Identifying Human Failure Events (HFEs) for External Hazard Probabilistic Risk Assessment

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Abstract: In recent years, several advancements in nuclear power plant (NPP) probabilistic risk assessment (PRA) have been driven by increased understanding of external hazards, plant response, and uncertainties. However, major sources of uncertainty associated with external hazard PRA remain. One source discussed in this study is the close coupling of physical impacts on plants and overall plant risk under hazard events due to the significant human actions that are carried out to enable plant response and recovery from natural hazards events. This makes human reliability and human-plant interactions important elements in to consider in enhancing PRA to address external hazards.

One of the challenges in considering human responses is that most existing human reliability analysis (HRA) models, such as SPAR-H and THERP, were not developed for assessing ex-control room actions and hazard response. To support this new scope for HRA, HRA models will need to be developed or modified to support identification of human activities, causal factors, and uncertainties inherent in external hazard response, thereby providing insights regarding event timing and physical event conditions as they relate to human performance. In this study, the first step of such work is performed by identifying human failure events (HFEs) for human response to flooding hazards. These HFEs are human actions or inactions that are involved in human response to flooding hazards and could contribute to the loss of a critical function for the plant in the scenario being examined. Several resources are used to identify these HFEs, including flooding reports from the Nuclear Regulatory Commission (e.g. NUREG/CR-7256: Effects of Environmental Conditions on Manual Actions for Flood Protection and Mitigation), interviews with experienced PRA and HRA analysts, and tabletop walkdowns of flooding scenarios with a project team. Also, task decomposition analyses using the cognitive-based Phoenix HRA model are also used to identify HFEs. This paper will discuss early results of these analyses.

1. INTRODUCTION

Probabilistic risk assessment (PRA) can be defined as the methodology used to provide a quantitative assessment of a complex system's potential risk in terms of design, operation, and maintenance vulnerabilities and their consequences [1]. It is used to determine frequencies and consequences of an unsafe and unstable end state for a nuclear power plant. The scope and level of detail of a PRA vary by the specific application and are mainly determined by its intended use. According to the Nuclear Regulatory Commission (NRC), the scope of a PRA is defined in terms of the following: (1) risk characterization metrics, (2) plant operating states, and (3) causes of initiating events that can disrupt normal plant operations [2].

Risk characterization is expressed through the metrics of core damage frequency (CDF), large early release frequency (LERF), and radiological consequences to the public. Plant operating states are used to subdivide the plant operating cycle into unique states by examining operational characteristics such as reactor power level, in-vessel temperature and pressure among others. Initiating events are the disruptions to the plant steady state that challenge plant control and safety systems, whose failure may lead to core damage or radioactive releases. These initiating events have causes attributed to either internal or external hazards. External hazards include seismic events, high winds, external flooding on coastal and river sites. The International Atomic Energy Agency (IAEA) has published general requirements for external hazards and specific requirements for each hazard type [3], [4].

Recently, there have been improvements in the capabilities of many nuclear power plant (NPP) PRAs due to a greater understanding of external hazards, plant response, and sources of uncertainty. However, several significant uncertainties related to the following issues remain: (1) complexity and diversity of natural phenomena, (2) impacts on structures, systems and components (SSCs), and (3) close coupling of the impacts of physical hazards, plant response, and the human reliability of actions associated with plant response and recovery. Among the uncertainties of the third issue is the time (both required and available) to complete those actions under the hazards as well as the conditions under which the actions will be performed, given that many are performed outside the control room. Thus, human actions and human-plant interactions are key elements of successful prioritization of uncertainties within an external hazard PRA.

Within the wider PRA framework, HRA methods can be used to qualitatively and quantitatively assess the human contributions to the overall risk of a system. This done by building an understanding of human failure events (HFEs), estimating their probability and impacts, and proposing measures to reduce those errors. However, one of the shortcomings of a majority of human reliability analysis (HRA) strategies, such as THERP and SPAR-H, is that they were developed for internal events [5]. Starting from internal events PSA, licensed nuclear sites have attempted to account for the effects of external hazards by using human error probability (HEP) multipliers to modify the performance influencing factors (PIFs), which are driving factors influencing personnel behavior. The subjective nature of the multiplying factors can impact the overall results and identification of dominant human errors [6]. Several limitations exist for first-generation methods (e.g. THERP), including the lack of procedures for identifying human errors of commission and providing a convincing basis or theoretical foundation for quantifying error probabilities. While second-generation methods (e.g. SPAR-H) emphasized context and operator cognition, they lack theoretical and experimental basis for many fundamental assumptions and causal models that enable linking operator response to measurable PIFs [7]. In this work, this shortcoming will be addressed by modifying and exercising cognitive-based HRA methods (to be discussed in the literature review) to support the identification of human activities, causal factors, and uncertainties.

