Understanding Methodological Differences in Human Reliability Analysis

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Abstract: Human Reliability Analysis (HRA) is an important component of Probabilistic Safety Assessment (PSA) used to estimate Human Error Probability (HEP) in nuclear power plants. Various HRA methodologies have been developed, but differences in their theoretical backgrounds and quantification procedures can produce different HEP results for the same scenario. This study compares IDHEAS-ECA and K-HRA methodologies for full-power internal event PSA of NPP for the FRAMATOME-design 3-loop pressurized water reactor(PWR). The comparison results showed that HEP estimates vary depending on task complexity and the characteristics of each methodology. For example, the HEP estimated by the IDHEAS-ECA methodology increased as task complexity or operator workload increased. These findings provide useful insights for selecting appropriate HRA methodologies and improving the reliability of PSA results.

1. INTRODUCTION

Human Reliability Analysis (HRA) is a probabilistic approach used to estimate human reliability that operators may fail to successfully perform assigned tasks under specific system conditions. HRA estimates Human Error Probability (HEP) by considering various factors that influence human performance, such as operational environment, task stressor, and conditions [1]. In Probabilistic Safety Assessment (PSA) for nuclear power plants, HRA is recognized as a key element because human actions play an important role in both accident prevention and mitigation. By systematically evaluating operator actions during abnormal and accident conditions, HRA can significantly affect PSA results and contribute to improving the overall safety and reliability of nuclear power plants.

Various HRA methodologies have been developed, including THERP, ASEP HRA, K-HRA and IDHEAS-ECA. Although numerous HRA methodologies have been developed, differences in analysis results have often occurred depending on the analyst because of the detailed procedures, levels of analysis, analysis criteria [2]. In Korea, K-HRA, a standardized HRA methodology developed by the Korea Atomic Energy Research Institute (KAERI) based on the THERP and ASEP methods [2], has been widely applied to Korean nuclear power plants. Meanwhile, various HRA methodologies have been developed and utilized worldwide such as IDHEAS-ECA. IDHEAS-ECA is an HRA methodology developed by the U.S. Nuclear Regulatory Commission (NRC) to support risk-informed decision-making. It provides a structured framework for analyzing human events and quantifying HEPs for use in Probabilistic Risk Assessment (PRA). Building upon IDHEAS-G (NUREG-2198), the methodology was developed to enhance the applicability of HRA to a broader range of operational scenarios beyond the scope of conventional HRA methods while addressing NRC regulatory needs [3].

The uncertainty of HRA results may be caused by several factors, including (1) insufficient human error data, (2) limited understanding of human error mechanisms, (3) the lack of standardized analysis methods and procedures, and (4) subjective evaluations by analysts [4, 5]. In this regard, relying on a single HRA methodology may have limitations, so the use of additional methodologies may facilitate cross-verification of HRA results.

The purpose of this study is to quantitatively compare various HRA methodologies, including recently developed methods, and to provide insights into the potential benefits of applying multiple methodologies for cross-verification of HRA results. Since HRA results can vary significantly depending on the methodology used, applying the same K-HRA methodology adopted in utility PSA models to regulatory verification may reduce the independence of the regulatory review process.

For the comparison, HRA analyses were performed for full-power internal events of a Korean NPP for the FRAMATOME-design 3-loop pressurized water reactor(PWR) using both the IDHEAS-ECA and K-HRA methodologies, and the results of the two methods were compared. Several NPPs designs, including OPR1000, APR1400, and Framatome designed plants, are operated in Korea. While comparative studies of HRA methodologies have been conducted for the OPR1000 and APR1400 designs, so the Framatome-design reactor was selected as the representative plant for this study [6].

2. METHOD

In this study, two HRA methodologies, K-HRA and IDHEAS-ECA, were selected for performing the HRA analysis. K-HRA has been widely applied to Korean nuclear power plants. IDHEAS-ECA , developed by the U.S. NRC, incorporates knowledge from advanced cognitive models and has a broad range of applicability. In particular, the methodology can be applied to human reliability analysis for human error events involving portable equipment. In addition, IDHEAS-ECA provides systematic guidance for detailed scenario analysis, task analysis, and documentation procedures, which helps reduce the variability of HRA results among analysts. For these reasons, K-HRA and IDHEAS-ECA were selected as the methodology for human reliability analysis in this study.

