WHITE PAPER

NEI White Paper: Selection of a Seismic Scenario for an EPZ Boundary Determination

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Notice

Goal, Objectives, and Scope

The goal of this paper is to develop a technology-inclusive framework for the selection of a seismic scenario to use in an analysis for determining the boundary of a plume exposure pathway Emergency Planning Zone (EPZ). The Nuclear Energy Institute (NEI) has established several objectives for the proposed framework to ensure that the resulting selection process would meet regulatory requirements, set reasonable selection criteria backed by a sound technical basis, and support efforts to achieve regulatory efficiency and stability. The objectives for the framework are to:

- Be consistent with the philosophy discussed in NUREG-0396, “Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants.” [1]
- Allow definition of a site-specific plant damage state to be used for a required radiological dose assessment calculation.
- Avoid over-reliance on the highly uncertain tails of the hazard curves.
- Not require that a site-specific Probabilistic Risk Assessment (PRA) be completed prior to the selection of the scenario.[1]

Although the goal is to develop a technology-inclusive framework, the scope of this paper does exclude certain reactor designs and applicants. Specifically, it does not cover:

- Existing or future large (i.e., gigawatt scale) light water reactors with a 10-mile EPZ, as determined by NUREG-0396, including evolutionary (Gen-III/III+) reactor designs such as the Westinghouse AP1000™ reactor.
- Nuclear power plant applicants who chose to follow the “maximum hypothetical accident” option[2] in Regulatory Guide 1.242, “Performance-Based Emergency Preparedness for Small Modular Reactors, Non-Light-Water Reactors, and Non-Power Production or Utilization Facilities.” [2]

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[1] It is important that the EPZ be determined early, as part of the site selection process. At this point in the process, there will only be a seismic margin study (provided by the vendor) and a GMRS that will have been completed as part of the site characterization. It is too early for there to be a site-specific PRA.

[2] RG 1.242 provides an option for plants to use a bounding source term to simplify the process of selecting the scenario used for determining the EPZ size. For example, an SPRA may not be needed by an applicant seeking an operating license under the anticipated regulatory framework for microreactors.

Key Insights and Conclusions

The key insights and conclusions from this white paper are:

- The EPZ boundary determination for an applicant or licensee complying with the requirements in 10 CFR 50.33(g)(2) should consider an earthquake of two (2) times the site-specific GMRS or one with a 1.0g PGA and mean frequency less than 3E-05/yr, whichever is lower. In cases where the 1.0g PGA earthquake frequency is higher than 3E-5/yr, a PGA cutoff should be based on an earthquake with a 3E-5/yr frequency.
- The plant state used for the dose calculation should assume that all structures, systems, and components (SSCs) whose $C_{10\%}$ is less than the selected earthquake, when evaluated in accordance with the guidance in Section H.5 of NEI 12-06, "Diverse and Flexible Coping Strategies (FLEX) Implementation Guide," [3] have failed in the way that would result in the highest calculated dose. All other SSCs would be considered functional. No credit for operator actions in the first 24 hours following the earthquake is assumed in this evaluation unless analyzed to show the Human Error Probability (HEP) less than 0.1.

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1 INTRODUCTION

Regulatory Guide (RG) 1.242 identifies methods and procedures the staff of the U.S. Nuclear Regulatory Commission (NRC) consider acceptable for use by applicants and licensees for small modular reactors (SMRs), non-light-water reactors (non-LWRs), and non-power production or utilization facilities (NPUFs). By following these methods and procedures, an applicant or licensee can demonstrate compliance with performance-based emergency preparedness (EP) requirements in Title 10 of the Code of Federal Regulations (10 CFR) 50.33, “Contents of applications; general information,” and § 50.160, “Emergency preparedness for small modular reactors, non-light-water reactors, and non-power production or utilization facilities.” RG 1.242, Appendix A, “General Methodology for Establishing Plume Exposure Pathway Emergency Planning Zone Size,” describes a methodology and associated steps for determining the boundary of a plume exposure pathway EPZ.[3] The first step in the General Methodology described in Appendix A is “Event Selection,” i.e., the applicant determines the radiological releases from the facility to be evaluated in a radiological dose assessment (also referred to as a consequence analysis) to aid in determining the location of the EPZ boundary. The spectrum of events selected for the radiological dose assessment includes both internal and external events.

2 APPROACH TO SELECTION CRITERIA

This white paper describes an approach for selecting a seismic scenario to support completion of the first step in Appendix A of RG 1.242. The approach can be applied to an SMR, including small LWRs, non-LWRs, and micro-reactors. It is risk-informed and utilizes insights from past seismic PRAs and other relevant engineering sources. The approach addresses two specific topics:

- The selection of the earthquake severity.
- The definition of the plant state (i.e., the bounding scenario) to be used in the radiological dose assessment.

The proposed seismic event selection criteria are consistent with the philosophy discussed in NUREG-0396, “Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants.” Specifically, the seismic event to be analyzed will be determined based on a review of the full spectrum of seismic events, informed by frequency considerations, and used to establish the EPZ.[4] As discussed in RG 1.242, the plume exposure pathway EPZ will be of sufficient size to ensure that projected doses from most core melt sequences would not exceed U.S. Environmental Protection Agency (EPA) Protective Action Guide (PAG) levels outside the EPZ and, for the most severe core melt sequences, immediate life-threatening doses would generally not occur outside the EPZ.

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[3] In the interest of brevity, all subsequent references to “EPZ” mean “plume exposure pathway EPZ.”

[4] As stated in NUREG-0396, the task force concluded that “A spectrum of accidents (not the source term from a single accident sequence) should be considered in developing a basis for emergency planning.”

3 KEY TERMS USED IN THIS PAPER

Beyond Design Basis Event (BDBE): These are events that are of greater severity than the events for which the plant is required to be designed (that is, more severe than a DBE). For seismic, this means an earthquake that is "larger" than the GMRS (e.g., more energy, higher accelerations, greater displacement).

> Note - In 10 CFR 50.155, "Mitigation of beyond-design-basis events," a rule promulgated after the events at Fukushima Daichi, the NRC established a requirement that plants be reasonably able to withstand BDBEs such that the risk of core damage is low, even though the plants were not specifically designed for these events.[5] While a BDBE earthquake, may exceed regulatory design requirements, it might not exceed the CSDRS for a design since the selection of the CSDRS by a vendor is not based on either the GMRS or the BDBE seismic event at any particular site.

$C_{10\%}$: An approximation of the seismic acceleration level for which there is a 10% likelihood of failure. It is the ground motion level (expressed as PGA) at which the probability of failure is at most 0.1.

Certified Seismic Design Response Spectrum (CSDRS): Because new plants of the same technology are intended to be exact replicates (as much as possible), a reactor vendor may specify a standard or generic earthquake, independent of any site-specific GMRS, to govern the plant design; this is called the CSDRS.

> Note - The CSDRS is intended to bound the GMRS at most potential sites where a facility of that design could be built. If the CSDRS bounds the GMRS (which is the SSE), then the plant complies with (and likely exceeds) the NRC seismic design requirements at that site. If it does not, then either additional analyses or changes to the plant design would be required to achieve compliance.

Design Basis Event (DBE): These are postulated events that a nuclear facility must be designed and built to withstand without loss to the systems, structures, and components necessary to ensure public health and safety. For seismic hazards, it is the SSE defined in Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants" [4] for existing plants and the GMRS defined in Regulatory Guide 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," [5] for new plants.

> Note - It is the site-specific earthquake severity and spectral shape (i.e., the GMRS) that governs the seismic-related design aspects of safety-related SSCs for a given nuclear power plant. The site-specific GMRS will likely be different than the design-related CSDRS; ideally, the former is intended to be bounded by the latter for almost all sites.

EPZ Earthquake: This is the site-specific ground motion used to determine the plant damage state for a dose consequence calculation performed to set a site EPZ boundary distance. It is expressed in terms of PGA and is defined as the spectral shape that is obtained when one scales the full CSDRS up from the CSDRS PGA to the EPZ earthquake PGA.

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[5] The rule addresses requirements for licensees to develop mitigation strategies for beyond-design-basis external events consistent with the intent of NRC Order EA-12-049, including strategies that apply for the reevaluated seismic and external flooding hazards at each site. Guidance for compliance with this rule is provided in Regulatory Guide 1.226 [9].

EPZ Seismic Scenario: The characterization of the plant damage state that is used to calculate an offsite dose. It consists of two parts: 1) the site-specific EPZ earthquake (PGA and spectral shape), and 2) the plant-specific list of SSCs that are assumed to have been failed by the earthquake.

