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Application of Phoenix Human Reliability Analysis Methodology to Model External Operation with FLEX Strategies consideration

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This paper examines the application of the Phoenix Human Reliability Analysis (HRA) methodology to model external operations in nuclear power plants during Beyond-Design-Basis External Events (BDBEEs), incorporating Diverse and Flexible Coping Strategies (FLEX). BDBEEs, such as those observed during the Fukushima disaster, challenge conventional safety systems and HRA methodologies due to extreme conditions like seismic events and station blackouts (SBOs). FLEX strategies, which leverage portable equipment and multi-phase operational protocols, are critical in addressing these scenarios.

The Phoenix HRA methodology integrates Event Sequence Diagrams (ESDs), Fault Trees (FTs), and Bayesian Belief Networks (BBNs) to quantify Human Error Probabilities (HEPs) and model operator performance. This paper conducts a case study of an SBO caused by an earthquake. First, the operation of mobile power supply vehicles, a key FLEX equipment, is modeled alongside conventional SBO recovery operations. Second, critical tasks, failure modes, and performance-influencing factors (PIFs) are identified. Third, the methodology quantifies HEPs for securing FLEX equipment and evaluates overall recovery operations under environmental challenges such as road inaccessibility.

Quantitative results demonstrate the impact of environmental factors on HEPs, providing insights to enhance human reliability during FLEX operations. This study advances human-system interaction modeling under extreme scenarios and offers practical guidance for integrating FLEX strategies into the Phoenix HRA methodology. The findings aim to support the HRA community in addressing the unique challenges posed by BDBEEs.

Keywords: Human Reliability Analysis, FLEX Strategies, BDBEEs, Station Blackout, Phoenix HRA.

1. Introduction

The Beyond-Design-Basis External Events (BDBEEs), referring to the external events that exceed the design parameters of nuclear power plants (NPPs), are significant for NPP safety because they represent extreme scenarios capable of overwhelming conventional safety systems. The Fukushima disaster exemplifies the devastating consequences of a BDBEE, where an earthquake and subsequent tsunami led to widespread loss of power, cooling system failures, and core damage, resulting in severe radioactive release (Xu et al., 2021; Son et al., 2017). Such events, including earthquakes, flooding, tsunamis, and fires, pose unpredictable risks by disrupting systems and safety barriers, while severely complicating human operations under high stress and degraded conditions (NRC, 2012).

Human Reliability Analysis (HRA), which aims to identify, model, and quantify human errors, has been applied to analyze BDBEEs by quantifying operator error probabilities and evaluating procedural adherence under stress, such as SPAR-H (Parka et al., 2021). However, these attempts fall short in addressing the unique environmental and logistical complexities of BDBEEs, such as debris, communication failures, and the physical challenges of deploying portable equipment. Unlike control room operations, BDBEEs often force operators to work outside under degraded and unpredictable conditions, increasing stress, complicating decisions, and raising the likelihood of errors (Xu et al., 2021; Park et al., 2021; Cooper et al., 2020).

The Diverse and Flexible Coping Strategies (FLEX) initiative was developed post-Fukushima to enhance resilience against BDBEEs (Xu et al., 2021). FLEX emphasizes using portable, on-site and off-site equipment, such as generators and pumps, to maintain core cooling and containment integrity under adverse conditions (Son et al., 2017). FLEX's advantages include its flexibility in adapting to diverse scenarios, redundancy through multiple layers of defense-in-depth, and portability that ensures operability even when fixed systems fail (Cooper, 2020; Xu, 2021). Integrating FLEX into HRA and Probabilistic Risk Assessment (PRA) is critical because it enables the modeling of dynamic, real-world scenarios where human actions and equipment performance interact under extreme stressors (Son et al., 2017). By quantifying the effectiveness of FLEX strategies, HRAs can better inform risk-informed decision-making and enhance the reliability of nuclear safety systems (Xu et al., 2021; Park et al., 2021).

