Assessment of Uncertainty in Scenario Development for External Hazard Probabilistic Risk Assessment for Nuclear Power Plants

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ABSTRACT

Probabilistic Risk Assessment (PRA) has been widely accepted and implemented by nuclear power plants (NPPs) as an important tool for risk assessment and decision-making. Recent events such as the Fukushima Daiichi accident have increased the focus on external hazards as potentially significant risk contributors to the core damage frequency of NPPs. However, limited models and tools are available to support probabilistic assessment of external hazards at NPP PRAs, particularly for natural hazards (e.g. floods), for which it is important to consider warning time, event progression, and event duration. Since the spatially and temporally dynamic nature of physical event impacts leads to significant sources of uncertainty associated with hazard impacts and event progression, limited access to relevant information poses considerable challenges to modeling these impacts within a PRA structure. In this paper, we develop an integrated assessment strategy to overcome these limitations in external hazard PRAs for NPPs. The plant response model development is the primary focus of this paper. A hybrid mechanistic computational model was developed to estimate the NPP system's event progressions in response to external flooding events. The external flooding PRA response model is currently in development following the proposed flood propagation path to identify the critical plant structures, systems, and components as well as their failure modes that are significant to the risk and would potentially be affected by the external flooding. For demonstration, the loss of offsite power (LOOP) initiated short-term and long-term station blackout (SBO) scenarios under external flooding events for a generic PWR are established and assessed with the developed integrated framework. The results offer valuable insights into the significance of flood assumptions and the consequences of external flooding events on nuclear power plants. The integrated framework will facilitate identifying and characterizing the sources of uncertainties associated with external flooding hazards to ensure the safety and reliability of NPPs.

Keywords: *Risk Assessment, External flooding, PRA, Uncertainty*

1. INTRODUCTION

Several severe external natural hazard events have occurred at nuclear power plants (NPPs) worldwide in recent years. Among these external natural hazards, flooding is considered to be one of the most significant external hazards for NPPs. It can be caused by various natural or man-made phenomena, such as extreme rainfall, dam failures, storm surges, and tsunamis. External flooding incidents, such as those at the Le Blayais site in 1999 [1], the Fukushima Daiichi site in 2011 [2], and the St. Luice site in 2014 [3], have increased the focus on the safety and integrity of NPPs under external flooding events. External flooding events on an NPP site can significantly impact the plant's safety, resulting in a postulated initiating event that needs to be considered in the plant safety analysis. The accumulation of water in different plant areas may induce failures in safety-related systems, such as the emergency power supply and electric switchyard, which may ultimately result in losing external connectivity to the offsite power grid, decay heat system, and other essential systems [4].

To ensure the safety of NPPs under external flooding events, it is necessary to evaluate and manage the risks of potential failures or hazards that can affect their operation. Probabilistic risk assessment (PRA) is a systematic methodology to assess and manage risks and has been widely accepted and implemented by NPPs. However, the current external flooding risk assessment practices are deterministic [5]. Existing models and tools to support PRA of external hazards for NPPs are limited, particularly for dynamic factors (e.g., flooding). Modeling the plant response to external flooding also presents many unique challenges due to its high spatial and time-dependent nature [6]. The conventional event tree and fault tree method in a static PRA may not be sufficient to address these challenges and accurately represent the plant behavior actions during a flooding event [6]. Additionally, there are significant uncertainties surrounding external hazard PRA, including the uncertainty related to the severity, frequency, and temporal evolution of the hazard, the uncertainty in the impacts of hazard events on NPP structures, systems, and components (SSCs), and event progressions, as well as the uncertainty linked to the coupling of the physical aspects of hazards with human performance [7].

To address these challenges, this paper proposes a proof-of-concept computational analysis framework that connects the external flooding hazard data to the NPP models to offer an integrated PRA environment. The framework comprises an operating experience review, external flood hazard analysis, fragility evaluation, and plant response model, with our primary focus on the plant response model development. The work being presented here is part of the ongoing research project sponsored by the United States Department of Energy (DOE) Nuclear Energy University Program [7].

