Models and Knowhow for Human Reliability Analysis on Internal Flooding Termination in Internal Flooding Event

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Abstract: The Nuclear Risk Research Center of the Central Research Institute of Electric Power Industry published “Human Reliability Analysis (HRA) Guide with Emphasis on Narratives” in 2019 and revised it in 2021 and 2024. The HRA guide published in 2024 prepares a new appendix that includes model and know-how on HRA on internal fire event and HRA for internal flooding termination in internal flooding event, based on our experience in HRA on internal hazards (internal fire and internal flooding). The present study introduces HRA on internal flooding termination. This is an operation to prevent leakage by closing a valve to stop the water flow to the leaking piping when an internal overflow occurs, thereby preventing the occurrence of an initiating event or minimizing the impact of the flooding on equipment even after an initiating event occurred. This operation is unique to internal flooding PRA and may be important for risk assessment in some scenarios; however, it is assumed that there are cases in which detailed procedures for this operation have not been prepared, and thus additional analytical models and know-how need to be developed for HRA on this operation. This study introduces points on developing narratives (e.g., how to confirm and identify leaking pipes), modelling of this operation process ((1) recognize/determine the possibility of internal flooding occurrence, (2) identify the location of internal flooding, (3) prepare a procedure for terminating flooding, and (4) execute internal flooding termination operation), examples of interpretations of the THERP method (for errors in preparing procedure) and the Cause Based Decision Tree (CBDT) method in their application to this operation for estimating the human error probability of this operation, and evaluation of dependency between flooding termination operations (before and after the occurrence of an initiating event).

Keywords: Human reliability analysis, Probabilistic risk assessment, Internal flooding

1. INTRODUCTION

Since the Fukushima Daiichi Nuclear Power Station Accident in 2011, probabilistic risk assessment (PRA), which systematically identifies potential risks and quantitatively treats them including residual risk (risks remaining after a risk has been addressed) beyond the safety design, has become important to improve the safety of nuclear power plants, as well as deterministic safety analysis which is a conservative approach for risk assessment.

In addition to facility and equipment failures, PRAs need to also take into account human failure events (HFE) which are events happening in situations where operators/other personnel are executing certain tasks and are unable to achieve the task objective or fail to accomplish the task, thereby significantly impacting an accident. The probability of failing at such a task is known as human error probability (HEP) and assessment of this probability is a required part of human reliability analysis (HRA). In conducting HRA, it is pointed out that it is important to specifically understand the situation in which human tasks are performed in qualitative analyses [1, 2].

In 2019, the NRRC of the CRIEPI published the HRA Guide (HRA guide 2018) [3] that compiles qualitative analysis methods to collect plant-specific and scenario-specific conditions that affect human performance as “narratives”, reflecting the latest research trend. After that, the HRA guide was revised in 2021[4] and 2024[5].

The HRA guide revised in 2021 (HRA guide 2020) [4] adds methods for selecting tasks that should be subjected to detailed qualitative analysis and requirements for ensuring appropriate understanding of the accident scenario, thereby providing a guide that enable one to conduct qualitative analyses efficiently and that reflect realities more appropriately.

The HRA guide revised in 2024 (HRA guide 2023) [5] describes three techniques for collecting information to develop narratives and show how to select appropriate techniques for each case and prepares a new appendix that includes model and know-how on HRA on internal fire event and HRA for internal flooding termination in internal flooding event, based on our experience in HRA on internal hazards (internal fire and internal flooding). The present study introduces HRA on internal flooding termination in internal flooding PRA.

2. INTERNAL FLOODING TERMINATION OPERATION

One potential threat to the safety of nuclear power plants is an internal flooding event, characterized by damage to pipes and other components within a building. This damage can result from various causes, leading to the leakage of water or steam from the pipes, which in turn may harm equipment. Such incidents risk impairing the functionality required to prevent or mitigate abnormal events.