Advanced HRA methods incorporate FLEX strategies through tools like IDHEAS-ECA and EMRALD, which address specific challenges associated with BDBEEs. For instance, IDHEAS-ECA evaluates human error probabilities (HEPs) by integrating cognitive and environmental factors into its models (Cooper et al., 2020). EMRALD provides dynamic simulations incorporating equipment failures and operator actions in real-time, enabling a more realistic assessment of FLEX's effectiveness (Park et al., 2021). These tools address issues of environmental conditions, and timing uncertainties and equipment reliability, respectively. This integration has enhanced the ability to model operator responses during long-term SBOs or other BDBEEs, thereby reducing core damage frequency and improving the robustness of PRA models.

To consider degraded environmental conditions, equipment reliability, and operators' real-time interactions with FLEX equipment in BDBEE, this paper explores the applicability of the Phoenix HRA method to BDBEE, focusing on a station blackout caused by an earthquake. By applying Phoenix HRA with FLEX consideration, this study examines its functionality and provides new insights into advancing human error assessment for SBO at earthquake occurrence.

The outline of this paper is as follows. Section 2 introduces the Phoenix HRA method and FLEX strategies. Section 3 provides an example of Power recovery actions with mobile air-cooled power supply car for SBO (no RCP seal LOCA) at earthquake occurrence. The conclusion is presented in Section 4.

2. Phoenix HRA method and FLEX strategies

2.1. *Phoenix HRA method*

Phoenix is a model-based HRA method, initially developed for control-room operations in NPP field (Ekanem et al., 2016, 2024), and has been extended to oil and gas (Ramos et al., 2020) and maritime field (Ramos et al., 2020; Cheng et al., 2024). Moreover, it shows capability to model and analyze human error in other types of activities, such as severe accidents (Chen et al., 2021), external operation with flooding occurrence (Al-Douri et al., 2023), maintenance operations (Cheng et al., 2025), digital control-room operations (Cheng et al., 2024; Ramos et al., 2023), and organizational activities (Cheng et al., 2025). Compared to the traditional HRA methods, the model-based Phoenix is capable of presenting traceability of causal and probabilistic relationships, providing flexibility to extend the model with updated data. Phoenix can be applied using the Phoenix software developed by the Garrick Institute for the Risk Sciences in UCLA, which can perform HEP calculations automatically and efficiently (Mosleh et al., 2024).

Phoenix includes a flowchart for generating Crew Response Trees (CRTs), and a set of Crew Failure Modes (CFMs) and Performance Influencing Factors (PIFs), modelled though four layers, as shown in Figure 1. The Master Event Sequence Diagram (ESD) models a series of Human Failure Events (HFEs). The success or failure of each HFE is modeled using a CRT, a forward-branching tree that identifies critical tasks by modeling the interaction between the crew and the plant. Next, the crew's failures to perform the critical tasks are modeled using Fault Trees (FTs), which include the human response model and lead to CFMs. Finally, the influence of the context on the CFMs, represented by the causal model, is modeled using Bayesian Belief Networks (BBNs) that consist of CFMs and PIFs.

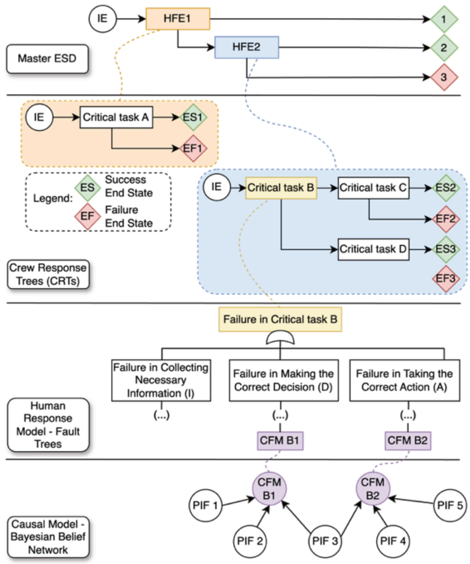

Figure 1 Overview of Phoenix HRA model

The analysis is divided into qualitative and quantitative parts. The qualitative analysis consists of: 1) identifying and developing the accident scenarios for analysis; 2) developing the CRTs; 3) identifying the CFMs for CRT branches; 4) developing the CRT scenarios for HFEs in terms of CFMs and relevant PIFs; and 5) analyzing the scenario, writing the accident narrative, and tracing dependencies among actions. This results in an integrated model comprising CRTs, FTs, BBNs, and CFM cut sets. The quantitative analysis is performed through 6) assessing PIFs states; 7) quantifying the integrated model layer by layer from BBNs, FTs, to CRTs; and 8) calculating the HEPs.

