DEVELOPMENT OF THE INTERNAL FLOODING PRA GUIDE FOR USE BY THE JAPANESE NUCLEAR INDUSTRY

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ABSTRACT

The Nuclear Risk Research Center (NRRC) is promoting R&D activities on risk assessment to contribute to the implementation of Risk-Informed Decision-Making (RIDM) processes for safety control and improvement in Japanese nuclear power plants. Regarding internal hazard events (e.g., internal fire and flooding), although the utilities have deterministically evaluated and managed the impact of these events for the business licensing activities to restart the NPPs in Japan, the NRRC has been working on the R&D activities to promote the development of technologies for assessing the risks due to internal hazard events.

The NRRC expects to ensure the scientific rationality and transparency of newly developed techniques through discussion in academic societies or associations, to quantify the uncertainties associated with such risks and with their assessment, and to achieve realistic (i.e., free from excessive conservatism) assessment by applying PRA and other developed methodologies to use them in daily activities, such as responding to regulatory inspections, revising procedural documents and improving training programs. This paper will focus on key issues related to recent innovative research results obtained from NRRC risk assessment activities, particularly the development of the internal flooding PRA guide. The guide is expected to be published by the end of 2025.

Keywords: Internal hazard, Internal Flooding, Risk-Informed Decision-Making, Flooding Propagation Event Tree, Internal Flooding Damage State

I. BASIS FOR DEVELOPING NUCLEAR RISK RESEARCH CENTER INTERNAL FLOODING PRA GUIDE

I.A. Introduction

Internal Flooding Probabilistic Risk Assessment (IF-PRA) serves as an effective systematic assessment tool for evaluating the baseline risk contribution from internal flooding (IF). It is also an important consideration during plant operations, including corrective and predictive maintenance on both safety and non-safety-related systems. Additionally, insights gained from IF-PRA can help enhance various plant programs, such as piping aging management and in-service inspection.

Japanese nuclear power plant owner-operators, along with the Japanese regulator, are highly interested and motivated to conduct high-quality IF-PRA to better understand baseline risk, identify potential vulnerabilities, and integrate these models into a comprehensive strategy for transitioning to risk-informed programs, including the Significance Determination Process (SDP) and On-Line Maintenance (OLM) [1].

I.B. Objectives for Developing the NRRC's IF-PRA Guide

To address the nuclear industry's need for developing high-quality IF-PRAs, the NRRC evaluated existing IF-PRA guidance documents (IF-PRAG), such as those from the Electric Power Research Institute (EPRI), as well as publicly available IF-PRA reports, including that for the Surry Power Plant. Based on this evaluation, the NRRC initiated the development of a comprehensive IF-PRAG with the following objectives and with the aim of completing the establishment of the IF-PRAG by the end of 2025:

- Improve the ease of application in Japan, taking into account the current state of practice and expertise in the country [2]
- Incorporate NRRC's research in specific areas, such as the narrative base human reliability analysis (HRA) methodology [3], impingement direction [4] and the potential failure of flood doors [5]
- Fully leverage publicly available information, especially the data and specific methodologies outlined in the EPRI reports, through referencing these valuable sources of information [6], [7]

Conducting the IF-PRA analysis in Japan using this guide will facilitate the systematic collection, integration and evaluation of operational experience that is unique to nuclear power plants in Japan. This includes site-specific maintenance practices, localized equipment failure data, and historical records of piping degradation and structural failures. Incorporating these insights enables the analysis to more accurately reflect actual plant conditions and the operational environment. In addition, the approach outlined in the guide enables the identification of high-priority research areas where further investigation could yield significant safety and reliability improvements. At the same time, the methodology supports the use of relevant international data and best practices, ensuring consistency with global standards and enabling benchmarking and continuous improvement. This dual benefit of leveraging both domestic and international experience enhances the robustness and applicability of the IF-PRA results for regulatory, operational and research purposes.

