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Original Article

Conceptual design of dynamic emergency operating procedural system for NPPs: Integration of dynamic task management and safety monitoring

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ABSTRACT

This study proposes a dynamic emergency operating procedural system to address the limitations of static, paper-based emergency operating procedures in nuclear power plants. Despite digital main control rooms, traditional procedures remain static and poorly suited to rapidly changing plant conditions. Operators must still search for relevant steps while ignoring those that do not apply, increasing workload and delaying decisions. The static format also hinders real-time tracking and verification, risking omission of safety-critical actions. To resolve these issues, this study developed the Emergency Guidance Intelligent System (EGIS), which provides real-time monitoring and required task blocks.

EGIS comprises three core functions: the Task Block Browser, which delivers only necessary tasks in real-time using a functional-hierarchical task grouping framework; the Critical Safety Function Score Evaluator, which evaluates critical safety functions using fuzzy logic; and the Plant Status Monitor, which visualizes system status and consequence through Multilevel Flow Modeling. EGIS was verified using the Compact Nuclear Simulator with a Loss of Coolant Accident scenario. The results demonstrated that EGIS reduced operation time compared to conventional procedures while effectively replacing the role of traditional paper-based procedures. EGIS is expected to enhance the safety and efficiency of emergency operating procedures in nuclear power plants.

1. Introduction

1.1. Background

Operators in nuclear power plants gather information through Human-Machine Interfaces (HMIs) and respond to various situations from the main control room by following operating procedures. To prepare for potential accidents, plants are equipped with safety systems comprising various sensors and devices. During emergencies, operators must evaluate parameter statuses, diagnose plant conditions, and implement mitigation actions. However, multiple simultaneous alarms and rapid changes in plant conditions during such events significantly increase the likelihood of human error.

Probabilistic safety assessments of Korean nuclear power plants indicate that human errors account for 44 % of core damage frequency [1]. The TMI-2 (Three Mile Island-2) accident highlights how inadequate procedure design and inefficient HMIs contributed to severe accidents, underscoring the importance of well-designed HMIs and procedures [2].

Nuclear power plant operations are categorized into normal, abnormal, and emergency operations [3]. Preventing operator errors during emergencies is critical to avoiding severe accidents. Emergency Operating Procedures (EOPs) are employed to assist operators in assessing plant conditions and taking appropriate actions. Traditionally, Paper-Based Procedures (PBPs) have been widely used in analog Instrumentation and Control (I&C) systems and analog main control room, but their static nature is able to make them a potential source of human error [4].

PBPs face challenges in addressing the dynamic environments of nuclear power plants. They are designed to cover as many scenarios as possible, leading to increased operator workloads as they must filter irrelevant information. For instance, during a rapidly evolving event, an operator might have to manually flip through pages containing conditional steps and parameters that do not apply to the current plant state. This process of manually verifying and discarding irrelevant information not only consumes valuable time but also significantly heightens the risk of overlooking a critical instruction or making an error in judgment. Consequently, operators often rely on external resources, such as plant

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layouts, additional manuals, or their own expertise, to accurately assess real-time conditions [4].

In recent years, analog main control rooms have transitioned to digital control rooms [5,6], influencing the nature of operating procedures. PBPs are gradually being replaced by Computer-Based Procedures (CBPs), which can utilize real-time plant data. For instance, South Korea's APR1400 employs a CBP system that allows operators to share procedural progress and access various support systems during emergencies [7,8].

While existing CBPs can process more information than PBPs, many retain static characteristics and do not fully resolve the fundamental issues identified in PBPs [9]. These challenges increase cognitive workloads, lead to skipped steps, incorrect actions, and confusion during procedure transitions. Advanced CBPs aim to address these issues by "automating parameter retrieval, comparison, and monitoring" and "displaying only relevant information based on actual conditions," which directly helps to reduce the operator's cognitive workload. Specifically, by "automating parameter retrieval, comparison, and monitoring," CBPs free up the operator's limited cognitive resources from the repetitive, low-level tasks. For instance, instead of an operator manually verifying that the 'Steam Generator water level is above the reference value' or confirming that a 'Reactor Coolant Pump has successfully started,' the system can perform these routine checks automatically and present the result (e.g., "RCP A START - CONFIRMED"). This frees the operator from the burden of constantly checking instrument readings against procedural thresholds, allowing them to focus on higher-level diagnosis and decision-making. Similarly, by 'displaying only relevant information based on actual conditions,' the system dynamically hides irrelevant procedural branches, decluttering the interface and ensuring that operators are presented only with actionable steps, which is crucial for timely and accurate emergency response. They also improve navigation, manage multiple procedures, and provide information with selectable levels of detail. Additionally, CBPs enable simultaneous monitoring of multiple parameters [10], improve diagnostics, facilitate continuous step management, reflect operator inputs, and effectively reduce human error [3].

