External Flooding in Regulatory Risk-Informed Decision-Making For Operating Nuclear Reactors in the United States

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The United States (US) Nuclear Regulatory Commission (NRC) has made significant recent efforts in understanding the safety risk of various regulatory activities that include the impact of external flooding via insights from Probabilistic Risk Assessment (PRA) methods. In part, this stems from multiple actions taken after the Fukushima nuclear accident related to inspection findings and activities on flood re-evaluations in the United States. Hence, the NRC is currently engaged in reevaluating and enhancing its risk-informed tools, including the use of PRA modeling, in terms of improving the assessment of inspection activities with respect to regulatory decision-making in the area of external flooding.

Efforts in this area were initiated prior to the Fukushima nuclear accident in 2011, as the treatment of external flooding in risk analysis has long posed challenges not yet fully addressed for implementation in PRA. It is recognized, for example, that for different natural phenomena the maturity of available methodologies and data for assessing the likelihood of occurrence of hazards that may challenge plant safety varies significantly for different flooding mechanisms, and can involve wide uncertainty in both the intensity and frequency of an event. Specific findings related to flooding protection for a number of sites led to considerations on flooding frequency analysis in general, as well as the probabilistic treatment of specific flooding mechanisms, such as dam failures. Additionally, the actual flooding events in the Missouri River in April 2011 which challenged the flooding protection of Fort Calhoun Station also provided additional insights into flooding response and mitigation.

After the Fukushima accident, the NRC established a Task Force to review insights from this event and subsequent activities are on-going, which includes the reevaluation of potential flooding hazards for nuclear facilities regulated by the NRC. The NRC has also directly engaged other US government institutions in pursuing methodologies to both develop and establish a common understanding in the area of Probabilistic Flooding Hazard Assessment (PFHA) in terms of advancing and using risk tools a risk-informed decision making framework. This paper will include a discussion of relevant findings and events, the approaches used by the NRC in obtaining risk insights using readily available tools and methods, their relationship with the Fukushima Lessons-Learned activities, and areas of research.

I. INTRODUCTION

A significant effort related to the risk-informed consideration of external flooding impacts for operating reactors in the US has recently taken place in oversight activities for which the NRC is responsible. In the context of this paper, external flooding events include hazards resulting from a range of phenomena such as localized precipitation, riverine flooding, coastal surge, and other mechanisms that may produce a range of impacts at a nuclear power plant (NPP).

Efforts undertaken in this area by the NRC include development of risk assessments for reactor oversight, analysis of actual events, and consideration of enhancements needed to the existing capabilities for risk-informed decision-making in this area. In particular, the NRC is responsible for ensuring the effectiveness of the Reactor Oversight Process (ROP), which is the Agency'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, performed in coordination between Regional and Headquarters NRC staff.

While specific hazards are continuously evaluated and added to the suite of PRA tools and models available at the NRC for oversight activities, external flooding events remain a challenging area for quantitative risk modeling for a number of reasons. First and foremost, it is a highly site-specific hazard that depends on geographical, meteorological, hydrological, and hydraulic information needed to characterize potential events relevant to the site. Second, there is limited data available to characterize the ranges of interest in the PRA tools commonly applied to NPPs. For example, flood flow and/or precipitation gages usually include a limited available historical record of approximately 100 years for a single location and, therefore, characterizing the full spectrum of floods with an appropriate level of confidence (including characterization of data and modeling uncertainty) is challenging. In addition, external flooding events may include combinations of both natural and man-made hazards, such as a severe storm event followed by an operational dam failure that leads to the uncontrolled released of a large downstream or upstream reservoir. Various other combinations between meteorological and hydrological events can also provide relevant risk contributions and have been observed (see Section II.B). Appropriately addressing these potential combinations probabilistically requires characterizing the conditional probabilities of such events occurring, including any potential dependencies involved (e.g., a seismically-induced dam failure).

Finally, unlike seismic hazard assessments for NPPs, which have fully incorporated probabilistic concepts for both design and risk assessment[1], the current state-of-practice in flooding in this area is primarily deterministic and involves the incorporation of expert judgment and conservative analyses in the development of scenario-based events usually referred to as “probable maximum” phenomena. The main reference under this deterministic framework for the design of NPPs published by the NRC is Regulatory Guide 1.59, “Design Basis Floods for Nuclear Power Plants”[2], where “probable maximum” scenarios are hypothetical flood events used for design that include the most severe combination of critical conditions, theoretically converging on possible physical limit(s). This concept is currently applied to the range of flooding phenomena to include precipitation, river flood, tsunami, surge, and seiche. As described in NUREG/CR-7046, “Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America”[3], these events are considered to be the most severe reasonably possible at the location of interest and are thought to exceed the severity of all historically observed events. Despite the use of the “probable maximum” term to describe such events, there is no direct translation for their likelihood of occurrence and the probability of exceedance (although improbable) cannot be treated as zero in a probabilistic framework. Although more recent guidance on combined deterministic-probabilistic methods in surge hazard has been incorporated for specific regulatory applications[4], the deterministic approach still dominates flood hazard characterization for US NPPs.

