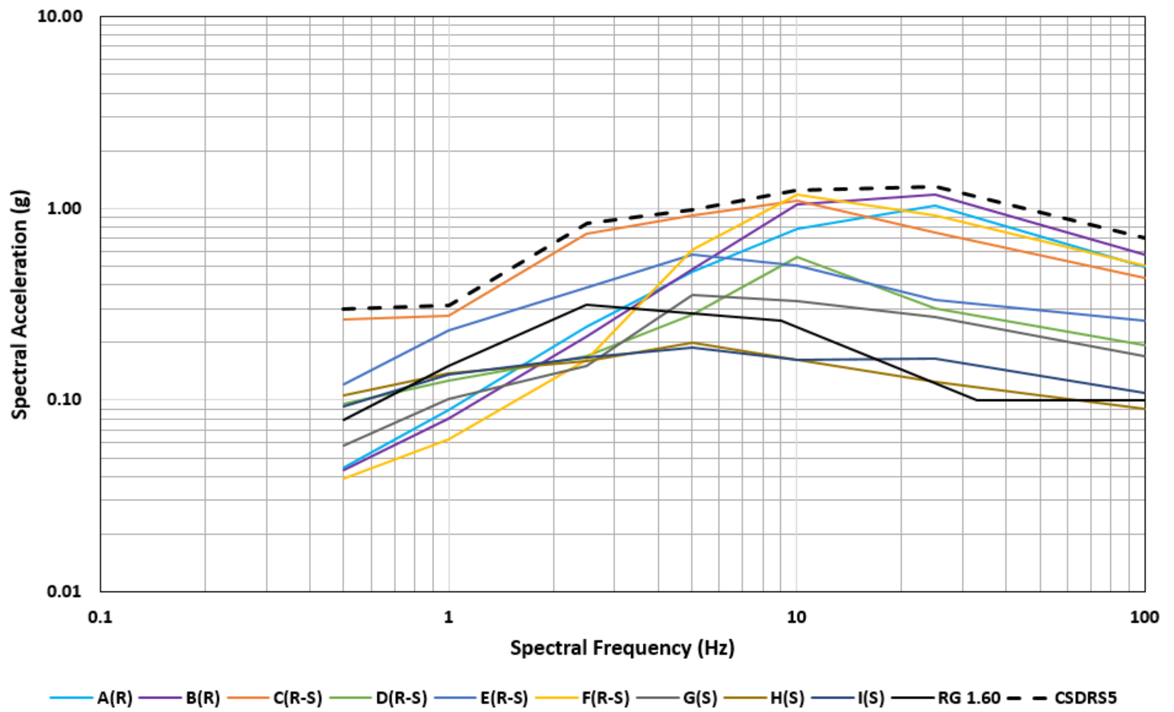

Figure 3-10 SSDRS-5 for all nine CEUS sites, compared an RG 1.60 spectrum anchored at 0.1g and the corresponding CSDRS

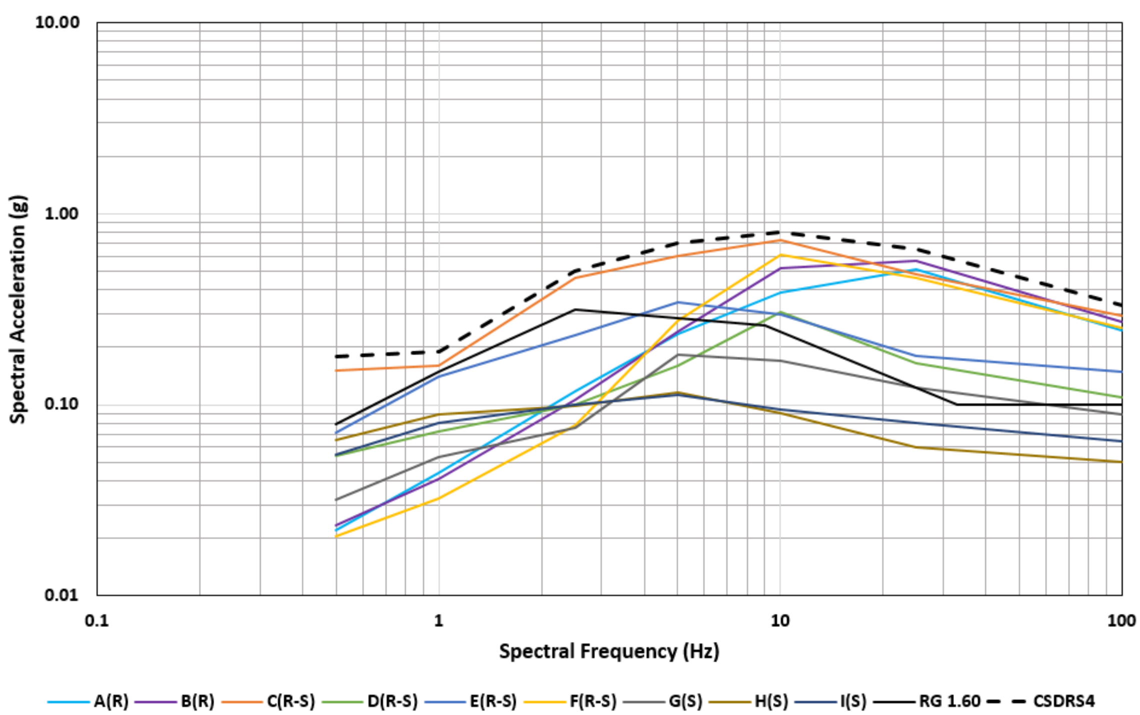

Figure 3-11 SSDRS-4 for all nine CEUS sites, compared an RG 1.60 spectrum anchored at 0.1g and the corresponding CSDRS

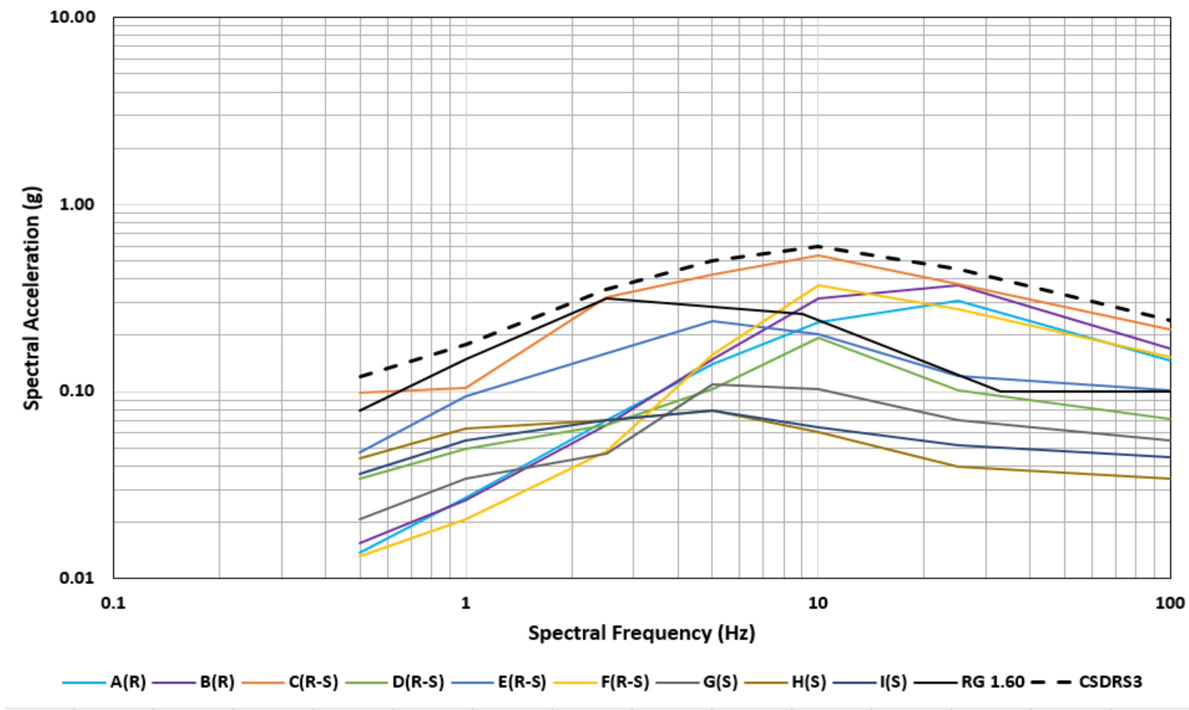

Figure 3-12 SSDRS-3 for all nine CEUS sites, compared an RG 1.60 spectrum anchored at 0.1g and the corresponding CSDRS

Table 3-6 Deformation and Damage by LS

Limit State	Expected Deformation	Expected Damage
LS-A	Large permanent distortion, short of collapse	Significant damage
LS-B	Moderate permanent distortion	Generally reparable
LS-C	Limited permanent distortion	Minimal damage
LS-D	Essentially elastic behavior	Negligible damage

Table 3-7 Reduction in Seismic Demand for a Shear Wall Due to Inelastic Deformation

Reinforced concrete shear walls, in-plane	Ratio of forces for different LSs		
Shear controlled walls	LS-A/LS-D	LS-B/LS-D	LS-C/LS-D
Aspect ratio: height/length < 2.0	0.50	0.57	0.67

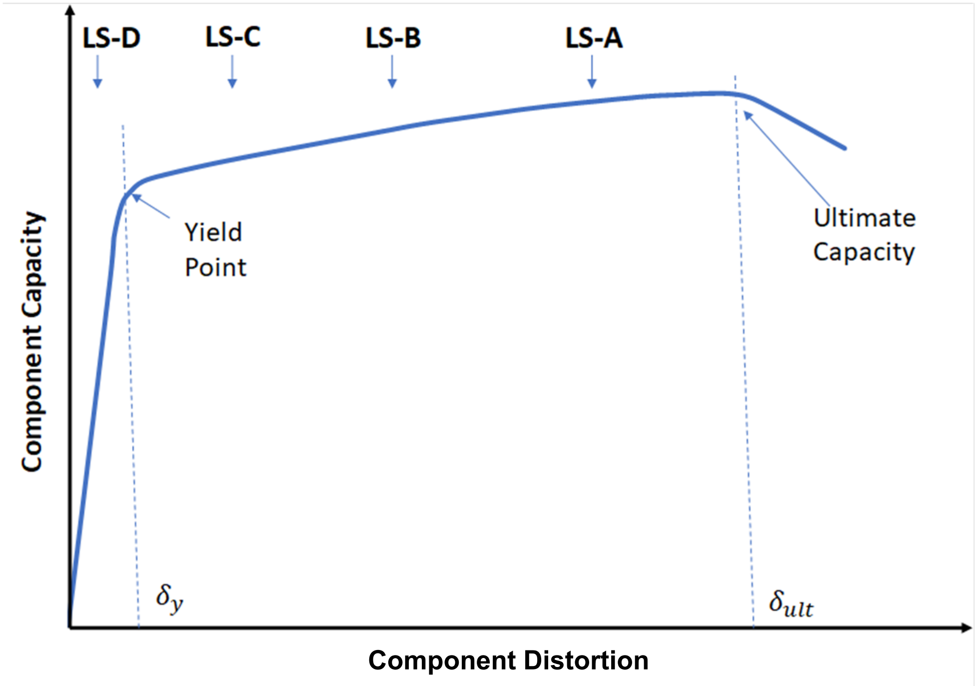

Figure 3-13 Typical load-deformation curve and LSs (adapted from ASCE 43)

3.3.1.2 Considerations for Choosing LSs

In addition to the selection of the SDCs, another fundamental decision in this report's proposed approach to seismic design is the selection of the appropriate LSs. Table 3-6 shows the damage LSs per ANSI/ANS-2.26 (ANSI/ANS, 2004). Under the current version of ANSI/ANS-2.26, LS-D is the only LS applicable to NPP design. The other, less stringent LSs are for nuclear facilities with lower risk profiles. The examples in Chapter 4 of this report consider SSCs designed to less stringent LSs to evaluate how this aspect of NPP design contributes to risk.

Figure 3-13 illustrates the definitions of Table 3-6 in graphical form; here, δ_y is the distortion or deformation at yield, δ_{ult} is the distortion or deformation at failure, and the LSs are those of Table 3-6. A comparison of Tables 3-5 and 3-7 shows how seismic demand reductions due to LS choice differ from those due to SDC choice. The shear wall example in Chapter 4 examines several combinations of SDC and LS. In general, for reactor and spent fuel pool risks, LS-B and LS-A are not likely options for safety-related components (those in the first four rows of Table 3-2); these LSs may be appropriate for other radiological sources, such as waste holdup tanks, and for low-risk facilities such as microreactors.

