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APPLICATION EXAMPLE TO DEMONSTRATE RIPB SEISMIC DESIGN CONCEPTS FOR ADVANCED NUCLEAR POWER REACTORS

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ABSTRACT

The proposed process for the seismic safety of advanced nuclear power reactors is based on the Licensing Modernization Project (LMP) that relies on a risk-informed performance-based (RIPB) approach as described in NEI (2018) and NRC (2020). The implementation of the LMP framework for sequences initiated by earthquakes is developed in Chokshi et al. (2021), referred to as the LMP/ASCE 43 integration process. The main components of this process include: (i) individual structures, systems, and components (SSCs) seismic design in accordance with American Society of Civil Engineers (ASCE) 43-19 (2019); (ii) seismic probabilistic risk assessment (SPRA); and (iii) integrated decision-making, using a new risk metric incorporating event sequence frequencies and public dose estimates plotted on a frequency-consequence graph (called an "F-C curve") and including consideration of defense-in-depth (DID) adequacy. Such an approach allows the reactor designer to link the performance-based design of SSCs in accordance with ASCE 43-19 to their risk-significance at both plant and event sequence levels through SPRA and F-C criteria. This approach makes it possible to establish different seismic design categories (SDC) (seismic design basis ground motions) and seismic design limits, termed Limit States (LS), for various SSCs, and therefore achieving a more risk-balanced design in a graded manner. The application of this RIPB seismic design approach based on LMP/ASCE 43 integration is demonstrated through an example. A regulatory guide for trial use is under development to implement the RIPB seismic design concepts for advanced reactors with several options.

INTRODUCTION

The Licensing Modernization Project (LMP) approach for licensing and regulating the safety of advanced nuclear reactors proposed by NEI (2018) has been endorsed by NRC (2020). The LMP framework relies on risk-informed performance-based (RIPB) approaches that are currently in use by the U.S. Nuclear Regulatory Commission (NRC) in its licensing philosophy for operating reactors and other nuclear facilities. The implementation of the LMP framework for evaluating seismic risk and seismic design of structures, systems, and components (SSCs) is developed in Chokshi et al. (2021), called the LMP/ASCE 43 integration process. American Society of Civil Engineers /(Structural Engineering Institute (ASCE/SEI) 43-19 (ASCE, 2019, henceforth referred as ASCE 43-19) contains a graded approach that allows for consideration of risk significance of each component in the seismic design. ASCE 43-19 and companion standards [e.g., ASCE/SEI 4-16 (ASCE/SEI, 2017)] use established and currently practiced design procedures in the nuclear industry. Adequate margins and balance in a design are achieved through appropriate selection of seismic design categories (SDCs) and design limit states (LS). A companion paper, Dasgupta et al. (2022), discusses the design approach for individual SSCs using LMP/ASCE 43 integration process.

As discussed in Chokshi et al. (2021), the seismic design process within the LMP framework is distinguished from the established practices in the current regulatory framework because it incorporates the RIPB concepts in the seismic design itself, so that the seismic hazard levels and design performance limits of each safety related SSC are commensurate with the SSC's contribution to risk and other safety considerations. The main components of this process include: (i) individual SSCs seismic design in accordance with ASCE 43-19; (ii) seismic probabilistic risk assessment (SPRA); and (iii) integrated decision-making, using a new risk metric incorporating event sequence frequencies and public dose estimates plotted on a frequency-consequence graph [called as frequency-consequence "(F-C) curve"] and including consideration of defense-in-depth (DID) adequacy. In the RIPB seismic design process, the safety margins of individual SSCs are built-in according to their contribution to system-level and plant-level risk, the process achieves a more risk-balanced design in a graded manner by reducing unnecessary conservatisms (or providing additional margins, as needed). Such an approach allows the reactor designer to link the performance-based design of SSCs in accordance with ASCE 43-19 to their risk-significance at both plant and event sequence levels through SPRA and F-C criteria. The approach makes it possible to establish different SDCs and seismic design limits, termed LS, for various SSCs. The seismic design concepts for advanced reactors based on the RIPB-LMP framework are incorporated as one of the options in the trial regulatory guide (RG) being developed by the NRC.

