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Development and Initial Evaluation of a Prototype Dynamic Emergency Operating Procedure System for Nuclear Power Plants

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1. Introduction

Currently, the instrumentation and control (I&C) systems and the main control room (MCR) of nuclear power plants have been digitalized [1, 2], leading to the adoption of computer-based procedures (CBP). This digitalized environment integrates operational tasks into a computer-based system, making it easier to implement various operator support systems.

The procedure types are as follows. The first type is Paper-Based Procedures (PBP). PBPs are cost-effective to develop and easy to validate. They have been used for decades in commercial nuclear reactors, proving their safety. However, due to their static nature, operators must manually review all content, which limits the ability to provide relevant information in dynamic situations [3]. PBPs also heavily rely on the operator's expertise and understanding of the plant, posing a significant limitation [3]. To address these issues, the industry transitioned to Computer-Based Procedures (CBP). CBPs improved step navigation and browsing capabilities, enhancing operational efficiency. They also introduced task synchronization features, enabling operators to monitor the tasks their colleagues are performing. However, CBPs are digital conversion forms of PBPs. PBPs retain many of the static limitations of the paper-based system [4].

Consequently, CBPs still struggle to fully adapt to the dynamic characteristics of plant operations. This research proposes an advanced computer-based emergency operating procedure system that can dynamically adapt to the plant's operational environment. The system collects real-time data from the plant and provides only the tasks necessary based on critical safety functions (CSFs), reducing the operator's workload. Additionally, an improved interface design is implemented to allow operators to intuitively access critical information, enhancing their situation awareness (SA). This system aims to overcome the limitations of existing procedures, reduce operator workload, enhance task performance and SA, and minimize human errors during emergency situations.

2. System Framework and Development

2.1 System Framework

In this study, the system for implementing the Dynamic Emergency Operating Procedural System is proposed as the Emergency Guidance Intelligent System (EGIS). This system is composed of four main functions. The first function is the Task Block Browser. This function aims to receive dynamic information from the plant in real-time and provide only the information necessary for operators. By summarizing and intuitively displaying the critical tasks that operators need to perform, it helps them efficiently understand the overall status of the plant. The second function is the CSF Status Evaluator. In emergency situations, it is crucial to track various parameters in real-time. This function supports comprehensive assessment of the plant's status by utilizing CSF scores to provide a summarized overview. The third function is the Plant Status Monitor. This function visually represents the impact of emergency situations on various systems or functions of the plant. It allows operators to intuitively understand how these situations may affect the plant and enables them to respond appropriately. Finally, these three functions are integrated into a single interface, providing operators with all necessary information in one place. This integration allows operators to quickly and easily grasp the situation, enabling efficient SA and decision-making. The overall framework is shown below figure.

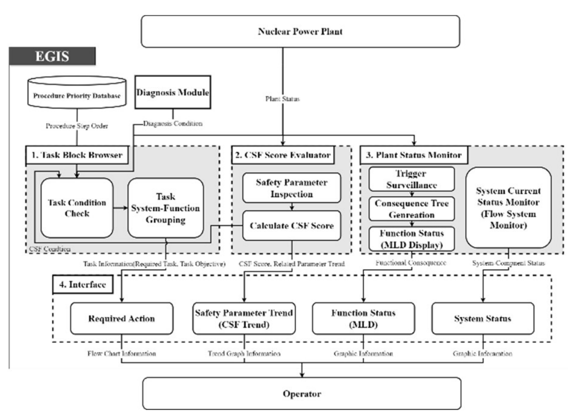

Fig. 1. The Framework of EGIS

2.2 System Development

Based on the APR1400, when a trip occurs, the process transitions through the Standard Post-Trip Action phase, followed by initial response actions. After completing these actions, the process moves to a Diagnosis Action phase to determine whether the plant's state matches a specific scenario. If a match is identified, the process proceeds to the Optimized Recovery Procedure (ORP); if not, it transitions to the Functional Recovery Procedure (FRP). An analysis of the Emergency Operating Procedures (EOP) revealed that Common Tasks were observed in both ORP and FRP. Tasks were categorized into Common Tasks, Scenario-Specific Tasks, Status-Specific Tasks, and Diagnosis Tasks. Diagnosis Tasks were excluded from the analysis as they rely on an automatic diagnosis module.

- ***Common Tasks:*** Simple status checks and control tasks shared across most procedures in general situation (e.g., verifying SI system operation, cooling the steam generator).
- ***Scenario-Specific Tasks:*** Tasks performed in specific scenarios based on diagnostic results (e.g., entering recirculation mode in a LOCA scenario, isolating the ruptured steam generator in an SGTR scenario).
- ***Status-Specific Tasks:*** Tasks performed under extreme conditions or when safety systems are unavailable, based on operator judgment (e.g., forcibly starting the RCP when reactor cooling is degraded, performing feed-and-bleed operations in a Loss of All Feedwater (LOFW) scenario).

In ORP, Common Tasks and Scenario-Specific Tasks were predominant, while FRP primarily involved Common Tasks and Status-Specific Tasks. This analysis suggests that dynamic procedures can reduce redundancies and provide optimized procedural guidance. This is illustrated in the figure below, where green represents common tasks, blue represents diagnosis tasks, yellow represents scenario-specific tasks, and red represents status-specific tasks.