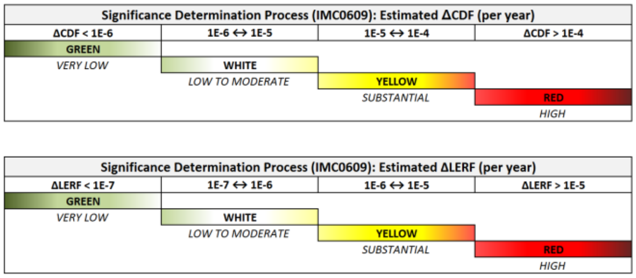
The NRC has engaged in discussions with other federal agencies and institutions in the development of a probabilistic flood hazard assessment (PFHA) framework via multiple initiatives such as workshop on the topic held on January 29–31, 2013[5], coordinated with the US Department of Energy (DOE), US Department of the Interior’s Bureau of Reclamation (USBR), US Geological Survey (USGS), US Army Corps of Engineers (USACE), and Federal Energy Regulatory Commission (FERC). In efforts such as these, the common themes on the challenges discussed above are highlighted and the insights from the discussions indicate additional activities needed in order to bridge the current state of knowledge between extreme flood assessments and risk assessments of critical infrastructures.

The next sections will discuss the role of external flooding in reactor oversight activities by the NRC; relevant sources of information; ROP findings and events associated with external flooding (pre- and post-Fukushima), the approaches used by the NRC in obtaining risk insights using readily available tools and methods, and their relationship with the Fukushima Lessons-Learned activities, as well as areas of research.

II. NRC’s SDP AND EXTERNAL FLOODING

External event risk contribution is a consideration for SDP analysis, Notices of Enforcement Discretion (NOEDs), and the NRC Incident Investigation Program for operating NPPs in the US. The NRC Inspection Manual includes a number of chapters related to the processing of external events-related information as risk insights to help determine the safety or security significance of inspection findings as part of the risk-informed SDP. Attachment 4 in the NRC’s Inspection Manual Chapter (IMC) 0609[6] discusses the initial screening and characterization of findings (i.e., SDP Phase 1) and includes external initiator contributor considerations.

For example, Appendix A to IMC 0609[7] includes risk significance and justification guidance for plant-specific estimates (i.e., SDP Phase 2), which directs the NRC inspector to SDP Phase 3 analyses (i.e., for findings departing guidance provided in Phase 1 or Phase 2) for initiators such as external events. Regardless of the initiator or condition, the NRC uses the thresholds shown in Figure 1 for the final determination of the safety significance of a finding (whether quantitative or qualitative). The guidance in IMC 0609 Appendix A states that “since there are a limited number of licensees who have external event PRA models, the Phase 3 analysis should not attempt to place more quantitative emphasis on the SDP result than is reasonable.” Furthermore, the potential impact of external events on inspection findings is acknowledged: “…accounting for external initiators could result in increasing the risk significance attributed to an inspection finding by as much as one order of magnitude.” With respect to SDP Phase 3 analyses, guidance is provided to consult the Risk Assessment Standardization Project (RASP) handbooks that contain technical guidance for modeling external event initiators[8].



Significance Determination Process (IMC0609): Estimated ΔCDF (per year)			
ΔCDF < 1E-6	1E-6 ↔ 1E-5	1E-5 ↔ 1E-4	ΔCDF > 1E-4
GREEN			
VERY LOW	WHITE		
	LOW TO MODERATE	YELLOW	
		SUBSTANTIAL	RED
			HIGH

Significance Determination Process (IMC0609): Estimated ΔLERF (per year)			
ΔLERF < 1E-7	1E-7 ↔ 1E-6	1E-6 ↔ 1E-5	ΔLERF > 1E-5
GREEN			
VERY LOW	WHITE		
	LOW TO MODERATE	YELLOW	
		SUBSTANTIAL	RED
			HIGH

Fig. 1. The ΔCDF and ΔLERF thresholds used for determining the safety significance of an inspection finding in SDP by the NRC.

As highlighted in the previous section, potentially risk-significant contributions from external events that are not currently modeled explicitly are acknowledged in the PRA community and past ROP experience. External events can also be dealt with in SDP via an approach developed on the premise of the unavailability of detailed PRA models. This extends to the PRA models used by the NRC, i.e., the Standardized Plant Analysis Risk or SPAR models[9].

When specific quantitative results are not available, a specific process within NRC's SDP framework can be used for overall qualitative decision-making: IMC 0609 Appendix M, "Significance Determination Process Using Qualitative Criteria"[10]. In this process, guidance is provided for assessing the significance of inspection findings when the PRA methods and tools, including more quantitative guidance contained in other IMC 0609 appendices, cannot adequately address the finding's complexity or provide a reasonable estimate of the significance due to modeling and other uncertainties that challenges the timeliness of NRC's decision-making. This includes situations where the uncertainties associated with a risk evaluation using an existing SDP tool are too broad for decision-making. The Appendix M process then allows for consideration of bounding quantitative and/or qualitative evaluation, if feasible, using best available information to determine the initial significance of the finding. If this shows that a finding could be quantified as exceeding the ΔCDF threshold of 1E-6/year (i.e., above the "Green" threshold), then specific qualitative attributes need to be considered to determine the significance of the finding. These include considerations of (1) defense-in-depth elements, (2) reduction in safety margin, (3) extent to which the condition of the performance deficiency affects other equipment, (4) degree of degradation of failed or unavailable components, (5) period of time the performance deficiency existed; and (6) likelihood that the licensee's recovery actions would successfully mitigate the performance deficiency. As it will be discussed in Section IV, many findings assessed in ROP by the NRC in the post-Fukushima timeframe challenged the use of quantitative tools and the Appendix M process had to be used for multiple findings.

