Goal:

It is the goal of this project to develop a risk-informed and performance-based regulatory guide as an alternative option to the current Standard Review Plan (SRP) approach for seismic design and analysis, which focuses on safety while providing design and review flexibility through a graded approach.

Summary of Key Objectives:

- As part of NRC seismic, geotechnical, and structural engineering research program plan for FY2017 – 2021, the staff planned to explore more effective and flexible approaches to seismic safety that utilizes risk-informed and performance–based concepts than the traditional hazard-based seismic design and assessment practice.
- Articulate a new, alternative approach for seismic safety of advanced non-light water reactors (ANLWRs) to support the NRC implementation of the Nuclear Energy Innovation and Modernization Act (NEIMA) signed by the President on January 14, 2019.
- Base the approach on technology inclusive, risk-informed and performance-based concepts (TI-RIPB) used with frequency-consequence targets (F-C targets) appropriate to the size and characteristics of anticipated ANLWR source terms in contrast to surrogate risk metrics such as core damage frequency (CDF) currently used in light water reactor (LWR) design.
- Provide a graded approach and flexibility in safety evaluation that emphasizes safety and can accommodate a variety of ANLWR designs in contrast to the current standard review plan (SRP) deterministic approach.
- Leverage and appropriately integrate industry's licensing modernization project (LMP) risk-informed categorization of structures, systems and components (NEI 18-04) and consensus standards for performance-based seismic design published by the American Society of Civil Engineers (ASCE), focusing on bridging gaps using the reliability performance target concept for the seismic design of safety significant structures, systems, and components (SSCs).
- Utilize a two-phase development process: 1) near-term goal (6 months) to develop principle attributes and criteria for the TI-RIPB that align technically with NEI 18-04 and ASCE methodologies; 2) intermediate-term goal (2-years) to identify risk information and design problems to demonstrate the use of the TI-RIPB in practical applications and illustrate the effectiveness and flexibility afforded by the TI-RIPB in contrast to the current SRP deterministic approach to the seismic design/analysis.

Purpose and Desired Outcome:

This white paper provides an update of the current thinking and strategy for developing an integrated, risk-informed and performance-based (RIPB) approach to seismic safety. It also highlights the benefits of the proposed alternative approach for new nuclear power plant designs. It is the goal of this project to develop a regulatory guide as an alternative option to the current Standard Review Plan (SRP) approach for seismic design and analysis, which focuses on safety while providing design and review flexibility through a graded approach.

Background:

As part of NRC seismic, geotechnical, and structural engineering research program plan for FY2017 – 2021, the staff planned to explore more effective and flexible approaches to seismic safety that utilizes risk-informed and performance –based concepts than the traditional hazard-based seismic design and assessment practice.

The “Nuclear Energy Innovation and Modernization Act,” which was signed into law on January 14, 2019, in part, directs the NRC to develop strategies to implement a technology-inclusive (TI) regulatory framework as an optional regulatory pathway with an increasing use of risk-informed and performance-based evaluation techniques and guidance for licensing of commercial advanced nuclear reactors.

To facilitate and modernize the licensing process for new reactor designs, a Licensing Modernization Project (LMP) led by Southern Company and cost-shared by the US Department of Energy (DOE) has developed a TI-RIPB approach that uses an integrated decision process (IDP) to streamline the safety analysis for a wide spectrum of advanced non-light water reactor (ANLWR) designs. Although the LMP focuses primarily on ANLWR licensing, the underlying approach is general in nature and should also be applicable with appropriate adjustments to all reactor designs including light-water reactors (LWRs). A key facet of this approach is the integrated process that considers both risk insights and the deterministic defense-in-depth (DID) philosophy. This integrated approach uses a structured, systematic, and reproducible process in selecting the licensing-basis events (LBEs) and categorizing safety-significant structures, systems, and components (SSCs). These selection and categorization make use of the frequency-consequence performance targets (F-C targets) established in compliance with regulatory dose limits and quantitative health objectives (QHOs) for reactors. The LMP’s approach has been documented in NEI 18-04 [1].