This paper is organized as follows: Section 2 provides the current statutes and related work on external flooding PRA for NPPs. Section 3 describes an overview of the integrated assessment framework, with a specific focus on the plant response model development; Section 4 presents the results of a case study conducted to demonstrate the framework's applicability in assessing the risks associated with external flooding events. Section 5 concludes this paper by discussing our findings and future work.

2. CURRENT STATUS

The Nuclear Regulatory Commission (NRC) Regulatory Guide 1.59 [8] requires that structures, systems, and components critical to safety be designed to withstand the effects of natural phenomena such as floods, tsunamis, and seiches without loss of capability to perform their safety functions. To comply with NRC regulations, a safety analysis is necessary to protect critical SSCs against any flooding impact. The NUREG/CR-7046 [9] report provides a comprehensive overview of the current approaches and methods for assessing flood hazards at NPPs. It also included a brief discussion of the probabilistic methods for estimating the design-basis floods. However, for some reason, the deterministic approach is still recommended for the near future. Firstly, there is no comprehensive framework for the full implementation of a Probabilistic Flood Hazard Assessment (PFHA). Secondly, it is essential to maintain consistency with existing practices [9].

Performing an external flooding PRA for an NPP is a challenging and complex task. It requires both collective experience and a well-established method for performing a PFHA that can address the relevant range of exceedance frequencies for NPP PRAs [10]. However, these are lacking in the current practice. There is currently a scarcity of models and tools that can aid in the probabilistic evaluation of hazard characteristics, particularly when considering temporal factors such as warning time, event progression, event duration, and hazard intensity [11]. The standardization of PRA for external flooding is also limited. Nevertheless, the ASME/ANS RA-Sa-2009 standard [12] includes a chapter that touches upon external flooding PRAs on a general level. According to this standard, there are three main technical elements for performing external flooding PRA for NPPs under a general framework: (1) External Flood Hazard Analysis (XFHA); (2) External Flood Fragility Evaluation (XFFR); (3) External Flood Plant Response Model and Quantification (XFPR). XFHA estimates the frequency of various magnitudes (e.g., height, duration) of external flooding events at a site. It considers both historical data and site-specific information. XFFR evaluates the vulnerability of SSCs based on the severity of flooding. It utilizes plant-specific information and an engineering approach to assess the likelihood of failure. XFPR aims to develop a response model to simulate the dynamic behavior of NPPs under external flooding scenarios. It takes into account any resulting initiating events and failures that could cause core damage or large early release. The conditional Cumulative Distribution Function (CDF) and Large Early Release Frequency (LERF) derived from this model are integrated with the frequency of the damage states of the plant to get the unconditional CDF and LERF.

Due to its spatial and time-dependent nature, modeling the plant response to external flooding also presents many challenges. Several studies have been conducted to evaluate the external flooding risk for NPPs using mechanistic simulation models and probabilistic methods. For example, Ma et al. [6] proposed a comprehensive framework to model dynamic external flooding scenarios using simulation-based techniques. The framework involves a new type of PRA technique called State-based PRA Modeling, which integrates time-dependent interactions from physical simulations and random failures into traditional PRA logic models. Another example is Sezen et al. [13], who presented a computational risk assessment method that integrates the risks arising from flooding and seismic events into the traditional PRA. Their approach demonstrates the potential benefits of reducing subjective judgment dependence in PRA and provides a more realistic representation of the external hazards. Jankovsky et al. [14] presented a dynamic event dynamic PRA approach to analyze a seismic-induced internal flooding event using accident progression trees (ADAPT) and severe accident analysis code MELCORE.

These studies highlight the importance of developing a computational analysis framework that establishes a linkage between external flooding hazard data and NPP models. Such a framework would provide an integrated PRA environment to identify and evaluate flooding hazards' uncertainties and assess the effectiveness of the response strategies.

