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RISK-INFORMED PERFORMANCE-BASED DESIGN PROCESS FLOW FOR STRUCTURES

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ABSTRACT

Some advanced reactors (ARs) will be licensed following the 10CFR50 Construction Permit (CP) / Operating License (OL) pathway using the Licensing Modernization Project (LMP) methodology and corresponding guidance in Nuclear Energy Institute (NEI) 18-04 (NEI, 2019), which is endorsed in Regulatory Guide (RG) 1.233. The LMP / NEI 18-04 methodology leverages probabilistic risk assessment (PRA) risk insights to inform design elements such as structure, system, and component (SSC) safety classifications, licensing basis events (LBEs), defense-in-depth (DID) adequacy, and risk-informed performance-based (RIPB) design criteria. While NEI 18-04 and related industry and regulatory guidance (e.g., NEI 21-07, RG 1.253, which endorses NEI 21-07, and ASME/ANS RA-S-1.4-2021) provide a useful framework for RIPB design, they provide few implementation details on the development of structural design criteria and special treatments within the framework. Research Information Letter (RIL) 2021-04 (USNRC, 2021) and Draft Guide (DG) 1410 (USNRC, 2022) provide some guidance, but details are limited to seismic events and the approach is primarily based on the application of nuclear-specific codes and standards (C&Ss) for seismic design (specifically ASCE/SEI 43). To enable cost-effective structure design, X-energy required an RIPB design criteria development and justification approach that is general to all hazards and permits the use of C&Ss consistent with industrial best practices rather than strictly nuclear-specific C&Ss. This paper summarizes one option of an RIPB design process flow for establishing initial design criteria for civil structures at the conceptual design stage and describes high-level lessons learned from implementation of the process.

INTRODUCTION

For decades, the design and licensing of nuclear power plants in the United States (U.S.) have followed a prescriptive approach rooted in detailed regulatory requirements and conservative assumptions targeting large light water reactors (LWRs) and their typical means to ensure safety. Under requirements of 10 CFR Part 50 and Part 52 regulations, structural design criteria for safety-related SSCs have been largely based on rigid classification schemes and the use of nuclear-specific C&Ss that are also written with large LWRs in mind. While these approaches ensure the safety of nuclear power facilities, it is unclear whether the special nuclear requirements that go beyond non-nuclear industrial best practices provide safety benefits commensurate with their associated costs.

In recent years, the development of ARs in the U.S. has moved away from these prescriptive approaches toward more flexible RIPB approaches. These approaches better align with the diverse design philosophies of AR technologies, which may incorporate passive safety features, functional containment strategies, and modular designs. One such RIPB design approach, outlined in NEI 18-04 and elsewhere, integrates PRA to inform SSC safety classification, LBE definitions, and DID adequacy assessment. Risk insights (from PRA or otherwise) inform performance-based design objectives that ensure SSCs will perform their safety functions with adequate reliability dependent on their relative importance to safety.

Despite high-level guidance available in NEI 18-04 (NEI 2019) and related industry and regulatory documents (e.g., NEI 21-07, RG 1.253, ASME/ANS RA-S-1.4-2021), there remains a need for detailed implementation guidance, such as for development of structural design criteria and special treatments. The value of such guidance is particularly important during early design stages when developers need to make impactful and irreversible facility design decisions without the benefit of having detailed analysis in hand, and yet must balance safety, regulatory expectations, and cost-effective engineering practices across a range of potential hazards. To address this need, SGH and X-energy adapted and implemented an RIPB design process to support the early structural design of Xe-100 reactor building structures. This process guides the designer to develop initial structural design criteria using general industry standards while maintaining consistency with the LMP framework and the NRC's regulatory expectations. This paper presents the proposed RIPB design process flow and describes its key implementation details.

