Probabilistic Flood Hazard Assessment

Research Plan

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ENCLOSURE

1 Introduction

This Probabilistic Flood Hazard Assessment (PFHA) Research Plan outlines research that the Office of Nuclear Regulatory Research (RES) will perform to enhance the U.S. Nuclear Regulatory Commission's (NRC's) risk-informed and performance-based regulatory approach with regard to external flood hazard assessment and safety consequences of external flooding events[1]. This plan describes a body of research that will establish a technical basis and regulatory tools incorporating use of risk-informed approaches for application to licensing and oversight of commercial nuclear facilities. The current limited risk-informed guidance with respect to flooding constitutes a significant gap in the NRC's risk-informed, performance-based regulatory approach to the assessment of natural hazards and potential consequences for safety of commercial nuclear facilities[2].

1.1 Purpose

This plan is designed to support development of regulatory tools (e.g., regulatory guidance, standard review plans, and regulations) for permitting new nuclear sites, licensing of new nuclear facilities, and oversight of operating facilities. The probabilistic technical basis developed under this plan will provide a risk-informed approach for future regulatory decisions and, as needed, rulemaking.

In developing this research plan, NRC staff[3] identified projects that address specific regulatory issues or requirements. Some of the research needs have been identified during previous work on implementation of probabilistic or risk-informed performance-based approaches. In some cases the plan identifies innovative research to inform future regulatory guidance or possible regulation. Other research activities are intended to independently assess the adequacy of proposals or approaches forwarded by industry. In all cases, research has been focused and designed to meet the regulatory goals of the NRC and regulatory products have been identified. Issues related to individual plants or that are best investigated by industry are not included in this research plan.

1.2 Objective and Scope

The various elements of the research plan are intended to support development of technical bases and tools needed by staff reviewing regulatory submittals that apply a risk-informed approach to determine a site's flood hazards and potential consequences. The objective is to

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[1] From this point forward, the qualifier, "external", will not be used. All references to flooding and flood hazards should be understood to refer to external flooding unless otherwise specified.

[2] The NRC Strategic Plan for Fiscal years 2014-2018 (Safety Strategy 2) aims to enhance the risk-informed and performance-based regulatory framework in response to advances in science and technology, policy decisions, and other factors. The Strategic Plan identifies research to confirm the safety of operations and enhance the regulatory framework by addressing changes in technology, science, and policies as a key contributing activity to Safety Strategy 2.

[3] This plan was developed by a core group of staff in RES, Office of New Reactors (NRO), and Office of Nuclear Reactor Regulation (NRR). Consultation with staff in other offices and the Regions was coordinated through the Flooding Issues Technical Advisory Group.

provide guidance and tools to support: 1) review of early site permit (ESP) and combined license (COL) applications; 2) inspection findings under the reactor oversight program (ROP); and 3) risk assessments under the significance determination process (SDP).

Specifically, this plan describes necessary research in the area of probabilistic flood hazard assessment, including: 1) site-scale flooding hazards due to local intense precipitation; 2) riverine flooding due rainfall and/or snowmelt in the contributing upstream watershed; 3) coastal flooding due to storm surge and tsunami; and 4) flooding due to combined events. The plan also supports risk assessment needs by including research to assess and evaluate methods for quantifying the reliability of flood protection features and procedures, flood mitigation strategies and total plant response to flooding events.

The main focus areas of the PFHA Research Plan are provided below. Additional discussion and details are provided in the Section 3.

1. Leverage available frequency information on flooding hazards at operating nuclear facilities and develop guidance on its use
2. Develop and demonstrate PFHA framework for flood hazard curve estimation
3. Assess and evaluate application of improved mechanistic and probabilistic modeling techniques for key flood generating processes and flooding scenarios
4. Assess and evaluate methods for quantifying reliability of flood protection and plant response to flooding events
5. Assess potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection at nuclear facilities.

Work under this plan will proceed in three phases. Phase 1 focuses mainly on the probabilistic hazard assessment element of the risk analysis, but does include work on reliability of flood protection features and procedures, flood mitigation strategies, and initial work on quantitative assessment of total plant response to a flooding event. Phase 2 will comprise two to three pilot studies to gain real-world experience in applying the hazard assessment and risk analysis methods developed in Phase 1. Phase 3 will comprise finalizing guidance for conducting a complete flooding PRA (i.e. comprehensive and detailed quantitative risk assessment framework that integrates flooding hazards with other external and internal hazards).

This research plan will be updated periodically. For example, as Phase 1 work (flood hazard assessment and the initial work on reliability of flood protection features and procedures and total plant response) matures, the detailed scope and schedule for Phase 2 and Phase 3 work, addressing an integrated approach to quantitative risk assessment for external and internal hazards, will be refined. The research plan will also be updated as needed to include any adjustments in flood hazard research activities that may be necessary to support the agency's regulatory needs. For example, the staff may revise this plan to include additional research that may be appropriate to support the review and licensing of evolutionary nuclear reactor designs, based on requests from regulatory offices.

1.3 Expected Outcome

The expected outcome of this research will be a technical basis and regulatory tools (updated regulatory guidance and standard review plans) for a comprehensive and detailed quantitative risk assessment framework that integrates flooding hazards with other external and internal hazards.