The American Society of Civil Engineers (ASCE) recently completed the first revision to the ASCE/SEI 43-05 [2] standard (hereafter called ASCE 43), which was the first consensus standard to apply a performance-based approach to the physical design of a nuclear facility’s SSCs. This approach groups the SSCs into specific seismic design categories (SDC) based on the radiological consequences of an SSC failure in accordance with American Nuclear Standard (ANS/ANSI) 2.26 [3] (hereafter called ANS 2.26) for the categorization of SSCs for seismic design. For each SDC, ASCE 43 assigns a quantitative reliability target (performance goal) to the SSCs to ensure that the SSCs are sufficiently robust to perform their intended safety function to prevent unmitigated radiological consequences from a seismic event. To this end, ASCE 43 provides the seismic design criteria for the physical design of SSCs in order to meet their performance goals. For a given category, SSCs designed based on ASCE 43 are expected to achieve a relatively uniform seismic fragility. Although the current version of ANS 2.26 only applies to Department of Energy (DOE) facilities, a future revision is underway to include commercial reactors in its scope.

Considering the LMP's approach to the risk-informed categorization of SSCs and the ASCE 43 criteria for the performance-based seismic design, a new framework for TI-RIPB seismic approach can be envisioned by integrating the two approaches using the reliability targets (performance goals) to ensure that the physical designs meet the expectations for the functional design.

This white paper articulates how the Office of Nuclear Regulatory Research (RES) plans to develop the framework for TI-RIPB approach to seismic safety as an alternative to the current practice for the seismic design and analysis as outlined in SRP Chapter 3. The white paper also examines the applicability of the new framework to a variety of regulatory activities. Although the methods used are intended for the seismic events, the underlining approach should be applicable, with proper adjustments, to other natural phenomena hazards.

Current Practice for Seismic Design and Analysis:

Chapter 3 of the SRP provides guidance for the seismic design and analysis of SSCs for commercial nuclear power plants. The SRP guidance relies on a conservative and deterministic approach to provide high confidence that the SSCs important to safety will perform their safety functions during and after a seismic event. In this approach, SSCs are grouped into two categories, seismic category I and non-seismic category I. Seismic category I SSCs perform functions that are either safety-related (e.g., containments) or important to safety (spent fuel racks for example) while non-seismic category I SSCs do not perform any safety functions but should be evaluated to ensure their failures will not impact the functionality of adjacent seismic category I SSCs.

According to the SRP, the seismic demands (loads) are determined based on the safe shutdown earthquake (SSE) ground motion established in accordance with 10 CFR Part 100 and Appendix S to Part 50. These seismic demands are utilized for the design of seismic category I SSCs using a bounding approach to account for variability and uncertainty in the properties of soils and structures in propagating the seismic design input into the structures and components. The resulting seismic demands are then compared to their capacities for sizing structural members and components based on conservative design codes and standards developed for nuclear facilities. Additional code provisions (e.g., detailing) and regulatory requirements (e.g., quality assurance) should be met to ensure that the as-built SSCs are consistent with the design and they will be capable of performing their intended functions. This SRP approach focuses on designing SSCs to withstand the SSE ground motion input.

This design practice has been used for both the operating fleet of LWRs and new reactor designs such as AP1000, ESBWR, etc. The extent of the conservatism inherent in this practice is typically evaluated *post-facto* through either a seismic probabilistic risk assessment (SPRA) or a PRA-based seismic margin assessment (SMA) of the seismic design in accordance with the guidance in SRP Chapter 19. The SPRA/SMA for large LWRs are predicated on meeting the surrogate safety goal metrics of core damage frequency (CDF) and large early release frequency (LERF) as well as equivalent margin expectations based on an SMA. Using this approach, it is possible to quantify the inherent conservatism of the SRP seismic design based upon the results of the SPRA or SMA analysis. A possible consequence of this approach could be for designers and analysts to take a conservative approach to the seismic design of individual SSCs to avoid design iterations after the SPRA or SMA analysis. This can often result in a very conservative overall seismic design.

An aspect of the current approach that already uses RIPB concepts is the development of site-specific seismic design input, which relies on probabilistic seismic hazard analysis (PSHA). As described in Regulatory Guide 1.208, this site-specific seismic design input is expressed in terms of a performance-based ground motion response spectra (GMRS). The GMRS is developed by modifying a uniform hazard response spectra (UHRS) using the ASCE/SEI 43 performance-based method. In this process, a quantitative performance goal of 10^{-5}/year is assumed that can be achieved at the component level of seismic category I SSCs using the SRP-based design practice. With this approach, the site-specific GMRS no longer has a uniform hazard exceedance frequency across the spectral frequency band. Instead, it is expected to lead to uniform performance for the seismic category I SSCs with structural reliability (performance goal) of 10^{-5}/year. This approach can be directly incorporated into a more risk-informed process.

