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INSIGHTS GAINED FROM SEISMIC PROBABILISTIC RISK ASSESSMENTS FOR OPERATING U.S. NUCLEAR POWER PLANT SITES[a]

Shilp Vasavada[1], De (Wesley) Wu[2], Michael Franovich[3], and Sujit Samaddar[4]

[1] Senior Reliability and Risk Analyst, Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission, Rockville, MD, USA (Shilp.Vasavada@nrc.gov)
[2] Reliability and Risk Analyst, Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission, Rockville, MD, USA
[3] Director, Division of Risk Assessment, Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission, Rockville, MD, USA
[4] NRC Staff

ABSTRACT

As part of the U.S. Nuclear Regulatory Commission's (NRC's) post-Fukushima activities, certain licensees performed contemporary seismic probabilistic risk assessments (SPRAs) for their sites. Information about and insights from these SPRAs were used by the NRC staff to determine the appropriate plant-specific regulatory response. The licensees performing SPRAs covered a range of primary and secondary seismic hazards as well as plant designs. Based on its reviews, the NRC staff gained valuable insights about the impact of seismic risk at operating nuclear power plants in the U.S.

The aim of this paper is to describe these insights. This paper will: (1) discuss dominant risk contributors and most frequent risk contributors based on the results of the SPRAs; (2) demonstrate that seismic risk can be a non-trivial, and in certain cases, the dominant, contributor to the overall plant risk; and (3) illustrate how licensees manage the seismic risk at their facility and enhance safety based on the insights from their SPRAs.

The primary conclusions of the paper are: (1) SPRAs are a powerful tool to provide plant-specific insights on the impact of seismic risk; (2) SPRAs focus attention and resources on effective management of plant-specific seismic risk; and (3) the insights from SPRAs submitted as part of NRC's post-Fukushima actions are valuable for a broader understanding of seismic risk at nuclear power plants.

BACKGROUND

The NRC established a senior-level agency task force, referred to as the Near-Term Task Force (NTTF), following the accident at the Fukushima Dai-ichi nuclear power plant (NPP). The NTTF recommended improvements to the agency's regulations and processes considering the events at Fukushima Dai-ichi (NRC, 2011). With respect to seismic hazards, the NTTF's recommendation (termed Recommendation 2.1) was:

> *Order licensees to reevaluate the seismic and flooding hazards at their sites against current NRC requirements and guidance, and if necessary, update the design basis and SSCs important to safety to protect against the updated hazards.*

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Recommendation 2.1 was implemented through the issuance of a request for information to licensees and construction permit holders pursuant to Title 10 of the Code of Federal Regulations, Part 50, Section 54(f) (10 CFR 50.54(f)) (NRC, 2012). The purpose of that request was to gather sufficient information from the addressees to enable the NRC staff to determine whether any nuclear plant license(s) should be modified, suspended, or revoked in response to new information regarding seismic hazards.

Details of the phased decision-making approach undertaken by the NRC based on the re-evaluated seismic hazards have been documented previously (e.g., Flanders et al., 2017) and are not repeated here. Based on the review of the re-evaluated seismic hazards, 28 plants, corresponding to 15 sites, developed SPRAs and submitted the results to the NRC. The SPRAs that were developed in response to the 10 CFR 50.54(f) letter followed the NRC-endorsed guidance in Electric Power Research Institute (EPRI) Report 1025287, referred to as the SPID (NRC, 2013). The development of these SPRAs was consistent with NRC's fundamental framework for PRA technical acceptability in that the SPRAs were developed based on a consensus PRA Standard and subject to an industry peer-review against the consensus PRA Standard.

The NRC staff used the submitted information, supplemented by information available during regulatory audits, to make risk-informed decisions on the need for further regulatory action on a case-by-case basis. The results of the NRC staff's decisions are documented in publicly available staff assessments for each submitted SPRA.

KEY INSIGHTS

The wealth of information available in the SPRA submittals revealed several useful insights. These insights provide valuable understanding of the impact of seismic event and the resulting seismic risk not only for the plants that submitted SPRAs but also for operating US plants in general. It is important to point out that these SPRAs were developed using the re-evaluated seismic hazard. While this re-evaluated seismic hazard represents the latest knowledge about the seismic hazard at a site, it is not the same as a plant's licensing basis seismic hazard.

Dominant Risk Contributors (Component Level)

The dominant risk contributors at the component level provided in the SPRAs were used to determine how frequently different risk contributors occur. Figure 1 shows the frequency of occurrence of different risk contributors across SPRAs. This information provides insights on which type of contributor at a component level is most prevalent in the results from the SPRAs. It is important to point out that this information is about the frequency of occurrence of each risk contributor and not the relative contribution of each contributor. Therefore, the y-axis in Figure 1 represents the contribution relative to the total number of dominant risk contributors reported in the SPRAs. Further, individual dominant risk contributors were grouped together to develop Figure 1. For example, the contributors under the alternating and direct current (AC and DC, respectively) systems category include seismically induced failures of emergency diesel generators as well as battery racks.