1.4 Schedule

The bulk of the research to be undertaken will be performed during Fiscal Years (FY) 2015–2019. Anticipated follow-on work will be performed on a schedule agreed upon by RES, NRO, and NRR.

2 Background

The development of robust and credible estimates for flooding hazards is generally required to support design, operation, and emergency planning for nuclear facilities. The specific use of flood hazard estimates by NRC staff include: 1) the flood resistant design of structures, systems and components important to safety; 2) design of flood protection features; 3) advanced planning of flood protection procedures; and 4) evaluation of flood mitigation capabilities. NRC staff currently applies deterministic methods that provide little quantitative insight into risk. This research plan aims to provide technical basis and regulatory tools for a comprehensive and detailed quantitative risk assessment framework that integrates flooding hazards with other external and internal hazards.

2.1 Regulatory Basis

The regulatory basis governing flood hazards assessment is provided in the appropriate sections of 10 CFR Part 50, Part 52, and Part 100 (Refs. 4-6). The regulatory criterion for protection of structures, systems, and components (SSCs) important to safety against natural phenomena is provided in 10 CFR Part 50 Appendix A, General Design Criterion (GDC) 2. GDC-2 states that SSCs important to safety shall be designed to withstand the effects of natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated. The regulation also states that the appropriate combinations of the effects of normal and accident conditions for the effects of natural phenomena should be considered. The requirements for the contents of applications for new reactor applications is provided in 10 CFR Part 52, more specifically 10 CFR 52.17(a)(1)(vi), for Early Site Permit (ESP) applications, and 10 CFR 52.79 (a)(1)(iii), for Combined License (COL) applications, as they relate to the hydrologic characteristics of the proposed site with appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area and with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated. Neither 10 CFR Part 50 nor Part 52 defines what constitutes a sufficient margin. In practice, deterministic estimates of maximum credible events (see below) have been used in flood hazard assessments for nuclear facilities regulated by the NRC.

The reactor site criteria are provided in 10 CFR Part 100, which lists the factors to be considered when evaluating sites, including identifying and evaluating hydrologic features of the site. The requirements to consider physical site characteristics in site evaluations are specified in 10 CFR 100.10(c) for applications before January 10, 1997, and 10 CFR 100.20(c) for applications on or after January 10, 1997.

2.2 Historical Perspective

Flood hazard assessment and flood protection in the design and operation of nuclear power plants (NPPs) and other nuclear facilities has been an ongoing and evolving issue since the introduction of civilian nuclear facilities. The early rules and guidance predate the NRC, having originated with the Atomic Energy Commission (AEC).

To date, the treatment of flooding hazards has predominantly taken the form of deterministic regulation and guidance, under which the current fleet of nuclear reactors and facilities was designed, constructed, and licensed and is now operated. The design of nuclear power plants (NPPs) that were licensed in this environment have undergone several review cycles, including the individual plant examinations (IPEs) and the individual plant examinations of external events (IPEEEs). These and other reviews provide the basis for confirmation that, on the basis of information available at the time, the Nation's existing NPPs are acceptably safe with respect to flooding events.

In response to the 2011 tsunami-induced severe accident at Fukushima Daiichi in Japan, the NRC is currently engaged in a comprehensive review of flooding hazard and flood protection features and procedures for U.S. NPPs. As with previous such reviews, the current effort relies mainly on deterministic analysis approaches.

2.3 Flooding Mechanisms and Flooding Hazards

Flooding hazards that must be assessed for nuclear power plant design and operation may arise due to a number of causative mechanisms and processes or combinations of such. The selection of credible flooding scenarios and their analyses must be performed on a site-specific basis. A conceptual description for several types of flooding hazards is shown in Figure1. In general, there will be:

1. A phenomena that is the source of flood waters (e.g. locally heavy rainstorm at the plant site, synoptic or mesoscale rainstorms over the watershed where the site is situated, dam failure upstream of the plant site, tropical cyclones, seismic-induced displacement of the ocean water surface as tsunami source)
2. Some process by which the flood waters propagate to the site (e.g. rainfall runoff at the site, rainfall runoff to streams and subsequent routing of flood waters through the stream network, routing of dam-break flood waves, surge and wind wave generation along the tropical cyclone track, tsunami ocean surface displacement propagating as gravity waves)
3. Near-field interactions of the flood wave with local features that significantly influence site-scale inundation (e.g., local bathymetry and topography, wave setup, runup and splash)
4. A resulting set of spatially and temporally distributed loads that act on structures, systems or components (e.g., water levels, hydrostatic and hydrodynamic forces, flood-borne debris impacts, sedimentation, and/or erosion).

2.3.1 Deterministic Approach

A typical deterministic flood hazard assessment applies a progressively refined, stepwise estimation of site-specific hazards that evaluates the safety of structures, systems, and components (SSCs) important to safety with the most conservative plausible assumptions consistent with available data. NRC staff refer to this as the hierarchical hazard assessment approach (HHA, see Ref.1) The HHA process starts with the most conservative simplifying assumptions[4] that maximize the hazards from the “probable maximum event” for each flood-causing phenomenon expected to occur in the vicinity of a site. If the site is not impacted by floods and associated affects from any of the phenomena to a degree critical for safe operation of the SSCs, no further flood-hazard assessment would be needed. If the assessed hazards results in an adverse effect or exposure to any SSC important to safety, a more site-specific hazard assessment is performed for the probable maximum event. Several iterations of the flood-hazard assessment, each based on inclusion of additional site-specific data, may be needed to demonstrate that the assessed hazards from the probable maximum event are still based on conservative assumptions yet do not adversely affect the SSCs. If the iterative process identifies a situation that is considered the most site-specific, based on available data and still results in exposure or adverse effects to the safety-related SSCs, flooding protection measures should be employed to protect the affected SSCs. The HHA approach is carried out for each flood-causing mechanism (and relevant combinations) for a proposed site. The deterministic estimated for the design-basis flood is the event that results in the most severe hazard to the safety-related SSC.