Figure 3-13 also provides qualitative insight into the available margin of an SSC to ultimate failure (e.g., fragility failure mode in an SPRA), for beyond-design-basis loads. As LS-C, LS-B, and LS-A permit inelastic deformations, these LSs have reduced margins to ultimate failure. Fragility calculations should reflect these capacity reductions.

3.3.1.3 Other Considerations for Choosing SDCs and LSs

Sections 3.3.1.1 and 3.3.1.2 were primarily concerned with the potential benefits of selecting alternative SDCs and LSs over the current practice of using SDC–5 and LS-D for all safety-related SSCs in NPPs. These benefits arise mainly from reductions in seismic demand, which could lead to designs that have more uniform margins and conservatism consistent with risk significance, while still meeting overall risk metrics. However, these benefits need to be balanced against additional practical and regulatory considerations in the selection of less stringent SDCs and LSs.

One important consideration is the stability of the design, especially at the design certification stage, at which the seismic design should yield a power plant that is viable for a range of seismic conditions without requiring substantial site-specific modifications. Stability also encompasses operability over a plant's lifetime, especially as new knowledge about seismic hazards emerges.

Another important consideration is the availability of design details at the time of choosing SDCs and LSs. If few details are available, it may be necessary to choose relatively conservative SDCs and LSs to avoid excessive iteration and significant design changes later in the process. Decisions and choices at the design certification stage should identify clear site-specific interfaces and activities that are easy to implement. Seismic interfaces have emerged as an important issue in recent experience with combined license (COL) applications. The requirements related to the minimum design ground motion are particularly important for site-specific component design and for SDC selection for the site-specific ground motion.

It is also important to consider the designation of the operating-basis earthquake (OBE). Appendix S to 10 CFR Part 50 requires the following:

> (i) The Operating Basis Earthquake Ground Motion must be characterized by response spectra. The value of the Operating Basis Earthquake Ground Motion must be set to one of the following choices:
>
> (A) One-third or less of the Safe Shutdown Earthquake Ground Motion design response spectra. The requirements associated with this Operating Basis Earthquake Ground Motion in Paragraph (a)(2)(i)(B)(I) can be satisfied without the applicant performing explicit response or design analyses, or
>
> (B) A value greater than one-third of the Safe Shutdown Earthquake Ground Motion design response spectra. Analysis and design must be performed to demonstrate that the requirements associated with this Operating Basis Earthquake Ground Motion in Paragraph (a)(2)(i)(B)(I) are satisfied. The design must take into account soil-structure interaction effects and the duration of vibratory ground motion.

Based on recent design certification applications, Option A seems most likely to be used. However, the selection of multiple SDCs could imply multiple OBE ground motions, complicating decisions about plant shutdown and restart should an earthquake occur. ISG-01 (NRC, 2008) partially addresses this situation, as it discusses the interpretation of the OBE for the certified design portion and for the site-specific design portion of a plant. The more important question here is that of restart after an earthquake, especially in relation to the ability or need to restore the plant to its original licensed conditions, should the design allow limited damage (consistent with LS-C, for example). In the current practice of designing to LS-D, which requires elastic response (i.e., no permanent damage), aftershocks are not an important factor in seismic design.

Finally, when choosing SDCs and LSs, it is important to consider combinations of accident and earthquake loads.

Although many SDC and LS combinations are possible (16, to be precise, in ASCE 43), practical applications should consider four options—SDC–5 and LS-D, SDC–5 and LS-C, SDC–4 and LS-D, and SDC–4 and LS-C—for safety-related components involved in reactor and spent fuel risks. SDC–3 and LS-D may also be acceptable for a few SSCs. One important advantage of using LS-D is that the seismic responses and demands from one SDC analysis can be scaled to other SDCs (with some approximations), because the responses are linear. More detailed insights on scaling approaches will come from potential future activities employing the methods discussed in Chapter 4.

3.3.2 Step 2 (Optional)—Perform Preliminary Design/Fragility Assessment

Step 2 is to implement preliminary seismic design according to ASCE 43, ASCE 4, ASCE 1, applicable NRC and industry guidance, and any codes and standards relevant to selected SDCs and LSs. Current design approaches and the dominant experience are based on SDC–5 and LS-D, following ASCE 43, ASCE 4, and ASCE 1. Thus, by maintaining LS-D while relaxing the SDC–5 requirement, one can reduce the design ground motions while using existing response analysis and design methods (with some changes to numerical values of parameters, such as damping). Although ASCE 43 and ASCE 4 outline approaches for designs that include LS-C and lower, experience in applying these inelastic design options to nuclear-grade structures and equipment is limited. The examples in Chapter 4 provide some insights into how an NPP design might realize alternative SDCs and LSs within an RIPB framework.

As part of an iterative process, this step does not imply a rigorous redesign of the entire plant, but rather allows the option of a design assessment for the components that are candidates for alternative SDC and LS designations, so that more realistic fragilities can be estimated in the next step.

3.3.3 Step 3—Determine Fragilities

Step 3 is to determine the fragilities of the SSCs included in the SPRA model, in consultation with the LMP Component Group and in accordance with any applicable ASME/ANS SPRA standards. This requires consideration of some important aspects of the SPRA, beyond the evaluation of risk and performance metrics. These aspects include the SPRA's role in supporting safety and SDCs of SSCs that are needed for NRC licensing.

The availability of design details largely dictates whether realistic, component-specific fragilities are achievable. Based on current experience,[7] it is unlikely that completely realistic fragilities will be developed at the initial design stage; rather, the goal is to obtain a realistic range of fragilities to inform the basic SSC design parameters derived through the iterative process. Current NPP designs use generic fragilities based on LS-D. They also include factors such as the

[7] From past design certification reviews, the best that can be expected is to achieve conservative fragilities for structures, while assigning fragility values for components and equipment to be confirmed at COL (or before fuel load).

combination of accident and seismic loads, other external hazards, and, in some cases, a more conservative design basis. It is not clear that such margins will exist in future NPP designs.

In the context of the proposed seven-step design process, more realistic fragilities can be developed using the separation-of-variables (SOV) method, based on the currently available industry guidance, as the process defines component design levels iteratively. To maximize the benefits of reclassifying SSCs to different seismic design levels based on risk criteria, the screening of SSCs should be limited.

Current experience in developing fragilities is focused on components designed to LS-D, while the process described in this report requires fragilities for components designed to different LSs and different damage levels. Chapter 4 discusses ways to modify a component fragility based on LS-D to reflect the application of LS-C instead.

3.3.4 Step 4—Perform a Seismic Probabilistic Risk Assessment

In Step 4, the analyst performs an SPRA using the probabilistic seismic hazard curves, the fragilities from Step 3, and the SPRA models developed using the applicable ASME/ANS codes. The role of the PRA marks a crucial difference between current licensing procedures and the LMP/ASCE 43 Integration Approach. Current procedures require PRAs at various stages (design certification, COL, and fuel loading), but these PRAs are not part of the licensing basis. In the LMP/ASCE 43 Integration Approach, PRAs play a more significant role in determining LBEs and other considerations, and they become a part of the licensing basis.

Performing an SPRA at the design certification stage is also a departure from the current approach of doing a PRA-based margin analysis (ISG-020, NRC, 2010b), which does not require a seismic hazard analysis. The LMP/ASCE 43 Integration Approach requires seismic hazard curves at the design certification stage. Several approaches to this are possible; two of them are described here to illustrate ways of incorporating seismic hazard information into the design certification process.

The presentation of these two approaches requires three elements from PSHA results. The first is the hazard intensity at the annual exceedance frequency corresponding to the selected SDC (e.g.,1×10^{-4}). The second is the slope of the hazard curve over a range of annual exceedance frequencies (e.g., 1×10^{-2} to 1×10^{-7}), which can be used to evaluate beyond-design-basis ground motions. (Specifically, for the same component designed to the same design-basis ground motion, a steep hazard curve over this range will result in smaller failure probabilities than a shallow hazard curve.) The third is the spectral shapes of the response spectra (UHRS or GMRS), which are site-specific, because they depend on the nature of the controlling seismic sources, ground motion attenuation, and geotechnical conditions (hard rock, stiff soil, or soft soil). As shown in Figure 3-3 through Figure **3-6**, the site-specific UHRS differ significantly from site to site. The generic design certification process needs to account for these site-specific differences in the response spectral shape and associated fragility curves. In addition, it is instructive to examine site-specific issues during the design certification stage to achieve a more robust design and identify the necessary interfaces for a COL.

Approach 1 for incorporating seismic hazard information into the design certification process is to use a bounding hazard curve that envelops site-specific hazard estimates at the sites where the design may be located. Since PSHA results are available for all CEUS sites, this is straightforward to accomplish. (Figure 3-2 shows hazard curves for nine sites with varying site conditions.) However, Approach 1 does not explicitly consider the issue of different UHRS spectral shapes and may miss some important insights.

Approach 2 is more involved, requiring additional fragility evaluations to account for various site conditions. In some ways, this approach resembles the current approach for demonstrating the adequacy of a certified seismic design for multiple site conditions. In the latter, site-specific soil structure interaction analyses are performed for selected sites to determine site-specific seismic demands using the CSDRS. Results from all site cases are enveloped. Similarly, for an SPRA, an applicant may use site-specific hazard curves and UHRS shapes for some representative sites[8] to demonstrate that the design is acceptable and fulfills risk and performance criteria. It is anticipated that SPRAs will include nonseismic failures and human error probabilities (HEPs). As discussed in Step 5, this may be important input for the plant design.

3.3.5 Step 5—Check Proposed Classifications against Risk, Defense-in-Depth, Reliability, and Other Qualitative Criteria

In Step 5, the LMP Component Group evaluates the SPRA results to make sure that individual event sequences meet the F-C target dose limits and the integrated risk criteria; it also identifies the risk-significant LBEs, which are those within a 1-percent margin of the F-C curves. The group also checks defense-in-depth adequacy, other qualitative factors related to risk-informed decisionmaking (e.g., balance between prevention and mitigation, avoidance of singleton failures that control the risk), and other LMP guidelines. Based on this evaluation, the LMP Component Group determines whether any SSCs need to be strengthened or assigned to a different SDC. It may also (in consultation with the seismic design engineers) identify opportunities to design an SSC to a lower SDC or a less stringent LS.

The LMP Component Group provides this feedback to the seismic design and SPRA teams so that they can reclassify the components as necessary, then recompute the fragilities. The examples in Chapter 4 give additional insights into this step.

In some current LWR SPRAs, nonseismic failures and HEPs have been found to be dominant or important contributors. In such cases, the changes required to ensure that the design meets the risk criteria may not be related to the seismic design. It is important that the SPRA models include these failure modes to the extent possible.

The end states of the event sequences for advanced reactor SPRAs (or PRAs for any other initiators) may differ greatly from the end states of a Level 1 LWR PRA, which are the CDF and LERF. The examples in Chapter 4, if carried out in potential future activities, may illuminate the important question of how to assess whether external hazard event sequences comply with the F-C target.

Because the risk criteria for advanced reactors are used for design purposes and SPRAs are performed at the design certification stage, the current HCLPF requirement at 1.67 times the design-basis earthquake is neither applicable nor necessary. However, for an LWR design, it may be useful to retain this concept.

8 From discussions with its developers, Approach 2 appears to be consistent with LMP principles.

3.3.6 Step 6—Iterate

Steps 2 through 5 are repeated until the process is stabilized and all risk criteria are met. It may be possible to streamline the iterative process by applying some simple methods to adjust fragilities for different SDC and LS combinations.

3.3.7 Step 7—Determine Final Structure, System, and Component Categorization for Seismic Design

The final SSC categorization becomes the basis for the licensing and design of the plant. The interface requirements for a COL application are based on this seismic design categorization, and the final design is implemented using it. The final categorization may differ from that of Step 1; for example, some safety-related components may be designed to a lower SDC but retain their status as safety-related, while some NSRST components may need to be strengthened (assigned to a higher SDC), but with no special treatment. Table 3-8 illustrates this with an example that involves four licensing-basis and design-basis ground motions: CSDRD-5, CSDRS-4, SSDRS-5, and SSDRS-4. The feasibility demonstrations in Section 4.3 will show how much effort is required to reach this final step.