A series of questions constitutes a flowchart that analysts use to generate CRTs. Ekanem et al. (2024) provides definitions and selection criteria for CFMs and definitions and questionnaires for PIFs, which analysts can use to quantify HEPs.

2.2. *FLEX strategies*

2.2.1. Overview of FLEX

The FLEX strategy employs a three-phase approach to maintain critical safety functions during BDBEEs (US NRC, 2012), such as extended loss of alternating current power (ELAP) and loss of ultimate heat sink (LUHS).

In Phase 1, operators initially rely on installed equipment like emergency generators and batteries to sustain core cooling, containment integrity, and spent fuel pool cooling. This phase covers the immediate aftermath of the event.

In Phase 2, portable on-site equipment, such as pumps, generators, and batteries stored in protected locations, is deployed to transition from the reliance on installed equipment. Operators follow predefined FLEX Support Guidelines to ensure timely and efficient deployment.

In Phase 3, long-term coping strategies involve deploying off-site resources, including additional portable equipment and logistical support from centralized facilities. This phase ensures sustained safety functions until normal systems are restored, requiring coordination across multiple teams and resources.

2.2.2. Considerations for SBO During earthquake occurrence

Several critical factors must be addressed when a station blackout occurs alongside an earthquake to ensure adequate response and safety (US NRC, 2012).

(1) Seismic resilience is paramount, requiring FLEX equipment to be stored in locations robust against seismic events and protected from debris or structural damage. (2) Accessibility and deployment logistics must account for damaged infrastructure, with pathways and procedures established to clear debris and deploy equipment. (3) Environmental stressors, such as aftershocks, disrupted communications, and physical hazards, must be managed to avoid hindering operator performance. (4) Additionally, redundancy and coordination are essential to compensate for potential on-site equipment failures, ensuring off-site resources can be mobilized seamlessly. (5) Lastly, the timeline and human factors play a critical role, as earthquake-induced SBO scenarios demand rapid and efficient action under high stress. Operator fatigue, decision complexity, and procedural clarity must be carefully considered to optimize performance in such challenging conditions.

3. Example of adopting FLEX equipment in SBO at earthquake occurrence

This section presents an example showing how the Phoenix HRA method is applied with the aforementioned FLEX consideration to a SBO accident at earthquake occurrence. The investigation report of the Fukushima accident happened in 2011 is referred in the following subsection (Tokyo Electric Power Company, 2012).

3.1. *Accident scenario description*

On March 11, 2011, at 14:46, the Tohoku-Chihou-Taiheiyo-Oki earthquake struck, causing significant structural shaking at the Fukushima Daiichi Nuclear Power Station (Tokyo Electric Power Company, 2012). Units 1–3, which were operational, immediately underwent scram procedures as external power was lost. Emergency diesel generators (EDGs) activated to sustain critical cooling functions. By 15:27, the first tsunami wave arrived, followed by a second wave at 15:35, which overtopped the 10-meter seawall and inundated the site, flooding the turbine buildings and disabling the EDGs. At 15:42, a total SBO was declared as both alternating current (AC) and direct current (DC) power sources failed. This plunged operators into darkness, left instruments inoperable, and created severe challenges for monitoring reactor conditions and initiating emergency responses.

Several recovery attempts failed. Immediately after the earthquake at 14:46, EDGs were activated to provide backup power. However, the tsunami waves at 15:27 and 15:35 flooded the site, rendering the EDGs inoperable. DC batteries provided temporary power but were depleted by the evening of March 11, leaving the plant without tools for monitoring and control. Attempts to reconnect functional panels to unaffected systems were blocked by damage, and portable generators were unusable.

To restore power, emergency measures were initiated to deploy power supply cars. By 16:10 on March 11, TEPCO headquarters coordinated with other utilities and the Self-Defense Force (SDF) to mobilize high-voltage and low-voltage power supply vehicles. However, road damage and debris delayed their arrival. At 22:00, the first high-voltage power supply car reached the site, and others followed, arriving between 1:20 and 3:00 on March 12. Temporary cables were laid to connect the power supply cars to key panels, including the Unit 2 power center (P/C 2C) transformer and Unit 1 standby liquid control system. Despite aftershocks and logistical challenges, workers completed the cable setup under extreme conditions, enabling limited power restoration to critical systems.

