Identification and Prioritization of Sources of Uncertainty in External Hazard Probabilistic Risk Assessment: Project Update

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ABSTRACT

The value and importance of external hazard probabilistic risk assessment (PRA) for nuclear facilities have been increasingly recognized over the past decade. However, the state of knowledge/practice in external hazard PRA has not kept pace with this evolution, particularly for temporally and spatial dynamic hazards such as floods. As a result, research is needed to build upon the existing state of knowledge to develop a technically sound, risk-informed strategy for identifying, characterizing, and prioritizing drivers of hazard uncertainty in external hazard PRA. This presentation summarizes the ongoing progress of a multi-year research project seeking to develop a structured process for identifying, evaluating, categorizing, and communicating the impact of uncertainties on XHPRAs. The project explores uncertainties from the perspective of hazard characterization, the physical response of the plant, and human performance. This paper (and associated presentation) provides an update on project activities and seeks feedback from the PRA community that may benefit from project insights.

Keywords: External hazards, PRA, uncertainty

1 INTRODUCTION

Probabilistic risk assessment (PRA) is used to estimate risks associated with complex systems such as nuclear power plants (NPPs). PRAs provide quantitative information about risks and (perhaps most importantly) are used to develop insights about the strengths and vulnerabilities in an NPP's design or operation. PRA provides a systematic approach to defining potential event/accident sequences and tracking, characterizing, and quantifying uncertainties.

PRAs may consider events originating within the facility (e.g., equipment failures, human errors, electrical faults, fires, and pipe breaks) or outside the facility. A wide variety of natural and human-induced hazards can be caused by events originating external to the facility. These hazards may arise from diverse geologic, meteorological, and other physical phenomena (e.g., earthquakes, storms, and offsite explosions). The resulting characteristics of hazard events and how they may affect NPPs are spatially and temporally dynamic. There is a complex coupling between the physical impacts of external hazard events, the plant response, and the human reliability of actions associated with plant response. As a result of this complexity, there remain important sources of uncertainty related to the frequency and severity of hazards and the

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associated response of the interconnected system of structures, mechanical equipment, humans, and other components that comprise the NPP. These uncertainties persist despite recent improvements in our collective understanding of external hazards and associated plant response.

The impacts and importance of uncertainties may differ by plant, hazard, the intended purpose of the PRA, and other conditions. Moreover, limited resources are available to perform PRAs, and resources intended to characterize or reduce uncertainties must be dedicated to those most impactful to the analysis in light of its intended purpose. This paper summarizes the ongoing progress of a multi-year research project [1] focused on identifying and prioritizing uncertainties in external hazard PRA for NPPs. An overview of this project was previously documented and presented [2] to engage the broader community. Similarly, this paper (and the associated presentation) seeks to provide an update on project activities and an opportunity to engage with PRA practitioners.

2 PROJECT OBJECTIVES AND GOALS

This project is responsive to the need for research to develop a technically sound strategy for identifying and characterizing drivers of hazard uncertainty. As previously documented in [2], this project has three primary goals. First, this project seeks to identify significant sources of uncertainty in external hazard PRA, particularly emphasizing how they relate to a hazard event's frequency, severity, and temporal evolution. Second, this project aims to understand the effects of key sources of uncertainty from the perspective of hazard severity, temporal evolution, physical event impacts, event progression, and the interplay between human response and physical event impacts. Finally, this project intends to integrate insights related to key sources of uncertainty to develop a risk-informed process for prioritizing measures to reduce hazard uncertainty.

3 PROJECT STRUCTURE AND TASKS

Research activities are structured under five tasks:

- **Task 1: Stakeholder Outreach and Development of Uncertainty Taxonomy** – This task includes a survey of literature and engagement with external experts to understand their insights and perspectives regarding drivers of uncertainty to support the development of a structure and taxonomy to support the identification and treatment of uncertainties in external hazard PRA [3].
- **Task 2: Hazard Uncertainty Characterization and Data Analysis** – This task seeks to identify key sources of uncertainty in characterizing hazards associated with external flooding events. A particular emphasis is placed on understanding timing information related to events and characterizing uncertainty associated with warning time and duration of impacts in a manner amenable to use in external flooding PRA, using hurricanes as a hazard of focus [4], [5].
- **Task 3: Assessment of Uncertainty in Scenario Development** – This task focuses on plant response, particularly event progressions and timing. It links hazard information (Task 2) with plant response, considering event progressions using mechanistic simulation models and conventional PRA tools [6].
- **Task 4: Characterization of Uncertainty in Human Response Under Physical Effects** – This task focuses on the reliability of human actions, considering the hazard and plant response context based on insights from Tasks 2 and 3 [7], [8].
- **Task 5: Integration & Development of Method for Prioritization of Uncertainties** – This task will integrate, synthesize, and generalize insights from previous tasks to identify key drivers of uncertainty in external hazard PRA.

