Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira, Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p26209-cd

Development of EMBRACE-Support Software: An Integrated System for Empirical Human Reliability Analysis in Digital Nuclear Control Rooms

Yochan Kim

Risk Assessment Research Division, Korea Atomic Energy Research Institute, Daejeon, Republic of Korea.
E-mail: yochankim@kaeri.re.kr

Young-suh Kim

Digital Development, FNC Technology Co., LTD., Republic of Korea.
E-mail: dudtj0512@fnctech.com

Jaewhan Kim

Risk Assessment Research Division, Korea Atomic Energy Research Institute, Daejeon, Republic of Korea.
E-mail: jhkim4@kaeri.re.kr

The increasing digitalization of nuclear power plant control rooms and the diversification of human–machine interfaces have created pressing needs for human reliability analysis (HRA) methods based on plant-specific data. The EMBRACE (Empirical data-Based crew Reliability Assessment and Cognitive Error analysis) method integrates empirical HuREX (Human Reliability data Extraction) database measurements with structured modeling of human failure events. While the method has been theoretically validated, its practical implementation in risk assessment workflows remains limited by the absence of a dedicated software system. This paper presents the development of EMBRACE-Support Software (ESS), a dedicated computational system that operationalizes the EMBRACE method for digitalized environments. ESS features a modular architecture that interconnects heterogeneous databases—including those for procedure structures, primitive error probabilities, and time distributions—to automate the quantification process. The software also provides interactive visualization capabilities by generating procedure flowcharts and timeline graphs that allow analysts to intuitively decompose tasks and compare the time available and the time required. Through a systematic linking of these databases with the user interface, ESS automates the complex computational logic for both failure probability of timely performance (FPtp) and failure probability due to cognitive error in procedural tasks (FPce). At present, the software is currently undergoing verification through pilot user tests. Preliminary results indicate significant improvements in reproducibility, traceability, and computing efficiency compared to manual EMBRACE calculations. Ongoing development efforts are also being directed toward automating the documentation of both the analysis workflow and its results, aiming to improve the usability and efficiency of HRA application.

Keywords: EMpirical data-Based crew Reliability Assessment and Cognitive Error analysis (EMBRACE), Human error probability, Human reliability analysis, Support software, Probabilistic risk assessment.

1. Introduction

The modernization of nuclear power plants (NPPs) has driven a significant transition in main control rooms (MCRs) from analog and hard-wired interfaces to fully digitalized systems (Porthin et al. 2020; Boring et al. 2019). The APR1400 plant, for example, utilizes computer-based procedures (CBPs) as well as workstation-based displays and soft-control interfaces, fundamentally altering the cognitive and physical tasks of operators (Kim et al. 2014; Bye 2023). While these digital environments offer enhanced information processing capabilities, they also introduce new types of human error modes related to interface management, screen navigation, and complex decision-making sequences that were not prevalent in conventional analog control rooms (Park and Jung 2015; O'Hara et al. 1992). In light of these technological changes, it is essential to note that traditional human reliability analysis (HRA) methods, such as THERP

(Technique for Human Error Rate Prediction), ASEP (Accident Sequence Evaluation Program), and CBDT (Cause-Based Decision Tree), rely heavily on data and task classifications derived from analog environments (Swain and Guttmann 1983; Swain 1987; EPRI 1992). These first-generation methods often depend on expert judgment or outdated military data for probability estimation, leading to high uncertainty in analysis results. Moreover, these methods fall short in explicitly capturing the cognitive errors embedded within the dynamic progression of procedural tasks, such as errors in transitioning between procedures (Liao et al. 2019).

To address these limitations, the Korea Atomic Energy Research Institute (KAERI) has developed EMBRACE (EMpirical data-Based crew Reliability Assessment and Cognitive Error analysis) (Kim et al. 2025; Vechgama et al. 2025; Kim and Kim 2026). This method decomposes operator actions into “primitive tasks” (PTs) based on the specific syntax of emergency operating procedures (EOPs) and estimates human error probabilities (HEPs) using empirical data collected from full-scope simulators (i.e., the HuREX—Human Reliability data EXtraction—database) (Jung et al. 2020; Kim 2022). By utilizing observed data rather than subjective judgment, EMBRACE aims to provide a more objective and realistic assessment of human reliability in digital environments.

