

Internal Flooding Risk Assessment in the Pre-Defueled Phase of BWR/4 Mark I Nuclear Power Plant

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Abstract: This study extends previous investigations on the Pre-Defueled (PD) phase of the Decommissioning Transition Stage for a reference BWR-4/Mark-I plant by examining internal flooding risk under the same transitional plant configuration. During the PD phase, spent fuel remains in the reactor core, and the reactor cavity is hydraulically connected to the Spent Fuel Pool (SFP). Decay heat removal is maintained by the Residual Heat Removal (RHR) system or the SFP additional cooling system (SFPACS), depending on system alignment.

While earlier work focused on internal initiating events and the evolution of fuel risk during the PD phase, the present study addresses internal flooding as a hazard that may challenge electrical distribution and decay heat removal capability. An internal flooding Probabilistic Risk Assessment (PRA) is developed in accordance with the Electric Power Research Institute (EPRI) methodology, incorporating flood initiating sources, propagation pathways, and their impacts on safety-related functions.

Quantification results indicate that the dominant contributor to flooding risk is a flood propagation scenario originating in the 4.16-kV switchgear room. The associated flood area exhibits substantially higher risk significance than other evaluated zones, primarily due to its influence on power supply availability and the integrity of decay heat removal functions.

The results provide additional risk insights into hazard management and configuration control during the PD phase, complementing prior internal event analyses and further clarifying the risk profile of the Decommissioning Transition Stage.

1. INTRODUCTION

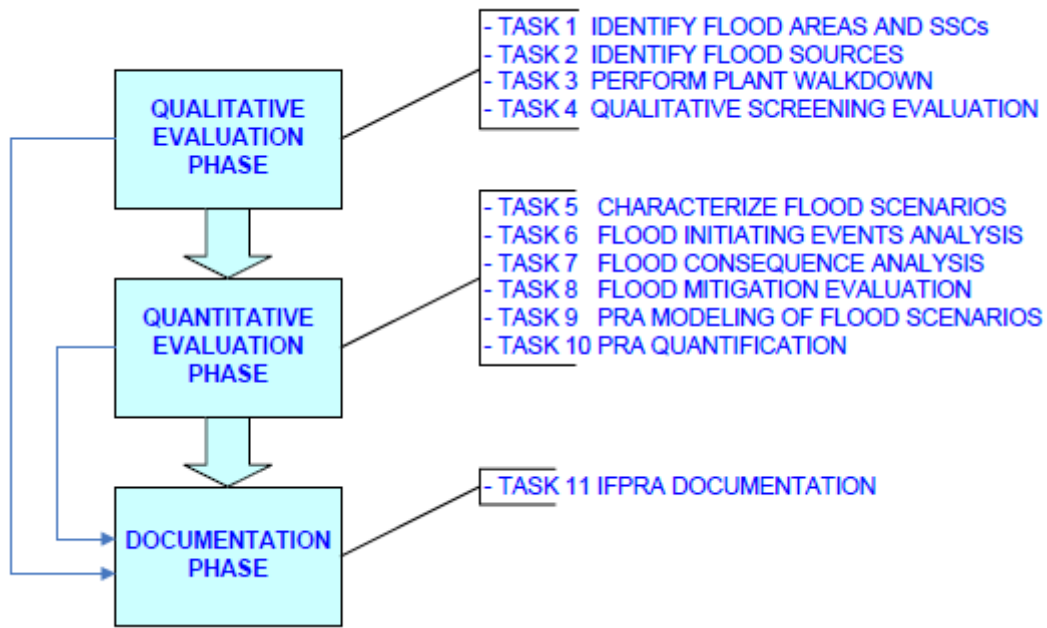
The pre-defuel (PD) phase is the transition phase before the decontamination and demolition stages. The PD phase is similar to the low power and shutdown (LPSD) phase. The focus of this study is limited to the accident sequences and risk profiles of fuel damage in the reactor and the spent fuel pool (SFP) caused by flooding events under pre-defuel conditions.

This study combined two parts, one with the fuel from the last cycle in the reactor pressure vessel and the other with the total spent fuel in the spent fuel pool connecting with the reactor cavity. The reference type of this nuclear power plant is BWR-4/Mark-I. During normal operation of the PD phase (18 months), there is no movement of fuel. Section II outlines the methodology, the flood model differences between power operation and PD phase are discussed in section III, and section IV presents the conclusions.

