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Assessment of Flood Fragility for Nuclear Power Plants: Challenges and Next Steps

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ABSTRACT

The United States Nuclear Regulatory Commission's risk-informed regulatory framework incorporates the use of risk tools consistent with the Commission's policy on the use of Probabilistic Risk Assessment (PRA). The NRC's PRA Policy Statement (Ref. [1]) formalized the Commission's commitment to risk-informed regulation through the expanded use of PRA. It states that the NRC will increase the use of PRA methods in nuclear regulatory matters to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements the NRC's deterministic approaches. Benefits expected from this approach are the consideration of a broader set of potential challenges to safety, providing a logical means for prioritizing these challenges based on risk significance, and allowing consideration of a broader set of resources to defend against these challenges.

Similar to other PRA applications used at the NRC, a PRA for external flooding involves multiple elements. One technical element of the external flooding PRA involves the evaluation of the fragility of flood protection features and other relevant structures, systems, and components (SSCs) exposed to flooding. There are several key challenges that arise related to development of flood fragility for flood protection features and flood-exposed SSCs at United States nuclear power plants. This paper describes these challenges and activities underway at the NRC related to assessment of flood fragility.

INTRODUCTION

A PRA for external flooding involves three key technical elements:[1] (1) external flood hazard analysis, (2) external flood fragility evaluation, and (3) external flood plant response modelling and quantification. In general, collective experience with external flooding PRA for nuclear power plants (NPPs) is limited. This paper focuses on the challenges associated with the second technical element related to flood fragilities as well as activities underway at NRC related to assessment of flood fragility.

BACKGROUND

Estimation of fragility involves the evaluation of the susceptibility of plant structures, systems and components (SSCs) to damage or failure as a function of the severity of a hazard. Flood fragility functions are a probabilistic mapping between a site-specific measure of flood severity (e.g., flood height, associated effects, or flood event duration) and component performance. More specifically, each fragility function describes the probability that a component experiences a

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[1] The term "technical element" is used in the PRA Standard (Ref. [11]). PRA technical elements define the scope of the analysis and are associated with technical requirements.

specified damage state or greater for a given demand (i.e., level of flood severity). This may be expressed as:

$$F(\mathbf{s}, \boldsymbol{\theta}) = \Pr(\{g(\mathbf{X}, \boldsymbol{\theta}) \leq 0\} | \mathbf{S} = \mathbf{s}) \tag{1}$$

where $g(\mathbf{X}, \boldsymbol{\theta})$ is the limit state function for a given component (typically composed of a capacity term and a demand term), $\mathbf{X}$ is a set of random variables influencing the performance of the component, $\boldsymbol{\theta}$ is a set of model parameters (e.g., estimated from data or analytical models), and $\mathbf{S}$ is a vector of variables representing flood severity. Typically, $\mathbf{S}$ is represented by a scalar measure (i.e., a single measure of hazard severity such as flood height) so that a plot of $F(\mathrm{s}, \boldsymbol{\theta})$ versus s yields a conventional fragility curve rather than a fragility surface. SSCs will generally have multiple damage states (e.g., slight, moderate, or highly damaged), however, in many cases, a probabilistic binary representation (e.g., given in terms of failure) is used in the PRA.

It is acknowledged that limit state functions and fragility functions may simplify or idealize response to flood hazards. However, idealizing component performance is typically both reasonable and computationally necessary. In some applications it may be appropriate to utilize fragility functions developed for a given class of flood protection, however risk-significant components will generally require more detailed evaluations. Examples of generic and structure-specific flood fragility functions for non-nuclear applications can be found in available literature (e.g., see Ref. [2]).

Fragility functions may be developed using empirical observation, analytical approaches (e.g., structural reliability methods), and engineering judgement (Ref. [2]). These approaches are associated with sources of uncertainty. For example, uncertainty may arise due to missing variables and idealizations used in analytical models (e.g., modelling non-linear systems as linear or modelling flood severity by a single measure such as flood height) or measurement and statistical errors when utilizing empirical observations. Use of engineering judgement is associated with varying degrees of rigor, which may or may not systematically capture and address sources of uncertainty. Therefore, defining fragility functions requires care in properly understanding and (if possible) accounting for uncertainties that arise from idealization of SSC performance. Moreover, as discussed later in this paper, it is important to consider possible sources of correlation between estimated performances of similar SSCs.