The objective of this paper is to demonstrate the application of the RIPB seismic design process within the LMP framework developed in Chokshi et al. (2021) and Stamatakos et al. (2021) using a facility design as an example. To achieve this objective, we evaluated selected event sequences to examine impacts of alternate SDC and LS categories with respect to the F-C criteria. Two Central and Eastern United States (CEUS) sites with different seismic hazards were studied.

Available SPRA information was used to develop simplified functionally coherent event sequences for an advanced nuclear power reactor (also referred to as "advanced reactors") design. We selected and simplified the sequences that result in consequences in terms of doses. For a base case, the analysis was performed assuming initial generic fragility values as if the design reflects current NRC seismic design criteria (i.e., SDC 5 and LS D of ASCE 43-19). Based on the SPRA results and comparison with the F-C criteria, it was determined that the SSCs could be designed to alternative SDCs and LSs. These alternative SDC and LS categories were used to evaluate changes in the risk quantification. The fragilities of components were revised to reflect the designs conducted for alternative selection of SDCs and LSs. The event sequence results were compared with the base case and the F-C criteria, and the conclusion was that alternate designs would still meet the F-C targets.

OVERVIEW OF LMP/ASCE 43 INTEGRATION APPROACH

An LMP/ASCE Integration Approach is illustrated in Figure 1; the step-by-step approach is summarized in the following discussion. This procedure was developed in the context of ASCE 43-19 and associated standards and codes. However, the approach is flexible enough to allow alternative seismic codes and standards to be used other than ASCE 43-19.

Step 1: This step is related to the initial selection of ASCE 43-19 SDC and LS Categories for SSCs that are modelled in a SPRA. For example, for advanced reactors whose designs are already in progress or have been completed and whose seismic design is based on an approach akin to ASCE/SEI 4-16 (ASCE/SEI, 2017) and ASCE 43-19 using SDC-5 and LS-D requirements, initial fragilities needed in Step 3 can be assigned based on currently available generic fragility values. These initial values are used to help determine whether a different SDC and LS can be assigned through this iterative process. For newer advanced reactor designs, there are more seismic design options using combinations of SDCs and LSs, such as SDC-5 and LS-D, SDC-5 and LS-C, SDC-4 and LS-D, and so on, which could be selected at the onset based on available design information. Additional considerations on the initial selection of SDC and LS categories include regulatory requirements, stability of the designs, ease of design, and available information. The selection of an LS for an SSC is related to its intended safety function and risk-significance.

Step 2: Conduct a preliminary design and a fragility assessment to determine if more realistic fragilities using more design specific information related to important SSCs are needed. This optional step may only be necessary in subsequent iterations to implement Step 5 more comprehensively. In most cases, once the SDC and LS categories are chosen, one can proceed to Step 3 to assign fragilities. However, in some cases, it may be necessary to have a better understanding of the design and/or a better estimate of a fragility to support a more informed and robust decision. This step provides such an opportunity.

Step 3: Based on the assignments of SDC and LS categories in Step 1 and available data, fragilities can be calculated or can be estimated using generic information, engineering judgment, or experimental data. For the purposes of determining SDC and LS categories, precise values of fragilities are not necessary, provided they are within a realistic range. Chokshi et al. (2021) discusses some of the considerations involved in adjusting these fragilities for different SDC and LS combinations.

Step 4: This step involves performing an SPRA using the fragility values determined in Step 3. The LMP approach requires an SPRA at the stage of design development. Chokshi et al. (2021) describes some options for choosing probabilistic seismic hazard(s) for this stage. Outputs from the SPRA include F-C values for event sequences, dominant contributors, and ranking of sequences (e.g., in order of frequency or standard importance analysis approaches).