2. RELEVANT LITERATURE

This work constitutes part of a larger effort to exercise cognitive-based HRA models to support identification of human tasks, causal factors, and uncertainties. Second-generation HRA methods are notable for their extensive grounding in psychological literature [8], [9]. However, this cognitive nature of these methods means that their primary application is the analysis of control-room actions, where the physical nature of tasks is minimal and the bulk of errors occur in following procedures, reading signals, or other knowledge-based tasks. Furthermore, no existing HRA method includes all of the elements necessary to meet the requirements of a third-generation HRA method. An ideal method would be comprehensive, research-based, adaptable, and multipurpose [10].

The Information-Decision-Action in Crew Context (IDAC) method [8] has been identified as a useful framework for considering the conceptual component of error for the purposes of this work. The method's cognitive model considers three main stages of human response: Information, the automatic process of gathering knowledge of the situation; Decision, the operator response phase of situation assessment, diagnosis, and planning; and Action, the process of executing the correct course of action. Each I-D-A phase can be decomposed into further I-D-A structures. For example, within the Information stage, the operator must first recognize the incoming information (I-in-I), decide how to process the information (D-in-I), and passing this information to their decision-making strategy (A-in-I). Crew interactions are also considered, characterized by formal communication, informal communication, and coordination, but due to their highly complex and dynamic nature, these are not modeled beyond the crew members' primary responsibilities [8].

The Phoenix HRA methodology [7] expands upon IDAC through a layered qualitative analysis framework. The analyst must first gather PRA scenario information by developing, or obtaining, a detailed task analysis. This scenario information is used in concurrence with a guiding flowchart in order to develop a Crew Response Tree (CRT) at the top layer. A CRT is a forward-branching tree systematically covering all crew-system interaction scenarios leading to the identification of human failure events [11]. In the next layer, the human response model employs I-D-A to identify crew failure modes (CFMs) for the crew responses determined in the CRT. Phoenix proposes a set of CFMs, shown in Table 1, to enumerate each possible form of failure that can occur at the Information, Decision, and Action stages. In order to determine which CFMs are applicable at each point in the scenario, a Fault Tree (FT) can be developed for each CRT branch point. Only a subset of the CFMs will be applicable depending on the I-D-A stage. After breaking down the failure context through an I-D-A lens, the lowest-level endpoints will consist of the HFE's relevant CFMs. The final layer of Phoenix involves selection of performance influencing factors (PIFs) for each CFM and encoding these factors into a hierarchical causal structure, such as Bayesian networks (BNs).

Table 1: Set of Crew Failure Modes (CFMs) Proposed by the Qualitative Phoenix Framework [7].

ID	Crew Failure Modes in "I" phase	ID	Crew Failure Modes in "D" phase	ID	Crew Failure Modes in "A" phase
I1	Key alarm not responded to (intentional or unintentional)	**D1**	Plant/system state misdiagnosed	**A1**	Incorrect timing of action
I2	Data not obtained	**D2**	Procedure misinterpreted	**A2**	Incorrect operation of component/object
I3	Data discounted	**D3**	Failure to adapt procedures to the situation	**A3**	Action on wrong component/object
I4	Decision to stop gathering data	**D4**	Procedure step omitted (intentional)		
I5	Data incorrectly processed	**D5**	Inappropriate transfer to a different procedure		
I6	Reading error	**D6**	Decision to delay action		
I7	Information miscommunicated	**D7**	Inappropriate strategy chosen		
I8	Wrong data source attended to				
I9	Data not checked with appropriate frequency				

The IDAC method has been used in the maritime industry to mitigate collision risks between autonomous surface ships. Similar flowcharts to those used in the Phoenix method are used to develop event sequence diagrams (ESDs), which are analogous to CRTs. I-D-A is also used to identify task phases in a hierarchical task analysis for supervising and assessing ship safety [12]. This is expanded upon in a concurrent task analysis, which re-describes tasks until they relate to only one of the I-D-A phases. Concurrent task analysis also identifies the interface tasks, which exhibit dependency on another agent of the system [13].