Flood fragility functions may be generally characterized by (a) a step function (e.g., a cliff-edge[2]) for overtopping and brittle failure modes for SSCs with well-understood capacities, or (b) smooth functions for elastic and complex SSCs as well as those with poorly understood capacities. There is substantial literature related to development of fragility functions in general and for certain hazards (e.g., earthquakes). However, there is a comparatively limited literature related to assessment of flood fragility.

In order to successfully develop external flooding PRAs for NPPs, it is necessary to understand the performance and reliability of flood protection and other flood-exposed SSCs, and to develop associated flood fragility functions. This necessitates an understanding of in situ conditions and performance of flood protection based on operating experience as well as complementary

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[2] The term “cliff-edge” is used to indicate that “the safety consequences of a flooding event may increase sharply with a small increase in the flooding level” (Ref. [22]).

research activities. Moreover, there are important aspects of flood events (e.g., dependence of flood protection integrity on manual actions) that are unique when compared with other hazards and that should be considered when developing the external flooding PRA.

RECENT OPERATING EXPERIENCE

United States NPP operating experience related to flooding provides important insights regarding the performance and reliability of flood protection. As noted above, development of realistic flood fragility functions should reflect insights gleaned from operating experience regarding potential failure modes as well as observations regarding common in situ conditions. Recently, there have been a number of events that provide insights in this regard. In January 2014, a site experienced heavy rainfall and storm drain blockage caused water to backup within the emergency core cooling system pipe tunnel. Water entered the reactor auxiliary building through two degraded conduits that lacked internal flood barriers (Ref. [3]). In March 2013, a site experienced a collapse of a temporary crane that resulted in the rupture of a fire main. Water from the fire suppression system migrated to several areas of the turbine building and leaked through floor hatches into the auxiliary building. From its extent of condition review, the licensee identified other pathways for water to enter. Although this event involved internal flooding, it led to identification of issues of relevance to external flooding (Refs. [4], [5] and [6]). During the summer of 2011, Missouri River flooding significantly challenged operations at a plant due to river levels in excess of site grade. Challenges that were encountered during the event included the rupture of an aqua berm used for asset protection (Ref. [7]). In March 2013, with the plant in cold shutdown conditions during a refueling outage, a site discovered water from dredging operations inside two electrical manholes located in the Vital Switchgear Rooms, which had entered the two manholes through a partially dislodged flood seal in an underground spare conduit that communicates with the Switchgear Room manholes. An extent of condition review identified additional water intrusion pathways (Ref. [8]).

A common observation that emerges from this operating experience relates to the possibility of unsealed conduits. In developing the external flooding PRA, the issue may be addressed through plant walkdowns and use of design control processes to ensure seals are installed in accordance with relevant specifications. It is noted that the treatment of unsealed penetrations may differ from the treatment of degraded seals, which would generally necessitate a change in the parameters of the fragility function to account for the degradation.

In addition to the aforementioned operating experience, there have been a number of flood related findings under the NRC's Reactor Oversight Process (ROP)[3] that have resulted from the implementation of flooding walkdowns performed as part of the NRC's response to the events at Fukushima.[4] Specifically, a number of performance deficiencies were identified by NRC

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[3] The ROP is the NRC's program to inspect, measure, and assess the safety and security performance of operating commercial NPPs. A portion of this program is focused on determining the safety significance of inspection findings through the Significance Determination Process (SDP) and other risk-informed activities.

[4] Following the events at the Fukushima Dai-ichi site, the NRC established a task force of senior agency experts referred to as the Near-Term Task Force (NTTF). The NTTF conducted a systematic and methodical review of NRC regulations and processes and determined if the agency should make additional improvements to these programs in light of the events at Fukushima Dai-ichi. The NTTF's report (Ref. [22]) documents the results of their review. The NRC issued a request for information to all power reactor licensees and holders of construction permits under 10 CFR Part 50.54(f) on March 12, 2012 (Ref. [23]). Among other requests, the March 12, 2012 letter requests that

