Insights from Human Performance Experiments Integrating Operator Support Systems in Emergency Situations

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1. Introduction

During emergency operations in nuclear power plants, Emergency Operating Procedures (EOPs) are used to prevent operator errors. Properly developed EOPs are necessary to prevent such errors.

Paper-Based Procedures (PBPs) have been long proven as a means for ensuring the safety of power plants. However, as PBPs use paper as a medium, the type of information they can handle is limited to static information [1]. This means that operators need to dynamically collect current information about the plant and sift through irrelevant information to find content related to the current situation. Operators must utilize their experience or information detailed in additional documents to gain an accurate understanding of the current state, which can lead to incorrect responses or unnecessary time consumption in situations where swift action is required [1]. Previously, EOPs mainly took the form of Paper-Based Procedures (PBPs), but with advancements in power plant technology and the introduction of digitized instrumentation and control systems and control room equipment, the format has shifted to Computerized Procedure Manuals (Park Jin-kyun 2015, 2017) [2, 3]. The Computerized Procedure System (CPS) applied in the current APR1400 has made significant improvements over paper-based procedures [4], the overall structure still retains the characteristic of paper procedures.

Taking a further step, we proposed an operator support system that actively utilizes the dynamic characteristics of the power plant's digital environment [5-7], and we conducted experiments to assess human performance using this system, in comparison with the paper procedure environment. This paper describes this series of system development and evaluation processes and proposes strategic approaches for the newly applicable emergency operation support system based on these.

2. System Deevelopment and Evaluation Experiment

2.1 System Development

EOPs for APR1400 are classified into four types of procedures: Standard Post Trip Actions (SPTA), Diagnostic Actions (DA), Optimized Recovery Procedures (ORPs), and Functional Recovery Procedures (FRPs). Based on the order of execution, they can be simplified into two stages. The first stage is initial response and diagnosis (SPTA, DA), and the second stage is accident mitigation tasks (ORP, FRP). The developed system is called the Emergency Guidance Intelligent System (EGIS), and as shown in Figure 1, it targets SPTA and DA, which correspond to the initial response and diagnosis.

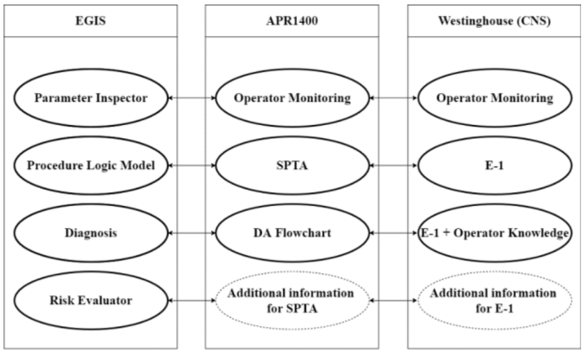

Fig. 1. Role comparison between EGIS and SPTA + DA [5]

