Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Quantitative Assessment of Human Error Probability Dependencies through the EMBRACE Method

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Keywords : Human error probability, dependency, LOFW, EMBRACE, EPRI Calculator

1. Introduction

It is well-known, through safety evaluations, operational experiences, accident cases, and various data, that the behavior of operators, particularly in industries like nuclear power plants, significantly impacts safety. To enhance the safety of nuclear power plants, it is crucial to prevent or reduce errors induced by operators. For this purpose, analyzing and assessing errors from the perspective of power plant operators is essential. Human reliability analysis (HRA), which evaluates the probability of operator errors, has been widely used in the field of nuclear safety assessments. Traditional reliability evaluation models assumed the independence of operator errors and equipment failures within accident scenarios. However, since operator actions influence each other, it is necessary to predict the probability changes of successor events due to antecedent events through dependency analysis. In human reliability analysis, dependency is quantified as the conditional probability of successor events. Therefore, in risk assessments, dependencies can sometimes have a critical impact. This paper proposes a newly devised method for dependency assessment, considering several issues.

1.1 Current dependency assessment method

Until now, most methods for analyzing dependencies between HFEs have relied on the framework of THERP (Technique for Human Error Rate Prediction). THERP individually analyzes the dependency between two HFEs by considering spatial-temporal relationships, functional relevance, stress, and personnel similarity. This method provides a formula for calculating the conditional probability of successor events based on the assessed level of dependency.

Table1. Dependency levels and equations in the THERP method [1]

Dependency level	Equation	Approximate value
Zero	HEP	HEP
Low	(1+19*HEP)/20	0.05
Medium	(1+6+HEP)/2	0.14
High	(1+HEP)/2	0.5
Complete	1.0	1.0

Following the THERP method, more specific rules for dependency assessment methods have started to emerge. The SPAR-H (Standardized Plant Analysis Risk Human Reliability Analysis) method determines the crew sameness to evaluate personnel similarity. When operators are identical, the dependency can be determined to be low or moderate. Numerous studies are being conducted to enhance the traceability of assessment methods and reduce uncertainty. As a result, various methodologies have been devised.

1.2 EMBRACE method

This paper reviews a new method for quantifying the dependency between two HFEs and calculating the conditional failure probability of successor events which is developed by Kim et al. [2]. This approach addresses the dependency between two HFEs using feasibility impact, PSF (Performance Shaping Factor), resource impact, and mental model impact. The quantification method involves six features and has been validated based on empirical data, expert opinions, and similarity measures. Notably, this assessment method is considered in the emergency situation assessment model caused by internal events and is developed as an extension of the EMBRACE (Empirical Data-Base Crew Reliability Assessment and Cognitive Error Analysis) methodology.

2. Proposed Method

The proposed method is based on the techniques utilized in the EMBRACE method developed for the Advanced Power Reactor-1400 (APR-1400) that has a fully computerized control room. It incorporates the EMBRACE definitions of time required and time available, as well as rules for selecting crucial procedural steps, into the current dependency assessment approach.

In EMBRACE, the HEP comprises the failure probability of timely performance and cognitive error. The failure probability of timely performance represents the likelihood that the required time will exceed the available time, where the time required spans from a significant cue to the completion of tasks contributing to an HFE. The time available is the interval between the significant cue and the final point where the HFE achieves its success criteria.

The failure probability due to cognitive error is computed by summing primitive task failure probabilities in important procedural steps, accounting for PSF effects. These steps encompass operative steps defining HFE success criteria and transition steps to enter procedures with operative steps. Steps lacking procedure transitions and merely situated in the preceding sequence of operative steps are not deemed critical to the given HFE when operators follow procedure steps sequentially.

In this study, we propose a new method to calculate the conditional failure probability of a successor HFE based on quantitative evidence of the dependency between two events.

Considering the factors influencing dependency, the proposed method can be expressed by Eq. (1).

$$HEP(B|A) = [TRI + \{PTS + CRD\} * RF] * CS + HEP_B * ACE_B \quad (1)$$

A and B are sequentially occurring human failure events, and HEP B is the human error probability of HFE B. Temporal Resource Insufficiency (TRI) is the probability of insufficient temporal resources when performing both HFEs. PTS (Procedure Transition Similarity) is the similarity of procedures between the two events. CRD (Cue Recognition Dependency) is the dependency of recognizing the same device signal within the two events. RF (Recovery Factor) is an additional recovery factor for HFE B. CS (Cue Sameness) indicates whether there is consistency in operator group between the two HFEs, and ACE (Additional Contextual Effect) represents additional influences affecting HFE B.