While existing CBPs represent a significant step forward, their evolution into truly dynamic decision aids depends on integrating advanced functionalities from the broader field of Operator Support Systems (OSS). Yet, a comprehensive review of these technologies reveals that critical challenges and research gaps remain in achieving seamless and effective integration. To clarify the unique contribution of our work, we have established a clear progression of prior research and its limitations. Early CBPs (e.g., Computerized Procedure Manual II, COPMA-II [11]) successfully digitized procedures but retained a static, linear flow. More advanced systems (e.g., Computerized Operator Support Systems, COSS [12], Safety Parameter Display System, SPDS [13]) integrated various plant data but often presented safety status in discrete, static terms (e.g., color-coded alarms), lacking the dynamic trend information necessary for proactive decision-making or for providing operators with intuitive feedback on how their actions impact plant safety. While some model-based systems, such as those using Multilevel Flow Modeling (MFM) for root-cause analysis [14], focused on diagnostics, they often stopped identifying the cause, leaving a gap in guiding the operator's next steps. These latest endeavors include generative models like LLMs for decision support (e.g., EvoTaskTree) [15], and systems aiming for fully autonomous operation (Autonomous Emergency Operation System, A-EOS) [16]. While powerful, these cutting-edge methods introduce critical challenges regarding 'black-box' explainability and the 'Out-of-the-Loop' (OOTL) problem, respectively.

1.2. Objective

While Computer-Based Procedures (CBPs) offer notable advantages over traditional Paper-Based Procedures (PBPs), many CBPs still inherit limitations from PBPs. Operating procedures in nuclear power plants are broadly classified into normal, abnormal, and emergency domains, and exist in two main formats: PBPs and CBPs. Among these, CBPs remain an evolving area with substantial room for advancement. In this study, we focus on the emergency domain—EOPs—as the application area for an enhanced form of CBP. This focus was chosen because emergency operations place the greatest cognitive and operational demands on operators, making them the most critical environment for evaluating and maximizing the benefits of a dynamic CBP system.

The existing Computer-Based Procedures (CBPs) have made significant advancements compared to traditional Paper-Based Procedures (PBPs), but many systems still remain focused on the digitalization of information rather than providing cognitive support for operators. In contrast, recently proposed highly automated systems (e.g., A-EOS) or AI models with limited explainability (e.g., LLM-based systems) may pose a potential risk of causing the "Out-of-the-Loop" (OOTL) problem, which reduces operators' Situation Awareness (SA) and isolates them in the decision-making process.

This OOTL problem has been a core issue deeply addressed in the field of human factors engineering. Endsley and Kiris (1995) reported that as the level of automation increases, operator intervention decreases, leading to the OOTL problem, which impairs the ability to respond effectively during emergency situations [17]. They also pointed out that the degradation of performance due to OOTL is related to two major issues of automation: the loss of manual skills and the loss of awareness of the system state and processes (situation awareness) [17,18]. These challenges can result in serious consequences, especially in complex and high-reliability systems like nuclear power plants.

The reduction of operator situation awareness due to system intelligence can also negatively affect task performance. As seen in the graphs below (Figs. 1 and 2), once the level of system automation exceeds a certain threshold, operator situation awareness sharply decreases, leading to a decline in task performance [19]. Therefore, designing a dynamic Emergency Operating Procedure (EOP) system that balances maintaining operator situation awareness and supporting their performance is crucial.

The core objective of this study is to establish and validate the concept of a dynamic Emergency Operating Procedure (EOP) system, namely the EGIS, based on a human-centric design Philosophy that leverages the advantages of advanced information technology to effectively support operators while systematically preventing Out-of-the-Loop (OOTL) phenomena. EGIS does not aim to replace the operator, but rather seeks to enhance the operator's cognitive abilities, reinforcing their role as the final decision-maker.