Step 5: In this step, the integrated decision-making team checks the proposed classification against the risk, DID considerations, and other criteria. The team evaluates the results of the initial SPRA to determine whether the individual event sequence risks are within the F-C Target goals[1] and whether the cumulative risk criteria are met. This team also evaluates DID adequacy, reliability, other qualitative factors related to the risk-informed decision-making (e.g., an appropriate balance between prevention and mitigation, and avoidance of event sequences caused by failure of a single SSC, that control the risk), and other LMP guidelines. The LMP safety classification and component group may identify opportunities to design SSCs to a less stringent SDC or LS. This feedback is provided to the seismic design and SPRA teams for recalculation of the SSC fragilities, as needed.

Step 6: Steps 2 through 5 are repeated, as needed, to optimize the design to meet the desired safety and business goals and comply with all regulatory requirements. This process ends when final selections of SDCs and LSs are made for SSCs.

Step 7: Based on the iterative process described in Step 6, a final SSC categorization in support of the seismic design is determined. This becomes the basis for the final seismic design and licensing of a plant. This categorization and associated fragilities will be used in the final SPRA.

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[1] The F-C target does not correspond to actual regulatory acceptance criteria but is a vehicle to assess a range of events to determine risk significance, support SSC classification, determine special treatment requirements, identify appropriate programmatic controls, and confirm the adequacy of DID.