inspectors that were entered into the ROP framework. A subset of these performance deficiencies were then screened as findings and further assessed to determine their safety significance. These further assessments utilized a more detailed risk evaluation or analysis. Ref. [9] provides a summary of these findings as well as a review of relevant insights stemming from use of PRA methods to identify the safety significance of the deficiencies. For example, Ref. [9] identifies that estimation of human error probabilities (discussed in a separate section of this paper) for events outside the control room is currently challenging due to the lack of a single human reliability analysis method for assessing manual actions under flooded conditions. Moreover, the modelling of the temporal component of flooding events (e.g., warning time and period of inundation) was also challenging. Ref. [9] also observes that there is scarcity of reliability data for SSCs affected by flooding, including the reliability of temporary protective measures. Many of these components required the application of qualitative judgements in order to address the issue under the significance determination process (Ref. [10]). Like the aforementioned recent events, Ref. [9] notes that several findings involved deficiencies associated with flood seals.

CHALLENGES

There are several key challenges that arise related to development of flood fragilities for NPP applications, including: (1) the diversity of flood protection features employed at NPPs sites, (2) limited existing resources and lack of standardized testing protocols, (3) the importance of manual actions, (4) system-level aspects, and (5) the multi-dimensional nature of hazard characterization. While these are important challenges that should be considered, they should not be interpreted as precluding the importance of performing external flooding PRAs. Instead, these challenges are described to provide a list of considerations for practioners and for research efforts underway at NRC.

Diversity of SSCs and Associated Failure Modes

In external flooding PRAs, there are (at a high level) two different types of SSCs that may be affected by the flood event and for which fragility must be characterized: flood protection features and other (non-flood protection) SSCs exposed to flooding. Flood protection features are intended to protect other SSCs in the NPP from the effects of a flood event and are affected by external flooding events when floodwaters impinge upon the feature(s). Flood protection features at NPPs may be generally classified using two classes of indicators (1) active or passive[5] and (2) exterior, incorporated, or temporary.[6] A flood protection feature is typically classified

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respondents perform plant walkdowns to verify the capability of the plants to respond to the flood events for which they were designed and licensed. A flooding walkdown procedure (Ref. [24]) developed by the Nuclear Energy Institute and endorsed by the NRC (Ref. [25]) was produced to verify that plant features that are credited in the current licensing basis for protection and mitigation from external flood events are available, functional, and implementable under a variety of site conditions. The implementation of these walkdowns was part of a short-term action to be performed while the NRC implements longer-term hazard reevaluations and associated integrated assessment as part of its Fukushima Lessons-Learned activities.

[5] Active features are incorporated, exterior, or temporary flood protection features that require the change of a component's state in order for it to perform as intended. Conversely, passive feature are incorporated, exterior, or temporary flood protection features that does not require the change of state of a component in order for it to perform as intended (Ref. [24]).

[6] Exterior features are engineered passive or active flood protection features that are external to the immediate plant area and credited to protect safety-related SSCs from inundation and static/dynamic effects of external floods. Incorporated features are engineered passive or active flood protection features that are located at the structure-

using an indicator from each class. For example, passive-exterior features include levees, dikes, and floodwalls whereas a pump station is an example of an active-exterior feature. Examples of passive-incorporated barriers include seals and structural walls (e.g., the walls of NPP buildings) whereas a sump pump is an example of an active-incorporated barrier. Valves are active features that may be exterior or incorporated depending on their location. Finally, examples of passive-temporary barriers include sandbag walls and portable panels whereas a portable pump is an example of an active-temporary feature. In addition to flood protection, other SSCs may be affected by floodwaters (e.g., via inundation or submergence) when flood protection barriers fail or are otherwise not available. For example, some SSCs may not be protected from external flooding by design or they may be subject to flooding if flood protection barriers fail (i.e., are sufficiently damaged such that they cannot perform as intended) or are otherwise bypassed or overtopped.

