Identifying and Prioritizing Sources of Uncertainty in External Hazard Probabilistic Risk Assessment: Project Activities and Progress

Michelle Bensi[a], Katrina Groth[b], Zeyun Wu [c], Zhegang Ma[d], Ray Schneider[e], Ahmad Al-Douri[f], Somayeh Mohammadi[g], Tao Liu[h], Camille Levine[i]

[a] University of Maryland, College Park, USA, mbensi@umd.edu
[b] University of Maryland, College Park, USA, kgroth@umd.edu
[c] Virginia Commonwealth University, USA, zwu@vcu.edu
[d] Idaho National Laboratory, USA, zhegang.ma@inl.gov
[e] Westinghouse Electric Company, USA, schneire@westinghouse.com
[f] University of Maryland, College Park, USA, aaldouri@umd.edu
[g] University of Maryland, College Park, USA, somayeh@terpmail.umd.edu
[h] Virginia Commonwealth University, USA, liut8@vcu.edu
[i] University of Maryland, College Park, USA, clevine1@umd.edu

Abstract: There are inherently significant sources of uncertainty in external hazard probabilistic risk assessment (PRA) for nuclear power facilities. The state of knowledge and practice associated with these uncertainties varies across hazard groups (e.g., earthquakes, wind, and floods). There is currently a research need to build upon the existing state of knowledge to develop a technically sound, risk-informed strategy for identifying and characterizing drivers of hazard uncertainty in external hazard PRA for multiple classes of hazards. This paper summarizes the ongoing progress of a multi-year research project that seeks to: (1) develop a structured process for identifying, evaluating, categorizing, and communicating the impact of uncertainties on external hazard PRAs, (2) investigate the spectrum of uncertainties associated with parsing the hazard and realistically integrating hazard information into the external hazard PRA, (3) understand how uncertainties in the physical hazard characteristics/timing interfaces with plant response strategies (e.g., plant physics and human reliability), and (4) assess the combined impact of these uncertainties (and uncertainty reduction efforts) on the development of the external hazard PRA. This research will ultimately help to facilitate the prioritization of uncertainty reduction activities based on their risk significance, risk reduction benefit, and value.

1 INTRODUCTION

Nuclear power facilities may be exposed to a range of natural and human-induced external hazards. The understanding of external hazards, associated plant response, and sources of uncertainty have increased in recent years, and there have been overall enhancements in the capability of many aspects of nuclear power plant (NPP) probabilistic risk assessment (PRA). Nonetheless, significant uncertainties remain.

Uncertainties arise due to the complexity and diversity of natural phenomena that may challenge plant sites and the spectrum of effects such hazards may have on a site. Typically, hazards affecting range from rapid onset hazard events (e.g., earthquakes) to slower evolving hazard events (e.g., hurricanes events with warning time). While NPPs are designed to accommodate a broad spectrum of severe hazards, there is limited data on the severe, low-frequency hazard events. This paucity of data and the uncertainty arising from different technical interpretations of available data, models, and methods used to assess the frequency of hazard events of various characteristics poses challenges to assessing the design of the plant and the extent to which the design can accommodate severe low-frequency hazards.

The characterization of the external hazard for integration into the PRA is further complicated by the need to understand and model the performance of (1) plant features intended to alter the ways in which a hazard affects a site (e.g., protection and mitigation features) and (2) plant responses to mitigate the consequences of the hazard. Plant response strategies for external hazard events often involve significant human actions, many of which include actions executed outside the main control room (e.g., actions to install or construct temporary protection features). As a result, there is a close coupling between the physical impacts of hazard events, the plant response, and the human reliability of actions associated with plant recovery and response to a hazard event. Potentially significant sources of uncertainty in the external hazard PRA are associated with the quantification of: the time required to complete actions in light of the (uncertain) impact of physical conditions generated by the hazard; the time available to complete actions under the identified hazard; and the conditions under which those actions will be taken.