I.C. An Example of Differences Between NRRC IF-PRA Guide and EPRI Guides

The two EPRI IF-PRA related reports that are extensively leveraged in the NRRC IF-PRAG are:

- "Guidelines for Performance of Internal Flooding Probabilistic Risk Assessment", EPRI 1019194, Final Report, December 2009
- "Pipe Rupture Frequencies for Internal Flooding Probabilistic Risk Assessments", Revision 5, EPRI 3002024904 Final Report, August 2023

The first listed EPRI document is directly equivalent to the NRRC's IF-PRA guide. This EPRI document is over 190 pages and contains highly valuable and insightful information. This valuable information include:

- Material which forms the basis for the latest version of the EPRI guide (e.g., section 1.31., "Lessons Learned from Ft. Calhoun IFPRA" and section 1.3.2, "Results of 2009 Survey on IFPRA"),
- Use of specific example to provide a methodology. For example, in Section 5.5, "Flood From HELB-Induced Fire Protection System Actuation" (from page 5-10 to page 5-26), an example for a specific plant SDP is used " to show how to address several technical issues and associated requirements in the ASME/ANS PRA Standard."

The NRRC's IF-PRAG values and leverages this insightful information while streamlining the assessment steps to enhance ease of application. It eliminates historical background and unnecessary direct information for performing an analysis step while incorporating other publicly available resources and NRRC's research findings to complement the information in the EPRI report and the significant publicly available IF-PRA report [8] that the NRRC's guide leverages.

II. Overall Task Flows

A task flow chart of the overall IF-PRA is divided into two major phases:

- ***Qualitative phase (Phase A)***, consisting of Tasks 1 through 4.
- ***Quantitative phase (Phase B)***, consisting of Tasks 5 through 14.

II.A. Qualitative Phase A

II.A.1. Task flow of Phase A

Fig.1 shows the task flow of Phase A. This phase pertains to acquiring the information that forms the foundation for the IF PRA and performing the qualitative phase of the project.

- ***Task 1 - Plant Boundary Definition, Flood Areas and SSCs***: The purpose of this task is to clearly delineate the areas within a facility that are to be included in the scope of the internal flooding PRA analysis and to identify flood characteristics of the locations.

- ***Task 2 - IF Scenarios***: The IF scenarios are first developed in this task using conservative assumptions. The output of this task is a list of the IF scenarios that start at a specific source and end with either exhaustion of the source or reaching a steady state (i.e., no further failures and no increase in flood depth).
- ***Task 3 - Walkdown***: Walkdown is a critical element of IF-PRA. The key issues of plant walkdowns are as follows:
  - Verification of Information
  - Identification of Vulnerabilities
  - Assessing Consequences
  - Gathering Accuracy and Completeness
- ***Task 4 - Qualitative Screening***: Those flood areas that their pertinent flooding scenarios do not impact any PRA SSCs or operator actions are screened out at this step.

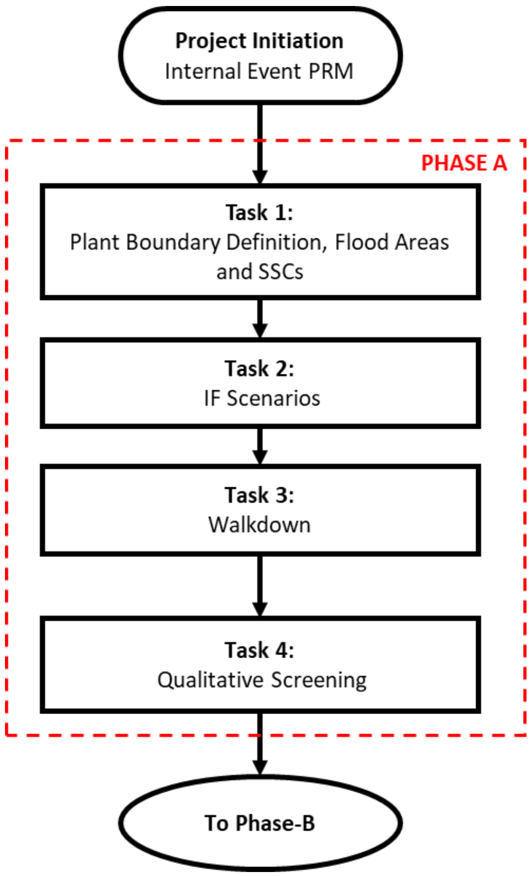


FIGURE 1. QUALITATIVE PHASE (PHASE A) OF AN IF-PRA

II.A.2. Discussion: Importance of Plant Walkdowns

In the NRRC's IF-PRAG, the importance of plant walkdown is emphasized. Plant walkdowns are a critical element of the IF-PRA process. They play a vital role in defining flood areas and identifying potential flood sources, affected components, propagation paths, and features for damage prevention and mitigation. The most significant contributions of walkdowns include:

