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INSIGHTS GAINED FROM POST-FUKUSHIMA REVIEWS OF SEISMIC AND FLOODING HAZARDS AT OPERATING U.S. NUCLEAR POWER PLANTS SITES

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ABSTRACT

As a part of the post-Fukushima activities, licensees performed (and NRC staff have reviewed) seismic and flooding walkdowns and revaluated seismic and flooding hazards for all operating reactors sites. A number of insights have been gained from these activities, interactions with the industry and other government agencies, development of the industry and the NRC staff guidance documents, and plant-specific inspections and audits as a part of the review process. These insights relate to technical issues, guidance, gaps in technology and needed research, and enhancements in review and regulatory processes. The principal objective of this paper is to describe these insights.

INTRODUCTION AND BACKGROUND

Following the events at the Fukushima Dai-ichi nuclear power plant (NPP), the U.S. Nuclear Regulatory Commission (NRC) established a senior-level agency task force referred to as the Near-Term Task Force (NTTF). The NTTF conducted a systematic and methodical review of the NRC regulations and processes and assessed whether the agency should make additional improvements to these programs in light of the events at Fukushima Dai-ichi. As a result of this review, the NTTF developed a comprehensive set of recommendations (NRC, 2011a). With respect to seismic and flooding hazards, the NTTF made the following recommendation:

Recommendation 2, The Task Force recommends that the NRC require licensees to reevaluate and upgrade as necessary the design-basis seismic and flooding protection of SSCs (structures, systems, and components) *for each operating reactor. The Task Force recommends that the Commission direct the following actions to ensure adequate protection from natural phenomena, consistent with the current state of knowledge and analytical methods. These should be undertaken to prevent fuel damage and to ensure containment and spent fuel pool integrity:*

- *2.1 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.*

- *2.2 Initiate rulemaking to require licensees to confirm seismic hazards and flooding hazards every 10 years and address any new and significant information. If necessary, update the design basis for SSCs important to safety to protect against the updated hazards.*

- *2.3 Order licensees to perform seismic and flood protection walkdowns to identify and address plant-specific vulnerabilities and verify the adequacy of monitoring and maintenance for protection features such as watertight barriers and seals in the interim period until longer-term actions are completed to update the design basis for external events.*

IMPLEMENTATION

The activities undertaken in response to Recommendation 2 are illustrated in Figure 1. Activities associated with Recommendations 2.1 and 2.3 (R2.1 and R2.3, respectively) were implemented through 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) (50.54(f) letter) (NRC, 2012a). The purpose of that request was to gather sufficient information to enable the NRC staff to determine whether nuclear plant licenses should be modified, suspended, or revoked in response to new information regarding seismic and flooding hazards.

In response to NTTF R2.3, the 50.54(f) letter requested that licensees perform walkdowns to verify that plant features that are credited in the current licensing basis for protection and mitigation of seismic and flooding events are available, functional, and properly maintained. The walkdowns were intended as a near-term activity used to verify plant capabilities while the longer-term activities associated with NTTF R2.1 and Recommendation 2.2 (R2.2) are undertaken.

In response to NTTF R2.1, the 50.54(f) letter requested a series of activities related to the revaluation of seismic and flooding hazards. The R2.1 activities are being carried out in two phases. Phase 1 is further partitioned into two stages. In Phase 1, Stage 1, licensees reevaluated the seismic and flooding hazard(s) at their sites using present-day regulatory guidance and methods. If the reevaluated hazard exceeded the design basis, licensees were requested to proceed to Phase 1, Stage 2 in which licensees will perform an assessment of plant response. Licensees were also requested to submit an interim action plan with the hazard reevaluation report that documents actions, planned or taken, to address the reevaluated hazard while the Phase 1, Stage 2, activities are completed.

During Phase 2, NRC staff will use the Phase 1 results to determine whether additional regulatory actions are necessary (NRC, 2016a). The 50.54(f) letter uses the term “risk evaluation” to describe the Phase 1, Stage 2 plant response assessments, which reflects the NRC’s desire to use risk-informed approaches for Phase 2 decisions regarding any additional regulatory actions. In response to R2.2, NRC staff plan to implement a process to ensure that natural hazards continue to be assessed on an ongoing basis. However, this paper focuses on the R2.1 and R2.3 activities, which are further discussed below.