NEED FOR RIPB DESIGN WORKFLOW

In the NEI 18-04 LMP framework, the AR developer is encouraged to introduce a PRA in the early stages of design and advance it as design progresses. The PRA is expected to inform the design process, including developing structural design criteria. However, a PRA process typically treats structures in a relatively simplified and conservative fashion, if at all (ASME/ANS RA-S-1.4-2021 (2021)). Internal events PRAs often do not include structural failures in their analyses since structures tend to be very reliable under normal operations and thus do not significantly contribute to internal events risk. External events PRAs also tend to treat structural failures in a relatively simplified fashion such that only the most limiting failure modes and functions are identified and included in the PRA models. The consequences of structural failures are simply and conservatively assumed to be very severe (e.g., for LWR PRAs, structural failures are often mapped directly to core damage and/or large early release). Such conservative and simplified treatment of structures in PRA for existing LWR plants is reasonable because structural failures typically do not significantly contribute to the total risk, often because they are more reliable than other SSCs. When structures do contribute significantly, risk mitigation options (e.g., structural strengthening) are often cost-prohibitive. Therefore, refined treatment of structures in the PRA models of existing plants is normally not warranted.

Conversely, in the context of RIPB design for new plants, refined treatment of structures in risk assessment can be key to developing more cost-effective designs and criteria. Since the design and PRA in the LMP framework are interdependent, iterative, and evolving, it is less straightforward to simplify the PRA modeling of structures and limit the PRA scope to the governing aspects of the structure (since they result directly from design decisions). The external hazard PRA approaches have historically modeled structures in a simplified and conservative way, little guidance or experience exists for developing refined models of structure systems in the PRA (e.g., when defining initiating events, event sequences, success criteria). Similarly, traditional LWR structural design does not require detailed consideration of structural functions since the governing codes, standards, and guidance rely on underlying assumptions about required structural performance (e.g., safety-related structures remain elastic). For RIPB design, a process is needed to analyze structural functions, responses, failure modes, and the consequences of each failure mode, to

support a more refined treatment in PRA and, consequently, risk-informed, performance-based design within the LMP framework.

The design workflow described in the subsequent sections guides the designer in evaluating structural designs to provide inputs for structural risk assessment, which can then be used to inform PRA and support risk-informed design. The process is framed using terminology familiar to structural engineers (e.g., structural functions, hazards, structural behavior and response, limit states). The information generated through this process should be valuable to PRA analysts for informing key elements of the risk assessment (e.g., initiating events, event sequences, success criteria, systems analysis) as well as the LMP RIPB design (e.g., PRA safety functions (PSFs), capability and reliability targets). In this way, the process helps bridge the gap between structural design and risk assessment, enabling the development of risk insights that can support risk-informed, performance-based structural design criteria.

ELEMENTS OF DESIGN WORKFLOW

Figure 1 illustrates the steps for the RIPB design process proposed in this paper. Each step is described in a subsequent subsection. The sequence of the process represents a logical progression, but is not necessarily implemented in a linear fashion. In practice, it may be applied in varying orders and iteratively. For example, one might begin with an assumed design criterion and then work through steps such as identifying the associated hazard, structural behavior, and other factors to substantiate that criterion. Nonetheless, the process is organized in a logical, linear structure to facilitate the development and documentation of a sound technical basis for structural design criteria.

The process illustrated in Figure 1 provides a high-level overview of various elements that need to be accomplished for design development without reflecting the iterative nature of the process. As mentioned earlier, incorporating PRA in the design process necessitates an iterative workflow in which design and PRA evolve together. Each step of design or PRA may also be iterative. For example, Figure 3-2 of NEI 18-04 illustrates the process for selecting and evaluating LBEs, which is iterative and involves cycles of design and PRA developments. The process outlined herein aligns predominantly with Step 2 of that figure—Design Development and Analysis. In the context of structural design, during the early or conceptual design stages, limited information may be available regarding structural configuration, site-specific hazards, dose consequences of various structural failures, and so on. Therefore, the process may initially rely on low-resolution and qualitative descriptions of these elements, with any assumptions made during implementation documented for future refinement. Early characterizations should ideally be somewhat conservative to maintain margin for future design changes. As the design progresses and more detailed and specific information becomes available, the analysis and characterization at each step can be refined accordingly, until the elements accurately reflect the as-to-be-built and as-to-be-operated plant, aligned with the regulatory positions in RG 1.247 regarding PRA scope.