3.2 *Modeling the master ESD*

Based on the above description of the SBO accident and the recovery actions with power supply cars, the following critical functions are identified. They constitute the master ESD, as shown in Figure 2.

CF1: Judgement of Initiating Event

CF2: Secure AC & DC Power

CF2-2: Secure mobile power supply cars

CF3: Depressurize Secondary System

CF4: Depressurize RCS Using PZR PORVs

CF5: Align alternate permanent LPI pump

CF6: Align self-cooled HPI pump

CF7: Long-term TD-AFWP control

CF8: Injection of SW into SG using fire pump

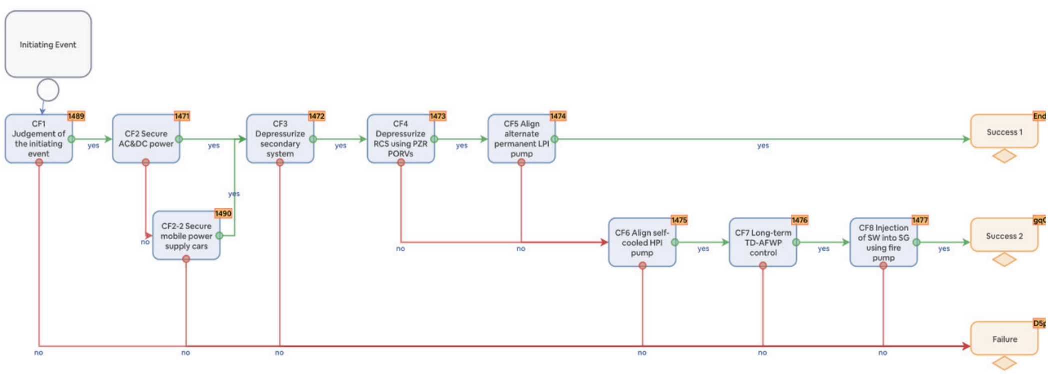

Fig. 2 Master ESD of Operations with FLEX equipment for SBO at earthquake occurrence

3.3. *Developing CRTs for HFEs*

Take the CF2-2 as an example. Its CRT is modeled as in Figure 3, including the HFEs and the failure events of technical systems and the environment.

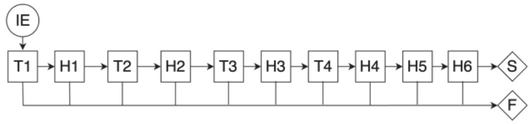

Fig. 3 The CRT of CF2-2: Secure the mobile power supply vehicles

- H1: Crew responds to the cues and is aware of the needs for mobile power supply cars
- H2: Crew selects the procedure for operating the mobile power supply cars
- H3: Crew decides the arrival location and drives the Mobile power supply cars to the EDG room
- H4: Crew connects cable reels with the mobile power supply cars to the emergency power in the EDG room
- H5: Crew connects portable fuel transfer pump with the fuel oil tank
- H6: Crew connects cable reels with mobile power supply cars and portable fuel transfer pump
- T1: Availability of the Communication systems with the Emergency response center (wireless phone)
- T2: Availability of Mobile power supply cars
- T3: Availability of the road outside of the EDG room
- T4: Availability of Cable reels

Finally, CF2-2's success path will connect to the next CF3, which will perform safety depressurization and injection and containment heat removal (RWST/CSR); CF2-2's failure path will lead to a core damage accident.

3.4. *Identify CFMs, PIFs, and assess PIF states*

For each HFE in the CRT, we referred to the CFM selection guide (Ekanem et al., 2016) to identify potential CFMs for all HFEs. Then, based on the contextual information in this case (Fukushima investigation report) and by referencing the meaning of PIFs, we selected PIFs for each CFM. For these PIFs, we evaluated their states by answering a questionnaire. The evaluation results are then input into the next step to determine the HEP. Below, we use H2 and H3 as examples to illustrate this process.