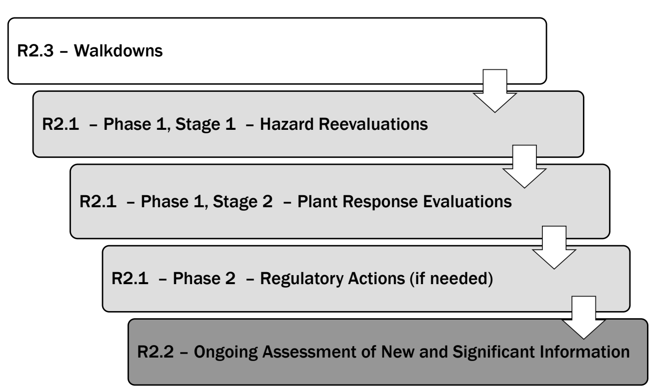

Figure 1: Overall Implementation Plan for NTTF Recommendation 2

R2.3 Seismic Walkdown

To undertake the seismic walkdowns, the 50.54(f) letter requested that licensees: (1) develop a methodology and acceptance criteria for seismic walkdowns to be endorsed by the NRC staff; (2) perform seismic walkdowns using the NRC-endorsed walkdown methodology; (3) identify and address degraded, nonconforming, or unanalyzed conditions through the corrective action program; and (4) verify the adequacy of licensee monitoring and maintenance procedures.

Both the development of guidance and conduct of walkdowns were completed within approximately nine months after the issuance of the request. The NRC worked with stakeholders to establish the guidance for these walkdowns, which is contained in EPRI (2012a). In addition to the performance of walkdowns by licensee personnel, NRC inspectors independently verified the licensee's seismic walkdowns using Temporary Instruction 2151/188, NRC (2012b).

In developing the seismic walkdown guidance, NRC staff and industry were able to draw on extensive experience with previously performed seismic walkdowns and detailed guidance that is available in EPRI (1991). Nonetheless, given that the walkdowns were a near-term activity, there were necessarily short timelines associated with development of the new guidance, performance of the walkdowns, and inspection by NRC staff. That led to development of a smart sampling approach across functions, systems, and equipment categories. The walkdowns were equipment focused and intensive and included opening of selected cabinets and verification of anchorage design. The seismic equipment list was further augmented by area walk-bys. The walk-bys focused on visual inspections of nearby equipment and looked for seismic interactions and potential sources of seismically induced fires and floods, such as gas bottles and tanks.

R2.3 Flooding Walkdowns

To undertake the flooding walkdowns, the 50.54(f) letter requested that licensees: (1) develop a methodology and acceptance criteria for flooding walkdowns to be endorsed by the NRC staff; (2) perform flooding walkdowns using an NRC-endorsed walkdown methodology; (3) identify and address degraded, nonconforming, or unanalyzed conditions through the corrective action program; (4) identify and address cliff-edge effects through the corrective action program; and (5) verify the adequacy of licensee monitoring and maintenance procedures. The NRC-endorsed industry guidance is provided in NEI (2012). NRC issued guidance for NRC inspectors is contained in Temporary Instruction 2151/187 (NRC, 2012c).

The flood walkdown guidance focused on verifying a range of flood protection features as credited in the current licensing basis, including permanent and temporary/portable flood features (e.g., equipment and temporary barriers) as well as procedures needed to install and/or operate the features. The walkdown guidance set up an expectation that all flood protection/mitigation features be subject to visual inspection and, if necessary, functional tests. Manual actions required by procedures were subject to reasonable simulation, which is discussed below. In addition, the guidance required that licensees verify that changes made to the plant since initial licensing (e.g., security barrier installations and topography changes) do not adversely affect flood protection and that execution of procedures will not be impeded by adverse weather conditions that could be reasonably expected to occur during a flood event. The guidance did not require testing of any active component.