The performance goal of 10^{-5}/year, which defines the reliability target for seismic category I SSCs, was developed based on the understanding of the plant-level risk insights (in terms of CDF) of the operating reactor fleet. Specifically, it was determined that the performance goal of 10^{-5}/year for the seismic category I SSCs at the component level would result in the plant level risk lower than the mean CDF computed from the operating fleet.

The current SRP seismic design process is largely deterministic and not amenable to the direct application of risk principles. Further, it likely has a significant conservative bias, which may be difficult to quantify. In addition, the surrogate risk metrics for evaluating the risk from LWRs may not be applicable to other reactor designs such as ANLWRs, which typically have much smaller source terms and employ more passive and inherent safety features than LWRs. As a result, a new risk-consistent framework for the seismic design based on TI-RIPB concepts should be developed. Although primarily for ANLWRs, because this framework is technology inclusive it also should be applicable as an alternative approach to LWRs.

Framework for TI-RIPB Approach for Seismic Safety:

The consequence-based, risk-informed approach developed by the Licensing Modernization Project (LMP) and the performance-based seismic design standard developed by the ASCE provide the key elements essential to the framework for a fully integrated and consistent TI-RIPB process to seismic design. The paragraphs below describe key elements of these two aspects and how to integrate them in the TI-RIPB process for seismic design.

<u>TI-RIPB Process (LMP Approach)</u>

The LMP approach described in NEI 18-04 contains the following key elements:

- Establishing the frequency-consequence targets (F-C targets) for the design:

  - Achieve uniform risk across the range of high-frequency, low-consequence events, and low-frequency, high consequence events
  - Document consistency with regulatory dose limits in Parts 20, 50 and 100, and quantitative health objectives (QHO) for prompt fatality and latent cancer events
  - Establish acceptable design limits for event sequence mean frequency and mean dose exposure at the exclusion area boundary. (sequence-level)
  - Establish acceptable design limits for cumulative risk metrics that involve risk contributions from various event sequences. (plant-level)
  - The area under F-C targets offers a wide range of acceptable design alternatives.
- Establishing license basis events (LBEs)[1]:
  - Populated in the frequency band in three non-overlapping zones: AOO, DBE and BDBE (AOO – Anticipated operational occurrences with mean frequencies greater than 10^{-2} /year, DBE – Design basis events with frequencies less than 10^{-2}/year but greater than 10^{-4}/year, and BDBE – Beyond design basis events with frequencies less than 10^{-4}/year but greater than $5x10^{-7}$/per year)
  - Acceptable LBEs should be below the F-C target with adequate margins
  - F-C criteria to define risk significant LBEs within 1% of the F-C target for both frequencies and doses.
  - Use of PRA to establish LBE sequences in system design, which is evaluated across the layers of defense in depth (DID) to ensure adequate barriers in LBE sequences
  - Evaluation of LBEs in different categories based on mean values and 5% / 95% values to account for uncertainties in both frequencies and doses.
- Categorization of SSCs into three groups depending on their safety functions and performance expectations
  - A category of SSCs called safety-related (SR), which are those selected by the designer to perform required safety functions (RSFs) as defined in NEI 18-04.
  - A category of non-SR with special treatment (NSRST) SSCs for which the accident sequence analysis determines risk-significant functions or whose functions are needed for DID adequacy. (NEI 18-04).
  - All other SSCs.
- DID evaluations
  - Plant capability,
  - Programmatic capability.

The LMP approach focuses on the functional design aspects to achieve system level performance. This approach also describes the importance of defining reliability performance targets for SSCs to ensure that these SSCs can perform intended functions to support LBEs in different categories in order to meet the F-C targets with sufficient margins as well as to demonstrate the DID adequacy.

[1] The set of LBEs is the collection of event sequences considered in the design and licensing basis of the plant.

The LMP concept of reliability performance targets can be related to the concept of the performance goals used in the performance-based physical design of SSCs embodied in the ASCE 43 standard. This can be used to bridge between the functional design using the LMP approach and the physical design based on the ASCE approach to obtain an integrated, consistent risk-informed and performance-based approach.