However, the practical application of EMBRACE poses significant challenges. The method requires a detailed decomposition of procedural steps into PTs, application of various performance shaping factors (PSFs), and calculation of recovery failure probabilities (RFPs). To calculate time-related probabilities involving multiple cues, the method also employs a complicated algorithm for determining the reference cue time. Performing these calculations manually is not only time-consuming but also prone to calculation errors, making it difficult to ensure consistency across different analysts.

Consequently, there is a critical need for an automated support tool that can systematically implement the EMBRACE logic. This paper presents the development of EMBRACE-Support Software (ESS), an integrated system designed for efficient and accurate application of the EMBRACE method. The software automates the linkage between procedural instructions and PTs, visualizes procedure flows, and performs real-time probabilistic calculations based on the HuREX database (DB).

The remainder of this paper is organized as follows. Section 2 outlines the theoretical framework of the EMBRACE method, including the concepts behind its probability models for time-based failure and cognitive errors. Section 3 details the architecture and core workflows of the developed software, specifically focusing on the logic for scenario definition, timeline modeling, task analysis, and probability calculation. Section 4 explains the user interface layout through a case study of a specific human failure event (HFE) in a digital MCR. Finally, Section 5 concludes the paper with a summary of the contributions and future research directions.

2. EMBRACE Method

The EMBRACE method quantifies HFEs by summing two distinct failure probabilities: failure probability of timely performance (FPtp), and failure probability due to cognitive error in procedural tasks (FPce) (Kim et al. 2026).

2.1. *Failure probability of timely performance (FPtp)*

The FPtp variable quantifies the risk of the operating crew failing to complete the required actions within the system’s safety time limits. This probability is determined through a probabilistic comparison between the time available (Ta) and the time required (Tr). Ta is defined as the temporal success criterion allowed by the system from the reference cue time, which accounts for the time when the cue is initially presented. The temporal success criterion is usually derived from the system’s thermal-hydraulic response or expert judgment. Tr represents the actual time needed for the crew to perform the task. It is modeled as the sum of the durations for the procedure-following activities and the execution times for the physical actions. Because there are cases where operators should wait for the presentation of instrumentation cues to check the procedural conditions, the time for the instrumentation cues is also an important input for Tr estimation.

In the EMBRACE method, Tr has a probabilistic distribution (typically log-normal) while Ta is determined as a point value. Therefore, FPtp is calculated as the probability that the required time exceeds the available time with the equation $1 - \Phi\ (ln\ (Ta\ /\ Tr)\ /\ \sigma$. Here, Φ indicates the cumulative normal distribution function, and σ is the shape parameter of the lognormal distribution. This parameter can be estimated by statistical analysis of empirical data, such as laboratory experiment data or simulator training observations.

To calculate reasonable durations for Ta and Tr, establishing a precise reference cue time is essential (Kim et al. 2021). Fundamentally, the reference cue time is defined as the initial occurrence time of the cue associated with the HFE. However, in scenarios where the instrument indication is significantly delayed, the reference cue time must be adjusted to account for this delayed occurrence. This determination logic is illustrated in the algorithm in Fig. 1.

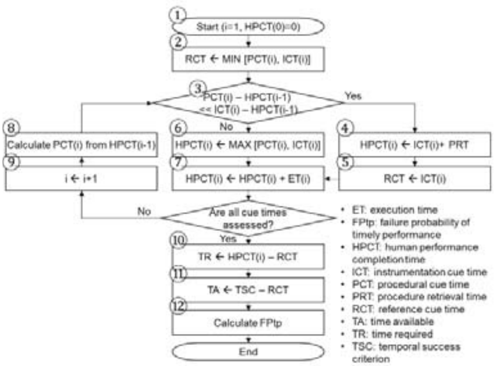

Fig. 1. Algorithm to determine Ta and Tr and calculate FPtp (Kim et al. 2025).