Each of these types of flood protection and other flood-exposed SSCs are associated with diverse types of failure modes. For example, passive flood protection features (exterior, incorporated, and temporary) may be subject to overtopping as well as structural failure modes as a result of hydrostatic and hydrodynamic loads (e.g., wind waves, currents) and debris. Moreover, certain types of barriers (e.g., external embankments) may be vulnerable to geotechnical failure modes such as slope instability and internal erosion. In addition to structural failure modes, active flood protection features may be subject to mechanical failures (e.g., failure to start or failure to run). Other flood-exposed SSCs may be subject to failure as a result of inundation or spray (usually, it is assumed that equipment submerged by the flood waters and not designed for submerged operation will not be able to perform its safety function, Ref. [11]) as well as many of the failure modes that are relevant for flood protection (e.g., a flood-exposed SSC may fail as a result of debris impacts). The large diversity of SSCs and the associated failure modes implies that multiple types and multiple levels of complexity will need to be addressed in fragility models developed to support external flooding PRAs.

Limited Existing Resources

There are relatively few existing resources documenting the flood fragility flood protection features and other SSCs exposed to flooding. Moreover, there is an overall lack of standardized testing protocols to collect data and develop empirical models of flood protection performance. This may be contrasted with relatively extensive testing protocols that have been developed for testing of fire seals at NPPs (e.g., Ref. [12]).

Outside of nuclear applications, fragility studies have been performed for limited types of protective features. A United States Army Engineer Research and Development Center Report (Ref. [2]) describes existing literature related to flood fragility, the availability of which has increased in the past decade. The summary in Ref. [2] demonstrates that existing studies have focused on certain types of flood protection, particularly earthen levees and floodwalls. Some of these studies have been related to regional- or national-scale assessments, which have required the development of generic fragility functions. Others studies have been focused on

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environment interface and used to protect safety-related SSCs from inundation and static/dynamic effects of external flooding. Temporary features are passive or active flood protection features within the immediate plant area that protects safety-related SSCs from inundation and static/dynamic effects of external flooding and that are temporary in nature (i.e., their installation must be done prior to the start of the external flood) (Refs. [21] and [24]).

specific applications, which may have limited applicability to other flood protection structures. For comparative purposes, it is noted that the number of studies related to development of flood fragilities is significantly smaller the number of studies performed for seismic hazards. This creates a challenge for the PRA practioner due to the lack of existing resources or standardized protocols for gathering new information.

System-level Considerations

A flood protection system may be thought of set of flood protection features that are intended to protect a specific SSC or group of SSCs (e.g., features used to protect the intake structure) or the entire plant (e.g., a levee around an entire site) and that are primarily separate and independent from the flood protection used to protect other SSCs (Ref. [13]). Generally, flood protection systems involve multiple structures or components. For example, the flood protection system protecting specific equipment sets (e.g., emergency diesel generators) may consist of structural walls, seals, louver covers, and flood doors. If any of the individual flood protection features comprising the system fails, the protected equipment may be rendered unable to perform its intended function. For example, failure of the flood protection system may be defined as loss of barrier integrity or leakage rate into a room exceeding a specified threshold.

As described earlier, it is also important to understand and, to the extent practical, account for sources of uncertainty associated with fragility functions and effects on systems models. For example, as a result of having a limited number of observations available when developing fragility functions for a class of components based on empirical observations, there is often statistical uncertainty associated with the estimates of the parameters of fragility functions. This statistical uncertainty is common to all components within the class, which gives rise to correlations among the perceived component capacities (Ref. [14]). Moreover, limit-state functions and fragility models are idealizations of component performance and there is error resulting from this idealization. For example, the observed states of components following a flood event will differ from those predicted using a limit state function based on flood height (a common measure of flood severity) and there will be component to component variability amongst a set of identical components subjected to floods with the same height. This is, in part, because using a single measure (flood height) to characterize flood severity is a simplification of the hazard, which realistically includes other effects such as hydrodynamic forces and debris loads (as described below). Thus, a portion of the error is random from component to component and a portion is common, which leads to correlation. The computed reliability of a system with correlated components may differ from that computed under an assumption of independence.

Failure modes and effects analysis is a common tool for systematically identifying possible failure modes of a SSC and evaluating the effects of the failure on other SSCs. Logic structures, such as event trees, provide a way to represent the various outcomes that can occur as a result of the flood scenario parameters. In performing a PRA, it is necessary to decide the appropriate level of system model detail. For example, the analyst must decide whether failures of each individual component will be explicitly represented as events in logic models or whether sets of components (or an entire system) will be modelled using a surrogate element (e.g., whether the failure of individual seals will be represented explicitly or whether the event will be defined as combination of inflow through all penetrations that exceeds a critical threshold).