As illustrated in the HHA process described above, deterministically derived conservative estimates such as probable maximum precipitation (PMP), probable maximum flood (PMF), probable maximum hurricane (PMH), probable maximum storm surge (PMSS) and probable maximum tsunami (PMT) have traditionally been used to provide the sufficient margin called for in GDC-2. Although “probable” appears, it must be stressed that these are strictly deterministic estimates arrived at via semi-empirical methods. Thus, the margins are not explicitly quantified in either a physical or risk sense. In addition, deterministically derived conservative estimates are not very useful in examining the risk due to some lower level of flooding (e.g. that would impact the plant’s ability to respond to a non-flood-induced failure), and they do not account for the fact there is a non-zero probability of “beyond design-basis” flooding.

2.3.2 Probabilistic Approach

A truly risk-informed and performance-based approach requires quantitative probabilistic models for the flooding phenomena combined with probabilistic models for the fragility of flood protection features and reliability of flood protection or mitigation procedures.

Probabilistic models for estimating floods are generally based on approaches that characterize the extreme flood as a random event, describe the properties of this random phenomenon using probability distributions, and use these probability distributions to estimate floods corresponding to a specified probability-of-exceedance. Fundamentally, two approaches to probabilistic flood hazard estimation are available: 1) frequency analysis techniques based on statistics gleaned from the historical and/or paleoflood record (e.g. Ref. 2), and 2) Monte Carlo simulation techniques which use hydrologic simulation models to transform a range of hydrometeorological inputs (sampled from their joint distributions) to estimate corresponding ranges of flood parameters of interest (e.g., Refs. 3-4). The principle advantage of these methods is that uncertainty in inputs, model parameters, and antecedent conditions can be explicitly considered.

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[4] A certain level of subjectivity is involved in determining the level of conservatism associated with a simplifying assumption, and also in what may be considered a site-specific scenario.

In a probabilistic flood hazard assessment, the loads are characterized by family of hazard curves. The design-basis selection criteria can then be based on selecting a probability-of-exceedance of the flood hazard or on the risk to which the safety-related SSCs may be exposed. Probabilistic treatment of flood hazard phenomena provides quantitative estimates of flood protection margin, as well as inform the estimates of risk due to flooding less severe (or more severe) than the design basis.

The hazard curves developed in the hazard assessment can then provide input to failure models (e.g. fragility curves for active or passive flood protection features and feasibility/reliability assessment of flood protection and/or mitigation measures) to arrive at the total plant response to the flooding event (see Figure 2). The quantitative assessment of the plant response to the flooding event is then a key input for a complete flooding PRA or, when integrated with other hazards, complete external hazards PRA.

2.4 Need for Research

Although probabilistic risk assessment for external flooding has been carried out at several nuclear power plant sites, detailed methods and guidance are currently not available for hazard assessment or for fragility. Current NRC oversight activities for operating nuclear facilities (such as the significance determination process for evaluating inspection findings at NPPs) have used probabilistic flooding hazard estimates only on an ad hoc basis and in a limited manner.

As discussed in Section 2.2, the agency has reevaluated the impact of floods on nuclear power plants in the past, including the 1977 Systematic Evaluation Program and the 1991 Individual Plant Examination of External Events (IPEEE) program. During these programs the agency has looked at the full range of hydrologic hazards (using mainly deterministic methods) just as is currently done. However, there have been significant scientific and technological advances since flooding hazards were initially evaluated. Specifically, there are longer periods of record for datasets such as precipitation, river discharge, and tides, increased understanding of climate change (which continues to evolve), and significant developments in numerical simulation models used to evaluate flood hazards.

Risk assessment of flooding hazards and consequences of flooding events is a recognized gap in NRC's risk-informed, performance-based regulatory framework. The Advisory Committee on Reactor Safeguards (ACRS) has advocated the application of PFHA in NRC's regulatory activities (Ref. 5). In 2013, RES sponsored an interagency workshop that assessed the current state of PFHA and identified research needs for wider application of PFHA to both inland and coastal flooding (Ref. 6). In a recent report on lessons learned from the 2011 Fukushima accident, the National Research Council recommend that the US nuclear industry and the NRC pursue more complete application of modern risk analysis approaches in nuclear safety, especially for assessing potential consequences of beyond-design-basis accidents due to external hazards such as extreme floods (Ref. 7).

A number of recent activities (e.g., flooding related inspection findings, flooding of the Fort Calhoun Station, flood hazard reevaluations and integrated assessments in response to the Fukushima accident) have highlighted the need to better risk-inform NRC's regulatory actions with respect to flooding hazards. NRC staff has recognized that risk-informing NRC's regulatory actions with respect to flooding hazards both for licensing and oversight purposes will require extensive application of PFHA. In addition, in the course of the current review of flood hazards for operating reactors, industry representatives have expressed their interest in using PFHA methods and the need for NRC to develop guidance in this area.