Step 1 - Structural Functions

The fundamental step in the proposed RIPB design workflow is to identify the functions performed by the structure. Structures tend to perform many different functions, some of which may be safety functions (e.g., provide a reliable and predictable load path to support equipment), and many of which are not (e.g., provide physical partitions between spaces to allow heating, ventilation, and air conditioning (HVAC) systems to control the internal environments for occupant comfort and/or achieve zones of negative pressure and controlled filtration). In the context of licensing basis and regulatory compliance, the primary focus of design would be on the structure's safety functions. In the LMP design framework, safety functions are either PRA safety functions (PSFs) or required safety functions (RSFs). NEI 18-04 defines a PSF as any function by any SSC modeled in the PRA that is responsible for preventing or mitigating a release of

radioactive material from any radioactive material source within the plant. RSFs are a subset of PSFs that are necessary and sufficient to meet the Frequency-Consequence (F-C) Target for Design Basis Events (DBEs) and high-consequence Beyond Design Basis Events (BDBEs), while also conservatively ensuring compliance with the dose requirements of 10 CFR 50.34.

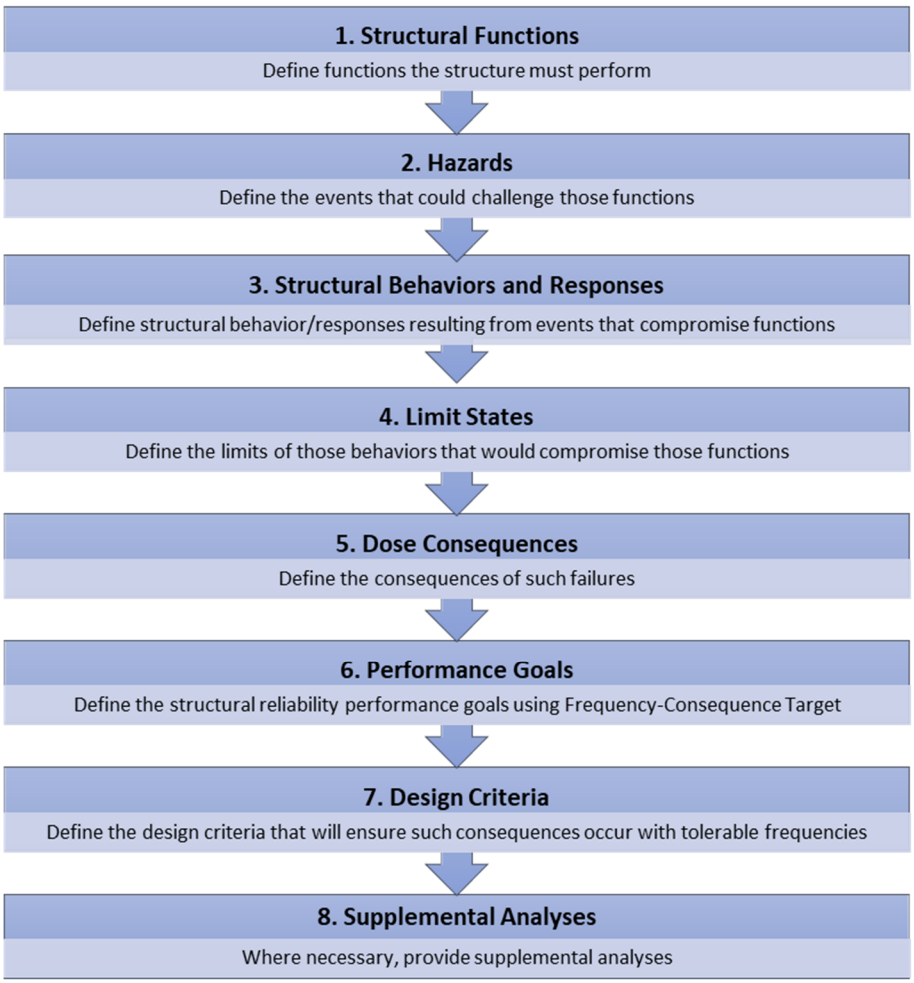

Figure 1. Steps in the Proposed Structural Design Criteria Development and Justification Process.