Despite being a relatively new method, Phoenix has also been used to identify HFEs arising in industry scenarios. For oil refinery and petrochemical plant operations, the method has been applied with modified CFMs to address fundamental differences between these facilities and nuclear power plants [14]. Phoenix has been used to guide the development of a qualitative HRA framework for severe accident conditions at nuclear power plants [15]. This work describes human error modes (HEMs) corresponding to the CFMs identified in Phoenix, as well as PIFs aggregated from a variety of existing HRA methods.

3. METHODS AND DATA

Current methodologies for HRA can generally be classified into first- and second-generation methods. First-generation methods include the Technique for Human Error Rate Prediction (THERP) and the Human Error Assessment and Reduction Technique (HEART), among others [16], [17]. These methods have several limitations including their lack of procedures for identifying human errors of commission (EOC) and lack of a causal picture of operator error. Second-generation methods that have been developed include the Cognitive Reliability and Error Analysis Method (CREAM), Standardized Plant Analysis Risk Human Reliability Analysis (SPAR-H), and the Information, Decision, Action in Crew context (IDAC) [5], [8], [18]. These methods placed an increased emphasis on context and operator cognition in comparison to their first-generation counterparts, but still lack a causal mechanism linking operator response to measurable performance influencing factors (PIFs).

3.1. Scenario Development Resources

In this work, the qualitative Phoenix method is used to guide the process of identifying human failure events (HFEs) and characterizing the precursor scenarios in the case of external hazards, specifically flooding. This process begins by developing the PRA scenario(s) leading to the HFEs and gathering the needed information to support the construction of the crew response tree (CRT) [19]. These scenarios can be developed in a variety of ways, including plant visits and operator interviews, tabletop walkdowns with a project team, reviews of plant procedures and training manuals, governmental reports and documents, and formal task analysis.

3.2. Development of Crew Response Tree (CRT)

The objective of the CRT is to find the paths to predefined or new HFEs and identify possible opportunities for recovery. The CRT also allows the analysts to perform a detailed assessment of the conditions that could lead crews to take inappropriate paths. The main resources used to define the scenario being examined in this work were a tabletop walkdown session with the project team and the NUREG/CR-7256 report titled "Effects of Environmental Conditions on Manual Actions for Flood Protection and Mitigation" [20]. The report provides an approach to decompose manual actions into tasks, subtasks, specific actions and performance demands and presents a typology of these demands. Specifically, Section 6.3 of the report provides three decomposition examples that were achieved through group discussion and consensus building by a research team representing a wide array of expertise.

The decomposition example selected in this paper is the setup and operation of a portable pump, which is performed in response to an external flooding event and has subtasks performed at both sheltered and unsheltered locations. The tasks involved in it are as follows: (1) clear debris, (2) load and unload portable pump, (3) set up the portable pump, and (4) operate the portable pump. The research team selected and decomposed Task 2 "Load and unload portable pump" into subtasks and specific actions.

Table 2: Decomposition of the Loading and Unloading of a Portable Pump Task [20].

Specific Actions	Degree of Sheltering	Location	Comments
Subtask 2.1 – Drive Transport Vehicle to Equipment Storage Building			
Walk to the transport vehicle location from reactor building	Unsheltered	Variable	Transport vehicle is located away from reactor building and equipment storage building
Enter the transport vehicle	Unsheltered	Fixed	Personnel must unlock and open the vehicle.
Operate the transport vehicle to move it from its location to the equipment storage building	Semi- sheltered	Variable	This involves driving to a location away from the reactor buildings. Considered semi-sheltered because weather could affect visibility and hearing.
Exit the transport vehicle	Semi- sheltered	Fixed	
Open the equipment storage building door (i.e., high bay door of the storage the building)	Unsheltered	Fixed	This task involves unlocking the door and operating the door mechanism.