Ground Motion Response Spectrum (GMRS): A risk-informed, performance-based earthquake severity and spectral shape for a specific nuclear power plant site based on RG 1.208, which provides guidance for implementing the requirements of 10 CFR 100.23(d)(1) using the methodology from ASCE 43-05, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities." It is expressed as the free-field horizontal and vertical ground motion response spectra at the plant site determined on the ground surface or on the uppermost competent material.

> Note – For a new plant at a given site, the GMRS serves as the seismic licensing basis (i.e., the SSE) for the plant. For existing plants, it serves only as an evaluation basis to assess how those plants might perform given this new knowledge about site seismicity.

High-Confidence of a Low-Probability of Failure (HCLPF): An approximation of the seismic acceleration level for which there is 95% confidence that there is less than a 5% probability of failure. It is the ground motion level (expressed as PGA) at which the probability of failure is at most 1%.

> Note – The HCLPF can apply to several different failure types (failure modes) of a specific SSC including structurally, functionally, seismic interactions between SSCs (II/I), and floods or fires induced by the event. The HCLPF can be applied in a PRA to analyze the performance of an SSC and the failure to prevent core damage or a release.

Peak Ground Accelerations (PGA): The free-field zero-period ground acceleration (in g) in the horizontal direction, which is taken to refer to the acceleration at 100 hz associated with a spectral shape, such as the GMRS or the CSDRS. It is typical in the nuclear industry to use this point on the response spectrum as an anchor for both the DBE (SSE) and the seismic event severities used in a seismic PRA.

Protective Action Guides (PAGs): Radiation dose guidelines established by the U.S. EPA that would trigger public safety measures, such as evacuation or staying inside, to safeguard public health after a radiation emergency has occurred. The PAGs help responders plan for and respond to radiation emergencies.

Safe Shutdown Earthquake (SSE): The maximum earthquake potential for which certain structures, systems, and components, important to safety, are designed to sustain and remain functional.

> Note – For the existing fleet of plants, the SSE was based on a deterministic assessment of the maximum credible earthquake for the site and a standard response spectral shape from RG 1.60. The RG did not consider regional seismicity characteristics. For new plants, the SSE is based on a probabilistic assessment performed in accordance with RG 1.208, which includes consideration of regional seismicity characteristics.

4 BACKGROUND

RG 1.242 provides the following guidance with respect to the selection of BDBEs to be used in an EPZ sizing analysis.

> “The applicant should determine the radiological releases from the facility that are evaluated in the radiological dose assessment to aid in the determination of the plume exposure pathway EPZ. In its safety analysis report, the applicant describes the licensing basis events relevant to the facility. The applicant should consider these licensing basis events as candidates for the development of the radiological releases. These licensing basis events may include both design-basis accidents and beyond-design basis events. Event likelihood may be used to determine whether the accident should be included in the range of accidents used in this analysis. For light-water reactor (LWR) power reactors, the licensing basis events should include the design-basis events, design-basis accidents, and beyond-design-basis events evaluated in Chapter 15, ‘Transient and Accident Analysis,’ and Chapter 19, ‘Severe Accidents,’ of NUREG-0800, ‘Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition.’ For non-LWRs, the applicant may opt to use the technology-inclusive, risk-informed, and performance-based methodology endorsed by Regulatory Guide 1.233, ‘Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors,’ to determine their licensing basis events.”

The guidance also states that “For the purposes of this discussion, licensing basis events are the entire collection of event sequences considered in the design and licensing basis of the facility. Further, “These licensing basis events may include both design-basis accidents and beyond-design basis events.” Finally, the guidance makes clear that “For beyond-design-basis-event scenarios, the applicant should evaluate the frequencies to allow quantitative consideration of the relative likelihood of a range of accidents,” and “The operation of structures, systems, and components according to their capability under the plant conditions for the event may be modeled in the evaluation of beyond-design-basis events.”

While there are still uncertainties, the physical processes leading to end states that result from internal events are relatively well understood and there is general agreement as to what the most severe end states entail. For external hazards, the situation is more complex. New plants will be required to be designed to meet or exceed the GMRS for a site, and so each vendor has specified a spectrum that they use for the purpose of the design (commonly called a CSDRS, but some vendors may use an alternative name for the same thing) to be used for the actual design, which is intended to envelope the GMRS at most (if not all) of the likely US sites for deployment of their technology. Therefore, to adhere to the guidance in RG 1.242, the radiological dose assessment for determining the size of an EPZ must consider a seismic event greater than the GMRS (i.e., a BDBE earthquake), which (depending on the site) may not exceed the CSDRS. However, the uncertainties with regard to plant response for such events are higher than for internal events[6] and must be considered when deciding how much beyond the GMRS the selected BDBE earthquake should be in order to meet the intent of the regulation. It should be noted that RG 1.242 does not require consideration of the highest severity event that can be hypothesized.

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[6] The larger the earthquake, the greater the uncertainty in the seismic demand placed on the SSCs. In addition, while the validated methods for calculating the response of structures to seismic accelerations can determine the way a building would fail up to a point, at very high accelerations these methods cannot accurately determine the full extent of building damage (e.g., total collapse, partial collapse (and end state), displacement, etc.) much less the specific damage that would occur to equipment inside the buildings).

5 SELECTION OF A BDBE EARTHQUAKE SEVERITY FOR EPZ SEISMIC SCENARIO DEVELOPMENT

While the new light water SMRs and non-LWRs (referred to as "other new technologies" by the NRC) will differ from existing plants in many ways, the results of the seismic probabilistic risk assessments (SPRAs) for currently operating power reactor facilities in the U.S. can be instructive in developing a risk-informed selection framework. Advanced reactor designs, which range from evolutions of LWR technology to completely different non-LWR technologies, employ various features to improve safety, including smaller cores, passive cooling, minimal safety-related electrical power requirements, better fuel performance, etc. These features serve to suppress the risk contribution (relative to the legacy plants) from moderate earthquakes that exceed the plant design basis, which are important to legacy plant seismic risk because of their dependence on safety and support systems with active components. However, when it comes to seismic analysis and the consideration of large earthquakes, the limiting features and concerns are similar to those for existing plants, e.g., failures of structures, piping, vessels, instrumentation and control panels/cabinets, instrumentation and control power, etc. Therefore, the SPRA results for the existing fleet can provide a sound technical basis for the development of a risk-informed framework for selecting an EPZ seismic scenario.[7] Properly formulated, basing the framework on the legacy plants' risk profile will encourage the reactor designers to suppress the contribution from earthquakes as much as possible since doing so would result in a smaller EPZ. The benefit from a public safety perspective is that demonstrating that PAGs are not exceeded for beyond design basis seismic events that are reasonably high relative to the site GMRS is much preferable to having a greater dependence on emergency response to assure the safety of the public.

The SPRAs reviewed during the preparation of this white paper were submitted by large LWR licensees to the NRC following the events at Fukushima Daiichi (i.e., in response to Near Term Task Force [NTTF] Recommendation 2.1). This paper does not suggest that the results of these SPRAs are directly representative of the seismic risk profiles of these newer plant designs, but rather that they can form the basis for a risk-informed framework that can then be applied to these new designs.

One way to look at the SPRA results is to consider the high confidence of low probability of failure (HCLPF) acceleration[8] for each plant/site; this is the earthquake acceleration at which there is a mean conditional probability of core damage of 0.01. Figure 5.1 plots the core damage HCLPF[9] PGA for each of the plants/sites that submitted post-Fukushima SPRAs to the NRC. In general, the HCLPF PGA values fall within a relatively narrow range of 0.15g to 0.40g, except for a few outliers in the 0.7g range.

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[7] As implied by the discussion, it is understood that the passive design features of advanced plants and the reduced dependence on active support system functions "suppress," but do not eliminate, the risk from seismic events at moderate accelerations that typically comes from failures of those support systems. However, at the high accelerations that are of most concern for selecting a seismic EPZ scenario the dominant contributors, which are structural failures, will be comparable for both existing and advanced plants. It is for these reasons that there are valid insights from seismic PRAs of existing plants that can inform the selection of a BDBE seismic event for EPZ planning.

[8] All of the earthquake accelerations in this paper are stated in terms of peak ground acceleration (PGA), with units of gravity or g's. As used in the nuclear industry, PGA is taken to mean the ground acceleration in the free field (i.e., away from structures that could influence the ground motion) in the horizontal direction at a vibratory frequency of 100 hertz (Hz).

[9] HCLPF is understood and used in different ways. Each SSC in the plant has a HCLPF (the earthquake acceleration associated with a 0.01 probability of the failure of the SSC to perform its function). The core damage (or plant level) HCLPF, which is what is used in this paper, is the earthquake acceleration associated with a 0.01 probability of failure to prevent core damage.