For H2, the potential CFM is 'Inappropriate Transfer to a Different Procedure,' because the crew may fail to follow the correct procedure due to transferring to an incorrect one. This behavior may involve the crew's teamwork, referring to "some operators felt helplessness and questioned why they had to stay when they 'couldn't do anything'. The shift supervisor had to calm the team to mitigating teamwork strain" (p.170, Tokyo Electric Power Company, 2012), as mentioned in the report. Therefore, we selected the PIF 'team effectiveness'. Specifically, it was considered that the crew has limited experience working together and that some crew members are unclear about their responsibilities. Thus, in the questionnaire for Team Effectiveness, the following questions are answered by "yes": (1) Does the crew have a short experience in working together such that it could impact their capability to work as a team? (2) Is there tight communication/coordination demands? (3) Is the crew lacking formal training to work together? For example, a team that has not undergone formal training for dealing with loss of power events. Other questions were answered by "no".

Table 1. CFMs, PIFs and probabilities of degraded PIFs in H2

CFMs	PIFs	Probability of degraded PIF
Inappropriate Transfer to a Different Procedure	Team Effectiveness	0.57

In H3, CFM1 Failure to Adapt Own Knowledge to the Situation is selected, a failure mode in the Decision phase. This means that the crew may fail to adapt their knowledge to identify the destroyed area due to the earthquake and evaluate the road conditions. Humans' diagnosis is 68 impacted by their stress level. Therefore, considering the crew's precepted urgency and the severity of the situation, the Stress PIF was selected.

In the questionnaire of Stress PIF, the following questions were answered by "yes": "(1) Is the crew likely to be under pressure / tensed due to their assessment of the urgency of the situation, i.e., their perception that they should act rapidly for preventing the situation from escalating? (2) Is the crew likely to be under pressure / tensed due to their assessment of the severity of the situation, i.e., their perception of the possible consequences of the situation?"

Additionally, since this is not an everyday event, the crew may lack familiarity with the decision-making task and face multiple competing demands on their attention, making it difficult for them to adapt their knowledge to the current situation. Therefore, the Knowledge/Abilities questionnaire includes the following questions, both answered with "yes": (1) Is the crew likely to have multiple competing demands on their attention? (2) Is the crew unfamiliar with the task?" One example of the calculation of probability of degraded Knowledge/Abilities is shown in the Appendix. Questions in the second column are responded to and filled in the fourth column based on scenario analysis. According to the instruction on the bottom of the table, the probability of degraded PIF can be obtained through P (degraded PIF) = Total number of Yes/ total number of (Yes + No), and 0.25 is obtained for the degraded Knowledge/Abilities.

CFM2: Inappropriate Strategy Chosen by Following Own Knowledge, is selected, which is a failure mode in the Decision phase. It means that by following the crew's knowledge, they may fail to determine appropriate strategy for deciding the route to pick up the mobile supply cars. This failure can also be impacted by stress.

In addition to the aforementioned PIFs, Team Effectiveness is also selected since the strategy is assumed to be determined through teamwork. In the questionnaire of Team Effectiveness, other than the questions mentioned in H2 are answered by "yes", the following questions are also answered by "yes": "(1) Is there a shortage of personnel required to make up the crew? (2) Are there factors (e.g. after shocking) that affect the ability of the crew to correctly obtain the required information?"

The "inappropriate strategy" associated with this CFM involves not only deciding the route but also arranging crew members to drive the mobile supply cars. During the driving process, the crew members are expected to encounter a complex external environment, which may impose additional workload. Thus, the PIF Task load is selected. Specifically, the question of "Are there external situational factors and conditions that would induce physical demands on the crew?" is answered yes.

Finally, CFM3, CFM4, and CFM5 are failure modes in the Action phase: CFM3 (Incorrect timing) refers to the crew taking too long to drive the cars; CFM4 (Action on Wrong Object) refers to the crew driving the wrong cars that were not arranged; and CFM5 (Incorrect Operation of Object) refers to the crew performing incorrect actions on the cars, such as driving at an improper speed. The same considerations are applied to these three CFMs as in CFM2. Specifically, Team Effectiveness and Knowledge/Abilities are assessed by answering the corresponding questions mentioned earlier, with all relevant questions being answered with "Yes."