2.1 Temporal resource insufficiency (TRI) estimation

This assumes that the crew cannot concurrently execute tasks associated with multiple HFEs. In practical terms, this implies that the temporal failure probability of the subsequent event, when delayed by the antecedent event, constitutes a facet of the conditional HEP for the successor event. Temporal resource insufficiency (TRI) is thus the overlap possibility of the two performance times corresponding to two HFEs.

Based on these ideas, the proposed TRI formula is Eq. (2):

$$TRI = 1 - \phi\left[\frac{ln\left(T_{a_{B,end}} - T_{r_{A,end}}\right)/\left(T_{r_{B,end}} - T_{r_{B,start}}\right)}{\sigma}\right] \quad (2)$$

Where $T_{a_{B,end}}$ is the point at which the time available for the successor event ends, and $T_{r_{A,end}}$ is the point at which the time required for the antecedent event ends. Likewise, $T_{r_{B,end}} - T_{r_{A,start}}$ indicates the length of the time required of the successor event. Φ and σ are the cumulative standard normal distribution and the standard deviation of the logarithmic time values, respectively.

2.2 Procedure transition similarity (PTS) measurement

In this method, it is observed that the conditional HEP of the successor HFE related to the procedure cue is proportional to the similarity of the two procedural flows. This is because a human error occurring during a shared part of the procedural flows can lead to failure of both events.

Procedure transition similarity (PTS) can be computed as a relative ratio by dividing the maximum similarity values of two sequences in the two HFEs by the average maximum similarity value of two identical sequences. The PTS formula is Eq. (3) :

$$PTS = \frac{H_{AB}(m,n)}{\left(H_{AA}(m,m) + H_{BB}(n,n)\right)/2} \quad (3)$$

2.3 Cue recognition dependency (CRD)

Based on empirical evidence of the failure probability of recoveries with the identical cue, the conditional HEP of the successor HFE is estimated to be 0.5 when both HFEs are initiated by the same instrument cue. For different instrument cues, the Cue recognition dependency (CRD) is 0.

2.4 Recover factor (RF) application

In this method, recover factor (RF) is a recoverability when successor event has sufficient time. For example, when the time available of the antecedent event is too short while the time available for the successor event is sufficient, the recovery of the antecedent event is impossible. The RF is 0.5 when recoverability exists in the successor event, otherwise it has 1.

2.5 Crew Sameness (CS) evaluation

The sameness of the crew (CS) in two HFEs is critical in determining whether TRI, PTS, and CRD affect the dependency between the two HFEs. CS is 0 when two crews are different, dependency is considered independent. Otherwise, CS is 1.

2.6 Additional contextual effect (ACE) quantification

An additional contextual effect (ACE) is appraised when the antecedent HFE transmutes the PSF level of the successor HFE from the PSF level reflected in the individual HEP. For example, ACE is considered when it is predicted that the stress of the operators performing the successor event will increase as the antecedent event exacerbates the accident situation, compared to the stress level when assessing the individual HEP of the successor event. The HEP of the successor event is thus multiplied by 5 when the levels of task complexity or subjective stress additionally increase. Even if the tasks for both events can be completed with ample available time, simultaneous occurrences of instrument cues in both events can lead to heightened task complexity, increasing the likelihood of task omissions. Consequently, if all cues for the successor event manifest before the time required for the antecedent event elapses, the ACE value for the successor event is set at 5. In cases where there is no anticipated alteration in the PSF level of the successor event, the ACE value remains at 1.

3. Case study

A case study was conducted to verify the applicability of the proposed method. The procedure step numbers and contents including the component indices are arbitrarily presented. The dependencies in two pairs of HFEs were assessed by the proposed method and the EPRI assessment method. The conditional HEPs based on the two methods were also compared.

An accident sequence in the loss of all feedwaters (LOFW or LOAF) accident in APR-1400 was analyzed. It is a scenario where, following the initial event, appropriate measures are not taken at each stage, resulting in core damage. Immediately after the initial event occurs, the reactor successfully shuts down, and Pilot operated safety relief valve (POSRV) operates successfully. However, the attempt to remove heat through main steam atmospheric dump valve (MSADV) and main steam safety valve (MSSV) fails, leading to entry into the safety depressurization stage. Operator checks opening of safety valve of pressurizer and directly conducts feed and bleed through open safety valve of safety depressurization systems.