Table 3-8 Example of Final SDCs and LSs Following the Seven-Step Seismic Design Process

Design Categories	Initial ASCE 43 SDC and LS	Final ASCE 43 SDC and LS
SSCs selected by the designer to perform required safety functions to mitigate the consequences of DBEs to within the F-C target, and to mitigate design-basis accidents to meet the dose limits of 10 CFR 50.34 using conservative assumptions.	SDC–5 LS-D CSDRS-5 (or SSDRS-5)	SDC–5 LS-D CSDRS-5 (or SSDRS-5)
SSCs selected by the designer to perform required safety functions to prevent the frequency of BDBEs with consequences exceeding 10 CFR 50.34 dose limits from increasing into the DBE region and beyond the F-C target.	SDC–5 LS-D CSDRS-5 (or SSDRS-5)	SDC–5 LS-C CSDRS-5 (or SSDRS-5)
Nonsafety-related SSCs relied on to perform risk-significant functions, which are those that keep LBEs from exceeding the F-C target or that contribute significantly to the cumulative risk metrics selected for evaluating the total risk from all analyzed LBEs.	SDC–5 LS-D CSDRS-5 (or SSDRS-5)	SDC–4 LS-D CSDRS-4 (or SSDRS-4)
Nonsafety-related SSCs relied on to perform functions requiring special treatment for defense-in-depth adequacy.	SDC–5 LS-D CSDRS-5 (or SSDRS-5)	SDC–4 LS-C CSDRS-4 (or SSDRS-4)

3.4 Seismic Design Process

As Table 3-8 shows, the outcome of the LMP/ASCE 43 Integration Approach is the designation of SDCs and LSs for each SSC. This section gives an overview of a possible design process. The process uses ASCE 43, for consistency with the rest of this report; however, compliance with risk criteria may be shown using other design codes, such as ASCE 7. The steps are as follows:

- Derive DRS for each SDC from the PSHA results, using ASCE 43.
- Perform seismic response analysis using ASCE 4 methods (as is done under current requirements).
- Design SSCs following engineering approaches in appropriate codes and standards.
- Design building elements to meet American Concrete Institute standards ACI 349-13 and ACI 359 and American National Standards Institute (ANSI)/American Institute of Steel Construction (AISC) standard ANSI/AISC N690.
- Design mechanical equipment, piping systems, cable tray systems, and heating, ventilation, and air conditioning systems following ASME codes.
- Follow IEEE standards for seismic design and qualification of electrical components.
- Pursue design alternatives (e.g., base isolation) and sophistication (e.g., nonlinear analysis) as appropriate.

As these steps show, the primary difference between the LMP/ASCE 43 Integration Approach and current design practice is that the former allows the selection of multiple SDCs and LSs for SSCs, leading to reduced design loads relative to those from SDC–5 and LS-D.

In the LMP framework, compliance with risk criteria is shown through the SPRA. Under current 10 CFR Part 52 requirements, final SPRAs are performed at the following three completeness stages, with each SPRA relying on the design information available at that stage:

- certified design application
- COL application, using site-specific hazard, site, and other information
- before fuel loading, considering as-designed, as-built, and other operating conditions

Plant- and site-specific fragility analyses and SPRAs should follow the accepted methodologies specified in either the LWR PRA standard or the non-LWR PRA standard of ASME/ANS RA-S-1.4 (ASME/ANS, 2020). The results of these SPRAs will serve as final checks against applicable risk criteria and other integrated decision-making considerations, such as defense in depth.

3.5 Application to Advanced Nonlight-Water Reactors or Light-Water Reactors

Although the LMP framework is for advanced nonlight-water reactors (ANLWRs), the process of Sections 3.2 and 3.3 also applies to ALWRs or LWRs, if adjusted for different risk criteria. Its feasibility may be demonstrated to some extent using SPRAs of existing LWRs.

There is extensive experience with the seismic design of LWR SSCs, and many SPRAs are currently available that use rigorous and plant-specific fragilities. Some of these SPRAs have been used to obtain regulatory relief under 10 CFR 50.69, which allows for each SSC to be assigned to a risk-informed safety class (RISC) using a process that determines whether it performs any safety-significant functions and identifies those functions. The risk categories in 10 CFR 50.69 are as follows:

- RISC-1 SSCs: safety-related SSCs that perform safety-significant functions
- RISC-2 SSCs: nonsafety-related SSCs that perform safety-significant functions
- RISC-3 SSCs: safety-related SSCs that perform functions of low safety significance
- RISC-4 SSCs: nonsafety-related SSCs that perform functions of low safety significance

In the context of these definitions, a safety-significant function is one whose degradation or loss could have a significant adverse effect on defense in depth, safety margin, or risk.

Figure 3-14 shows these risk categories in graphical form. Because 10 CFR 50.69 has been applied to several operating plants, reliable information now exists on how SSCs are distributed among different risk categories.

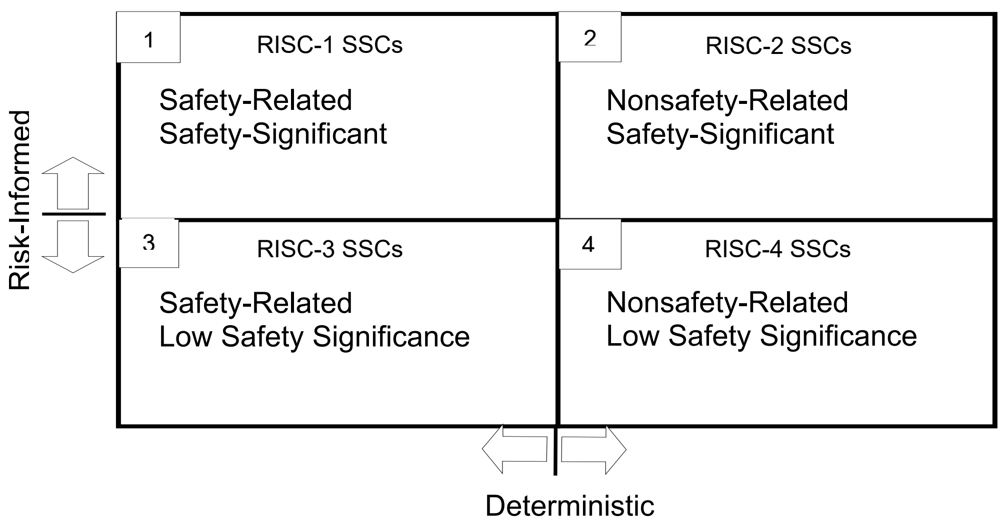

Figure 3-14 The 10 CFR 50.69 RISC matrix

The availability of this information, detailed SPRA models, and fragility calculations alters the implementation of some of the seven steps in the LMP/ASCE 43 Integration Approach, as described below:

- Step 1: Select initial ASCE 43 SDCs and LSs.

  Because several 10 CFR 50.69 analyses are available, this initial selection is much better informed. The initial SDCs and LSs can be selected based on the RISC categories in Figure 3-14. For example, SSCs belonging to RISC-1 may be assigned to SDC–5 and LS-D, while SSCs belonging to RISC-2 may be assigned either to SDC–5 and LS-C or to SDC–4 and LS-D.

- Step 2 (Optional): Perform preliminary design/fragility assessment.

  Step 2 in Section 3.3.2 also applies to LWRs. However, this step may not be needed, because detailed information should be available from the industry's extensive experience with LWRs.

- Step 3: Determine fragilities.

  Step 3 in Section 3.3.3 also applies to LWRs. However, detailed information for estimating fragilities should be available from the industry's extensive experience with LWRs.

- Step 4: Perform an SPRA.

  As Section 3.3.4 states, the SPRA should use the fragilities determined in Step 3, the SPRA models developed based on the applicable codes, and those used in developing LBEs. The considerations discussed earlier for selecting probabilistic seismic hazards also apply. Whereas the current approach for ALWRs permits a PRA-based margin analysis at the design certification stage, the LMP/ASCE 43 Integration Approach requires an SPRA in the context of establishing LBEs and the basis for the seismic design of SSCs.

  After the SPRA is complete, the results are provided to the LMP Component Group, which checks (in Step 5) whether they meet the applicable risk performance targets, such as CDF and LERF targets, and other qualitative criteria.

- Step 5: Check proposed classifications against risk, defense-in-depth, reliability, and other qualitative criteria.

  In this step, the LMP Component Group evaluates the SPRA results to make sure that the individual event sequences meet the risk targets (assuming the SPRA outputs dose estimates and frequencies of event sequences), the integrated risk criteria are met, and the risk-significant LBEs are within applicable risk criteria. It then determines whether any SSCs need reclassification, and whether any other actions are necessary. The group may also identify opportunities for designing components to lower SDCs or less stringent LSs. It may point out nonseismic factors, such as HEPs, that are controlling factors and need to be addressed. The LMP Component Group provides this feedback to the seismic design and SPRA teams so that they can adjust SDCs and LSs as necessary, then recompute the fragilities.

For LWRs, the current requirement of a plant-level HCLPF level of 1 percent at 1.67 times the design-basis ground motion might still be useful if the end states of a PRA are similar to the CDF and LERF.

- Step 6: Iterate.

  Step 6 in Section 3.3.6 also applies to LWRs.

- Step 7: Determine final SSC categorization for seismic design.

  Step 7 in Section 3.3.7 also applies to LWRs.

4 APPROACHES FOR EVALUATING THE FEASIBILITY OF THE SEVEN-STEP SEISMIC DESIGN PROCESS

4.1 Background

This chapter evaluates the feasibility of the seven-step seismic design process described in Chapter 3, through a discussion of preliminary and exploratory examples that provide insight on the possible benefits and implementation costs of the process. Based on these examples, it identifies potential future activities to support the development of a technical basis for the U.S. Nuclear Regulatory Commission's (NRC's) guidance on seismic safety design. These examples will also form a basis for discussions with stakeholders on alignment and potential collaboration.

No existing designs for commercial nuclear power plants (NPPs) use the performance targets from the American Society of Civil Engineers (ASCE) standard ASCE 43[1] (ASCE/SEI, 2005), although the ASCE 43 approach for seismic designs based on the most stringent seismic design category (SDC) and limit state (LS), namely SDC–5 and LS-D, is quite similar to current design practice. It is difficult to assess directly how the full ASCE 43 approach might affect seismic risk evaluations. The assessment of a more comprehensive implementation of ASCE 43 would require alternative fragilities of structures, systems, and components (SSCs).

As discussed in Chapter 3, an important difference between the design approach for currently operating plants (those licensed before the publication of the revised Title 10 of the *Code of Federal Regulations* (10 CFR) Part 100, "Reactor site criteria," in 1997) and the ASCE 43 approach for SDC–5 with LS-D is the design-basis ground motion. Current plants were designed to a deterministic, broadband response spectrum anchored to a peak ground acceleration (PGA) and determined in accordance with Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," to 10 CFR Part 100. The ASCE design response spectrum (DRS) for SDC–5 is a modified uniform hazard response spectrum (UHRS) (with annual exceedance frequency less than 1×10^{-5}).

This chapter explores the following three examples:

- Example 1: Generic fragility calculations are performed for selected combinations of SDCs and LSs, using the underlying assumptions of ASCE 43 and ASCE/SEI 4-16 (ASCE/SEI, 2017) for performance goals.

- Example 2: A simple structural element is designed using selected combinations of SDC and LS, following ASCE 43 and ASCE 4. The same element is also designed using the conventional approach in the Standard Review Plan. Fragilities for both cases are developed and compared, then used to compute failure probabilities.

- Example 3: This example is a multi-layered examination of the seven-step process for light-water reactors (LWRs) and for advanced reactors; it aims to identify potential activities that would strengthen the development of a technical basis for future NRC guidance on seismic safety. These activities could involve a combination of simplified

[1] The current version of ASCE 43 is ASCE 43-05, published in 2005. A new version is planned to be published soon. Both versions have the same basic philosophy. In this chapter, ASCE 43 is therefore cited without the year of publication.

probabilistic risk assessment (PRA) models and complex longer-term modeling. They would contribute not only to evaluating the risk impacts of the proposed process, but to assessing implementation issues—in particular, to developing detailed ground rules, understanding the efforts involved, and formulating guidance for key managerial and technical decisions.

Example 3 draws on NUREG/CR-7214, "Toward a More Risk-Informed and Performance-Based Framework for the Regulation of the Seismic Safety of Nuclear Power Plants" (Budnitz and Mieler, 2016), which describes an ideal risk-informed and performance-based (RIPB) framework for ensuring seismic safety.

Example 3 also examines whether there are any methods for recomputing existing fragilities of SSCs as if they were designed to different ASCE 43 SDC and LS combinations. If so, it may be feasible to evaluate the risk impact of different choices of SDC and LS using existing seismic probabilistic risk assessments (SPRAs), through an approach similar to that of NUREG/CR-7214.

4.2 Example 1—Computation of Generic Fragilities

This section describes an approach to deriving the fragilities of SSCs designed to the ASCE 43 criteria. Here, the SSCs are assumed to be designed to the full limits of the criteria. In practice, different SSCs may have different design margins; however, these design margins do not affect fragility evaluations at the conceptual design stage. Seismic loading is typically the dominant load, but the design could also be controlled by other loads and load combinations.