III. PRE-FUKUSHIMA ACCIDENT INSIGHTS

The impact of external flooding as a risk contributor has been acknowledged in seminal studies on PRAs for specific NPPs such as "NSAC/60: Oconee PRA: A Probabilistic Risk Assessment of Oconee Unit 3" by the Nuclear Safety Analysis Center (NSAC) of the Electric Power Institute (EPRI) performed in 1984[11]; as well as several IPEEE submittals performed through the 1990s in response to the NRC's issuance of Supplement 4 to Generic Letter (GL) 88-20, "Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities"[12].

In some cases, these studies incorporated explicit components of external flooding in their analyses, while in many instances this hazard was screened from further analyses using semi-quantitative or qualitative insights. One example where external flooding was incorporated explicitly was the series of studies performed in the 1980s for the NRC by the Sandia National Laboratories (SNL) on shutdown decay heat removal analysis for the different nuclear steam supply system (NSSS) designs used in the US (e.g., NUREG/CR-4710[13]). In these latter studies, the concepts of hazard curves for site-specific flooding mechanisms, the development or adaptation of event sequences for flooding scenarios, consideration of flooding fragilities for specific components, and the overall characterization of external flooding CDF was performed with the information available at the time; indicating that such implementation is indeed amenable to PRAs for NPPs. On the other hand, additional developments in the characterization of flood hazards, consideration of uncertainties, and the enhancement in the capability and complexity of plant PRAs to model such events has significantly evolved since all the aforementioned studies were developed. While a more detailed review of past literature is beyond the scope of this paper, these studies indicate that the issue of external flooding assessments within PRAs for NPPs is not a new issue and, furthermore, that the challenges identified earlier are not intended to imply this hazard includes complexities that would impede further development and application.

More recent additional items identified within NRC's regulatory oversight before the Fukushima Accident in March 2011 are discussed below. This also highlights that the NRC's understanding on external flooding in particular (and natural hazards in general) was in progress well before March 2011 and continues to evolve as new information and methods are made available. While other external flooding issues had been considered in the past, these two findings highlight specific aspects of the challenges in dealing with this hazard within NRC's ROP framework, as well as the importance of flooding contributors to overall plant safety.

III.A. Oconee Standby Shutdown Facility Finding

An SDP was performed with respect to a finding at the Oconee Nuclear Station (ONS) involving the failure to effectively control maintenance activities and to assess and manage the risk associated with removing an access cover in a wall of the standby shutdown facility (SSF) to facilitate installation of temporary electrical power cables[14]. The NRC used a blended qualitative and quantitative assessment to issue a final significance determination of a "White" finding for this deficiency (i.e., low to moderate safety significance, see Figure 1). Part of this deficiency included the evaluation of dam failure frequency estimates, including historical values originally issued under NSAC/60.

This eventually led to the issuance of an NRC Information Notice (IN) 2012-02 titled "Potentially Nonconservative Screening Value for Dam Failure Frequency in Probabilistic Risk Assessments"[15] which referred to NSAC/60 and other sources. In this IN, the NRC staff reviewed currently available databases for US dams in order to determine generic dam failure frequencies based on (1) the number of historical failures of dams of a particular characteristic, such as dam type, and (2) the total number of years of operation for dams of the same characteristic. Although the most recent information was used (see IN reference for details), it was observed that specific inherent challenges existed in the databases reviewed with regards to completeness of failure event accounts (e.g., construction year of failed dam and failure mode) and the consistency of definitions used on both failed and operating dams (e.g., dam types). In particular, eliminating selected failure modes from consideration without sufficient technical basis while retaining the population contribution for total number of years can produce an artificially low dam failure frequency. In conclusion, the IN indicated that a generic failure frequency estimate used in previous references combined generic information with site-specific screening criteria that produced median values lower than those obtained by the NRC staff as well as those available in published literature.

This IN was not focused on the specific dam failure frequency for any single dam, but instead tried to highlight the fact that data available in these databases can be useful in identifying failure mechanisms and performance insights as well as approximate generic dam failure rate estimates, but may not provide sufficient basis for site-specific estimates or to screen out the contribution of external flooding sources or loss of ultimate heat sink to the overall plant risk.