- ***Verification of Flood Protection Systems:*** Walkdowns can verify that flood barriers (e.g., walls and doors), and protection measures are or are not capable and reliable under various flooding conditions.
- ***Verification of Information Accuracy:*** Walkdowns can verify the accuracy of the information used in the PRA (e.g., flood sources, flood propagation pathways, etc.)

- ***Gathering Supplemental Information:*** Walkdowns can provide additional information that may not be available in plant drawings and documents.

Walkdowns are typically conducted multiple times throughout the completion of an IF-PRA, including the following phases:

- ***Plant Familiarization Walkdown***: Conducted before the analysis phase of the project (e.g., prior to developing scenarios as outlined in Task 2). This walkdown allows team members to become fully acquainted with the plant layout and flood area configuration. This early familiarity is especially critical if the analytical work is performed by an internal flooding expert who may not be fully knowledgeable about the plant.
- ***Verification Walkdown***: Typically performed prior to the screening phase to ensure that the scenarios identified in Task 2 are reasonable and that no potential scenarios have been overlooked.
- ***Detailed Analysis Walkdown***: Typically conducted to gather additional information needed for the detailed analysis. This may include measuring the height of components or verifying the spray zone of influence.

The IF-PRAG presents the procedures for performing all three types of walkdowns in Task3 as described later, aiming to streamline the structure of guidance. However, it is crucial for IF analysts to be fully aware of all three walkdown types and to ensure that thorough walkdowns are conducted.

II.B. Quantitative Phase B

II.B.1. Task flow of Phase B

Fig.2 shows the task flow of Phase B. The quantitative analysis is conducted using IF scenarios that have passed Phase A. Phase B may involve several iterations in which risk-significant scenarios are further detailed. The process concludes when either the scenarios can no longer be refined or when the risk reduction becomes negligible.

- ***Task 5- Flood Propagation Event Tree (FPET) Preparation***: The purpose of this task is to initiate an event tree that represents flood propagation through different stages for each flooding source. For each flood source a FPET is developed based on the applicable failure mechanisms (e.g., equipment failure vs. maintenance-induced), applicable failure mode (e.g., spray or pipe breaks), and any mitigating features or operator actions that are credited to terminate flooding to limit the damage. This may result in a flooding scenario to be sub-divided into a number of sub-scenarios.
- ***Task 6 - IF Scenario Frequencies and Flooding Rates***: The IF scenarios are first developed in this task using conservative assumptions. The output of this task is a list of the IF scenarios that start at a specific source and end with either exhaustion of the source or reaching a steady state (i.e., no further failures and no increase in flood depth).
- ***Task 7- Equipment Damage Probability***: The scope of this task is to provide guidance on estimating probability of equipment damage, in a particular flooding area, based on the scenario and area specific flooding scenario characterization derived from performing Tasks 5 and 6.
- ***Task 8 - Internal Flooding Damage State (IFDS) Characterization***: The purpose of this task is to establish a comprehensive process for characterizing IFDS based on the end states derived from flood propagation event trees for each area within the facility.
- ***Task 9 - PRM for IF-PRA***: The purpose of this task is to review and modify the internal-events PRM to reflect the postulated IFDSs.
- ***Task 10 - Analysis of Operator Action***: The purpose of this task is to review and modify the human failure events (HFEs) included in the PRM to account for the impact of IFs, conduct a HRA of the HFEs added to the PRM that address IF specific conditions, identify process parameters that should be added to the PRM to properly model human actions and update the human error probabilities (HEPs) and dependency matrix.
- ***Task 11 - Risk Quantification***: The purpose of this task is to quantify the risk for each postulated IFDS, summation of which will provide an estimate of the IF risk. The main objectives of the risk quantification task are quantifying risk levels and identification of key contributors.
- ***Task 12 - Reduction in Conservatism***: The purpose of this task is to provide a list of items (e.g., event timing, refinements in HEP Evaluation, spray direction, location and range and so on) that can be utilized to reduce conservatism in the characterization and risk quantification of IFDSs.
- ***Task 13 - Uncertainty Analysis and Sensitivity Analysis***: A set of sensitivity analyses cases are defined in this task to examine the effect of certain assumptions incorporated in the analysis on the final results.