For simplicity, the SSC fragility is derived in terms of median PGA capacity and the composite variability. Other measures, such as the spectral acceleration at a specified frequency, could also be used. This stage of the fragility calculation uses generic estimates of safety factors and their variabilities. The fragility estimates may be modified at later stages using site- and plant-specific data.

Normally, a fragility evaluation of an SSC uses the actual design data. For example, for a shear wall, the design data includes wall thickness, reinforcement, nominal concrete strength, and the earthquake-imposed load. For a switchgear, it includes dimensions, anchorage, qualification test results, and in-structure response spectra. If the response analysis has been performed to the design response spectra (DRS) input, the critical shear wall among all the walls at a particular floor will be identified for fragility assessment. Similarly, the switchgear mounted on different floors may have different designs and anchorage, and the fragility assessment will account for these differences.

Because this level of data is unavailable at the conceptual design stage, the objective at this stage is to determine the fragilities based solely on the ASCE 43 criteria. Therefore, a shear wall is assumed to barely meet the ASCE 43 design criteria (i.e., criteria for DRS, seismic response analysis, the American Concrete Institute (ACI) requirements in ACI 349-13 (ACI, 2013), etc.). Similarly, electrical equipment is tested to Institute of Electrical and Electronics Engineers (IEEE) requirements for the specified in-structure response spectra based on ASCE 4 seismic response analysis requirements.

At the conceptual design stage, the PRA would use these fragility estimates for all similar SSCs. Because of this simplification, however, the PRA will fail to capture one important feature: the variation of seismic response due to differences in the physical locations of SSCs (buildings and floors). The fragility analysis can be refined in subsequent phases of the project as more design details and information become available.

4.2.1 ASCE 43 Design Criteria

The following steps summarize the seismic design process for SSCs according to ASCE 43:

(1) Assume SDC–5 for all safety-related SSCs.

(2) Select performance goal (P_F) of 1×10^{-5} per year for SDC–5.

(3) Derive DRS[2] for the design-basis earthquake (DBE) using the equation DRS = SF × UHRS for the P_F, where SF is the scale factor and UHRS is the uniform hazard response spectrum at exceedance frequency $H_P = P_F$.

(4) ASCE 43 specifies the following additional performance targets: 1-percent probability of unacceptable performance for DBE shaking and 10-percent probability of unacceptable performance at 1.5 DBE shaking. The design criteria in the selection of the DBE and the seismic response analysis per ASCE 4-16 (for design codes such as ACI 349-13 for concrete structures and American Institute of Steel Construction (AISC) codes for steel structures) have been shown to meet these performance targets.

(5) Assume LS-D (elastic behavior).

(6) Compute the scale factor (SF) for a spectral frequency specific to the site seismic hazard, based on the following equations:

$SF = \max(SF_1, SF_2, SF_3)$,

$SF_1 = A_R^{-1}$,

$SF_2 = 0.6\, A_R^{-0.2}$,

$SF_3 = 0.45$,

where $A_R = SA_{HP}/SA_{HD}$. In this equation, SA_{HP} and SA_{HD} denote the spectral accelerations at the exceedance frequencies H_P and H_D, respectively. Note that $H_D = 10\, H_P$, where $H_P = P_F$.

(7) Based on Site A seismic hazard results for PGA (see, e.g., Figure 3-2) and 5 Hz (Table 3-3), the values for the parameters are

DBE DRS = 0.47 UHRS and DBE PGA = 0.50g.

(8) Perform seismic response analysis following ASCE 4-16; this achieves an 80-percent probability of nonexceedance response given the DBE shaking.

[2] The procedure used to derive the DRS is based on a newer (and unpublished) version of ASCE 43. For the purposes of this evaluation, the procedure in ASCE 43-05 produces the same DRS.

(9) Design structural elements (e.g., shear walls, beams, columns, tanks) using ACI 349-13 and AISC codes.

(10) For equipment qualified by testing, use the test response spectrum (TRS) equal to 1.33 times the required response spectrum (RRS). RRS at the equipment mounting (floor) level is obtained for the DBE DRS and seismic response analysis in accordance with ASCE 4-16.

4.2.2 Development of Fragilities

At the conceptual (or design certification) stage, all that is known is that SSCs will be designed to meet the ASCE 43 design criteria. In practice, not all SSCs will be designed to the design limits; other loads and load combinations could govern the design dimensions. The calculations below use generic variabilities (β values).

4.2.3 Structural Fragility

This example assumes a shear wall in a safety-related building in the plant. The structural fragility of the shear wall is evaluated in three cases.

4.2.3.1 Fragility of shear wall designed to LS-D

The median ground acceleration capacity, A_m, can be written as

$$A_m = F_T \times DBE \times PGA,$$

for the total factor $F_T = F_{Strength} F_\mu F_R$. Here, the strength factor, $F_{Strength}$, is the product of the factors reflecting the uncertainty in the material property (reinforcing steel) (F_{mat}) and in the shear failure formula ($F_{formula}$). F_μ is the inelastic absorption factor, and F_R is the response factor. The numerical values of these factors are based on Electric Power Research Institute (EPRI) TR-103959 (EPRI, 1994) and on past SPRAs. Future work could use more recent test data reported in ASCE 43. The values used here are as follows:

$F_{mat} = 1.20$; $\beta c = 0.10$;

$F_{formula} = 2.00$; $\beta c = 0.20$;

$F_\mu = 1.80$; $\beta c = 0.20$.

The response factor, F_R, is obtained by invoking the ASCE 4-16 goal of an 80-percent probability of nonexceedance of response for DBE shaking:

$F_R = \exp(0.842\ \beta_R)$, where $\beta_R = 0.35$, so

$F_R = 1.34$.

The total safety factor is thus given by

$$F_T = 1.20 \times 2.00 \times 1.80 \times 1.34 = 5.80;\ \beta_{\mathbf{c}} = 0.46.$$

Therefore, the median ground acceleration capacity of the shear wall designed to LS-D is A_m = 5.8 × 0.50g = 2.9g. The high-confidence low-probability-of-failure (HCLPF) capacity is 1.00g.

4.2.3.2 *Fragility of shear wall designed to LS-C*

If the shear wall is designed to LS-C, the design demand is reduced by a factor representing the inelastic energy absorption (see Equation 5-1a of ASCE 43). All other factors being the same, the median ground acceleration capacity will also be reduced by this factor. Table 5-1 of ASCE 43 gives this reduction factor as 1.5 for LS-C.

Therefore, the median ground acceleration capacity of the shear wall designed to LS-C is 2.9g/1.5 = 1.93g. The HCLPF capacity is 1.00g/1.5 = 0.67g.

Note that a shear wall designed to LS-C will have less reinforcement (other design features, such as span, height, and wall thickness, may not change). Designing for a lower LS generally results in some cost savings.

4.2.3.3 *Fragility of shear wall designed to SDC–4*

If the shear wall is designed to SDC–4 for LS-D, the input for the seismic demand analysis will be based on the performance goal of 4×10^{-5} per year. The DBE PGA is 0.25g, rather than the value of 0.50g for SDC–5. The median ground acceleration capacity of the SDC–4 shear wall is thus 2.9g × 0.25/0.50 = 1.45g. The HCLPF capacity is 0.48g.

Note that a shear wall designed to SDC–4 will have less reinforcement (other design features, such as span, height, and wall thickness, may not change), because the DRS input is lower. Designing for a lower SDC generally results in some cost savings

4.2.4 Equipment Fragility—Functional Failure

The RRS is calculated as the floor response spectrum at the level of equipment mounting, using the ASCE 4-16 procedure for the DBE shaking. The response factor is given by

$F_R = \exp(0.842\ \beta_R)$, where $\beta_R = 0.35$, so

$F_R = 1.34$;

TRS/RRS = 1.33.

The qualification test capacity (TRS) is judged to be a 95-percent probability (confidence) value. Therefore, the median capacity factor is $F_C = \exp(1.65\ \beta_C) = 1.39$ for $\beta_C = 0.20$. The other values are as follows:

- total safety factor: $F_T = 1.34 \times 1.33 \times 1.39 = 2.48$
- median ground acceleration capacity: $A_m = 2.48 \times 0.50g = 1.24g$
- total variability in ground acceleration capacity: $\beta_c = (0.35^2 + 0.20^2)^{1/2} = 0.40$
- HCLPF capacity: 0.49g

4.2.5 Equipment Fragility—Anchorage Failure

Anchorage is designed so that the governing failure is ductile; therefore, the capacity of steel controls. The relevant quantities are as follows:

- Tensile capacity of anchor = 1.6 F_a As, where F_a = 20 ksi and As = bolt area.

- Ultimate tensile capacity = ϕ F_{um} As, where F_{um} = 58 ksi and ϕ = 0.9.
- Strength factor = code capacity / ultimate capacity = 1.80; β = 0.13.

Designers typically use the equivalent static method for design of anchorage, where the peak spectral acceleration is multiplied by 1.5 to calculate the anchor load. Therefore, there is a minimum additional safety factor of 1.5. The strength factor (F_s) is hence revised as 1.8 × 1.5 = 2.7.

The RRS is calculated as the floor response spectrum at the level of equipment mounting, using the ASCE 4-16 procedure for the DBE shaking. The response factor is given by

$F_R = \exp(0.842\ \beta_R)$, where β_R = 0.35, so

F_R = 1.34;

this could be considered the "structural response factor."

Equipment response factor is obtained by accounting for the additional safety factors as follows:

- qualification method factor: F_{QM} = 1.0, β = 0.10
- damping factor: F_D = 1.29, β =0.08, assuming design damping is 3 percent and median damping is 5 percent
- modeling factor: F_M = 1.0, β = 0.10
- mode combination factor: F_{MC} = 1.0, β = 0.10
- earthquake component combination factor: F_{ECC} = 1.0, β = 0.10
- total equipment response factor: 1.29
- total safety factor: 2.7 × 1.34 × 1.29 = 4.68
- variability in equipment response: 0.21
- median ground acceleration capacity: 4.68 × 0.50 = 2.34g
- total variability in ground acceleration capacity: $(0.13^2 + 0.35^2 + 0.21^2)^{1/2}$ = 0.43
- HCLPF capacity: 0.86g

4.3 Example 2—Shear Wall Design

This section shows the process of designing a shear wall, as an example, following procedures based on ASCE 43 and ASCE 4. The objectives are, first, to explore the design and fragility differences that may result from using different combinations of SDCs and LSs, and, second, to understand how these designs compare with those produced by current approaches.

This analysis considers a simplified shear wall for the following reasons:

(1) Shear walls are major structural elements used to resist seismic loads in NPPs.

(2) A simplified shear wall represents a common design element that can be used to evaluate different combinations of SDC and LS and the resulting fragilities within the ASCE 43 and ASCE 4 design framework.

(3) In several past and recent SPRAs, shear wall failures under seismic loads have contributed significantly to both seismic core damage frequency (SCDF) and seismic large early release frequency (SLERF). Furthermore, the failure of a shear wall under a seismic load has been a singleton failure leading directly to SCDF, and in a few cases to SLERF.

(4) This simplified situation can provide useful insights into how to adjust fragilities in existing SPRAs to incorporate various combinations of SDC design ground motions and damage LSs.

4.3.1 Shear Wall Characteristics and Analysis Assumptions

The analysis in this section assumes the following:

(1) The example shear wall is located on a hard rock site (Site A in Chapter 3), and thus there is no need to account for soil-structure interactions.

(2) The rock site mimics a hard rock site in the Central and Eastern United States (CEUS), for an NPP with an existing probabilistic seismic hazard analysis (PSHA) and various DRS (Figure 3-7) developed during the recent SPRA updates in response to Near-Term Task Force Recommendation 2.1.

(3) The shear wall dimensions are typical for internal shear walls in an NPP, with aspect ratio less than or equal to two.

(4) The initial shear wall resonant frequency is between 5.0 Hz and 8.0 Hz, preferably closer to 5.0 Hz. To produce the desired fundamental frequency and substantial in-plane shear forces, additional mass is placed at the top of the wall.

(5) Only in-plane failure modes and designs are explored; the top mass is assumed to be restrained from out-of-plane motion.

(6) Only in-plane and vertical excitations are considered. The design motions are in accordance with the DRS in Figure 3-7.

(7) The height and width of the shear wall are fixed, but the reinforcement ratios and thicknesses vary to account for different combinations of SDC and LS.

