Application of the Diagnosis Error Probability Formula Considering Shift Technical Advisor's Absence in Fire Events

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1. Introduction

Fire incidents in nuclear power plants (NPPs) can simultaneously trigger reactor shutdowns and damage multiple systems responsible for safe shutdown and accident mitigation, significantly impacting NPP safety. As a result, fire risk quantification has become a critical topic in NPP safety research, with ongoing studies addressing this issue both domestically and internationally.

Fire probabilistic safety assessment (PSA) quantifies fire risks in NPPs by evaluating the core damage frequency (CDF) resulting from fire events. Domestically, fire PSA began with the methods and data from TR-105928[1], developed by the Electric Power Research Institute (EPRI) in 1995. The U.S. Nuclear Regulatory Commission (NRC), in collaboration with EPRI, developed a new fire PSA methodology outlined in NUREG/CR-6850[2]. Since its release, U.S. NPP operators have widely implemented this methodology for fire PSA evaluations. Additionally, research has been conducted to adapt and apply this approach to domestic NPPs[3-4].

According to the definition provided in NUREG-1921[5], fire human reliability analysis (HRA) aims to identify and quantify human failure events (HFEs) used in the quantification of fire PSA models. Fire HRA modifies existing HFEs from internal event PSA to account for fire impacts and fire accident scenarios or defines new fire-related HFEs to be incorporated into fire PSA models.

The Korea Atomic Energy Research Institute (KAERI) developed a fire HRA guideline[6-7] for detailed analysis based on the process and assumptions for the fire HRA of NUREG-1921. This fire HRA guideline used the framework of the K-HRA methodology and incorporated fire HRA procedures and assumptions for fire scenarios outlined in NUREG-1921, along with two types of supplements[8-9]. K-HRA[10] is a standard method for HRA of domestic internal event PSA developed by KAERI and was updated to K-HRA Rev.1[11] to meet the technical requirements set by the Korean regulatory body in 2023.

The purpose of this paper is to present the modification of the nominal diagnosis error probability (DEP) formula to reflect one of the assumptions in fire scenarios that when a fire occurs at an NPP, the shift technical advisor (STA) must be dispatched to the fire scene to assess the situation and organize the fire brigade. Additionally, this paper provides an example of calculating the nominal DEP using the modified approach.

2. Modified Nominal Diagnosis Error Probability Calculation Formula

To quantify the human error probability (HEP) of an HFE, the K-HRA method breaks the task into two components: diagnosis and execution. The total HEP is then calculated by summing the diagnosis error probability (DEP) and the execution error probability (EEP). In K-HRA, the analysis of diagnosis errors is conducted using the time reliability curve (TRC) of the Technique for Human Error Rate Prediction (THERP) from Fig. 1 (Figure 12-4 of NUREG/CR-1278[12]) to determine the nominal DEP. After obtaining the nominal DEP, adjustments are made by applying the effects of relevant performance shaping factors (PSFs). The nominal DEP is initially derived as the median value from the THERP TRC, which is then converted into a mean DEP for further calculations. K-HRA defines the formula for the nominal DEP (mean) based on Fig. 1. In essence, the nominal DEP formula is expressed as a function of the time available for diagnosis.

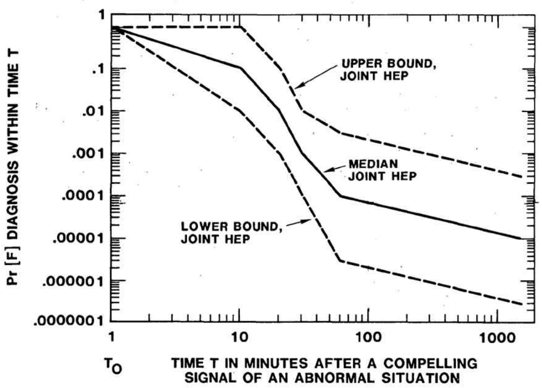

Fig. 1. Nominal Diagnosis Error Probability Curve by THERP (NUREG-1278)

As mentioned above, one of the features of the fire situation is an STA's absence to arrange a fire brigade. We reflected the feature into a nominal DEP. It was assumed that the reduction in MCR personnel due to the absence of the STA would impact the quality of diagnostic tasks. Based on the interview with MCR operators, we assumed a total absence time of 30 minutes for the STA (20 minutes for fire brigade arrangement and 10 minutes for stabilization upon returning to the MCR). Therefore, the nominal DEP for the 30 minutes of the STA's absence during a fire was adjusted. To achieve this, the methodology for calculating the joint human error probabilities (JHEPs) for diagnosis of MCR operators at 10, 20, and 30 minutes in NUREG/CR-1278(pp. 12-21) was applied.

According to JHEPs of the MCR operators' diagnosis in NUREG/CR-1278, when calculating the DEP within 10 minutes, no credit is given to the actions of the STA, so the existing curve was applied without any modifications. For the period between 10 and 20 minutes, the JHEP of 0.01265 (= 0.1 × 0.55 × 0.23), which accounts for the absence of the STA, is 1.8 times higher than the JHEP of 0.007 (= 0.1 × 0.55 × 0.23 × 0.55) provided in NUREG/CR-1278, which includes the STA. Based on the above calculation results, for the period between 10 and 30 minutes after the fire outbreak, twice the DEP derived from the curve in Figure 1 was applied. After 30 minutes, the DEP derived from the curve in Fig. 1 was applied. However, for the DEP between 30 and 60 minutes, an interpolation technique was applied using the modified DEP from the 10 to 30-minute period. Table 1 presents the DEPs derived from the curve in Fig.1 for K-HRA, along with the modified DEPs that account for the STA's absence during a fire in the fire HRA analysis.

