Internal Flooding Probabilistic Risk Assessment for Multi-Module High-Temperature-Gas-Cooled Reactor

Zhihao Du[1] Jingyu Li[1]

[1] Chinergy Co. Ltd, Beijing, China, 100193, zhhdu@chinergy.com.cn

ABSTRACT

Internal flooding represents a critical hazard in nuclear power plants (NPPs), necessitating quantitative evaluation through Internal Flooding Probabilistic Risk Assessment (IFPRA). However, traditional IFPRA methodologies face significant limitations in addressing challenges arising from the multi-module design features of High Temperature Gas-Cooled Reactors (HTGRs), including multi-module initiating events, system correlations among multiple modules, and Dual common cause failures. This paper presents a novel IFPRA methodology tailored for multi-module HTGRs, which comprehensively incorporates the systematic modeling of multi-module design characteristics, the quantification of risk contributions from complex interactions, and the identification of critical flooding source systems. The methodology is applied to a 600MW HGTR NPP to evaluate its overall flooding risk. The results show that the flooding risk caused by multi-module features is the main contribution to the internal flooding risk of HTGR. The flooding source system with the highest risk contribution is the plant water system (PWS), with the residual heat removal (RHR) system ranking second. Based on the results, this paper proposes several improvement measures such as pressure interlock automatic isolation of the PWS and optimizing pipeline layout. These measures significantly improve the flood protection capability and overall safety performance of the NPP. Empirical validation through engineering practice confirms the applicability of the proposed IFPRA framework for future multi-module HTGR NPPs, offering a scalable solution for risk-informed decision-making.

Keywords: Internal Flooding, PRA, HTGR, Multi-Module Design Features, Flooding Risk

I. Introduction

Following the Fukushima nuclear accident, the public, government, and regulatory authorities have increasingly focused on nuclear safety, particularly the severe nuclear accidents caused by internal and external hazards. Internal flooding is one of the primary sources of hazard risk in NPPs. The Internal Flooding Probabilistic Risk Assessment (IFPRA) is used to quantitatively assess the overall risk posed by internal flooding to the NPPs. It is one of the most critical safety analysis methodologies concerned by nuclear safety regulatory authorities. According to the Chinese Nuclear Safety Regulation HAF102[1], design must account for internal hazards, including flooding and fluid release. In the guideline HAD102/17[2], "internal flooding" is listed as an assumed initiating event in safety analysis. In the risk-informed nuclear safety regulatory framework developed for non-light-water reactors (NLWRs) in the United States in recent years, IFPRA is also identified as one of the essential conditions for meeting the technical adequacy of PRA [3][4][5].

Traditional IFPRA methods are primarily tailored for light-water reactors (LWRs) and are unable to address a series of challenges arising from the multi-module design features of high-temperature gas-cooled reactors (HTGRs) in safety analysis. The ASME/ANS RA-Sb-2013 standard [6] outlines the technical requirements for IFPRA in LWRs, while the guideline EPRI 1019194 [7] provides a feasible IFPRA methodology for LWRs. The report EPRI 1013141 [8] statistically determines the pipe rupture frequency used in IFPRA based on operational historical data of LWRs. However, traditional methods fail to address the following issues:

(1) Multi-Module Initiating Event Issue

HTGRs are characterized by multi-module initiating events. Specifically, flooding events may trigger single-module initiating events, but they may also lead to multi-module initiating events.

(2) System Correlation among multiple modules Issue

HTGRs exhibit system correlations among multiple modules. Following a multi-module flooding initiating event, multiple modules may simultaneously initiate accident mitigation. The functional dependencies among modules necessitate the consideration of shared systems that simultaneously provide mitigation functions to multiple modules. Traditional methods analyze only the accident progression of a single reactor, failing to account for the accident progression in multi-module systems or the functional dependencies among modules during the accident.

(3) Dual Common Cause Failure Issue

HTGRs face dual common cause failure issues. Redundant systems within a single module may experience common cause failures, and higher-order common cause failures may also occur across multiple modules. For example, the Reactor Compartment Cooling System is designed with 3 redundant trains per module reactor. In the model, both dual common cause failures (e.g., the common cause failure of the 3 redundant channels in a single module reactor) and higher-order common cause failures (e.g., the higher-order common cause failure of the 18 redundant channels across six module reactors) must be considered simultaneously. Traditional methods mainly focus on single-module common cause failures and pay less attention to higher-order common cause failures in multi-module systems.

In response to the aforementioned issues, this paper develops an IFPRA methodology suitable for HTGRs based on the traditional IFPRA methodology for light-water reactors (LWRs). The IFPRA was conducted for the new-generation HTGR 'HTR-PM600' in China, and the analysis results and conclusions are presented.