As seen in Figure 1, seismically induced failures of AC and DC systems, major components, and seismically induced relay chatter occur most frequently among the dominant risk contributors to both seismic CDF and seismic LERF. Seismically induced failure of offsite power components, structures, control panels and instrumentation, and piping contribute about equally to seismic CDF and seismic LERF. Structural failures contribute more to seismic LERF compared to seismic CDF because of the common assumption of direct LERF for certain structural failures such as the reactor building. The 'Others' category includes contributors such as seismically induced fire and flood. These failures do not occur frequently which demonstrates their plant-specific nature.

Dominant Risk Contributors (Initiators)

Several SPRAs submittals provided information on the dominant initiators for seismic CDF and LERF. In certain cases, this information was not directly provided and needed to be parsed based on the description of cutsets and dominant risk contributors at the component level.

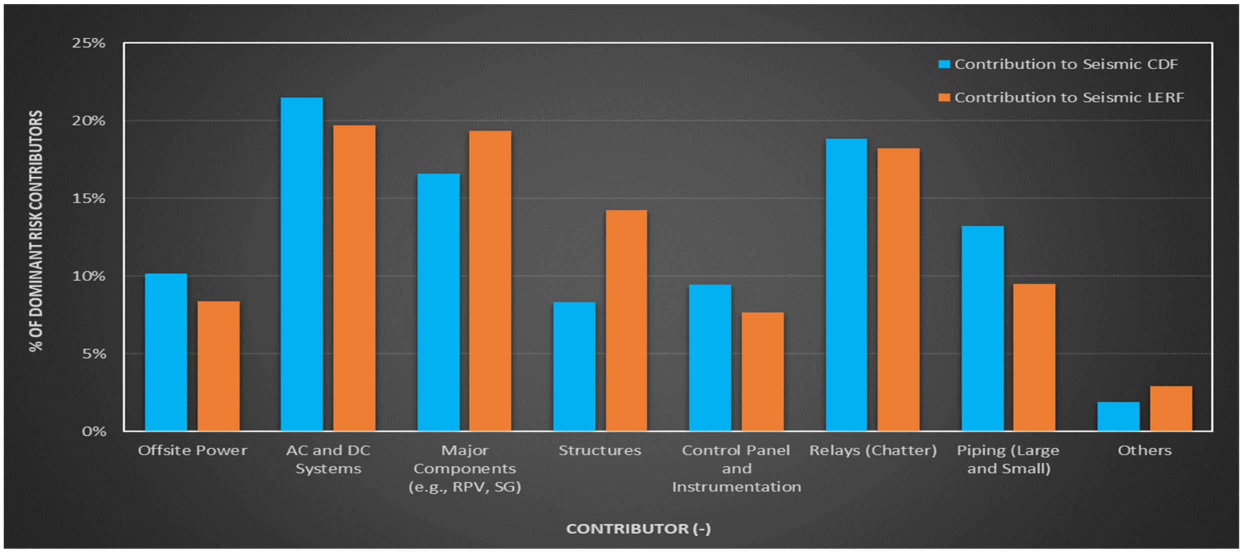

Figure 1: Component-level dominant risk contributors

Based on this information, seismically induced loss-of-offsite power (LOOP) was the most common dominant initiator for seismic CDF. It manifested itself both via station blackout (SBO) sequences as well as transient (TRANS) sequences. This insight is consistent with both prior SPRAs and earthquake experience. It is driven by the high failure probability of offsite power components (such as the ceramic insulators on transmission towers). Seismically induced loss-of-coolant accident (LOCA) and anticipated transients without scram (ATWS) also appeared frequently among dominant initiators for seismic CDF. Among seismically induced LOCAs, seismically induced small and very small LOCAs contributed more followed by medium LOCAs. Seismically induced small LOCAs were the dominant initiator for one of the SPRAs. Seismically induced very small LOCAs are a unique initiator for SPRAs and new event trees are added to the internal events PRA, which forms the foundation for SPRAs, to model such LOCAs in the SPRAs. ATWS events occurred due to seismically induced failures of reactor protection system components. However, unique dominant initiators were also identified on a plant-specific basis such as seismically induced structural failures which resulted in a LOOP and loss of secondary side injection (i.e., a consequential loop as opposed to a seismically induced LOOP). The dominant initiators for seismic LERF were more varied compared to those for seismic CDF. In addition to LOOP sequences leading to SBO and TRANS, containment bypass sequences due to seismically induced failures and seismically induced containment isolation failures were frequent dominant initiators for LERF. Gross structural and soil failures were also dominant initiators for seismic LERF, under the assumption of a direct core damage and large, early release for such failures.

These insights demonstrate that while the “usual suspects” are frequent dominant initiators for core damage, others such as seismically induced very small LOCAs and ATWS events are also important and in certain cases the dominant initiators are unique and plant specific. The same insights apply to large early release where the “usual suspects” are seismically induced gross structural and containment isolation failure with other dominant initiators revealed on a plant-specific basis. These insights would not have been identified in the absence of SPRAs because non-SPRA approaches have focused on seismically induced LOOP and small LOCA and have not extended to detailed consideration of large early release.