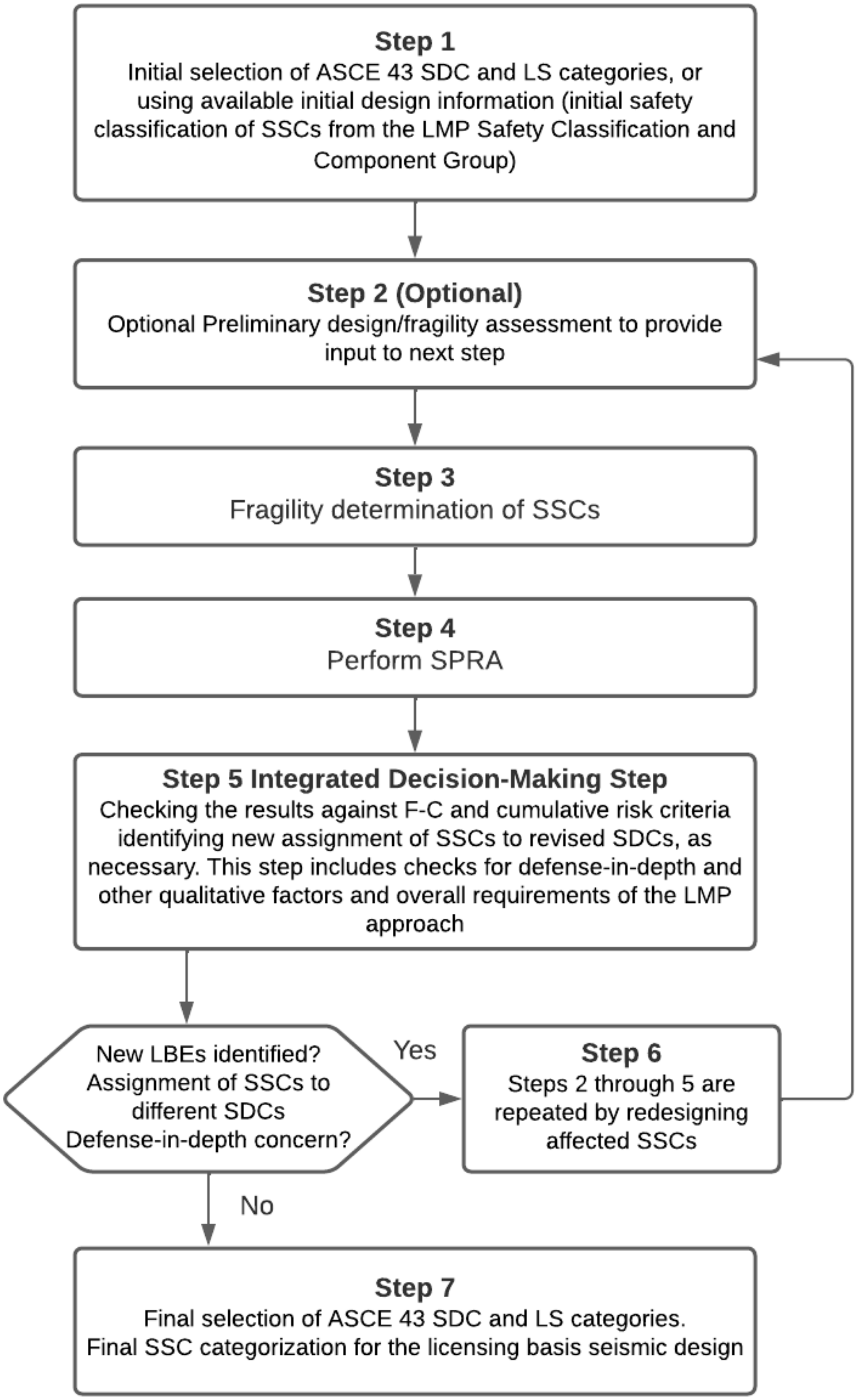

Figure 1. LMP/ASCE Integration Approach

SEISMIC DESIGN PROCESS UNDER THE LMP FRAMEWORK

This section briefly outlines how the above process is used in actual design. As shown in Figure 1, the output of the LMP/ASCE Integration Approach is a designation of SDC and LS categories for each SSC or group of SSCs. The following provides an overview of how the design process may proceed based on current practice and consistent with ASCE 43-19 and ASCE/SEI 4-16 (ASCE/SEI, 2017).

1. Design basis ground motions for each SDC in terms of Design Response Spectra (DRS) are derived from a probabilistic seismic hazard analysis (PSHA) using the selected SDC and the procedure in ASCE 43-19.

2. Seismic response analysis is performed using ASCE/SEI 4-16 (ASCE/SEI, 2017) methods similar to current requirements.

3. Design of SSCs follows engineering approaches in appropriate codes and standards and applicable NRC (RGs) and standard review plan sections.

4. Design of building elements and anchorages is performed to meet American Concrete Institute (ACI) and American Institute for Steel Constructions (AISC) codes.

5. Design of mechanical equipment, piping systems, cable tray systems and heat, ventilation, and air-conditioning (HVAC) systems follows the American Society of Mechanical Engineers (ASME) codes.

6. Seismic design and qualification of electrical components follow Institute of Electrical and Electronics Engineers (IEEE) codes.

7. Final SPRAs using plant-specific and site-specific fragility will satisfy applicable regulatory requirements and use the accepted methodologies specified in the ASME non-LWR PRA standard and trial RG 1.247 (NRC, 202X).

The primary difference in the LMP/ASCE Integration Approach compared to current design practice is the possibility of selecting different combinations of SDC/LS for various SSCs informed by their contributions to system and plant level safety as opposed to assigning SDC-5 and LS-D to all safety-related SSCs.

EXAMPLE APPLICATION

In this example, a simplified SPRA model of an advanced reactor design is utilized to demonstrate application of the basic concepts of the LMP/ASCE Integration Approach. The primary objective of this example is to show the effect on individual event sequence frequencies and consequences from alternative selections of ASCE 43-19 SDC and LS categories for design. These results will show at a conceptual level whether alternate designs are feasible, how the event sequence frequencies vary, and how the approach is applied. This simple example does not explore the following topics: Effect on cumulative risk from all internal and external hazards; changes in risk insights, such as changes in dominant sequences, dominant contributors, and non-seismic failures; complex decision and implementation considerations; and impact of other regulatory and technical considerations.