4.3.2 ASCE 43 Seismic Design Categories and Limit States Evaluated

The following ASCE 43 SDCs and LSs are evaluated:

(1) SDC–5 and LS-D

(2) SDC–5 and LS-C

(3) SDC–4 and LS-D

(4) SDC–4 and LS-C

(5) SDC–3 and LS-D

(6) SDC–3 and LS-C

(7) Regulatory Guide 1.60 (NRC, 2014) spectrum anchored to site SSE PGA and traditional design criteria (LS-D)

The first six combinations in this list, which are consistent with the discussion in Chapter 3, are more likely to be used in practice than other combinations. The seventh gives insight into how to adjust existing fragility values to account for alternate design-basis ground motions; it could be used in future work to evaluate design and fragility differences using design ground motions and design criteria that have been applied to many operating reactors.

The fragility calculations are performed assuming in-plane shear failure and using the separation-of-variables (SOV) approach from Electric Power Research Institute (EPRI) TR-103959 (EPRI, 1994).

4.3.3 Design and Calculation Procedures

The following are some key steps and pertinent sections of ASCE 4 and ASCE 43 used in the analysis:

(1) The design standards are ASCE 4 (Chapters 1–4), ASCE 43 (Chapters 2–5), and ACI 349-13 (ACI, 2013).

(2) Rock site selection is based on Site A of Table 3-3 in this report.

(3) Modeling is based on a two-dimensional finite element model, fixed base (no SSI or incoherency), and response spectrum analysis (Chapter 3 of ASCE 4). It uses the following:

- desired fundamental frequency between 5 and 8 Hz
- damping corresponding to the response level for the chosen LS (Table 3.1 of ASCE 4)
- stiffness calculations: Table 3.2 of ASCE 4

- modeling of mass: Section 3.4 of ASCE 4
- shear walls: Section 3.8.3 of ASCE 4

(4) Design ground motions are given by the DRS for Site A shown in Figure 3-7:

A. SSDRS-5

B. SDDRS-4

C. SSDRD-3

The analysis considers two ground motion components: in-plane horizontal and vertical. It uses the same ratio of vertical to horizontal ground motion that was used for the specific plant and site.

(5) The analysis method is that of Chapter 4 of ASCE 4. The response spectrum analysis follows Section 4.3 of ASCE 4.

(6) The design is according to the following sections of ASCE 43, with the provisions for earthquake design in ACI 349-13:

- sections on evaluation of seismic demand
- sections on structural capacity
- sections on load combinations and acceptance criteria

(7) The fragility methodology is SOV.

The fragility calculations consider three failure mechanisms (diagonal shear cracking, flexure, and shear friction) and a functional drift criterion of 0.007, in accordance with EPRI TR-103959 (EPRI, 1994).

(8) The probability of failure is computed by convolving hazard curves and fragility curves for various SDC and LS combinations.

4.3.4 Results, Insights, and Potential Future Activities

The wall element has the following dimensions:

- height: H = 15 feet (ft)
- length: L = 30 ft
- base case thickness: Th = 2 ft

The base case is the design associated with SDC–5 and LS-D; the other cases are evaluated in the context of this case. As stated earlier, the only variables that change for different SDC and LS combinations are thickness and percentage of steel. In particular, the functional requirement of the vertical load supported by the wall is unchanged. Tables 4-1 and 4-2 show the results of the design and fragility computations for the six SDC/LS cases listed in Section 4.3.2, along with the values of the basic shear wall parameters and the input PGA levels. Table 4-1 shows the results for a 2-foot wall thickness. The parameters in Table 4-1 are as follows:

- $\rho_H = \rho_V$, steel rebar to concrete cross section ratio in horizontal and vertical directions[3]
- A_{m}, median capacity ($C_{50\%}$)
- βc, composite variability
- HCLPF ($C_{1\%}$);
- P_F, probability of failure, evaluated by convolving the fragility curves with the mean hazard curve (PGA) for Site A in Figure 3-2

The shear wall performance in each case is compared to the base case (the 2-foot-thick wall designed to SDC–5 and LS-D). Table 4-2 shows the results of the same calculation but for a shear wall thickness of 1.5 feet. It compares these results with the base-case results from Table 4-1.

Table 4-1 Fragility and Performance of Shear Wall (L = 30 ft, H = 15 ft, Th = 2.0 ft), Using Inelastic Absorption Factor F_μ, Calculated Using EPRI (1994) Methodology[4]

	SDC–5 LS-D (base case)	SDC–5 LS-C	SDC–4 LS-D	SDC–4 LS-C	SDC–3 LS-D	SDC–3 LS-C
PGA (g)	0.5	0.5	0.25	0.25	0.15	0.15
$\rho_H = \rho_V$	0.0141	0.0073	0.0055	0.0036	0.0033	0.0025
A_m (g)	3.07	2.92	2.83	2.71	2.7	2.64
βc	0.43	0.45	0.46	0.47	0.48	0.47
HCLPF (g)	1.13	1.05	1.00	0.93	0.91	0.90
P_F	1.11×10^{-6}	1.34×10^{-6}	1.51×10^{-6}	1.77×10^{-6}	1.83×10^{-6}	1.93×10^{-6}
Ratio of P_F to base-case P_F	1	1.2	1.36	1.60	1.65	1.74

3 A more precise definition of ρ_V is the ratio of the cross-sectional area of the vertical rebars (vertical shear reinforcement area) to the gross area of the horizontal section of concrete. Similarly, ρ_H is the ratio of the total cross-sectional area of the horizontal rebars to the gross area of the vertical section of concrete.

4 The Fμ (inelastic absorption factor) value used is based on EPRI guidance. Section 4.2 used a generic value of Fμ, which differs significantly from the specific values calculated for the example shear walls. Scientific Notebook 1331E (Dasgupta, 2020) documents an additional sensitivity study assessing these differences.

Table 4-2 Fragility and Performance of Shear Wall (L = 30 ft, H = 15 ft, Th = 1.5 ft), Using Inelastic Absorption Factor F_μ, Calculated Using EPRI (1994) Methodology

	Th = 2 ft (base case)	Th = 1.5 ft				
	SDC–5 LS-D	SDC–5 LS-C	SDC–4 LS-D	SDC–4 LS-C	SDC–3 LS-D	SDC–3 LS-C
PGA (g)	0.5	0.5	0.25	0.25	0.15	0.15
$\rho_H = \rho_V$	0.0141	0.0090	0.0067	0.0045	0.0040	0.0027
A_m (g)	3.07	2.54	2.45	2.34	2.32	2.25
βc	0.43	0.44	0.45	0.43	0.46	0.47
HCLPF (g)	1.13	0.92	0.87	0.86	0.80	0.77
P_F	1.11×10^{-6}	1.94×10^{-6}	2.19×10^{-6}	2.37×10^{-6}	2.64×10^{-6}	2.9×10^{-6}
Ratio of P_F to base-case P_F	1.00	1.74	1.97	2.13	2.37	2.61

No generic conclusions should be drawn from the example of a single simple structural element. Section 4.4 considers structural and equipment fragilities in a broader sense. However, the shear wall example yields certain insights:

(i) While reductions in required steel and thicknesses are possible, they may be limited by the other loads that a wall must withstand and by other functional considerations.

(ii) Cases with lower SDC or LS have lower median capacities than the base case; on the other hand, as expected, because of the large uncertainties associated with the seismic hazard, the probabilities of failure are not that sensitive.

(iii) For this simple shear wall problem, the benefits of choosing a lower SDC (relative to the base case) are comparable to those of choosing a lower LS. However, in actual design situations, it is much easier to keep the LS as LS-D and change the SDC.

It is also instructive to compare the shear wall fragilities resulting from the generic approach of Section 4.2 with the specific design cases of this section. Table 4-3 shows this comparison (with design-specific fragilities for the 2-foot wall thickness).

Table 4-3 Comparison of Generic and Design-Specific Fragility Parameters

	SDC–5 and LS-D		SDC–5 and LS-C		SDC–4 and LS-D	
	Generic fragility	Design-specific fragility	Generic fragility	Design-specific fragility	Generic fragility	Design-specific fragility
A_m (g)	2.9	3.07	1.93	2.92	1.45	2.83
β_c	0.43	0.43	0.43	0.45	0.43	0.46
HCLPF (g)	1.08	1.13	0.72	1.05	0.53	1.00

The generic fragility calculations in Section 4.2 assume that the seismic loads govern the overall seismic design, and hence the median capacity. This is evident from the values obtained for SDC–4 and LS-D. The generic median capacity for SDC–4 is exactly half that of SDC–5, because the design PGA is exactly half. On the other hand (for the case of 2-foot wall thickness), the design-specific fragility parameters for the lower SDC and LS are much closer to those of the base case. This indicates that the use of generic fragilities derived from ASCE 4 and ASCE 43 assumptions (as in Section 4.2) may show greater benefit, but also may overestimate the risk compared to the actual plant design fragility values. (These observations do not necessarily apply to generic fragilities that are based on past experience.)

Based on the outcome of the simplified shear wall example, the following future activities are proposed:

(i) Compute LS performance target frequencies for the cases analyzed, by adjusting median capacities and using beta values from the fragility analysis, to shed light on the adjustment of the SPRA fragilities, as discussed in Section 4.4.

(ii) Analyze additional shear wall examples with other aspect ratios, to generate broader insights.

(iii) Investigate a simple three-dimensional structural system to assess how various SDC/LS combinations affect floor response spectra, and to explore the feasibility of using LSs other than D in a more complex situation.

(iv) Perform nonlinear analyses of the shear wall using alternative approaches identified in ASCE 4 and ASCE 43 to evaluate the actual ductility demands and resulting drifts for LS-C.

4.4 Example 3—Progressive Use of Seismic Probabilistic Risk Assessments

The examination of available SPRAs provides further insights into the implementation of the LMP/ASCE 43 Integration Approach and the overall feasibility of using alternate SDCs and LSs from ASCE 43. Available SPRAs can be used to evaluate the risk impact of using alternate design categories, to examine the dominant sequences, and to develop criteria for selecting potential LBE sequences (or LBEs themselves), as proposed in the Nuclear Energy Institute (NEI) guidance document NEI 18-04 (NEI, 2018).

Ideally, currently available SPRAs for both LWRs (or advanced light-water reactors (ALWRs)) and advanced reactor designs should be used to explore implementation issues. Section 4.4.1 examines the application of the seven-step process to LWR or ALWR SPRAs, and Section 4.4.2 does the same for advanced reactor SPRAs, to identify detailed analyses that could be carried out in the future to support the development of a technical basis for an enhanced NRC regulatory guide on seismic safety.

Although the Licensing Modernization Project (LMP) framework has been developed for non-LWR designs, a detailed example exploring LWR SPRAs would provide robust implementation insights. A second exploratory example using an advanced reactor SPRA would help establish how to implement the frequency-consequence (F-C) target criteria and how to identify LBEs. LWR SPRAs and advanced reactor SPRAs have different end states, and considerations that are unique to advanced reactors may be identified by examining SPRAs.

Example 3 explores methods of recomputing or adjusting SSC fragilities for alternative SDC/LS combinations, starting from the fragilities for SDC–5 and LS-D. If such adjustments are feasible, existing SPRAs can be used to evaluate the risk impact of different SDC/LS combinations more fully.

The level of information available constrains the nature and robustness of potential insights from SPRAs. Because advanced reactor designs are still in the early stages, there is less detailed information available for them than for existing LWRs. However, even this limited information will allow the NRC, NRC contractors, and LMP technical engineers to examine potentially unique aspects of design-stage SPRAs within the RIPB framework.

The exploratory examples in this section are drawn from NUREG/CR-7214 (Budnitz and Mieler, 2016).

4.4.1 Use of Light-Water Reactor Seismic Probabilistic Risk Assessments

The study of existing LWR SPRAs used to support recent applications under 10 CFR 50.69, “Risk-informed categorization and treatment of structures, systems and components for nuclear power reactors,” can facilitate the exploration of the implementation of the LMP/ASCE 43 Integration Approach in several ways:

(1) The current SPRAs use the most recent PSHA and UHRS spectral shapes, those shown in Chapter 3. The use of UHRS as spectral shapes alleviates the issue of adjustment of fragilities for different design-basis ground motions.

(2) Extensive and detailed seismic response and fragility analyses have been carried out for several SPRAs. These would facilitate the adjustment of fragilities to different designs.

(3) Because the fragilities in existing SPRAs are realistic and plant-specific, they are more amenable to use in studying the impact of alternate design approaches.

(4) Existing SPRAs include more accurate information on human error probabilities (HEPs) and nonseismic failures.

(5) For plants that have implemented the 10 CFR 50.69 process, the categorization of SSCs by RISC is already available.