Contribution of Seismic Risk to Total Quantified Plant Risk

The SPRAs revealed that risk from seismic events can be a non-trivial contribution to the quantified plant risk. To determine the contribution of seismic risk to the quantified plant risk information on the plant-specific risk from non-seismic hazards was collected. This information for non-seismic hazard risk was obtained from either publicly available documents for risk-informed applications for each plant, which use PRAs that meet the NRC’s PRA technical acceptability guidance, or, in a couple of instances, from older (circa 1990s) risk assessments.

Figures 2 and 3 provide different perspectives of the contribution of seismic risk to the total quantified plant risk. In each of these figures, separate units at a site are identified distinctly only if the SPRAs provided different risk estimates for each unit. Figure 2 shows the absolute quantitative value of CDF from different hazards. This figure clearly reveals that, for most plants, the absolute value of seismic CDF cannot be overlooked when understanding plant risk. Figure 2 also demonstrates that seismic CDF can not only be comparable to but also, in several cases, be higher than the internal fire CDF. Figure 3 provides the relative contribution of quantified seismic risk to total quantified plant risk. Seismic CDF is clearly a major contributor to the quantified plant CDF. It exceeds 25% relative contribution for most plants, including a few outliers where it contributes more than 70% to the quantified plant risk. It should be noted that the seismic risk from SPRAs in Figures 2 and 3 is without credit for safety improvements that were voluntarily identified and committed to be performed by licensees, as discussed in a separate section of this paper.

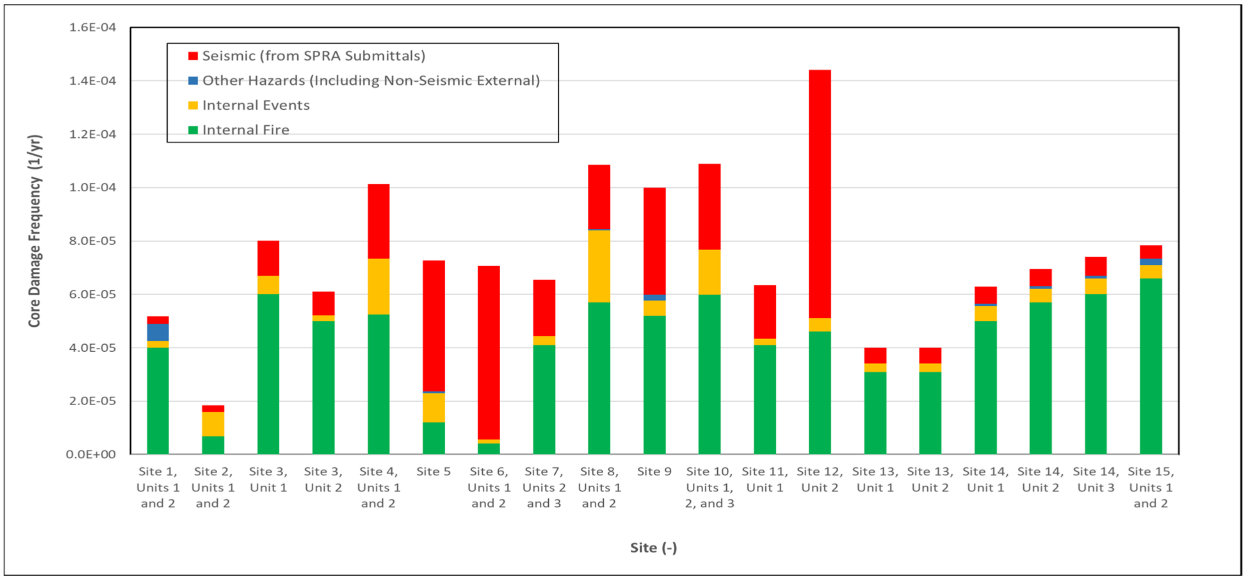

Figure 2: Absolute contribution of seismic risk to plant risk for core damage frequency

Figures 4 and 5 provides the same information as Figures 2 and 3, respectively, but for seismic LERF and the quantified plant LERF from non-seismic hazards. Note that quantified LERF information for non-seismic external hazards is available only for one and therefore, is not included in Figures 4 and 5. Further, the internal events and internal fire LERF is unavailable in publicly available documents for Sites 3 and 10, and the internal fire LERF is unavailable for Sites 2 and 6. Consequently, Sites 3 and 10 are not shown in Figure 5. The insights for seismic CDF provided in the previous paragraphs are not only valid but also amplified for seismic LERF. Seismic LERF contributes more than 50% to the quantified plant LERF for most of the plants. One of the reasons for this insight is the seismically induced gross structural failures at higher ground motions which are expected to lead directly to large early release because of limited, if any, opportunity for mitigation of the release. Such sequences are a non-trivial portion of the seismic LERF and are unique to seismic events compared to internal events and internal fires.