Table 1. Nominal DEPs from K-HRA and fire HRA

Time Available for Diagnosis, T (min)	DEP of K-HRA		DEP of Fire HRA	
	Median	Mean	Median	Mean
10	1.00E-1	2.66E-1	1.00E-1	2.66E-1
20	1.00E-2	2.66E-2	2.00E-2	5.33E-2
30	1.00E-3	2.66E-3	2.00E-3	5.33E-3
60	1.00E-4	8.48E-4	1.00E-4	8.48E-4

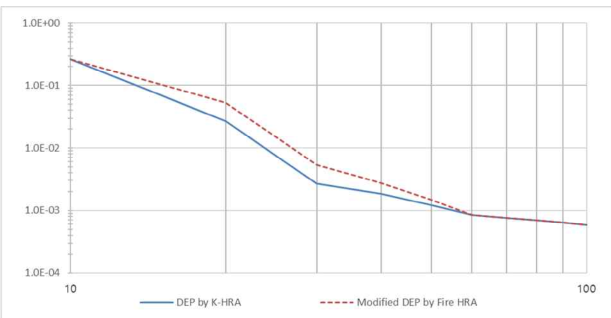

Fig. 2. Nominal DEP(Mean) by K-HRA and Fire HRA

Fig. 2 shows the nominal DEP (mean) by K-HRA and modified DEP reflecting the contents described above.

3. Case Study of the Modified Nominal DEP Based on Time Available for Diagnosis

This section presents a case study applying the nominal DEP formula that considers the absence of the STA, as established earlier. The nominal DEP is determined as a function of the time available for diagnosis, with the impact of the STA's absence considered within the 10 to 30-minute range. Since diagnosis starts once the operator recognizes the cue, referred to as cue recognition time, the modified nominal DEP formula is applied to the nominal DEP corresponding to the time available for diagnosis up to 30 minutes after cue recognition. The original K-HRA nominal DEP formula is used to calculate the nominal DEP for the remaining diagnosis time after the STA has returned to his/her duty.

Table 2. Application of Nominal DEP Formula

Cue Recognition Time (CRT) and Time Available for Diagnosis (TAD)	Nominal DEP Application Method	Description
CRT + TAD ≤ 10 min	DEP by K-HRA	Since the diagnosis is completed before 10 minutes, only DEP by K-HRA is used.
CRT ≥ 30 min	DEP by K-HRA	Since the diagnosis occurs entirely after STA has returned, K-HRA DEP is applied
10 min. < (CRT + TAD) ≤ 30 min	modified DEP formula	Since the entire diagnosis occurs within the STA absence period (10-30 min), only the Modified DEP is applied.
CRT ≤ 10 min, but (CRT + TAD) > 10 min	-(10 min - CRT) / TAD: DEP by K-HRA -(30 min - max(10 min, CRT)) /TAD: Modified DEP -(CRT+ TAD - 30 min) / TAD: DEP by K-HRA	-Diagnosis starts before 10 min: DEP by K-HRA -Modified DEP is applied between 10-30 min -If (CRT + TAD) > 30 min, DEP by K-HRA is applied again after 30 minutes.
10 min < CRT < 30 min, but (CRT + TAD) > 30 min	-(30 min - CRT) / TAD: Modified DEP -(CRT + TAD - 30 min) / TAD: DEP by K-HRA	-Since the diagnosis starts after 10 min, Modified DEP is applied -After 30 min, DEP by K-HRA is applied

Table 2 summarizes the nominal DEP application method based on variations in the cue recognition time and the time available for diagnosis. For a given HFE with a cue recognition time of 5 minutes and an available diagnosis time of 45 minutes, the nominal DEP application scheme is the fourth one in Table 2. That is, the nominal DEP calculation for the fire HRA is performed in three parts as follows:

- 0-10 minutes: DEP by K-HRA is applied for (10-5)/45 minutes, as this period occurs before the STA's absence is considered.
- 10-30 minutes: Modified DEP is applied for (30-10)/45 minutes, since the STA is absent during this period.
- 30-50 minutes: DEP by K-HRA is applied for (50-30)/45 minutes, since (cue recognition time + time available for diagnosis) > 30 minutes, DEP by K-HRA is applied again after 30 minutes.

Thus, the nominal DEP calculated by considering the STA's absence is 1.72E-03, whereas the result obtained by applying only the K-HRA formula is 1.50E-03.

4. Conclusions

This study modified the nominal DEP formula to account for the impact of the STA's absence during fire events in NPPs. Additionally, the modified nominal DEP application method was summarized based on cue recognition time and time available for diagnosis. We assumed that since the STA plays a crucial role in managing fire situations, his/her temporary absence affects the cognitive workload and diagnostic performance of MCR operators. The modified DEP formula incorporates this effect by adjusting the DEP during the STA's absence.

The results indicate that the DEP increases when the STA is unavailable, particularly within the first 30 minutes following a fire event. By applying this modified DEP formula, fire HRA can better reflect real-world operational conditions, leading to more accurate fire PSAs.

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