Multi-dimensional characterization of hazard severity

Flooding hazards can be generally characterized by parameters such as maximum stillwater surface elevation plus the following factors (referred to as *associated effects,* Ref. [13]): wind waves and run-up effects; hydrodynamic loading, including debris; and effects caused by sediment deposition and erosion. Concurrent site conditions, including adverse weather; groundwater ingress site accessibility, and other pertinent factors may also be important associated effects. In addition, flood event duration is an important element of the flood hazard. The flood event duration is defined as the length of time in which the flood event affects the site, beginning with conditions being met for entry into a flood procedure or notification of an impending flood (e.g., a flood forecast or notification of dam failure), including preparation for the flood and the period of inundation, and ending when water has receded from the site and the plant has reached a safe and stable state that can be maintained indefinitely (Ref. [13]).

Flood height (either stillwater elevation, or stillwater plus wind waves and runup elevation) is a common measure of severity against which to define flood fragility. However, in defining flood fragility, it is important to understand other hazard parameters. For example, debris loads may adversely affect flood protection by exerting impact loads and increasing drag forces as well as leading to blockage of drainage systems. As another example, flood protection failure probabilities may increase with period of inundation (e.g., an increase in the amount of time water impinges upon a seal may increase the probability of leakage or “blowout” failures; increased period of inundation may affect the foundations of structures and may provide time for seepage to develop leading to degraded capacity and eventual failure of geotechnical systems).

For seismic hazards, some work has been done relative to vector based intensity measures (e.g., Ref. [15]), which goes beyond characterization of hazards by a single parameter (e.g., peak ground acceleration). The authors are not aware of similar work in the area of flooding. Therefore, while the state of practice in flood fragility estimation may currently require consideration of a single or small number of measures of severity against which to define performance, it is important to address technical issues (including, to the extent practical, accounting for resultant uncertainties arising from simplifications in hazard characterization) associated with the full characterization of hazard.

It is noted that sites may have a diversity of flood hazards to which they are exposed and it may be necessary to define multiple sets of flood scenario parameters to capture the different plant effects from the diverse flood scenarios associated with applicable mechanisms. In some cases, this may be addressed through the amalgamation of the hazards and representation via a single measure of hazard severity (e.g., flood height). In other cases, hazard characteristics (e.g., warning time or period of inundation) may be sufficiently different that such a combination is not appropriate and separate treatment may be required (e.g., via mechanism-specific fragility functions that represent hazard severity using flood height but implicitly address other hazard characteristics). It is further noted that certain flooding scenarios may be associated with multiple phenomena. For example, a seismic event may affect both an upstream dam (which could cause dam failure that affects the NPP site) and the flood protection at the site, which may not be designed to withstand seismic loads. In the case of seismically-induced floods, it may be appropriate to also account for seismically-induced degradation in flood protection performance.

Manual actions

Human performance takes on added importance during many flooding events compared to normal plant operations. For example, the establishment of temporary flood protection features may rely heavily on manual actions such as constructing sandbag barriers, deploying and operating portable pumps, or relocating equipment. Significant manual actions may also be associated with mitigation actions, including actions that may leverage equipment, personnel, or other resources in nontraditional ways. In addition, failed or degraded instrumentation and controls in the main control room (MCR), as well as the unavailability of equipment and systems, may create challenges (Ref. [13]). Typically, in PRAs, the impact of human actions is included explicitly via the estimation of human error probabilities (HEPs) associated with specific tasks. Typically, most human HEPs are derived for actions taken inside the MCR, since the framework and methodologies used for developing HEPs are calibrated for human performance within the MCR environment. As such, most approaches used in NPP PRAs are not focused or calibrated for actions that may be expected to take place outside the MCR during an external flooding event. However, like failure probabilities of flood protection or other flood-exposed SSCS, human error probabilities may be highly dependent on the severity of flood hazards. For example, the ability of humans to perform tasks may degrade as flood heights and water velocities increase. Moreover, there is potentially strong coupling between the performance of certain types of flood protection and associated manual actions (e.g., actions required to construct a sandbag barrier and performance of the barrier).