This design philosophy clearly distinguishes EGIS from previous research. While the early Computer-Based Procedure (CBP), COPMA-II [11], merely digitized static procedures, EGIS dynamically recommends tasks based on real-time plant conditions. Unlike comprehensive support systems like COSS [12], which tend to list various pieces of information, EGIS refines and integrates all information using Multilevel Flow Modeling (MFM) and fuzzy logic, selectively presenting only the

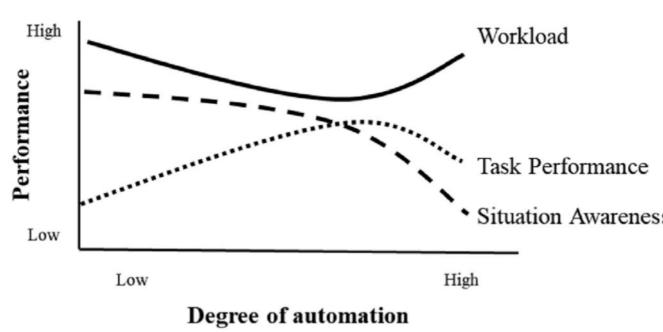

Fig. 1. Hypothesized changes in task performance, SA, and workload as a function of degree of automation [19].

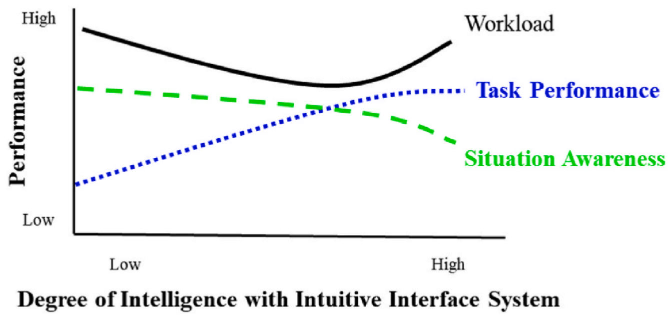

Fig. 2. Hypothesized changes in task performance, SA, and workload as a function of degree of intelligence with intuitive interface system.

most important information based on the core criterion of "safety functions." In contrast to standard Safety Parameter Display Systems (SPDS) [13], which only display safety states in discrete colors, represents safety levels as continuous scores ranging from 0 to 100, allowing operators to track subtle changes and trends. Moreover, while MFM-based alarm analysis [14] often remains limited to diagnostics, EGIS offers an integrated solution that links diagnosis, prediction, and task guidance. Finally, unlike the "black-box" issues of LLM-based systems such as EvoTaskTree [15] or the fully automated orientation of A-EOS [16], EGIS is designed as a cognitive support tool based on transparent and verifiable models that avoid OOTL issues and place human operators at the center of decision-making.

To achieve this core objective, this study sets the following three integrated sub-goals:

- **Development of a Dynamic, Context-Aware Task Management System:** By applying Hierarchical Task Analysis (HTA) principles, a dynamic task management system will be developed that filters unnecessary procedural steps based on real-time plant conditions while ensuring operators can clearly understand the relationship between individual tasks and higher safety objectives. This aims to reduce cognitive load while preserving understanding of task goals, thereby maintaining situational awareness.
- **Design of Continuous, Trend-Based Safety Monitoring Functionality:** A safety monitoring function will be designed using fuzzy logic to transform complex and diverse plant variables into intuitive continuous scores. This system moves away from the discrete alert systems of traditional safety variables (SPDS), enabling operators to proactively identify subtle changes in safety margins and trends, thus supporting predictive responses.
- **Implementation of Explainable and Predictive System Status Visualization:** A system status monitoring function will be implemented using Multilevel Flow Modeling (MFM) to provide operators with a transparent, qualitative model of the functional state of the plant system and its potential cascading effects. This aims to support operators in deeply understanding and trusting the "why" behind plant recommendations, enabling them to make trust-based decisions rather than blindly following system suggestions.

Overall, this study aims to present a new paradigm that maximizes operator performance through advanced computing technologies while firmly establishing humans as the final authority in situational awareness and control. This approach will contribute to demonstrating the utility of an innovative integrated solution that bridges the critical gap between simple CBPs and fully automated systems.