II. Methodology of IFPRA for Multi-module HTGR

This section presents a novel IFPRA methodology, which identifies internal flooding sources and SSCs (structures, systems, and components) related to multiple modules in the qualitative analysis. Subsequently, it identifies and models multi-module flooding initiating events, system correlations among multiple modules, and higher-order common cause failures in the quantitative analysis.

II.A. Framework

Based on the traditional IFPRA methodology, this paper proposes an IFPRA approach suitable for multi-module HTGR. The framework of the proposed methodology is illustrated in Figure 1. Steps 1–12 are based on the traditional methodology for LWRs from reference [7]. The additional parts in yellow font represent the special treatment for multi-module design features.

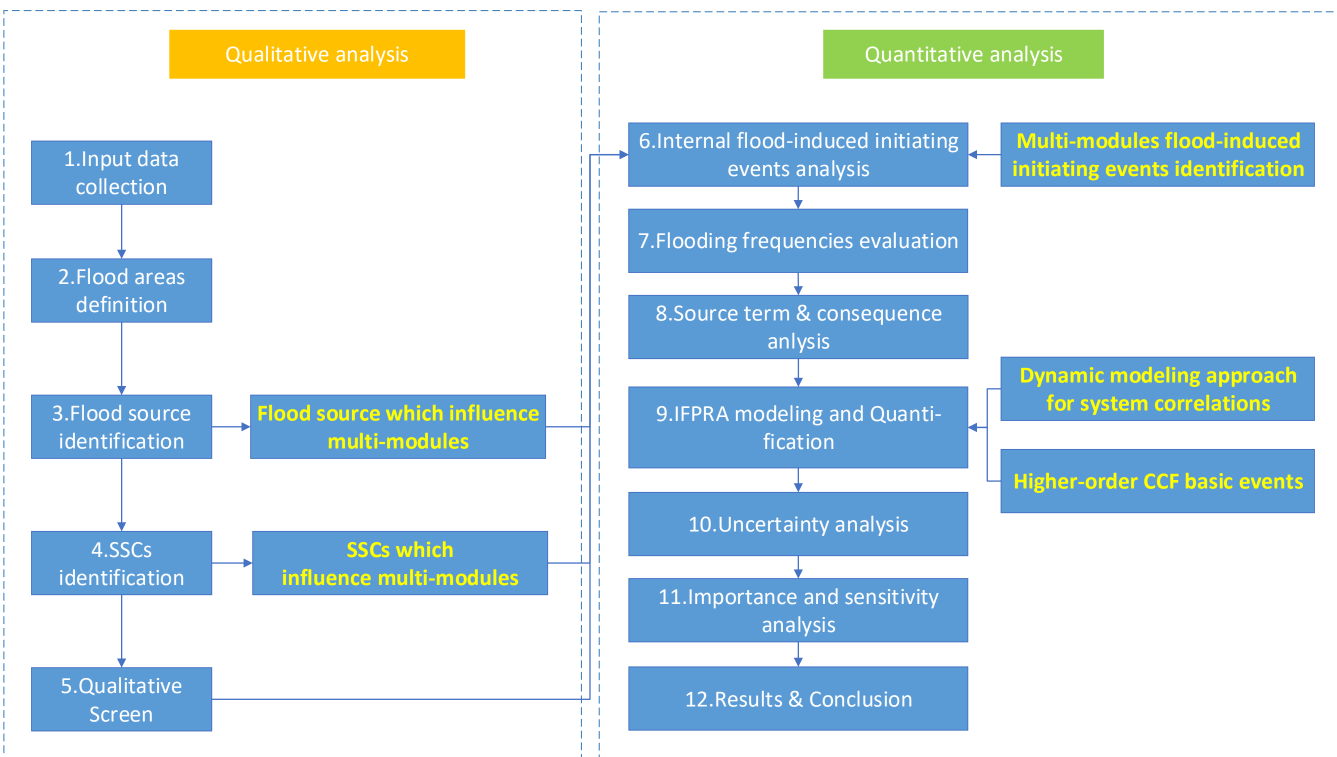

FIGURE 1. Framework of the Proposed IFPRA Methodology for Multi-module HTGRs

A brief introduction to the technical elements within this framework is provided below.

Step 1. Input data collection from design, construction and operation documents.

Step 2. Flooding areas definition. Based on the architectural design information, the plant is divided into several zones, in each of which the occurrence of flooding and its impact are relatively independent.

Step 3. Flooding source identification. Based on the fluid system design information, identify the various flooding sources, such as liquid pipelines and equipment, within each flooding zone, along with their characteristics, and determine the flooding mechanisms. Considering the multi-module design features, it is also necessary to analyze whether the functions of the fluid system are applied to a single module or multiple modules.