Table 2. CFMs, PIFs and probabilities of degraded PIFs in H3

CFMs	PIFs	Probability of degraded PIF
1 Failure to Adapt Own Knowledge to the Situation	Stress	0.33
	Knowledge Abilities	0.25
2 Inappropriate Strategy Chosen by Following Own Knowledge	Stress	0.33
	Knowledge Abilities	0.25
	Team Effectiveness	0.70
	Task Load	0.125
3 Incorrect timing	Team Effectiveness	0.70
	Knowledge Abilities	0.25
4 Action on Wrong object	Team Effectiveness	0.70
	Knowledge Abilities	0.25
5 Incorrect Operation of object	Team Effectiveness	0.70
	Knowledge Abilities	0.25

3.5 Quantifying the Phoenix HRA model

The probabilities of the degraded PIFs are input to the integrated model, and the probabilities of CFMs are subsequently calculated. As shown in Figure 1, the failure probabilities of critical tasks consisting of the corresponding CFMs are obtained; and the failure probabilities of CFs represented by CRTs are calculated. Finally, the overall HEP of the master ESD is calculated.

Table 3. HEPs of CFs and the Master ESD

Critical functions	HEPs
CF1	3.936e-2
CF2	5.282e-2
CF3	2.126e-4
CF4	3.613e-3
CF5	7.322e-2
CF6	9.582e-4
CF7	5.466e-3
CF8	4.627e-3

We provide three assumptions for the probability of "Road is inaccessible" (P(Ri)), as 0.0001, 0.5, 0.9999, respectively. Three probabilities of CF2-2 are derived, so does the master ESD.

Table 4. Comparison of HEPs between three assumptions of P (Road is inaccessible)

P(Ri)	HEP of CF2-2	HEP of Master ESD
0.0001	9.333e-3	6.255e-2
0.5	5.406e-3	1.070e-1
0.9999	2.404e-3	1.263e-1

The results indicate that when assuming P(Ri) is 0.0001, the HEP of CF2-2 (securing the mobile power supply car) is the lowest, as is the HEP of the master ESD. This is followed by the scenario where P(Ri) is 0.5, in which the HEP of CF2-2 is the second lowest. Conversely, when assuming P(Ri) is 0.9999, the HEP of CF2-2 is the highest, and the HEP of the master ESD is also at its highest in this case.

4 Concluding remarks

This paper applies the Phoenix HRA method with the consideration of FLEX strategies to examine the adaptability of the Phoenix HRA approach to BDBEE and FLEX scenarios, with a specific focus on a SBO caused by an earthquake. Using the Fukushima accident as a case study, we model the tasks for control room operators, including conventional SBO recovery actions and external operations introducing mobile power supply vehicles. Cognitive failure modes of the crew are identified, along with the corresponding PIFs. By responding to PIFs' questionnaire, we assessed the probability of degraded PIF states and ultimately calculated the HEP for the entire recovery action.

In addition, by assuming three probabilities of road inaccessibility, we investigate the impact of external environmental damage on the HEP of securing mobile power supply cars, as well as the HEP of the overall recovery action sequences. Through the application of Phoenix HRA with FLEX consideration, this study not only demonstrates the method's capabilities but also provides valuable insights to the HRA community for human error assessment for SBO scenarios at earthquake occurrence.

Appendix A. Example on calculation of probability of degraded PIF

Table 5. Questionnaire of PIF Knowledge/ Abilities

ID	Questions	Lower Level PIF	Resp
1	Is it likely that crew form a wrong mental model of the situation?	Knowledge / Experience / Skill (Content)	no
2	Does the crew lack the required knowledge or experience/skill?	Knowledge / Experience / Skill (Content)	no
3	Does the crew lack the training required to detect alarm / system malfunctions?	Task Training	no
4	Does the crew lack the training required to detect recognizable patterns that point to the system problem?	Task Training	no
5	Is the crew unfamiliar with the task?	Task Training	yes
6	Is there a tendency to fail to adhere to STAR (stop, think, act, and review)?	Knowledge / Experience / Skill (Access)	no
7	Is the crew likely to have multiple competing demands on their attention?	Attention	yes
8	Is the crew slow in thinking, moving, monitoring, and communication?	Physical Abilities and Readiness	no
PIF Level Estimate			0.25
Instruction: The estimated PIF level (degraded state) = Total no. of Yes / Total no. of (Yes + No).			

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