Two key concepts were introduced as part of the walkdown guidance: (1) verification of manual actions and (2) understanding cliff-edge effects. These components are more important for flooding hazards than for seismic hazards. As part of the walkdowns, manual actions were verified using reasonable simulation. Reasonable simulation is a walkthrough of a procedure or activity to verify that the procedures or activity can be executed as specified or written within allocated time frame. Reasonable simulation verifies that: resources are available; equipment/tools are properly staged; execution of the activity will not be impeded by the event and/or adverse weather conditions; and adequate training is provided for the activity. A "cliff-edge" effect occurs when a small increase in the hazard (e.g., flooding level) may sharply increase the number of SSCs affected and lead to adverse consequences. In order to get insight and data related to potential cliff-edge situations, a concept of "Available Physical Margin" (APM) was developed and included in the walkdown guidance. The concept of APM is illustrated in Figure 2. As shown in this figure, in its simplest form, the APM is a difference in height between the top of the barrier and the licensing-basis flood height. Additional considerations related to the APM are discussed in the guidance (NEI, 2012). The APM data provide important input to R2.1 plant response evaluations.

Figure 2: Cliff-Edge Effects vs. APM

R2.1 Hazard Reevaluation – Seismic

Most plants were licensed using a deterministic framework that focused on specification of a safe shutdown earthquake (SSE). Present-day NRC requirements and guidance used to characterize seismic hazard use a probabilistic approach to develop a risk-informed, performance-based ground motion response spectrum (GMRS) for a site. This approach is described in Regulatory Guide (RG) 1.208, NRC (2007). RG 1.208 recommends the use of the Senior Seismic Hazard Analysis Committee (SSHAC) approach for treatment of expert judgment and quantifying uncertainty to support development of the GMRS (NRC, 1995; NRC, 2012d). An example of GMRS compared to an SSE is shown in Figure 3.

In order to carry out the necessary analyses for both hazard and risk evaluations, the industry published Electric Power Research Institute (EPRI) Report 1025287, referred to as the SPID (EPRI, 2012b). This NRC-endorsed guidance document discusses methods for developing site-specific GMRS and probabilistic seismic hazard curves, seismic probabilistic risk assessment (SPRA), risk quantification and the identification of significant contributors to risk (i.e., seismic core damage frequency and seismic large early release fraction), and spent fuel pool evaluations. The industry has developed additional guidance documents (e.g., high frequency response, and spent fuel pool evaluations) that are not discussed here.

Criteria for how to determine whether a plant proceeds to the Phase 1, Stage 2 of the R2.1 process are discussed in EPRI (2012b). In simple terms, plants whose reevaluated seismic hazard ground motion response spectra exceed the licensing-basis SSE in the 1-10 Hz range and do not meet the criteria for low seismic hazard or narrow band exceedance were expected to perform an SPRA. The NRC, on further examination of results for all sites, determined that sites with reevaluated hazards that have low to moderate exceedances of the current design-basis do not need to perform an assessment of plant response using a SPRA. The NRC issued a letter to inform licensees of the evaluations and assessments, including SPRAs that would need to be completed and the associated due dates (NRC, 2015a). Figure 3 compares the SSE, licensee's GMRS, and the NRC staff-developed GMRS to illustrate the concept of screening. For the examples shown, a plant with the significant exceedances in the frequency range of 1 to 10 Hz will proceed to perform a SPRA. In several cases, the GMRS was enveloped by the site SSE in the 1 to 10 Hz frequency range, however, there were exceedances in the higher frequencies. For such cases, a SPRA is not needed but a separate high frequency evaluation may be needed using the above cited EPRI guidance. The results of SPRA will be used in Phase 2 decision-making process (NRC 2016a).