2. METHODOLOGY

The methodology is based on EPRI-1019194: Guidelines for Performance of Internal Flooding Probabilistic Risk Assessment. This report provides standardized guidance for performing an Internal Flood Probabilistic Risk Assessment (IFPRA) for nuclear power plants. It covers flooding and High Energy Line Breaks (HELB) originating from sources outside the containment structure, including high, moderate, and low-energy piping systems. The IFPRA process is divided into three major phases encompassing 11 tasks as figure 1.

Figure 1. Major Phases and Tasks of IFPRA



2.1. Qualitative Evaluation Phase

Task 1 Identify Flood Areas And SSCs

The definition of flood areas begins with identifying buildings and zones containing potential flood sources (including areas where water pipes pass through) to delineate the flood area boundaries. Simultaneously, it must be confirmed whether PRA-significant equipment or flood mitigation equipment (such as sump pumps and dikes/berms) are located within these defined areas. The Structure, System, and Components (SSCs) was defined by internal PRA model in the PD phase.

Task 2 Identifying Flood Sources

When analyzing each selected flood area, the analysis should encompass: the flood source, such as pipeline, tank, heat exchanger. Reviewing the elevation of flood sources relative to PRA-significant equipment helps optimize and reduce the workload for flood scenario development. Critical components are based on the PRA model of normal operation of PD Phase in the Decommissioning Transition Stage.

Task 3 Perform Plant Walkdown

The objective of the plant walkdown is to verify the accuracy of the collected information, supplement deficiencies in the documented materials, and obtain a clear understanding of the plant's actual flooding scenarios.

Both task 1 and task 2 require on-site walkdowns to verify the accuracy of the information, such as confirming the flooding sources for each flooding area and the inventory and locations of important components. In the subsequent determination of flooding scenarios, walkdowns are also required to confirm the SSCs and their spatial locations in order to determine the flooding elevation that would cause the failure of each SSC (i.e., the critical water damage elevation).

The walkdowns also confirm the space occupied by equipment in all flood areas, the flooding mitigation features (e.g., drainage pipes, curbs, water level alarms), flooding propagation pathways, and the dimensions, materials, and lengths of flooding sources (e.g., piping or tanks).

Task 4 Qualitative Screening Evaluation

In IFPRA, a systematic qualitative screening is first conducted across the entire plant. This process optimizes the analytical focus by early elimination of non-significant structures and areas, thereby

prioritizing high-impact flood zones. The screening scope retains areas containing safety-significant equipment essential for core or SFP cooling, as well as regions with potential flood sources. The screening methodology follows a hierarchical approach, transitioning from macro to micro levels: (1) Plant-wide Qualitative Screening and (2) Flood Area Qualitative Screening.

Task 4.1 Plant-wide Qualitative Screening

Also referred to as preliminary or coarse screening, this phase utilizes the individual building as the basic unit of analysis. Considering the plant state during the decommissioning transition phase, five specific criteria (Criteria A–E) are established for exclusion:

Criterion A: Reactor buildings where internal equipment is designed to withstand the harsh environments of a Loss of Coolant Accident (LOCA).

Criterion B: Areas containing no safety-significant equipment and possessing no flood propagation pathways.

Criterion C: Standalone outdoor structures with no safety-significant equipment, no internal water sources, and no propagation pathways.

Criterion D: Areas with neither flood sources nor propagation pathways.

Criterion E: Areas where the only safety-significant component susceptible to flood damage is the water source itself, with no further propagation pathways.

To ensure analytical conservatism, the preliminary screening assumes a worst-case failure mode: all target SSCs within a building are assumed to fail simultaneously upon flood initiation, regardless of existing flood mitigation measures. This prevents premature exclusion of areas that might otherwise distort the risk profile.

Task 4.2 Flood Area Qualitative Screening

This stage, known as fine screening, uses Flood Areas (typically aligned with fire compartments) as the analytical units. To justify the exclusion of a flood area from subsequent quantitative analysis, it must satisfy a two-stage verification: (1) Intra-area screening criteria and (2) Inter-area propagation criteria.

1. Intra-area Screening Criteria (Impact Codes):

Code F: No potential flood sources exist within the area.

Code U: The area contains no equipment other than cabling. If no propagation pathways exist, the area is screened out.

Code N: The simultaneous failure of all equipment (excluding cables) triggers no initiating events relevant to the PRA and involves no safety-related components. Screening is contingent on the absence of propagation.

Code D: The only SSC susceptible to damage is the flood source itself. Screening is contingent on the absence of propagation.

Code I: The area contains equipment critical to the cooling of the reactor core or SFP; these areas are mandatory inclusions for quantitative analysis.

2. Inter-area (Propagation) Screening Criteria:

A flood area is identified as having a propagation pathway if it meets any of the following technical conditions:

Direct Connectivity: The area is open to adjacent flood areas.