2.2. *Failure probability due to cognitive error in procedural tasks (FPce)*

The FPce variable is a quantitative metric designed to assess the reliability of an operating crew in adhering to procedural instructions within a digital MCR. Unlike time-dependent failures, which are governed by the physical availability of time, FPce specifically targets the cognitive and execution errors that occur during the step-by-step performance of EOPs.

Central to the calculation of FPce is the systematic decomposition of procedural steps into PTs, which serve as the fundamental units of analysis in EMBRACE. Instead of assigning a holistic error probability to a broad task, the method breaks down each procedural instruction into specific cognitive or physical actions—such as 'Check', 'Verify', 'Select', 'Manipulate'—based on the specific syntax of the procedure. For each identified PT, a corresponding primitive error probability (PEP) is retrieved from the HuREX DB. This DB provides empirical error rates derived from extensive observations of operator performance in digital simulators, thereby minimizing the reliance on subjective expert judgment and ensuring that the baseline probabilities reflect actual operational behaviors. Table 1 presents the list of PTs and their PEPs.

Table 1. PTs and PEP values (Kim 2025).

Category	PT	PEP
Information gathering	Verifying alarm occurrence	1.10E-04
	Verifying state of indicator	1.10E-04
	Synthetically verifying information	1.51E-03
	Reading simple value	1.10E-04
	Comparing parameter	1.10E-04
	Comparing in graph constraint	1.10E-04
	Comparing for abnormality	1.10E-04
	Evaluating trend	3.08E-04
Situation interpretation	Diagnosing cause of problem	2.16E-03
	Identifying current overall plant status	2.16E-03
	Predicting future (or long-term) status	2.16E-03
Response planning	Entering succeeding step in procedure	1.85E-04
	Transferring to procedure	5.62E-03
	Transferring to step in same procedure	5.62E-03
	Directing information acquisition	6.22E-05
	Directing manipulation	1.96E-03
	Directing external notification/request	1.85E-04
Control execution	Simple discrete manipulation	1.84E-03
	Simple continuous manipulation	1.53E-02
	Dynamic manipulation	1.49E-02
	Notifying/requesting to MCR outside	1.84E-03

To bridge the gap between generic error rates and specific operational contexts, the method applies

PSFs to the baseline PEPs. Various PSFs are quantified as multipliers, including digital environmental factors such as the quality of the CBPs and the clarity of the human–machine interfaces. For each procedural step, the relevant PSFs are evaluated, and their corresponding multipliers are applied to the sum of the PEPs for the PTs within that step. This process effectively scales the error probability up or down, capturing the impact of situational conditions on the operator's reliability.

The final quantification of FPce is achieved through a structured aggregation logic that incorporates recovery factors (RFs). Even if an error occurs, operators often have opportunities to detect and correct their mistake through mechanisms such as system alarms, peer checking, or procedural reviews. The failure probabilities of these recovery actions, denoted as RFPs, are multiplied by the PSF-adjusted error probabilities. Accordingly, the total FPce for an HFE is calculated by summing the failure probabilities of all constituent procedural steps, adjusted for PSF states and recovery potential. This bottom-up aggregation ensures that the final probability is a comprehensive representation of the cumulative risk across the entire procedural sequence.

3. EMBRACE-Support Software Logic

To operationalize the theoretical framework of EMBRACE, we developed ESS. The software features a modular architecture that automates the retrieval of empirical data, visualizes procedural flows, determines the durations of Ta and Tr, and executes probabilistic algorithms for both FPtp and FPce. Details are provided in the following sections.

3.1. *System architecture*

ESS is built upon a three-tier architecture comprising a database layer, a computational logic layer, and a graphical user interface (GUI) layer.

- Database layer: This layer integrates heterogeneous DBs, including a procedure structure DB (containing logic flows of EOPs), a procedure sentence DB (EOP sentences and their PTs), the HuREX DB (storing PEPs and time distributions), and a PSF/RFP DB (providing multipliers and recovery factors).
- Computational logic layer: This core engine processes user inputs to map instructions to PTs, to combine time information for Ta and Tr estimation, and to calculate the failure probabilities and the final HEP.
- GUI layer: The interface provides interactive dashboards that allow analysts to modify task parameters and visualize results in real time, ensuring the traceability of the analysis process.