ASCE Approach to Seismic Design of SSCs

The ASCE 43 standard provides the RIPB approach for the physical seismic design of SSCs. This standard was published in 2005 (as ASCE 43-05) and its first revision is scheduled for publication in 2019 as ASCE 43-19. ASCE 43 provides a set of graded design criteria based on the performance-based approach to ensure that SSCs are designed for the appropriate seismic hazards with adequate strength and serviceability requirements to meet the required performance goals. The performance goals are defined as targeted annual frequencies of exceeding the acceptable performance levels for the SSCs. The acceptable performance levels are described by the limit states the design intends to achieve for the SSCs. The limit states are consistent with the risk significance of the SSCs or facility.

The following paragraphs describe the key concepts of ASCE performance-based seismic design:

- Target performance goals: The standard uses the same concept as the reliability performance targets in the LMP functional design approach and defines the performance levels for the physical design of SSCs commensurate with their safety functions for achieving the system level performance. ASCE 43 prescribes design criteria for targeted performance goals ranging from $4x10^{-4}$/year to $1x10^{-5}$/year. The highest performance goal, which corresponds to the lowest annual frequency of exceedance, achieves the highest reliability for the seismic performance of the SSCs. Therefore, a graded approach is applied in that more stringent seismic design criteria are used to achieve higher seismic performance for SSCs.
- Seismic design input: In the performance-based seismic design, the target performance goal for an individual SSC is calculated by performing an integration with respect to acceleration of the product of the design fragility and the slope of the seismic hazard curve. The design fragility is established by the probability goals as described later and the seismic hazard curve is fitted using a power law. To achieve the target performance goal, the ASCE 43 approach modifies a uniform hazard response spectrum (UHRS) to achieve a risk-consistent seismic design input response spectrum (as indicated above in relation to the GMRS which is tied to the performance goal of 10^{-5}/year).
    - In contrast to the traditional approach where the physical seismic design focuses on withstanding a given seismic input, in the performance-based seismic design process, because the annual frequency of exceedance (AFE) for defining the seismic input is directly tied to the performance goals to be achieved for the SSCs the seismic design input can be different for SSCs of varied importance.

- Probability (reliability) goals: ASCE 43 provides a set of acceptance criteria aimed at achieving two conditional probability goals:
  - Less than 1% annual probability of unacceptable performance conditional on the design basis seismic input
  - Less than 10% annual probability of unacceptable performance conditional on 150% of the design basis seismic input.

  These probability goals establish the design fragility that ensures the seismic performance of SSCs consistent with the expected performance goal. Therefore, the performance-based design aims to achieve more uniform design fragility / performance for SSCs than the traditional deterministic approach which often leads to large differences in fragilities for different SSCs.
- Approach to achieve probability goals: To achieve these probability goals, ASCE 43 relies on modern seismic analysis methods and nuclear design codes and standards to deliver the following:
  - The seismic response analysis procedures to achieve seismic demands for the design basis seismic input shaking at the 80th percentile non-exceedance probability
  - Design strengths in codes and standards for various construction materials and types of structures (concrete, steel, mechanical and electrical equipment for example) that deliver SSC capacities at the 98th percentile exceedance probability
  - Keeping inelastic deformation capacities at the 95th percentile exceedance probability.

Scope of Applicability

ASCE 43 with support from additional ASCE RIPB standards for seismic response analysis and for geotechnical engineering (ASCE 4 and ASCE 1, respectively) should deliver SSC designs that meet the requisite performance goals (reliability targets) for their intended prevention and mitigation functions. Fully integrating the LMP approach and ASCE criteria bridges the risk-informed categorization and associated performance goals and will lead to a consistent TI-RIPB process.

Although the TI-RIPB process as presented here focuses on licensing of ANLWRs, nothing precludes its application to LWRs and other facilities. The major benefit of this approach over the traditional SRP approach lies in the integrated decision-making process with enhanced emphasis on safety while providing flexibility and options based on a process that provides explicit consideration and traceability of the various risk-contributing factors.

Organizational Plan for RES Activities and Moving Forward:

RES already initiated research to describe and detail an integrated TI-RIPB process for seismic design. This research is assisted by two primary contractors from Brookhaven National Laboratory (BNL) and Southwest Research Institute (SWRI). The goal is to endorse this process in a regulatory guide, which will serve as an alternative option to the current SRP guidance for seismic design. The research will use a phased approach with near-term (6 months) and intermediate-term (2 years) goals.