Step 4. SSCs identification. Based on the design information of SSCs and specific screening criteria, identify the SSCs within each flooding zone that are susceptible to flooding and are related to the initiating events or the mitigating facilities. Considering the multi-module design features, it is also necessary to analyze whether the functions of the SSCs are applied to a single module or multiple modules.

Step 5. Qualitative Screen. Based on whether there are flooding sources and SSCs within each flooding zone, some flooding zones are filtered out. This ensures the completeness of flooding scenarios while avoiding excessive attention to zones with low flooding risk or limited safety significance. This allows for a focused and detailed analysis of the risk-significant areas and scenarios.

Step 6. Internal flood-induced initiating events analysis. Analyzing the impact of component failure caused by flooding on system functionality helps identify flood-induced initiating events and the mitigation functions affected after flooding occurs. Based on the multi-module design features, it is also necessary to analyze which module stacks are affected by flooding and determine whether the initiating events caused by internal flooding are multi-module initiating events.

Step 7. Flooding frequency evaluation. Based on the design information of the plant's liquid piping and the general data on pipe rupture frequency [8], calculate the frequency of flooding occurring in each flooding area.

Step 8. The methodology for source term and consequence analysis is based on the internal event PRA of HTGRs.

Step 9. Based on the internal event PRA model, an IFPRA model is established and quantified, resulting in the NPP's flooding risk.

Step 10. Conduct an uncertainty analysis of the quantified results.

Step 11. Conduct an importance and sensitivity analysis of the quantified results.

Step 12. Based on the analysis results, draw conclusions and propose flood protection design improvement recommendations for high-risk items. A risk-informed flood protection design can be further conducted.

II.B. Special Treatments for Multi-module Design Features

II.B.1. Multi-module initiating events

In the IFPRA model, multi-module initiating events are modeled using the pre-tree approach. The pre-tree is used to represent the group, frequency, and consequences of flood-induced initiating events. This pre-tree is then connected to the event tree from the internal event PRA to complete the modeling of multi-module initiating events.

A series of flood-induced initiating events groups are shown in Table 1 as an analysis case.

TABLE I. Analysis Case of Flood-induced Initiating Events Groups

No.	**Number of Modules**	**Initiating Events Groups**
1	1	Loss of Main Feedwater
2	1	General Transient combine Loss of a Train of RHR System
3	6	General Transient
4	6	Loss of Component Cooling Water (CCW) System

II.B.2. System Correlation among multiple modules

This paper employs a dynamic modeling approach to address the temporal and functional correlations of systems in the use of event sequence. The dynamic characteristics of multi-module accident sequences are represented in the form of cut sets, which can realistically reflect the coupling between multiple modules and the interdependencies among systems during an accident.

The technical principle of the dynamic modeling approach is to analyze the specific event sequences in which module stacks call the shared systems in multi-module accident scenarios. After logical processing, the calling logic of the shared systems among multiple modules is obtained. Based on this calling logic and the system functional correlations under the scenario where multiple modules simultaneously call the system functions, the system success criteria are determined, and the corresponding logic switches are set in the model.

When multiple module stacks simultaneously perform accident mitigation, if a shared system among multiple modules in a specific event sequence needs to be applied to multiple module stacks at the same time, a switch in the fault tree model is triggered. This causes the success criteria of the system fault tree to change in dependence on the correlations, thereby enabling the modeling of this issue.

II.B.3. Dual Common Cause Failure

The modeling approach for dual common cause failures is shown in Figure 2. For the multi-module common cause failure groups shown in the figure, the modeling is completed by introducing higher-order common cause basic events into the PRA model.