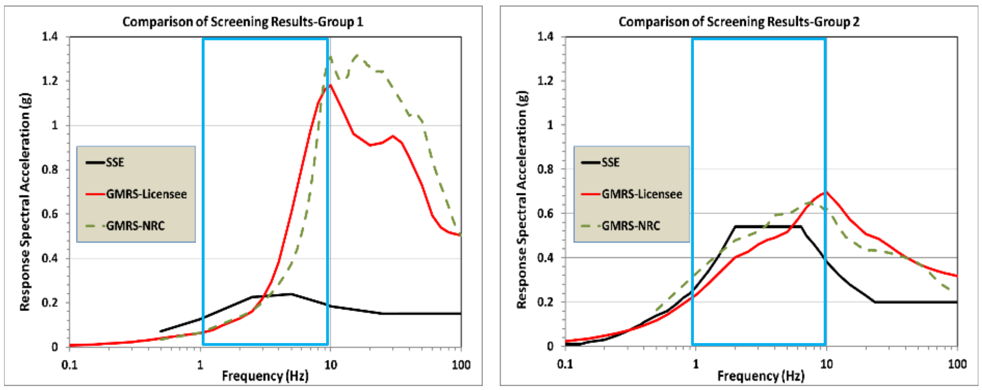

Figure 3 – Comparison of Reevaluated Hazard and SSE

R2.1 Hazard Reevaluation – Flooding

Consequential site flooding may occur as a result of a variety of flood mechanisms such as: local intense precipitation (LIP); flooding in streams and rivers; dam breaches and failures; storm surge; seiche; tsunami; ice induced flooding; channel migration or diversion; and combinations thereof. Unlike seismic hazards, the current approaches for evaluating flood hazards at NPP sites are primarily deterministic. Deterministic assessment uses a concept of hierarchical hazard assessment, which is as a progressively refined, stepwise estimation of the site-specific hazards. It begins with the most conservative plausible assumptions consistent with available data and further refines, if needed and feasible. Current guidance is contained Regulatory Guide (RG) 1.59 (NRC, 1980). The NRC staff is in the process of updating RG 1.59 to address advances in flooding analysis in the 35 years since the last revision was published. Although the update to RG 1.59 update is not complete, the 50.54(f) letter referenced NUREG/CR-7046 (NRC, 2011b), which documents present-day methodologies used by the NRC to review early site permits and combined license applications.

As described earlier, for the sites where the reevaluated flood is not bounded by the current design-basis hazard for the flood mechanisms applicable to the site, licensees and construction permit holders were requested to submit an interim action plan and to perform a plant response assessment (referred to as an integrated assessment in the 50.54(f) letter). In 2012, the NRC staff published interim staff guidance (NRC, 2012e) that provides guidance to evaluate the total plant response to external flood hazard, considers both the protection and mitigation capabilities, and can use all available resources as appropriate. In 2014, following continued interactions with external stakeholders and as directed by the Commission, the NRC staff developed a modified process for performing the Phase 1 activities associated with NTTF R2.1. Under the revised process, the majority of sites with reevaluated hazards in excess of the design-basis would perform focused evaluations rather than integrated assessments. Focused evaluations are used to screen plants out from further evaluation based on factors such as APM (which may include existing or planned design features, equipment, and actions), and in cases for which LIP is not bounded by the current licensing basis, demonstration of a feasible response to address the hazard. The remaining sites (i.e., sites with flooding hazards that exceed the design-basis flood and where the exceedance could not be addressed through a focused evaluation) would perform more in-depth integrated assessments. Guidance documents were developed by the industry and the NRC to implement this revised approach (NRC, 2016b and NEI, 2016).

STATUS OF ACTIVITIES AND SCHEDULES

R2.3 Walkdowns – Seismic and Flooding

All plant licensees submitted reports documenting the completion of the majority of their walkdowns in 2012, with the exception for seismic of some inaccessible areas that can only be inspected during outages. Inspection reports for inaccessible areas were submitted to the NRC in March 2015. The NRC staff performed selected audits and NRC inspectors have done follow-up inspections and the NRC has issued plant-specific assessments of the licensee's walkdown reports and determined that plant walkdowns met the intent of the guidance.

R2.1 Hazard Reevaluation – Seismic

All of the Central and Eastern US sites (CEUS - east of Rockies) submitted their reevaluated hazard reports by March 2014 and the Western US (WUS) sites submitted their reports by March 2015. The NRC staff has completed its reviews of all submittals, including independent confirmatory calculations, and issued staff assessments. Based on these reviews, the NRC staff issued letters with screening and prioritization results to licensees using criteria discussed earlier. Based on the results of the screening, the status of activities related to plant response analysis (Stage 2 of Phase 1, Figure 1) is shown in Table 1 (as of April 2017). As shown in the table, about 18 plants (out of 61 site hazard submittals) will perform SPRAs using the guidance discussed earlier. Results of these SPRAs will be used in the Phase 2 decision-making for any further regulatory actions, if needed. The rest of the plants will not need to go to Phase 2 decision-making. The last of the SPRAs is expected by the end of December 2019. Most of the spent fuel pool evaluations for low hazard sites are complete. The remaining high frequency (HF) submittals are expected by August 2017.