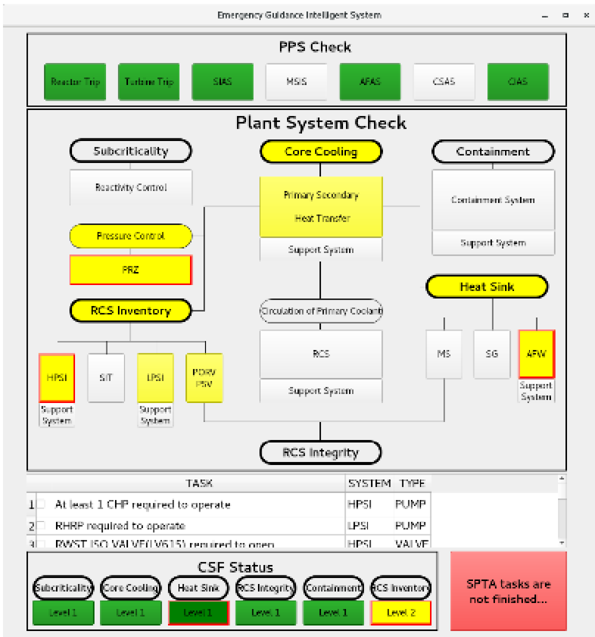

Fig. 2. EGIS Interface

This system collects real-time data and provides only the procedures that require action, and helps the operators understand through the master logic diagram (MLD) how component/system anomalies affect various safety functions. After all initial response actions are completed [5], it provides diagnostic results to the operators through an artificial intelligence diagnostic system capable of responding to sensor faults [6]. This system is designed to deliver information to the operator through PyQT, combining rule-based logic, multilevel flow modelling, and gated recurrent unit artificial intelligence technologies. The system has been applied in the Compact Nuclear Simulator developed by the Korea Atomic Energy Research Institute (KAERI) [8].

2.2 Human Performance Measure Experiment Setting

To evaluate EGIS, human performance evaluation was conducted. The performance evaluation criteria were selected based on the NUREG-0711 report [9]. The evaluation was carried out for six factors: task performance, situation awareness, cognitive workload, and anthropometric/physiological factors. Previously, a human performance evaluation methodology had been proposed based on these factors to verify the human elements of the control room in nuclear power plants [10]. For the EGIS evaluation, task performance, situation awareness, and cognitive workload were selected as the primary evaluation factors, and eye-tracking equipment was used to collect gaze information for supplementary quantitative evaluation. The participants consisted of university students and graduate students majoring in nuclear engineering, totaling 17 individuals. Among them, 9 participated in experiments in the PBP environment, and 8 in the EGIS environment. Task performance was measured by using real-time check sheet and video recordings to measure task errors, diagnostic errors, and execution time. Workload was assessed using the NASA-TLX and Modified Cooper Harper (MCH) scales, and situation awareness was measured using the Situation Awareness Rating Technique (SART).

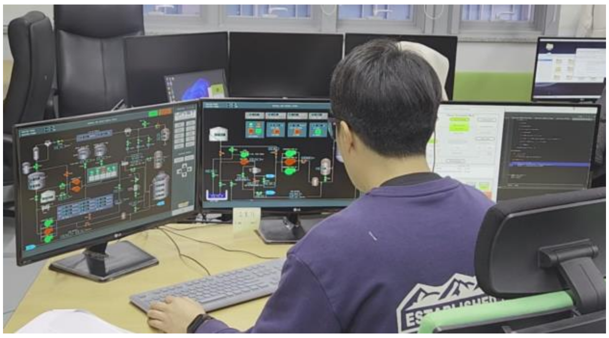

Fig. 3. Experiment Environment

2.3 Experiment Result

Task performance metrics included the measurement of execution time, task errors, and diagnostic errors. The average initial response execution time for EGIS users was 2 min 47 sec, while for PBS users, it took an average of 15 min 21 sec. The task error rate for EGIS users was 0.56%, compared to 2.48% for PBS users. Moreover, incorrect diagnoses occurred only in the PBS user group, with two instances of misdiagnosis. Both experimental groups experienced task omissions for the same factors. EGIS had cases where the time taken for recovery was shorter, being 1 min 17 sec compared to 12 min 34 sec for PBP.

Table I: Task Performance Result

	EGIS	PBS
Error of Omission	1	5
Error of Commission	0	0
Error Rate (%)	0.56	2.48
DA Error	0/8	2/9
Recovery	1	1
Recovery Time (sec)	77	754

As mentioned before, workload was measured using the MCH and NASA-TLX. EGIS users scored 1.9 on the MCH scale, while PBS users scored 5.8, confirming lower workload for EGIS operators. In the NASA-TLX, EGIS showed better results than PBS in mental, performance, effort, and frustration aspects (T-test). In the SART, a measure for situation awareness, EGIS outperformed PBS in aspects of variability and division of attention, showing statistically significant differences in the T-test. However, no statistical significance was found in gaze information from participants using eye-tracking equipment.