3 Research Topics

Additional discussion of main focus areas of the PFHA Research Plan and details are provided in the following sections.

3.1 Leverage Available Frequency Information on Flooding Hazards at Operating Nuclear Facilities and Develop Guidance on its Use

There is a near-term need for probabilistic information in operating reactor oversight, where the use of hazard information and insights is already an on-going input in the determination for follow-up inspection actions and resource allocation, and the evaluation of risk-informed licensing actions. While the treatment of extremely low likelihood flood events may still require middle- to long-term research efforts for wider implementation current methods and guidance already exist for higher likelihood events. Hence, a hybrid approach that leverages the availability of information and methods, dependent on the range of the risk spectrum, should be coupled with existing probabilistic modeling tools to evaluate the risk of severe accidents at NPPs. It is important to note that the timeline for many actions such as NRR's Significance Determination Process (SDP) is relatively short (typically a few months). Thus, there is a need to proactively collect and organize as much information as possible. It is envisioned that building a database of currently available flood hazard frequency information will be prioritized according to anticipated need and level of perceived flooding risk. Where information is already being collected and maintained by other entities (e.g. NOAA/NWS databases on precipitation frequency and hurricane storm tracks), the focus will be on providing guidance on accessing and the using of the information in NRC's risk-informed decision making process. The main initiatives in this research theme include:

- Organize flooding information and build database of currently available flood hazard frequency information, prioritized according to anticipated need and level of perceived flooding risk.
- Develop guidance on use of currently accepted extrapolation methods for river flooding hazard information.
- Develop guidance on use of currently available extrapolation methods beyond the current consensus limits.

3.2 Develop and Demonstrate PFHA Framework for Flood Hazard Curve Estimation

For NRC safety reviews of nuclear facility license applications, design-basis flood hazard estimates are needed for a range of annual exceedance probabilities[5] (AEPs) possibly as low as 1×10^{-4} to 1×10^{-7}. Estimation of the associated uncertainty is also needed. While design-basis flood hazard estimation may usefully focus on characterizing the tails of the flood hazard curve, the full hazard curve is needed to fully assess risk at operating facilities.

Research carried out under the PFHA framework focus area will include development of a formal PFHA framework as well as efforts concentrating on framework application for key

[5] NRC guidelines on man-related hazards establish a screening level AEP of 10^{-7}. An AEP of 10^{-7} is also used for design-basis tornado and hurricane winds.

flooding scenarios and the use of expert judgment[6]. The use of expert judgment has been studied extensively in the probabilistic seismic hazard assessment (PSHA) field, and a structured process called the Senior Seismic Hazard Analysis Committee (SSHAC) process has been developed (under NRC sponsorship) and applied to numerous NPP projects. It is very likely that ideas, elements and procedures used in the SSHAC process can be used and/or adapted to develop a structured process for the use of expert judgment in PFHA studies, which we have chosen to call the Structured Hazard Assessment Committee Process for Flooding (SHAC-F).

The main initiatives in the PFHA framework focus will consist of

- Develop formal framework that is applicable to multiple flooding mechanisms as well as combined events.
- Investigate formal approaches for assessing uncertainty and the use of experts
- Develop example applications of framework (e.g. site-scale flooding due local intense precipitation, river flooding, coastal flooding) with cooperation of stakeholders and other federal agencies where feasible and appropriate.

3.3 Application of Improved Modeling Techniques for Key Flood Generating Processes and Flooding Scenarios

There have been a number of advances in analytical and computational methods, as well as advances in computer technologies over the last twenty years that have applications to both deterministic (e.g., physically based mechanistic) and probabilistic modeling techniques for flood hazard assessment. Thus, one focus on this research plan will address application of such improved computational resources and modeling techniques to key flood generating processes and flooding scenarios for NRC use. The following topics will be addressed:

- Assessment and evaluation of numerical modeling methods for estimating extreme precipitation events and processes
- Assessment and evaluation of probabilistic methods for estimating inland (riverine) flood events and processes
- Assessment of paleoflood study methods for extending flood records.
- Assessment and evaluation of methods for estimating probability of dam failure
- Assessment and evaluation of methods for modeling dam breach and developing dam breach hydrographs
- Probabilistic modeling of tsunamis due to submarine landslides
- Practical issues in application of joint probability methods to coastal flooding
- Evaluation of methods for estimation of flooding due to combined events

[6] Expert judgment will be required to address questions related to appropriate process models and uncertainty characterization and quantification for very low probability events.

3.4 Assess and Evaluate Reliability of Flood Protection and Plant Response to Flooding Events

Information on the engineering reliability of flood protection features is needed to guide a number of decisions including siting, design, inspections, and risk assessments[7]. The feasibility and reliability of flood protection (and possibly mitigation) procedures is also important. The following research topics are aimed at developing the basis for quantitative evaluation of "flood fragility curves" that need to be convolved with the hazard curve to arrive at quantitative risk insights.