2.1. K-HRA

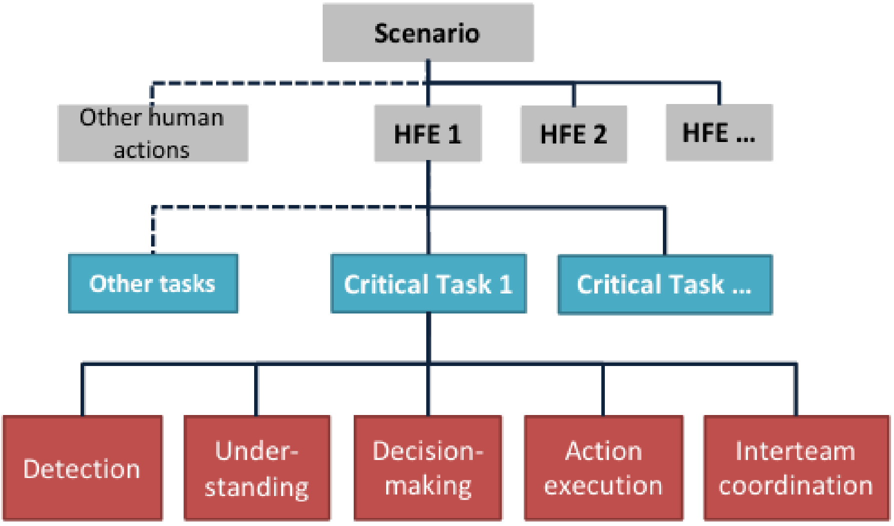
K-HRA is an HRA methodology developed by the Korea Atomic Energy Research Institute (KAERI) to improve consistency among PSA organizations and HRA analysts in Korea. It has been adopted as the standard HRA methodology for Korean NPP PSAs. The method is primarily based on the SRO (Stimulus, Organism, Response) model and provides simplified guidelines for human failure event (HFE) identification and screening analysis.

K-HRA classifies human errors into diagnosis errors and execution errors and estimates HEP by considering factors such as available time, task characteristics, performance shaping factors (PSFs), and error recovery probability. In K-HRA, the available time is determined using the time window, cue time, and execution time, and is used to estimate diagnosis error and recovery failure probabilities. The diagnosis error probability is calculated using the THERP time reliability curve in combination with PSFs. For execution errors, critical actions are identified, and the failure probability of each action is evaluated considering task type, stress level, PSFs, and recovery probability. The overall execution error probability is obtained by combining the failure probabilities of all critical actions. Finally, the diagnosis and execution error probabilities are integrated to derive the overall HEP.

2.2. IDHEAS-ECA

IDHEAS-ECA is a recently developed HRA methodology introduced by the U.S. NRC to support risk-informed decision-making and to improve the consistency of HRA results. Unlike traditional HRA methods, IDHEAS-ECA incorporates advanced cognitive models based on the NUREG-2114 cognitive framework, including Cognitive Basis Structures (CBS) and Performance Influencing Factors (PIFs). The methodology focuses on identifying cognitive failure mechanisms (CFMs) associated with operator behavior and evaluates how these mechanisms contribute to human error under specific scenarios. In addition, IDHEAS-ECA provides systematic guidance for scenario analysis, task analysis, and documentation procedures, which helps reduce variability among analysts and improves traceability of the analysis process. The method also explicitly considers uncertainties related to the time available and the time required for operator actions, enabling a more comprehensive evaluation of human performance in complex operational environments.
The hierarchy of IDHEAS-ECA for modeling a human event is as follows:

Figure 1: IDHEAS-ECA Hierarchy for Modeling a Human Event[7]



2.3. Comparison of K-HRA and IDHEAS-ECA

This study performed quantitative comparisons between IDHEAS-ECA and K-HRA. From a theoretical perspective, IDHEAS-ECA is based on the cognitive model presented in NUREG-2114 and utilizes CBSs and PIFs. In contrast, K-HRA is based on the relatively simple SRO model. These differences influence how human performance and human errors are modeled.

The two methodologies also differ in their error classification schemes. IDHEAS-ECA classifies human failures into cognitive failures associated with CFMs and failures caused by time uncertainty, whereas K-HRA categorizes errors into diagnosis errors and execution errors. In addition, IDHEAS-ECA identifies critical tasks that determine HFE success or failure, while K-HRA identifies critical actions during execution error analysis.

Differences are also observed in the HEP quantification process. IDHEAS-ECA calculates cognitive failure probabilities by summing the failure probabilities of CFMs obtained by applying PIF weights to base HEP values. Failure probabilities caused by time uncertainty are estimated using probabilistic distributions. In this study, available time was assumed to follow a point distribution and required time was assumed to follow a lognormal distribution.

$$P_t = 1 - \emptyset\left[\frac{\ln\left(T_{avail}/T_{req}\right)}{\sigma}\right] \tag{1}$$

A standard deviation value of 0.3403 derived from the HuREX database was applied. In contrast, K-HRA estimates execution error probabilities by considering task type, stress level, and recovery potential, while diagnosis error probabilities are calculated by applying PSF multipliers to base HEP values derived from the THERP time reliability curve.