The event tree model used in this example is shown in Figure 2. This is a simplified event tree from a publicly available model for an advanced non-LWR. However, hazards and fragilities used in this demonstration have no relationship to the published analysis. This model still maintains the functional coherency of the event sequences, so that the dose consequences from the earlier analysis can be used.

Simplifications are in terms of deleting some top events and mostly representing failure of a top event through a single component failure. An event sequence related to "Building Failure" was added to evaluate the impact on event sequence frequencies for alternative SDC and LS categories. No dose consequences are calculated for these event sequences. Two event sequences, sequences 3 and 6, lead to dose consequences labelled Dose 1 (lower dose) and Dose 2 (medium dose) in Figure 2. Sequence 7 (building failure) is assumed to lead to some dose consequences, but doses are not estimated.

The four components whose fragilities are used in the simple SPRA model are listed in Table 1, where HTS is Heat Transport System and SCS is Shutdown Cooling System. A_m represents the median capacity of a component and β_c, the composite uncertainty.

Analysis Approach and Results

The analysis approach is demonstrated in the context of the stepwise procedure described in Figure 1.

Step 1: The SPRA model of Figure 2, based on the available design information at the time, is utilized in this step. For the purposes of this demonstration, the following assumptions are made:

1. This design is assumed, is to be a generic design for a site in the CEUS which can be placed at other CEUS sites.

2. The design input is assumed to be similar to that being used for recent Advanced Light Water Reactor (ALWR) designs. Specifically, the design input corresponds to SDC-5 for initial fragility estimates.

3. The initial design utilizes the LS-D, similar to the current practice. Thus, the initial design is in accordance with SDC-5 and LS-D. This is considered the base case, LMP Design 1 in Table 1.

Step 2 (optional): For this demonstration example no additional specific analysis is carried out in the initial and subsequent iterations.

Step 3: Because the design is assumed to reflect the SDC-5 and LS-D design, the generic fragility values reflecting plant design in the CEUS can be used for the initial trial. Additional considerations involved in choosing the fragility values are described in Chokshi et al. (2021) along with examples of some generic approaches. That report also discusses how to adjust the fragilities to reflect different design alternative combinations, such as SDC-5 and LS-C, SDC-4 and LS-D, etc.

The initially assigned fragility values, in-terms of median capacity, A_m, and composite uncertainty, $ß_c$, values for LMP Design 1, the base case, are listed in Table.1.