3.2. *Module for FPtp*

The FPtp module evaluates the time-based reliability of the crew through four phases: (1) scenario definition, (2) timeline modeling, (3) distribution definition, and (4) probability calculation (Fig. 2). In the scenario definition phase, the analyst describes the scenario and cue information of the given HFE. In the timeline

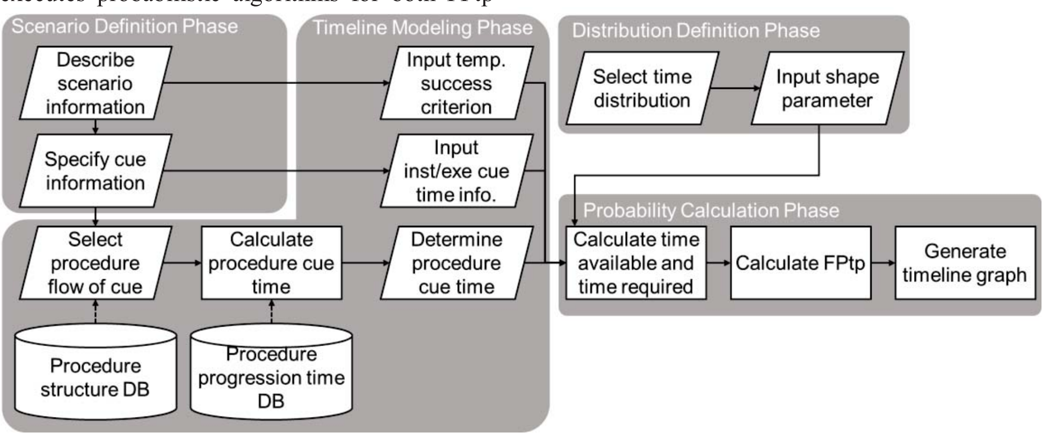

Fig. 2. Computational workflow diagram for the FPtp module of ESS.

modeling phase, the analyst inputs critical time parameters such as the temporal success criterion, instrumentation cue time, procedure cue time, and execution time. The module aids the analyst in calculating the procedure cue time by combining the procedure progression time data with the flow of the procedure. In the distribution definition phase, the time distribution (such as normal or log-normal) and the shape parameter are selected. Finally, the module calculates Ta and Tr by applying the algorithm shown in Fig. 1 and computes FPtp using the probability density function. The module also presents a timeline graph comparing the cue generation times, Ta, and Tr.

3.3. *Module for FPce*

The FPce module automates calculation through a three-phase workflow: procedure visualization, task analysis, and probability calculation (Fig. 3). First, when the analyst selects a target procedure, the software queries the procedure structure DB to automatically generate a dynamic flowchart that visualizes the logical connections between steps. Second, in the task analysis phase, the system identifies key instructions within the selected steps and recommends candidate PTs from the procedure sentence DB (i.e., instruction-to-primitive task mapping DB). This assists the analyst in decomposing complex instructions into standardized task units (Table 1). Once the analyst selects the PTs relevant to the given HFE, the module calculates the sum of the PEPs for the selected PTs. Lastly, the analyst evaluates the states of PSFs and RFs and calculates the PSF multiplier and RFP by linking to their respective database, instantly deriving the final FPce.

4. EMBRACE-Support Software Interface with Application Example

To demonstrate the practical utility of ESS, a case study was conducted on the HFE of feed and bleed (F&B) initiation during a loss of all feedwater (LOAF) event in a digitalized APR1400 control room. F&B initiation is a time-critical action where operators must open a safety valve, called the pilot-operated safety relief valve (POSRV), by following several procedures when secondary heat removal is unavailable. This HFE was modeled and quantified through the ESS integrated interface that guides the analyst through standardized phases.

The user interface of ESS is divided into three panes. The navigation pane, located on the far left of the interface, provides a centralized menu for accessing the core functional modules, such as settings, HRA quantification, and dependency assessment. The central HFE management pane enables analysts to organize and edit the list of HFEs required for the HRA quantification process. The analysis pane on the right features three specialized tabs that facilitate the documentation of basic HFE information and provide a computational environment for determining FPtp, FPce, and the overall HEP.