Structural functions are specific to each structure and are informed by input from various design and analysis teams. A generic list of example structural functions is provided below:

- Ensure a reliable and predictable load path for supported SSCs, such as limiting excessive translations and rotations (both static and dynamic) of supported SSCs, avoiding transfer of excessive loads (static or dynamic) onto supported SSCs, providing adequate restraints to limit deformations and associated stresses and strains in supported SSCs, or allowing the intended behavior of supported SSCs (e.g., thermal expansion) without interference.
- Provide or support energy-absorbing or deflecting barriers to protect supported and/or housed SSCs from internal and external hazards.
- Support physical partitions/barriers between designated spaces to enable other systems or programs to fulfill their functional requirements (e.g., flood barriers between adjacent units, HVAC control for maintaining environmental conditions and/or achieving zones of negative pressure and controlled filtration, or security measures).
- Provide or support radiation shielding.

- Avoid adverse interactions with other SSCs that could compromise their functional performance.

While not exhaustive, this list captures most of the typical functions that structures may serve. Not every structure will perform all of these functions, and the evaluation conducted in this and subsequent steps will likely eliminate several based on the specific characteristics of the structure. This list of example functions can serve as a starting point for identifying structure-specific functions during analysis. Enclosure 2 of SECY-18-0096 (2018) also provides a list of structure functions and may be used to inform and guide the definition of structural functions.

The complementary SMiRT-28 paper *An Overview of Function Analysis Complications in Risk-Informed Performance-Based Design of Structures* by Cappa et al. (2025) summarizes lessons learned from a refined analysis of structural functions for RIPB design of the Xe-100 RB structures.

Step 2 - Hazards

Another key element of the proposed RIPB design workflow is to identify and characterize hazards that could challenge the structural functions defined in the previous step. Appendix B of RG 1.247 (2022) offers a list of hazards and their potential impacts that should be considered in a PRA to support NLWR risk-informed activities, including licensing applications. That list provides a helpful starting point for identifying relevant hazards when developing and/or justifying structural design criteria within the LMP/NEI 18-04 RIPB licensing framework. Examples of external hazards that could potentially affect structural functions are seismic, external flooding and fire, extreme temperature, high winds and wind-generated missiles, ground shifts, and snow.

Some hazards are typically screened from consideration in developing structural design criteria on the basis that they are not expected to substantively influence structural design. As the design matures, hazards may be further screened and/or augmented as needed to identify the hazards that could affect the structural functions identified in the previous step. As the structure designs and PRA mature, the list of hazards affecting structural functions should converge with the initiating events and LBEs modeled in the PRA, and structural fragilities will be developed as needed to model the probability of structural failure conditional upon the occurrence of each hazard.

In the early stages of design, it is common to identify and focus on some of the most governing hazards and resulting postulated loads that could challenge the structure and drive the overall design (i.e., concept design) of the structure. For example, depending on the location of the selected site, seismic or wind-borne missile hazards may dominate the external hazard risk and drive the design of the structure (in combination with other, non-hazard related requirements such as radiological shielding). In such cases, the primary focus would be on the governing external hazards and design of the structures for corresponding loads following the RIPB design process. When the design further matures (e.g., preliminary design), other external hazards will be also assessed to ensure the adequacy of design under postulated loads from other hazards.

Step 3 - Characterization of Structural Responses

This step describes how the structures behave in response to the hazards defined in the previous step. This includes describing the structural load path for various loads and quantifying corresponding structural response quantities such as internal forces, support reactions, and global and local deformations, displacements, and accelerations. The level of detail in the characterization of structure responses depends on the design maturity. During the early stages of design, structural response is typically characterized using

qualitative descriptions and/or simplified models and analyses. As the design progresses, more detailed structural analyses are conducted to develop quantitative and refined characterizations of structure response.