There is limited literature available regarding, for example, the ability of pedestrians through flooded areas (e.g., Ref. [16]). This may be contrasted with the more extensive consideration of manual action reliability for fire hazards (Refs. [17] and [18]). However, it is noted that the guidance issued to support the flooding integrated assessments[7] (Ref. [13]) contains a general framework for evaluation of manual actions associated with plant flood response.

CURRENT ACTIVITIES AND NEXT STEPS

NRC is working to compile operating experience and lessons-learned from the post-Fukushima walkdowns. For example, NRC recently documented a series of observations and inspection findings from the post-Fukushima flooding walkdowns and other flooding events at U.S. commercial NPPs in an Information Notice (Ref. [4]).[8] 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. NRC is also working to compile lessons-learned from the aforementioned findings under

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[7] As part of the response to the events at Fukushima, NRC requested (Ref. [23]) that operating power plants perform a reevaluation of flooding hazards at their sites, considering all appropriate external flooding sources, using present-day regulatory guidance and methods. If the reevaluated hazard exceeds the plant's design basis, the plant is subsequently requested to perform an assessment of the plant's capability to respond to the reevaluated hazard. This assessment is known as an integrated assessment for external flooding. In 2012, the NRC published guidance to support the performance of the integrated assessments in JLD-ISG-2012-05, "Guidance for Performing the Integrated Assessment for External Flooding" (Ref. [13]).

[8] Information notices communicate operating or analytical experience to the nuclear industry. Information notices may also communicate the results of recently completed research. The industry is expected to review the information for applicability and consider appropriate actions to avoid similar problems

the Reactor Oversight Process (e.g., as described in Ref. [9]). Analysis of these lessons learned provides important insights into the risk and reliability of flood protection.

As part of a larger effort related to external flooding PRA, NRC is implementing a Research Plan (Ref. [19]) related to probabilistic flood hazard assessment as well as assessment of flood protection reliability and performance. The effort will include technical research related to the assessment of the performance and reliability of: exterior barriers; incorporated barriers; temporary protective measures; and operator manual actions associated with flood protection and mitigation. Activities to be undertaken under the Research Plan relative to flood protection include:

- Compilation of available information on reliability of active and passive flood protection features, including lessons learned from implementation of related Fukushima NTTF recommendations.
- Development of guidance for the application of human factors and human reliability analysis methods to flood protection and mitigation procedures.
- Development of methods for evaluating total plant response to flooding events using PRA and/or margins analysis approaches.

The efforts under the Research Plan are intended to build upon the existing state of knowledge and begin to address some of the aforementioned challenges. This is intended to support practical improvements in the state of practice for external flooding PRA.

CONCLUSION

Estimation of flood fragility involves the evaluation of the susceptibility of plant SSCs to damage or failure as a function of the severity of external flooding. There are a number of challenges associated with the current state of practice in external flooding PRA, and more specifically addressed in this paper, the assessment of flood fragilities. These challenges are described in this paper along with recent NRC efforts aimed at addressing some of these challenges.

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DISCLAIMER

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

REFERENCES[9]

[1] U.S. Nuclear Regulatory Commission, 60 FR 42622, Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities: Final Policy Statement, 8/16/95.

[2] M. T. Schultz, B. P. Gouldby, J. D. Simm and J. L. Wibowo, ERDC SR-10-1, "Beyond the Factor of Safety: Developing Fragility Curves to Characterize System Reliability," U.S. Army Engineer Research and Development

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[9] Many of the references below include accession numbers for use in conjunction with the NRC's Agencywide Documents Access and Management System (ADAMS).

Center, Geotechnical and Structures Laboratory, 2010.

[3] Florida Power and Light Company, St. Lucie Unit 1, Licensee Event Report 2014-001-03, 2014.

[4] U.S. Nuclear Regulatory Commission, NRC Information Notice 2015-01: Degraded Ability to Mitigate Flooding Events, ADAMS Accession No. ML14279A268, 2015.

[5] U.S. Nuclear Regulatory Commission, Arkansas Nuclear One - NRC Augmented Inspection Team Report 05000313/2013011 And 05000368/2013011, ADAMS Accession No. ML13158A242, 2013.