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

3.5 Assess Potential Impacts of Dynamic and Nonstationary Processes on Site Characteristics, Flood Hazard Assessments and Flood Protection

This focus area will address uncertainties in flood hazard assessment and flood protection measures due to dynamic and nonstationary processes such as climate change, and changes in land use/land cover. The scientific understanding with regard to the anticipated rate of change in dynamic and nonstationary processes such as climate and land use/land cover, and the capability to model their potential impacts, have advanced considerably since most of the current reactor fleet was first licensed. There is a need to evaluate how new information and methods can best be applied to licensing and oversight of nuclear facilities.

Processes and mechanisms related to site parameters and external hazards that may be impacted by climate change and thus are of interest to NRC include: 1) magnitude, distribution and frequency of precipitation events; 2) magnitude, distribution and frequency of surge generating storms (e.g., tropical and extra- tropical cyclones); 3) antecedent conditions important to flood generation (e.g. snowpack, soil moisture, land use); 4) extremes in temperature and humidity; extremes in snow and ice loads on structures; and 5) magnitude, distribution and frequency of tornado and hurricane winds

Climate change issues have been raised in the staff safety and environmental reviews of new reactor license applications. Specifically, the ACRS has raised questions on addressing climate change in the projections of severe climatologic site conditions and the Commission recently provided guidance to the staff to consider greenhouse gases in all environmental impact statements (EISs). Although no immediate concerns have been identified during the NRCs licensing analyses, the NRC is committed to ensuring that current licensee's and future applicants consider the potential effects of climate change on SSCs important to safety.

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[7] In the area of seismic hazard assessment, the target annual exceedance probability is informed by a consensus regarding approaches to assessing seismic fragility and allowing credit for the seismic capacity or margin inherent in the design and construction of NPPs. No equivalent body of technical information or consensus is currently available for flooding.

Land use and land cover within watersheds are important factors in controlling runoff and subsequent flooding hazards, so land use and land cover change (LULCC) over the expected lifetime of the nuclear facility may be a significant source of uncertainty in flood hazard assessments[8]. Modeling approaches for estimating LULCC have advanced considerably since most of the current reactor fleet was first licensed.

Research topics in this focus will include:

- Produce periodic reports that 1) summarize recent scientific findings; 2) report on activities of federal agencies with direct responsibility for climate science and policy; and 3) analyze the potential impacts relevant to NRC regulatory activities
- Assess and evaluating the modern state of practice in LULCC modeling with respect to NRC licensing and oversight activities over the expected life of nuclear facilities..

4 Implementation

Implementation of the research plan is described in the following section, including proposed phased approach and schedule, contract support, and coordination with internal and external entities.

4.1 Phased Approach

As discussed in the introduction and in the preceding sections, a comprehensive and detailed quantitative risk assessment framework that integrates flooding hazards with other external and internal hazards will require a phased research approach. The phased approach envisioned is as follows:

Phase 1-Focus of This plan

This phase focuses mainly on the probabilistic hazard assessment element of risk analysis, but does include work on reliability of flood protection features and procedures, flood mitigation strategies, and initial work on quantitative assessment of total plant response to a flooding event.

Phase 2- Conduct Pilot Studies

Phase 2 will comprise developing and performing up to three pilot studies to gain real-world experience in applying the methods developed in Phase 1. It is anticipated that one coastal site and two inland sites will be selected for the pilot studies, in order to exercise methods for a wide range of hazards. This phase will also include work to fill in gaps or deficiencies identified during the pilot studies. This phase will include significant interactions with external stakeholders (e.g. one or more licensees, industry research organizations).

Phase 3- Develop Guidance for Conducting Flooding PRAs

Phase 3 will comprise developing guidance for conducting a complete flooding PRA. The focus will be on integrating flooding hazards (and other associated external and internal hazards) with

[8] Considering early site permits, initial operating license, and license extensions, the lifespan of certain nuclear facility may approach or possibly even exceed 80 years. This length of time is comparable to or exceeds the record length of stream flow and precipitation data sets available when many operating plants were first licensed.

PRA models of plant internal performance. This phase will also include updating existing NRC PRA guidance and significant interactions with internal and stakeholders, as well as standards-developing entities

4.2 Contract Technical Support

Contract technical support will be required to implement this research plan. The staff will implement Department of Energy (DOE) laboratory contracts and Interagency Agreements with other federal agencies to provide access to the bulk of required technical support. Federal agency sources include the National Oceanic and Atmospheric Administration (NOAA), U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (USBR), and U.S. Geological Survey (USGS).

4.3 Coordination, Cooperation, and Collaboration

Implementation of this research plan will include both internal and external coordination, cooperation and collaboration. Internal coordination with User Offices is essential for effective and efficient implementation of the planned research. Cooperation and collaboration with external entities (e.g., other federal agencies, domestic and international research organizations) will be pursued in order to leverage their valuable work and experience. Research progress will be shared with industry stakeholders and the public.

4.3.1 Coordination with User Offices

Implementation of the research plan will be coordinated with User Offices (mainly NRO and NRR) through a User Need Request and technical briefings. Periodic research briefings and meetings of the Flooding Issues Technical Advisory Group (FITAG) will allow coordination with the wider community of NRC technical staff and management both at HQ and in the Regions. In addition, RES plans to organize annual PFHA Research Program workshops to communicate results, assess progress, collect feedback and chart future activities. These workshops will bring together NRC staff and management from RES and User Offices, technical support contractors, as well as interagency and international collaborators. These interactions will also be an important vehicle for further defining the scope and schedule of this plan.