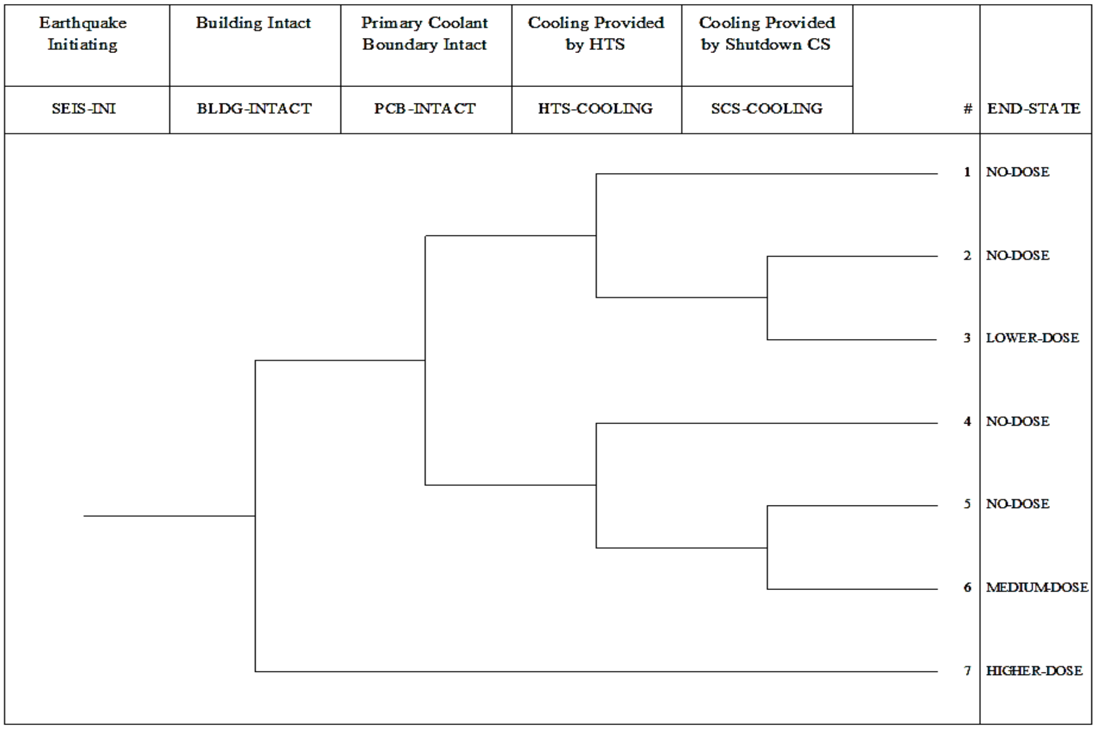

Figure 2. Simplified Event Tree for a Hypothetical Advanced Reactor

Table 1: Fragilities for Different Design Cases

	LMP Design 1 SDC-5/LS-D Base Case		**LMP Design 2 SDC-4/LS-D**		**LMP Design 3 SDC-5/LS-C**		**LMP Design 3 SDC-5/LS-C Sensitivity S1**	
	A_m	β_c	A_m	β_c	A_m	β_c	A_m	β_c
Shear Wall	2.90	0.46	1.45	0.46	1.93	0.46	1.93	0.46
Primary Boundary	2.90	0.46	1.45	0.46	1.93	0.46	1.93	0.46
HTS Cooling	1.24	0.40	0.62	0.40	1.24	0.40	0.93	0.40
SCS Cooling	1.24	0.40	0.62	0.40	1.24	0.40	0.93	0.40

Step 4: For the purposes of performing an SPRA, two CEUS sites are chosen: Site A is a relatively high hazard site in the CEUS and Site I is a more moderate seismic hazard site. Figure 3 shows the two mean seismic hazard curves that are used for quantification. These curves are based on the results submitted to NRC in response to a generic request following the Fukushima Daiichi event.

The results of quantification by using the hazard curve for Site A for the LMP Design 1 for Sequences 3 and 6 are shown in Figure 4, by red squares. Doses for Sequences 3 and 6 are the same, as in the original model as phenomenologically these sequences are the same. Figure 4 also shows the simplified version of the target F-C curve of the LMP framework. The frequency of Sequence 7 is in the order of 1E-6 based on assumed fragility.

The same results for Site I are shown in Figure 5. Frequencies of event sequences that result in doses are significantly lower for the LMP Design at Site I compared to Site A.

Step 5: This is the integrated decision-making step. An examination of the results of the computed frequencies and doses for two sequences, in light of the F-C target for both sites, reveals significant margins, even considering future hazard changes and other factors as discussed in Chokshi et al. (2021). Therefore, it was decided that two additional relaxed design cases should be evaluated. The two cases are designated as LMP Design 2 that utilizes SDC-4 and LS-D design, and LMP Design 3 that utilizes SDC-5 and LS-C, respectively as shown in Table 1. All the components were assumed to be designed to these new categories.

Step 6: This is the step that goes back to Step 2 if design changes are being considered. In this demonstration example, the fragilities for additional design cases, LMP Design 2 and LMP Design 3, were adjusted based on the procedure discussed in Chokshi et al. (2021) and Dasgupta et al. (2022). For example, the design basis ground motion (DBGM) for SDC-4 is about half of the SDC-5 DBGM. Thus, for a linear system, under certain circumstances, the median seismic capacity of a component designed to SDC-4 would be half of the median capacity if that component was designed to SDC-5. Table 1 shows the fragilities for LMP Design 2 and Design 3 reflecting such adjustments. The results of quantifications for these two additional design cases are shown in Figures 4 and 5 for Site A and Site I, respectively, with designations SDC-4/LS-D (LMP Design 2) and SDC-5/LS-C (LMP Design 3).