Enter the transport vehicle	Semi- sheltered	Fixed	
Operate the transport vehicle to move it into the equipment storage building	Semi- sheltered	Variable	Involves pulling the transport vehicle into the storage facility.
Exit the vehicle	Semi- sheltered	Fixed	
Subtask 2.2 – Load Diesel Driven Pump into Transport Vehicle			
Operate the powered hoist to load the pump on the transport vehicle	Sheltered	Fixed	This task involves positioning the hoist over the load, and lifting, moving, and lowering the load into place using the hoist controls.
Perform manual work with simple equipment (i.e., secure pump on the transport vehicle)	Sheltered	Fixed	This task involves primarily physical movements, such as gripping and pulling, to apply load constraints.
Subtask 2.3 – Drive Transport Vehicle to Equipment Storage Container			
Enter the transport vehicle	Unsheltered	Fixed	Personnel must unlock and open the vehicle.
Operate the transport vehicle to move the pump from the equipment storage building to the equipment storage container location	Semi- sheltered	Variable	Includes driving the transport vehicle from the equipment storage building to the equipment storage container location. Considered because weather could affect visibility and hearing
Exit the transport vehicle	Semi- sheltered	Fixed	
Subtask 2.4 – Load Equipment from Outdoor Container on Transport Vehicle			
Open the large container door	Unsheltered	Fixed	Involves unlocking and opening the Sea-Van container.
Load equipment (i.e., hoses and fittings) on the transport vehicle	Unsheltered	Semi-fixed	Involves gathering (gripping and lifting) hoses and fittings from the storage container and loading them onto the transport vehicle. This subtask is assumed to be mostly unsheltered and to occur when opening the container.
Perform manual work with simple equipment (i.e., secure equipment onto the transport vehicle)	Unsheltered	Fixed	This task primarily involves physical movements, such as gripping and pulling, to apply load restraints.
Subtask 2.5 – Drive Transport Vehicle to Reactor Building Location Where Equipment Will Be Unloaded			
Enter the transport vehicle	Unsheltered	Fixed	Personnel must unlock and open the vehicle.
Operate the transport vehicle from the equipment storage container location to the reactor building	Semi- sheltered	Variable	Includes driving the transport vehicle from the storage container location to the reactor building where the pump will be unloaded. Considered semi-sheltered because weather could affect visibility and hearing.
Exit the transport vehicle	Semi- sheltered	Fixed	

Communicate electronically outside the reactor building (i.e., to get the high bay door open)	Semi- sheltered	Semi-fixed	Involves communication and coordination with individuals in the reactor building to have the high bay door opened.
Operate the transport vehicle to move it inside the reactor building	Semi- sheltered	Semi-fixed	Includes driving transport vehicle into the reactor building.
Exit the transport vehicle	Semi- sheltered	Fixed	
Subtask 2.6 – Unload Pump, Hoses, and Fittings from Transport Vehicle			
Operate the powered hoist to unload the pump and other equipment from the transport vehicle	Sheltered	Fixed	Involves positioning the hoist over the load, and lifting, moving, and lowering the load using the hoist controls and physical movements.

After completing the task analysis, CRTs are developed to HFEs corresponding to a given safety function. Since the Phoenix framework was developed for internal hazards in NPPs, safety functions are defined as the intended function of a specific plant system, a desired state of the plant in response to an upset event, or a combination of both. Using the modular approach proposed in the qualitative framework, one CRT is developed for each identified safety function using the following inputs: HFE definition, crew and plant context, and all procedures used to carry out the safety function. The CRT output is in the form of an event tree that can be used to find the failure and success paths of the function.

3.3. Identification of Crew Failure Modes (CFMs) for CRT branches

The Phoenix methodology presents a set of 19 main crew failure modes (CFMs), with each being defined based on the particular Information (I), Decision (D), or Action (A) phase in which it occurs. These CFMs, shown in Table 1, are defined as the generic functional mode of failure of the crew in its interactions with the plant and represent the proximate cause of failure. They are also defined as mutually exclusive or orthogonal to avoid double counting crew failure scenarios during human error probability (HEP) estimation. After constructing the CRT, fault trees are developed based on the branch points identified. In these fault trees, the HFEs are the top event and CFMs are the basic events.