In response to such incidents, operators typically undertake actions to prevent initiating events, such as the total loss of the safety system's high-voltage AC bus bar [6], by isolating the leaking piping upon detection of an internal flood. Moreover, efforts are made to halt internal flooding to minimize the impact on equipment, even after an initiating event has occurred (Figure 1). The present study focuses on HRA concerning the termination of internal flooding, an operation unique to internal flooding events and crucial for risk assessment.

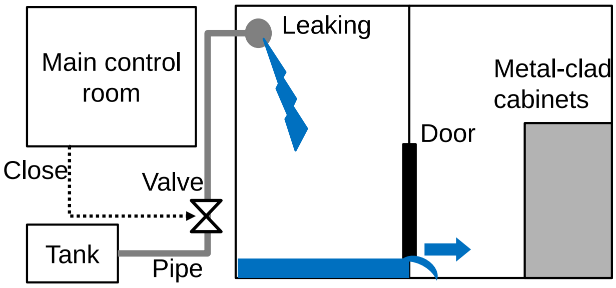

Figure 1. Images of internal flooding and internal flooding termination

3. CONSIDERTAION OF THE NEED FOR THE EVALUATION

In the PRA for internal flooding, two types of initiating events[1] are contemplated. The first type involves initiating events triggered by the effects of water leaking from break points, such as water exposure or submerged conditions, which may include a total loss of the high-voltage bus bar due to flooding of metal-clad cabinets caused by leakage from fire suppression water pipes. The second type pertains to initiating events resulting from damage to plant systems, including the source of flooding itself, such as a break in a water supply pipe outside the containment vessel.

Initially, these initiating events are presumed to occur concurrently with the flooding events to streamline an evaluation. Subsequently, if detailed evaluation becomes necessary due to a high core damage frequency or other factors, the scenarios are refined[2] and categorized into those that foresee flooding termination operations before the occurrence of initiating events and those that do not. The high core damage frequency might partly result from the unanticipated nature of internal flooding termination operations before the onset of initiating events. In such instances, to enhance the realism of the evaluation, the interval between the commencement of flooding and the initiating event and the feasibility of flood detection must be defined. This can be achieved through event progression analysis and operator interviews, incorporating the success or failure of these operations into the evaluation. Furthermore, if internal flooding persists in impacting the

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[1] PRA may distinguish between initiating events and internal floodings, because an initiating event is an event that causes a plant to deviate from its normal operating condition (e.g., a LOCA or transient), while an internal flooding is an internal hazard that causes initiating events.

[2] It is conducted as part of the detailed analysis in internal fire PRAs and internal flooding PRAs.

plant following an initiating event, scenarios where flooding termination occurs subsequent to the initiating event must be considered.

4. BASIC APPROACH TO EVALUATION

4.1. Points for Developing Narratives

To ascertain the occurrence of internal flooding and pinpoint the locations or lines of leaked piping, operators can in addition to monitoring parameters in the main control room (MCR), physically inspect the site within the building. In certain instances, it may not be possible to close the valves of the leaking piping from the MCR, necessitating manual valve closure on site. Consequently, the development of narratives for internal flooding events is expected to encompass a broader range of topics compared to internal events, including on-site work environments, necessary equipment, the feasibility of on-site access based on various scenarios, the time required for such activities, and the factors influencing this timeframe.

Moreover, should an initiating event arise as a consequence of an internal flooding event, the need for personnel resources to address the initiating event concurrently with efforts to terminate the flooding may surpass that required for an internal event. This necessitates a comprehensive evaluation of resource allocation and operational planning to effectively manage both the initiating and flooding events. Table 1 summarizes points considered when developing narratives for response to internal flooding events.

4.2. Modeling of Internal Flooding Termination Operation

Given the multitude of piping systems within a plant susceptible to leaks, while procedures to assess the potential of internal floodings exist, detailed procedures that exhaustively outline the steps for identifying valves to be isolated for every possible flooding pattern may not be available. The HRA Guide [2] presents an evaluation example titled “Watertight Door Inadvertently Left Open During Building Evacuation before a Tsunami Strike,” illustrating the assessment of a human failure event in the absence of a procedure. It suggests that HRA for such operations should initially model the operational process.