III.B. Fort Calhoun Flooding Strategies Finding

In January 2010, the NRC had identified specific inadequacies at Fort Calhoun Station (FCS) with respect to the protection of buildings against the impact of flooding events via inspections at the FCS site. In particular, the NRC indicated that the FCS site flood protection strategy may not be fully effective during worst-case Missouri River flooding scenarios[16]. This lead to the assessment by the NRC of a violation against NRC requirements that eventually was also considered under the NRC's ROP. In this case, the NRC determined that a "Yellow" finding (i.e., a finding of substantial safety significance, see Figure 1) was appropriate[17].

This finding included a discussion of an extrapolated flood hazard curve for precipitation; runoff and snow melt for the FCS site based on available data. To estimate ΔCDF, insights from flood hazard information were coupled with a risk assessment developed for the purposes of this finding, considering the impact to the site and the available mitigating actions in a flooding scenario that exceeded plant grade elevation. Limited information from the FCS IPEEE study could be used in this case, although a study of values published in the IPEEE submittal were used for sensitivity purposes. For mitigating actions, the assessment of the credit for actions such as installing weld steel plates over the entrances of specific buildings that would be impacted by the flood were considered (ranging between 0.31 and 0.4 probability of failure in implementing the action, given available human reliability assumptions).

Specific challenges associated with flooding issues post-Fukushima were highlighted in this finding, such as: (1) credit for hardening a facility prior to flood waters affecting the site, and (2) assessing credit for limited available actions during a flood scenario based on timing availability (e.g., procuring additional equipment during or after the flood). After issuing a preliminary finding determination in the "Yellow" range, the NRC considered information provided by licensee during a public meeting (i.e., a Regulatory Conference between the NRC and the specific licensee, as stipulated by the SDP process) and it found that some additional credit for hardening the facility over a 2-day period was warranted, in addition to a revised failure rate for mitigating equipment. However, the NRC's ΔCDF estimate still exceeded the threshold of 1E-5/year. Consideration of the information provided by the licensee via the qualitative IMC 0609 Appendix M approach in SDP was also evaluated and the finding was reaffirmed as "Yellow" when assessing issues such as defense-in-depth and safety margin aspects.

IV. POST-FUKUSHIMA ACCIDENT INSIGHTS

Significant focus and effort was directed at natural hazards in general (and external flooding and seismic initiators in particular) with regards to NPP safety worldwide after the events that resulted in severe accident conditions (i.e., core damage) at multiple units at the Fukushima Dai-ichi NPP site in Japan. Within the US, the NRC published a report titled "Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review Of Insights From The Fukushima Dai-Ichi Accident" [18], in response to Commission direction to conduct a systematic and methodical review of NRC's processes and regulations to determine whether the agency should make additional improvements to its regulatory system and to make recommendations to the Commission for its policy direction, in light of the accident at Fukushima Dai-chi. While a discussion of the NRC's Near Term Task Force (NTTF) report (or the Fukushima Accident) is beyond the scope of this paper, its relationship with NRC's ROP will be presented in the following sections. However, before discussing these issues, it is important to also mention the insights of the Missouri flooding aspects which took place immediately after the Fukushima Dai-ichi Accident in 2011 and the insights it provided, since a finding related to external flooding protection had taken place one year prior as discussed in Section III.B.

IV.A. Missouri River Flooding

Between May and September of 2011, the Missouri River in the United States was impacted by a number of hydrological and meteorological events that resulted in significant flooding conditions affecting multiple communities and infrastructure. One of the facilities that experienced this event was the FCS site, located in the state of Nebraska. It also impacted the Cooper Nuclear Station, located downstream from FCS; as well as other power-generating facilities, numerous substations, and transmission and distribution lines located near the river [19].

The FCS site is located on the west bank of the Missouri River, north of the town of Omaha, Nebraska. In the months leading up to June 2011, a mixture of above normal snowpack conditions, lower than expected temperatures, and record precipitations across various parts of the basin produced severe flooding conditions. A series of storms in May 2011 raised the total amount of precipitation to exceed more than 300 percent above normal. As indicated by the US Army Corps of Engineers (USACE), certain areas received a total amount of rain within two weeks that would be comparable to the expected total precipitation in one year[20]. The USACE, which is responsible for the operation of multiple dams upstream of the FCS site, authorized the record release of outflow volume from multiple dams in order to manage the severe flooding across the river system, with significant flooding impacts downstream.

The FCS site had entered a planned shutdown in early April 2011 for a scheduled refueling outage. During late May 2011, the impact of the raising elevations in the Missouri River led to the initiation of preparations to protect the site against flooding impacts. The FCS site procedures against flooding include actions to protect specific buildings within the site up to 1014 feet [309 meters] above mean sea level (MSL) per licensing basis[16]. In preparation for the flood, the FCS site staged needed materials and equipment for protecting critical areas and functions (e.g., portable pumps, fuel containers, tanks, and generators); and initiated sandbagging and installation of flood gates[21]. For example, an earthen-berm was built around the switchyard for additional protection against flooding[22].