Figure 1 shows an event tree starting with initial LOFW. In sequence 18th, two HFEs occur resulting in core damage. There are two HFEs in this accident sequence: (1) starting start-up feedwater pump, and (2) operating the relief valve of the pressurizer. The success criterion for the antecedent event is to press button of the start-up feedwater pump within 45 mins. The action takes 15 mins. The instrument cue for this action is a low level of the steam generator. The cue of low level of steam generators is associated with the reactor trip. The success of the successor event, the initiation of feed-and-bleed operation, was defined as manually pressing the open button of the pressurizer relief valve within 65 mins and the action takes about 20 mins. It can be performed in both case where the steam generator level becomes low, and the safety valve of the pressurizer is opened due to high pressure of the pressurizer. The cue occurs at 25min. TRI is calculated as 3.52E-03 when the time required and time available of the two events are combined. Antecedent event goes through diagnostic action (DA) and 6-steps of optimal recovery guideline (ORG). And the other go through DA, 7-steps of ORG, and 101-steps of functional recovery guideline (FRG). PTS is 0.4[=1/((2+3)/2)] since there is only one DA in common between the two events [3]. The cue of both antecedent and successor event occur by same instrument, and there is no additional cue, CRD is 0.5. In successor event there is insufficient time margin, thus RF is 1. Operators are same and stress level is higher, but it is already reflected in successor event, both CS and ACE are 1. The conditional probability of the successor event is 0.90846 by Eq. (1), approximately two times larger than EPRI method. Therefore, the final composite probability is calculated as 8.71E-03 by multiplied with probability of antecedent event. In the EPRI method, since there is a high dependency relationship between the two events, the final composite probability derived by multiplying the probability of antecedent event and high dependency value of 0.5 is 4.79E-03.

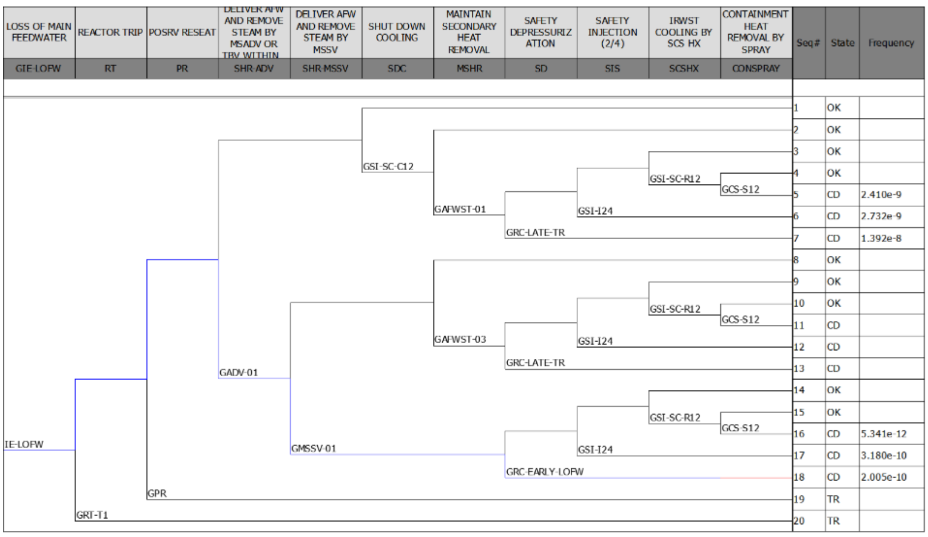

Figure 1. Event tree of loss of all feedwater accident in APR-1400 PSA model

Table II: Comparison dependency assessment methods

	HEP(A)	CHEP(B) by Eq. (1)	HEP(A)* CHEP(B)
Independent case	0.00959	0.00494	4.74E-05
EPRI dependency assessment		0.5	4.79E-03
Proposed dependency assessment		0.90846	8.71E-03

4. Conclusion

Using the newly developed method, quantitative assessment of HEP dependency was conducted for a LOFW scenario involving HFEs. In contrast to the widely used EPRI method, which has fixed probability values and does not incorporate data on human errors, the proposed method reflects human errors in computerized control room. The probability value derived from the new method is 8.71E-03, approximately 1.8 times larger than that of the EPRI method. This result suggests a significant impact on core damage frequency, indicating a need to investigate the mechanisms causing differences between the two methods to more accurately assess the nuclear safety. Additionally, further studies such as uncertainty analysis, examining other factors influenced by the time available of operators, should be conducted.

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