First, the software interface facilitates the defining of scenarios and HFEs. As shown in Fig. 4, basic information about the F&B initiation and corresponding analysis is written in the basic information tab. Once all processes of FPtp and FPce calculation are completed, the resultant HEP is displayed in the middle of this tab.

Fig. 5 shows the FPtp calculation screen for the F&B initiation. The analyst first inputs the temporal success criterion of the HFE and specific cue information, such as steam generator (SG) level low and POSRV open. The analyst can

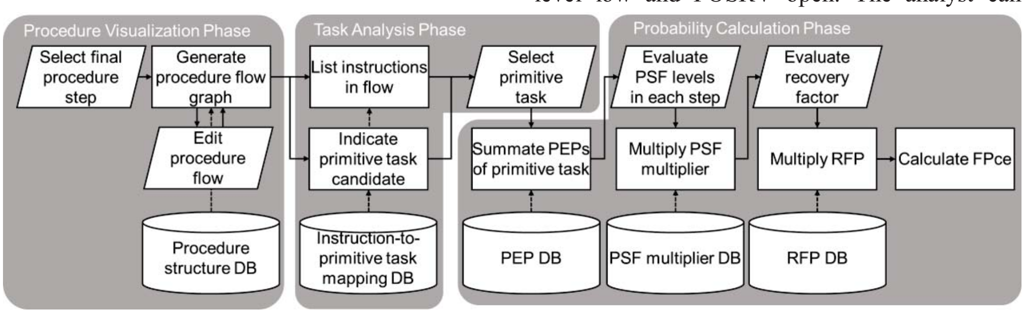

Fig. 3. Computational workflow diagram for the FPce module of ESS.

specify the instrumentation cue time, procedure cue time, and execution time required for the given HFE. Once all the time information and the distribution parameter are selected, the module shows the completion time for each cue and establishes the reference cue time (see the red-shaded row in Fig. 5). Based on the selected reference cue time, the module calculates the lengths of Ta and Tr along with computation of FPtp. A graph is shown that visually compares the durations that the crew followed the procedures and operated the systems for the cues with Ta, Tr, and the temporal success criterion. In this case study, the reference cue time was 25 min after reactor trip, i.e., the time at which the initial instrumentation cue appeared. As a result, Tr was calculated as 19 min and Ta as 40 min, and FPtp was estimated to be 1.43E-02.

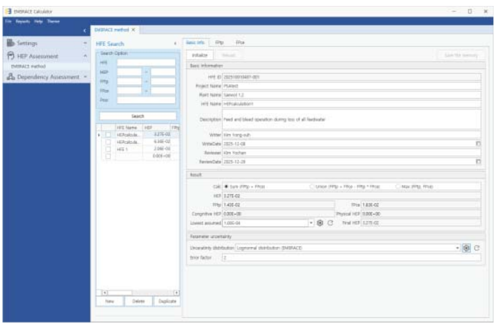

Fig. 4. Screenshot of the basic information tab for F&B initiation.

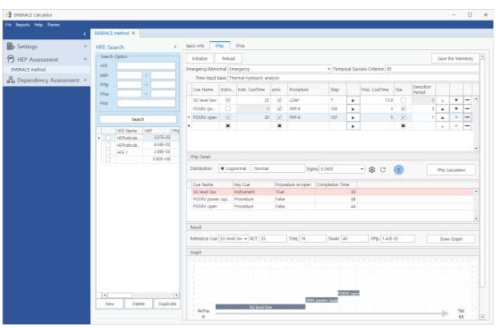

Fig. 5. Screenshot of the FPtp tab for F&B initiation.

To calculate FPce, the analyst must first identify the overall procedure flow by selecting key procedural steps. As illustrated in Fig. 6, once the analyst selects the final target step, the software generates a procedure flow graph by querying the procedure structure DB. The analyst can further refine this flow by inserting significant intermediate steps, which prompts the software to update and display the modified procedural sequence. Within this flow, the steps highlighted in light blue represent critical steps, such as procedure transitions or component manipulations. The procedural instructions and corresponding PTs for these steps are extracted from the database and presented in a tabular format. The analyst can then select the relevant PTs and adjust the number of their performances.