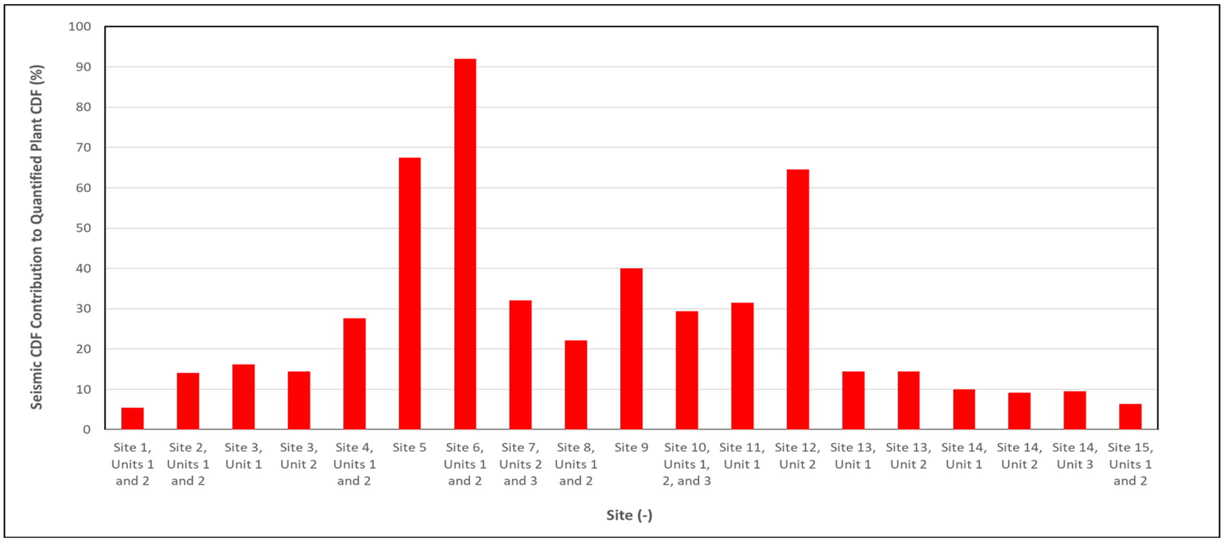

Figure 3: Relative contribution of seismic risk to plant risk for core damage frequency

The insights discussed above provide a contemporary understanding of the impact of seismic risk on plant risk. Till recently, risk from internal events and internal fires has received attention in terms of quantification, insights, and plant improvements to reduce these risks. Consequently, the relative contribution of seismic risk is increasingly important when considering plant risk, even for plants without a contemporary SPRA. It should be noted that PRAs are 'living models' that are updated to reflect, among other things, the as-built and as-operated plant. Therefore, it is highly likely that the quantified risk metrics presented here will change. However, the insights derived from the results and discussed here are expected to remain valid regardless of changes in the quantified risk metrics.

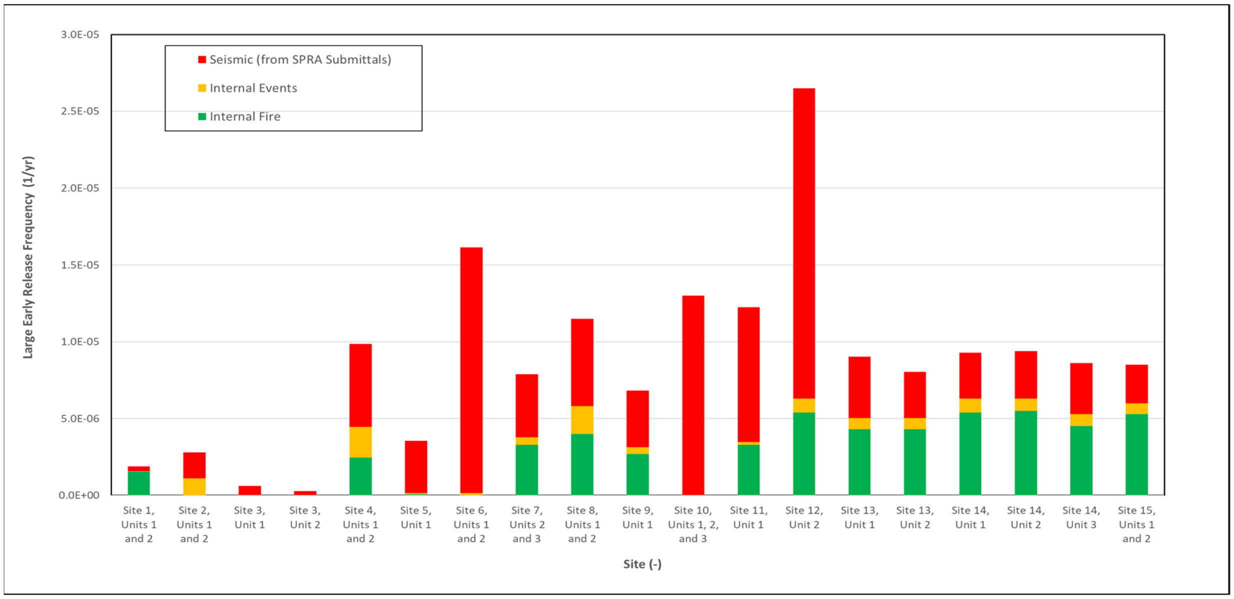

Figure 4: Absolute contribution of seismic risk to plant risk for large early release frequency