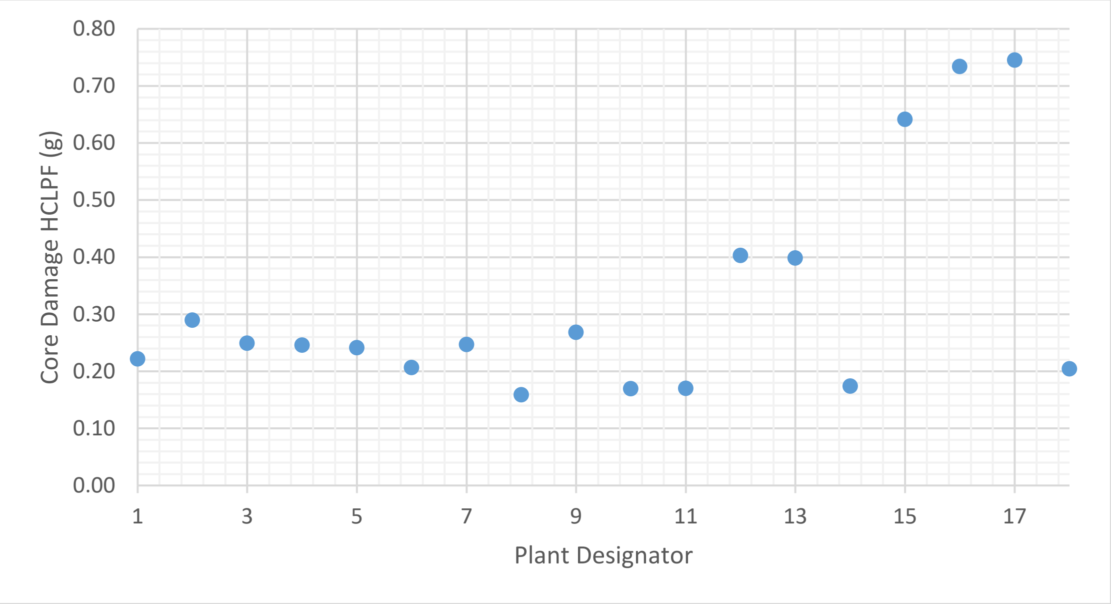

Figure 5.1: Core Damage HCLPF Accelerations for Selected Existing Plants

Another useful perspective is to consider the relationship between the plant core damage HCLPF PGA and the PGA of the largest earthquake for which the plant was designed (i.e., the design basis earthquake). The design basis earthquake for current nuclear power plants is the SSE. Using the SPRAs referred to above, Figure 5.2 plots 5.1) the SSE PGA for each plant/site (on the x-axis) versus 2) the ratio of the HCLPF PGA to the SSE PGA (on the y-axis).[10]

What this figure shows is that most of these plants have Core Damage HCLPF PGA margins up to about 2.5 times their design basis PGA. There is one two-unit site with an extremely high margin, but it is an outlier relative to the other plants. Focusing on the main body of data (i.e., the typical plants excluding the outlier), there is a slight trend downwards in the ratio as the design basis (i.e., the SSE) increases. This is to be expected given the rather narrow range of the HCLPF values. Moreover, it suggests that the plant HCLPF for these plants is somewhat insensitive to the design basis and that other factors, such as margin in the structural codes and standards, play a role in the HCLPF margin.

Using the SSE when looking at the margin for these existing plants is of limited value from a risk perspective, because the SSE for these plants was not developed in a probabilistic manner. The spectral shapes do not represent a uniform hazard response spectrum (UHRS) (i.e., in an UHRS all the points along the spectrum have the same annual frequency, which is not the case for the SSEs for the existing fleet). Furthermore, there is a wide variation in the annual frequency from site to site. For these reasons, it is not possible to conclude what the relative risk is based on the relationship of HCLPF to SSE alone.

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[10] There are 17 units in the data, representing both single unit and multi-unit sites. These are all the plants that submitted SPRAs with the exception of a single unit located on a deep soil site with extensive soil liquefaction issues that is not representative of the population for the purpose of developing risk insights.

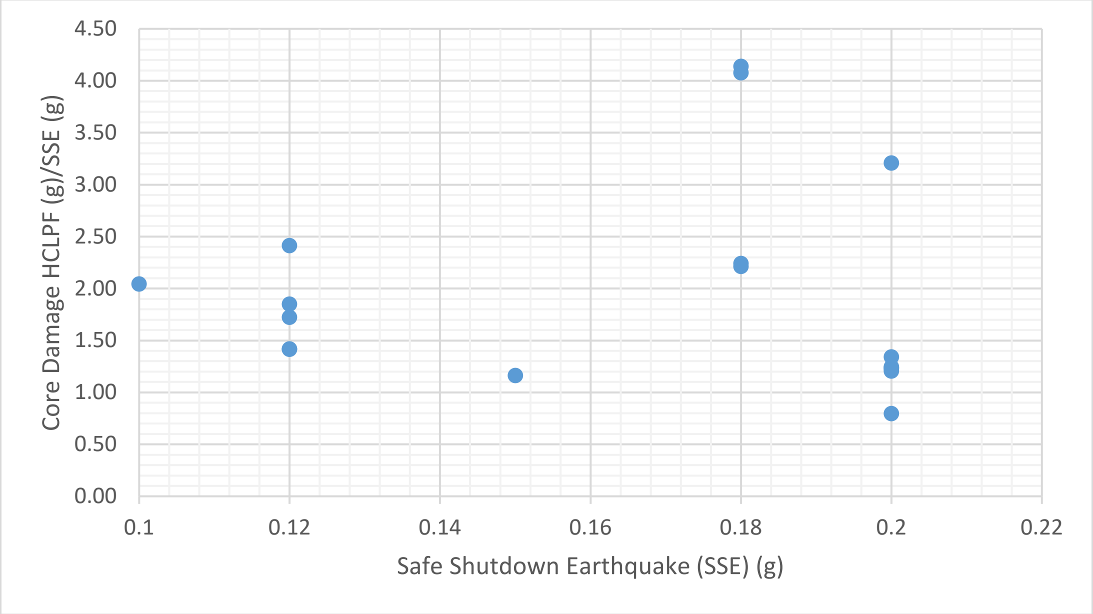

Figure 5.2: Ratio of Core Damage HCLPF to Plant SSE

As mentioned earlier, the SSE for a new plant will be the GMRS for the site. Although current plants were not designed to the GMRS for their respective sites, because this concept did not exist when their SSEs were determined, it is still instructive to consider the relationship of the plant HCLPF to the GMRS. The GMRS are uniform hazard response spectra and are defined to have an annual frequency in the range of 1E-5/yr to 1E-4/yr. Thus, if we use a multiple of the GMRS to relate it to the HCLPF value for a given plant site, we are using a BDBE earthquake that has a lower annual frequency and additional margin to core damage (a conditional core damage probability or CCDP of 0.01, which is the definition of the HCLPF). Stated another way, we are considering seismic scenarios (and their associated potential releases) that have frequencies on the order of 1E-6/yr or less.[11] While not providing sufficient information to fully rank the plants by relative risk, it does support the conclusion that plants with a higher HCLPF/GMRS ratio are likely to have lower seismic risk relative to the others.

Even though existing plants were not designed to a site-specific GMRS, the increased understanding of seismic hazards over time has resulted in plant modifications to address seismic vulnerabilities. All U.S. plants performed an Individual Plant Examination Program for External Events (IPEEE) in the 1990s, and numerous plants made upgrades to address seismic vulnerabilities. More recent retrospective looks conducted as part of post-Fukushima evaluations (e.g., ESEP, seismic MSA) have provided additional insights. The plants that have submitted SPRAs, the ones included in this study, have implemented changes to address the higher hazard associated with the current GMRS and reduce risk. So while these plants were not specifically designed to a site GMRS (their design basis is still the original SSE), their safety performance has been improved relative to the GMRS. Therefore, the results of these SPRAs can provide insights into their performance relative to a GMRS. Figure 5.3 plots a plant's GMRS PGA (on the x-axis) versus the ratio of the Core Damage HCLPF Acceleration of the plant to its associated GMRS PGA (on the y-axis).

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[11] For existing plants, all core damage accidents will lead to some release. It may not be early, and in fact may not be large, but it will be measurable. For some advanced plants, the definition of core damage as presently used will not apply, so ultimately for the EPZ scenario selection process the focus needs to be on release.