For the quantitative comparison, 26 post-initiator HFEs from the full-power internal event PSA of NPP for the FRAMATOME-design 3-loop pressurized water reactor(PWR) were analyzed using both methodologies. In the IDHEAS-ECA application, actions performed by the same operator at the same location on a single system under a consistent objective were defined as one critical task. CFMs and PIF levels were determined according to the criteria provided by IDHEAS-ECA.

3. RESULTS

A quantitative comparison was performed between the K-HRA and IDHEAS-ECA methodologies using the same HFE scenarios of NPP for the FRAMATOME-design 3-loop pressurized water reactor(PWR). Although the detailed tendencies varied for each HFE, several overall trends were identified.

For HFEs with relatively low failure probabilities, IDHEAS-ECA generally produced lower HEP estimates than K-HRA. In contrast, for HFEs with relatively high failure probabilities and greater task complexity, IDHEAS-ECA produced similar or higher HEP estimates compared with K-HRA.

These differences are considered to result from the methodological characteristics of IDHEAS-ECA, which evaluates multiple CFMs for each critical task. As task complexity increases, a larger number of CFMs can be applied, leading to increased cognitive failure probabilities and consequently higher overall HEP estimates. Therefore, the identification of appropriate CFMs and the assignment of suitable PIFs are important aspects of IDHEAS-ECA methodology.

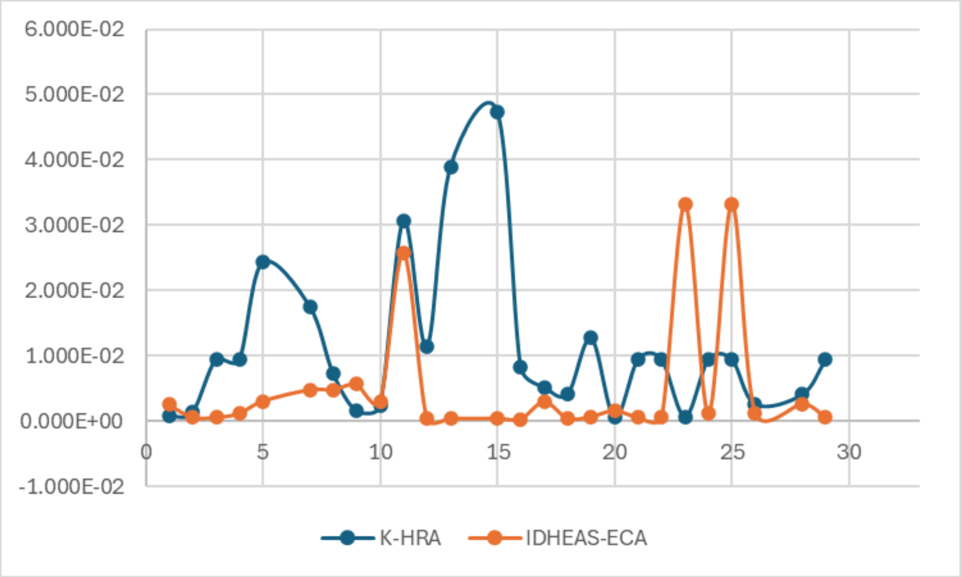
The comparison results indicate that HEP estimation is significantly influenced by the applied HRA methodology and task complexity. These findings demonstrate that methodological differences in cognitive modeling, error classification, and quantification procedures can lead to different PSA results even when analyzing the same HFE scenarios.

Table 1: Comparison between HEP of K-HRA and IDHEAS-ECA

HFE No.	Description	Method 1 K-HRA	Method 2 IDHEAS-ECA
1	Operator Fails to Makeup ASG TK 001BA or Connect JPD for ASG Water Source	7.780E-04	2.490E-03
2	Operator Fails to Start ASG PP 001/002/003PO	1.320E-03	5.630E-04
3	Operator Fails to Initiate EAS Actuation Signal	9.410E-03	5.400E-04
4	Operator Fails to Operate EAS Recirculation	9.410E-03	1.160E-03
5	Operator Fails to Initiate Aggressive Cooldown during SGTR	2.430E-02	3.040E-03
6	Operator Fails to Perform Bleed Operation(SLOCA)	1.760E-02	4.800E-03
7	Operator Fails to Perform Bleed Operation	7.300E-03	4.800E-03
8	Operator Fails to Perform Cooldown Operation for RRA Operation (SGTR)	1.540E-03	5.640E-03
9	Operator Fails to Perform Cooldown Operation for RRA Operation (SLOCA)	2.350E-03	3.040E-03
10	Operator Fails to Perform Feed and Bleed Operation	3.070E-02	2.580E-02
11	Operator Error to Isolate Affected SG, 001GV	1.140E-02	4.000E-04
12	Operator Fails to Isolation Faulted SG before Overfill	3.890E-02	4.000E-04
13	Operator fails to transfer LXX Power Supply from Normal to Alternate Source (1HR)	4.740E-02	3.830E-04
14	Operator fails to transfer LXX Power Supply from Normal to Alternate Source (2HR)	8.200E-03	3.200E-04
15	Operator Fails to Refill RWST	5.230E-03	2.950E-03
16	Operator Fails to Initiate Emergency Boration	4.130E-03	4.000E-04
17	Operator Fails to RCP Seal Injection from PTR 001BA	1.270E-02	6.700E-04
18	Operator Fails to Perform Hot Leg Recirculation	5.470E-04	1.600E-03
19	Operator Fails to Operate RIS Recirculation	9.410E-03	5.400E-04
20	Operator Fails to Operate RIS Injection	9.410E-03	5.400E-04