Table 1 – Status of Seismic Plant Response Evaluations

Plant Response Evaluation Activity	Total Number of Evaluations	Submitted to NRC	Completed Staff Evaluations
SPRA (including HF evaluations)	18	1	0
Spent Fuel Pool Evaluation – low hazard	30	30	29
Spent Fuel Pool Evaluation – high hazard	9	0	0
Only HF evaluations	34	23	20
Response to R2.1 completed	28		

R2.1 Hazard Reevaluation – Flooding

As of February 2017, all sites have submitted their flood hazard reevaluation reports. The NRC staff has issued interim staff responses for all sites and final staff assessments for roughly 2/3 of the sites. Out of 61 sites, 55 sites have reevaluated hazards in excess of the design basis. The majority of exceedances were associated with the LIP hazard, which was not part of the licensing basis for several sites. Table 2 shows the number of sites for which the reevaluated hazard exceeded the current design basis for the various flood causing mechanism (some sites had exceedances associated with multiple mechanisms). It is expected that all sites with exceedances will submit either a focused evaluation (to be completed by June 2017) or integrated assessments (to be completed by December 2018). Results from the integrated assessments will be used in Phase 2 decision-making process (NRC, 2016a), if needed.

Table 2 – Exceedances by the Flood Causing Mechanisms

Hazard	**# of sites with exceedances**	**Hazard**	**# of sites with exceedances**
LIP	54	Seiche	2
Riverine	26	Tsunami	3
Dams	18	Ice	4
Surge	17	Channel	1

INSIGHTS

R2.3 - Seismic Walkdown Insights

A number of seismic walkdowns have been conducted as part of past regulatory activities. As a result, only issues of very low safety significance were identified as part of the seismic walkdowns. These issues included: degraded equipment/hardware (e.g., missing bolts, corrosion, and open s-hooks); interactions of components during an earthquake; and problems associated with housekeeping procedures and/or implementation (e.g., temporary installations, portable equipment).

The seismic walkdowns used a sampling approach and were limited in scope compared to full walkdowns that are conducted in conjunction with performing a SPRA. A significant challenge in conducting walkdowns was related to assembling a sufficient number of trained and experienced walkdown teams. Past and ongoing training programs by the industry were critical factors in timely completion of these activities. These walkdowns increased the awareness of both the plant personnel and NRC inspectors regarding potential housekeeping issues, adverse interactions, and potential fire and flood sources associated with a seismic event. Number of plants enhanced housekeeping procedures based on the walkdowns. As the plant and site configurations change and maintenance and construction activities continually occur, this awareness is important from the safety perspective and to avoid potential adverse situations

R2.3 - Flooding Walkdown Insights

Unlike the seismic walkdowns, there was limited experience with flooding walkdowns and detailed guidance was not available at the time the 50.54(f) letter was issued. In addition, development of guidance was challenging due to: (1) the diversity of flood protection features used by plants, (2) dependence of some plant response strategies on procedures and manuals actions that require warning time, (3) recognition of the importance of considering associated effects, and (4) the diversity of flood causing mechanisms and associated potential failure mechanisms.

The walkdowns highlighted three key areas of potential flooding vulnerabilities: inadequate seals that would allow floodwaters into safety-related spaces; procedurally directed actions that could not be accomplished in the time allotted by the final safety analysis report for design-basis flooding events; and incomplete procedures that did not provide sufficient direction during design-basis flooding events. As a result of the walkdowns, licensees have repaired, replaced, or installed missing, damaged, or unanalyzed seals. Many licensees have enhanced procedures and practices and training programs, and identified better locations to store flood protection equipment. The walkdowns also have provided a better perspective of certain potential adverse conditions concurrent with a flood hazard.

Finally, there have been a number of flood related findings that have resulted from the implementation of flooding walkdowns. Ferrante (2015) provides a summary of these findings as well as a review of relevant insights stemming from use of Probabilistic Risk Assessment (PRA) methods to identify the safety significance of the deficiencies. In addition, NRC documented a series of observations and inspection findings from the flooding walkdowns and other flooding events at U.S. commercial NPPs in an Information Notice (NRC, 2015b). The Information Notice informs addressees of recent operating experiences related to external flood protection where deficiencies with equipment, procedures, and analyses relied on to either prevent or mitigate the effects of external flooding at licensed facilities have resulted in degraded ability to mitigate flooding events.