Before discussing the application of the seven-step process to LWRs, it is instructive to consider an approach presented in a case study in NUREG/CR-7214. (NUREG/CR-7214 includes two case studies, only one of which (that of Plant A) is summarized here; the reader is referred to NUREG/CR-7214 for details.) This case study is an analysis of an operating NPP located in the eastern United States with a relatively recent SPRA available. The SPRA represents the baseline configuration of the plant at the time the SPRA was conducted; because it is the configuration of an operating NPP, it is assumed to satisfy all the requirements of the current NRC regulatory basis. In other words, the analysis and design processes are very similar to those of ASCE 43 for SDC–5 and LS-D. (However, there is a difference in the design ground motion.)

NUREG/CR-7214 also studies two adaptations or modifications of the baseline configuration. In the second of these, the baseline design is adjusted so that all SSCs satisfy the provisions of SDC–5 and LS-D in ASCE 43-05 (i.e., so that for each SSC, the annual probability of failure from earthquakes is less than 1×10^{-5}). This is a conservative assumption, because the ASCE 43 performance target for an LS associated with SDC–5 is itself 1×10^{-5} per year. The actual functional failure[5] probability will be less. (The third configuration, dealing with defense in depth, is not discussed here.)

Table 4-4 shows the SSCs included in the analysis of Plant A, which fall into three general groups: structural, mechanical, and electrical. Table 4-4 lists basic fragility parameters for each SSC, including median seismic capacity A_m and uncertainty parameters β_r and β_u. Table 4-5 shows the dominant seismic event sequences included in the analysis of Plant A, as derived from the SPRA. These sequences are combinations of failures of the SSCs listed in Table 4-4. Together, Tables 4-4 and 4-5 describe the baseline configuration of Plant A. This baseline configuration represents the NPP as it was originally designed and analyzed; therefore it is assumed to satisfy the provisions of the regulatory basis that were in effect at that time. In total, the analysis considers eight SSCs and nine seismic event sequences. Tables 4-4 and 4-5 also summarize the results of a simplified SPRA of the baseline configuration. The seismic core damage frequency (CDF) for the baseline configuration of Plant A is 3.04×10^{-5} per year. This number is referred to as the baseline seismic CDF for Plant A. Note that a single seismic event sequence, SEQ1, contributes disproportionately to the plant's seismic risk profile, accounting for approximately 40 percent of the seismic CDF.

Table 4-4 Properties of SSCs in the Baseline Configuration of Plant A

SSC	A_m (g)	β_r	β_u	HCLPF (g)	P_f
MECH1	0.77	0.25	0.22	0.35	2.54×10^{-6}
MECH2	0.68	0.18	0.32	0.30	4.18×10^{-6}
STRUC1	0.32	0.07	0.20	0.20	2.62×10^{-5}
MECH3	0.13	0.24	0.32	0.05	1.75×10^{-4}
MECH4	0.68	0.30	0.30	0.25	5.04×10^{-6}
ELEC1	0.30	0.27	0.40	0.10	4.62×10^{-5}
ELEC2	0.69	0.23	0.36	0.26	4.88×10^{-6}
STRUC2	0.53	0.23	0.42	0.18	1.20×10^{-5}

Table 4-5 Properties of Dominant Seismic Sequences in the Baseline Configuration of Plant A

Sequence	HCLPF (g)	P_f	Percentage of seismic CDF
SEQ1	0.17	1.20×10^{-5}	39.37%
SEQ2	0.34	3.14×10^{-6}	10.32%
SEQ3	0.36	2.85×10^{-6}	9.35%
SEQ4	0.38	2.79×10^{-6}	9.18%
SEQ5	0.34	2.40×10^{-6}	7.88%
SEQ6	0.38	2.00×10^{-6}	6.59%
SEQ7	0.40	1.97×10^{-6}	6.48%
SEQ8	0.42	1.74×10^{-6}	5.73%
SEQ9	0.45	1.55×10^{-6}	5.10%
CDF	—	3.04×10^{-5}	100.00%

Figure 4-1, reproduced from NUREG/CR-7214, plots the sensitivity of the seismic CDF to changes in the seismic capacities of individual SSCs. More specifically, it plots the absolute

[5] Functional failure means a failure of the required safety function, as opposed to failure to meet the performance target (which corresponds to exceeding an LS). Because of the conservatism in the design process, functional failure probabilities are much smaller than the probabilities of exceeding the LSs (performance target probabilities). SPRAs use functional failure fragilities.

change in seismic CDF produced by changing the median capacity of each individual SSC, one at a time. Some SSCs have more impact on the seismic CDF than others. The impact of a particular SSC depends on several factors, including its overall strength/capacity (as reflected by its fragility parameters) and its role in the overall system (i.e., in the event sequence or sequences in which it participates). Several observations emerge from Figure 4-1. First, strengthening the most fragile SSC in the analysis, MECH3, has almost no impact on the plant's seismic CDF, which implies that simply strengthening the weakest SSCs in the plant is not necessarily the most effective way to improve overall plant safety. In the context of the ASCE 43 approaches on which this report focuses, this observation also implies a possibility of designing to a lesser SDC and LS. Second, the plant's seismic CDF is disproportionately sensitive to changes in the strength of STRUC2. A 30-percent decrease in median capacity for STRUC2 produces a 60-percent increase in seismic CDF, meaning that an error in the design, analysis, operation, or maintenance of STRUC2 that reduces its capacity can significantly affect the safety of the plant. This observation also provides insights into the use of SDCs and LSs other than SDC–5 and LS-D. Of particular interest are the portions of the curves corresponding to reduced median capacities relative to the baseline configuration, as the use of alternate SDCs and LSs will reduce the median capacities. Median capacities for alternate SDCs and LSs can be expected to be over 30 percent lower than those for SDC–5 and LS-D, as shown in Figure 3-7 to Figure 3-9 and in the examples in Sections 4.2 and 4.3.

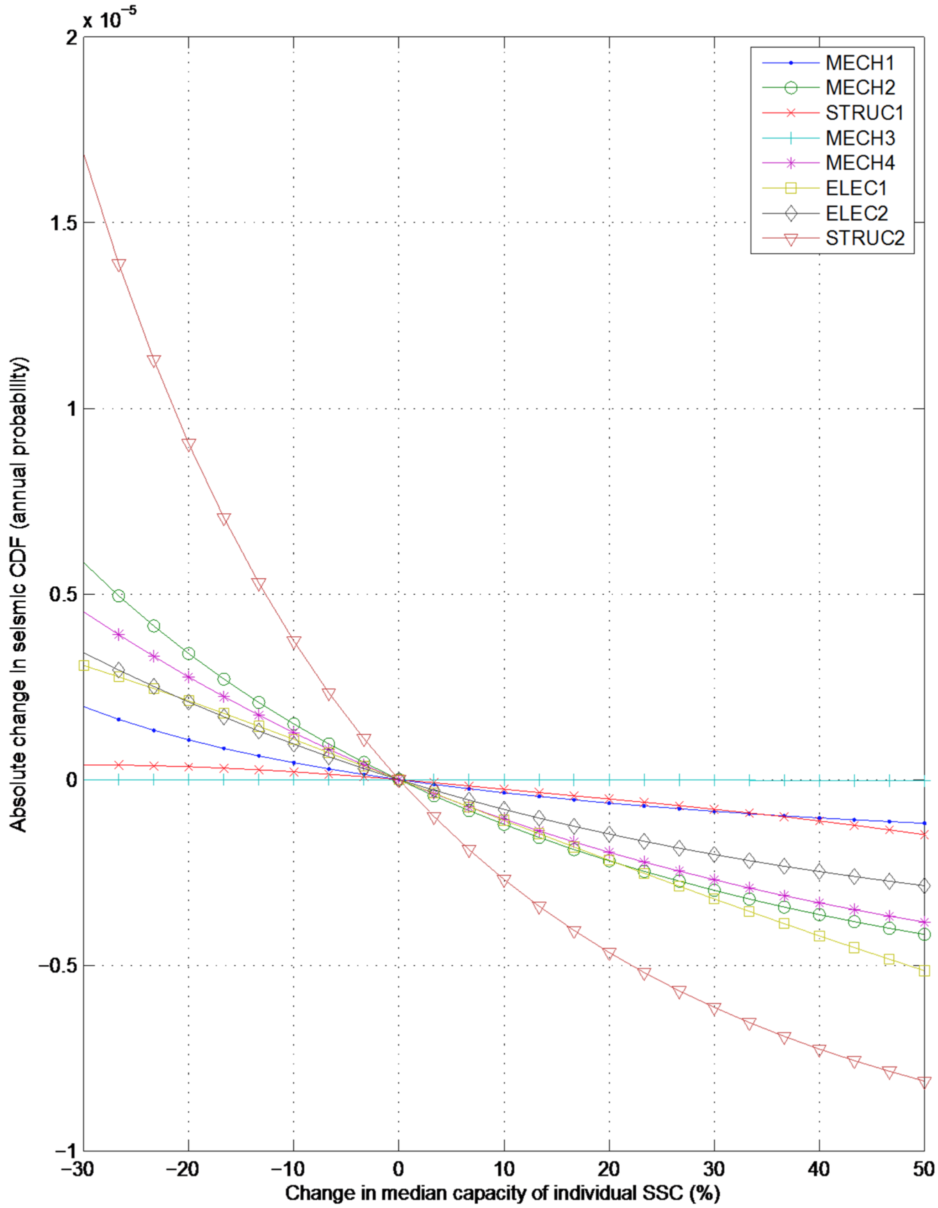

Figure 4-1 Sensitivity of the seismic CDF to one-at-a-time changes in the median seismic capacities of individual SSCs in the baseline configuration of Plant A (with the ordinate giving frequencies in units of 1×10^{-5} per year)

NUREG/CR-7214 also produces an alternate configuration by adjusting the fragilities of a small number of SSCs whose annual probability of failure is greater than 1×10^{-5}. Table 4-4 contains four such SSCs. In the alternate configuration, the median seismic capacities of these SSCs are increased until their annual failure probabilities are less than 1×10^{-5}. NUREG/CR-7214 calls this the "ASCE 43-05 configuration," because the performance target for SDC–5 in ASCE 43-05 calls for the annual frequency of exceeding an LS to be less than 1×10^{-5}. This is not an actual functional failure probability; however, in some sense it puts a lower bound on median capacity. Table 4-6 shows the revised fragilities of the four SSCs after this adjustment.

Table 4-6 Changes in Seismic Capacities of SSCs in the "ASCE 43-05 Configuration" of Plant A

SSC	Baseline A_m (g)	Updated A_m (g)	% change in A_m	Baseline P_f	Updated P_f	% change in P_f
STRUC1	0.32	0.45	40.6%	2.62E-5	9.91×10^{-6}	−62.2%
MECH3	0.13	0.53	307.7%	1.75E-4	9.58×10^{-6}	−94.5%
ELEC1	0.30	0.57	90.0%	4.62E-5	9.99×10^{-6}	−78.4%
STRUC2	0.53	0.57	7.5%	1.20E-5	9.88×10^{-6}	−17.5%

Overall, these changes lower the plant's seismic CDF by 35 percent, from 3.04×10^{-5} to 1.98×10^{-5}.

In using the methods of NUREG/CR-7214 to verify the feasibility and validity of the LMP/ASCE 43 Integration Approach, the following additional points should be considered:

(1) The baseline fragilities need to be adjusted to reflect a design that uses alternate SDCs and LSs.

(2) The SPRA needs to consider the fragilities of all the affected SSCs simultaneously, rather than examining changes in the fragilities of individual SSCs one at a time.

(3) The SPRA model should include nonseismic failures and HEPs that are plant-specific.

(4) The entire SPRA model needs to be analyzed to identify additional sequences, changes in the dominant sequences, and changes in the dominant contributors. This is necessary to verify whether the assigned SDCs and LSs are acceptable or need to be changed.

The discussion below assumes the availability of recent SPRAs (ideally, one pressurized-water reactor and one boiling-water reactor SPRA) that have also been used for a 10 CFR 50.69 application. This is the most desirable situation; however, it may be possible to proceed with less information, although this may yield fewer insights. The seven-step process for LWR SPRAs is as follows:

- Step 1: Select initial ASCE 43 SDCs and LSs.

  Because several 10 CFR 50.69 analyses are available, the initial selection of SDCs and LSs can use the RISC categories shown in Figure 3-6. For example, SSCs belonging to RISC-1 may be assigned to SDC–5 and LS-D; SSCs belonging to RISC-2 may be assigned to SDC–5 and LS-C, or to SDC–4 and LS-D. In any case, this initial selection is much better informed because of the RISC information.

- Step 2 (optional): Perform preliminary design/fragility assessment.