Near-term goals include:

- Aligning with the LMP approach
- Developing strategies linking ASCE seismic performance goals to LMP risk-informed SSC categorization
- Evaluating the adequacy of ASCE criteria in meeting target performance goals.
- Developing a plan for the intermediate-term phase including consideration of processes to take full advantage of the LMP categorizations.

A product for the near-term phase will be a concise principles document outlining the TI-RIPB framework based on LMP and ASCE approaches. The starting considerations for the near-term research include:

- Although the proposed TI-RIPB allows different performance goals to be assigned to different SSCs according to their safety significance, the current regulatory framework requires the use of the safe shutdown earthquake (SSE) for the seismic design of the facility, resulting in a single performance goal for the entire facility. This can preclude realizing the full potential of the TI-RIPB approach. The design space from the TI-RIPB is defined by the area under the F-C target curve and any point in the F-C space below the F-C target is considered an acceptable design. When the design point is closer to the F-C target curve, the reliability demand for SSCs is less than when the design point moves away from the F-C target. This design approach affords flexibilities that provide tremendous opportunities and design options for the designer to come up with an optimal design with a more uniform performance goal that can satisfy the current regulatory framework. An alternative would be to use the rulemaking process to adopt performance-based seismic input.

- Use of the staff position in RG 1.208 that the target performance goal of 1×10^{-5}/year for the seismic design of LWRs meets the NRC safety goals. As newer reactors either have smaller source terms and/or incorporate passive and inherent safety features resulting in much safer design, the performance goal of 1×10^{-5}/year could be treated as a threshold limit. Performance goals other than the threshold limit would be justified, for example, using the F-C targets and the LMP criteria for categorization of SSCs.

- The ANS-2.26 approach places the DOE facilities in several risk categories, each being assigned a value for the target performance goal. The difficulty in applying ANS-2.26 is that the diverse nature of future designs is likely to pose challenges to binning in fixed risk categories. An approach to address this issue is to evaluate the suitability of using the same or modified F-C target for various facilities (ANLWRs and fuel processing facilities for example) for use in conjunction with facility specific LBEs.

- Limiting the design to performance levels corresponding to elastic limit states and permit limited inelastic limit states to be used to demonstrate no adverse impact on risk significant SSCs from adjacent SSCs that are not considered to be risk significant.

The near-term work also involves communicating with both internal and external stakeholders to obtain feedback on the principles and already available details of the framework.

The intermediate-term activities should aim at:

- Illustrating the effectiveness and efficiency of the TI-RIPB process for various applications. Quality SPRAs for reactors and other non-reactor facilities can be used to contrast between the traditional approach and the proposed approach. These illustrative examples can be especially helpful to communicate with internal and external stakeholders. These examples can also help identify potential weakness and inadequacies of the approach and help enhance the basis for the intended regulatory guide.
- Using physical design problems to demonstrate how ASCE performance-based seismic design complements the LMP risk-informed categorization in the integrated TI-RIPB process.
- Consideration of approaches that expand the near-term developments to take full advantage of the SSCs categorization approaches in the LMP and if and how this may enhance the ASCE 43 performance-based design process.
- Work with stakeholders to achieve consensus on the approach and guidance going forward.

Conclusions:

This white paper presents a rationale for developing new TI-RIPB seismic guidance. It describes an approach that leverages the LMP's work for integrating PRA insights and DID philosophy for functional design and safety-focused treatment of SSCs with ASCE performance-based seismic design standards.

The outlined TI-RIPB approach is expected to provide an integrated and consistent process that is fully risk-informed and performance-based. It also gives the designer flexibility and options to achieve safety by providing explicit consideration and traceability of the factors contributing to risk.

As newer designs are increasingly looking at technologies that provide passive and inherent safety features, the risk due to internally initiated events may be reduced substantially. For these designs, seismic risk represents a dominant risk contributor especially because of the large hazard uncertainty. The proposed TI-RIPB approach can offer an effective and efficient means for managing the seismic risk and facilitating the licensing review of applications.

References

1) NEI (2018), Risk-informed Performance-based Guidance for Non-Light Water Reactor Licensing Basis Development. Nuclear Energy Institute (NEI), Technical Report NEI 18-04.

2) ASCE (2005), Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities. American Society of Civil Engineers (ASCE), Standard ASCE/SEI 43-05.
3) ANS (2004), Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design. American Nuclear Society (ANS) Standard ANS/ANSI 2.26.