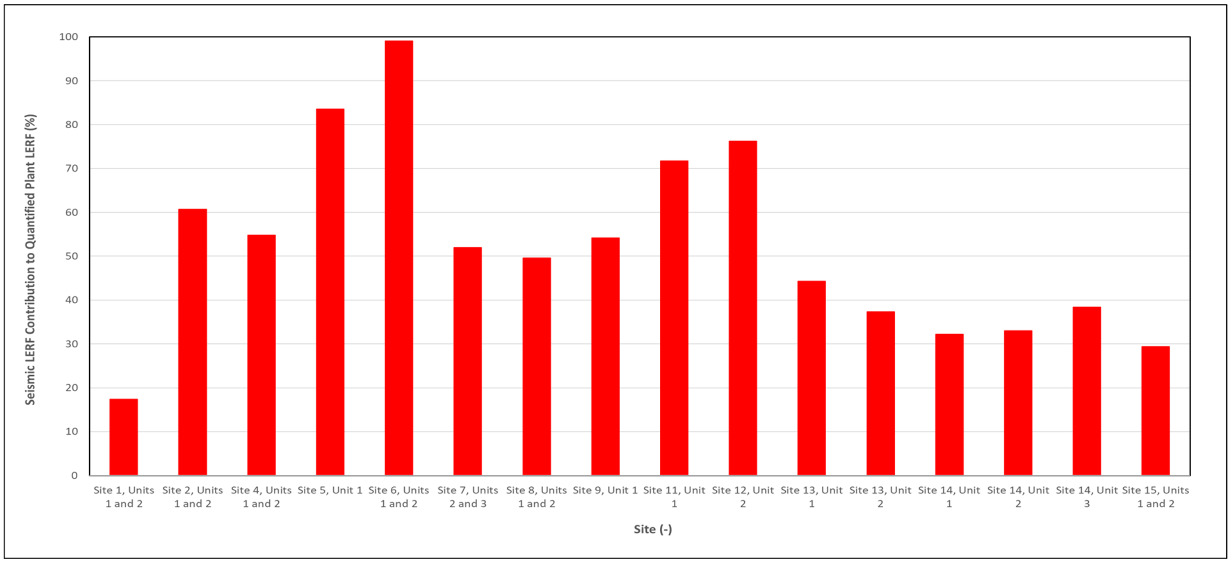

Figure 5: Relative contribution of seismic risk to plant risk for large early release frequency

Plant-Level Fragility

SPRAs are developed by discretizing the seismic hazard into ‘bins’. Each ‘bin’ also has a representative spectral acceleration, which is used to determine the fragilities (conditional failure probabilities) of SSCs for that ‘bin’. The mean conditional core damage probability (CCDP) for each ‘bin’ can be derived by dividing the mean CDF from a ‘bin’ by the initiating event frequency for the same ‘bin’. Plotting this data results in the mean CCDP curve based on the SPRA. Properties of the lognormal nature of the CCDP curve can be used to determine the high confidence of low probability of failure (HCLPF) plant-level fragility (PLF) as discussed in Appendix C of NRC, 2010. Alternately, the HCLPF PLF can be determined from the CCDP curve by either identifying the spectral acceleration at which the CCDP is 1% on the mean CCDP curve or identifying the median fragility (A_m) as the spectral acceleration at which the CCDP is 50% on the mean CCDP curve and then assuming a combined lognormal uncertainty parameter (β_c; $\beta_c = 0.4$ is commonly assumed).

Based on the available information, the HCLPF PLF was determined using the approach in Appendix C of NRC, 2010. The results are listed in Table 1 which provides the HCLPF PLF with the corresponding β_c, licensing basis safe shutdown earthquake (SSE), and HCLPF plant-level fragility estimates from NRC, 2010. The estimates from NRC, 2010, that are based on previous (circa 1990s) seismic evaluations such as seismic margins analysis (SMA). The site numbers in Table 1 correspond to those in Figure 2 and some of the sites are not included because necessary information was unavailable for all sites. The results are plotted as a histogram in Figure 6. Note that Sites 4 and 11 are not listed in Table 1 because of the non-typical shape of the corresponding CCDP curves and the lack of previous HCLPF PLF information. Figure 7 compares the HCLPF PLF from SPRAs with those from previous seismic evaluations.