- ***Task 14 – IF-PRA Final Report***: IF-PRA includes a wide range of documents and computer files that should be organized in a fashion amenable to quality control and updates at a later time when plant or other changes are considered. It should be noted that the detailed documentation for each task is included in each task and this task provides guidance for a summary report for the IF-PRA.

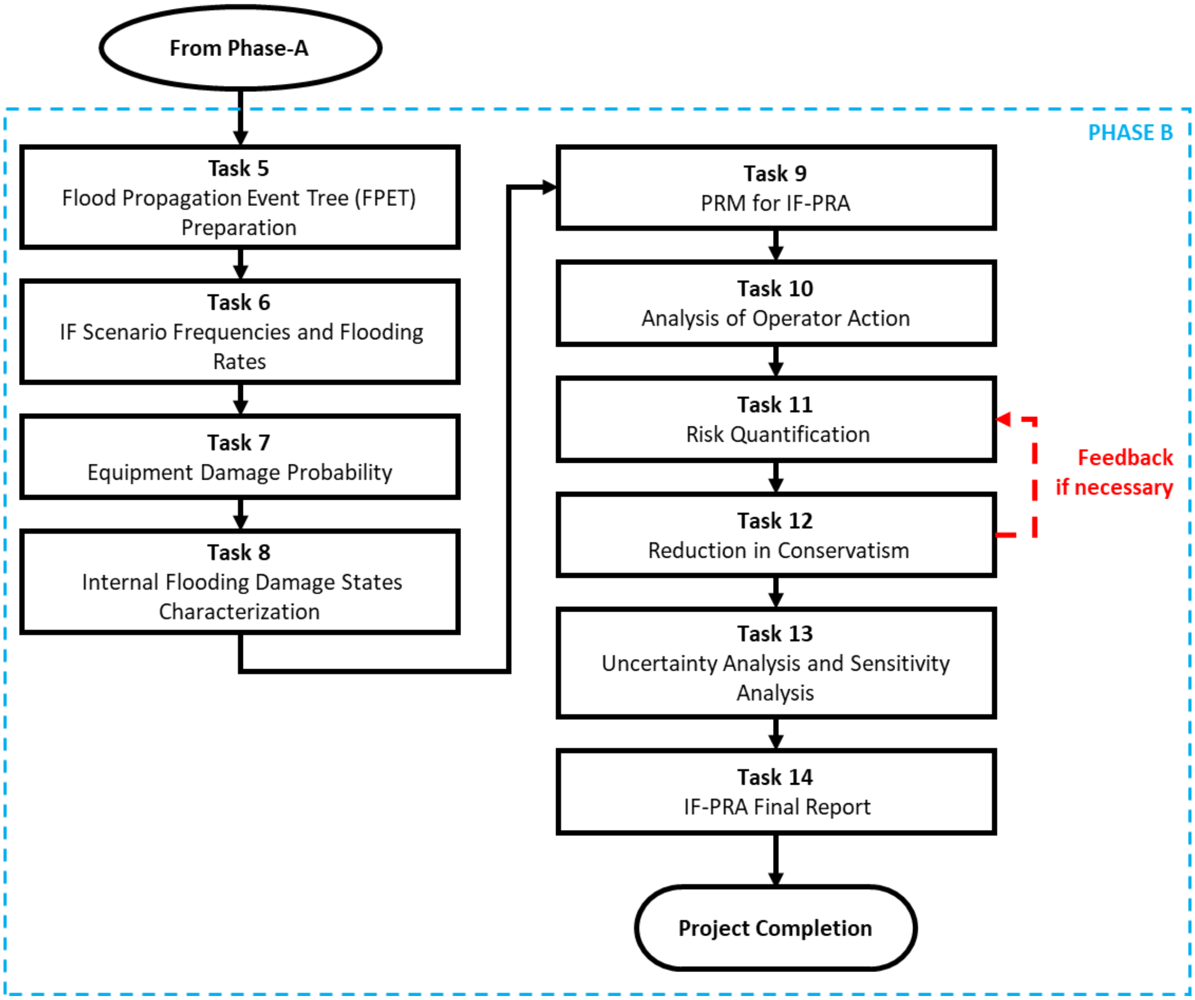


Figure 2 QUANTITATIVE PHASE (PHASE B) OF AN IF-PRA

II.B.2. Discussion: Practical Implementation of Uncertainty Analysis

When performing IF analysis, several key parameters should be assessed for uncertainty. These parameters include flood initiation frequency, flood volume and rate, flood propagation Modeling, SSC failure criteria and fragility, HRA, and success criteria and logic modelling. This guide discusses the following recommendations for practical implementation.

- Begin with a qualitative uncertainty evaluation to ensure reasonable assurance that important scenarios are not missed
- Focus detailed uncertainty quantification on risk-significant scenarios or sequences
- Revisit uncertainty treatment as plant configuration, data, or methods evolve
- Coordinate IF uncertainty analysis with the broader PRA uncertainty framework to ensure consistency

An important consideration is the strategic use of NUREG-1855 [9] and the concept of 'consensus models'. This strategy plays a critical role in establishing the credibility and regulatory acceptability of the technical models used in PRA. Its benefits are summarized below.

- Reduced burden of justification
- Increased regulatory confidence

- Alignment with NUREG-1855's risk-informed framework
- Facilitates consistency across PRA applications

In summary, due to the modeling complexity, lack of reliable input data, dominance of epistemic uncertainties, and complexity of the analysis, full-scale uncertainty analysis for IF PRA may provide limited value. Instead, a qualitative uncertainty screening, supported by targeted sensitivity analyses and justified conservative modeling assumptions, is likely to offer a more efficient and technically defensible approach for addressing uncertainty in internal flooding analyses.