R2.1 – Seismic Hazard Reevaluation Insights

The most important insight gained from the seismic hazard reevaluations is the vital importance of having previously approved seismic source and ground motion characterization models readily available for licensees to implement at their CEUS plant sites. Both the CEUS seismic source characterization model (NRC, 2012f) and the ground motion models (EPRI, 2013), were developed using the SSHAC Level 3 approach (NRC, 2012d), and provided agreed upon estimates of rock hazard at each of the CEUS site. To develop hazard curves near the surface or "control point" elevation as well as the final GMRS, licensees performed a site response evaluation. Because the amount of information on the subsurface properties at the CEUS plant sites varies considerably, industry and NRC staff collaborated on the development of guidance for performing the site response analyses. This guidance, referred to as the SPID (EPRI, 2016), also provided further detail on the screening process and seismic PRAs.

It has long been recognized that the amplitude and frequency content of ground motions at a given site are strongly influenced by the physical properties of the near-surface materials. For most sites, however, the properties of the near-surface materials and the parameters that control the dynamic response are not known with certainty. This uncertainty takes at least two forms, the uncertainty in actually measuring or estimating the properties, as well as the spatial variability in those properties. Both of these types of uncertainty in the parameters that represent the physical properties of the near-surface materials need to be accounted for when performing seismic hazard calculations and developing site-specific hazard curves. Many sites, particularly those licensed in the early 1970s, do not have detailed, measured soil and soft-rock parameters to the depths necessary for robust site response analyses. As a result, the uncertainty in the base-case material properties was treated as an epistemic uncertainty. In other words, alternative base-case profiles and/or properties were developed and then the randomization process was carried out about each profile. An important insight from NRC staff review of the site response analyses is that large epistemic uncertainties in the base-case profiles led to potential over broadening of the site amplification factors and final GMRS. Additional insights from the site response analysis were the importance of accounting for the uncertainty in kappa (low strain, frequency-dependent, diminution of ground motion amplitude that occurs in near-surface geologic materials) as well as the potential nonlinear behavior of the soil and/or rock. The SPID guidance specified that multiple alternative base-case profiles, kappa values, shear modulus and damping curves, and input source spectra should be implemented as part of the site response analysis.

For the three WUS sites, the licensees developed regional specific SSHAC Level 3 source and ground motion models in order to characterize the hazard and develop GMRS for screening purposes. The seismic source models developed for the WUS sites necessitated the characterization of multiple individual faults in complex geologic settings. In addition, licensees implemented ground motion prediction equations that separated out the site-to-site component of variability, which was captured instead as part of the site response analysis.

NRC staff continue to evaluate the lessons learned from its review of the seismic hazard reevaluations at each of the plants as it proceeds with updating its regulatory guidance documents. The NRC Office of Nuclear Regulatory Research has developed a seismic research plan to systematically evaluate the issues discussed above. The research also includes issues identified as a result of new reactor licensing reviews. The research plan focuses on the methodologies for characterizing uncertainty in site properties; frequency-dependent nonlinear material properties; and methodologies for evaluating sites that are not appropriately modeled as one-dimensional; and addressing how uncertainties in SPRA are incorporated into the site-specific seismic hazard calculations and subsequently input to structural analyses and PRA. In addition, the staff is currently revising its most recent SSHAC guidance (NRC 2012d) to implement lessons learned from the recent reviews.

In addition to the insights from the hazard reevaluations, the NRC staff found that the implementation of the SPID hazard screening criteria was more complicated than initially thought. The NRC staff found that the screening needs to consider both the hazard exceedances and dynamic characteristics of NPP SSCs to have a better understanding of potential impact on the safety. In addition to the hazard exceedances, the NRC staff also looked at various other factors, such as results from the previous risk studies and insights into containment performance (NRC, 2015a).