While Task 1 focused on a range of external hazards (e.g., earthquakes, floods, and wind), Tasks 2-4 utilize external flooding PRA as a target/focus hazard to identify key sources of uncertainty. Task 5 will then take a more general approach to develop insights of relevance to a range of hazards.

4 TASK INTEGRATION

While research activities are structured across five tasks to enable project execution, the inputs and outputs of tasks are integrated to provide more complete insights regarding drivers of uncertainty in external hazard (particularly, external flooding) PRA. Figure 1 illustrates the overall integration of project tasks.

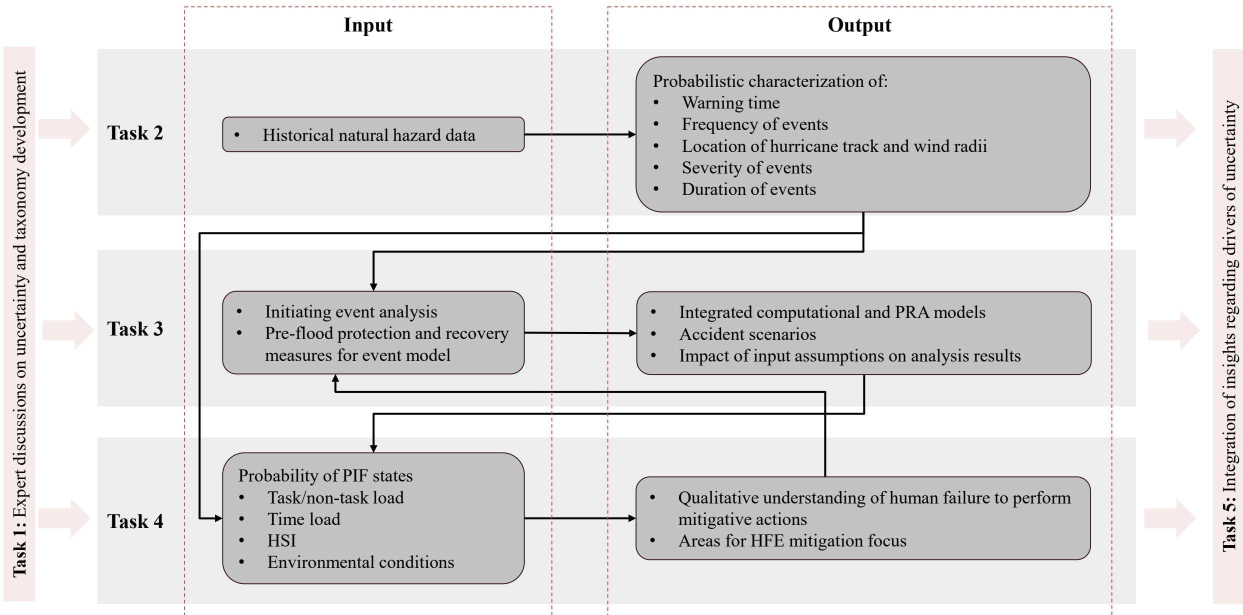

Figure 1. Task integration

As shown in Figure 1, the outcomes of Task 1 provide overall insights regarding potentially significant sources of uncertainty in external hazard PRA. For example, engagement with experts highlighted several key challenges related to external hazard PRA, which helped inform subsequent project activities. Task 2 has leveraged historical natural hazard data (e.g., information related to historical hurricane tracks and forecasts). Geospatial statistical analysis has been used to quantify differences between forecasted and observed storm information as well as the duration of storm impacts. This provides insights regarding event severity, warning time, and duration uncertainty. In turn, this hazard information informs the analysis of potential physical plant impacts under Task 3 (e.g., information about the potential timing of the loss of offsite power). It also informs human reliability analysis under Task 4 (e.g., information about uncertainty in the time available to complete actions and duration of adverse conditions on site). Task 3 then links the hazard information with models of plant response, particularly integrated mechanistic and PRA models. This provides insights into physical event progression within the plant and associated uncertainty. Task 4 leverages hazard (Task 2) and plant mechanistic response (Task 3) information to provide context under which human actions are performed (e.g., to define timing constraints and environmental conditions). Task 4 then builds a framework for assessing the reliability of ex-main control room human actions. Finally, Task 5 seeks to integrate insights across all tasks to identify and prioritize drivers of uncertainty in external hazard PRA. Additional information about ongoing activities is provided below.