3. INTEGRATED ASSESSMENT FRAMEWORK

3.1. Overview

In this work, an integrated assessment framework is developed to address the challenges associated with external flooding hazards in NPPs and shown in Figure 1. The framework aims to identify and characterize sources of uncertainties related to external flooding hazards to ensure the safety and reliability of NPPs.

The framework integrates external flooding data with hybrid NPP response models to provide a more accurate and realistic assessment of the potential risks associated with external flooding events.

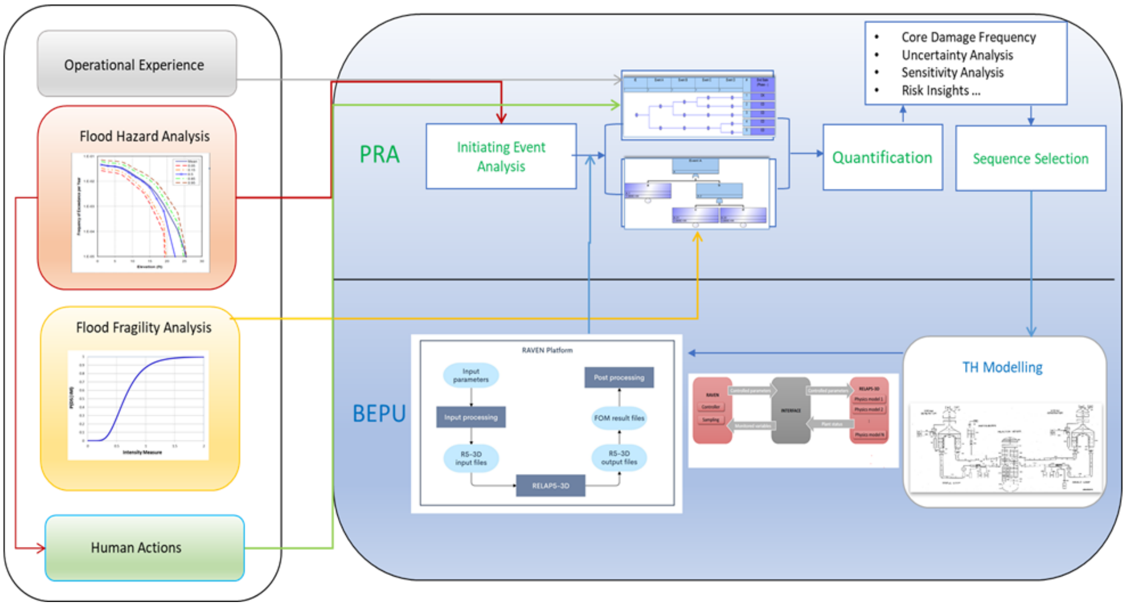

Figure 1. Integrated Risk Assessment Framework for External Flooding PRA.

The integrated risk assessment framework for external flooding PRA mainly consists of three key elements: external flood hazard analysis, fragility evaluation, and plant response model. Considering the specific purposes of the present work, the primary focus discussed in this paper is given to the plant response model development, which is shown by the blue block in Figure 1. Other research groups within our project team will carry out other blocks within the framework, such as the operating experience review, hazard and fragility analysis, and human actions. The outputs from these different groups will be utilized as input information to develop event scenarios that accurately represent external flooding event progressions.

The development of the plant response model involves two main parts. The first part entails developing a hybrid mechanistic computational model that estimates event progressions of a generic PWR NPP under various external flooding scenarios. This mechanistic model takes into account several critical factors, including the design of the plant, the characteristics of the flooding event, and the behavior of various systems and components within the NPP. The focus is on investigating the impact of flooding input assumptions on event timing and sequencing. The second part integrates the developed mechanistic model with an external flooding PRA model to take into account the uncertainties associated with various input parameters. The integration will facilitate the identification of the areas of uncertainty associated with physical flooding characterization and potential approaches for reducing those uncertainties. The details of these two parts involved in integrated framework development are provided in the following sub-sections.