Vertical Propagation: The area is on an upper floor with pathways leading to the basement/lowest level.

Shared Infrastructure: The area is on the lowest level or shares common drainage systems with other structures.

A propagation pathway is defined as "effective" only if the flooding of the secondary area results in the failure of additional SSCs beyond those already compromised in the source area.

2.2. Quantitative Evaluation Phase

Task 5 Characterize Flood Scenarios

Potential flooding scenarios encompass source-specific failures, water spray, and inundation. Based on the volumetric flow rate, inundation is categorized into "General Flooding" and "Major Flooding," both of which account for intra-area failures and inter-area propagation. The flow rate thresholds are defined as follows: Spray (< 100 gpm), General Flooding (100–2,000 gpm), and Major Flooding (> 2,000 gpm).

Task 6 Flood Initiating Event Analysis

Utilizing the Plant Flood Database, the specific flooding characteristics of each flood area are established. This includes identifying localized flood scenarios and their corresponding Initiating Event (IE) categories and frequencies. Furthermore, the analysis models flood propagation phenomena facilitated by identified pathways and evaluates the resulting IE types and their occurrence frequencies.

Task 7 Flood Consequence Analysis

The objective of this phase is to evaluate the deterministic impact on SSCs. The analysis delineates the progression of each flood-induced event by integrating parameters such as fluid source type, discharge rate, spatial location, and the time-to-critical-volume required to induce functional failure in target components.

Task 8 Flood Mitigation Evaluation and Human Reliability Analysis (HRA)

This task involves evaluating the efficacy of flood mitigation features and the Operator Action Time Window. By calculating Human Error Probabilities (HEP) for recovery actions, the frequency of unmitigated flood sequences can be refined. Key hardware considered in the mitigation assessment includes water level instrumentation, floor drains, sumps, and curbs.

Task 9 PRA Modeling of Flood Scenario

During the quantitative screening analysis, flooding scenarios are postulated based on the characteristics of each flood area. The assumed flooding scenarios generally include local flooding scenarios—in which important equipment within the flood area containing the flooding source is assumed to be damaged by water—and propagation flooding scenarios—in which important equipment within both the flood area containing the flooding source and adjacent flood areas is assumed to be damaged by water.

The flooding scenarios considered include the following:

1. Spray-induced flooding causing failure of the flooding source itself.
2. Local spray flooding scenario.
3. General flooding causing failure of the flooding source itself.
4. Local inundation due to general flooding.
5. Major flooding causing failure of the flooding source itself.
6. Local inundation due to major flooding.
7. General flooding propagating to adjacent flood areas.
8. Major flooding propagating to adjacent flood areas.

Task 10 PRA Quantification

The quantification process utilizes the Fuel Uncovery Frequency (FUF) analysis model from internal events. Scenarios are integrated using an OR Gate logic structure that aggregates all flooding initiating event categories.

For each IE category, flood scenarios are further organized under an OR gate using their respective scenario codes. When mapped to a corresponding internal event IE, the initiating frequency is set to 1; otherwise, it is 0.

Quantitative Screening Analysis is conducted at the scenario level. To optimize analytical resources, a conservative assumption is applied—presuming the failure of all equipment within the flood area—to prioritize areas requiring detailed refined analysis.

2.3 Documentation Phase

Task 11 Internal Flooding PRA Documentation

The objective of this phase is to systematically aggregate, structure, and finalize all technical requirements for the IFPRA report and its associated supporting documentation. This involves the

formal consolidation of analytical results, technical bases, and verification data to ensure the traceability, reproducibility, and regulatory compliance of the risk assessment findings.

3. NUCLEAR POWER PLANT DURING THE DECOMMISSIONING TRANSITION STAGE

During PD phase in decommissioning transition Stage, the plant configuration undergoes significant modifications. The reactor pressure vessel (RPV) head has been removed, and the refueling cavity is maintained at high water levels, forming a contiguous volume with the SFP. Given that the reactor coolant system (RCS) is at ambient temperature and atmospheric pressure, the risk contribution from High-Energy Line Breaks (HELB) is eliminated and need not be considered in the flood scenario development.

Regarding qualitative screening, since the Power Conversion System (PCS) has been permanently decommissioned, associated secondary systems—including the Feedwater System, Main Steam System, and Condensate System—have been fully drained out. Consequently, these systems no longer serve as potential internal flood sources.