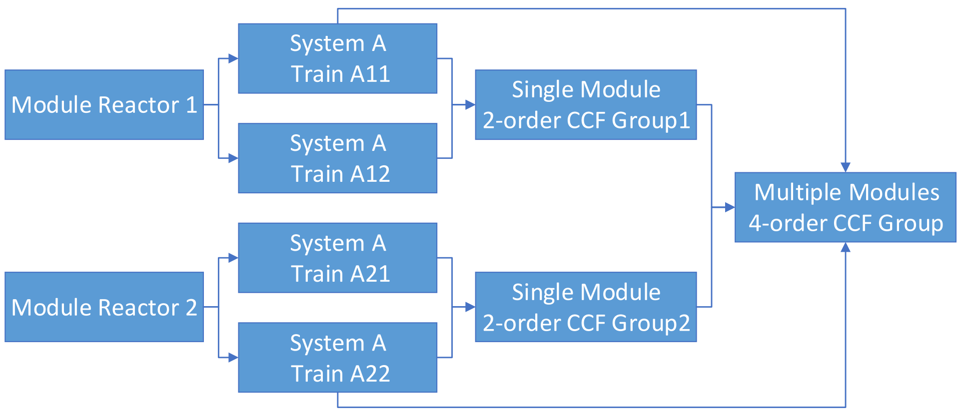

FIGURE 2. Modeling of Dual Common Cause Failure

III. Application Case in 600MW HTGR NPP

The proposed IFPRA methodology has been applied in a 600MW HTGR NPP. It should be noted that this is a simplified case, in which only the nuclear island area was evaluated based on a conservative assumption: that all equipment within the flooded area fails immediately when flooding occurs. The RiskSpectrum software was used for the IFPRA modelling. The key assumptions for the IFPRA are as follows:

a) The flooding hazard is assumed to occur under the operating conditions of the reactor unit.
b) It is assumed that two or more flooding events will not occur simultaneously at the same site.
c) Internal flooding is not considered to occur simultaneously with other independent initiating events.
d) The flooding height is not analyzed in detail; it is conservatively assumed that equipment within the flood areas fails when flooding occurs in that area.
e) The human reliability analysis at this stage is consistent with that of the internal event PSA.
f) The analysis considers the impact of flooding on multiple reactor modules.

The quantitative results show that the frequency of RC50 release category caused by internal flooding in the nuclear island area is 7.47E-09 per unit year, indicating a low level of flooding risk. Among these, the risk caused by single-module initiating events is 1.62E-09 per unit year, while the risk caused by multi-module initiating events is 5.81E-09 per reactor year. The flooding risk arising from the multi-module design features accounts for a higher proportion, approximately 77.78%.

The PWS is the system that contributes the most to the flooding risk of the NPP, with a contribution rate of 64.39%. The results shows that this part of risk mainly arises from the rupture of the plant water pipeline, which leads to the CCW pumps were submerged, resulting in an 6-modules initiating event . Further evaluation indicates that if the PWS can achieve a pressure interlock automatic isolation upon a pressure signal anomaly, the risk caused by PWS flooding can be eliminated.

The flooding risk in the HTGR reactor building accounts for 25.44%, which is the second-highest proportion. According to the analysis results, this risk contribution mainly stems from the rupture of the RHR system piping, which leads to RHR system degradation. This type of flooding event can slightly weaken the defense-in-depth of the NPP. Optimizing the pipeline layout to reduce the overall system complexity can help lower the flooding risk of the RHR system.

IV. CONCLUSIONS

This paper addresses the issue that traditional LWR IFPRA methods are unable to model the multi-module design features of HTGRs. A framework for an IFPRA methodology suitable for multi-module HTGRs is developed, and a method for incorporating multi-module design features into the IFPRA model is proposed.

The proposed framework is applied to a 600MW HGTR NPP, and the following conclusions are drawn: (1) the multi-module design features are the primary contributors to the internal flooding risk in HTGRs; (2) the PWS system and the RHR system are the systems with the highest and second-highest flooding risk contributions, respectively; and (3) improvement measures such as pressure interlock automatic isolation of the PWS system and optimized pipeline layout can effectively enhance the flood protection capability of the NPP and reduce its overall flooding risk.

The applicability of the proposed IFPRA framework for future multi-module HTGR NPPs is based on the current theoretical and methodological development. It is expected to provide a robust solution for risk-informed decision-making in future applications..

REFERENCES

[1] China National Nuclear Safety Administration, *Nuclear Power Plant Design Safety Regulations*, HAF102-2016, Beijing(2016).
[2] China National Nuclear Safety Administration, *Nuclear Power Plant Safety Evaluation and Verification*, HAD102-2006, Beijing(2006).
[3] Wayne L Moe, *Modernization of Technical Requirements for Licensing of Advanced Non-Light Water Reactors: Probabilistic Risk Assessment Approach*, INL/EXT-20-60395, Idaho (2020).
[4] U.S. Nuclear Regulatory Commission, *Acceptability of Probabilistic Risk Assessment Results for Non-Light Water Reactor Risk-Informed Activities*, Regulation Guide 1.247, USA (2022).
[5] ASME & ANS, *Probabilistic Risk Assessment Standard for Advanced Non-LWR Nuclear Power Plants*, ASME/ANS RA-S-1.4-2013, NY (2013).
[6] ASME & ANS, *Standard for level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications*, ASME/ANS RA-Sb-2013, NY (2013).
[7] J-F Roy, *Guidelines for Performance of Internal Flooding Probabilistic Risk Assessment*, EPRI 1019194, CA (2009).
[8] F Rahn, *Pipe Rupture Frequencies for Internal Flooding PRAs*, EPRI 1013141, CA (2006).