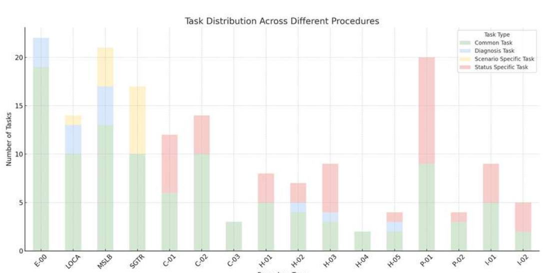

Fig. 2. Task Distribution in EOP

The Task Block Browser aims to enhance operators' situational awareness by providing necessary tasks and their objectives in a hierarchical structure (CSF, system level, component level) based on the plant's status. To achieve this, existing procedures were analyzed, and tasks were categorized using a response not obtained (RNO)-Free approach to eliminate unnecessary actions. Detailed tasks from existing procedures were integrated into system- and function-level task blocks, designed using the Functional-Hierarchical Task Grouping Framework. Additionally, EGIS monitors the plant's status in real time, offering only the necessary tasks to operators and forming a single integrated procedure structure. This approach clarifies task objectives and improves procedural efficiency.

The CSF Score Evaluator was developed to summarize and evaluate plant safety parameters. The most critical factor in plant safety is the CSF status, which has traditionally been evaluated using a procedural tree. However, traditional procedural trees categorize plant states into discrete states rather than continuous ones, posing challenges in accurately reflecting dynamic plant conditions. To address this limitation, a continuous evaluation method using fuzzy logic was developed. The overall process is as follows. First, membership functions were defined for each input parameter. Next, reasoning tables were constructed based on the CSF tree logic. Empirical sensitivity analysis was then performed, and finally, the CSF score function was developed. This evaluation method overcomes the limitations of discrete classification methods and enables a more precise representation of dynamic plant states.

The Plant Status Monitor is designed to summarize and intuitively present the status of plant systems and functions to operators. This system utilizes Multilevel Flow Modeling (MFM) to model CSFs, plant systems, and their components [5, 6]. The Plant Status Monitor provides two key functionalities. The first is the Function Status Monitor, which uses operational and anomaly information to generate a Consequence Tree and presents this information in the form of a Master Logic Diagram (MLD) to the operators. The second is the System Status Monitor, which models the flow structure of each system using MFM and summarizes the current system status for presentation. By systematically and visually representing plant conditions, this monitor enhances operators' situational awareness and supports timely decision-making.

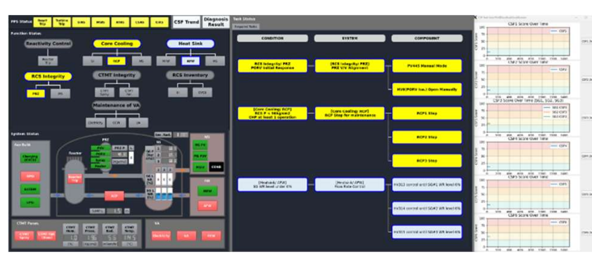

Fig. 3. EGIS Interface Overview

The interface integrates three main functions and presents them to operators in an appropriate format. Its primary purpose is to provide only the necessary tasks and enable operators to intuitively grasp the plant's status, thereby preventing situational awareness degradation. As shown in the figure, the interface consists of three main sections arranged from left to right: the Plant System Overview (Function Status Window and System Status Window), the Task Block Browser, and the CSF Status Graph. Each section is linked to its corresponding function: the Task Block Browser is connected to the Task Block Browser function, the Plant System Overview is linked to the Plant Status Monitor, and the CSF Status Graph is associated with the CSF Score Evaluator. To enhance operator understanding, buttons within the interface are color-coded buttons were used to enhance intuitive recognition.

3. System Evaluation

To validate the system's functionality, a case study was conducted based on a predefined scenario. This study utilized the Compact Nuclear Simulator (CNS) for the Westinghouse 960MW model, developed by KAERI [7]. The scenario assumed a LOCA situation with a 60cm² break in the cold-leg 1 of the coolant pipe. After performing the initial emergency response procedures, the situation was stabilized through cooling control, considering the abnormal state of Critical Safety Function 2 (CSF2) related to core cooling. Once CSF2 was stabilized, the safety injection (SI) termination was verified, followed by a transition to the low-pressure recirculation mode. The case study included a scenario where depressurization and cooling steps were carried out to control the pressurizer pressure to below 45kg/cm². This process allowed the system's functionality to be assessed, and an observation sheet for ergonomic experiments was developed.

To evaluate the system's performance, an ergonomic experiment was designed to assess human performance under different system conditions. Human performance was measured across three metrics: task performance, workload, and situation awareness. The experiment involved seven graduate students specializing in nuclear engineering, with data collected from 21 test cases under the following three operational conditions:

- Paper-Based Procedures System Environment (PBS)
- EGIS without UI, where only task information was provided
- EGIS with UI, where full support information was provided

The average task completion times observed were 24 minutes 8 seconds for PBS, 13 minutes 16 seconds for EGIS without UI, and 12 minutes 30 seconds for EGIS with UI. ANOVA and Tukey tests revealed significant differences between PBS and EGIS without UI, as well as between PBS and EGIS with UI. These results demonstrated that the EGIS system contributes to improved operational efficiency and human performance.