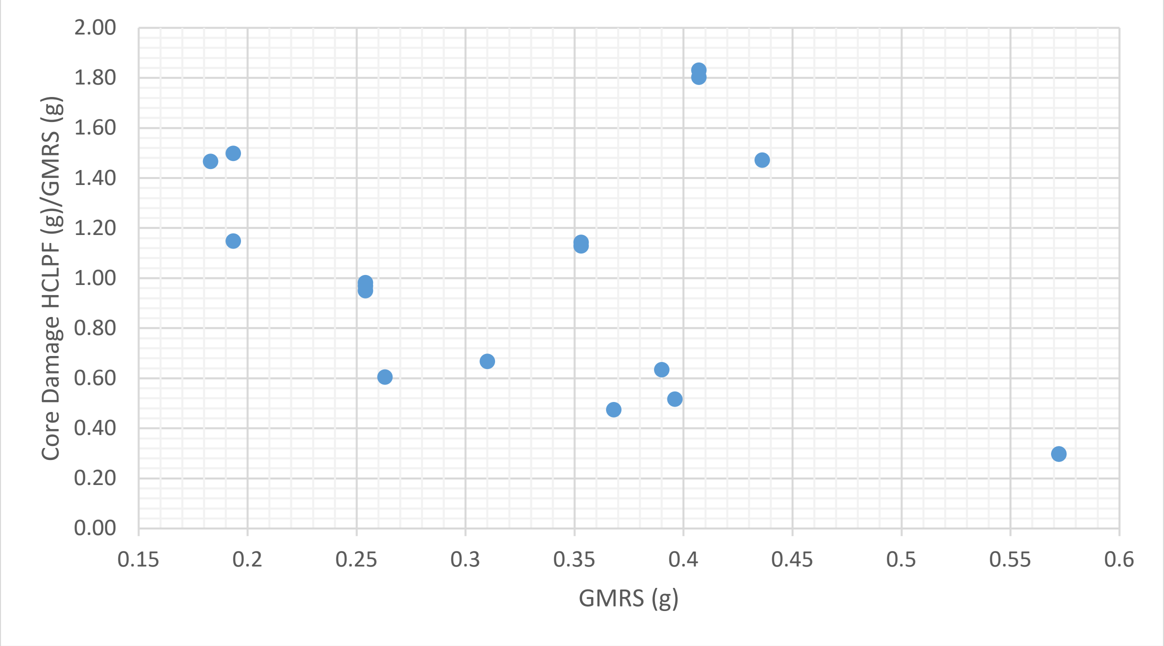

Figure 5.3: Ratio of Core Damage HCLPF to GMRS versus Site GMRS

As can be seen from this plot, these plants have HCLPF values ranging up to about 2 times the GMRS. While all of the plants have been determined to be safe by NRC, we again see a generally downward trend in the extent of margin as the GMRS increases. This is not particularly surprising given that these operating plants were not designed to the GMRS and the GMRS values for these sites are higher than the plant design bases (SSE).[12]

Again, it is not suggested that the newer plants would exhibit the same risk profile as these legacy plants. The HCLPF, whether it be a core damage HCLPF or a radiological release HLCPF, will be higher. The margin ratios will also be higher. It is expected that new plants, whether light-water SMRs or other new technologies, would have an even greater variation and would not display the same response behavior to seismic events as indicated in the analysis shown in Figure 5.3. As previously stated, while the contributors to risk at the very high earthquake levels would be similar for both legacy and new plants, the passive features of the new plants will suppress the risk contribution from beyond design basis seismic events that are reasonably high relative to the site GMRS earthquake levels and so somewhat skew the profile. Nonetheless, as noted above, the insights from this information should be considered when establishing a risk-informed framework for the selection of the seismic event to use in establishing the boundary of the EPZ.

Based on the above insights, it is proposed that an applicant for an SMR or other new technology reactor select the seismic event for their EPZ boundary analysis using a multiplier to the site-specific GMRS (i.e., an event severity some factor above the site-specific SSE). Using a factor rather than trying to select a risk level is helpful because while the GMRS is a uniform hazard response spectrum, the

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[12] This change in the understanding of seismic hazard is the reason for various additional evaluations required by NRC, going back to the IPEEE in the 1990s through the post-Fukushima Expedited Seismic Evaluation Program (ESEP), Seismic Mitigating Strategies Assessment (Seismic MSA). For the plants considered in this paper, the requirement to perform a Seismic Probabilistic Risk Assessment (SPRA) was imposed specifically because the GMRS was higher than the SSE at these sites. These programs allowed plants to identify potential seismic vulnerabilities relative to the new hazard information and to implement plant modifications to bring the plant design and operation up to a level commensurate with the new hazard.

GMRS from site-to-site does not have the same annual frequency. When determined in accordance with Regulatory Guide 1.208, the GMRS will vary from site-to-site but still fall in the 1E-4/year and 1E-5/year range. In proposing this approach, it is recognized that a reasonable upper bound cutoff is necessary; a proposed cutoff value is discussed below. Using an event selection framework based on insights from legacy plants should provide additional safety margin because of the reduction of the potential for release at moderate to high earthquake levels.

6 UPPER BOUND CUTOFF

As has been demonstrated many times in the past, extreme seismic events can have significant impacts on buildings and other structures throughout a wide area. This observation leads to another consideration when selecting an earthquake PGA for an EPZ sizing analysis – recognition of seismic-related performance limits for the facilities, systems, and equipment supporting emergency planning functions. During an extreme earthquake, some emergency response facilities, systems, and equipment will likely become unavailable prior to failures of plant safety SSCs, particularly those located offsite. This is also true for the local infrastructure needed to implement offsite emergency response plans (e.g., roads and bridges, local emergency operations centers, communications towers).

At the plant core damage HCLPF acceleration, where the conditional probability of core damage is 0.01, the conditional probability that emergency response capabilities would be significantly degraded is likely much higher. For example, the fragility of a regional power grid[13] is estimated in SPRAs to have a median failure acceleration of 0.3g (50% probability of failure at 0.3g). Using this information, it is possible to calculate the mean failure probability for the offsite power infrastructure. Table 6.1 shows the failure probability of offsite power as a function of earthquake severity.[14]

Table 6.1: Fragility of Offsite Power

Peak Ground Acceleration, g	Mean Probability of Failure of Offsite Power
0.2	2.3E-01
0.3	5.1E-01
0.4	7.1E-01
0.5	8.3E-01
0.6	9.0E-01
0.7	9.4E-01
0.8	9.7E-01
0.9	9.8E-01
1	9.9E-01
1.1	9.9E-01
1.2	9.9E-01
1.3	1.0

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[13] This is not referring to a loss of onsite AC power at the affected nuclear plant.

[14] From EPRI, Advanced Light Water Reactor Utility Requirements Document (ALWR URD) Volume III, Chapter 1 Appendix A: PRA Key Assumptions and Ground Rules, Revision 7. These values are based on the failure of ceramic insulators on large transformers and have been used in seismic PRAs for more than 20 years and have been generally accepted across the seismic PRA community and was confirmed in EPRI 3002015993 (2019) using earthquake experience data. When it comes to the loss of power over a large area, the probability would apply individually to the sites where transformers are located and not all sites would be affected equally. However, if the failure probability of each transformer site is 1.0, the failure of all is 1.0.

As can be seen in Table 6.1, at seismic accelerations exceeding about 0.7g the likelihood of a regional loss of all electric power is extremely high and at seismic accelerations exceeding 1.0g, there would essentially be a 100% probability that all electric power would be lost in the region around the plant.

To account for the above observations, it is proposed that the earthquake PGA used in an EPZ sizing analysis be subject to an upper bound cutoff of 1.0g. This is not to suggest that there is an emergency response failure “cliff” at 1.0g, a PGA beyond which response capabilities become nonfunctional. Rather, this cutoff reflects the fact that it becomes increasingly difficult to determine and assess the selection and level of effectiveness of pre-planned prompt protective measures at higher PGA levels. Given this uncertainty, what can be acknowledged is that a site’s pre-planned prompt protective measures for the public may not be the most suitable set of actions given the potential offsite conditions following a severe seismic event. In such situations, State and local emergency managers would need to assess the status of offsite emergency response capabilities and infrastructure as well as other competing response priorities (e.g., search and rescue in collapsed structures), and then determine ad hoc protective actions based on their knowledge and experience. For this reason, considering earthquakes beyond 1.0g when establishing the size of an EPZ and associated response measures will not meaningfully benefit emergency planning for a site. It is therefore concluded that a 1.0g PGA cutoff is a reasonable limit for the selection of a seismic event to use in an EPZ sizing determination

In addition to the 1.0g consideration above, it is important to account for uncertainties in the frequency of beyond design-basis earthquakes. To determine that the 1.0g earthquake is an appropriate upper bound cutoff, the applicant should confirm that the annual frequency of the 1.0g earthquake is low enough to provide assurance that the resultant EPZ seismic scenario damage state frequency meets the intent of NRC guidance. A discussion of the appropriate frequency range is provided in Section 13 of this paper. That section concludes that the frequency range of the EPZ earthquake will typically be between about 3E-05/yr and 1E-05/yr, so the use of a 1.0g cutoff for the EPZ earthquake would be considered appropriate if its mean frequency is less than 3E-05/yr. If 1.0g PGA earthquakes occurred with a mean frequency higher than 3E-5/yr at a given site, a PGA cutoff based on the 3E-5/yr earthquake should be used.