The SPID contains detailed guidance on implementing certain provisions of the ASME/ANS SPRA Standard, (ASME, 2009). One of the challenges associated with undertaking development of several SPRAs at the same time is the lack of available expertise. The focus of SPID, in part, was to address this issue. Although, only one SPRA has been submitted to the NRC so far, some of the industry insights presented at various conferences (e.g., NC State Symposium, 2016) indicate that significant efforts are needed to realistically characterize plant responses and fragilities. For several sites, this has resulted in the development of detailed models, conducting soil structure interaction, and incoherency analysis. The need for frequent interactions between plant logic analysts and fragility analysts were also noted to minimize efforts. In addition, an insight from the SPRAs has been that HF ground motion produces significantly large HF responses in structures and more realistic methods are important. The industry has initiated a research program to address this issue. A code case has been developed for SPRA (ASME/ANS Standard RA-S, 2009) to incorporate some of the lessons learned and to address several challenges that have been identified during the peer reviews of the SPRAs.

R2.1 – Flood Hazard Reevaluation Insights

As discussed earlier, NRC's current regulatory guidance for evaluation of flooding hazards is deterministic and generally focuses on concepts of hypothetical "probable maximum" events that are intended to reflect the most severe hazards reasonably possible at the location of interest. Deterministic methods have historically considered flood height as the dominant measure of flood severity and thus focused on identifying and evaluating those hypothetical events that are capable of producing the highest water level at the site. Experience with the R2.1 and R2.3 activities has highlighted the importance of characterizing floods in a manner that appropriately reflects the spatially and temporally dynamic characteristics of flood events. Specifically, the nature and severity of flood hazard characteristics will vary spatially across a NPP site such that there are different flood depths and effects at different locations across a site. In addition, the depth and duration of floodwater on site and the relationship to incipient building flooding may vary locally depending on the site topography and the timing of the flood event. As a result, as part of the R2.1 efforts, NRC staff and industry developed a formalized construct for characterizing flood hazards using a set of multiple parameters representing flood severity. These parameters include: flood water depths or elevations, parameters related to associated effects, and flood event duration. Associated effects is a term used to capture factors, other than flood height (elevation) that may adversely affect a site. Associated effects may include factors such as wind waves and run up effects; hydrodynamic loading, including debris; effects caused by sediment deposition and erosion; concurrent site hazards, including adverse weather conditions; and groundwater ingress. Flood event duration is used to define the length of time that the flood event affects the site. It generally begins with conditions being met for entry into a flood procedure or notification of an impending flood (e.g., a flood forecast, notification of dam failure) and ends when water has receded from the site. Experience as part of the R2.1 efforts has also shown the value in capturing the spatial variability of these parameters (e.g., through inundation and flood velocity maps).

Another key lesson is a new emphasis on the concept of consequential flooding. Consequential flooding is a term used to identify conditions in which the flood severity exceeds the capability of protection features (if available), including considerations for flood level, duration and/or associated effects, such that key SSCs may be impacted. Consequential flooding may occur for events that are less severe and with differing characteristics (e.g., shorter warning time) than the deterministically defined probable maximum events.

Some of the aforementioned lessons learned emphasize the value in performing an integrated assessment of plant flood response using a risk-informed framework and through application of PRA concepts and tools. The NRC is currently executing a Probabilistic Flood Hazard Assessment Research Program to support the development of risk-informed licensing and oversight guidance and tools for assessing flooding hazards and plant response.

CONCLUSION

Significant safety enhancements have occurred from implementation of the post-Fukushima Recommendations and plants have increased their capabilities to deal with seismic and flooding events. The NRC staff is developing detailed reports on lessons learned from post-Fukushima activities and updating its guidance, as necessary. Because our understanding and knowledge related to the natural hazards are continually evolving and changing, questions of adequacy of design basis may arise from time to time. There are large uncertainties inherent in characterizing a natural hazard. The probabilistic hazard analysis provides a rational approach to explicitly incorporate the uncertainties in the analysis and reflect them in results. To account for potential impact on the plant safety due to changing hazard, both the hazard and plant response to the hazard need to be considered. An integrated total plant response that considers design, construction, operational, as-built, and as-operated aspects, and accounts for both prevention and mitigation features provides the information needed for risk-informed, performance-based decision-making. Therefore, the development and uses of probabilistic hazard analysis and probabilistic risk assessments for natural hazards are critical going forward.

DISCLAIMER

Any opinions, findings and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the United States Nuclear Regulatory Commission.

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