There are limited existing models and tools available to support probabilistic assessment of hazard characteristics of relevance to NPP PRAs, particularly with respect to warning time and event duration. The spatially and temporally dynamic nature of physical event impacts on complex engineering systems such as NPPs leads to significant sources of uncertainty associated both with these impacts and with the characteristics of event/accident progression.

There are limited existing models and tools available to support probabilistic assessment of hazard characteristics of relevance to NPP PRAs, particularly with respect to temporal factors such as warning time, event progression, event duration, and hazard intensity. While the spatially and temporally dynamic nature of physical event impacts leads to significant sources of uncertainty associated with hazard impacts and event/accident progression characteristics, it further poses a considerable challenge to model these impacts within a PRA structure realistically.

This paper summarizes the ongoing progress of a multi-year research project [1] focused on identifying and prioritizing uncertainties in external hazard PRA for nuclear power facilities.

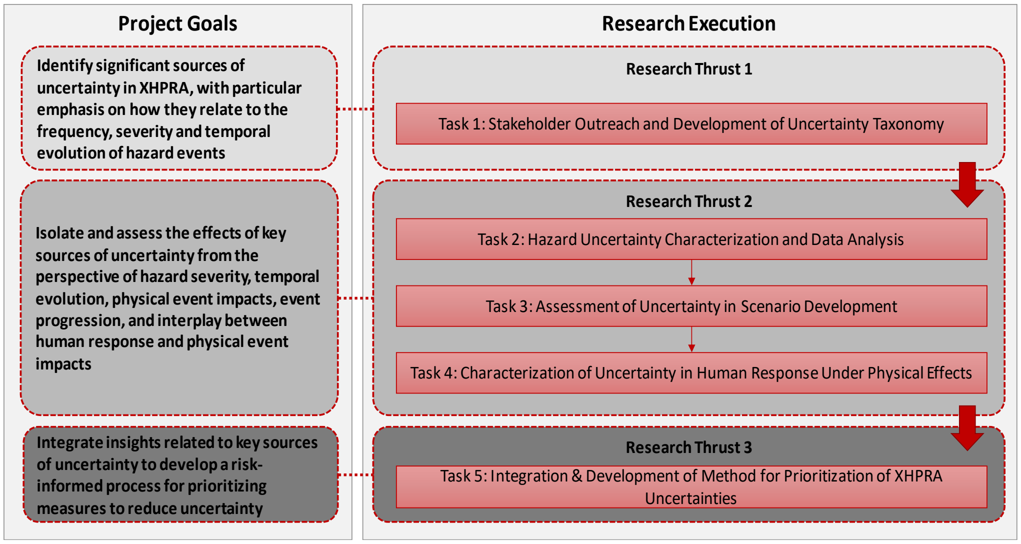
2 PROJECT STRUCTURE

The goals of this project are to:

1. Identify significant sources of uncertainty in external hazard PRA, with particular emphasis on how they relate to the frequency, severity, and temporal evolution of hazard events
2. 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
3. Integrate insights related to key sources of uncertainty to develop a risk-informed process for prioritizing measures to reduce hazard uncertainty.

Figure 1 provides a conceptual overview of project goals and how they relate to the project's three primary research thrusts. The first research thrust focuses on a broad exploration of uncertainties in external hazard PRA, emphasizing their relationship to physical hazard characteristics. The second research thrust focuses on creating tangible insights related to uncertainties associated with (1) characterization of hazard frequency, severity, spatial effects, and temporal evolution, (2) the physical impacts of hazards and event progression, and (3) the coupling between human response and physical event impacts. The third research thrust focuses on an integrative research activity intended to leverage insights from activities performed under Thrusts 1 and 2 to develop an approach for identifying, evaluating, and prioritizing hazard uncertainties.