III. FLOOD PROPAGATION EVENT TREE (FPET) EXAMPLE

In this guide, an example of a flood propagation event tree is introduced, which illustrates the potential scenarios that may occur during flooding incidents within the designated areas of an assumed facility. For this illustration, we are focusing on two specific assumed flood areas as shown Fig.3, which are:

- Flood Area 01 (FA-01): High Head Injection Pump 1A Room
- Flood Area 02 (FA-02): High Head Injection Pump 1B Room

Each of these two postulated flood areas house a high head charging pump. These rooms are physically separated by a fire door, which has a two-inches gap at the bottom. This design element is critical as it slows down the propagation of floodwater between the two rooms. Additionally, both FA-01 and FA-02 incorporate the following critical flood protection measures designed to reduce the impact of a potential flooding event:

- Elevated Installation of Charging Pumps- Each charging pump in FA-01 and FA-02 is mounted on a 30 cm (approximately one-foot) high base. This elevation serves a dual purpose: it raises the pump above potential floodwaters and provides additional time to isolate a faulted header should there be a loss of structural integrity within the piping system. By allowing personnel a brief window to respond to the situation, this measure helps limit water damage.
- Construction of Berms- A 60 cm (approximately two feet) high berm has been strategically constructed around the door that connects FA-01 and FA-02. This berm acts as a vital containment feature, specifically engineered to mitigate the impact of flooding by effectively blocking water from entering or exiting the designated areas. The berm is designed to withstand potential floodwater, providing a physical barrier that helps protect the sensitive infrastructure and equipment within both flood zones.
- An alarm in the sump in each flood area, which alarms in the control room, to notify operators of a flooding event in each flood area.
- Abnormal operating procedure to respond to the sump alarm in each room.