Step 7: This is the final step in which decisions are made with respect to classification of SDCs and LSs for various SSCs. Looking at the quantification results in Figures 4 and 5, for this hypothetical design with low dose consequences, a design may be acceptable using the combination of SDC-4 and LS-D.

The above example demonstrates the basic concepts of the RIPB seismic design approach. A full SPRA model needs to be utilized in actual applications to fully reflect different outputs in the frequency-dose calculations. As the fragilities are changed to reflect alternate seismic designs, changes in the dominant sequences and contributors also are likely. The cumulative risk also needs to be considered from the seismic and other initiators. This simplified example does demonstrate the feasibility of this approach and opportunities to modify the design considering safety and cost benefits.

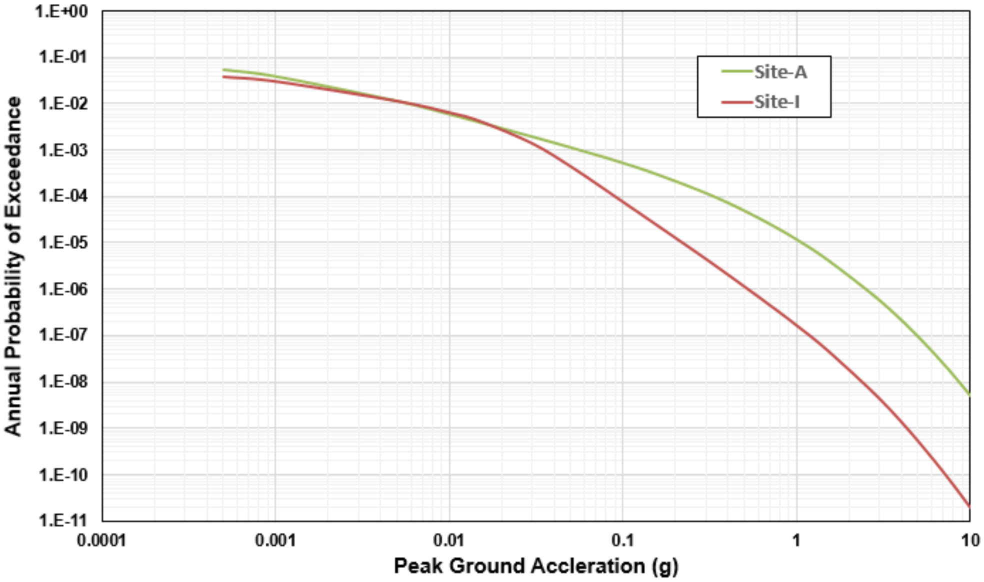

Figure 3. Hazard Curves for Sites A and I used in the example

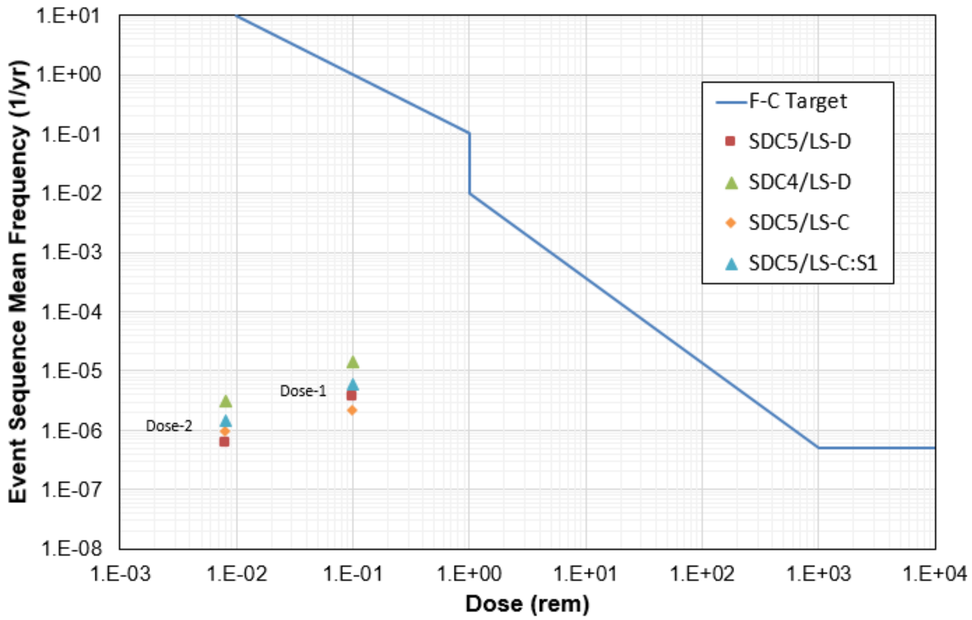

Figure 4. Event Sequences and Dose plotted on F-C curve for Site A

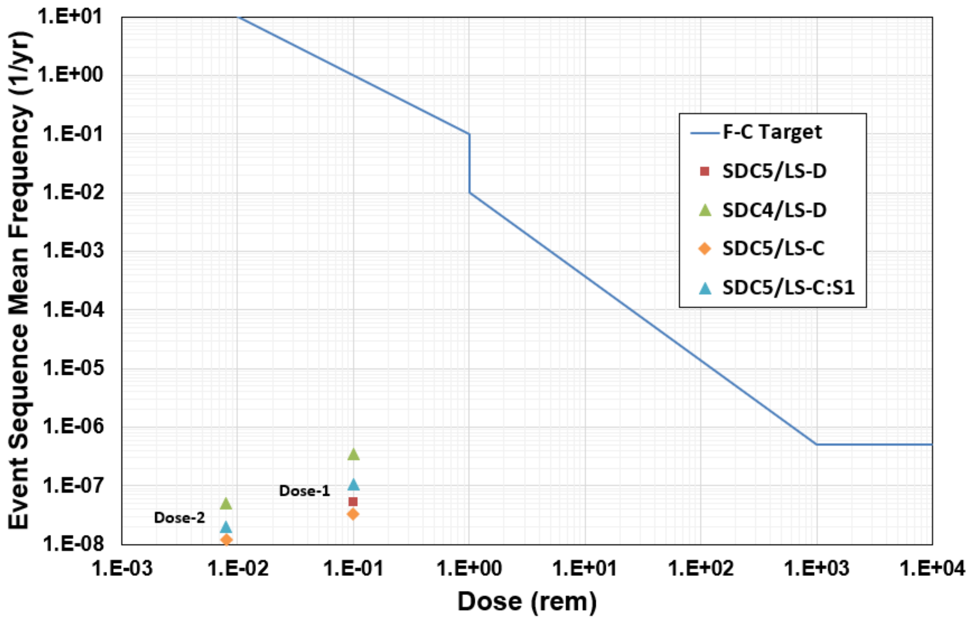

Figure 5. Event Sequences and Dose plotted on F-C curve for Site I

CONCLUSION

This paper discusses the results and lessons learned from an example application of RIPB design to one facility. The main insights are summarized and some of the considerations involved in the process application are highlighted. An important conclusion based on this example is that use of the process is feasible and has potential benefits. The paper also describes how the seismic design will proceed under the RIPB framework. As discussed, the application of RIPB concepts defines the SDCs for SSCs and thus defines the alternative seismic DBGM. It allows the determination of an LS or a desired design performance for an SSC. Once the SDC and LS are determined, the design can proceed in accordance with the current and familiar approaches. This process, along with other RIPB options, is being incorporated in an upcoming draft NRC regulatory guide, "Regulatory Guide for a Technology-Inclusive Risk-Informed, and Performance-Based Methodology for Seismic Design of Advanced Reactors."

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