As stated previously in this section, this paper does not suggest that seismic PRAs for new plants would have the same HCLPFs or the same HCLPF ratios to their SSE/GMRS as legacy plants. Quite the contrary. It is expected that by virtue of their advanced safety features, new plants will have greater capacity and greater margins against large releases resulting from seismic events. What the paper suggests is:

- that there is a certain level of earthquake margin provided by the legacy plants that can be determined by looking at the seismic PRA results for these plants;
- that a conservative estimate of this level of earthquake margin can be ascertained by considering the seismic PRA results from the plants that were determined by NRC to have the highest potential for seismic risk; and
- that this provides a basis for a framework for selecting the EPZ earthquake that can be applied on a technology inclusive basis to any reactor type.

Taking all of the above information together, it is reasonable to propose that the BDBE earthquake selected to support an EPZ sizing determination should be two (2) times the site-specific GMRS or one with a 1.0g PGA and mean frequency less than 3E-05/yr, whichever is lower. In cases where the 1.0g

PGA earthquake frequency is higher than 3E-5/yr, a PGA cutoff should be based on an earthquake with a 3E-5/yr frequency.

7 DEFINITION OF SEISMIC SCENARIO FOR EPZ DOSE CALCULATION

Having established the earthquake of interest for the EPZ sizing analysis, it is now necessary to define the scenario that would be used for the radiological dose assessment. For example, to do this for each of the sites considered in this paper, we need to assume that the identified EPZ earthquake (represented by the listed PGA and associated spectral shape) occurs at the site and link that to failure of specific SSCs. One acceptable approach to selecting the SSCs assumed to fail is to implement the concept of Mitigating Strategies Assessment for New Seismic Hazard Information (i.e., the Seismic MSA, Appendix H of NEI 12-06 [3]). In such a framework, EP can be considered as one aspect of an overall mitigating strategy when there is insufficient mitigation by other means. That is, it is a layer of defense-in-depth that is applied within an area where it has been determined that emergency response is warranted due to the potential for an earthquake scenario[15] to lead to exposure above the PAGs in the absence of emergency response. Specifically, for the selected EPZ seismic scenario, EP would be considered as the mitigating strategy for the area within which the 1 REM total effective dose equivalent (TEDE) over 96 hours from the time of release of radioactive material would be exceeded in the absence of any emergency response, as identified in RG 1.242.

In the seismic MSA, a precedent was established that credit would be allowed for any SSC that had a $C_{10\%}$ seismic capacity value (10% probability of unacceptable performance under a BDB earthquake) at least as high as the reference earthquake. That is, an SSC with that capacity was considered to have adequate performance to mitigate the reference earthquake. Section H.5 of NEI 12-06 [3] states:

> *"The use of a 90% probability of success is equivalent to a 10% probability of unacceptable performance. This use of the 10% probability of unacceptable performance has been used in the past as a criteria for demonstrating seismic adequacy for beyond design basis seismic performance reviews in standards such as ASCE 43-05 and in commercial criteria such as ATC-63".*

In the case of the EPZ seismic scenario, the BDB earthquake that would be used for this assessment is the one defined earlier in this paper (that is, the spectral shape that is obtained when the GMRS PGA is increased by a factor of 2 and the CSDRS spectral shape is maintained). The plant damage state to be used for the dose calculation should be that all SSCs whose $C_{10\%}$ is less than that earthquake, when evaluated in accordance with the guidance in Section H.5 of NEI 12-06, would be considered to have failed at the time of the earthquake ("T=0") in the way that would result in the highest calculated dose. That is, if there is a 10% chance of failure, the assumption would be that the SSC fails (probability 1.0). The actual calculation of the $C_{10\%}$ would be based on the CSDRS spectral shape scaled up to the EPZ earthquake PGA. Since the CSDRS spectral shapes are intended to bound the population of spectral shapes of the GMRS at sites in the US, the use of the scaled CSDRS spectral shapes for the calculation of the $C_{10\%}$ will assure (with margin) that they are greater than the $C_{10\%}$ that would be calculated using a scaled GMRS spectral shape.[16] All other SSCs (i.e., $C_{10\%}$ greater than the EPZ earthquake) would be considered to be capable of performing their functions. This criterion could be applied to all SSCs in the

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[15] It is understood that this does not apply only to earthquakes, but to all hazards. As this paper is focused on defining the scenario to be selected for the occurrence of an earthquake, this statement has been worded to emphasize that point.

[16] While the use of the scaled CSDRS is conservative relative to using the scaled GMRS, it simplifies the analysis since the reactor vendor will have used the CSDRS to perform the seismic margin analysis for the design and so it will avoid the necessity to develop site-specific foundation input response spectra and recalculate all of the SSC fragilities for determination of the EPZ scenario.

plant, regardless of their class designation (i.e., safety system, DID/RTNSS system, or non-safety system).[17]

Notably, the EPZ earthquake is significantly higher than the GMRS design basis (as shown in Table 13.1). When looking at large earthquakes, the dominant contributors to release will be similar for both existing plants and new plants because the limiting failure leading to release will be those structural failures that lead directly to a release. This is due to the use of the same structural codes and standards for the design of both existing and new plants. So, while existing plant seismic CDFs are dominated by system failures (in particular, support systems) that will not exist in advanced plants, the dominant release scenarios are more similar.

8 APPROACH TO CALCULATION OF $C_{10\%}$

To ensure that the determination of seismic-related failures is performed in a manner consistent with past practice, the method for the calculation of $C_{10\%}$ applies the guidance found in Appendix H of NEI 12-06.[18] This method follows the approach for a seismic margins analysis in accordance with EPRI-6041 SL Rev. 1 [7]. The method, as described in detail in Appendix H of NEI 12-06, can be summarized as follows:

- The scaled CSDRS will be the spectral shape used to evaluate the performance of the SSCs.
- The SSC capacity calculation will use design specific information.
- The $C_{10\%}$ can be calculated by:
    - Using the recommended values for β_C, β_R, β_U, the ratio of the median capacity $C_{50\%}$ to the $C_{1\%}$ capacity, and the ratio of the $C_{10\%}$ capacity to the $C_{1\%}$ capacity provided in Table H.1 of NEI 12-06, which are taken from EPRI 1025287 [8].
    - Calculating the $C_{1\%}$ capacity using the methods documented in past SPRA and seismic margin documentation and as summarized in EPRI 1025287.
    - Multiplying the $C_{1\%}$ capacity by the $C_{10\%}/C_{1\%}$ ratio based on the type of SSC being evaluated.
- Verify whether or not the $C_{10\%}$ capacity exceeds the scaled CSDRS demand.

9 CONSIDERATION OF RANDOM FAILURES AND OPERATOR ERRORS

In the case of this analysis, a “pass-fail” criterion is used for seismic failure where anything with a probability of failure greater than 0.1 is assumed to have failed. Using the same criterion for random failures and operator errors, and with the knowledge from the many PRAs that have been performed, it can be expected that no random failures or operator errors would have a failure probability greater than 0.1 and thus it would be justified to ignore such failures in the EPZ seismic scenario. However, given that there could be significant uncertainty in human error probabilities, it will be assumed that no operator actions will be successful in the first 24 hours following the earthquake unless a human reliability

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[17] This is consistent with how SSCs are handled in a seismic PRA. Any SSC, regardless of designation, can be subjected to a fragility analysis to determine the probability of failure as a function of earthquake severity and that probability credited in the PRA model. This includes both permanently installed and portable/mobile equipment (e.g., equipment required by 10 CFR 50.155(b)).

[18] This guidance is endorsed by the NRC in Regulatory Guide 1.226.

analysis is performed that shows that the HEP is below 0.1.

10 SENSITIVITY ANALYSIS TO CHECK FOR CLIFF EDGE EFFECT

The NRC guidance also recommends that a sensitivity analysis be performed to check for a “cliff edge effect.” Such effects have not generally been seen in seismic assessments and PRAs, as the risk and consequences tend to increase smoothly as earthquake severity increases (unlike, for example, external flood where a small increase in flood level can go from no impact to significant flooding due to overtopping flood barriers). It is therefore adequate to perform a simple sensitivity analysis to show that this is the case for the EPZ seismic scenario. To do this, the failure of any SSCs whose $C_{10\%}$ is less than the 84th percentile hazard at the return interval for EPZ earthquake on the mean hazard curve should be added to the EPZ seismic scenario, and a determination made as to whether the damage state of the plant is greatly altered (relative to the size of a potential release). This assessment is adequate to serve the function of the recommended sensitivity analysis. An example for a site with a GMRS of 0.3g is provided in Figure 10.1.[19] As a check to make sure that an adequate cliff-edge will be applied, in the rare case where the 84th percentile hazard at the return interval for the EPZ earthquake is less than 10% higher than the EPZ earthquake, a value 10% higher than the EPZ earthquake will be used for the sensitivity analysis.