By early June 2011, the FCS site expected the Missouri River level at the plant to reach 1004 feet [306 meters] above MSL (the base plant elevation). Once 1004 feet [306 meters] above MSL was exceeded, mobility around the site had to be performed with a series of raised scaffold walkways and bridges. Flood waters eventually surrounded the switchyard, the dry-cask storage area, the power block (i.e., containment and auxiliary buildings), and support buildings, (e.g., administrative building, training center, security building). In addition, the main buildings were protected by a water impounding device (i.e., the terms "aqua-dams" or "aqua-berms" have been used to identify them) which consisted of an empty rubber bladder filled with water. The river level peaked around 1007 feet [307 meters] in late June. The aqua-dam around the power block was inadvertently punctured due to onsite activities and caused operators to briefly disconnect from offsite power[23].

Due to the flooding impacts and other longstanding technical issues, the NRC determined that special additional oversight was needed for the FCS site. The licensee discussed post-flooding recovery actions and agreed not to restart the unit without NRC approval on July 27, 2011[24]. The flood waters receded below site grade elevation in late August 2011. After further NRC oversight to ensure commitments were met, the approval for restart was granted and the unit restarted in December 2013.

IV.B. Flooding Walkdowns

Specific recommendations in the NRC's NTTF Report included (1) seismic and flooding reevaluation and consideration to upgrade as necessary the design-basis seismic and flooding protection of SSCs for each operating reactor, and (2) performance of 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.

On March 2012, the US Nuclear Regulatory Commission (NRC) issued a letter[25] to all US NPP licensees requesting the implementation of flood protection walkdowns which included the considerations to identify and address plant-specific degraded, nonconforming, or unanalyzed conditions, as well as, cliff-edge effects through the corrective action program and consider these findings in flood hazard reevaluations; among other actions. A flooding walkdown procedure developed by the Nuclear Energy Institute and endorsed by the NRC 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[26]. The implementation of these walkdowns was part of a short-term action to be performed while the NRC implements the longer-term hazard reevaluations and associated integrated assessment as part of its Fukushima Lessons-Learned activities. While the event at Fukushima was caused by a tsunami, the guidance specifies consideration of protection for all flooding mechanisms (e.g., surge, river flooding, local intense precipitation) included in the plant's design basis.

IV.C. SDP Flooding Walkdowns-related Findings

From the NRC's NTTF flooding walkdown activities, a number of performance deficiencies were identified at US NPPs that entered into the ROP framework. Specific performance deficiencies were then screened as findings and required further assessment in a more detailed risk evaluation or analysis. Table I shows a list of the greater than green findings per plant, including final significance determination (except as noted) and associated references where additional detailed information beyond the scope of this paper can be found. Additional information about all the findings can be obtained via the ML numbers provided which can be obtained directly from NRC's official electronic recordkeeping system, i.e., Agencywide Documents Access and Management System (ADAMS).

It should be noted that this represents a significant number of SDP evaluations performed within a relatively short time frame (e.g., 3 years) all associated with a specific hazard (external flooding), especially when compared to pre-Fukushima ROP activities. Each SDP evaluation required site-specific considerations for the hazard (e.g., coastal surge, riverine flooding, dam failures), as well as an assessment of the plant protection and mitigation available to respond to this hazard. From this information, a decision was based on qualitative/quantitative considerations that included risk assessment evaluations to calculate ΔCDF and ΔLERF estimates. For the vast majority of these cases, IMC 0609 Appendix M was used, although in many cases quantitative estimates were also developed based on best available information by the NRC. Licensees also often provided estimates in response to the NRC's preliminary significance determination results.

Two specific findings that encompass several characteristics observed throughout these SDPs are presented next.

TABLE I. List of SDPs related to external flooding inspection findings per plant, final significance determination color and associated reference.

NPP Site	Significance Determination	Reference
St. Lucie[†]	White	ML14294A466
Ginna	White	ML14107A080
Point Beach	White	ML13221A187
Monticello[†]	Yellow	ML13240A435
Dresden	White	ML13213A073
Three Mile Island	White	ML13042A277
Watts Bar[*]	White	ML13155A572
Watts Bar[*]	Yellow	ML13155A572
Sequoyah[*]	White	ML13155A560
Sequoyah[*]	White	ML13155A560

[†] Discussed in more detail in the following sections.

[*] Two separate findings are discussed in the references for Watts Bar and Sequoyah.

IV.C.1. Monticello Flood Plan Finding

During the NTTF flooding walkdown, a finding was identified associated with the failure to maintain a flood plan to protect the site from external flooding events. More specifically, the finding impacted the capability to support the timely implementation of flood protection activities within the timeframe credited in the design basis[27]. If the necessary flood actions were not completed in time, then the station's accident mitigation equipment could be negatively impacted by flood waters.

The current licensing basis flood for Monticello is a probable maximum flood derived from rain and snow melt estimations, determined to result in a flood elevation of 939.2 feet [286 meters] above MSL. Procedures direct the licensee to build a ring levee around a significant portion of the protected area, including the turbine, reactor and control building; among other facilities. Current licensing basis specifies that 12 days would be needed for completion of flood protection activities. The NRC identified that the levee construction timeline based on existing evaluations would have taken longer than 12 days to complete and that specific critical path actions early in the process of constructing the levee would be challenged if needed material and resources were not made available in advance.