[6] U.S. Nuclear Regulatory Commission, Arkansas Nuclear One – NRC Augmented Inspection Team Follow-Up Inspection Report 05000313/2013012 and 05000368/2013012; Preliminary Red and Yellow Findings, ADAMS Accession No. ML14083A409, 2014.

[7] U.S. Nuclear Regulatory Commission, Official Transcript of Proceedings, Advisory Committee on Reactor Safeguards 595th Meeting, ADAMS Accession No. ML12165A588, Thursday, June 7, 2012.

[8] Entery Nuclear Operations, Licensee Event Report 05000271/2013-001-00, Potential to Flood Switchgear Room Due to Missing Conduit Flood Seal, 2013.

[9] F. Ferrante, “External Flooding in Regulatory Risk-Informed Decision-Making for Operating Nuclear Reactors in the United States,” in International Topics Meeting on Probabilistic Safety Assessment and Analysis (PSA 2015), Sun Valley, ID, USA, ADAMS Accession No. ML15152A290, April 26-30, 2015.

[10] U.S. Nuclear Regulatory Commission, NRC Inspection Manual Chapter 0609, ADAMS Accession No. ML14153A633.

[11] The American Society of Mechanical Engineers, Addenda to ASME/ANS RA-Sa-2009, Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, 2009.

[12] U.S. Nuclear Regulatory Commission, “Fire Barrier Penetration Seals in Nuclear Power Plants,” NUREG-1552, ADAMS Accession No. ML070600315, 1996.

[13] U.S. Nuclear Regulatory Commission, "Guidance for Performing the Integrated Assessment for External Flooding," JLD-ISG-2012-05, ADAMS Accession No. ML12311A214, November 30, 2012.

[14] A. DerKiureghian, “Bayesian methods for seismic fragility assessment of lifeline components,” Acceptable Risk Processes: Lifelines and Natural Hazards, ASCE, pp. 61-77, 2002.

[15] J. W. Baker and C. Cornell, “Choice of a Vector of Ground Motion Intensity Measures for Seismic Demand Hazard Analysis,” in 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, August 1-6, 2004.

[16] B.Russo, M.Gomez and F.Macchione, “Pedestrian hazard criteria for flooded urban areas,” Natural Hazards, vol. 69, pp. 251-265, 2013.

[17] U.S. Nuclear Regulatory Commission, "Demonstrating the Feasibility and Reliability of Operator Manual Actions in Response to Fire," NUREG-1852, ADAMS Accession No. ML073020676, October 2007.

[18] U.S. Nuclear Regulatory Commission, “"EPRI/NRC-RES Fire Human Reliability Analysis Guidelines," NUREG-1921,” ADAMS Accession No. ML12216A104, July 2012.

[19] U.S. Nuclear Regulatory Commission, Probabilistic Flood Hazard Assessment Research Plan, ADAMS Accession No. ML14296A442, 2014.

[20] Entergy Nuclear Operations, Inc., Licensee Event Report 05000271/2012-001-01, Potential to Flood Switchgear Room Due to Missing Conduit Flood Seal, 2012.

[21] U.S. Nuclear Regulatory Commission, Regulatory Guide 1.102, "Flood Protection for Nuclear Power Plants," Revision 1, ADAMS Accession No. ML003740308.

[22] U.S. Nuclear Regulatory Commission, "Recommendations for Enhancing Reactor Safety in the 21st Century, The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident," Enclosure to SECY-11-0093, ADAMS Accession No. ML111861807, July 12, 2011.

[23] U.S. Nuclear Regulatory Commission, “Request for Information Pursuant to Title 10 of the Code of Federal Regulations 50.54(f) Regarding Recommendations 2.1, 2.3, and 9.3 of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident,” ADAMS Accession No. ML12053A340, March 12, 2012.

[24] Nuclear Energy Institute (NEI), "Guidelines for Performing Verification Walkdowns of Plant Flood Protection Features," NEI 12-07, Revision 0-A, ADAMS Accession No. ML12173A215, May 2012.

[25] U.S. Nuclear Regulatory Commission, Endorsement of NEI 12-07, "Guidelines for Performing Verification Walkdowns of Plant Flood Protection Features", ADAMS Accession No. ML12144A142, June 14, 2012.