5 ONGOING ACTIVITIES

As an active research project, technical activities are ongoing and evolving. The following provides a summary of current project activities as well as references for obtaining additional details on task-specific project results.

5.1 Hazard Uncertainty Characterization and Data Analysis (Task 2)

Task 2 focuses on key sources of uncertainty in characterizing hazards associated with external flooding events. While existing studies consider primary measures of hazard severity (e.g., water levels and wind speeds), recent work under this task has focused on other sources of hazard uncertainty, namely warning time and event duration. These hazard characteristics are particularly relevant for informing assessments of plant mechanistic response and human performance. However, few or no existing resources support the quantification of uncertainty associated with them. Using hurricane events as a hazard of focus, a comprehensive geospatial analysis was performed under this task to understand the uncertainty associated with hurricane forecasts from the perspective of the location and timing of storm landfall as well as storm intensity. An additional geospatial analysis was performed to characterize uncertainty associated with the duration of storm impacts at various locations along the storm's path. The geospatial analysis is completed, and a summary of activities is provided in a companion paper [5]. Current efforts focus on exploring options for depicting and communicating analysis results in a manner most easily understood and leveraged for NPP PRA. This includes consultation with PRA subject matter experts to gather insights on how to enhance the applicability of the results for external hazard PRA.

5.2 Assessment of Uncertainty in Scenario Development (Task 3)

The overarching goal of Task 3 is to create an assessment framework to integrate external flooding hazard information with hybrid NPP response models to provide a more accurate and realistic assessment of the potential risks associated with external flooding events. One important part of the analysis framework development is to establish a plant response model that can integrate the PRA with mechanistic models of plant response. Recent activities under this task have focused on developing a mechanistic computational model based on the standard nuclear safety analysis code RELAP5-3D and RAVEN platform to estimate the event progressions in response to external flooding events. For demonstration purposes, the Task 3 project team members established and assessed the loss of offsite power (LOOP)-initiated short-term and long-term station blackout (SBO) scenarios under external flooding events for a generic pressurized water reactor (PWR) using the developed integrated framework. The results of this study offer insights into the significance of flood assumptions and the consequences of external flooding events on NPPs. Currently, the external flooding PRA response model is under development following the proposed flood propagation path. The intent is to identify the critical plant structures, systems, and components and the failure modes that are significant to risk and would potentially be affected by external flooding. A companion paper provides additional information about the proposed framework and other Task 3 activities [6].

5.3 Characterization of Uncertainty in Human Response Under Physical Effects (Task 4)

Task 4 focuses on assessing the reliability of ex-control room human actions during flood events. Recent activities on Task 4 have sought to characterize the causal relationships between performance influencing factors (PIFs) and crew failure modes (CFMs) that lead to human failure events (HFEs). A Bayesian network of factors leading to crew information-gathering failures has been developed following the causal mapping methodology defined in [9] and the Phoenix human reliability analysis (HRA) method [10]. The relationships in this structure are substantiated by psychological and organizational factors literature covering all areas of the BN. A key result from this work was the identification of a set of five causal clusters corresponding to mechanistic PIFs which act as cognitive mechanisms through which CFMs may occur. Capturing these causal pathways will enhance the accuracy and technical basis of HRA and pave the way for more accurate estimates of human error probabilities (HEPs). Also, it would allow for identifying root causes(s) of human failures so that effective mitigation strategies can be developed. Additional information in the companion paper [8] provides details on Task 4-specific activities.

6 NEXT STEPS

Activities described above are ongoing, and future work will focus on refining and extending project activities, focusing on ensuring quantitative project outcomes and other insights are presented in a manner amenable to inclusion within a PRA. Activities under Task 2 will continue to focus on refining the results of the geospatial analysis, including understanding the relationship between uncertainties associated with primary measures of hazard severity (e.g., water levels and windspeeds), warning time, and event duration. Future work under Task 3 will involve further development of the external flooding PRA model by developing event trees and fault trees that follow the flood propagation path to identify potential scenarios. This is intended to understand better uncertainties associated with event sequences associated with external flooding hazards. The next steps for Task 4 will involve the development of generic decision- and action-phase Bayesian networks and the implementation of a quantification scheme for multiple networks. Future activities under Task 5 will focus on the aggregation and integration of insights across all tasks. Overall, this research is contributing to the collective understanding of drivers of uncertainty in NPP external hazard PRA consistent with the growing recognition of the safety significance of external hazards.

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