At the time of the finding, flooding above plant grade is assumed to always lead to a station blackout per procedural actions to de-energize substation equipment and emergency power would be assumed lost because supporting components (e.g., diesel fuel oil storage tank) would have been impacted by the failure to construct the levee. Available inventory control options during an extended blackout would be the use of reactor core isolation cooling (RCIC) and decay heat removal option via hard pipe venting. Both actions were proceduralized and instituted for protection against internal flooding studies.

Based on this information, a simple set of event trees were developed that required hazard frequency information for exceeding specific flood elevations and the modeling of subsequent actions to prevent CDF. The inclusion of the action to successfully construct the ring levee allowed for the estimation of a ΔCDF since this is dependent on the change in the probability of core damage given failure to install the levee/bin walls prior to flooding.

Flood frequencies were used to represent relevant elevations contributing to the ΔCDF, derived using a curve fit technique with data from available information (i.e., the licensee's updated safety analysis report, USAR, and IPEEE submittal. It was recognized that there are no standard techniques or consensus methods to extrapolate flood frequencies in the ranges of interest (i.e., less than 1E-5/year annual exceedance probability) and that the method employed to obtain the frequencies were based on judgment. However, as prescribed in Appendix M, these allowed for a bounding quantitative assessment to be performed and for additional qualitative criteria to be considered. In terms of risk assessment insights, it was judged that the uncertainty associated with the flood frequencies was very high. In addition, the failure to run probability for RCIC was assumed to be high given the increased mission time of the pump following of an external flooding event compared to an internal event. For specific manual operation based actions, the NRC's SPAR-H Human Reliability Analysis (HRA) method[28] was used to estimate human error probabilities (HEP). Like flood frequency, uncertainty is inherent in these human failure probability estimates since under flooding circumstances procedures are less developed or practiced and plant configurations will change over time. It was fully recognized that HRA methods for evaluating such actions are not well established and that the focus of SPAR-H is on control room crew performance. However, in the absence of alternatives, the SPAR-H framework was used to provide an estimate that accounts for issues such as timeliness, ergonomics, and stress while performing these actions. The HEPs were given values ranging from 0.11 to 0.43 (and 1.0 for the case of failure to build the ring levee).

Sensitivity studies were performed to evaluate the influential assumptions with a resulting ΔCDF range of 8.1E-7/year to 9.4E-5/year; with a best estimate of 3.6E-5/year (i.e., "Yellow" in the SDP levels shown in Figure 1). Based on qualitative insights, the NRC staff determined this finding reduced the defense in depth of the site's flooding protective strategy which in turn decreased the safety margin for protection against external flooding events.

In response to the NRC analyses, the licensee provided a letter in which information regarding the various assumptions made by the NRC was included[29]. The information focused on (1) assumptions regarding the slow progression of a PMF event and the availability of time to respond to the event despite the performance deficiency, (2) additional analyses of flood frequency extrapolation that resulted in lower initiating flood frequency values than those NRC used, (3) reevaluation of HEPs associated with the operator manual actions in the sequences developed by the NRC, and (4) performance of a subsequent simulation to demonstrate that the ring levee could be installed within the available time. The NRC concluded that the uncertainty of the frequency estimates was large enough that the NRC's preliminary estimation of frequency remained valid and unchanged when weighted against defense-in-depth and other risk-informed information. Considerations of supporting assumptions used to derive the HEPs likewise led to the conclusion that the values used for the failure to operate RCIC during extended flood-induced Station Blackout scenarios should remain unchanged in the NRC analyses. In conclusion, the preliminary significance determination was reaffirmed as "Yellow".

IV.C.2. St. Lucie Degraded Conduits Finding

Another finding related to external flooding was recently given a final determination at the St. Lucie Plant Units 1 and 2, located in Florida[30]. This finding involved the failure to implement measures to ensure the watertight integrity of the Unit 1 reactor auxiliary building (RAB) below the design basis flood elevation when electrical conduits that penetrated the RAB wall were installed without internal flood barriers. This deficiency manifested itself during a storm on January 9, 2014. On that day, the St. Lucie site experienced a period of heavy rainfall, and approximately 50,000 gallons of water entered the RAB at an elevation of 0.5 feet [0.15 meters] below site grade through two degraded conduits in the emergency core cooling system (ECCS) pipe tunnel. As discussed in the Licensee Event Report (LER) submitted to the NRC[31], the cause of the internal flooding from the localized heavy rainfall was due to back up in the storage capacity of the site's storm drain system. This led to the accumulation of water in an area adjacent to the main buildings, including the RAB for Unit 1, which eventually flowed into the

ECCS pipe tunnel. Degraded conduits in this tunnel then created a flood path into the RAB, eventually entering the building through an electrical junction box which was below the elevation for which the RAB flood protection was designed. The flood waters then reached ECCS pump room sumps at a lower elevation in the RAB via drain systems connecting from the 0.5 feet [0.15 meters] below site grade elevation. Due to the continuous inflow of water from an external source, closing of the ECCS sump isolation valves to preclude flooding of the ECCS pump room would then cause flood at the higher elevation to continue to rise. This was addressed by a decision to cycle the ECCS sump isolation valves to allow for a controlled removal of the water inflow in both RAB elevations via the ECCS sump pumps. Although the event exceeded the site's storm drain system capacity, once the heavy rainfall subsided, drainage was regained and the flood waters internal to the RAB were removed without impact to accident mitigation and safe shutdown equipment.

