Improvements on Fire Human Reliability Analysis Procedure for Korean Nuclear Power Plants through Case Study

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1. Introduction

Many researches for a fire risk quantification in nuclear power plants (NPPs) have been performed since it was recognized that the fire hazard was a major challenge to safe operation of NPPs. Under a joint research between the U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI), NUREG/CR-6850 was developed to conduct of a fire probabilistic safety assessment (PSA) [1]. For a fire human reliability analysis (HRA) to support a fire PSA proposed by NUREG/CR-6850, NUREG-1921 was developed [2].

Based on the NUREG-1921, a fire HRA guideline for a fire PSA of full power operation of domestic NPPs was developed in 2018 by the Korea Atomic Energy Research Institute (KAERI) [3]. One of the major characteristics of the fire HRA developed by KAERI is that it uses the K-HRA method for a detailed quantification of a human error probability (HEP). The K-HRA is a standard method for HRA of a domestic internal event PSA developed by KAERI [4]. We made efforts to modify performance shaping factors (PSFs) of K-HRA to reflect fire situation and effects.

With the fire HRA procedure, we performed a case study on HEP quantification for a fire PSA of a domestic NPP [5]. With the existing fire PSA model for a domestic NPP, we derived several human failure events (HFEs) by a screening analysis first and then performed a detailed quantification analysis. In the process of the case study, through an interview with two main control room (MCR) operators of a reference plant (currently a shift supervisor and a shift technical advisor) and a review by three HRA experts from nuclear industry, we derived additional assumptions for a fire HRA to describe a fire situation and made some improvements on the fire HRA procedure. We reflected those improvements and assumptions into the fire HRA procedure. From the case study using the revised fire HRA procedure, we derived more realistic HEP reflecting a fire situation [6].

The purpose of this paper is to introduce some revised items of the fire HRA procedure we developed based on experience of the case study and to show an example of the case study using the revised fire HRA procedure.

2. Modifications to the fire HRA Procedure

As mentioned above, we performed a case study for a HEP quantification with the fire HRA procedure. During the case study, we identified that some modifications were required. It was probably thought that some of those things came from the gap between theory and practice.

2.1. Types of HFE

We defined four types of HFE for a fire HRA based on NUREG-1921, while NUREG-1921 classified HFEs into three categories. That is, we subdivided the HFEs from fire response action including main control room abandonment (MCRA) action into two types for application to domestic NPPs: HFEs from fire response action and HFEs from MCRA action.

However, we realized that it was inconvenient to perform a screening analysis with the defined HFE types. The reason is that the HFE definitions should be considered again to meet the set definition for the screening analysis. We subdivided Type 1 HFE into three kinds of HFEs since the Type 1 HFE (HFEs from the existing internal event PSA) was classified into three types of subcategories in the screening analysis. Table 1 shows the modified HFE types and a relation to the relevant 'set' for a screening analysis to be well matched with the modified HFE type.

Table 1. Modified HFE types and Related Set Type for Screening Analysis

HFE Type	Definition	Set Type for Screening Analysis
Type 1	HFEs from the existing internal event PSA	
Type 1-1	HFEs similar to internal event HFE	Set 1
Type 1-2	HFEs from the existing internal event HFE but with spurious equipment or instrumentation effects in one safety-related train	Set 2
Type 1-3	HFEs from the existing internal event HFEs needing to be significantly modified as a result of fire conditions	Set 3
Type 2	HFEs from fire response action	Set 3
Type 3	HFEs from MCRA action	Set 3
Type 4	HFEs from undesired operator responses to spurious instruments and alarms	Set 4

2.2. Basic HEP for Diagnosis

For a fire HRA, one of major considerations to reflect a fire condition is an absence of STA (Shift Technical Advisor) to command a fire brigade at a fire area. The absence time should be reflected for a HEP (Human Error Probability) quantification. We considered the absence of STA in the 'cue perceived time' and 'Basic HEP for diagnosis' in K-HRA. For an STA's unique task, a time to recognize the related cue was expected to be delayed due to the absence of STA. It was reflected in the 'cue perceived time'. Meanwhile, the absence of the STA caused a decrease in the number of operators in the MCR. This was considered to affect the quality of a diagnosis after the cue recognition and this situation was reflected in the 'Basic HEP for diagnosis', which evaluates a diagnosis HEP according to an allowed time for diagnosis using a diagnosis error probability function provided by THERP [7]. To reflect the possibility of lower quality of diagnosis due to the reduced number of operators in an MCR, we modified the formula for the diagnosis error probability. However, in applying the developed formula, a misinterpretation was recognized in determining the duration of application and was corrected this time.

In this paper, we modified the period to which the developed formula is to applied for estimation of a diagnostic HEP. Basically, the maximum of STA's absence was considered to 30 minutes. In other words, it was assumed that after the 30 minutes, the STA could perform his/her own tasks normally in an MCR. Therefore, the possibility of lower quality of diagnosis should be taken into account for the percentage of STA's absent time (maximum 30 minutes) during an allowed time for a diagnosis.