Figure 1: Project goals and research execution framework



3 PROJECT ACTIVITIES AND NEXT STEPS

Project activities are broken up into five tasks to facilitate project execution. These tasks are associated with the project research thrusts, as shown in Figure 1. The first task focuses on stakeholder outreach to better understand insights and perspectives regarding drivers of uncertainty in external hazard PRA. Task 1 also includes the development of a structure for understanding and communicating these drivers of uncertainty. Task 2 focuses on identifying key sources of uncertainty in the characterization of hazards, with a specific focus on external flooding. A particular emphasis is placed on understanding timing information related to event warning time and duration. Task 3 focuses on the plant response, particularly external flooding event progressions and timing. Task 4 focuses on the interaction of human reliability analysis, the NPP, and the hazard characterizations. Task 5 focuses on integration (including inter-relationships), synthesis, and generalization of project insights.

3.1 Task 1: Stakeholder Outreach and Development of Uncertainty Taxonomy

The project began with engagement with subject matter experts that have experience in PRA for a wide range of external hazards and from multiple perspectives within the nuclear industry. Initially, the project envisioned the execution of workshops that brought together a diverse group of experts. However, due to the COVID-19 pandemic, in-person meetings were not possible. Instead, a series of one-on-one and small group discussions were held via virtual meeting platforms. Experts involved in discussions had experience working with multiple types of external hazards (e.g., earthquake, wind, flood, and human-induced hazards) and applying PRA techniques and tools to a diverse range of technologies, from conventional large light-water reactors to new and innovative nuclear technologies. Experts were knowledge in hazard assessment, fragility, modeling, systems response, multi-unit PRAs, human reliability assessment, and related areas.

Experts extemporaneously responded to questions, and there was an open discussion between meeting participants. The discussions focused on a range of questions related to:

- Insights regarding the "most pressing" (from the perspective of need to characterize, reduce, etc.) sources of uncertainty
- The strategies that have been used to address drivers of uncertainty
- Identification of uncertainties that have the potential to change risk metrics
- Sources of "compounding conservatisms" and "blindspots"
- Inconsistencies in practices, conventions, etc. between hazard groups, technical elements, and other aspects of PRAs

In parallel with the expert discussions, the research terms performed a literature survey of taxonomies of uncertainty used in PRA and related fields as well as divergent fields. The team is currently working to integrate the insights from the literature survey with insights from the discussions with experts. In addition, the research team has developed a structure and taxonomy to support the identification and treatment of uncertainties in external hazard PRA. Initial findings are described in a companion paper presented at the current conference [2].

3.2 Task 2: Hazard Uncertainty Characterization and Data Analysis

While Task 1 focused on a range of external hazards (e.g., earthquakes, floods, and wind), Task 2 utilizes external flooding PRA as a target/focus hazard to identify key sources of uncertainty related to the probabilistic characterization of external hazard occurrence, severity, and timing. Probabilistic methods for characterizing primary measures of hazard severity (e.g., flood depth or elevation) are available or being developed for multiple types of natural hazards. Nonetheless, the extent to which this information has been integrated into external flood PRAs is limited, and uncertainties remain related to a range of modeling choices and the impacts of those choices on hazards with return periods of relevance to NPPs.

While primary measures of hazard severity (e.g., flood depth or elevation) are important, other factors, such as warning time and event duration, are also necessary PRA inputs. For example, NPPs may employ flood protection, mitigation, or response strategies that require (potentially substantial) manual actions. Human actions may be unsuccessful due to factors such as delayed decision-making (e.g., delayed decisions to begin implementation of flood protection strategies, which results in a reduced time available to complete actions) and human errors (e.g., errors in installing or constructing flood protection measures). A range of factors can contribute to or increase the probability of errors. For example, differences between predicted and experienced hazard characteristics can lead to delayed responses (e.g., if warning time is shorter than anticipated) or inadequate measures (e.g., if procedural measures underestimate the event's severity). Accurate external flooding PRAs must account for these possibilities. However, strategies are not yet available to probabilistically characterize factors such as warning time, the full suite of hazard impacts, and event duration. To address this issue, research under this project has used an existing database [3] of historical tropical cyclone (hurricane) tracks and warnings to understand uncertainty in assumed warning times and event durations. Initial research outcomes associated with tropical cyclone warning times are described in a companion paper presented at the current conference [4].