Workload was assessed using the Modified Cooper Harper Scale (MCH), a widely recognized method for evaluating perceived workload during task performance. Situation awareness was evaluated through two established methods: the Situation Awareness Rating Technique (SART) and the Situation Awareness Control Room Inventory (SACRI). SACRI consisted of 12 structured questions designed to assess operators' awareness of the system and operational context comprehensively. Workload was evaluated using the Modified Cooper Harper Scale (MCH). The average scores were 5.571 for PBS, 2.714 for EGIS without UI, and 2.286 for EGIS with UI. ANOVA and Tukey test revealed statistically significant differences between PBS and EGIS without UI, as well as between PBS and EGIS with UI. These results indicate that workload was significantly reduced under the EGIS conditions compared to PBS. Situation awareness was assessed using SART and SACRI. The SART scores were 12.857 for PBS, 23.286 for EGIS without UI, and 27.714 for EGIS with UI. Statistically significant differences were observed between PBS and EGIS without UI, as well as between PBS and EGIS with UI. These findings demonstrate that situation awareness was significantly improved under the EGIS conditions compared to PBS. For SACRI, the A' score, which approaches 1.0 for perfect discrimination of parameter stability and drifts, was 0.728 for PBS, 0.823 for EGIS without UI, and 0.929 for EGIS with UI. ANOVA analysis revealed a statistically significant difference only between PBS and EGIS with UI. This indicates that only the condition utilizing EGIS with all support information led to a significant improvement in situation awareness compared to PBS. These findings suggest that the EGIS system positively contributes to reducing workload and enhancing situation awareness. The overall trend of the human performance measure distribution is shown in the figure below.

While the integrated EGIS system as a whole showed improvements in performance, further analysis suggests that the Task Block Browser contributed significantly to reducing task completion time by simplifying procedural navigation. Meanwhile, the CSF Status Evaluator improved situational awareness by summarizing complex safety parameter trends in an intuitive format. The synergy of both modules played a key role in enhancing overall performance.

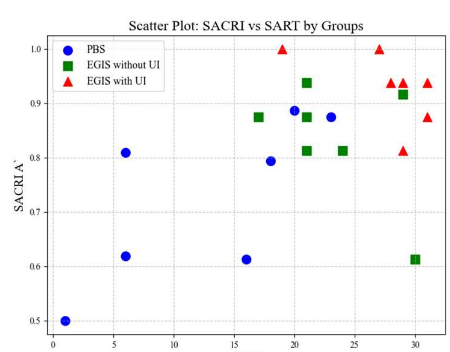

Fig. 4. Situation Awareness Distribution (SACRI A' – SART)

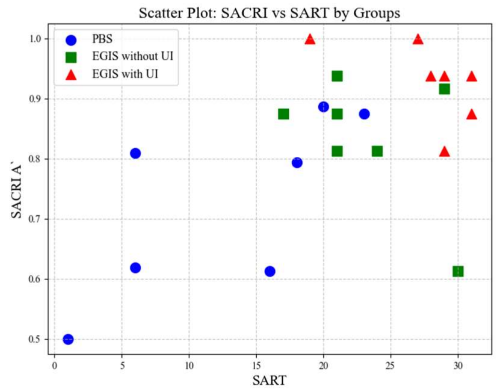

Fig. 5. Situation Awareness Distribution (SACRI A' – SART)

Although the experiment involved graduate students specializing in nuclear engineering rather than licensed operators, the findings still offer meaningful insights. Prior to applying the EGIS, task performance varied notably depending on individual familiarity with the simulator environment. After the application of EGIS, however, performance levels across participants became more consistent. This reduction in performance variance implies that the system may help mitigate differences in user proficiency. Given that variations in experience and skill also exist among licensed operators in real control rooms, this finding suggests that the system could contribute to reducing performance gaps and improving overall consistency in real-world applications.

4. Conclusions

This study developed and validated an advanced procedural system to address the limitations of existing nuclear power plant procedures and to improve operator task efficiency and situational awareness. The proposed system overcomes the static nature of traditional procedures by incorporating dynamic monitoring and optimized information provision, while also providing an intuitive interface that supports operator awareness. Results from a human factors experiment demonstrated that the system significantly reduced task completion time and workload, while enhancing situational awareness. These findings suggest that the system can serve as an effective tool to improve operator efficiency and support decision-making in emergency situations.

Future research should focus on evaluating the system's applicability in actual control room environments and on conducting experiments with professional operators to further validate its practical utility.

Despite the promising results, several challenges remain for real-world implementation. These include integration with existing safety-critical instrumentation and control (I&C) systems, operator training for the dynamic interface, and regulatory acceptance. Addressing these challenges will require close collaboration with control room designers, training departments, and regulatory bodies.

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