4. RESULTS & DISCUSSION

The task of loading and unloading a portable pump, whose decomposition is shown in Table 2, is mainly associated with the "A" phase of the IDAC operator behavior model (action). As previously shown, the decomposed task had 6 subtasks, each of which was used to construct a crew response tree. The CRTs generated a total of 16 branch points, 26 human failure events (HFEs), and 42 occurrences for 11 unique CFMs, which are shown in Table 3. For the HFEs identified, 19 of them were in the "A" phase, 4 in the "D" phase, and 3 in the "I" phase. The majority of the HFEs (73%) fall into the "A" phase, thus making the task mainly associated with it. Of the 42 CFM occurrences, 20 of them were in the "A" phase, 15 in the "D" phase, and 7 in the "I" phase. This was due to that the fault tree analysis determined the need to include several CFMs associated with the "D" phase in HFEs that were in the action "A" phase. This nested structure is described in [21], and is termed the decision-in-action (D-in-A) process, which determines how the skill-based action is performed. The action-in-action (A-in-A) process determines how the actual action is carried out. While all three CFMs associated with the "A" phase were utilized in the fault tree analysis, only five of the "D" phase and two of the "I" phase CFMs were included. The most commonly occurring decision phase CFMs were D2 (Procedure misinterpreted) and D7 (Inappropriate strategy chosen). For the information phase, I2 (Data not obtained (intentional)) and I7 (Information miscommunicated) were the most commonly occurring CFMs.

Table 3: Number of Occurrences of Identified CFMs.

CFM	Occurrences
I2	3
I7	4
D2	3
D3	1
D4	1
D6	1
D7	9
A1	1
A2	11
A3	3
A4	5
Total	**42**

However, the existence of only three CFMs associated with the "A" phase posed a challenge to the ability to fully describe how the crew assigned to the task fails in its interactions with the plant and other personnel. This is why the authors felt it was necessary to suggest the addition of a fourth CFM in the "A" phase with the following description: "No action taken on object or component". This additional CFM was used in Subtasks 2.1, 2.4, and 2.5. For the action phase, the most commonly occurring CFM by far was A2 (Incorrect operation of component/object).

Subtask 2.5 posed a particular challenge because it involved communication and coordination between the transport vehicle operator and individuals in the reactor building to coordinate opening a high bay door and driving the vehicle inside the building. This will require further development of the existing CFMs to involve the failure modes involved in communicating between different personnel in an external environment.

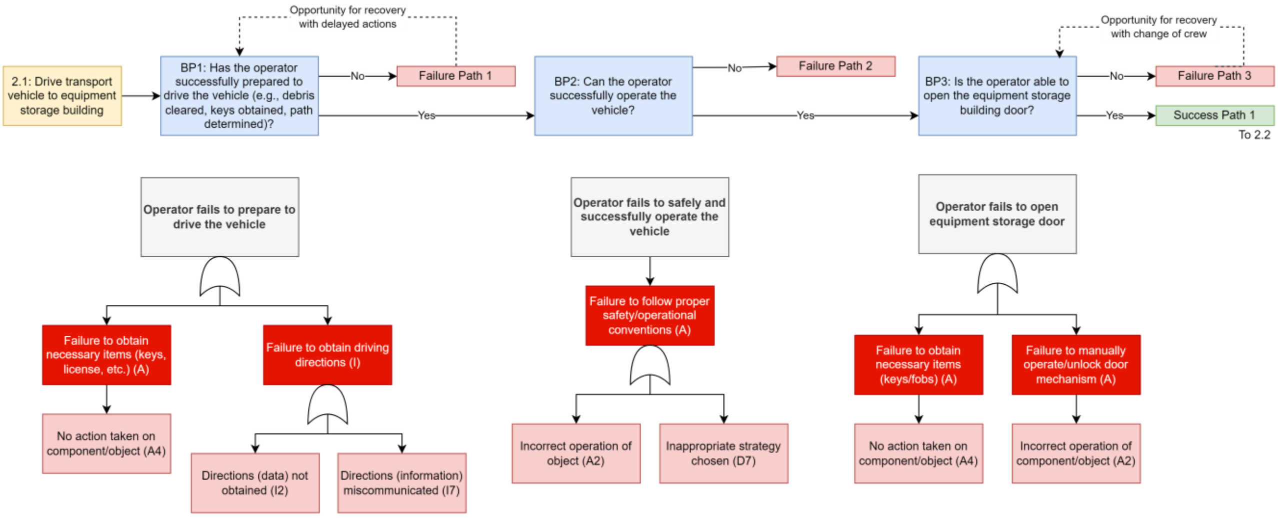

Figure 1: CRT and FT Diagrams for Subtask 2.1-Drive Transport Vehicle to Equipment Storage Building