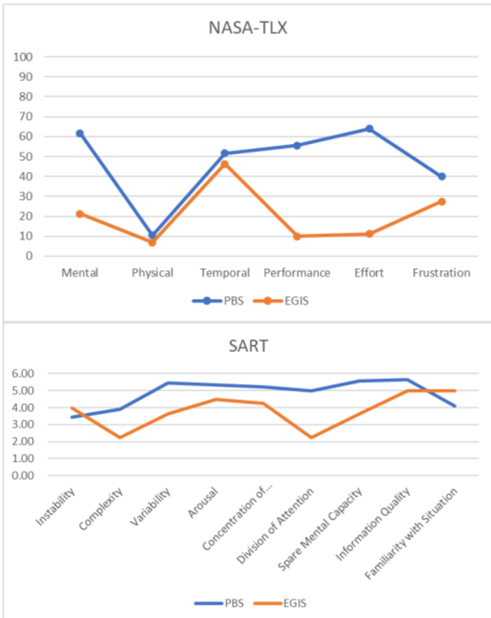

Fig. 4. NASA-TLX, SART Result

3. Lessons from Development and Experiment

Participants agreed that the EGIS system could increase task execution speed and decrease workload but expressed concerns about a possible decline in overall situation awareness. In other words, overreliance on an automated system can lead to a situation where operators are not adequately prepared to take over in out-of-the-loop (OOTL) scenarios, potentially leading to a decrease in operator capabilities. Although EGIS aimed to enhance operators' situation awareness through the MLD, it still might have limitations. Since EGIS is focused on initial emergency response, a lower level of situation awareness might not be a significant issue if the diagnostic results are reliable. However, this becomes a crucial issue to address in the subsequent phase of emergency mitigation operations (phase 2) following the initial response (phase 1).

In the initial operation phase, where EGIS is utilized, the prioritization of tasks was clear due to the need for rapid execution and the simple composition. However, in the subsequent emergency mitigation operation phase, more complex considerations are required to respond to a variety of situations, including available time and equipment performance. The advantage of performing tasks with dynamic information is reducing unnecessary tasks and executing based on priority. Therefore, priority assessment becomes essential in emergency mitigation situations.

Considering these points, the dynamic EOP to be developed in the future should focus on two main elements: enhancing situation awareness and assessing task priority. As shown in Figure 5, it is essential to have an operational path tracker (guiding current and required procedure paths) and a risk-averse navigator (evaluating which tasks should be performed first based on risk) as key features (priority assessment).

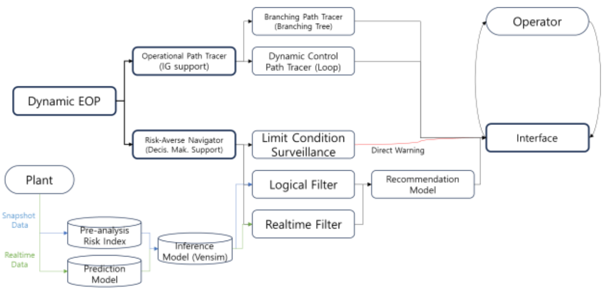

Fig. 5. Dynamic EOP Required Function Diagram

4. Conclusion

This paper introduces the development, experimentation, and evaluation process of the EGIS. This system is an operator support system developed by combining rule-based models, MFM, and gated recurrent units. The system was developed using CNS and Python, and a human performance evaluation experiment was conducted to assess the system's feasibility. The results of the human performance evaluation showed that EGIS had a positive impact on operators' task performance, workload, and situational awareness compared to PBP. However, it was observed that as the operator support functions become stronger, they could potentially reduce the operators' performance capabilities, leading to the selection of key features for the subsequently developed Dynamic EOP. Future research will focus on addressing and improving the issues present in the existing system, such as inconsistencies between the system color logic and the simulator color logic.

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