For example, in case that a STA's absence time equals 20 minutes and an allowed time for diagnosis is 50 minutes, a diagnosis HEP can be calculated by as follows:

Basic Diagnosis HEP = (20/50) * (modified formula by a fire HRA procedure) + (30/50) * (existing formula by K-HRA)

2.3. Additional Assumption for PSF Level Selection

For a case study, we had interviews with MCR operators with extensive operational experience of a reference plant to understand the characteristics of operator behaviors in case of a fire inside and outside the MCR. Based on the interviews, the following additional assumptions were made to determine the PSF level:

<u>Delayed 'cue perceived time' due to partly damaged instruments</u>

We already assumed that if the integrity of all instruments related to a HFE was not verified through the fire scenario analysis, the instruments were partly damaged in the event of a fire. To reflect the partly damaged instruments, just a lower 'man machine interface (MMI)' level than that of in a normal situation was considered in the fire HRA procedure. But, an additional time also should be required to recognize the specific situation related to a HFE due to the partly damaged instruments. Therefore, two minutes are added additionally for all HFE's 'cue perceived time' in the event of a fire except for a station blackout (SBO) case. In case of an SBO, operators can catch the situation regardless of the instruments' partly damage.

<u>Delayed 'cue perceived time' due to a fire inside an MCR</u>

The operators interviewed insisted that recognizing a cue in case of a fire inside MCR should be differentiated from that in case of a fire outside the MCR. The reason is that a fire inside a MCR can make the operators more confused. Therefore, we assumed additional three minutes for the 'cue received time' in case of a fire inside an MCR.

3. Example of a Case Study based on the improved fire HRA Procedure

In this paper, an example of the case study we performed was introduced. We first conducted a screening analysis with a fire PSA model for a reference plant using the screening analysis criteria we developed. As a result, six HFEs among 91 HFEs for the fire PSA model were not screened out. We conducted detailed quantification analysis for those six HFEs using K-HRA method which was modified to reflect a fire situation.

Table 2 shows the detailed quantification analysis for a 'SDOPHEARLY' which is the HFE for a failure of early feed and bleed operation. We compared three kinds of HFEs, which are the HFE similar to internal event HFE, the HFE from the case of a fire outside MCR, and the HFE from the case of a fire inside MCR [6].

Table 2. Example of Case study for Detailed Quantification Analysis

Group	PSF	HFE		
		SDOPH EARLY (internal event)	SDOPH EARLY (fire)	SDOPH EARLY-MCR (fire)
Basic DEP[1)]	Task allowable time	53 min.	53 min.	53 min.
	Cue occurrence Time	10 min.	10 min.	10 min.
	Cue perceived time	11 min. (1 minutes after cue occurrence)	13 min. (extra 2 minutes in addition to cue	16 min. (extra 5 minutes in addition to cue

			perceived time of internal event HRA)	perceived time of internal event HRA)
	Execution time	3 min.	3 min.	3 min.
	Time for wearing SCBA[2)]	N/A	N/A	5 min.
	Diagnosis available time	39 min. (53-11-3)	37 min. (53-13-3)	29 min. (53-16-3)
	Basic DEP	5.62E-03	8.17E-03	1.84E-02
PSF	MMI quality for diagnosis	High	Medium	Medium
	Training/ Education level	Medium	Medium	Low
	Procedure quality for diagnosis	High	High s	Medium
DEP		1.85E-03	5.39E-03	1.84E-01
PSF	MMI quality for feedback	High	Medium	Medium
EEP[3)]		2.00E-02	4.00E-02	4.00E-02
Total HEP		2.19E-02	4.54E-02	2.24E-1

1) DEP: Diagnosis Error Probability
2) SCBA: Self-Contained Breathing Apparatus
3) EEP: Execution Error Probability

In case of the second HFE considering a fire outside an MCR, the HEP was obtained about two times more than the result of detailed analysis derived from the internal event PSA by considering a lower level of MMI and a delayed cue recognition time due to partly damaged instruments. Meanwhile, in case of the third HFE for a fire inside the MCR, the HEP was obtained about five times more than the result of the case of a fire outside the MCR by considering a SCBA wearing time and additionally delayed cue recognition time.

4. Conclusions

The purpose of this paper is to introduce some revised items of the fire HRA procedure we developed based on experience of the case study and to show an example of the case study with the revised fire HRA procedure. We derived some improvements of the fire HRA procedure and additional assumptions to reflect a fire situation for a fire HRA based on the interview with MCR operators of the reference plant and the review of case study process by HRA experts.

- Subdivision of Type 1 HFE into three kinds of HFEs for a consistency with subcategories of a screening analysis
- Correcting errors related to application of proposed formula for 'basic diagnosis HEP'
- Additional delay time for 'cue perceived time' due to a fire inside an MCR by considering more confused situation of operators

With the revised fire HRA procedure, it is expected to achieve more realistic results those well reflect a fire situation.

In the case study, HFEs related to an MCRA were screened out during the screening analysis, even though a strategy was established in the fire HRA procedure. A scoping analysis was chosen as the detailed quantification method for HFEs related to MCRA since there was no appropriate methodology for a HEP quantification of the MCRA HFEs when we developed the fire HRA procedure. Recently, two kinds of reports about quantification analysis for HFEs related to MCRA were published [8-9] and also revised report about qualitative analysis for those HFEs was published by NRC and EPRI [10]. Those reports provided a guidance on how to develop the HEP for the HFE that represents the decision to abandon an MCR following a fire-induced scenario. The current HRA methods did not adequately address the operators' reluctance to abandon the MCR. We also did not consider the operators' reluctance. However, reluctance was considered to be an important factor for many NPPs. To apply the method by the research to domestic NPPs, we are to establish an HEP quantification method of HFEs related to MCRA considering the impact of the reluctance.

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