The NEI 18-04 design framework for risk evaluations generally requires consideration of hazards across a range of intensities (e.g., the full spectrum of potential earthquake or wind loads). Accordingly, the structural behavior and response may also need to be characterized for a broad range of loading. At lower intensities, structures typically respond elastically, while higher intensities may lead to inelastic behavior. In conventional prescriptive nuclear structural design, analysis is typically limited to elastic response, as nuclear design C&Ss (e.g., ACI 349 (2011)) do not allow inelastic behavior under design-level loads for many hazards. However, in RIPB design, inelastic behavior can be acceptable, as long as the structural functions are not impaired. Therefore, the structural behavior/response characterization may need to include consideration of nonlinear response when allowable per the performance-based design criteria.

Guidance for characterizing structural behavior and response is provided in various guidance documents (e.g., Seismic Review Plan, NUREG-0800, Chapter 3) and C&Ss (e.g., ASCE/SEI 4, ASCE/SEI 7, and ASCE/SEI 41).

Step 4 - Limit States

Limit states (LSs) are the thresholds beyond which the intended structural function would be compromised under the effects of hazards/loads. These LSs represent conditions tied to functional success criteria. LSs can be used to characterize the structural performance parameters (e.g., stresses or deformations) that correspond to end states or plant damage states modeled in the PRA (i.e., success criteria as defined in Section 4.3.4 of ASME/ANS RA-S-1.4-2021 (2021)). As such, LSs provide a basis for informing or defining Capability Targets for structures, as required by NEI 18-04. Generally, LSs are classified as either deformation-based (e.g., drift, settlement) or strength-based (e.g., yielding, rupture of pressure boundary). There may be also some unique LSs that are neither deformation-based nor strength-based, such as temperature limits. Nevertheless, defining LSs for various structural functions and characterizing the consequence of exceeding them are key tasks in the RIPB design process.

ANS 2.26 (2017) defines four LSs for structural systems that can be conveniently mapped to structural function failures. Those LSs are also adapted by ASCE/SEI 43 for performance-based seismic design of structures. Although the ANS 2.26 LSs are specific to seismic design, they may be used to develop similar LSs for other external hazard designs. ASCE/SEI 41-23 also defines structural performance levels for seismic evaluation of existing non-nuclear structures, which are analogous to LSs defined in ANS 2.26. The structural LSs defined in these standards are each associated with specific provisions that establish limits on structural response parameters (e.g., drift or member forces) based on deformation, strength, or other criteria necessary to meet the performance objectives specified by the codes.

Defining an appropriate LS for a given structure, function, hazard, and response requires sound engineering judgment, practical experience, and an understanding of how structures perform under load. When a structural function influences the performance of other SSCs, collaboration with the designers of those interfacing SSCs is essential to establish behavior limits that can be tolerated without compromising the associated SSC functions and success criteria. Structural LSs may be defined with varying levels of conservatism or realism, depending on factors such as the design stage, cost-benefit considerations, and the uncertainty surrounding the interaction between structural response and SSC functionality. An Integrated Decision-Making Process Panel (IDPP), as defined in NEI 18-04, can play an important role in confirming that the selected LSs are appropriately conservative or realistic.

Step 5 - Dose Consequences

When the structure responses reach and exceed a LS, the corresponding structural function fails, and that failure is modeled as a basic event in one or more LBEs. As indicated in NEI 18-04 and RG 1.233, the F-C chart is a means to assess LBEs and their risk significance. The F-C chart can serve as a guide for improving the design and making design decisions based on their impact on risk (i.e., failure occurrence frequency and dose consequence). To use the F-C chart as a guide, the dose consequence[1] corresponding to the failure of structural functions (exceeding LSs) needs to be evaluated (unless for extremely low frequency events). The analysis of LBE dose consequences involves several PRA elements including plant operating state analysis, event sequence analysis, success criteria development, systems analysis, mechanistic source term analysis, and radiological consequence analysis. Such analyses are beyond the scope of structural design. However, as indicated above, their outputs provide key input to structural design criteria development.