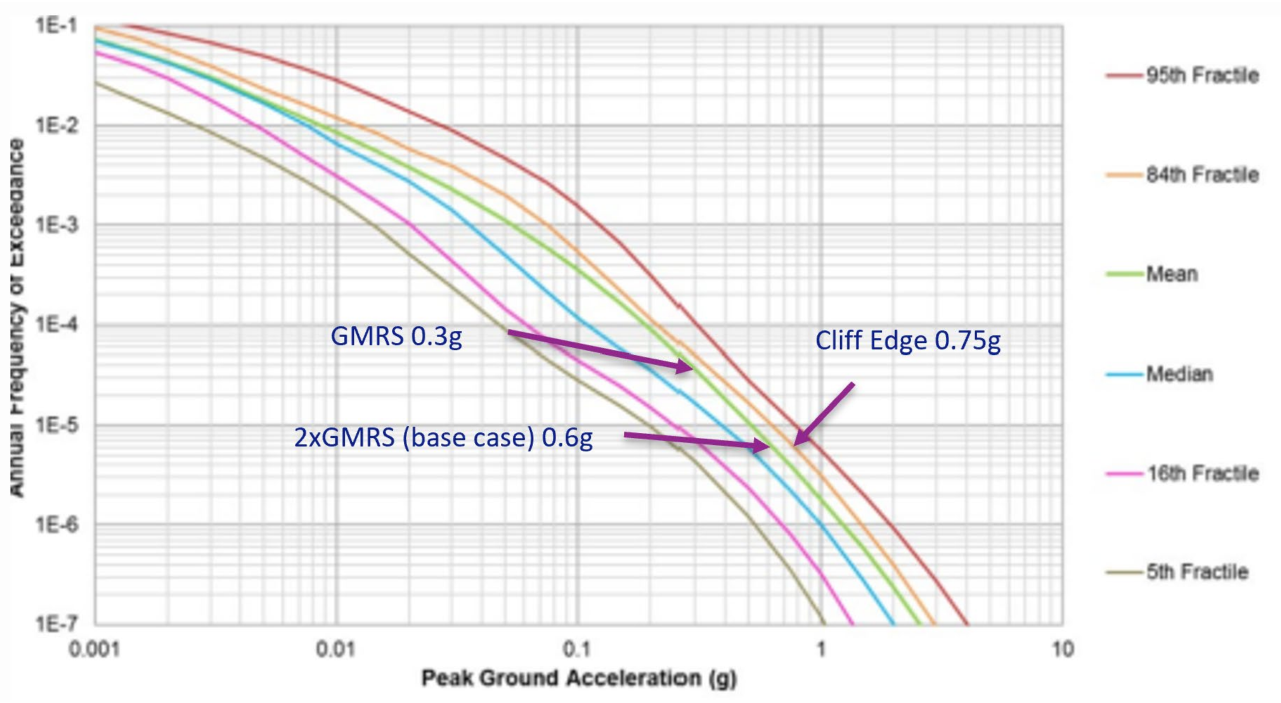

Figure 10.1: Example of Selecting the Cliff Edge Earthquake

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[19] Example: The example site for this illustration has a GMRS of 0.3g. So, for this site the EPZ earthquake is 2 x GMRS, or 0.6g. The return interval at 2 x GMRS on the mean hazard curve is 6E-6/yr. For a return interval of 6E-6/yr on the 84th percentile hazard curve, the PGA is 0.75g. The EPZ earthquake is a spectral shape anchored to a PGA of 0.6g and the $C_{10\%}$ for an SSC is calculated to be a PGA of 0.7g for that spectral shape. In the baseline plant damage state, that SSC is assumed to be undamaged. In the cliff edge sensitivity, it is assumed to be failed.

11 CONSEQUENCE CALCULATION

The dose consequence calculation consists of two parts:

- Source term
- Atmospheric dispersion and transport

The source term would be a plant design-specific calculation assuming the plant damage state defined by the seismic scenario. That is, the ground motion associated with the scaled CSDRS has occurred, the SSCs with $C_{10\%}$ less than the scaled CSDRS have failed, and no operator actions occur in the first 24 hours. The source term is then determined in accordance with the NRC-approved methods, approaches, and data. This paper does not suggest that there be any deviations from this guidance.

Similarly, the atmospheric dispersion and transport analysis would be conducted in accordance with standard practice.

The result of this calculation would be compared to the PAG of 1 REM in the first 96 hours. Specifically, the distance from the point of release to the point where the dose would exceed 1 REM in 96 hours would be identified. Note that the 96-hour timeframe is from the time of the release (not from the time of the earthquake), so the source term calculation would first need to determine, given the plant damage state, when the release would occur. The dose consequence calculation would start the 96 hour "clock" from that point.[20] In addition, the insights from the calculation (e.g., release timing) would be used to identify areas where pre-determined, prompt protective measures are necessary.

12 EXAMPLE

In order to better illustrate how the analysis would be performed, an example is provided here. This is based on an actual advanced SMR design. The specific names of components and systems have been made generic so as to prevent disclosure of protected proprietary information. The example works through the steps for defining a plant damage scenario to support EPZ sizing are as follows:

- Step 1: Determine the fragility parameters for the SSCs that perform the safety functions that would be credited for a seismic event (i.e, A_m, β_r, β_u).
- Step 2: Determine the GMRS for the site being considered, in accordance with the requirements of NRC Regulatory Guide 1.208 [5].
- Step 3: Calculate the $_{C10\%}$ for each of the SSCs from Step 1, using the GMRS from Step 2, in accordance with the Appendix H of NEI 12-06 [3]. Compare the $C_{10\%}$ for the SSCs to 2xGMRS and prepare a table of failures and a table of successes. See Table 12.1 for a list of seismic fragility failures for the example designs at an example site that has a GMRS of 0.25g and a 2 x GMRS of 0.5g. Table 12.1 shows the seismic fragility groups with $C_{10\%}$ less than 2 x GMRS of 0.5g that are assumed failed for the example scenario definition. As can be seen, for the example design 36 fragility groups would be considered failed. Table 12.2 shows the seismic fragility groups with

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[20] This prevents the possibility of screening out a seismic scenario with a significant release simply because the release does not occur within 96 hours of the earthquake.

$C_{10\%}$ greater than 2 x GMRS of 0.5g that are assumed available for the example scenario definition. As can be seen, for the example design 14 fragility groups would be considered successful.

- Step 4: Based on the tables of failure and successes, identify the functional failures and successes that define the plant damage states:
  - This combination of failures and successes for the example plant can be summarized as follows:
    - Damage to all buildings except the reactor building (SFR_nnn, SFR_nnn, etc)
    - Degraded reactivity control (SFR_nnn, SFR_nnn, etc)
    - Loss of all AC and DC power (SFR_nnn, SFR_nnn, etc)
    - Loss of normal reactor cooling (SFR_nnn, SFR_nnn, etc)
    - Loss of HVAC (SFR_nnn, SFR_nnn, etc)
    - Loss of spent fuel cooling (SFR_nnn, SFR_nnn, etc)
    - Primary piping failures (SFR_nnn, SFR_nnn, etc)
    - Passive air cooling degraded (SFR_nnn, SFR_nnn, etc)
    - Reactor building isolation success (SFR_nnn, SFR_nnn, etc)
  - As indicated, for each functional failure or success, the specific fragility groups that contributed to the conclusion would be identified.

- Step 5: Based on the defined plant damage state (functional failures and success), develop the source term in accordance with the guidance in NEI 24-05. This would be performed by utilizing the plant-specific source term code model. To determine the source term, all of the SSCs associated with the lost functions (i.e., those listed in Table 12.1) would be set to “unavailable” in the source term code and all of the SSCs associated with the successful functions (i.e., those listed in Table 12.2) would be set to “available” in the source term code. In addition, if there were any possible human actions associated with the successful SSCs, these would also be considered to fail for the first 24 hours. This did not affect the example plant because there are no credited human actions in the first 24 hours.

- Step 6: Based on the source term, perform a consequence calculation for the specified site in accordance with the guidance in NEI 24-05 using the site-specific consequence model.