During the quantitative screening, the classification of Initiating Events (IEs) is adjusted for the transition state. While power operation considers General Transient events like pipe ruptures (e.g., general reactor trip, loss of feedwater, loss of condensate, or loss of turbine building cooling water), the PD phase focuses on Loss of Decay Heat Removal (DHR) events, such as the Loss of Residual Heat Removal (RHR) system or the Loss of SFPACS. However, Loss of Offsite Power (LOOP) remains a constant initiating event in the assessment model.

4. RESULT

This reference plant has 127 flood areas. After initial screening, 7 buildings remained: reactor building, combination structure, turbine building, service building, pump house, essential service water pump house, and the fifth diesel generator building. Qualitative screening was based on whether the flood zone contained equipment that could interrupt fuel cooling of the core cavity or SFP, or potential flood sources. Further analysis was conducted to determine if there were effective flood spread paths between the flood areas. Based on this assessment, 14 flood zones were retained for the reactor building, 12 for the combined structure, 6 for the turbine building, and 5 for the service building. Although the loss of all circulating water pumps in the pump house would interrupt fuel cooling of the core or SFP, this area is an open space without a fire-fighting water system, so the loss of all circulating water pumps due to flooding is unlikely. Furthermore, on-site inspection revealed that the electrical room and pump room of the pump house have no water sources for flooding (i.e., no fire-fighting water or equipment cooling water), and the flooding risk is deemed non-existent. Therefore, quantitative screening is not required for this area. Although the essential service water pump house contains "equipment that could cause interruption of fuel cooling in the core or SFP," there are no other water sources that could render the pumps or the MCC electrical equipment room unusable; therefore, quantitative analysis is not required for this area. Based on the above, the quantitative screening results are shown in Table 1 below.

table 1 Screening analysis result

| Building | Flood Areas | Scenarios | FUF(/yr) |
|-----------------------|-------------|-----------|-----------|
| Reactor Building | 14 | 39 | 1.06E-15 |
| Combination Structure | 12 | 33 | *5.04E-07 |
| Turbine Building | 7 | 18 | 0.00E+00 |
| Service Building | 5 | 15 | 2.20E-16 |
| 5th DG | 1 | 6 | 0.00E+00 |

* Detailed analysis has not yet been conducted.

After screening and analysis, only one flood scenario was included in the detailed analysis. This scenario, after being included in the detailed analysis, considers the critical height, the area of the flood zone, the space of unoccupied equipment in the room, and the pipe diameter to calculate the time the equipment would be damaged by flooding. This timeframe is then compared with the operator's isolation time to calculate the human reliability. The detailed analysis of the flood spread scenario in

the 4.16 kV Switchgear Room yields a total FUF of 1.44×10^{-8} /yr. The total flood risk for the entire plant is 1.44×10^{-8} /yr.

5. CONCLUSION

In the reference plant's Internal Flooding PRA (IFPRA) for power operation, the quantitative screening phase encompassed approximately 45 flood areas and 150 flood scenarios, resulting in a Core Damage Frequency (CDF) on the order of 2×10^{-8} /yr. Subsequent detailed analysis involved 30 flood areas and 250 detail scenarios, with the final CDF estimated at 2×10^{-6} /yr.

In contrast, this study—focused on the PD phase—conducted quantitative screening for 36 flood areas and 112 flood scenarios. The Fuel Uncovery Frequency (FUF) obtained from this screening phase was statistically insignificant, falling below 1.0×10^{-14} /yr. For the detailed analysis, the study focused on a single critical scenario involving the 4.16 kV Switchgear Room, yielding a FUF of 1.44×10^{-8} /yr.

Detailed Case Study: 4.16 kV Switchgear Room Flood Scenario

The governing flood scenario identifies a catastrophic failure of a fire protection header within 4.16 kV Switchgear Room B. The resulting inundation propagates to 4.16 kV Switchgear Room A, leading to the concurrent loss of 4.16 kV Buses #1, #2, #3, and #4. Under these conditions, the Conditional Fuel Uncovery Probability (CFUP) is assigned a value of 1.0, signifying a deterministic loss of all critical power distribution.

As a mitigation strategy, the installation of an upstream manual isolation valve—maintained in a normally closed (NC) position and operated only upon demand—would effectively eliminate the initiating flood source, thereby allowing this scenario to be screened out from the high-risk profile.

In addition, the results provide additional risk insights into the configuration-dependent of internal flooding risk during the PD phase, illustrating how the integration of flood propagation, equipment vulnerability, and human reliability shapes the overall risk profile. The identification of a single dominant scenario underscores the importance of scenario-based prioritization in IFPRA and supports the application of risk-informed decision-making for targeted mitigation and operational control.

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