This step does not apply to the proposed feasibility demonstration, in which fragilities are adjusted to reflect SDC and LS in Step 3.

- Step 3: Determine fragilities.

  The availability of detailed, plant-specific fragilities facilitates the fragility adjustment process. The examples and discussions in Sections 4.2 and 4.3 provide some guidance for this step. Figure 4-2 shows one simple and approximate procedure for developing some generic adjustment rules, given the recent SPRAs that used UHRS for the structural shape.

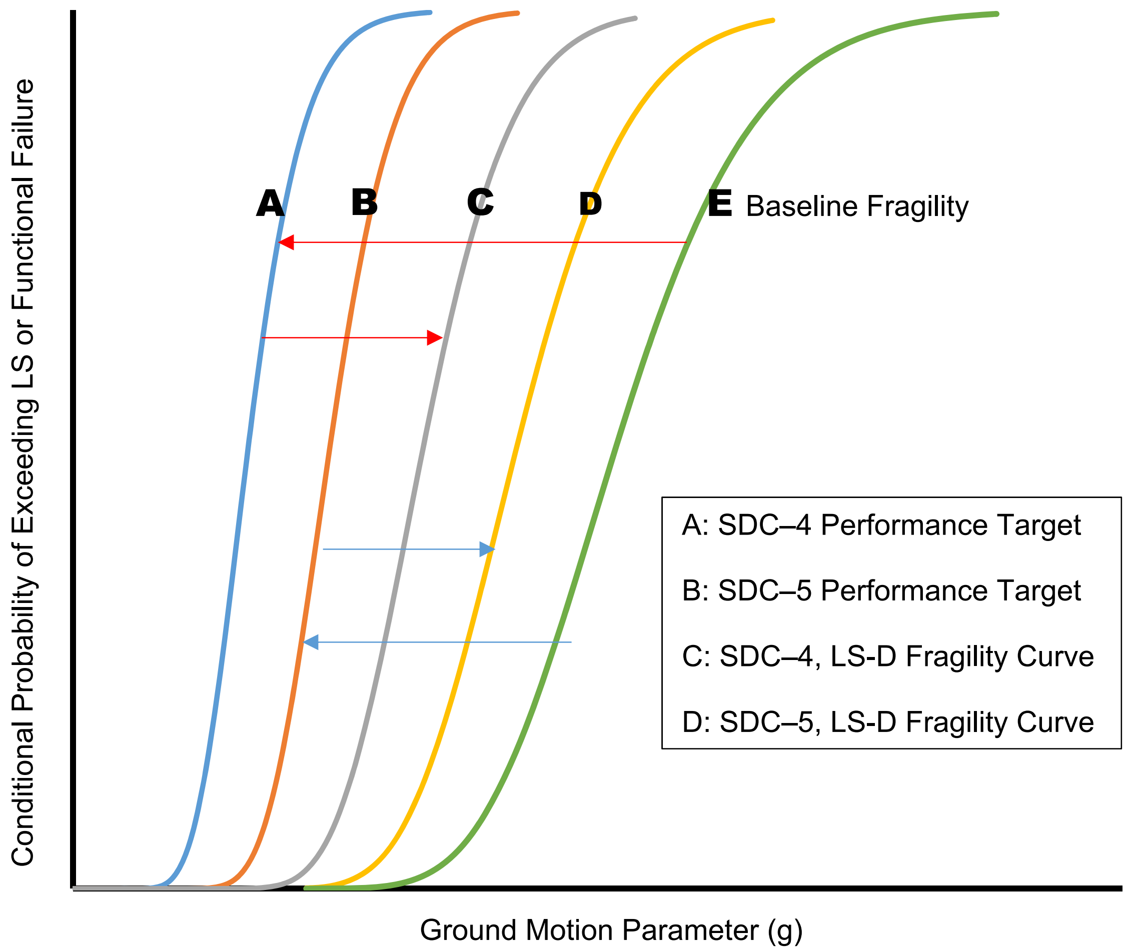

Figure 4-2 Illustration of fragility adjustment approach

For example, suppose that a component originally designed to different criteria has now been assigned to SDC–5 and LS-D. To obtain a fragility curve reflecting the new categorization (assuming that the baseline fragility, curve E in Figure 4-2, is available), consider the following steps:

(1) From the baseline fragility curve E, back-calculate a curve for the probability of exceeding the LS (footnote 5 explains distinction between these two curves). Specifically, from the baseline curve E (the fragility curve of the component from the SPRA, representing functional failure), obtain curve B, which represents the conditional probability that the component will exceed the LS, as a function of ground motion level. (Curve B is a performance target curve reflecting SDC–5.) To do this, calculate A_{mLS} (i.e., the ground motion value associated with the median probability of exceeding the LS) from the baseline A_m by removing nonapplicable median safety factors and associated variabilities. That is, for LS-D, retain only the terms associated with elastic response and strength.

(2) Convolve the site hazard curve and the LS fragility curve B to see whether the performance target is met. If not, adjust A_{mLS} until the desired performance is achieved. For example, for SDC–5 this target is an annual probability of 1×10^{-5} (under the ASCE 43 assumption discussed in Section 4.2) or some other value (in a component-specific situation as discussed in Section 4.3). Generally, in real designs based on ASCE 43 and ASCE 4, the actual performance target values will be less than 1×10^{-5}; the value of 1×10^{-5} is a theoretical upper bound.

(3) Using the revised A_{mLS}, recalculate the functional fragility to be used in the SPRA by considering the applicable safety factors in the original baseline analysis (curve E). For the example of SDC–5 and LS-D, the result is curve D in Figure 4-2. Although, in the figure, curve D is on the left of the baseline curve, in some cases it could appear on the right instead. The four components shown in Table 4-6 represent such a case.

(4) Use a similar approach to obtain a fragility curve for SDC–4 and LS-D for the same component, as shown in Figure 4-2 (curves A and C). Note that curve A is to the left of curve B, as the performance target for SDC–4 is 1×10^{-4}, compared to 1×10^{-5} for SDC–5. Correspondingly, the fragility curve, curve C, is to the left of curve D.

The above procedure may be benchmarked against the analyses in Sections 4.2 and 4.3. For demonstration purposes and for understanding the relative impact of choosing different SDCs and LSs, it is not necessary to use the most accurate fragilities. Approximate estimates of the potential changes in the median capacities will yield robust insights into feasibility.

- <u>Step 4:</u> Perform an SPRA using a progressive approach.

Although, in the actual application, the entire SPRA model should be rerun based on the revised fragilities, for the demonstration a progressive approach suffices.

In this progressive approach, instead of exercising the entire SPRA model, the analysis starts with the ten or so seismic event sequences that contribute the most to the failure risk (this is how the analysis for Plant A in NUREG/CR-7214 proceeds). Many LWR

SPRAs show single failures, such as building failures, that lead to core damage sequences. In such cases, it may be relatively straightforward to modify the fragility of the single component in question to match a different SDC and LS.

The next steps are to look at progressively more complex sequences that include components from different RISCs, nonseismic failures, and HEPs. The fragilities of components in different risk categories would be revised as in Step 3, and the event sequence frequencies would be recomputed.

Implementing this exercise may reveal some inherent constraints and limitations that would be relevant in practical applications of the seven-step process.

Eventually, the full SPRA model should be run to examine how the wholesale changes of fragilities influence event sequences and dominant contributors, and to obtain insights in other areas, such as defense in depth. As the LBE and safety classification are derived from PRAs in the RIPB framework, this is a very important step.

- Step 5: Check proposed classifications against risk, defense-in-depth, reliability, and other qualitative criteria.

  For LWRs, the end states of CDF and LERF can be adopted as risk criteria for determining whether any design categories or RISC classifications need to be revised.

- Step 6: Iterate.

- Step 7: Determine final SSC categorization for seismic design.

  This step would be implemented as described in Chapter 3.

4.4.2 Use of Advanced-Reactor Seismic Probabilistic Risk Assessments

There are several designs of advanced reactors in progress, for some of which (e.g., the standard modular high-temperature gas-cooled reactor) SPRAs exist. Among several differences between advanced reactor SPRAs and LWR SPRAs, advanced reactors are expected to have fewer safety-/risk-significant SSCs, because of the passive nature of their design, among other reasons. On the other hand, for some advanced reactors, the PRA end states are dose consequences and cumulative risk, rather than CDF and LERF as for LWRs. Assuming that an advanced reactor SPRA is available, the following discussion highlights how this might help demonstrate the feasibility and validity of the LMP/ASCE 43 Integration Approach. As the end states are dose consequences, software for quantifying event sequences will also be necessary. In general, initial consultations with the advanced reactor PRA team will facilitate this process.

The seven-step process for advanced reactor SPRAs is as follows:

- Step 1: Select initial ASCE 43 SDCs and LSs.

  Compared to the LWR case, this step is a little more complex, because advanced reactor SPRAs may use generic or less detailed fragilities. The assignment of SDCs and LSs may therefore require some judgment. However, because advanced reactors have fewer SSCs, and because high precision is unnecessary for demonstration purposes, several variations can be examined.

- Step 2 (optional): Perform preliminary design/fragility assessment.

  This step does not apply to the proposed feasibility demonstration, in which fragilities are adjusted to reflect SDC and LS in Step 3.

- Step 3: Determine fragilities.

  This step can follow the approach described in Section 4.4. Some additional judgments may be required if the SPRA lacks details or uses generic fragilities.

- Step 4: Perform an SPRA.

  This step is more complex than in the LWR case, because advanced reactor SPRAs have different end states and because there is limited experience with them. The progressive approach described for LWRs may also be implemented here. Eventually, the full SPRA model should be run to examine how the wholesale changes of fragilities influence event sequences and dominant contributors, and to obtain insights in other areas, such as defense in depth.

- Step 5: Check proposed classifications against risk criteria.

  In this step, the SPRA results are compared to the applicable risk criteria of the F-C target to identify whether any design categories need to be revised.

- Steps 6 and 7: These are anticipated to be the same as for LWRs.

4.4.3 Summary

If implemented fully, the examples described in this chapter should provide insights not only on the feasibility and validity of the ASCE 43 and ASCE 4 design approaches, but also on potential benefits such as more balanced design, more uniform safety margins, more effective and better-understood defense in depth, and cost savings. A complete analysis should also illuminate regulatory and practical considerations and suggest potential revisions of the current guidance.

5 SUMMARY, CONCLUSIONS, AND NEXT STEPS

This report examines concepts and processes for aligning the Licensing Modernization Project (LMP) with the existing risk-informed and performance-based (RIPB) framework for seismic safety, and it identifies potential future activities to further this goal. It also contributes to the technical basis for a future regulatory guide (RG) on the proposed approach.

The project included the following activities in support of its objectives:

- An alternative to the current approach to seismic design was developed, integrating RIPB seismic design concepts with the LMP framework presented in the Nuclear Energy Institute (NEI) guidance document NEI 18-04 (NEI, 2018). This alternative is called the RIPB/LMP Seismic Design Framework.

- To illustrate the regulatory benefits of the RIPB/LMP Seismic Design Framework, an example seismic design approach was developed that aligns the LMP concepts with the performance targets described in American Society of Civil Engineers (ASCE) standards, such as ASCE 43, for seismic design. This example approach is technology-inclusive and applies to an array of advanced nuclear power reactor designs.

  The example approach, referred to as the LMP/ASCE 43 Integration Approach, comprises seven steps that provide a conceptual framework. Two crucial factors in this framework are (1) the use of probabilistic risk assessments (PRAs) in making design decisions and (2) the integration of sequence-level and plant-level risk measures in an iterative design process. The LMP/ASCE 43 Integration Approach is a general process that can be used for applications under both Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic licensing of production and utilization facilities," and 10 CFR Part 52, "Licenses, certifications, and approvals for nuclear power plants." The process is also technology-inclusive.

  The process can accommodate the use of codes other than ASCE 43, such as ASCE 7 (ASCE/SEI 7-10, 2010), for design of facilities with low risks. Microreactors are special systems of relatively low risk, and the regulatory framework for them is evolving (e.g., BNL 2020). This report does not explicitly consider the application of the RIPB/LMP Seismic Design Framework to the seismic design of microreactors; this topic should be explored in the future.

- ASCE 1, ASCE 4, and ASCE 43 were reviewed to identify (1) the differences between the proposed design process and current methods, (2) the interplay among the different seismic design categories (SDCs) and limit states (LSs) in meeting risk metrics (as opposed to the current approach of using only a single SDC/LS combination, namely SDC–5 and LS-D), and (3) practical ways to implement explicit performance targets for individual structures, systems, and components (SSCs) in the seismic design process.