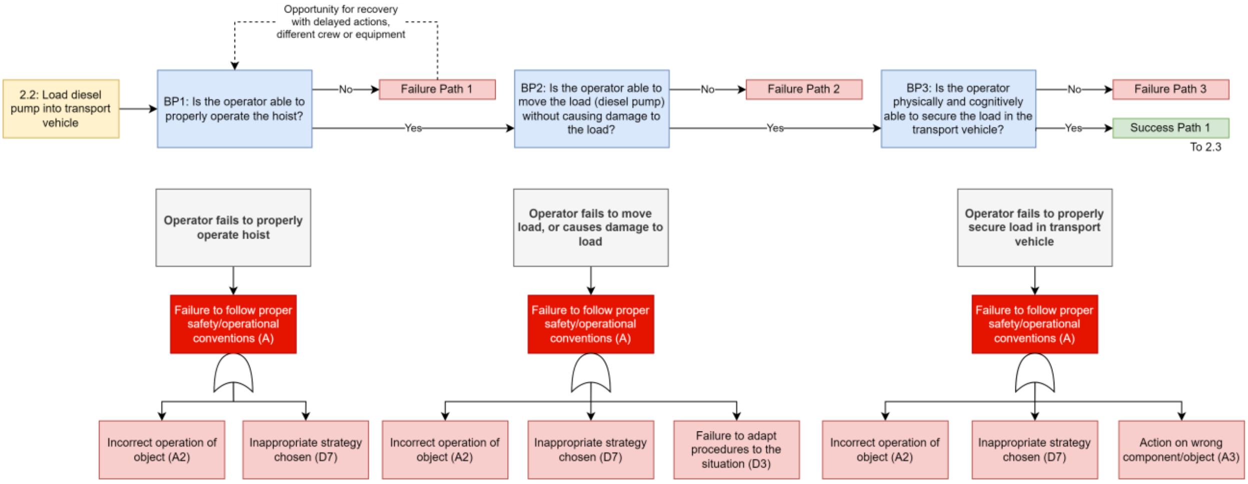

Figure 2: CRT and FT Diagrams for Subtask 2.2-Load diesel pump into transport vehicle

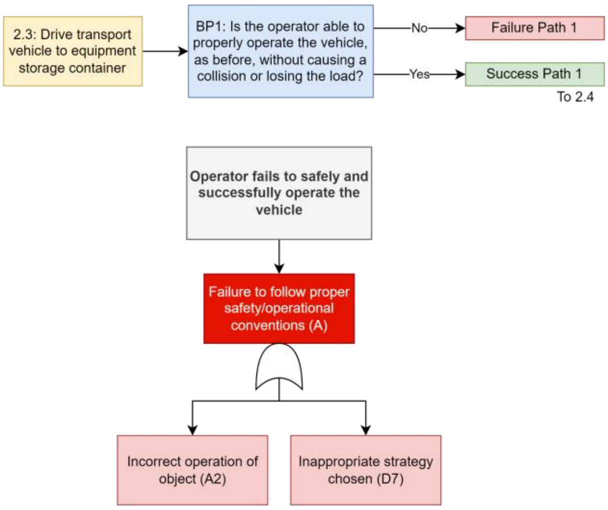

Figure 3: CRT and FT Diagrams for Subtask 2.3-Drive Transport Vehicle to Equipment Storage Container