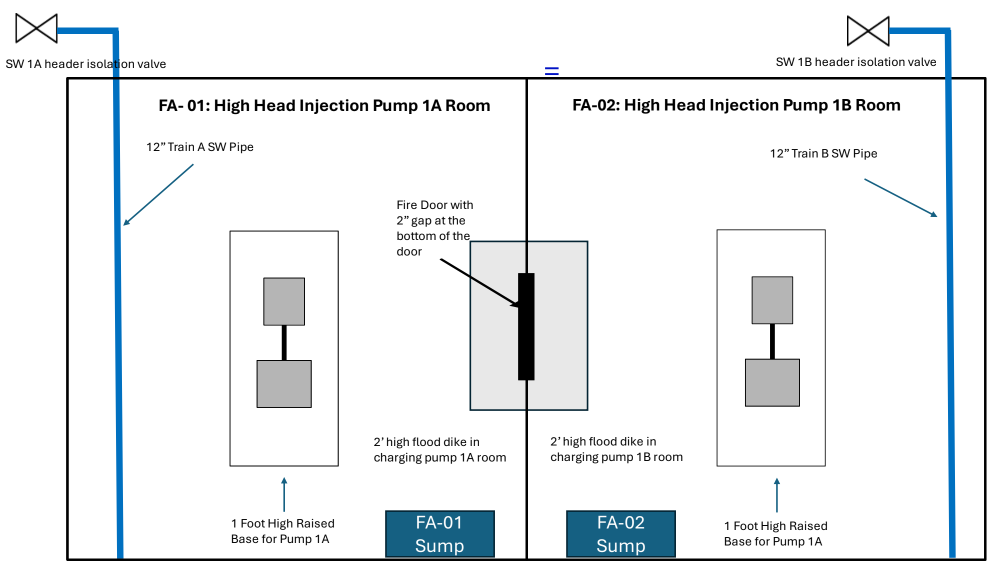


Figure 3 EXAMPLE OF FLOOD PROPAGATION SCENARIO

To simplify the example, the primary flooding source in each of these example flood areas is attributed to the pressurized Service Water (SW) headers. Specifically, within FA-01, the relevant header is identified as the SW 1A, while the header serving FA-02 is designated as the SW 1B. These pressurized headers transport service water throughout the facility for operational purposes, and their maintenance and integrity are crucial for mitigating flooding risks.

Each SW header is equipped with a manual isolation valve, which is a critical component for controlling the flow of service water. In the event of a leak or rupture in one of the headers, the appropriate isolation valve can be closed to quickly isolate the affected section, thereby minimizing the potential for flooding in the adjacent areas. It is essential to note that these isolation valves are strategically located in the corridor that lies adjacent to the two flood areas, providing easy access for personnel during emergencies.