In addition to insights regarding hazard uncertainty, the information and insights from Task 2 are also used as input information to develop event scenarios for consideration under Tasks 3 and 4. An initial set of candidate external flooding hazard scenarios has been identified based on the integration of insights from a review of flooding strategies employed at U.S. nuclear power plants and following multiple table-top exercises with project team members. Future work under this task will focus on understanding the potential "value of information" associated with uncertainty reduction (e.g., via more detailed assessments, data collection, or research).

3.3 Task 3: Assessment of Uncertainty in Scenario Development

Task 3 links hazard data (Task 2) with NPP models. It seeks to develop an integrated strategy for identifying and characterizing uncertainties associated with event progressions using mechanistic simulation models and conventional PRA tools. A preliminary mechanistic simulation framework that incorporates the best estimate plus uncertainty (BEPU) and PRA method was developed [5]. Initial research has also begun to integrate mechanic tool(s) with PRA model tools to facilitate probabilistic propagation of information.

Activities are currently underway to develop a computational model (considering the generic pressurized water reactor (PWR) model [6]) to estimate the NPP system's event progressions under selected external flooding events, considering the initial set of scenarios developed under Task 2. We have established and performed the thermal-hydraulic analysis of loss of offsite power initiated station blackout (SBO) scenarios under external flooding events for the generic PWR using the system-level reactor safety analysis code RELAP5-3D [7]. This study seeks to achieve several objectives. The first objective is to simulate the plant response during an SBO accident. The second is to predict the timing of key event sequences during SBO accidents, such as the occurrence of steam generator dryout, initiation of core uncovery, and possible core damage. The third objective is to provide the plant operator with the important actions and the time available at which those actions need to be executed to avoid and mitigate possible core damage.

The generic PWR model employed in this study was based on a typical Westinghouse-design four-loop PWR. The original generic PWR RELAP5-3D model was modified and optimized to meet the needs of this study. The reliability of the steady-state performance of the modified model was verified with the values from one standard PWR plant Final Safety Report. The simulation of loss of offsite power initiated short-term and long-term SBO scenarios for the generic PWR has been established and preliminarily tested. The response of various thermohydraulic performance parameters for both SBO scenarios is being examined. It is noted that the availability of the turbine-driven auxiliary feedwater pump is critical for preventing and mitigating the core uncover and possible core damage during SBO accidents under external flooding events. The ongoing analyses also indicate that the best estimate code RELAP5-3D is capable for the SBO accident studies until core damage starts during external flooding events.

Event timing constraints are also being addressed via representative event conditions such as loss of offsite power and SBO scenarios that happen at various points in an external flooding event (e.g., at various times before or after the onset of flooding conditions or with varying plant modes and levels of decay heat). Linking system simulations and event models will enable the investigation of various assumptions' impact on the timing and sequencing of external flooding events. Event timing parameters in an SBO event are being considered for developing the hypothetical scenarios during external flooding events, including warning time, the time at which the external flooding event begins to affect the plant, the failure time of the diesel generators and batteries, recovery time of the diesel generators, batteries, and offsite power grid.

Future work for this task will focus on the simulations of a series of hypothetical scenarios with different event timing incorporated during external flooding events to measure the plant response and evaluate how those event timing constraints would affect the probability and the time to reach core damage. Moreover, the obtained predictive timing of these event sequences could provide the plant operator with the time available at which the onsite or offsite power needs to be restored and started to avoid and mitigate possible core damage, which could also provide valuable insight for the risk-informed decision-making processes.

3.4 Task 4: Characterization of Uncertainty in Human Response Under Physical Effects

There is a close coupling between the physical hazard impacts on the plant and the overall plant response under hazard events due to the (potentially significant) reliance on human actions for flood protection and mitigation. As a result, human response and human-plant interactions are critical elements of prioritizing uncertainties within external hazards PRA, and notably within external flooding PRA. However, most human reliability assessment (HRA) strategies (e.g., [8]) have not been developed for assessing ex-control room actions and hazard response strategies. Recent HRA methods such as IDHEAS [9] emphasize operator cognition. Still, they lack consistent, standardized causal mechanisms linking human performance to measurable performance influencing factors (PIFs), which diminishes the usability of current HRA methods for addressing human-plant interactions associated with external hazards.