- Step 7: Based on the consequence calculation for the specified site, determine the distance to 1 Rem over 96 hours. A summary of the results for the example plant at the example site is shown in Table 12.3. As can be seen from the Table, the input from the seismic scenario to the decision on EPZ distance is that the distance from the reactor building would be between 25 and 100 meters (if the mean is used) or between 100 and 200 meters (if the 95th %-tile is used). Note that this is only one input into the NEI 24-05 process. In accordance with that process, the dose consequences would also need to be calculated for the scenarios from other (i.e., non-seismic) hazard groups

- Step 8: Perform the cliff-edge check as discussed in Section 10. For example, if the 84th %-tile pga at the return period for the 2xGMRS (0.5g as mentioned in Step 3) was 0.7 g, then Table 12.2 would lose the success of fragility group SFR_126, and it would be added to Table 12.1 as an additional failure. Steps 4-7 would be repeated accounting for this change and the dose consequence results would be compared to determine if there was a cliff edge.

Table 12.1: List of Seismic Fragility Failures for Example Scenario Definition

Fragility Group Code	$C_{10\%}$ (g)	Fragility Group Code	$C_{10\%}$ (g)	Fragility Group Code	$C_{10\%}$ (g)
SFR_112	0.06	SFR_103	0.18	SFR_124	0.24
SFR_128	0.06	SFR_111	0.18	SFR_125	0.24
SFR_135	0.06	SFR_113	0.18	SFR_134	0.24
SFR_136	0.06	SFR_114	0.18	SFR_145	0.24
SFR_137	0.06	SFR_115	0.18	SFR_102	0.30
SFR_139	0.06	SFR_116	0.18	SFR_106	0.30
SFR_140	0.06	SFR_122	0.18	SFR_107	0.30
SFR_147	0.06	SFR_138	0.18	SFR_109	0.30
SFR_149	0.06	SFR_104	0.24	SFR_110	0.30
SFR_121	0.12	SFR_118	0.24	SFR_123	0.30
SFR_144	0.12	SFR_119	0.24	SFR_127	0.30
SFR_101	0.18	SFR_120	0.24	SFR_143	0.30

Table 12.2: List of Seismic Fragility Successes for Example Scenario Definition

Fragility Group Code	$C_{10\%}$ (g)	Fragility Group Code	$C_{10\%}$ (g)	Fragility Group Code	$C_{10\%}$ (g)
SFR_126	0.60	SFR_130	1.49	SFR_133	1.79
SFR_146	0.90	SFR_141	1.49	SFR_142	1.79
SFR_150	1.20	SFR_105	1.79	SFR_131	2.99
SFR_117	1.49	SFR_108	1.79	SFR_148	2.99
SFR_129	1.49	SFR_132	1.79		

Table 12.3: Approximate Consequence Results for Example Seismic Scenario

Distance (m)	96-Hour TEDE (REM)		96 Hour Acute Bone Marrow (REM)	
	Mean	95th %-tile	Mean	95th %-tile
25	9	23	4.5	12
100	0.7	1.6	0.4	0.9
200	0.2	0.4	0.1	0.2
300	0.1	0.2	0.05	0.1
400	0.04	0.14	0.04	0.08
500	0.01	0.1	0.03	0.05

13 RISK-INFORMED INSIGHTS AND COMPARISON WITH NUREG-0396

Having proposed approaches for selecting the EPZ earthquake and developing the associated plant damage scenario, it is prudent to check the validity of this framework by considering the results it would produce for a new facility located at one of the existing sites that submitted an SPRA (those discussed above). In other words, determine whether the combination of using a response spectrum anchored to a PGA of two times the GMRS PGA (capped at the site-specific upper limit value determined per Section 6), with a failure criterion of $C_{10\%}$, results in a frequency of the EPZ seismic scenario at those sites that compares favorably to NRC guidance. This needs to be considered in a technology-inclusive context, i.e., that the approach proposed in this paper would comply with that guidance regardless of the technology or design being considered.

The key to this comparison is the following statement from NRC guidance [Reference 2, Section A-3.7].

> “The likelihood of exceeding a TEDE of 10 mSv (1 rem) at the proposed EPZ boundary should be consistent with the evaluation in Appendix I to NUREG-0396, which provides relative probabilities of exceeding certain critical doses as a function of distance from the facility for a spectrum of severe accidents. For example, NUREG-0396 examined the conditional probability of exceeding a variety of dose levels of interest, given a core melt accident with a stated frequency of $5x10^{-5}$ per reactor year.”

Therefore, the framework needs to assure that the EPZ scenario that will be used for the dose consequence calculation will have a frequency of less than the stated value. Using the framework and applying it to a selection of potential sites, it is possible to develop additional risk-informed insights about the selected EPZ seismic scenario. Using the information previously presented, this can be accomplished using the sites considered in this paper as examples. First, Table 13.1 considers the frequencies of the GMRS and the EPZ earthquakes for each of the sites evaluated in this paper.

The calculated exceedance frequencies tend to be somewhat higher than would be expected from the observed slopes of the curves because they were developed using linear interpolation between points on the hazard curves provided in the plants’ submittals to the NRC, and the hazard curves are not linear. Taking that into consideration, it is noted that the exceedance frequencies for the GMRS at each site range between 1E-4/yr and 4E-5/yr[21] but are not the same across all sites, which is expected given the approach specified in RG 1.208. As previously discussed, because RG 1.208 is risk-informed and not risk-based, the approach described therein will not result in the same exceedance frequency from site to site. The implications of this are discussed further later in this section.

As also discussed above, the recommended framework for selecting the earthquake is not based on a specific annual frequency; rather, it is based on a multiple of the GMRS PGA (a margin on the site-specific SSE). This addresses the fact that the GMRS does not always have the same annual frequency from site to site, and also that the hazard curves do not have the same slope from site to site. Applying the recommended earthquake selection approach discussed above yields exceedance frequencies for the EPZ earthquakes (i.e., 2 times GMRS) between approximately 3E-5/yr and 9E-6/yr,[22] so even before consideration of any failures the earthquake itself is already below the frequency cited in the guidance.

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[21] The GMRS PGA is shown in the second column of Table 13.1 and the associated frequency in the third column.

[22] The EPZ earthquake (i.e., 2 times GMRS earthquake or capped as discussed in Section 6; for this example we are assuming that the required study justified a cap at 1.0g) is shown in the third column of Table 13.1 and the associated frequency in the fourth column.

In the scenario definition framework, the scenario assumes failure of any SSC with a probability of failure at the EPZ earthquake of 0.1 or greater ($C_{10\%}$ > EPZ earthquake). Thus, it can be inferred that the conditional probability of that plant state is no greater than 0.1, since it is likely that more than one such failure is required to result in a release condition and that at least one of them will have a failure probability quite close to 0.1. Consequently, the EPZ seismic scenario using this framework is less than somewhere between 3E-6/yr and 9E-7/yr.[23]

The results discussed above are summarized in Table 13.1.

Table 13.1: GMRS, EPZ Earthquake & EPZ Scenario Frequencies

Plant	GMRS (PGA)	GMRS Earthquake Exceedance Frequency (/year)	EPZ Earthquake (PGA)	EPZ Earthquake Exceedance Frequency (/year)	EPZ Seismic Scenario Frequency (year)
A	0.19	1.1E-04	0.38	2.3E-05	<2.3E-06
B	0.25	6.4E-05	0.50	1.1E-05	<1.1E-06
C	0.31	4.4E-05	0.61	1.4E-05	<1.4E-06
D	0.39	6.8E-05	0.78	9.7E-06	<9.7E-07
E	0.26	6.0E-05	0.52	1.0E-05	<1.0E-06
F	0.18	8.7E-05	0.36	2.8E-05	<2.8E-06
G	0.57	4.9E-05	1.0	1.4E-05	<1.4E-06
H	0.37	5.6E-05	0.74	1.1E-05	<1.1E-06
I	0.44	1.3E-04	0.88	9.1E-06	<9.1E-07
J	0.41	7.3E-05	0.82	1.6E-05	<1.6E-06
K	0.4	5.3E-05	0.80	1.2E-05	<1.2E-06

In the framework recommended in this paper, the EPZ seismic scenarios that would be considered would be at least an order of magnitude below 5x10-5 per reactor year. The only difference is that these scenarios would not necessarily be “core melt accidents” since core melt may not be an appropriate end state for the reactor type. It would, however, represent a BDB accident state with frequency of approximately 3E-6/yr or less.