An example of modeling an internal flooding termination operation, in the absence of detailed procedures that specify the process for identifying the valves to be isolated, is as follows (with further details provided in Table 2):
(1) Recognize/determine the possibility of internal flooding occurrence.
(2) Identify the location of internal flooding.
(3) Prepare a procedure for terminating flooding.
(4) Execute the internal flooding termination operation.

In this model, as the specific response to internal flooding commences following steps (1) and (2), these steps are combined into the cognitive/diagnostic task, while steps (3) and (4) are combined into the execution task.

Table 1. Points When Developing Narratives for Response to Internal Flooding Event

Task structure information		Example
	Cue	Cues for detecting internal flooding and pinpointing leak points/pipes. When the flooding flow rate is low, enabling detection through periodic patrols and parameter checks.
	Success path	Methods for information gathering include parameter checks, personnel dispatch, and the use of surveillance cameras. The decision-making process during an internal flooding response, along with potential response procedures, must be clearly defined.
	Opportunities for error recovery	Personnel and cues that can be expected to recover from errors in determining the occurrence of internal floodings, identifying the location of the break, and responding to the situation.
Time Progression Information		
	T_{Sw}	Time until initiating event occurs, or mitigation system equipment is affected, calculated based on the flow rate and location of the flooding.
	T_{Delay}	The time from the occurrence of internal flooding to the transmission of an alarm signaling the possibility of such an event is calculated based on, for example, the volume of water discharged from drains and the thresholds for water level alarm transmission.
	T_{Cog}	Time required to confirm alarms, check relevant parameters, assess the possibility of flooding, and confirm the site. This includes considering the assumed access route to the break, the time needed for access, and the factors that could impede access (e.g., water depth, flow velocity, water quality, short-circuits, radiation, hot steam). The evaluation of whether these factors would occur in given scenarios, how to ascertain their occurrence, and the actions to take if they do occur (e.g., alternative routes) is necessary.
	$T_{Execute}$	Time required to prepare procedures and conduct operations (for on-site operations, including moving time to the site)
PSF information		
	Accessibility and operational availability of equipment to be operated	The assumed access route to the leak point and factors that could hinder access need to be assessed (e.g., water depth, flow velocity, water quality, short-circuit, radiation, hot steam). This assessment should consider whether these factors would occur in specific scenarios, how to determine their occurrence, and contingency plans (e.g., alternative routes).
	Workload	The potential lack of human resources due to parallel operations needs to be addressed. This includes resources (personnel, time, etc.) required to respond to an initiating event when main control room personnel are on-site to assess the flooding situation, cooperation with emergency response headquarters, the command system, and requests for support outside the main control room (e.g., dispatching additional personnel).
	Communication	The method and content of communication between on-site personnel and main control room personnel.
	Environment in which the action needs to be performed	Conditions under which on-site work can proceed (e.g., water level).
	The need for special tools and their impacts on performance	Equipment required to respond to flooding on site, such as raincoats and boots, time required for movement and work, impact on work activities, etc.
	Training and procedures	Whether training on internal flooding termination operations is conducted, and the detail of the procedures.

Table 2. Example of internal flooding termination operation procedure

Number	Procedure	Contents
(1)	Recognize/determine the possibility of internal flooding occurrence	Upon confirming alarms and suspecting the occurrence of internal flooding, as outlined in procedures and while considering alternative scenarios, operators in the main control room are tasked with onsite investigations in buildings to ascertain the presence of flooding and pinpoint the break's location. Concurrently, operators initiate flood detection efforts using monitoring cameras and begin gathering information by assessing related parameters.
(2)	Identify the location of internal flooding	Operators are deployed to locate the source of leaks within the building, with findings reported back to the main control room. Simultaneously, operators stationed in the main control room utilize monitoring cameras to verify flooding incidents and identify the affected compartment or water line. The examination of related parameters aids in pinpointing the compromised water line.
(3)	Prepare a procedure for terminating flooding	Utilizing the information compiled, operators in the main control room consult piping system diagrams to identify a valve operation necessary to halt the internal flooding. A temporary procedure for ceasing the flooding is subsequently formulated on the spot, with its details reviewed and authorized by a shift supervisor.
(4)	Execute the internal flooding termination operation	The execution of internal flooding termination operations follows, with adherence to the established procedures (e.g., closing manual valves on site or electric valves in the main control room).