Table 1 as well as Figures 6 and 7 reveal that while majority of the HCLPF plant-level fragilities for core damage are in the 0.2g-0.3g range, the individual values are plant-specific and have varying margins compared to the plant-specific SSE. This is primarily because: (1) safety related SSCs for each plant are designed based on its SSE, and (2) the regulatory guidance as well as design practices can differ between plans depending on the timeframe of licensing and construction. Table 1 also reveals that the majority of β_c values are approximately 0.3 rather than the usually assumed 0.4. Therefore, the key insights from the plant-level fragility for core damage revealed by the SPRAs are: (1) generic or representative values for these parameters are unsupported, even for the same type of reactor, (2) while the plant-level fragility for core damage can be higher than that based on a previous seismic evaluation (such as a SMA), its value is difficult to identify and justify absent a plant-specific SPRA, and (3) the HCLPF PLF is sensitive to the corresponding βc value; therefore, HCLPF PLF cannot be considered in isolation from βc and using a consistent approach to derive both these parameters is beneficial.

Table 1: HCLPF plant-level fragility and combined lognormal uncertainty derived from SPRA data

Site	**PGA HCLPF plant-level fragility for core damage from SPRA (g)**	**Combined lognormal uncertainty parameter (β_c) for core damage from SPRA (-)**	**PGA safe-shutdown earthquake (g)**	**PGA HCLPF plant-level fragility for core damage from GI-199 (g)**
Site 1, Units 1 and 2	0.63	0.28	0.20	0.30
Site 2, Units 1 and 2	0.81	0.30	0.18	0.30
Site 3, Units 1 and 2	0.21	0.33	0.12	0.20
Site 5, Unit 1	0.21	0.29	0.20	0.30
Site 6, Units 1 and 2	0.20	0.35	0.12	0.16
Site 7, Units 2 and 3	0.22	0.35	0.12	0.20
Site 8, Units 1 and 2	0.18	0.30	0.20	0.26
Site 9, Unit 1	0.23	0.25	0.15	0.22
Site 10, Units 1, 2, and 3	0.23	0.36	0.10	0.29
Site 12, Unit 2	0.16	0.31	0.20	0.28
Site 13, Units 2 and 3	0.26	0.29	0.20	0.20
Site 14, Units 1, 2 and 3	0.27	0.46	0.20	0.30
Site 15, Units 1 and 2	0.43	0.47	0.18	0.27

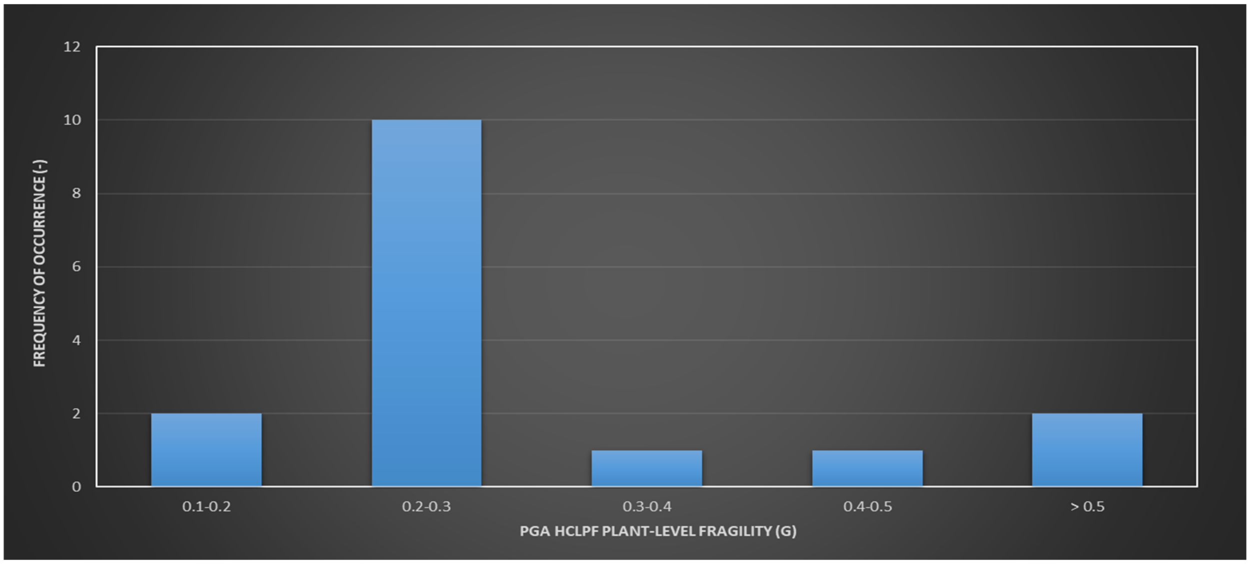

Figure 6: Histogram of HCLPF plant-level fragilities at PGA

Comparison of Convolution Approach for Seismic CDF Estimation

Convolution of the plant-specific seismic hazard with the corresponding plant-level fragility is a well understood and exercised method of estimating the seismic CDF in the absence of a SPRA (e.g., NRC, 2010, NEI, 2014). SPRAs provide quantified risk metrics that can be used for comparison against convolution-based estimates to determine the efficacy of the convolution method and the ability to use the corresponding estimates in absence of a SPRA.