2. System framework and architecture

The Emergency Guidance Intelligent System (EGIS) was developed to address the limitations of existing emergency operating procedures while enhancing operator support capabilities. This section describes the

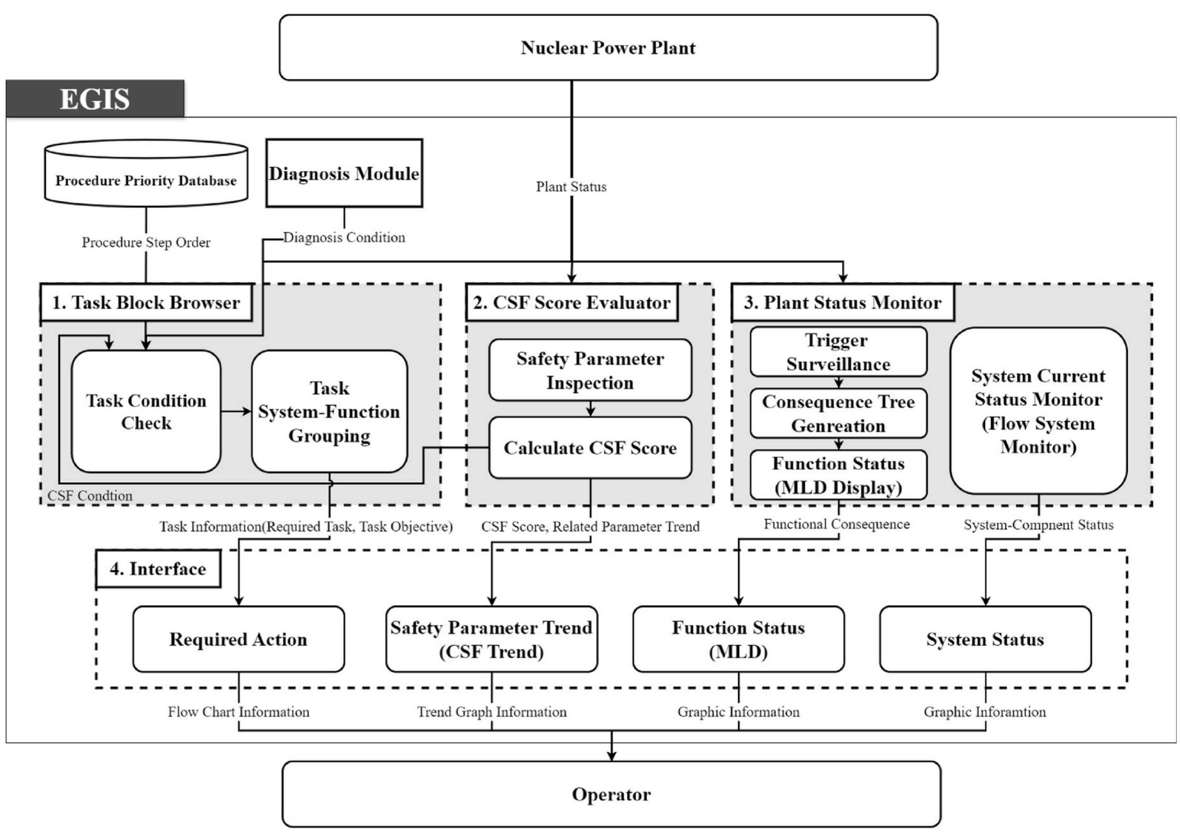

Fig. 3. EGIS framework.

overall framework of EGIS and its key architectural components (see Fig. 3).

2.1. Overall system framework

EGIS integrates three primary functions to provide comprehensive operator support during emergency situations: the Task Block Browser, which dynamically presents essential tasks based on real-time plant conditions; the Critical Safety Function (CSF, the fundamental safety barriers in nuclear plants including subcriticality, core cooling, heat sink, reactor coolant system integrity, containment integrity, and reactor coolant inventory) Score Evaluator, which continuously assesses critical safety functions; and the Plant Status Monitor, which provides intuitive visualization of system states and their implications.

The system collects real-time data from the plant's instrumentation and control system and processes this information through its core components to deliver 'optimized information' to operators. Furthermore, EGIS assumes that diagnostic results from an external AI-based diagnostic module are presented to the operator as supplementary information to aid their overall understanding of the situation. As current research shows that many AI-based diagnostic models for nuclear power plant accidents demonstrate high performance [20–26], this study presumes the availability of reliable diagnostic information, which serves to assist the operator's Situation Awareness independently of the core functions of EGIS.

