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Modification of K-HRA Method for Fire Human Reliability Analysis

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This study focuses on incorporating fire scenarios into the diagnosis error probability calculation of the existing K-HRA methodology, addressing the impact of the shift technical advisor's absence during fire incidents. Based on operator interviews, it was determined that the shift technical advisor was absent from the main control room for approximately 30 minutes to establish and stabilize the fire brigade. During this period, the joint human error probability doubles between 10 and 30 minutes, as determined by the NUREG/CR-1278 methodology. Accordingly, the nominal diagnosis error probability in K-HRA was adjusted to account for fire-related scenarios. In addition to modifying the nominal diagnosis error probability, the fire human reliability analysis incorporated fire-specific considerations into performance shaping factors. These include the simultaneous use of fire procedures with abnormal/emergency operation procedures, partial or complete human-system interface damage due to cable failures, and insufficient training related to reactor shutdown during fires. This research highlights the integration of fire conditions into the K-HRA framework, particularly addressing the shift technical advisor's absence. Future studies aim to compare the diagnosis error probability derived from the existing K-HRA and Fire human reliability analysis methodologies during the quantification of human failure events, such as operator manual actions. This work contributes to advancing fire-specific reliability assessments for nuclear power plant safety.

Keywords: Fire Human Reliability Analysis, Detailed Analysis, Diagnosis Error Probability, K-HRA Method.

1. Introduction

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

Fire probabilistic safety assessment (PSA) is a methodology used to quantify fire risks in NPPs by evaluating the core damage frequency (CDF) resulting from fire events. In South Korea, fire PSA studies began with the Hanbit NPP in 1992 and have since been applied to operating NPPs across the country. These studies incorporated methodologies and data from TR-1059281 (EPRI 2005), developed by the Electric Power Research Institute (EPRI) in 1995, with necessary modifications for local applications. In parallel, the U.S. Nuclear Regulatory Commission (NRC), in collaboration with EPRI, developed a new fire PSA methodology outlined in NUREG/CR-6850 (EPRI/NRC-RES 2005). Since its introduction, this updated methodology has been adopted by U.S. NPP operators for fire PSA evaluations. We also have conducted research (D. I. Kang et al 2016a, D. I. Kang et al 2016b) to adapt and apply this methodology to domestic NPPs.

According to the definition provided in NUREG-1921 (EPRI/NRC-RES 2012), 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 the fire PSA model. The Korean industry conducted fire HRA studies for all operating NPPs applying the screening analysis proposed in NUREG-1921. For detailed quantification, the Cause-Based Decision Tree Method (CBDTM) methodology suggested by EPRI has been employed.

The Korea Atomic Energy Research Institute (KAERI) adopted the screening and scoping analyses from NUREG-1921 and developed a fire HRA guideline for detailed analysis (S. Y. Choi et al 2019, S. Y. Choi and D. I. Kang 2020). The fire HRA guideline was based on the framework of the K-HRA method and incorporated the fire HRA procedures and assumptions for fire scenarios outlined in NUREG-1921 and two kinds of supplements (EPRI/NRC-RES 2019, EPRI/NRC-RES 2020). The K-HRA (W. Jung et al 2005) is a standard method for HRA of a domestic internal event PSA developed by KAERI and has been updated to the K-HRA Rev.1 (J. Kim et al 2023) to meet the technical requirements set by the Korean regulatory body in 2023.

This paper is to describe the modification of the K-HRA method for fire HRA. This paper specifically addresses the incorporation of fire situations into the diagnosis error probability (DEP) calculation formula of the K-HRA.

2. Diagnosis Error Analysis of the K-HRA Method

This section primarily describes the diagnosis error analysis within the K-HRA procedure. To quantify the human error probability (HEP) of an HFE, the K-HRA divides a task into diagnosis and execution; and then adds both HEPs, DEP and execution error probability (EEP) of an HFE. For HEPs of diagnosis and execution, the effects of performance shaping factors (PSFs) are evaluated and weighted. The analysis of diagnosis errors for the K-HRA involves using the Technique for Human Error Rate Prediction (THERP) time reliability curve (TRC) to determine the nominal DEP and a PSF multiplier decision tree to adjust the base DEP, as illustrated in Figures 1 and 2. The nominal DEP is extracted as the median value from the THERP TRC, while the base DEP represents the conversion of this median value to a mean DEP. The K-HRA defined a formula for the nominal DEP (median value) from the Figure 1 from NUREG/CR-1278 figure 12-4 (A. D. Swain and H. E. Guttmann 1983). In other words, the formula for nominal DEP is expressed as a function of the time available for diagnosis. The base DEP is adjusted by multiplying it with the PSF multiplier derived from the decision tree shown in Figure 2 to calculate the final DEP. These PSF multipliers were established through an expert elicitation process, accounting for various PSF states.