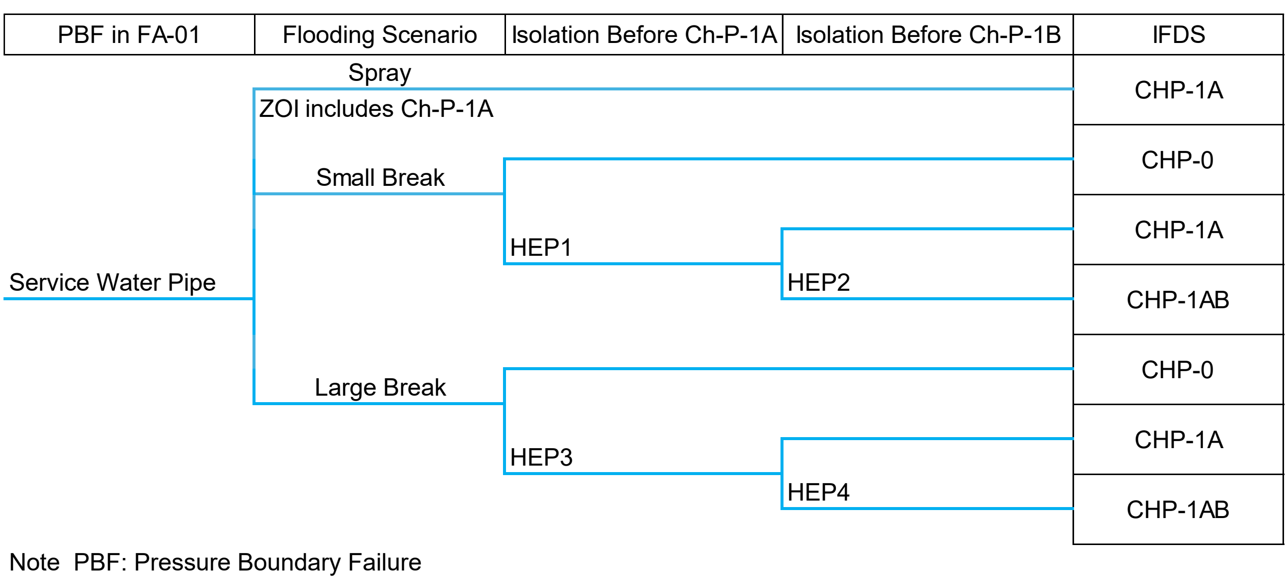
In the case of a flooding incident, prompt action is required to operate the manual valves, as any delay could result in significant water intrusion into FA-01 or FA-02. Therefore, it is imperative for staff to be well-trained in the procedures for swiftly accessing and operating these isolation valves. Regular drills and maintenance checks on both the headers and their associated valves should be conducted to ensure they remain functional and responsive in case of an emergency.

The above information is typically gathered during execution of Tasks 1-3. Additionally, neither of these areas are screened out in Task 4. Finally, step by step execution of Tasks 5 through 10 should be executed to develop a flood propagation event tree as well as quantifying the resulting internal flooding damage states.

In Task5, FPET preparation will be executed to establish a comprehensive and well-defined set of flooding scenarios based on the flooding sources in the area. This will facilitate analysis of the unique impacts of resulting scenarios on plant operations. This identification process serves as a crucial foundation for subsequent steps, such as grouping and screening the scenarios, as well as estimating the frequencies of flood-initiating events. This Task5 includes the following steps.

- Identify Flooding Initiator for Each Flood Propagation Event Tree
- Assign Flooding Mechanisms for Each Flooding Initiator
- Assign Flooding Modes (e.g., Spray, Small Breaks, Lage Breaks) to the Flooding Mechanisms
- Credit Each Flood Mitigating and Flood Damage Prevention Feature

Finally, after execution of Tasks 6-8. IFDS can be characterized based on the end states derived from FPETs for each area within the facility. Fig.4. shows the example of the FPET. As a result, the contributions of the aforementioned IFDSs to the plant internal flooding risk are calculated by quantifying the modified event trees. The total internal flooding risk contribution from FA-01 is estimated by summing up the risk estimates for the three IFDSs. The total internal flooding risk contribution from FA-02 is judged to be the same as FA-01 due to both FAs been identical from the flooding risk perspective.



Note PBF: Pressure Boundary Failure

FIGURE 4 EXAMPLE OF FPET

IV. CONCLUSIONS

The utility and regulator's desire for developing IF-PRAs for various purposes, ranging from understanding potential baseline vulnerabilities to applications in risk-informed programs, has necessitated the rapid development of high-quality IF-PRAs. Considering the current state of expertise and practice in Japan, along with a review of available guidelines, the NRRC concluded that the best option is to produce a high-quality, streamlined guide focusing primarily on the steps to be performed and the methodologies for executing them.

To this end, the NRRC’s IF-PRAG is being developed to:

a. Concentrate on the essential steps that need to be performed, and
b. Utilize the most relevant references - primarily the EPRI guide, supplemented by the results of the NRRC’s research - to clarify how to perform those steps. The importance of plant walkdowns is also emphasized extensively.

Additionally, a slightly different approach is suggested in certain areas, such as when addressing the potential consequences of spray flooding mode. Finally, the NRRC’s IF-PRAG aims to be consistent in its usage of IF-related terms by distinguishing between flooding sources, mechanisms, and modes. The guide is expected to be published by the end of 2025.

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