This 'optimized information' is not merely a list of data but a cohesive support framework designed to facilitate the operator's cognitive loop of Action → Feedback → Understanding. Specifically, the Task Block Browser provides clear guidance on 'what to do' (Action), the CSF Score Evaluator offers intuitive feedback on 'how the plant is responding' (Feedback), and the Plant Status Monitor delivers a deep, causal explanation of 'why it is happening' and its potential consequences (Understanding). This dynamic interaction between the components ensures that operators can maintain comprehensive situation awareness and make effective decisions.

2.2. Key system components

- Task Block Browser: Employs a functional-hierarchical task grouping framework to organize and present tasks. By continuously monitoring plant parameters, it identifies and displays only those tasks that meet specific execution criteria. This selective task presentation significantly reduces operator cognitive load while ensuring all necessary actions are addressed.
- CSF Score Evaluator: Implements a fuzzy logic-based assessment system that converts discrete safety function states into continuous numerical scores. This approach enables operators to detect progressive shifts in plant safety parameters and recognize potential problems at an early stage, prior to reaching critical limits. The system provides scores on a 0–100 scale, with clear visual indicators for different safety thresholds.
- Plant Status Monitor: Utilizes Multilevel Flow Modeling (MFM) to create an intuitive representation of plant systems and their interrelationships. This component not only displays current system states but also provides predictive information about potential consequences of system anomalies or operator actions.

2.3. Interface integration

The integrated interface consolidates information from all three components into a cohesive display that supports efficient operator decision-making. The interface employs a carefully designed color-coding system and hierarchical information structure to ensure critical information is immediately apparent while maintaining access to detailed data when needed.

3. System development

3.1. Analysis of emergency operating procedures

This investigation conducted a systematic analysis of existing emergency operating procedures to develop an effective dynamic emergency operating procedure system. The emergency operating procedures of the Compact Nuclear Simulator (CNS), developed by the Korea Atomic Energy Research Institute and based on Westinghouse 3-loop pressurized water reactor procedures, were selected for analysis.

Emergency operating procedures serve as a key element in implementing the defense-in-depth strategy of nuclear power plants. Prior to the Three Mile Island-2 (TMI-2) accident, event-based procedures were predominantly used. However, after limitations in responding to unforeseen accidents became apparent, a combination of event-based and symptom-based procedures was adopted.

The analysis revealed that CNS emergency operating procedures consist of three main components: initial emergency response procedure (E−00), Optimal Recovery Guidelines (ORG), and Function Recovery Guidelines (FRG). This structure closely parallels the Standard Post Trip Actions (SPTA), Optimal Recovery Procedures (ORPs), and Function Recovery Procedures (FRPs) used in the APR1400.

Through procedure analysis, tasks were classified into three distinct categories. Common Tasks, which are basic operations performed across most procedures, have been identified as a major source of excessive procedure volume and redundancy. Scenario-Specific Tasks are operations performed only in specific accident scenarios, with execution determined by diagnostic results. Status-Specific Tasks include operations performed when the plant faces extreme conditions or when safety systems become unavailable.

The analysis of CNS EOPs categorized procedural tasks into four main types: Diagnosis Tasks, Common Tasks, Scenario-Specific Tasks, and Status-Specific Tasks. Among these, Diagnosis Tasks were assumed to be handled by an automated diagnostic module and were therefore excluded from the analysis.

- **Common Tasks:** Fundamental tasks shared across most procedures, such as plant status checks and basic control operations.
- **Scenario-Specific Tasks:** Tasks performed only in specific scenarios, executed based on diagnostic results.
- **Status-Specific Tasks:** Tasks carried out under extreme conditions when safety systems are unavailable or based on the operator's judgment.

The E−00 procedure integrates the roles of SPTA and Diagnostic Action (DA), with 19 out of its 22 steps categorized as Common Tasks. ORPs are divided into E−01 (Loss of Coolant Accident, LOCA), E−02 (Main Steam Line Break, MSLB), and E−03 (Steam Generator Tube Rupture, SGTR), primarily consisting of Common Tasks and Scenario-Specific Tasks. In contrast, FRPs focus on maintaining CSFs and are mainly composed of Common Tasks and Status-Specific Tasks. The distribution of task categories within CNS procedures is illustrated in Fig. 4.