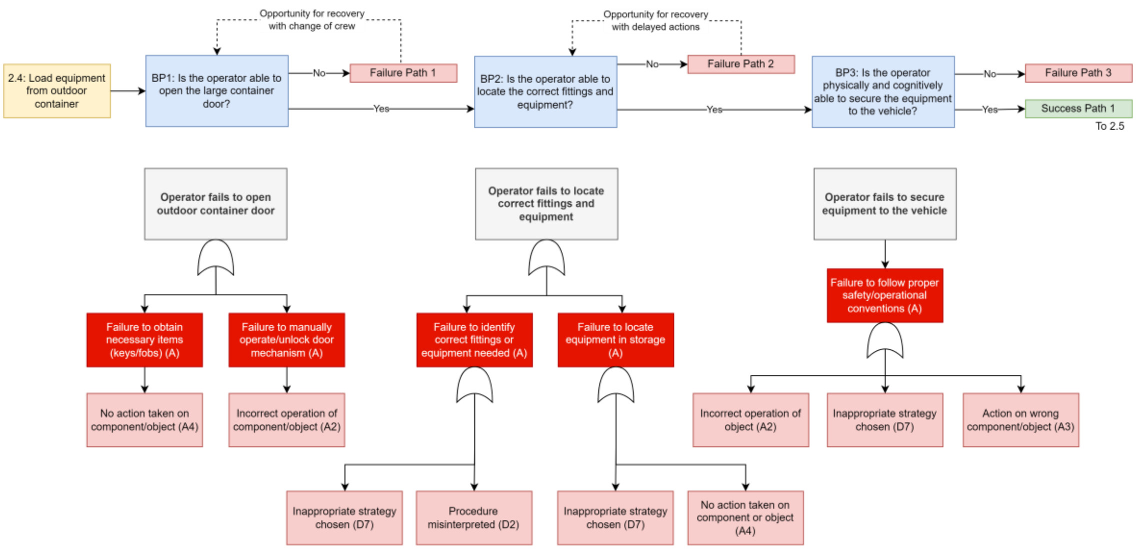

Figure 4: CRT and FT Diagrams for Subtask 2.4-Load Equipment from Outdoor Container