- Several initial insights were obtained from assessments of potential implementation issues. Potential effects of the RIPB/LMP Seismic Design Framework and the LMP/ASCE 43 Integration Approach on the broader regulatory and operational requirements of nuclear plant safety were also identified.

- The LMP/ASCE 43 Integration Approach was evaluated using site-specific ground motions from nine power plant sites in the Central and Eastern United States, representing various site conditions (namely, hard rock, stiff soil, and soft soil) and geographical areas. Ground motions corresponding to the top three SDCs in ASCE 43 were compared to the design ground motions derived from current seismic design requirements to demonstrate the benefits of the enhanced RIPB framework.

- Several simple calculations were performed to demonstrate the feasibility and validity of the LMP/ASCE 43 Integration Approach, to clarify implementation issues, and gauge the level of effort needed for potential future activities in support of the overall LMP/seismic safety integration goal. These calculations included the following:

  – calculations of generic fragilities based on underlying assumptions used in ASCE 43 for alternate SDC and LS selections

  – designs for simple shear wall elements using alternate SDC and LS combinations for the same site, to measure the effects of these combinations on physical designs and fragilities

  – a more detailed PRA-based analysis with progressive scope for future activities, including an exploration of approximated adjustments to SSC fragilities to emulate different SDC/LS combinations when a detailed seismic probabilistic risk assessment (SPRA) and supporting information are available

This report also describes and evaluates an initial set of practical considerations for implementing the LMP framework and related RIPB enhancements within existing seismic design processes. These considerations are evaluated in the context of the stylized seven-step process.

To demonstrate the potential benefits of relaxing the requirement that all safety-significant SSCs be designed to SDC–5, the report compares the peak ground acceleration (PGA) and 5-hertz (Hz) ground motions for SDC–4 and SDC–3 to the SDC–5 ground motions for nine sites in the Central and Eastern United States. These ground motions were derived from the probabilistic seismic hazard analysis (PSHA) results submitted to the U.S. Nuclear Regulatory Commission (NRC) by licensees in response to a request based on a recommendation of the NRC's Near-Term Task Force after the accident at Fukushima. (This recommendation required all licensees and certain other permit holders to compute new ground motions, using the present practices and guidance and the most recent earthquake data for each site.) To develop the PSHA and associated response spectra, licensees used procedures based on RG 1.208 (NRC, 2007c) and ASCE 43 (ASCE/SEI, 2005). This report also uses ASCE 43 to obtain the SDC–3 and SDC–4 ground motions for its comparisons.

In summary, for the nine sites analyzed, the average ratios of the PGA and 5-Hz spectral accelerations for SDC–4 to those for SDC–5 are close to 0.55, and the average ratios of those for SDC–3 to those for SDC–5 are close to 0.35. These results show that choosing alternate SDCs can substantially reduce design ground motions. This report includes comparisons of the entire spectra and derives detailed site-specific insights.

The following are the main conclusions of this report:

- There are no obvious impediments to implementing the RIPB/LMP Seismic Design Framework and recent updates to seismic design standards and RGs. The report discusses several technical, programmatic, and regulatory considerations for the successful implementation of the framework. These considerations form the basis for more detailed feasibility demonstration activities that may be undertaken in the future.

- The major benefits of the LMP/ASCE 43 Integration Approach come from the flexibility to assign different SDCs (i.e., different design-basis ground motion levels) and different design performance limits (i.e., different LSs) to SSCs, based on their risk significance and other risk-informed decision-making factors. (By contrast, the current approach uses a single design-basis earthquake and a very stringent elastic LS for all SSCs, irrespective of their risk significance.) Thus, in the LMP/ASCE 43 Integration Approach, the safety margins of individual SSCs are controlled according to their contribution to system-level and plant-level risk, which reduces unnecessary conservatism (or increasing margins where needed) and produces a more risk-balanced design.
- After the establishment of SDCs (design-basis ground motion levels) and LSs for the SSCs, the actual SSC design process is very similar to the process in current use. The analyses and procedures at this stage are therefore well practiced and rely on existing standards and guidance.
- The report contributes to a technical basis for an RG on RIPB seismic design.
- Additional analyses are recommended to fully demonstrate implementation and to identify pros and cons of the proposed changes to the seismic design process, within the larger context of seismic design, seismic safety, cost optimization, and existing seismic safety regulations.

The report also highlights several implications of current regulatory requirements, such as those addressing minimum earthquake design levels and earthquake shutdown and restart criteria. The detailed explanation of the seven-step process includes key management and technical considerations for efficient implementation of the enhanced RIPB concepts.

The following activities will be important for future regulatory evaluations of the RIPB/LMP Seismic Design Framework:

- Evaluate the seismic design of a small stylized system (going beyond a single shear wall) to more fully explore the adequacy of guidance in codes such as ASCE 43.
- In cooperation with industry, evaluate the concepts and process further through simplified and more detailed SPRA models, in order to obtain additional technical and regulatory insights into implementation issues and to clarify the enhanced RIPB concepts described in this report. Cooperative activities could include the following:
    - an examination of a simplified and a detailed SPRA of an actual light water reactor (or advanced light water reactor), and a practical implementation of the seven step process, to assess the advantages and limitations of the enhanced LMP approach to seismic safety
    - an examination of a PRA of an advanced reactor (for example, a standard modular high-temperature gas-cooled reactor or a fast-spectrum sodium-cooled small modular reactor), and an implementation of the seven-step process, to identify changes needed in current seismic safety guidance

- Ensure that the proposed approach aligns with the rulemaking for 10 CFR Part 53, “Licensing and regulation of advanced nuclear reactors,” which is underway.
- Examine the possible use of the RIPB/LMP Seismic Design Framework for microreactors and other low-risk facilities as the regulatory framework for these types of facilities evolves.

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APPENDIX A

Summary of the Virtual Public Workshop "Enhancing Risk-Informed and Performance-Based Seismic Safety for Advanced Non-Light Water Reactors" September 2–3, 2020

A.1 Introduction

The purpose of the virtual workshop was to discuss research conducted by the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research on a proposed alternative conceptual approach to seismic safety and design for advanced reactors. This approach is consistent with the framework of the Licensing Modernization Project (LMP) and uses risk-informed and performance-based (RIPB) seismic design criteria (e.g., those of the American Society of Civil Engineers (ASCE) standard ASCE 43). Its goal is to produce a risk-balanced seismic design that has potential safety and cost benefits, and that is consistent with existing licensing processes under Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, "Licenses, certifications, and approvals for nuclear power plants," and 10 CFR Part 50, "Domestic licensing of production and utilization facilities." The approach is called the RIPB/LMP Seismic Design Framework.

The focus of the workshop was to present this approach, demonstrate its application through selected examples, and gather feedback from stakeholders and the public to inform further investigations. The 1.5-day workshop was attended by approximately 100 participants representing vendors, engineering consultants, codes and standards developers, regulators, the Nuclear Energy Institute, and utilities.

At the workshop, NRC staff members and contractors presented perspectives on a proposed integration of seismic probabilistic risk assessment (SPRA) and the LMP framework into the seismic design process, accounting for defense in depth. There were four extended presentations on NRC-sponsored investigations. Presentations included overviews of the utility-developed RIPB LMP process and of the LMP's treatment of external events. Representatives from General Electric-Hitachi Nuclear Energy, Oklo, and NuScale presented perspectives and industry experience on RIPB seismic designs for small modular reactors. Two vendors of small advanced reactors presented seismic aspects of their designs. (Neither of these designs used the LMP framework; the ensuing discussion centered on how the proposed seismic safety approach would accommodate the needs of such small advanced reactors.)

Plans for future technical activities related to the proposed approach to seismic design will take into account the feedback received from the technical community and stakeholders during open discussions at the workshop.

This report was revised based on the workshop feedback, with clarifications and details added. Table A-1 lists documents giving details about the workshop and provides a link to each document.

Table A-1 Agencywide Documents Access and Management System (ADAMS) Links to the Workshop Agenda, Presentations, and Related RIPB/LMP Seismic Design Framework Documents

	Item	NRC Adams Accession Number
1	RIPB Workshop Agenda	ML20245E430
2	A Proposed Alternative Risk-Informed and Performance-Based Regulatory Framework for Seismic Safety at NRC-Regulated Facilities	ML20106F035
3	White Paper on RIPB Approach to Seismic Safety	ML20106F034
4	Enhancing Risk-Informed and Performance-Based Seismic Safety for Advanced Non-Light-Water Reactors	ML20230A169
5	RIPB Workshop Slides Set 2	ML20241A150
6	Research Overview on Moving Toward RIPB Approach for Seismic Safety	ML20241A151
7	RIPB Workshop Slides Set 3	ML20241A152

A.2 Feedback from Workshop Attendees

This section records comments and questions offered during the workshop, categorized by topic. The intention here is not to address these comments and questions, but to consolidate them as a reference for additional NRC-sponsored exploratory activities on the RIPB/LMP Seismic Design Framework.

LMP process:

- The RIPB seismic design process within the LMP framework is an iterative process, which calls for coordination between the safety analysts and the design team. Would this iterative approach be a significant burden compared to the existing processes that use deterministic and prescriptive design guidance?

- For sites with low seismic activity, the LMP guidance should clarify the requirement for minimum design spectra (0.1 peak ground acceleration) in Appendix S to 10 CFR Part 50.

- The sole use of probabilistic seismic hazard assessment to develop design response spectra may not result in a broad-banded design spectrum (which is typical of the Central and Eastern United States).

- The LMP calls for comparing the 95th percentiles of licensing-basis event (LBE) frequencies and doses to the frequency-consequence target. Supporting calculations may be computationally challenging, especially if there are many LBEs and design iterations.

- Does the LMP framework address design extension conditions?

- It was suggested that this project examine the graded approach in International Atomic Energy Agency seismic safety standards for reactors with reduced radioactive inventories.

Seismic design of structures, systems, and components (SSCs):

- Is there an opportunity to use other (commercial) design codes for SSCs that the LMP process classifies as nonsafety-related with special treatment (NSRST), rather than what is typically used for safety-related (SR) SSCs? Would the NRC's review be equivalent for SR and NSRST SSCs?

- Did the NRC consider the ANSI/ANS-2.26 criteria, which generically map failure consequence to seismic design category without explicitly requiring PRA and are applied across very different types of DOE nuclear facilities, as a guide for a regulatory framework?

- Discussion of beyond-design-basis events (BDBEs) in the LMP centers on sequence families with design-basis event hazards and SSC failures. What about the BDBEs associated with return frequencies of 10^{-6} per year or lower? If the design requirements account for all extremely low-frequency/high-uncertainty hazards, BDBEs will add design constraints and analyses with highly uncertain results that do not meaningfully improve safety.

- How will different seismic design categories be selected and assigned, especially when SR and non-SR structures are constructed on the same foundation or are otherwise physically connected?

- The discussions of limit states (LSs) in the NRC presentations focused on LS-C and LS-D. With the emphasis on performance-based design, is there a reason not to consider LS-B for structures (or structural elements) without confinement functional requirements?

Small advanced reactors:

- For inherently safe, simple plants, can the deterministic design approach in ASCE 4 and ASCE 43, which involves meeting performance goals (in terms of annual probability of unacceptable performance), be used in place of an SPRA?

- It is envisioned that some of the very small advanced reactors and microreactors (with negligible offsite consequences) can be seismically designed in accordance with ASCE 7. The LMP would impose an additional and undue burden in the reactor design process.

Miscellaneous:

- How is the cost of additional NRC review considered in assessing the costs and benefits of implementing a seismic safety approach consistent with the LMP?

- Is there a plan to engage the U.S. Department of Energy (DOE) and associated contractors in the NRC-sponsored exploratory LMP seismic safety studies? DOE has more than a decade of experience in applying codes for seismic design and analysis of nuclear facilities.

- Would the seismic safety guidance to be developed by the NRC be timely for nonlight-water reactor applicants intending to use the LMP?

A.3 Remarks

The workshop helped to identify important issues for future users. Participants posed general questions about the LMP framework, including questions on its technical details and implementation. Some of the presentations and comments focused on the flexibility in the proposed seismic safety approach to deal with facilities of different perceived risks (e.g., microreactors).

Based on feedback gathered during the workshop, this report was revised to clarify the RIPB/LMP Seismic Design Framework and to address questions on the scope and flexibility of the proposed approach. For example, revisions were made to recognize the potential use of codes other than ASCE 43, and to afford flexibility to deal with designs perceived to be of low risk. Microreactors and other reactors perceived to be of low risk should be addressed in the context of the evolving regulatory framework for advanced reactors, as well as in ongoing rulemaking efforts for the proposed 10 CFR Part 53, “Licensing and regulation of advanced nuclear reactors.”