4.3.2 Domestic and International Collaboration and Cooperation

Implementation of this research plan will necessarily include significant collaboration and cooperation with other federal agencies that are responsible for 1) maintaining observational networks, conducting scientific investigations, and providing forecasts for phenomena and processes related to inland and coastal flooding; 2) developing and applying tools for estimating design basis floods for critical infrastructure design and for emergency planning; and 3) ownership, operation or regulation of water control structures. Examples include:

- Department of Commerce, National Oceanic and Atmospheric Administration (NOAA)
- Department of Interior, Geological Survey (USGS) and Bureau of Reclamation (USBR)
- U.S. Army Corps of Engineers (USACE)
- U.S. Bureau of Reclamation, and the
- Department of Homeland Security, Federal Emergency Management Agency (FEMA)
- Federal Energy Regulatory Commission (FERC)

Research progress and results will be shared with the agencies mentioned above through direct communication with technical staff and through meetings of interagency advisory committees and subcommittees. Relevant entities include:

- Advisory Committee on Water Information Subcommittee on Hydrology (ACWI/SOH)
- U.S. National Science and Technology Council, Committee on Environment, Natural Resources and Sustainability, Subcommittee on Disaster Reduction.
- Interagency Committee on Dam Safety (ICODS)
- U.S. Global Change Research Program (USGCRP)

Research progress and results will be shared with international counterparts through individual technical exchanges, presentations at the Regulatory Information Conference (RIC) and other international meetings. Entities which have expressed interest in cooperation and collaboration on topics addressed in this research plan include:

- French Institute for Radiological Protection and Nuclear Safety (IRSN)
- International Atomic Energy Agency (IAEA)
- Organization for Economic Cooperation and Development, Nuclear Energy Agency, Committee on the Safety of Nuclear Installations (OECD/NEA/CSNI)

The pilot studies planned for Phase 2 will require the collaboration and cooperation of one or more licensees as well as industry organizations such as the Electric Power Research Institute (EPRI) or the Nuclear Energy Institute (NEI).

4.3.3 Informing Stakeholders and the Public

Research progress and results will be shared with various stakeholders and the public through the publication of NUREG series reports, draft and final regulatory guides, presentations at the RIC and other public meetings, as well as through the NRC website and social media channels.

5 List of Acronyms and Abbreviations

ACRS – NRC Advisory Committee on Reactor Safeguards
ACWI – Advisory Committee on Water Information
AEP – Annual Exceedance Probability
CFR – Code of Federal Regulations
COL – Combined Operating License
CSNI – OECD NEA Overview Committee on the Safety of Nuclear Installations
EIS –Environmental Impact Statement
EPRI – Electric Power Research Institute
ESP – Early Site Permit
FEMA – Federal Emergency Management Agency
FERC – Federal Energy Regulatory Commission
FITAG – NRC Flooding Issues Technical Advisory Group
GDC – General Design Criteria
ICODS – Interagency Committee on Dam Safety
IPEEE – Individual Plant Examination of External Events
IRSN – L'Institut de Radioprotection et de Sûreté Nucléaire (French Institute for Radiological Protection and Nuclear Safety)
LULCC – Land Use and Land Cover Change

NEA – OECD Nuclear Energy Agency
NEA – Nuclear Energy Institute
NPP – Nuclear Power Plant
NRC – U.S. Nuclear Regulatory Commission
NRO – NRC Office of New Reactors
NRR – NRC Office of Nuclear Reactor Regulation
NTTF – NRC Fukushima Near-Term Task Force
NWS – NOAA National Weather Service
OECD – Organization for Economic Cooperation and Development
PFHA – Probabilistic Flood Hazard Assessment
PMF – Probable Maximum Flood
PMH – Probable Maximum Hurricane
PMP – Probable Maximum Precipitation
PMSS – Probable Maximum Storm Surge
PRA – Probabilistic Risk Analysis
RIC – Regulatory Information Conference
SDP – Significance Determination Process
SOH – ACWI Subcommittee on Hydrology
SSC – Structures, Systems, and Components
SSHAC – Senior Seismic Hazard Analysis Committee
USACE – U.S. Army Corps of Engineers
USBR – U.S. Bureau of Reclamation
USGCRP – U.S. Global Climate Change Research Program
USGS – U.S. Geological Survey

6 References

1. Prasad, R., et al., "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," NUREG/CR-7046, November 2011, U.S. Nuclear Regulatory Commission, Washington, DC.
2. Stedinger J.R., R.M. Vogel, and E. Foufoula-Georgiou. 1993. "Frequency Analysis of Extreme Events." Chapter 18 in Handbook of Hydrology, D.R. Maidment (ed.), McGraw-Hill Book Company, New York.
3. Schaefer M.G. and B.L. Barker. 2002. "Stochastic Event Flood Model." Chapter 20 in *Mathematical Models of Small Watershed Hydrology and Applications*, V.P. Singh and D. Frevert (eds.), Water Resources Publications, Littleton, Colorado, p. 707-748.
4. U.S. Army Corps of Engineers (USACE). 2005. *Stochastic Modeling of Extreme Floods on the American River at Folsom Dam. Flood-Frequency Curve Extension*. Research Document 48, Institute for Water Resources, Hydrologic Engineering Center, Davis, California.
5. Advisory Committee for Reactor Safeguards, Letter from J.S. Armijo to R.W. Borchardt, Sept 25, 2012, ADAMS Accession No ML12271A121, U.S. Nuclear Regulatory Commission, Washington, DC.
6. NUREG/CP-0302, "Proceedings of the Workshop on Probabilistic Flood Hazard Assessment (PFHA)," Held at the U.S. Nuclear Regulatory Commission Headquarters, Rockville, MD, January 29–31, 2013, U.S. Nuclear Regulatory Commission, Washington, DC.