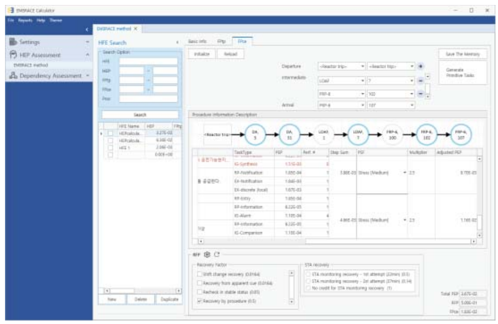

Fig. 6. Screenshot of the FPce tab for F&B initiation.

Furthermore, the sum of PEPs for each step can be adjusted by inputting specific PSF levels. The center table in Fig. 6 presents the corresponding PSF states, their multipliers, and the adjusted PEPs. At the bottom of the interface, applicable recovery sources can be selected, and all these inputs are integrated into the final FPce displayed in the lower-right corner. In this application example, five steps were initially identified as significant, but the analyst opted to select specific PTs from four of those steps. Additionally, the stress level was set to 'medium' for two of the steps, and only 'recovery by procedure' was evaluated as available. Accordingly, FPce was estimated to be 1.83E-02.

The final HEP was calculated to be 3.27E-02, which is displayed in the result section of the basic information tab (Fig. 4). The parameter uncertainty is also calculated by the selected calculation rule.

5. Discussion and Conclusion

This study presented the development of ESS, a dedicated computational system designed to operationalize the EMBRACE method for digitalized nuclear control rooms. While the theoretical framework of EMBRACE offers a granular approach to quantifying human reliability based on empirical data, its practical application has been hindered by the complexity of manual calculations and the management of extensive datasets. ESS addresses these challenges by implementing a three-tier architecture that seamlessly integrates heterogeneous databases—including PEPs, procedure structures, procedure sentences and PTs, time data, PSF multipliers, and RFPs—into a unified analytical environment.

The primary contribution of ESS lies in its significant enhancement of analytical efficiency and reproducibility. By automating the retrieval of PTs and their corresponding PEPs, the software minimizes the potential for calculation errors inherent in manual processes. The case study on F&B initiation demonstrated that ESS allows analysts to systematically identify the time required and the time available and also to intuitively decompose complex HFEs into standardized units. This standardization ensures that different analysts using the same scenario parameters will derive consistent probability estimates, thereby improving the overall reliability of the HRA results.

The three-pane layout of ESS organizes the general functional modules, and the tabbed interface facilitates a systematic evaluation of the three dimensions for each HFE: time-based failure, procedure-related failure, and the overall quantification outcome. Furthermore, the software significantly improves the comprehensibility and traceability of assessment through its interactive visualization capabilities. Automatic generation of procedure flowcharts and timeline graphs enables analysts to visually verify the logic behind FPtp and FPce. For FPtp analysis, the timeline graph illustrates the temporal relationship between cue generation and operator response times to validate the human competition time. Concurrently, for FPce estimation, the procedure flowchart renders the exact path of the operating procedures, assisting in the granular identification of cognitive and physical task units.

Based on general practical experience and comparisons with the EPRI HRA calculator (Kim and Kim, 2025; EPRI, 2022), the HEP estimates generated by the EMBRACE method tend to be comparable to, yet slightly higher than, those produced by the EPRI method. This tendency is primarily because the FPce calculation in EMBRACE explicitly accounts for the cognitive failure probabilities across all critical procedural steps, including procedure transitions. From a usability perspective, while the EPRI calculator typically links diverse informational databases—such as procedures, timing, and cues—on a per-HFE basis, the ESS leverages a comprehensive, plant-wide database of procedural sentences and step relationships. This distinct feature allows the ESS to drive a more granular analysis and interactive visualization.