3.2. Mechanistic Computational Model

A computational model was developed to estimate the NPP system's event progressions in response to external flooding events. The best estimate plus uncertainty (BEPU) framework, which was derived from our previous study [15], was utilized for this purpose. The BEPU framework was established by employing the best-estimate system-level reactor safety analysis code RELAP5-3D [16] and the data analysis platform RAVEN [17], developed by Idaho National Laboratory. The Generic RELAP5-3D model of the

Westinghouse four-loop design PWR was modified to simulate the external flood-induced accident. Within the framework, the RELAP5-3D model serves as a functional engine for conducting physics simulations and delivering predictions. At the same time, the RAVEN platform was utilized to integrate the physics model and perform the uncertainty propagation of the system responses. Fig. 2 demonstrates the interaction mechanism between RAVEN and RELAP5-3D within the BEPU framework.

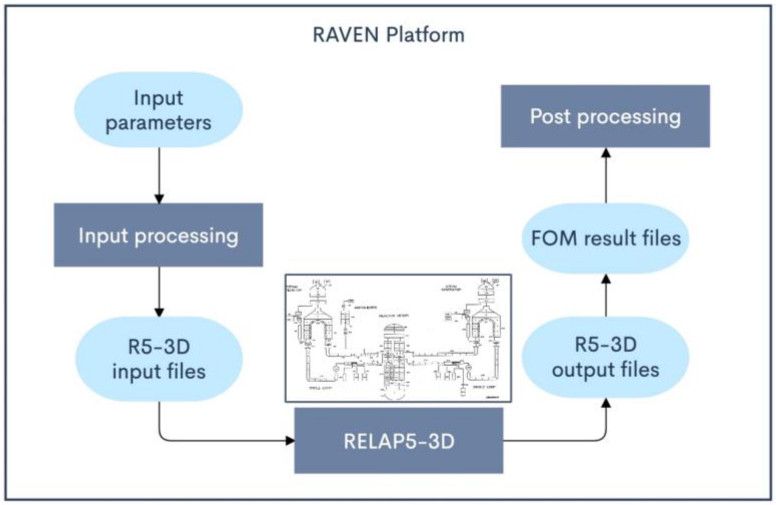

Figure 2. The data flow chart in the BEPU framework [15]**.**

The computational model that has been developed in this study is a critical component of our proposed integrated assessment framework for external flooding events in NPPs. The model is expected to offer a range of benefits that are described below.

Firstly, it facilitates the modeling of the progression of external flooding events and their interaction with NPP systems. It also enables the evaluation of critical input assumptions that impact the timing and sequence of external flooding events. Secondly, the computational model can complement the static PRA model to improve the analysis of external flooding events. For example, it can be utilized to assess the significance of specific components, such as the turbine-driven pump of the auxiliary feedwater system (TDAFWP), which are critical for an external flooding event and will be described in Section 4. It can also help identify areas where the static PRA model may not appropriately account for specific risks, thereby improving the accuracy and reliability of PRA models in assessing the risks associated with external flooding events. Moreover, the simulation results offer valuable insights into the significance of flood assumptions and the consequences of external flooding events on nuclear power plants. This enables operators to evaluate and prioritize mitigation strategies to reduce the risks associated with external flooding events.

3.3. External Flooding PRA Model

The external flooding PRA response model was developed using the standard static PRA code SAPHIRE [18]. As shown in Figure 3, the model consists of the external and internal response models. The external flooding response model tracks the propagation of external flooding to identify the critical aspect of the event progression, from offsite to onsite, outside and inside the risk-significant building (such as the control building, turbine building, reactor building, auxiliary building, emergency diesel generator building, intake structure, and switchyard), down to the rooms with significant risk systems and component that perform the safety functions to prevent reactor core damage. This model accounts for various protective measures implemented at the NPP site, including flood barriers, drainage systems, and other physical protections, to evaluate their effectiveness in preventing or mitigating flood damage.