It is recognized that the EPZ seismic scenario would not represent the same risk level (i.e., the same release frequency or release characteristics) from site-to-site. It is not reasonable to equalize risk levels since it is not clear how this would be performed in the absence of a full SPRA. Further, the approach proposed in this paper is based on demonstrating adequate margin to a risk target rather than determining an absolute risk value. The earthquake hazard differs from site-to-site, and there is also some variation in the exceedance frequency of the GMRS and (because of differences in the slope of the hazard curve) some variation in the exceedance frequency of a ground motion of two times the GMRS. In addition, the conditional probability of a release given the occurrence of that ground motion will also

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[23] If the EPZ earthquake is in the range 3E-5/yr and 9E-6/yr, and the conditional probability of the EPZ scenario given that earthquake is no more than 0.1, then the frequency of the EPZ scenario will be in the range of 3E-6/yr and 9E-7 or less.

vary based on the specific plant design as it relates to that ground motion. Until the SSC $C_{10\%}$ values are determined, the number of SSC failures that will be assumed in the plant damage state is unknown. Even for the same design this may vary from site-to-site due to differences in the site-specific ground motion. While there is high confidence that there will be enough SSC failures to assure a conditional release probability of at least 0.1, there could be enough failures assumed that it could be additional orders of magnitude below that. That is why the focus of this approach is to use a damage state whose frequency will be below the target, with margin. As noted, the far-right column of Table 13.1 demonstrates that this will be achieved by the proposed approach.

This supports the conclusion that the simplified approach of using two times the GMRS and $C_{10\%}$ as the basis for defining the two parts required for establishing the basis of the dose consequence calculation is reasonable. Certainly, it could also have been said to use the same exceedance frequency for the ground motion at each site, but this just makes the hazard analysis more complex since a site-specific UHRS would specifically need to be developed for that frequency rather than just scaling the GMRS. Also, the SSC failure criterion could be set at the HCLPF ($C_{1\%}$) but lowering the conditional probability of release by at least another order of magnitude (and possibly much more) is not warranted as the target is already met with margin. Furthermore, neither of these would result in the EPZ scenario having the same frequency for all designs at all sites, for the reasons discussed above. What is important is that using this approach will ensure that whatever the release frequency is for the EPZ scenario, it will be low enough.

The values above are based on mean hazard frequency. NRC guidance recommends that uncertainty also be considered. Table 13.2 evaluates the possible effects of considering uncertainty of the frequency estimates of the proposed EPZ earthquakes.

Table 13.2: 84%-tile and 95%-tile EPZ Earthquake Frequencies

Plant	EPZ Earthquake	84%-tile EPZ Earthquake Exceedance Frequency (/year)	84%-tile EPZ Seismic Scenario Frequency (/year)	95%-tile EPZ Earthquake Exceedance Frequency (/year)[24]	95%-tile EPZ Seismic Scenario Frequency (/year)
A	0.38	3.8E-05	<3.8E-06	7.4E-05	<7.4E-06
B	0.50	1.7E-05	<1.7E-06	2.8E-05	<2.8E-06
C	0.61	2.9E-05	<2.9E-06	3.7E-05	<3.7E-06
D	0.78	1.4E-05	<1.4E-06	4.0E-05	<4.0E-06
E	0.52	1.7E-05	<1.7E-06	n/a	n/a
F	0.36	4.3E-05	<4.3E-06	8.7E-05	<8.7E-06
G	1.0	2.2E-05	<2.2E-06	n/a	n/a
H	0.74	1.8E-05	<1.8E-06	n/a	n/a
I	0.88	1.3E-05	<1.3E-06	n/a	n/a
J	0.82	2.8E-05	<2.8E-06	n/a	n/a

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[24] About half of the plants did not report 95%-tile frequencies with their hazard submittals to USNRC. However, the plants that did report it provide an adequate distribution to provide the necessary insights.

Plant	EPZ Earthquake	84%-tile EPZ Earthquake Exceedance Frequency (/year)	84%-tile EPZ Seismic Scenario Frequency (/year)	95%-tile EPZ Earthquake Exceedance Frequency (/year)[24]	95%-tile EPZ Seismic Scenario Frequency (/year)
K	0.80	1.8E-05	<1.8E-05	3.5E-05	<3.5E-06

As can be seen from Table 13.2, the 84%-tile frequencies range from about 1E-5/yr to 4E-5/yr, and the 95%-tile frequencies range from about 3E-5/yr to 9E-5/yr. As discussed previously, the associated scenario frequencies would be about an order of magnitude lower. Therefore, even when uncertainty is considered, the EPZ seismic scenario (again considering that the CCDP would be less than 0.1), would still be below the 5E-5 per reactor year value cited in Appendix I to NUREG-0396. What this final check shows is that the proposed framework essentially guarantees that the seismic scenario used for the EPZ dose consequence calculation will have a frequency below the target value even when uncertainty is considered and thus the radius of the EPZ resulting from the consequence calculation will meet the intent of the RG.

The above insights support a conclusion that the risk-informed framework described in this paper for selecting a seismic scenario to use in determining an EPZ is consistent with the guidance in RG 1.242 and the foundational principles in NUREG-0396.

14 MAINTENANCE OF PERFORMANCE

The process described above is subject to the guidance for maintenance of performance in Section 5.1 of NEI 24-05 [10], which states:

> "Since there is the possibility of substantive changes to the PRA and LBEs over the lifetime of a facility, changes to the plant PRA must be tracked to evaluate their impact on the PEP EPZ determination and emergency plan."

The details of this guidance are contained in the cited section.

15 SUMMARY AND CONCLUSIONS

There is no single equation, formula or algorithm that incorporates all the information discussed above. Rather, the information was considered holistically and informed by professional judgement to select the earthquake severity to use in the radiological consequence analysis supporting an EPZ sizing evaluation. As discussed above, a value of two (2) times the GMRS would provide a reasonable basis for selecting the BDBE earthquake PGA to support the development of a seismic scenario. The information presented above supports this conclusion for the legacy plants, and by applying this same framework for the newer plants with their lower seismic risk profile, the overall effect will be to define an EPZ that affords a greater level of protection than that for the legacy plants, thus supporting the goal that while the legacy plants are (as has been stated numerous times by the Commissioners) safe, new generation plants should have the goal of being safer.

The overall conclusions of this paper can be expressed as follows:

- The review of existing SPRAs for legacy plants provided adequate insights to develop a risk-informed framework that can be used by a new power reactor facility to support the determination of the EPZ boundary location.

- Although the seismic risk profiles of new reactors are different than the existing fleet, the SPRAs were from plants that the NRC had assessed as having the highest risk from a seismic perspective, so the framework likely bounds the understanding of what constitutes an adequate EPZ size.

- Consistent with the guidance in RG 1.242, Appendix A, the framework ensures that the seismic event used for the EPZ sizing determination will be a BDBE.

- Consistent with the guidance in RG 1.242, Appendix A, and Appendix I to NUREG-0396, the framework also ensures that the frequency of the EPZ sizing scenario used for the radiological dose assessment will be below the 5x10-5 per reactor year goal, likely by an order of magnitude or more, even when uncertainty is considered.

- The framework ensures that a “cliff edge effect” assessment is performed.

- The framework applies a multiplier of 2 to the site seismic design basis (the GMRS) so as to enable a straightforward and early establishment of the EPZ sizing earthquake; applicants will not have to wait for completion of a site-specific SPRA.

- The framework establishes an approach for determining a site-specific upper bound PGA for the size of the seismic event in order to realistically account for the effects of a severe earthquake on area infrastructure and emergency response resources, thus ensuring that the planning basis is not premised on impractical response measures.

- The framework avoids dependence on the highly uncertain tails of the hazard curves where the risk-informed insights are much more questionable.

- The framework incentivizes reactor vendors to push high consequence seismic scenarios well out beyond the design basis since this will lead to a smaller EPZ. This benefits public safety as well as environmental protection by moving the focus more away from dealing with severe accidents and to preventing severe accidents.

16 REFERENCES

[1] NUREG-0396, “Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants”, December 1978.

[2] Regulatory Guide 1.242, “Performance-Based Emergency Preparedness for Small Modular Reactors, Non-Light-Water Reactors, and Non-Power Production or Utilization Facilities”, Revision 0, December 2021.

[3] NEI 12-06, “Diverse and Flexible Coping Strategies (FLEX) Implementation Guide, Revision 4, December 2016.

[4] Regulatory Guide 1.60, “Design Response Spectra for Seismic Design of Nuclear Power Plants,” Revision 2, July 2014.

[5] Regulatory Guide 1.208, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion”, Revision 0, March 2007.

[6] NUREG-1935, State-of-the-Art Reactor Consequence Analyses (SOARCA) Report, November 2012.

[7] EPRI NP-6041-SL Revision 1, “A Methodology for Assessment of Nuclear Plant Seismic Margin, Revision 1”, Palo Alto, CA, August 1991.

[8] EPRI 1025287, “Seismic Evaluation Guidance: Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic”, Palo Alto, CA, November 2012.

[9] Regulatory Guide 1.226, “Flexible Mitigation Strategies for Beyond-Design-Basis Events,” Revision 0, June 2019.

[10] NEI 24-05, “An Approach for Risk-Informed Performance-Based Emergency Planning,” Revision 0, June 2024