4.3. Quantitative evaluation policies

4.3.1 Cognitive/diagnostic task

The two most common methods for quantifying cognitive/diagnostic tasks are the cause-based decision tree (CBDT) method and the human cognitive reliability (HCR)/operator reliability experiment (ORE) method [7]. Should it be qualitatively assessed that ample time exists for cognition and decision-making during an internal flooding event, the application of the CBDT method is recommended (refer to HRA Guide 2018, Appendix A). Nonetheless, for its application to internal flooding scenarios, the definition of the CBDT method's branches must be adapted to reflect the specificities of internal flooding events. Table 3 provides an example of how these branches can be interpreted for application in such contexts.

4.3.2 Execution task

In the absence of a detailed procedure for identifying valves to be isolated, operators, upon pinpointing the leakage location, are anticipated to select valves for isolation using a system diagram and subsequently devise an on-the-spot procedure for their operation. This process might involve selecting and extracting a piping system diagram, marking the valves to be closed on the diagram, and obtaining confirmation from a shift supervisor.

Table 4 presents an example of employing the Technique for human error-rate prediction (THERP) method [8] based on the manner in which the procedure is formulated. It should be noted that the execution task, whether conducted with or without a detailed procedure, requires an evaluation of its HEP.

4.3.3 Error recovery: notes on on-site patrolling

Patrolling buildings to identify the location of flooding is a viable method for operators, but in situations of prolonged or large flow flooding, water levels in corridors and rooms may rise exceedingly high, rendering it impossible to approach the areas of leakage and thus identify the compromised pipes or piping lines responsible for the internal flooding. In other words, the identification of flooding points by on-site patrolling may not be expected depending on the water level, and directly considering this in the decision tree branches of the CBDT method would increase the complexity of the analysis. Therefore, it may not be considered in the decision tree branches of the CBDT method, but may be considered as a means of error recovery, that is, depending on the water level, whether or not on-site patrolling can be expected as an error recovery for cognitive/diagnostic tasks.

In certain scenarios, the cessation of rising water levels and water flow in a building's corridor, for instance, might be visually ascertainable from a safe vantage point within the building (e.g., from a higher location) without needing to approach the flooded area. Thus, if the success of flooding termination operations can be verified from a secure on-site location as part of the execution task, this verification could be regarded as error recovery for the execution task, independent of the water level.

The determination of water levels that enable mobility and operational capability should be based on field surveys, interviews with operators/workers, and literature reviews. When water levels surpass knee height (approximately 0.5 m for an adult male), walking speed significantly decreases, and individuals may experience fear [9][10]. Considering the time needed to retreat to a safe location before water levels impede the ability to walk or work, and considering the practicality of opening and closing doors, the threshold for water levels should be set below these critical heights.

Table 3. Examples of interpretations of the CBDT method[7] in its application to internal flooding events