The analysis revealed significant redundancy in Common Tasks across procedures, emphasizing the need for a dynamic procedural system. By designing a dynamic EOP, real-time plant conditions can be reflected, and only the necessary tasks can be provided to operators, enhancing procedural efficiency and operational safety.

A notable finding was the significant redundancy of Common Tasks across procedures. This redundancy remains an unresolved issue even in existing procedure systems.

Based on these analytical findings, the following requirements for the new system were identified:

1. The system must selectively provide only necessary tasks based on real-time plant conditions.

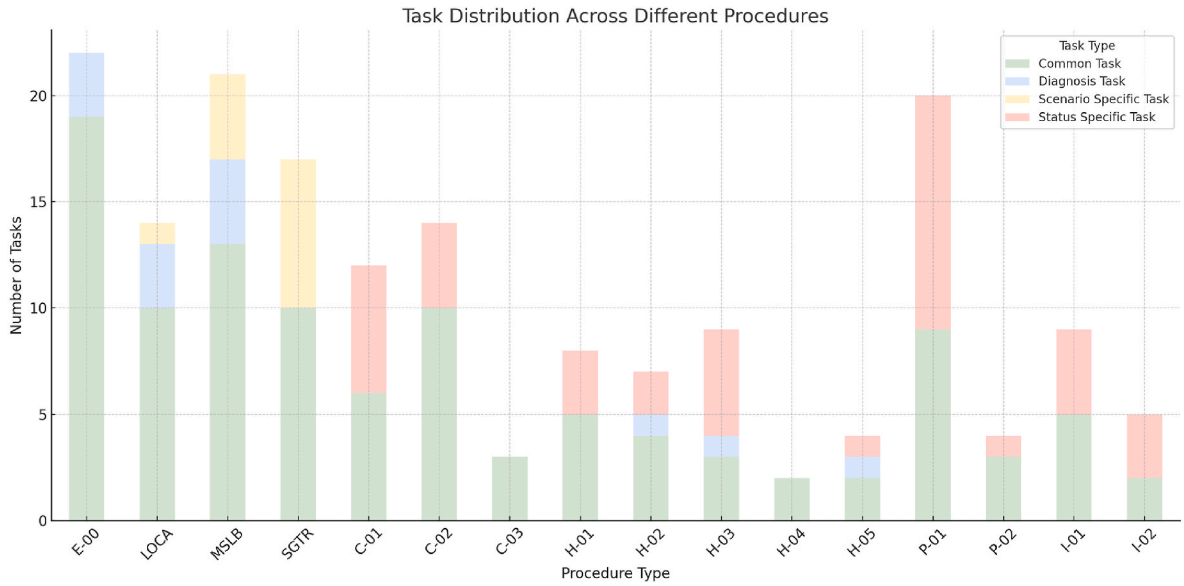

Fig. 4. EOP analysis result (task distribution result for ORP and FRP in CNS EOP).

2. A hierarchical task structure should clearly establish the relationship between individual tasks and their associated safety functions.
3. The system must effectively monitor the progress of continuous tasks.
4. An intuitive information delivery system is necessary to support operator situation awareness.

These analytical results and requirements formed the foundation for developing the three main components of EGIS: the Task Block Browser, CSF Score Evaluator, and Plant Status Monitor.

3.2. *Task Block Browser development*

The Task Block Browser was developed based on a systematic task analysis of existing Emergency Operating Procedures (EOPs) to address their inherent redundancy and inefficiency. The analysis process began by deconstructing every step of each procedure into its execution conditions and task actions. This deconstruction is purposeful: it enables a rule-based logic where the system can automatically filter necessary tasks by comparing real-time plant data against the defined conditions, thus automating low-level judgments. This analysis revealed that a significant portion of the EOPs consists of 'Common Tasks'—tasks for checking and controlling various systems that are redundantly described across multiple procedures.