21	Operator Fails to Trip Reactor via Reactor Trip Switchgear or MG Sets	6.680E-04	3.330E-02
22	Operator Fails to Generate MSIS Manually	9.410E-03	1.160E-03
23	Operator Fails to Reactor Trip	9.410E-03	3.330E-02
24	Operator Fails to Perform RRA System Operation	2.530E-03	1.200E-03
25	Operator Fails to Operate Standby DEG Chiller and Pumps	4.070E-03	2.660E-03
26	Operator Fails to Initiate EAS Actuation Signal	9.410E-03	5.400E-04

Figure 2: HFE Comparison between K-HRA and IDHEAS-ECA for FRAMATOME NPP



HFE No.21 and 23 were evaluated significantly higher by IDHEAS-ECA compared to K-HRA. These HFE were associated with a reactor trip scenario, which involves considerable operator burden and decision-making pressure. In such situations, operators may hesitate or experience increased psychological stress because an incorrect manual action could unnecessarily initiate a reactor trip and result in significant economic losses and operational impacts on the plant.

Due to these characteristics, IDHEAS-ECA reflected higher PIF weights related to psychological stress, task difficulty, and operator decision-making burden. In addition, the methodology considers detailed cognitive processes and potential CFMs associated with operator actions under stressful conditions. As a result, the corresponding HEP estimated by IDHEAS-ECA was evaluated significantly higher than that obtained from K-HRA.

This result indicates that IDHEAS-ECA is more sensitive to cognitive and psychological factors affecting operator performance, particularly in complex or high-pressure operational scenarios.

4. CONCLUSION

This study compares the IDHEAS-ECA and K-HRA methodologies in order to support the selection of appropriate HRA methods for PSA applications. The results indicate that HEP estimates vary depending on the applied HRA methodology and are influenced by task complexity.

In IDHEAS-ECA, HEP values tend to increase when multiple CFMs are identified and applied to a critical task, or when a large number of PIFs are assigned to the corresponding CFMs. Unlike K-HRA, which mainly evaluates human error based on predefined error categories and time-related considerations, IDHEAS-ECA evaluates operator performance by considering detailed cognitive processes associated with each critical task. As a result, more CFMs are generally applied as the HFE becomes more complex, difficult, and cognitively demanding. Consequently, complex HFEs are often evaluated with higher HEP values in IDHEAS-ECA compared to K-HRA.

On the other hand, when a critical task is relatively simple, proceduralized, or requires only limited cognitive processing, fewer CFMs are applied in IDHEAS-ECA. In such cases, the HEP estimated by IDHEAS-ECA tends to be lower than that estimated by K-HRA. This tendency indicates that IDHEAS-ECA is more sensitive to task complexity and cognitive characteristics than conventional HRA methodologies.

From this perspective, IDHEAS-ECA has the advantage of enabling a more systematic and detailed evaluation of critical tasks by explicitly considering cognitive failure mechanisms and performance influencing factors. In particular, the methodology provides structured procedures for scenario analysis, task analysis, and documentation, which can improve the traceability and consistency of HRA results.

However, despite these advantages, limitations still remain in the application of IDHEAS-ECA. The identification and selection of CFMs and the assignment of PIFs to a given critical task may still vary depending on the experience, interpretation, and judgment of the HRA analyst. Therefore, analyst dependency cannot be completely eliminated, and differences in analyst interpretation may still lead to variability in HRA results. For this reason, the appropriate application and review of CFMs and PIFs are considered important factors in improving the reliability and consistency of IDHEAS-ECA analyses. Furthermore, additional comparative studies covering a wider range of scenarios are warranted to further investigate the differences in HEP estimates between K-HRA and IDHEAS-ECA. Particular attention should be given to identifying the conditions under which the two methodologies produce divergent results and to determining the relative impact of factors such as task complexity, available time, and operator workload on the observed differences.

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