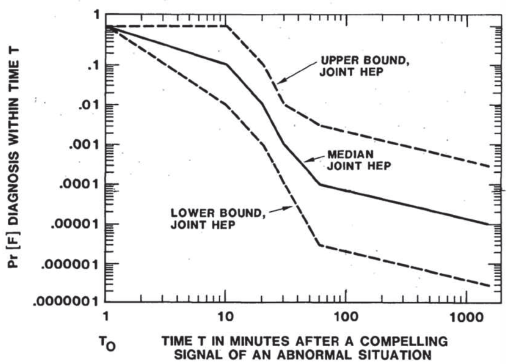

Fig. 1. Nominal Diagnosis Error Probability Curve by THERP (NUREG-1278)

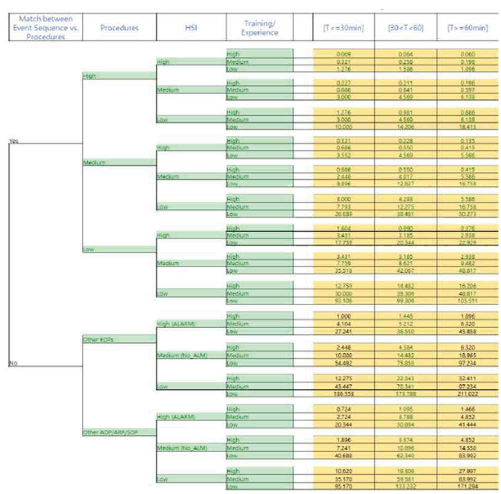

Fig. 2. PSF Multiplier Decision Tree for Adjusting Base DEP

3. Modification of nominal DEP calculation for fire HRA

One of the features of the fire situation is a shift technical advisor (STA)'s absence to arrange a fire brigade based on NUREG-1921. We reflected the feature into a DEP for the fire HRA. We conducted interviews with the plant operators to collect information about the STA's absence during a fire. The interview included four operators: two senior reactor operators (SROs) and two reactor operators (ROs). Their average operational experience was approximately 20 years, with the least experienced operator having 15 years of experience. Based on the interview results, we assumed a total absence time of 30 minutes for the STA, with the details outlined as follows:

- 20 minutes for fire brigade arrangement
- 10 minutes for stabilization upon returning to the MCR

Therefore, the nominal DEP for the 30 minutes, including the absence of the STA during a fire and the stabilization period after returning to the MCR, was adjusted using the nominal DEP curve shown in Figure 1. To achieve this, the methodology for calculating the joint human error probabilities (JHEPs) for diagnosis of MCR operators at 10, 20, and 30 minutes, as described in NUREG/CR-1278 (pp. 12-21), was applied. According to 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 Figure 1 was applied. However, for the DEP between 30 and 60 minutes, an interpolation technique was employed using the modified DEP from the 10 to 30-minute period.

Table 1 summarizes the DEPs calculated from the curve in Figure 1 for the K-HRA and the modified DEPs reflecting the absence of the STA during a fire for the fire HRA. Table 2 presents the DEP calculation formulas established in K-HRA based on Figure 1 and Table 1, along with the modified formulas that account for the absence of the STA during a fire for the fire HRA.

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

Diagnosis Time Margin, 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

Table 2. Nominal DEP (Median) Formulas from K-HRA and fire HRA

Diagnosis Time Margin, T (min.)	DEP Formula of K-HRA	DEP Formula of Fire HRA
1<T<10	10^(-log$_{10}$(T))	10^(-log$_{10}$(T))
10≤ T<20	10^ (-1+((log$_{10}$(T) - log$_{10}$(10)) / (log$_{10}$(20) - log$_{10}$(10))) * (-2 + 1))	10^(-1+((log$_{10}$(T) - log$_{10}$(10)) / (log$_{10}$(20) - log$_{10}$(10))) * (-1.6987+1))
20≤ T<30	10^(-2+((log$_{10}$(T) - log$_{10}$(20)) / (log$_{10}$(30) - log$_{10}$(20))) * (-3+2))	10^(-1.69897 + ((log$_{10}$(T) - log$_{10}$(20)) / (log$_{10}$(30) - log$_{10}$(20))) * (-2.69897+ 1.69897))
30≤ T<60	10^(-3+((log$_{10}$(T) - log$_{10}$(30)) / (log$_{10}$(60) - log$_{10}$ (30))) * (-4+3))	10^(-2.69897 + ((log$_{10}$(T) - log$_{10}$(30)) / (log$_{10}$(60) - log$_{10}$(30))) * (-4+2.69897))
60≤T	10^(-4+((log$_{10}$(T) - log$_{10}$60)) / (log$_{10}$(1500) - log$_{10}$(60))) * (-5+4))	10^(-4+((log$_{10}$ (T)- log$_{10}$(60)) / (log$_{10}$(1500) - log$_{10}$(60))) * (-5+4))

Figure 3 shows a nominal DEP (median) graph obtained from the two types of DEP formulas described in Table 2.