Because quantifying LBE frequencies and dose consequences is complex and depends on many PRA elements, most of which are not fully developed in the early design stages, structural design criteria can be established using simplifying assumptions. Examples of such simplifications include:

- Assuming structural failures (i.e., exceeding specified LSs) directly result in some dose consequence. Based on this assumption, the dose consequence can be obtained from existing LBE dose consequence analyses or else estimated based on consultation with the safety analysis team. This simplification is needed at the early design stage (e.g., conceptual design) while a refined PRA including structural failures is still not developed. As the PRA matures in later design stages, it can be used to more explicitly quantify the dose consequences of structural failures and provide refined feedback on the adequacy of RIPB structural design criteria.

- Selecting and evaluating design criteria based on LBE site boundary dose consequences only. Evaluation of cumulative risk targets[2] may be deferred to a later design stage when the PRA, design, and safety analyses mature.

Such simplifications facilitate estimating the dose consequence for the failure of a given structural function, under specific hazards.

Step 6 - Performance Goals

Task 6 in Section 4 of NEI 18-04 describes how to identify reliability and capability targets for SSCs. In that task, each SSC is assigned specific reliability targets to ensure that the underlying LBE frequencies and consequences meet the LBE evaluation criteria (e.g., F-C Target). These reliability targets will be used to develop specific design and special treatment requirements in the subsequent steps. The term "reliability target" is essentially the same as the performance goal, or annual frequency of unacceptable behavior, in the context of structural design C&Ss for external hazards. The reliability targets (hereafter referred to as performance goals) can be defined based on inputs from PRA and event frequency limits that are dependent on the LBE dose consequence and F-C Target. Although meeting the F-C Target is not a specific regulatory acceptance criterion, it serves as a tool to risk-inform structure performance goals and design criteria. The target performance goal serves as the key input for developing structural design criteria.

[1] Per NEI 18-04, the dose is defined as the dose calculated at the Exclusion Area Boundary (EAB) for the 30-day period following the onset of the release.
[2] Per NEI 18-04, cumulative risk targets are total frequency of 100 mrem site boundary dose, individual risk of early fatality within 1 mile of Exclusion Area Boundary (EAB) across all LBEs, and average individual risk of latent cancer fatalities within 10 miles of EAB.

The process of determining structure performance goals based on the F-C Target depends on how the structure functions are defined in the PRA model. When the failure of a structure function is a singleton, the structure's performance goal is essentially the same as the event frequency and can be set based on the F-C Target and the dose consequence (Figure 2, as an example, shows the event frequency determined from a dose consequence resulting from the postulated event). If the LBE includes other failure modes or mitigations, the structure's performance goal depends on the performance of those elements and the overall LBE evaluation. That scenario would require more analysis to map a dose consequence and event frequency onto a structure performance goal.

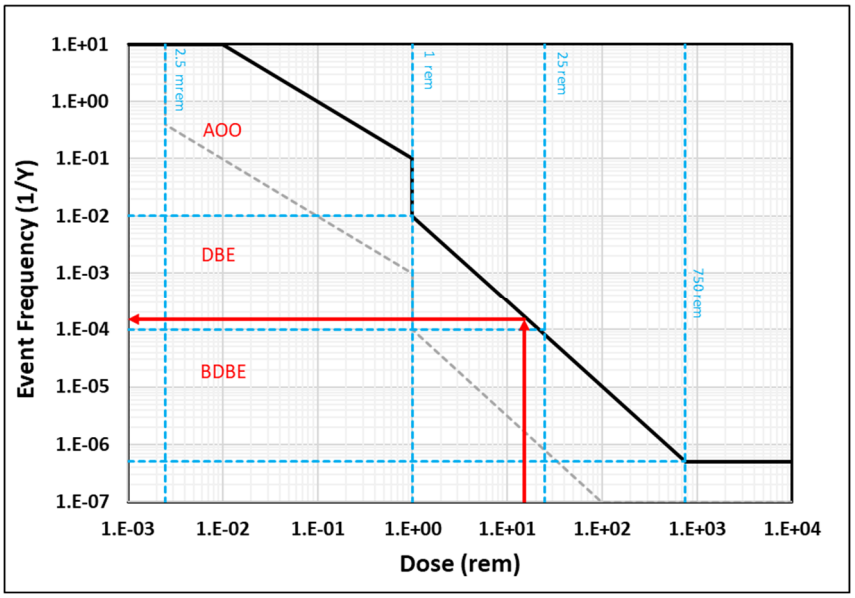

Figure 2. Frequency-Consequence Target.