Our research activities to date have focused on determining the extent to which existing HRA methods could be used to identify human failure events (HFEs) that reflect the types of human (and human-machine) actions and decisions involved in plant response under the hazard scenarios. Representative HFEs have been defined as part of plant response documentation reviews and table-top exercises completed under Task 2. The associated task decomposition and modeling framework is based on the cognitive-based Phoenix HRA model, which expands upon the Information-Decision-Action in Crew Context (IDAC) model [10], [11]. We completed the identification of HFEs and crew failure modes (CFMs) for representative manual actions selected by the U.S. Nuclear Regulatory Commission (NRC) for decomposition and analysis [12] by using the Phoenix task decomposition framework.

Initial outcomes of the task decomposition exercise are described in a companion paper presented at the current conference [13]. A literature review was conducted on existing applications of the Phoenix and IDAC methodologies in applications outside the context of NPP control rooms in order to examine their use in novel domains. Crew Response Tree (CRT) flowcharts were developed for each subtask of one representative flooding mitigation action task, "Load and Unload Portable Pump." Each CRT was then further decomposed using fault trees to identify possible HFEs and their underlying CFMs. This work demonstrated the applicability of Phoenix and IDAC to ex-control room actions. Additionally, it was found that the majority of HFEs and CFMs in this analysis belonged to the Action IDAC phase, which has less granularity and cognitive literature basis than the Information and Decision phases. This was identified as a potential uncertainty to be addressed in future work.

Future research activities will focus on identifying PIFs relevant to modeling/quantifying human-machine performance in flooding hazard response and the development of a framework built using Bayesian networks (BNs) that encode causal relationships between PIFs and human failure mechanisms in the context of external hazard PRA.

3.5 Task 5: Integration & Development of Method for Prioritization of Uncertainties

Task 5 will integrate, synthesize, and generalize insights from previous tasks to define a framework for identifying and prioritizing key drivers of uncertainty in external hazard PRA. In particular, Task 5 will leverage insights from Tasks 2-4, individually and in combination, to understand and identify which sources of hazard-derived uncertainty are potentially most significant for developing risk insights for an individual PRA technical element as well as total PRA metrics. These insights will be used to update the initial structure/taxonomy developed under Task 1. Then the team will work collaboratively to develop a process for prioritizing uncertainties for further study, considering the value of information motivated criteria (e.g., criteria based on the value to PRA in reducing the uncertainty as well as team's judgment regarding the feasibility and expense of further study seeking to reduce the uncertainties).

4 SUMMARY

This paper summarizes the ongoing progress of a multi-year research project focused on identifying and prioritizing uncertainties in external hazard PRA for nuclear power facilities. The objectives of this project are to:

- Develop a structured process for identifying, evaluating, categorizing, and assessing the impact of uncertainties on external hazard PRA modeling elements and create a common taxonomy for communicating these uncertainties across hazard groups
- Investigate the spectrum of uncertainties involved in the physical processes that underlie external hazards and assess the uncertainties associated with the estimation of hazard frequencies and parsing of hazard information into the external hazard PRA
- Investigate how uncertainties in the physical hazard characteristics and associated hazard timing interface with plant processes to prepare for, mitigate, cope, and recover from the external challenge and connect the impact resulting from the interaction of uncertainties in the hazard severity/evolution with human response
- Assess the impact of these uncertainties (and uncertainty reduction efforts) on developing the external hazard characterization in the external hazard PRA.

The proposed project will contribute to the state of knowledge and understanding in NPP external hazard PRA consistent with the growing recognition of the safety significance of external hazards. It may further identify areas for improvement and augmentation of existing models and methods.

5 ACKNOWLEDGEMENT

This research is supported by a research grant from the Department of Energy's Nuclear Energy University Program (NEUP) under grant/cooperative agreement DE-NE0008974. Any opinions, findings, and conclusions expressed in this paper/presentation are those of the authors and do not necessarily reflect the views of the funding agency or any other organization.