After the event, the NRC assessed that the licensee had failed to install internal flood barriers in conduits that penetrated the Unit 1 RAB exterior wall at elevations below the design flood height. In addition, the NRC concluded that these missing flood barriers were not identified during flooding walkdowns performed in response to the NRC's NTTF Recommendation 2.3. As such, the failure to implement measures to ensure the watertight integrity of the Unit 1 RAB resulted in a condition where external flood water was able to enter the Unit 1 RAB and challenge the operability of safety-related equipment.

For this finding, IMC 0609 Appendix M was also used. A bounding quantification of the risk then identified various qualitative factors that could affect the final values, either increasing or decreasing the preliminary significance determination, per process. A risk evaluation was performed that included the development of event trees for various plant modes and consideration of how the performance deficiency would be impacted by various site-specific hazards that include a hurricane-induced coastal surge, localized heavy rainfall, and internal flooding.

For the hazard frequency information, available data from the National Oceanic and Atmospheric Administration (NOAA) and other references were gathered to estimate approximate values for heavy rainfall and the probabilities associated with hurricane rainfall and intensity. Since the performance deficiency manifested itself at a much lower elevation than the design bases prescribed for protection, risk contribution from more frequent, albeit less intense storms also needed to be considered. However, for the ΔCDF estimation purposes, the full range up to more extreme events was considered, as prescribed in SDP guidance, to assess how potential scenarios would have impacted the site differently than observed on January 9, 2014. Since the protection features were intended to maintain the RAB dry for the elevations impacted by the rainfall, an assumption was made that the CDF estimate for the scenarios affecting the RAB essentially represented the ΔCDF contribution (i.e., negligible contribution if the performance deficiency was not present when compared to the degraded condition).

The dominant risk scenario was a postulated event where the plant is operating at full power when a significant rainfall event occurs (12 or more inches [30.5 centimeters]), a reactor trip occurs, and the floor drain valves in the RAB that isolate the ECCS rooms during a flooding event fail to close allowing water to flow unobstructed and submerge all of the ECCS pumps. Due to the nature of the event and the impact to ECCS systems in some scenarios, additional recoveries beyond 24 hours were considered based on the availability of multiple success paths to core cooling capability. Based on this qualitative information, along with estimated quantitative ΔCDF values ranging from 3E-6/year to 1E-5/year, a preliminary significance determination of "White" was issued. The licensee chose to respond with a letter[32] that did not challenge the assumptions made by the NRC in its risk assessment, and the "White" finding was made final.

V. INSIGHTS FROM OVERSIGHT ACTIVITIES

From the previous two sections, a selected discussion of specific insights obtained via NRC's oversight activities was presented. These highlight a significantly wider range of details, analyses, and additional insights beyond what can be presented in this paper. Therefore, additional references are provided for specific findings that were not included explicitly in the two findings discussed in sections IV.C.1 and IV.C.2. Ultimately, there is a significant body of experience that supports a number of specific insights discussed next.

First and foremost, developing flood hazard estimates to be used as initiating event frequency inputs into any risk assessment for the estimation of CDF in operating NPPs is still a challenging aspect (and it was the main driver for decision-making). Several licensees used available methods and data to extrapolate frequencies of events such as PMP and PMFs for use in quantitative analyses. As discussed in the workshop held at the NRC in January 2013, extrapolating the frequency of extreme events such as the PMP and the PMF are still a subject of significant debate in the state-of-practice and the state-of-art implementation of probabilistic flood hazard assessments. While some state-of-art approaches were discussed in this workshop and have been used in certain applications (e.g., such as the stochastic-based modeling of flooding phenomena for specific watersheds as opposed to more extrapolation-focused techniques), there are still challenges involved in estimating frequencies with limited data and techniques beyond the typical limits of extrapolation usually attributed as credible in the state-of-art. It was recognized that different ranges of frequencies may be supported by different sources of data and methods available. For example, the flow-based extrapolation uses an approach described in Bulletin 17B of the Hydrology Subcommittee, Interagency Advisory Committee on Water Data, “Guidelines for Determining Flood Flow Frequency” (1982) published by the US Department of Interior[33]. It is recognized that the applicability of this method is limited to AEPs in the ranges closer to the available historical record. As stated during the workshop held at the NRC, the applicability of such a method was not intended for AEPs in the range of 1E-4/year (or less likely events). Similarly, as discussed in the US Department of Interior, Bureau of Reclamation Report DSO-04-08 “Hydrologic Hazard Curve Estimating Procedures”[34], there is a relationship between the quality and quantity of data available and the limit on credible extrapolation flood estimates. This includes some of the methods used in the precipitation-based approaches (e.g., L-moments), as well as other methods not included in the ANO estimates (e.g., paleoflood information). Even when combined with “optimal” information, a limit of 1E-4/year or 10,000 years for credible information is acknowledged. While this USBR report focuses on areas in the western US, the discussions in the workshop held at the NRC in 2013 indicated these challenges exist when dealing with limited information throughout NPP sites in the US (some sites may be more amenable to collecting additional information such as paleoflood, although even in these cases the extrapolation beyond certain ranges may be limited).