In addition to the F-C Target, NEI 18-04 introduces other considerations that may influence the performance goal requirements for structures. For example, if the structural failure leads to dose consequences exceeding the 25 rem limit in 10 CFR 50.34, the structure may be classified as safety-related (SR), in which case its failure frequency for the corresponding LBE must be below 1E-4/yr.

Step 7 - Design Criteria

To achieve the performance goals identified in the previous step, the structural designer needs a set of design criteria to follow. For example, the design process requires a set of provisions for loading the structure and the design and detailing of structural members and connections. Those design criteria ensure that it can withstand the identified events without exceeding the defined behavior limits and corresponding dose consequences. Commonly, design C&Ss and corresponding provisions provide design criteria that can guide the design process.

One of the main LMP goals is to provide designers with increased flexibility in defining design criteria such that individual SSCs can be designed based on provisions that are commensurate with their safety significance. The flexibility encourages the designers to explore cost-effective design approaches, one of which may be considering design provisions from non-nuclear commercial C&Ss. It is then necessary to demonstrate those provisions achieve the required performance and conform to applicable 10 CFR regulations (if the structure falls under NRC jurisdiction). It is also possible that the performance achieved by the provision of the selected C&Ss is insufficient to meet the required reliability targets. In

such cases, the design criteria may be augmented by additional requirements to achieve the required performance. This process requires an understanding of the performance basis underlying the applicable provisions.

Key elements in developing design criteria include:

- Select acceptable codes and standards to perform structural design such that the structure meets performance targets.
- Determine design basis hazard levels consistent with performance targets of the selected C&S and safety classification of the structure.
- Determine design loads, including operational loads and those corresponding to the hazards and hazard levels identified above.
- Establish appropriate analysis methods to compute the structural responses to inform the design of structural components and connections.
- Determine requirements for developing the capacity of structural components that meet the demands and are consistent with provisions of selected C&Ss.
- Determine requirements for quality assurance.

Similar to many other elements of the RIPB design process, the process of developing design criteria can be iterative. For example, when the required performance is not satisfied by the selected provisions of C&Ss, a set of more stringent provisions or design parameters may be selected to improve the performance. Alternatively, the structure design configuration or LSs may be revisited to reduce the dose consequences and accordingly, increase the event frequency limits, which determine the required performance goals.

Step 8 - Supplemental Analyses and Actions

In practice, supplemental analyses and/or actions are necessary to complement the procedural design identified in the previous steps. Examples of such supplemental analyses and actions can include:

- Perform analysis (e.g., hazard convolution) to substantiate the proposed design criteria and ensure the required performance is achieved.
- Define an integrated decision-making process (IDP) and engage IDPP in design decisions (e.g., identifying dominant external hazards, assessing the adequacy of design criteria, and addressing issues relevant to the structural design criteria process). Section 5.7.2 in NEI 18-04 lists several broad questions that the IDPP should address as the design progresses. Depending on the responses to those questions, additional analysis and actions may be defined and exercised.
- Engage with the regulator and develop a licensing strategy that is reviewed by the governing jurisdiction during the design development. This is particularly important when there is regulatory uncertainty or gaps in existing design criteria as it relates to ARs.

SUMMARY AND CONCLUSION

The design process discussed in this paper provides a risk-informed approach to develop performance-based design criteria for structures. As discussed above and consistent with the LMP RIPB design approach, the proposed process is iterative and requires close collaboration among design and PRA teams. As the design of the civil structures and the PRA progresses, this process enables optimization of the design based on risk insights. The process proposed herein addresses gaps in the available guidance for applying the NEI 18-04 guidance to structural design. It provides a rational framework for developing and documenting an RIPB licensing basis for structures using terminology familiar to structural engineers and consistent with

the LMP conceptual framework, thereby helping to bridge a gap between traditional structural design practice and RIPB design for ARs.

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