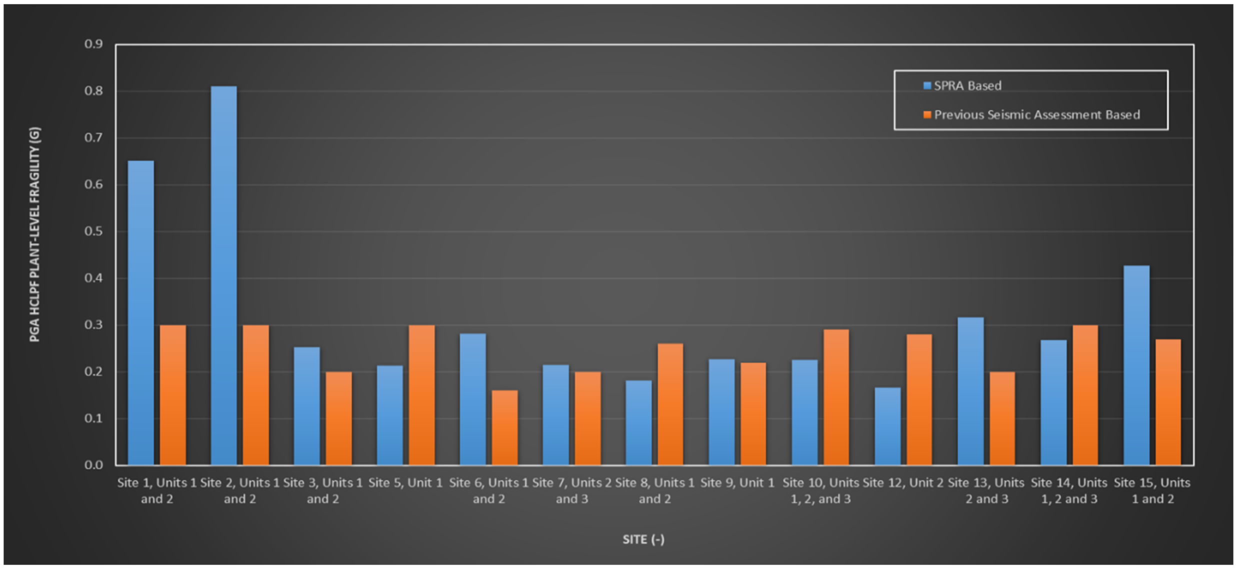

Figure 7: Comparison of HCLPF plant-level fragilities at PGA derived from SPRAs against values based on previous seismic assessments

To make such a comparison, the plant-specific re-evaluated mean seismic hazard curve was convolved with the corresponding plant-level fragility compiled in NRC, 2010. The approach discussed in NRC, 2010, was used along with the re-evaluated GMRS. Figure 8 provides a comparison of the seismic CDF from SPRAs against the estimate from the convolution approach for all the sites that submitted SPRAs. The convolution estimates were determined using the HCLPF PGA and βc value derived using the SPRAs (Table 1) as well as the HCLPF PLF and assumed βc values from NRC, 2010. It should be noted that seismic CDF from SPRAs used in Figure 8 is the point estimate.

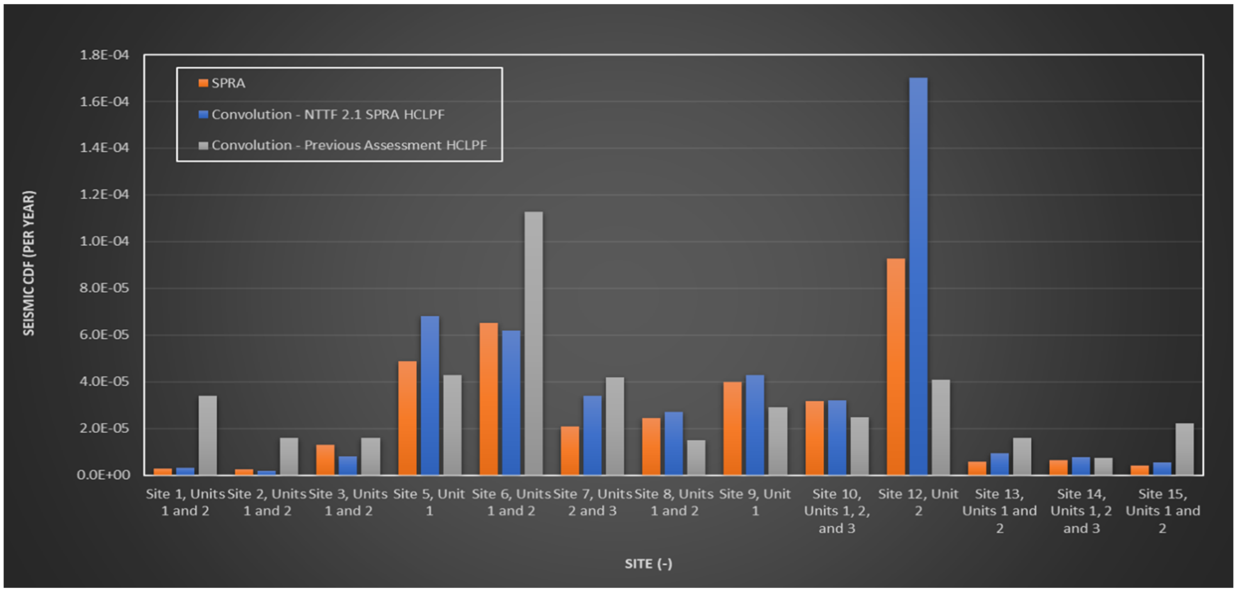

Figure 8: Comparison of seismic CDF from SPRAs against estimates from the convolution approach