The resulting impact from this insight is that significant uncertainty is included in any estimates derived from either extrapolations based on limited data or even state-of-art approaches (i.e., a significant reason for the extensive use of IMC 0609 Appendix M throughout the multiple SDP findings). This is not meant to imply that PRA applications for external flood are limited by the current hazard characterizations tools since treatment of uncertainty is one of the benefits provided by the use of probabilistic tools. Rather, it is the appropriate consideration of this aspect for risk-informed decision-making, where a balanced approach between specific attributes (e.g., defense-in-depth, safety margin) and quantitative initiating event frequency estimates should be considered that is the real insight from the experience gained. This is not to imply that quantitative estimates were not considered in the decision-making by the NRC in these SDPs (in some cases, similar data and tools were used as those available to the licensees), but that they were considered within the balanced process provided by IMC 0609 Appendix M.

A second major insight is the issue posed by consideration of deterministic-based “probable maximum” scenarios in flooding. For many findings, specific impacts of performance deficiencies below the flood elevations prescribed by these events were needed. Hence, a full range hazard curve that includes both relevant extreme events as well as more likely, less intense scenarios would provide more optimal risk information. This can be immediately compared to seismic hazard characterization for NPPs which, for the state-of-practice, has incorporated probabilistic concepts and, therefore, captures the ranges of ground motion intensities and their likelihood explicitly via seismic hazard curves (and associated uncertainties). While, again, this challenge does not preclude the consideration of risk insights in external flood risk assessment, it is an important aspect of ensuring the more complete list of contributors is captured. Due to the various flood mechanisms associated with any specific site, it is possible that a flood hazard curve could be a composite of different contributors (e.g., dam failure for certain ranges, and localized intense precipitation for other ranges). Ultimately, a main benefit of PRA applications is that they may indicate contributors of less intensity but more significant risk impacts than the “probable maximum” events, depending on protection and mitigation actions.

Other insights include the issue of estimating HEPs for events outside the control room which may include the construction of flood protection, ranging from installing steel plates and/or sandbagging building entrances to building levees (as in the case of Monticello). It was recognized that no single HRA method exists to evaluate actions which need to be performed during potential significant challenges resulting from an extreme flood (e.g., with significant stress and mobility issues). In order to be able to risk-inform a decision, some of the existing framework to assess the factors that could impact such actions was used. In addition, reliability data for structures and components affected by flooding is scarce. For several findings, deficiencies were identified with the existing flood sealing protection (similar to the finding discussed in Section IV.C.2) and assumptions were made about the impact of the degradation on the reliability of specific components (i.e., either assumed failure or assessed via sensitivities). In a similar way, credit for the reliability of the aforementioned temporary barriers themselves was also dependent on qualitative judgment. Finally, the consideration of timing aspects is also an important insight. Assumptions about the duration of the event, advanced warning, and their impact on actions that could take place prior and during a flood (e.g., if the site is flooded for the duration of the event at FCS) were discussed in these SDPs and also subject to qualitative judgment.

VI. CONCLUSIONS

This paper presents some of the major insights of the wide ranging experience gained by the NRC in assessing inspection findings related to external flooding under the ROP framework. The insights suggest the importance of external flooding as a risk contributor as well the need for additional support in the enhancement of the technical basis and risk tools to support such activities as areas of research.

The items that correlate back to the application of NPP PRAs are (1) the detailed modeling of sequences specifically related to external flooding that need to be considered, (2) the quantification of SSCs such as flood seals and flood protection that are credited in specific scenarios, and (3) the evaluation of operator manual actions outside the control room involving flood mitigation activities (e.g., manual actuation of equipment, implementation of flood barriers). Each of the two examples discussed in detail here covers aspects of the challenges and issues associated with the risk assessment of this hazard as well as how these challenges were handled quantitatively and qualitatively using NRC's process and guidance. While the intent of this paper is not to provide a general framework or specific assistance on how external flooding PRA should be handled, it does indicate how existing tools were used to inform decision making based on PRA insights. This included a discussion of available sources of data for hazard characterization, specific details on accident scenarios modeled, and quantification of equipment failure data and operator actions with knowledge of the limitations and context in which the results were produced.

Suggestions for the enhancement of the technical basis and tools for external flooding would be based on the discussion presented in Section V:

(1) Development of robust flood hazard estimates to be used as initiating event frequency inputs into NPP PRAs that account for the availability and quality of data, and modeling approach used (with appropriate consideration of uncertainty and the level of confidence on best estimates).
(2) Enhancement of available external flooding PRA modeling guidance so that accident scenarios that consider the relevant impacts to the site and the corresponding site response are appropriately incorporated into existing PRAs.
(3) Development and/or enhancement of existing tools for estimating HEPs for events outside the control room in situations that involve extreme events.
(4) Development of methods to collect/estimate reliability of specific components that may be credited specifically for external flooding scenarios such as temporary/permanent flood barriers.

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