Decision tree	Branch	Supplemental interpretation, etc.
Pca: Availability of Information	(2) CR Ind. Accurate	In assessing the integrity of instruments, determining if operators in the main control room can acquire information is crucial, aiding in the identification of leaked pipelines through means other than parameter checks, such as surveillance cameras.
P_cb: Data Not Attended to	Whole	This decision tree focuses on evaluating operators' ability to detect the occurrence of an event, emphasizing the initial cues (e.g., alarms) that signal an internal flooding event.
	(1) Low vs. Hi Workload	Before an initiating event, such as the total loss of the safety system's high-voltage AC bus bar caused by internal flooding, the workload is deemed equivalent to that of an internal event. This equivalence is due to operators concentrating on tasks such as investigating alarm causes. Conversely, after the initiating event, the workload escalates beyond that of a standard internal event. This increase is attributed to the necessity of simultaneously managing the response to the initiating event and the internal flooding termination operation, particularly under circumstances where the internal flooding cannot be immediately halted.
Pcd: Information misleading	Whole	This decision tree aims to highlight cues leading to the recognition of an event's occurrence and the initiation of response procedures, rather than encompassing all cues required for the entire response process.
Pcg: Misinterpret decision logic	(1) Not Statement	The evaluation is based on the current procedure manual, explicitly excluding temporary procedures.
	(2) AND or OR Statement：	It investigates whether determining the occurrence of internal flooding, pinpointing leak points/pipes, and identifying the isolation point requires a comparison of multiple information sources. A "Yes" response is warranted if a comprehensive decision is reached after reviewing multiple alarms, system parameter changes, and on-site verification results.
	(3)BOTH AND & OR：	Additionally, the branch assesses the potential for acquiring supplementary information to aid in identifying leak points/pipes. If leak identification is facilitated through on-site confirmation or surveillance footage, in addition to parameter data, the branch is set to "No," suggesting that identifying the flooding source may be simplified with these additional insights.

Table 4. Examples of application of the THERP method[8] to errors in preparing procedure

Case	Errors to be considered	THERP table to be applied
Write a procedure on a whiteboard or paper and use it as a written procedure.	Some information may be omitted or written incorrectly when developing documents such as procedures	Table 20-5 Estimated HEP per item (or perceptual unit) in preparation of written material
Prepare by writing directly on piping system diagrams	Mistake in selection of writing location when preparing procedures	Select the appropriate item from Table 20-12 as a selection error. For example, item3 "Select wrong control on a panel from an array of similar-appearing controls: arranged in well-delineated functional groups".

4.4. Evaluation of dependency between flooding termination operations (before and after the occurrence of an initiating event)

Even if the initial attempt at terminating flooding before the onset of an initiating event, such as the total loss of the safety system's high-voltage AC bus bar, is unsuccessful, efforts to mitigate the flooding continue to prevent further damage. In this scenario, the dependency between the initial and subsequent flooding termination operations must be evaluated. This dependency implies that the failure of a preceding task negatively impacts human performance, potentially leading to discouragement and increasing the likelihood of error in the immediately following task. A prominent method for assessing the dependency between human failure events is the decision tree method described in NUREG-1921[7].

A critical decision node “(3) Cognitive” in this method for determining dependency is whether the cues between human failure events are common. If determined to be common, the events are considered to have complete dependence, indicating that the HEP for the subsequent human failure event is assessed as 1.0. For instance, if the cues for detecting internal flooding or identifying the location/line of the leaking pipe remain unchanged before and after the occurrence of an internal event, the dependency between the two operations is deemed complete.

However, in practical scenarios, the occurrence of an initiating event may enable a reassessment of the potential for internal flooding and a clarification of the parameters and locations to be examined. Following the failure of a flooding termination operation aimed at preventing an initiating event, it may still be feasible to review and analyze the parameters, break points, and systems given adequate time. Consequently, assuming that a post-initiating event flooding termination operation is destined to fail is unrealistic. Thus, in such cases, the “Cognitive” branch may be interpreted as “Different,” assuming that the cues for the operations significantly differ.

5. QUANTIFICATION EXAMPLE

Adequate procedures and training are essential for the reliable execution of tasks. Especially for the CBDT method, the quality of procedures and the presence or absence of training influence the HEP estimation results. Therefore, quantification examples are prepared for the case in which no procedures for identifying the valve to be isolated and no simulator training is provided (poor case) and the case in which these procedures and training are provided (good case) to quantitatively examine the impact of these differences on the HEP.

The assumed scenario, operator responses and expected recoveries are outlined below. A pipe in a plant ruptures, causing an internal flooding, and a sump water level alarm is issued a few minutes later. As a cognitive/diagnostic task, operators notice this and split up to identify the ruptured pipe using monitoring cameras, identify the location of the ruptured pipe by patrolling the building and estimate the ruptured pipeline system by checking parameters. Considering the respective information, the ruptured pipeline is identified. Then, as the execution task, in the poor case, as there is no written procedure, the closing valve operation is performed after the procedure is prepared. In the good case, the valve closing operation is performed according to the procedures already prepared. Regarding the cognitive/diagnostic task, errors of “pce: Relevant Step in Procedure Missed” were assumed to be recovered by the deputy shift supervisor and errors of “pcf: Misinterpret Instruction” and “pcg: Error in Interpreting Logic” were assumed to be recovered by patrol operators. Regarding the execution task, errors of the valve operation were assumed to be recovered by checking the sump water level and the water surface changes in the field.