7. National Research Council, “Lessons Learned from the Fukushima Nuclear Accident for Improving Safety of U.S. Nuclear Plants,” National Academies Press, Washington, DC, 2014
8. *U.S. Code of Federal Regulations*, Title 10, Part 50, “Domestic Licensing of Production and Utilization Facilities,” U.S. Nuclear Regulatory Commission, Washington, DC.
9. *U.S. Code of Federal Regulations*, Title 10, Part 52, “Licenses, Certifications and Approvals for Nuclear Power Plants,” U.S. Nuclear Regulatory Commission, Washington, DC.
10. *U.S. Code of Federal Regulations*, Title 10, Part 100, “Reactor Site Criteria,” U.S. Nuclear Regulatory Commission, Washington, DC.
11. Regulatory Guide 1.59, “Design Basis Floods for Nuclear Power Plants,” Rev. 2, August 1977, U.S. Nuclear Regulatory Commission, Washington, DC.
12. Regulatory Guide 1.102, “Flood Protection for Nuclear Power Plants,” Rev. 1, September 1976, U.S. Nuclear Regulatory Commission, Washington, DC.
13. Regulatory Guide 1.200, “An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities,” Rev. 2, March 2009, U.S. Nuclear Regulatory Commission, Washington, DC.
14. NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition,” 2007, U.S. Nuclear Regulatory Commission, Washington, DC.
15. Resio, D.T., et al., “The Estimation of Very-Low Probability Hurricane Storm Surges for Design and Licensing of Nuclear Power Plants in Coastal Areas,” NUREG/CR-7134, October 2012, U.S. Nuclear Regulatory Commission, Washington, DC.
16. Kammerer, A.M., and Ake. J.P., Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies,” NUREG-2117, Rev. 1, April 2012, U.S. Nuclear Regulatory Commission, Washington, DC.
17. Budnitz R., et al., “Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts,” NUREG/CR-6372, Volumes 1 and 2, April 1997, U.S. Nuclear Regulatory Commission, Washington, DC.