6 ABBREVIATIONS

BEPU	Best estimate plus uncertainty
BN	Bayesian networks
CFM	Crew failure modes
CRT	Crew Response Tree
HFE	Human failure events
HRA	Human reliability assessment
IDAC	Information-Decision-Action in Crew Context
NEUP	Nuclear Energy University Program
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission
PIF	Performance influencing factors
PRA	Probabilistic risk assessment
PWR	Pressurized water reactor
SBO	Station blackout
ST	Short-term

7 REFERENCES

[1] M. Bensi, K. Groth, Z. Wu, Z. Ma, and R. Schneider, "Identifying and Prioritizing Sources of Uncertainty in External Hazard Probabilistic Risk Assessment," Proposed Under Department of Energy Nuclear Energy University Program [Work-Scope: RC-8: Evaluation of Physical Phenomena Data Impact and Improvements], 2020.

[2] M. Bensi *et al.*, "Uncertainty in External Hazard Probabilistic Risk Assessment (PRA): A Structured Taxonomy," presented at the PSAM 16, Honolulu, HI, 2022.

[3] USNRC, "Plant-Specific Safety Enhancements After Fukushima," *NRC Web*, Dec. 07, 2021. https://www.nrc.gov/reactors/operating/ops-experience/fukushima.html (accessed Mar. 31, 2022).

[4] S. Mohammadi *et al.*, "Analysing Uncertainty in Predicted Tropical Cyclone Path and Landfall Characteristics for Landfalling Storms to Support External Hazard Probabilistic Risk Assessments for Critical Infrastructure," presented at the PSAM 16, Honolulu, HI, 2022.

[5] T. Liu, Z. Wu, C. Lu, and R. P. Martin, "A best estimate plus uncertainty safety analysis framework based on RELAP5-3D and RAVEN platform for research reactor transient analyses," *Prog. Nucl. Energy*, vol. 132, p. 103610, Feb. 2021, doi: 10.1016/j.pnucene.2020.103610.

[6] Carlo Parisi *et al.*, "Risk-Informed External Hazards Analysis for Seismic and Flooding Phenomena for a Generic PWR (Technical Report) | OSTI.GOV," INL/EXT-17-42666, Jul. 2017. Accessed: Feb. 03, 2020. [Online]. Available: https://www.osti.gov/biblio/1376899-risk-informed-external-hazards-analysis-seismic-flooding-phenomena-generic-pwr

[7] USNRC, “RELAP5-3D Code Manual [Revision 2.3],” INEELEXT-98-00834, 2015.

[8] USNRC/INL, "The SPAR-H Human Reliability Analysis Method," NUREG/CR-6883, INL/EXT-05-00509, Aug. 2005. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6883/cr6883.pdf

[9] J. Xing, G. Parry, M. Presley, J. Forester, S. Hendrickson, and V. Dang, "NUREG-2199, Vol. 1, 'An Integrated Human Event Analysis System (IDHEAS) for Nuclear Power Plant Internal Events At-Power Application - Volume 1.,'" p. 317, May 2016.

[10] N. J. Ekanem, A. Mosleh, and S.-H. Shen, "Phoenix – A model-based Human Reliability Analysis methodology: Qualitative Analysis Procedure," *Reliab. Eng. Syst. Saf.*, vol. 145, pp. 301–315, 2016, doi: 10.1016/j.ress.2015.07.009.

[11] Y. H. J. Chang and A. Mosleh, "Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents: Part 1: Overview of the IDAC Model," *Reliab. Eng. Syst. Saf.*, vol. 92, no. 8, pp. 997–1013, Aug. 2007, doi: 10.1016/j.ress.2006.05.014.

[12] R. Prasad *et al.*, "Effects of Environmental Conditions on Manual Actions for Flood Protection and Mitigation." US Nuclear Regulatory Commission, May 2020.

[13] A. Al-Douri, C. Levine, and K. M. Groth, "Identifying Human Failure Events (HFEs) for External Hazard Probabilistic Risk Assessment," *PSAM 16*, Jun. 2022.