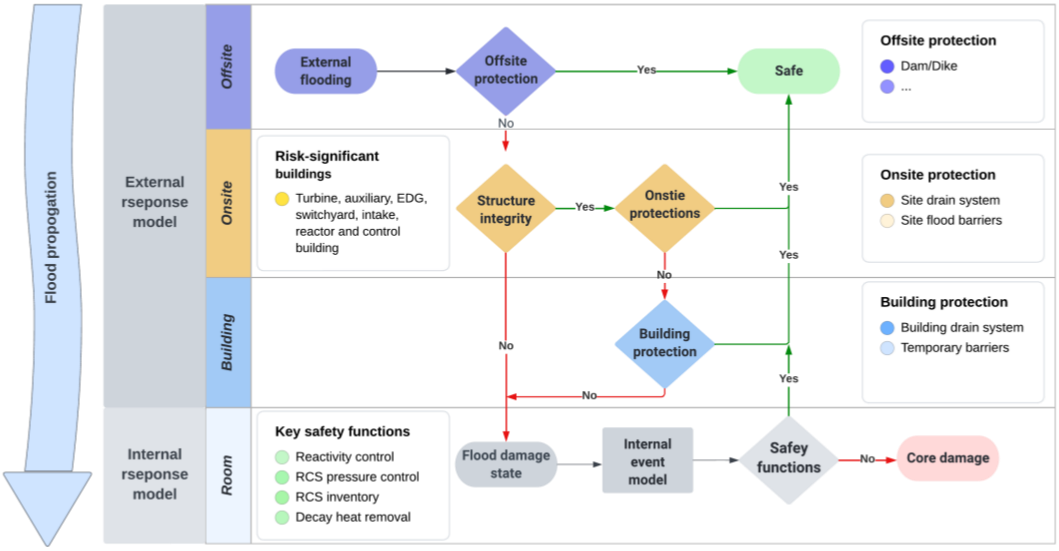

Figure 3. External flooding PRA response model flowchart.

The internal response model is developed based on the existing internal event PRA model, including potential failure under external flooding scenarios. In the event of loss of building integrity or failure of the as-designed and temporary flood protection measures to prevent water from entering risk-significant buildings, the plant's critical systems and components housed within the affected building would be at risk, potentially challenging the plant’s key safety functions, including core reactivity control, reactor coolant inventory and pressure control, and decay heat removal. In such cases, the plant's internal response model needs to account for the potential impact of floodwater on significant risk safety systems and assess the most effective course of action to mitigate the flooding risks. Following the proposed flowchart, the extensive external flooding PRA model is currently in development. To ensure its applicability and effectiveness, we have established two scenarios during the development phase for a case study.

4. CASE STUDY AND RESULTS

To demonstrate the applicability of the developed framework, a case study was conducted for two hypothetical external flooding scenarios at a generic PWR NPP. This case study aimed to assess the impact of external flooding on the safety of the NPP and to identify the key factors contributing to the uncertainties associated with the event progression.

4.1. Scenario Description

External flooding can lead to SBO events, potentially resulting in severe consequences at nuclear power plants. As such, understanding the potential risks associated with external flooding events and identifying the key factors contributing to the uncertainties related to the event progression is crucial. The Reactor Safety Study has shown that SBO events could significantly contribute to the overall risk of accidents at nuclear power plants. Therefore, investigating SBO accident scenarios caused by external hazards and analyzing the risks associated with plant responses during SBO accidents is essential for ensuring nuclear power plant safety.

The study focused on two scenarios, namely, short-term station blackout (STSBO) and long-term SBO (LTSBO), which were developed based on the external flooding PRA model. Although both scenarios entail core damage due to the loss of offsite and onsite power, there are notable differences in several key aspects that need to be considered during the progression of the accident sequences. These factors include the duration and height of the external flood, the effectiveness of flood protection measures, and the vulnerability of essential risk-significant components. The details of these two scenarios are shown in the table below.