Despite these advancements, the current version of ESS requires further validation. Future work will focus on extensive verification and validation activities involving a broader group of HRA experts to refine the user interface and ensure the robustness of the computational algorithms. Through these advancements, ESS offers a dedicated support tool for HRA methods in the context of domestic regulatory verification, ensuring reproducible and transparent safety assessments in the nuclear industry.

Acknowledgement

This work was partly supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) of the Republic of Korea (No. 2106054).

References

Boring, R.L., T.A. Ulrich, R. Lew, C.R. Kovesdi, and A. Al Rashdan (2019). A comparison study of operator preference and performance for analog versus digital turbine control systems in control room modernization. *Nuclear Technology* 205(4), 507–523.

Bye, A. (2023). Future needs of human reliability analysis: The interaction between new technology, crew roles and performance. *Safety Science* 158, 105962.

EPRI (1992). *An approach to the analysis of operator actions in probabilistic risk assessment*. EPRI Report TR-100259, Electric Power Research Institute.

EPRI (2022). *EPRI HRA Calculator 6.0b*. Electric Power Software Center.

Jung, W., J. Park, Y. Kim, S.Y. Choi, and S. Kim (2020). HuREX–A framework of HRA data collection from simulators in nuclear power plants. *Reliability Engineering & System Safety* 194, 106235.

Kim, Y. (2022, November). Estimate Comparison of Human Reliability Regression Models in Differently Classified Human Errors. *ASRAM2022 (Asian Symposium on Risk*

Assessment and Management 2022), Daejeon, Korea.

Kim, Y. and J. Kim (2025, August). Comparison of Methodological Characteristics between EMBRACE and the EPRI HRA Methodology: Case Study on Critical Operator Actions in an Advanced Control Room. *ASRAM2025 (Asian Symposium on Risk Assessment and Management 2025)*, Pattaya, Thailand.

Kim, Y. and J. Kim (2026). EMBRACEing HuREX Data: A Fundamental Approach to Develop a Plant-Specific Human Reliability Analysis Method. *Nuclear Engineering and Technology*. (Under revision).

Kim, Y., J. Kim, J. Park, S.Y. Choi, S. Kim, W. Jung, and S.K. Shin (2021). An algorithm for evaluating time-related human reliability using instrumentation cues and procedure cues. *Nuclear Engineering and Technology* 53(2), 368–375.

Kim, Y., J. Kim, and S.Y. Choi (2025). *Handbook of Human Reliability Analysis Using the EMBRACE-APR1400 Method.* KAERI/TR-10997/2025, KAERI.

Kim, Y., W. Jung, and S. Kim (2014). Empirical investigation of workloads of operators in advanced control rooms. *Journal of Nuclear Science and Technology* 51(6), 744–751.

Liao, H., J. Forester, V.N. Dang, A. Bye, Y.H.J. Chang, and E. Lois (2019). Assessment of HRA method predictions against operating crew performance: Part III: Conclusions and achievements. *Reliability Engineering & System Safety* 191, 106511.

O'Hara, J.M. and R.E. Hall (1992). Advanced control rooms and crew performance issues: implications for human reliability. *IEEE Transactions on Nuclear Science* 39(4), 919–923.

Park, J. and W. Jung (2015). Identification of key human performance issues that are affected by the control room modernization of nuclear power plants. KAERI/TR-6062/2015, *KAERI*.

Porthin, M., M. Liinasuo, and T. Kling (2020). Effects of digitalization of nuclear power plant control rooms on human reliability analysis–A review. *Reliability Engineering & System Safety* 194, 106415.

Swain, A.D. (1987). *Accident sequence evaluation program: Human reliability analysis procedure*. NUREG/CR-4772; SAND-86-1996, Sandia National Labs/U.S. NRC.

Swain, A.D. and H.E. Guttman (1983). *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications.* NUREG/CR-1278, U.S. NRC.

Vechgama, W., J. Park, Y. Kim, S. Wetchagarun, A. Pechrak, W. Pornroongruengchok, and K. Silva (2025). Suggestion of specific performance shaping factor update for the human reliability analysis framework of the TRIGA research reactor. *Reliability Engineering & System Safety* 260, 111010.