To resolve this issue of redundancy, this study introduces the Functional-Hierarchical Task Grouping Framework. This framework's core methodology is to reclassify the deconstructed tasks into three distinct types based on their execution context, and then to structure them hierarchically. This approach not only reduces redundancy but also clarifies the purpose behind each operator action. The three task types are defined as follows:

- **Common Task:** This group includes tasks performed based on general plant status, irrespective of a specific accident scenario or a severely challenged Critical Safety Function (CSF). A prime example is the Safety Injection (SI) system. SI operation is required following a reactor trip, and SI termination is required once the plant stabilizes. In conventional procedures, the numerous tasks needed for SI operation, such as signal verification, valve control, pump control, and flow checks, were scattered across many steps. EGIS consolidates these into a single, cohesive block.
- **Scenario-Specific Task:** These are tasks that require partial diagnostic results for their execution. For instance, in a Steam Generator Tube Rupture (SGTR) scenario, the task of isolating the faulted steam generator is essential. To perform this task, a diagnosis identifying which steam generator has failed must precede it. Task blocks that require such specific diagnostic conditions are classified into this group.
- **Status-Specific Task:** As seen in recovery procedures, there are special tasks instructed only under specific conditions where a CSF is severely challenged, rather than in typical situations. Task blocks activated based on these CSF status conditions fall into this category.

Based on this classification, the task blocks are organized hierarchically (see Fig. 5). To revisit the SI example, the scattered, detailed tasks (valve, pump, flow checks) are grouped into Component-Level subtask blocks. These are then consolidated into a higher System-Level task block, such as 'SI Operation and Termination.' This system-level block is, in turn, linked to its ultimate purpose at the highest CSF-Level: 'Core Cooling (CSF2)' and 'RCS Inventory Preservation (CSF6).' The execution conditions for each task block are also separated and linked to the corresponding block, as illustrated in Fig. 6.

This framework was developed by referencing methodologies from previous studies on task automation and procedural system development. For example, Kim and Lee proposed the Function-Based Hierarchical Framework (FHF) for designing an autonomous plant operation system using AI technologies [27,28]. Additionally, a study utilizing MFM proposed a function-oriented EOP development process, linking safety goals to functions and further connecting them to systems and tasks to enhance the systematic design of EOPs [29]. This hierarchical methodology of EGIS, inspired by such prior works, systematically connects the conditions of each task block with their higher-level task blocks, ensuring clarity and efficiency in task execution.

3.3. *CSF Score Evaluator development*

In the United States, fully analog main control rooms no longer exist. Following the Three Mile Island accident, U.S. nuclear power plants were mandated to implement the SPDS [13]. The SPDS digitally displays key plant indicators related to safety, enabling operators to assess critical safety parameters immediately. It also functions as a data recorder, allowing operators to track plant conditions during operations.

A limitation of existing SPDS systems is their discrete representation

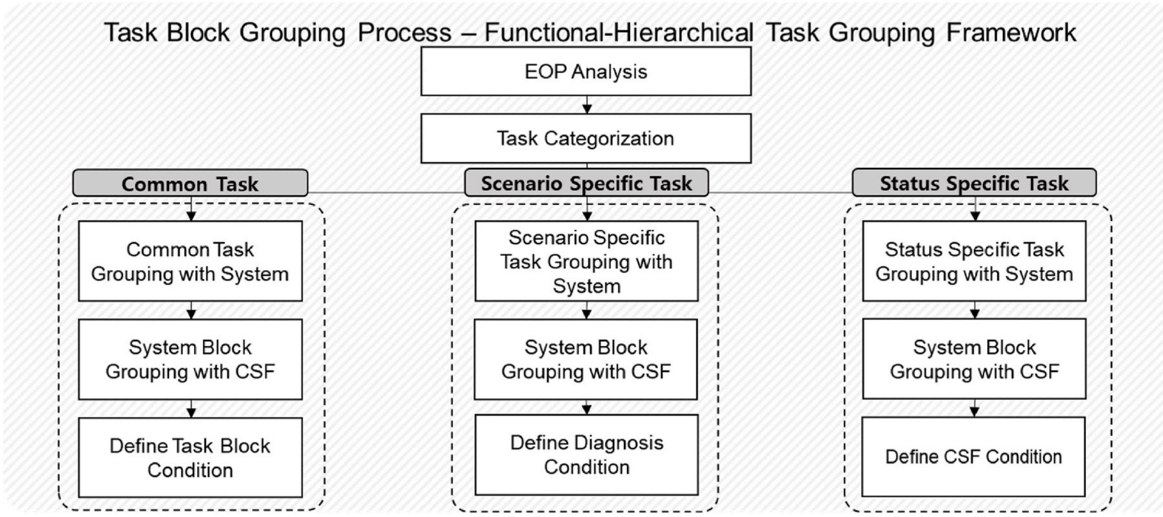

Fig. 5. Functional-hierarchical task grouping framework process.