Table I. Event Sequence for STSBO and LTSBO

Event sequence	Short-term SBO (STSBO)	Long-term SBO (LTSBO)
External Flooding	Heavy rainfall and overtopping of nearby river dikes can cause external flooding of the plant site. Flood height may reach x feet above ground level, with a short duration of up to 24 hours.	Heavy rainfall and overtopping of nearby river dikes can cause external flooding of the plant site. Flood height may reach y feet above ground level, with a long duration exceeding 24 hours.
Onsite Flood protection system	Activated, including sandbags, temporary barriers, and pumps. However, the floodwaters breach the perimeter and inundate the plant site.	Activated, including sandbags, temporary barriers, and pumps. However, the floodwaters breach the perimeter and inundate the plant site.
Loss of Offsite Power	Floodwaters inundate the electrical switchyard, causing a loss of offsite power.	Floodwaters inundate the electrical switchyard, causing a loss of offsite power.
Loss of Onsite Power	Floodwaters breach the EDG building, and DG fails. Station Blackout SBO is initiated.	Floodwaters breach the EDG building, and DG fails. Station Blackout SBO is initiated.
Loss of Emergency Core Cooling System	Flood waters enter the turbine building, causing the Turbine Driven Auxiliary Feedwater Pump (TDAFWP) to fail due to flooding damage, leading to a loss of the ECCS.	Adequate flood protection of turbine building or lower flood heights prevented flooding of TDAFWP and allowed for the continued operation of ECCS.
Core damage	The fuel begins to heat up without cooling, and core damage occurs after x hours.	TDAFWP operates until DC batteries are depleted or fail due to flooding, and fuel eventually melts, causing core damage.

One of the most significant differences between the two scenarios is the availability and failure time of the TDAFWP during an external flooding event. In the STSBO scenario, the TDAFWP fails due to flooding damage caused by floodwaters entering the turbine building. On the other hand, the LTSBO scenario assumes that the turbine building has adequate flood protection or lower flood heights, which prevented flooding of the TDAFWP and allowed it to continue operating to provide feedwater for core cooling. This means that the TDAFWP remains available and can serve until the batteries are depleted or fail due to flooding.

The differences in these factors could have significant implications for the likelihood and severity of core damage in each scenario and impact the time available for operators to undertake mitigation actions.

Therefore, thoroughly investigating these scenarios is crucial to understand better the potential risks associated with external flooding events and identify the key factors contributing to the uncertainties related to the event progression in nuclear power plants.

4.2. Scenario Analysis Results

To further illustrate the plant behavior of the generic PWR model under external flooding events, the BEPU framework discussed in section 2 was employed to simulate the developed STSBO and LTSBO scenarios.