Table 5 shows the HEP in the cognitive/diagnosis task using the CBDT method, and Table 6 shows the HEP differences between the poor case and the good case. In both cases, the HEP of the cognitive/diagnosis task with the CBDT method was dominant for the total HEP. The HEP in the good case were approximately 1/10th of that in the poor case.

In both cases, the CBDT method analysis showed that the decision trees of “pca: Data Not Available,” “pcb: Data Not Attended to,” “pcc: Data Misread or Miscommunicated,” “pcd: Information Misleading,” and “pch: Deliberate Violation” all had HEP=0.0. In the poor case, the node (2) “All Required Information” in the decision tree of “pcf: Misinterpret Instruction” was judge as “No.” Also, due to the absence of simulator training, the node (4) "Practiced Scenario" of "Pcg: Misinterpret decision logic" was judged as "No." In the good case, these nodes were judged as "Yes." These differences had an impact on the HEPs. The HEP of the execution task was also reduced. This is because the good case does not need to consider procedure preparation errors.

These results suggest that establishing a procedure for identifying valves to be isolated and conducting simulator training are effective to reduce HEPs. Since a success in flooding termination operations prior to the occurrence of an initiating event can deter the occurrence of the initiating event, efforts to reduce this HEP can contribute significantly to reducing the risk of plants.

Table 5. HEP in the cognitive/diagnosis task using the CBDT method

Decision tree	Branch and value (nominal HEP)		Dependence of recovery (recovery personnel)	HEP	
	Poor case	Good case		Poor case	Good case
p_ce: Relevant Step in Procedure Missed	(c) 3.0×10^{-3}	(a) 1.0×10^{-3}	LD* (Deputy shift supervisor)	1.59×10^{-4}	5.04×10^{-5}
p_cf: Misinterpret Instruction	(b) 3.0×10^{-3}	(a) 0.0	MD** (Patrol operator)	4.36×10^{-4}	0.0
p_cg: Error in Interpreting Logic	(j) 1.0×10^{-3}	(i) 3.0×10^{-4}	MD** (Patrol operator)	1.44×10^{-4}	4.72×10^{-5}
			Total HEP	7.39×10^{-4}	9.77×10^{-5}

* LD was set in accordance with Appendix B-(vi) Appended Table B-(vi)-3 in HRA guide 2018[3], assuming that stress levels are normal and that the deputy shift supervisor's role in error recovery is equivalent to that of the shift supervisor.
** MD was set in accordance with Appendix B-(vi) Appended Table B-(vi)-3 in HRA guide 2018[3], assuming that stress levels are normal and that the patrol operator's role in error recovery is equivalent to that of operators in a main control room.

Table 6. HEP differences between the poor case and the good case

Case	Note	HEP in cognitive/diagnosis task	HEP in execution task	Total HEP
Poor case	No detailed procedure and simulator training	7.39×10^{-4}	9.91×10^{-7}	7.40×10^{-4}
Good case	With detailed procedure and simulator training	9.77×10^{-5}	5.67×10^{-7}	9.82×10^{-5}

6. CONCLUSION

For HRA on internal flooding termination operations, which are unique to internal flooding events and can be directly linked to the occurrence or non-occurrence of initiating events, this study summarized points to be considered in developing narratives and organized the necessary analytical models and know-how. It also showed that preparing procedures for identifying valves to be isolated and simulator training were effective to reduce the HEP of this operation.

Acknowledgements

The members participating in the Level 1 PRA Sub-Working Group discussed and offered advice necessary for development of the models and knowhow and quantification example. We would like to express our gratitude to all of them.

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