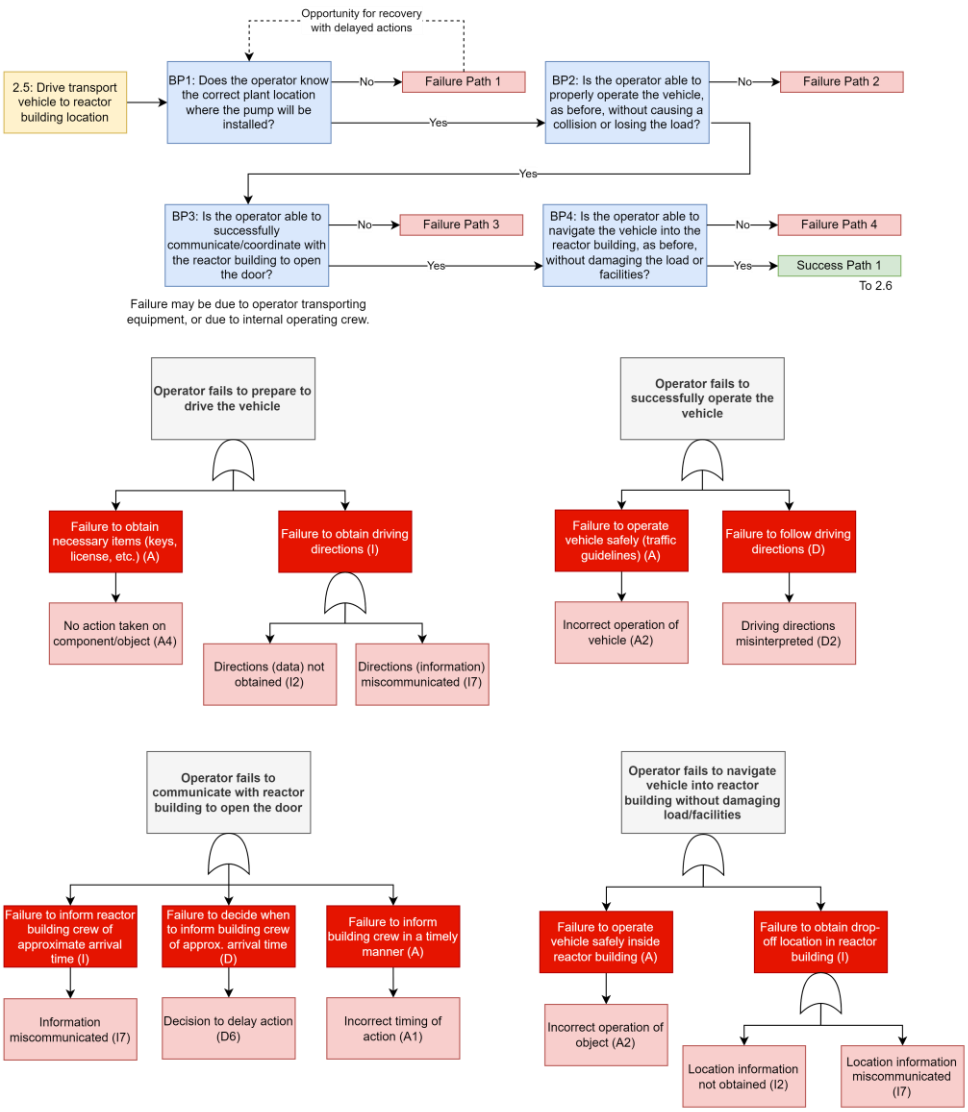

Figure 5: CRT and FT Diagrams for Subtask 2.5-Drive Transport Vehicle to Reactor Building Location

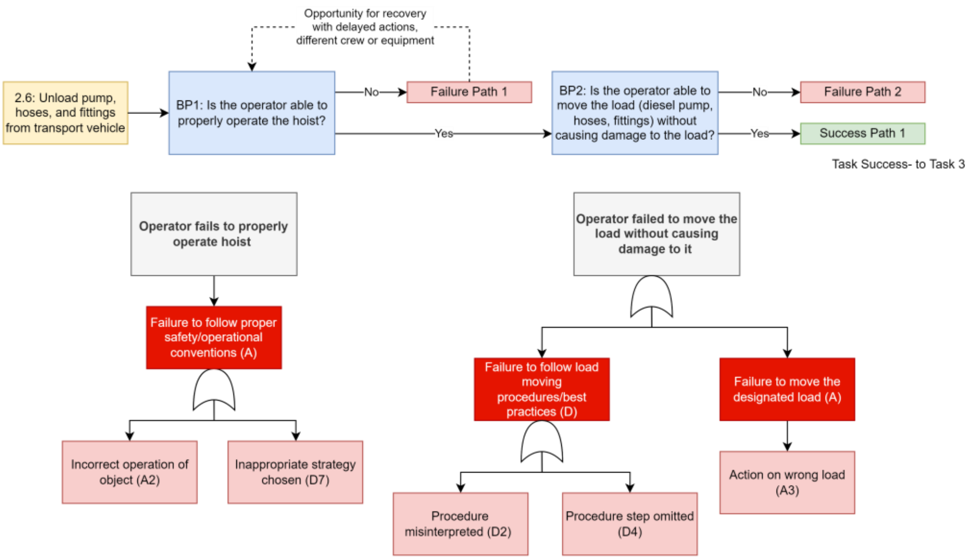

Figure 6: CRT and FT Diagrams for Subtask 2.6-Unload Pump, Hoses, and Fittings from Transport Vehicle

5. CONCLUSIONS

This work involved applying the Phoenix qualitative framework to identify human failure events (HFEs) and crew failure modes (CFMs) for a manual action that takes place in preparation for external flooding events in nuclear power plants. Since the Phoenix framework was developed for an NPP control room environment, this work demonstrated the framework's suitability to applications outside the control room. The comprehensive nature of the framework enabled the development of a crew response tree (CRT), used to find failure and success paths of the decomposed action being examined, and fault trees (FTs) for the HFEs identified from the CRT branches. Also, the CFMs presented in the Phoenix framework were found to be relevant to ex-control room manual actions. However, it was determined that further development of the CFMs in the action execution "A" phase of the framework is needed, as the tasks inherent in preparation for external flooding events are generally performed in an outside, unsheltered environment. This led to the suggestion of a fourth "A" phase CFM: action on an object or component not being performed. There were also specific actions within the analyzed task that involved communication and coordination between different sets of skilled workers in the plant. These findings aid in identifying the existing CFMs of the "A" phase of the Phoenix framework as a source of uncertainty in human reliability analysis for external hazards PRA. For further validation, two more tasks will be analyzed using the Phoenix framework and expert feedback will be sought to identify possible avenues to further develop the existing CFMs and mitigate some of the remaining uncertainties.

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