7 Figures

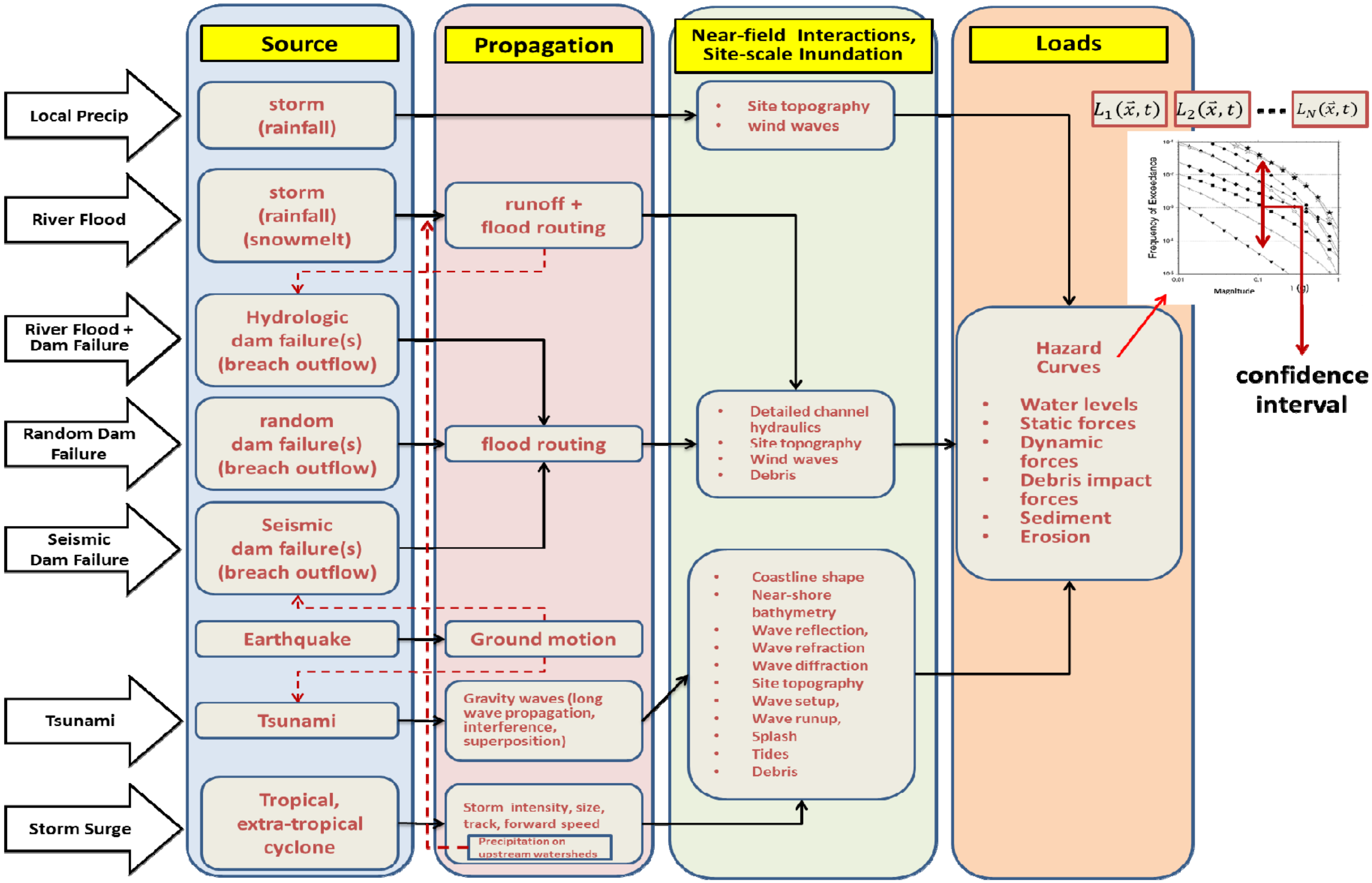

Figure 1. Conceptual flooding diagram (all flood mechanisms and combinations not shown)

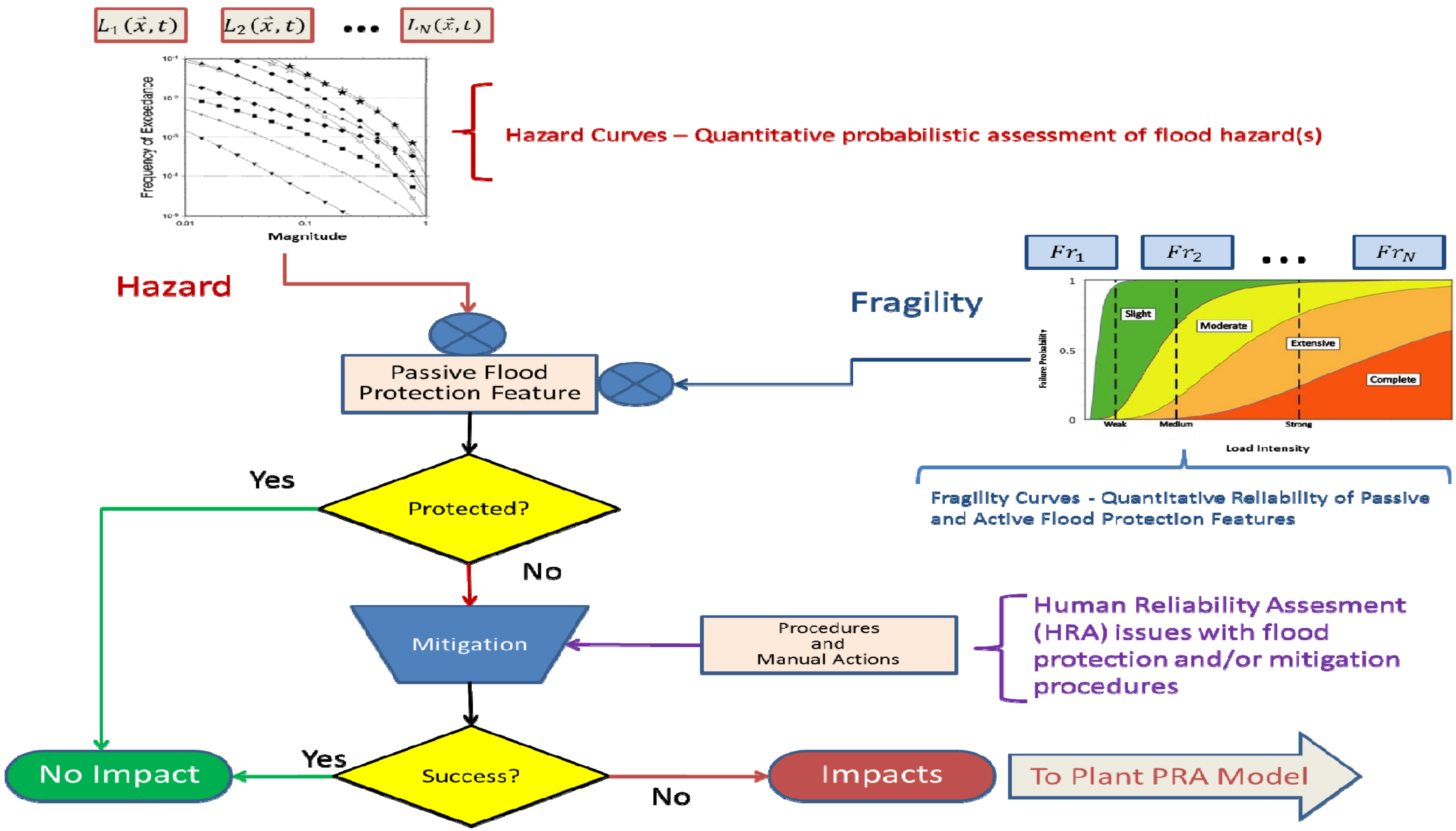

Figure 2. Conceptual model of total plant response to flooding event