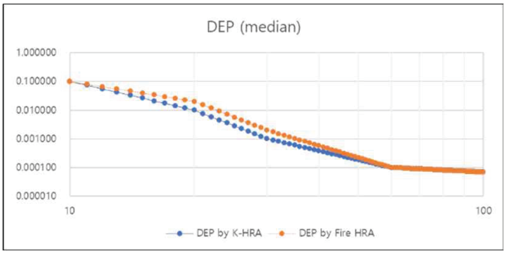

Fig. 3. Nominal DEP(Median) by K-HRA and Fire HRA

Table 1 summarizes the DEPs calculated from the curve in Figure 1 for the K-HRA and the modified DEPs reflecting the absence of the STA during a fire for the fire HRA. Table 2 presents the DEP calculation formulas established in K-HRA based on Figure 1 and Table 1, along with the modified formulas that account for the absence of the STA during a fire for the fire HRA.

4. Application of the Modified DEP

This section outlines the procedure for applying the nominal DEP formula that incorporates the STA's absence during a fire, as defined in Section 3. As previously explained, the nominal DEP is a function of the time available for diagnosis, and the impact of the STA's absence is applied between 10 and 30 minutes. Since diagnosis begins after the operator recognizes the cue, i.e., the cue recognition time, the modified DEP formula is applied to the nominal DEP corresponding to the time available for diagnosis up to 30 minutes after the cue recognition time. The original K-HRA formula is used for the remaining time available for diagnosis.

For example, suppose the cue recognition time is 10 minutes and the time available for diagnosis is 35 minutes. In that case, the formula in the row for (30≤T<60) from Table 2 is applied based on the time available for diagnosis, T. During the assumed 30-minute absence of the STA, the actual absence portion after cue recognition (10 minutes) is 20 minutes. Therefore, the modified formula is applied to the portion (20/35) corresponding to this 20-minute interval of the time available for diagnosis. For the remaining 15 minutes, the DEP formula from K-HRA is applied to the corresponding portion (15/35). Therefore, the nominal DEP (median) based on the above explanation is as follows:

$$\left(\frac{20}{35}\right) 10^{-2.69897 + \left(\frac{\log_{10} 35 - \log_{10} 30}{\log_{10} 60 - \log_{10} 30}\right)(-4+2.69897)} \times$$
$$\left(\frac{15}{35}\right) 10^{-3+\left(\frac{\log_{10} 35 - \log_{10} 30}{\log_{10} 60 - \log_{10} 30}\right)(-4+3)} = 8.44\text{E-}04$$

On the other hand, if the STA's absence is not considered and the nominal DEP formula by the K-HRA is applied, the following nominal DEP is derived:

$$10^{-3+\left(\frac{\log_{10} 35 - \log_{10} 30}{\log_{10} 60 - \log_{10} 30}\right)(-4+3)} = 5.99\text{E-}04$$

The nominal DEP derived by incorporating fire scenarios was found to be 1.4 times higher than the value obtained using the existing K-HRA method.

5. Conclusions

This paper addresses the incorporation of fire situations into the DEP calculation formula of the existing K-HRA method based on the assumption by NUREG-1921. In the event of a fire, the STA is required to leave the MCR and establish the fire brigade. Based on operator interviews, it was determined that it takes 30 minutes for the STA's absence to fully stabilize after returning to the MCR. Applying the JHEP calculation methodology for MCR operators outlined in NUREG/CR-1278, it was concluded that the JHEP is conservatively doubled during the 10 to 30-minute period after the STA leaves the MCR. Accordingly, the nominal DEP calculation formula in K-HRA was modified and applied for the fire HRA.

In addition, within the scope of fire HRA, the final DEP was derived by incorporating fire scenarios not only into the modified nominal DEP but also into the PSF described in Figure 2:

- Procedure: reflects the simultaneous use of fire procedures and abnormal operation procedure (AOP)/emergency operation

procedure (EOP), depending on the scenarios arising from the fire
- Human-System Interface (HSI): accounts for partial or complete damage to the HSI in the MCR due to cable damage caused by the fire
- Training/Education: considers insufficient training related to reactor shutdown under fire conditions

This paper is significant in addressing the challenges and solutions related to incorporating the absence of the STA during a fire into the existing the K-HRA methodology. As part of future plans, we aim to compare the DEP values derived from the existing K-HRA methodology with those obtained through the Fire HRA methodology during the quantification process of HFEs such as operator manual actions (OMAs), which is currently underway.

Acknowledgement

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