As noted from Figure 8, in general, the convolution method provides close estimates of the seismic CDF from seismic PRAs, especially using the HCLPF PLF derived using the SPRAs. However, it can over- or under-estimate the seismic CDF compared to seismic PRAs. Large differences between predictions using values from NRC, 2010 and the SPRA results are due to the PLF value and are directly correlated to the differences in Figure 7. Sensitivities revealed that using the HCLPF plant-level fragility derived from SPRAs with an assumed β_c can distort the results. This is because of the impact of β_c on derivation of the conditional seismic failure probabilities using the properties of a lognormal distribution. The insights revealed by the comparisons in Figure 8 is that the convolution approach to estimate seismic CDF can be used to obtain seismic risk estimates for risk-informed applications when a SPRA is unavailable. However, the convolution approach cannot identify plant-specific dominant contributors, areas of safety improvements, or provide information on the impact of parametric and modelling uncertainties. Further, as noted in the previous section, the seismic CDF estimates using HCLPF PLF are sensitive to the β_c value and only a SPRA provides information on both the HCLPF PLF and β_c. It is also important to be cognizant of the uncertainty, including the lack of a noticeable bias, in such convolution-based estimates, especially when HCLPF PLF from past seismic assessments is used with an assumed β_c. Consequently, the convolution approach is not a substitute for a SPRA.

SAFETY IMPROVEMENTS BASED ON SPRA RESULTS

The SPRA results provided the opportunity to identify safety improvements which can manage the seismic risk at a plant. The NRC staff used the information from the SPRAs to determine whether such improvements would result in substantial safety improvements and would be cost justified. The NRC staff developed and followed guidance for consistent, objective, and risk-informed decisions on plant improvements. This guidance (NRC, 2017) used risk information, especially the importance measures for the dominant risk contributors, from the SPRAs within the constraints imposed by the NRC's backfitting regulation.

Table 2: Examples of plant safety enhancements based on plant specific SPRA insights

Site	**Description of Safety Enhancement**	**Estimated Reduction in Seismic CDF Per Unit (%)**	**Estimated Reduction in Seismic LERF Per Unit (%)**
Site 4, Units 1 and 2	Modify switchgear room ventilation ducts and support to address differential movement	4.2	1.8
Site 5, Unit 1	Emergency supply transformer anchorage	16.5	-
Site 6, Units 1 and 2	Operator actions and training to recover relay chatter	17.0	6.0
Site 8, Units 1 and 2	Alternate power source for hydrogen igniter system	-	50.0
Site 10, Units 1, 2, and 3	Alternate means to isolate letdown line thereby avoiding interfacing systems LOCA	-	50 - 90.0
Site 12, Unit 2	Diverse and robust auxiliary feedwater supply	40.0	60.0

Several licensees voluntarily identified and committed to making safety improvements in their plants to address dominant risk contributors based on the results of their SPRAs. These safety improvements ranged from procedure change to permanent plant modifications such as installation of a new independent source of auxiliary feed water. Table 2 provides a list of the safety improvements voluntarily identified and committed to be performed by different licensees based on their SPRAs along with the corresponding seismic risk reduction estimates. The site numbers in Table 2 correspond to those in Figure 2. The risk reduction estimates are based on sensitivities performed with credit for the modifications. Consequently, the reduction estimates should be viewed as representative of the order of magnitude of the expected reduction rather than its exact amount. The SPRAs were valuable in focusing attention on items that provided the highest safety benefit enabling improved management of plant-specific seismic risk. This is evident from Table 2 where plant modifications committed to be performed by the licensees are expected to result in a non-trivial reduction in the quantified seismic risk. These modern SPRAs provide an effective platform to readily address future changes in the state of knowledge of seismic hazards and corresponding changes to plant-specific ground motion response spectra.

CONCLUSION

This paper distils data and identifies insights based on SPRA information submitted by 28 plants, corresponding to 15 sites, as part of the NRC's actions following the accident at the Fukushima Dai-ichi NPP. Based on the information available in the submittals, several important insights related to seismic risk have been derived. These insights are valuable for a broader understanding of seismic risk at US nuclear power plants. This paper also illustrates how licensees have identified safety improvements at plants based on the information and insights from their SPRAs. These improvements are expected to result in effective management of seismic risk at these facilities. The data, insights, and impact on safety clearly demonstrate that SPRAs are a powerful and useful tool to provide plant-specific insights on the impact of seismic risk by focusing attention and resources on effective management of plant-specific seismic risk.

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