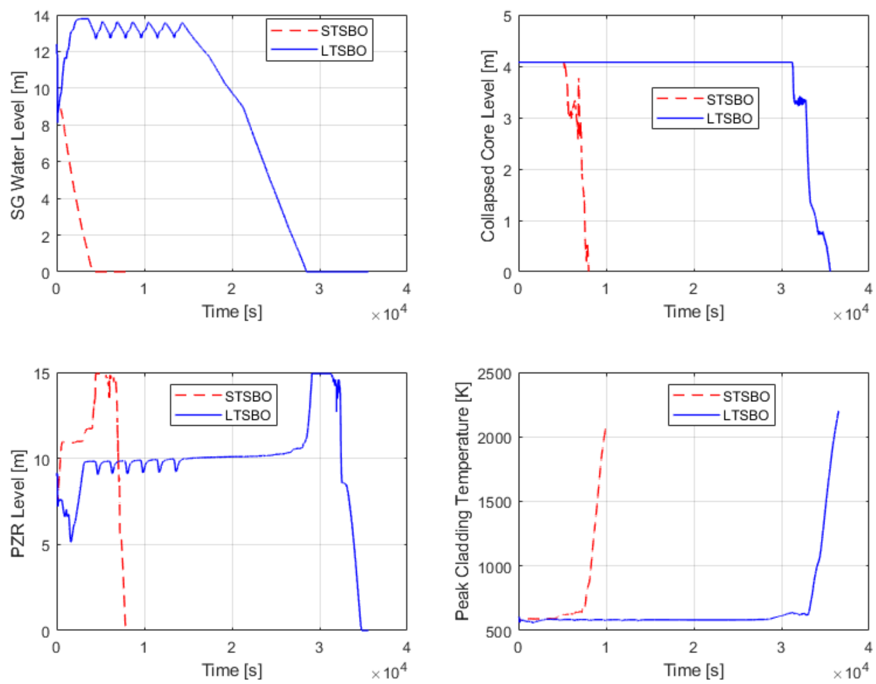

Figure 4. The behavior of critical thermal-hydraulic parameters in the STSBO and LTSBO.

The time-dependent behavior of key thermal-hydraulic parameters is analyzed. Specifically, this study focuses on the response of parameters such as steam generator (SG) water level, pressurizer level, collapsed core level, and peak clad temperature. These comparisons of the selected parameters of interest are presented in Figure 4. Comparing selected performance parameters shows that the two scenarios exhibit a similar trend, with the main difference being the timing of the occurrence of key event sequences. A quantitative comparison of the event sequences for both scenarios is summarized in Table II.

Table II. Comparison of Event Sequence for STSBO and LTSBO.

Event	STSBO (s/hr)	LTSBO (s/hr)
Steam generators dryout	4080 / 1.13	28500 / 7.92
Core uncover start	5200 / 1.44	31252 / 8.68
Pressurizer empty	7988 / 2.22	34796 / 9.67
Core fully uncovered	8000 / 2.22	35564 / 9.88
Core damage	8962 / 2.49	35064 / 9.74

The results show that the STSBO scenario experiences core damage approximately 2.5 hours after the SBO transient initiation. On the other hand, in the LTSBO accident, adequate flood protection or lower flood heights prevents flooding of the TDAFWP. It allows it to continue operating for 4 hours after the reactor shutdown, resulting in core damage occurring approximately 7.2 hours later than in the STSBO transients. Hence, the availability of the TDAFW system is critical in preventing potential core damage. Plant operators can gain insights into the time required to restore the emergency diesel generator or TDAFW pump to avoid potential core damage. Additionally, it can help identify areas where the static PRA model may not accurately account for specific risks, thus enhancing the accuracy and reliability of PRA models in assessing the risks associated with external flooding events.

5. CONCLUSIONS

This paper presented a proof of concept integrated assessment framework designed to address the challenges associated with external flooding hazards in NPPs. The framework integrates external flooding data with hybrid NPP response models to provide a more accurate and realistic assessment of the potential risks associated with external flooding events. Developing the plant response model involves creating a hybrid mechanistic simulation model that estimates event progressions of a generic PWR NPP under various external flooding scenarios and integrating the developed mechanistic model with an external flooding PRA model, taking into account the uncertainties associated with multiple input parameters.

We conducted a case study of two station blackout scenarios caused by external flooding to demonstrate the proposed integrated risk assessment framework. Multiple factors, including the duration and height of the external flood, the effectiveness of flood protection measures, and the vulnerability of essential risk-significant components, were incorporated to develop the scenario based on the external flooding PRA model. To further illustrate the plant behavior of the generic PWR model under external flooding events, the BEPU model was employed to simulate both scenarios; the time-dependent behavior of key thermal-hydraulic parameters has been analyzed. The results offer valuable insights into the significance of flood assumptions and the consequences of external flooding events on nuclear power plants.

In the future, the extensive external flooding PRA model will undergo further development to enhance its effectiveness. This will involve developing event trees and corresponding fault trees that follow the flood propagation path, allowing for the identification of various potential scenarios resulting from external flooding. By doing so, the key features of the event progression can be pinpointed, leading to a better characterization of the sources of uncertainties associated with external flooding hazards. This will ultimately improve the safety and reliability of nuclear power plants.

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