of Critical Safety Function (CSF) results using only text and colors. This approach fails to provide trend information, making it difficult for operators to take proactive measures in response to changing plant conditions. For instance, the SPDS system implemented in CNS [30] and the SPADES + system used in APR1400 [31] displays where a CSF resides within the CSF tree and indicate its current status using color coding. To address such issues, a study developed a system utilizing fuzzy set theory to support task prioritization decisions by comparing two critical variables on a unified scale. Following a similar approach, the methodology outlined below was developed [32].

The proposed system introduces the CSF Score Evaluator, which provides a more dynamic representation of plant conditions. Since CSFs are critical to ensuring plant safety, the CSF Score Evaluator evaluates plant state variables in real-time. Traditional procedural trees evaluate CSF status by classifying plant conditions into discrete states, which limits their ability to address the dynamic nature of plant conditions. To overcome this limitation, the proposed system employs fuzzy logic to enable a continuous evaluation of CSF states.

The overall process includes the following steps (see Fig. 7):

1. Membership functions are defined for each input parameter, and inference tables are constructed based on CSF tree logic.
2. Sensitivity analysis is conducted to refine the evaluation process.
3. A CSF Score Function is developed to dynamically represent the plant's safety status.

The sensitivity analysis is crucial for calibrating the model to ensure its stability and reliability. It involves systematically adjusting the weights of input variables and the boundaries of membership functions to evaluate their impact on the final CSF score. The goal is to make the model robust against minor sensor noise while remaining highly responsive to significant changes in plant safety status.

This process transitions CSF evaluation from traditional discrete methods to a continuous assessment approach, allowing early detection of degrading conditions and supporting proactive operator responses. The development of the CSF Score Evaluator began with a comprehensive analysis of CSFs and their associated parameters. The process of generating a score using fuzzy logic can be detailed in three steps, using the evaluation of core cooling status (which considers Core Exit Temperature (CET) and subcooling margin) as an example:

- Fuzzification: Raw, continuous sensor data is converted into linguistic variables. For instance, a CET value of 320 °C is mapped to fuzzy sets like 'Normal,' 'High,' or 'Critical,' with a corresponding degree of membership for each.
- Inference: A predefined rule base, constructed from expert knowledge and CSF tree logic, is applied. An example rule would be: "IF CET is 'High' AND subcooling margin is 'Low,' THEN Core Cooling is 'Challenged'." The system evaluates all relevant rules to produce a fuzzy output.
- Defuzzification: The fuzzy output is converted back into a single, crisp numerical value. This final step generates the intuitive 0–100 score, which provides clear trend information, enabling operators to detect subtle changes in plant safety status and respond before conditions reach critical thresholds.

3.4. Plant status monitor development

The Plant Status Monitor was developed to provide functional information (future state and consequence state) in the form of a Master Logic Diagram (MLD) and to visually display the current system status according to the system flow. For this purpose, MFM was utilized to model CSFs, plant systems, and components.

MFM is a qualitative evaluation-based functional modeling methodology that represents relationships between systems through goal-means relationships and whole-part structural decomposition and integration [33]. It expresses components as functions and models them as flow systems involving mass and energy flows, providing an optimal approach to systematically organizing and grouping complex systems and functions. MFM has been recognized by the IAEA (2008) as a modeling technique for nuclear power plants [34] and has proven its utility through various studies, including applications in diagnosing large-scale nuclear systems (PWRs, BWRs) [35], developing severe accident response strategies [36], analyzing core damage scenarios [37], and conducting root cause analysis for complex alarm systems [14].

For this study, MFM was chosen over other modeling techniques, such as 'black-box' AI models, precisely because of the 'glass-box' transparency inherent in its functional, goal-oriented approach. This is ideal for emergency situations, as it allows operators to understand why a system is failing and how that failure impacts higher-level safety objectives. This approach is crucial for building operator trust and preventing the 'Out-of-the-Loop' problem, making MFM an appropriate choice for a human-centric support system like EGIS.

The MFM model for this study was constructed based on the design of the Compact Nuclear Simulator (CNS), focusing on the complex relationships within the Nuclear Steam Supply System (NSSS). The development process was a systematic, top-down approach involving

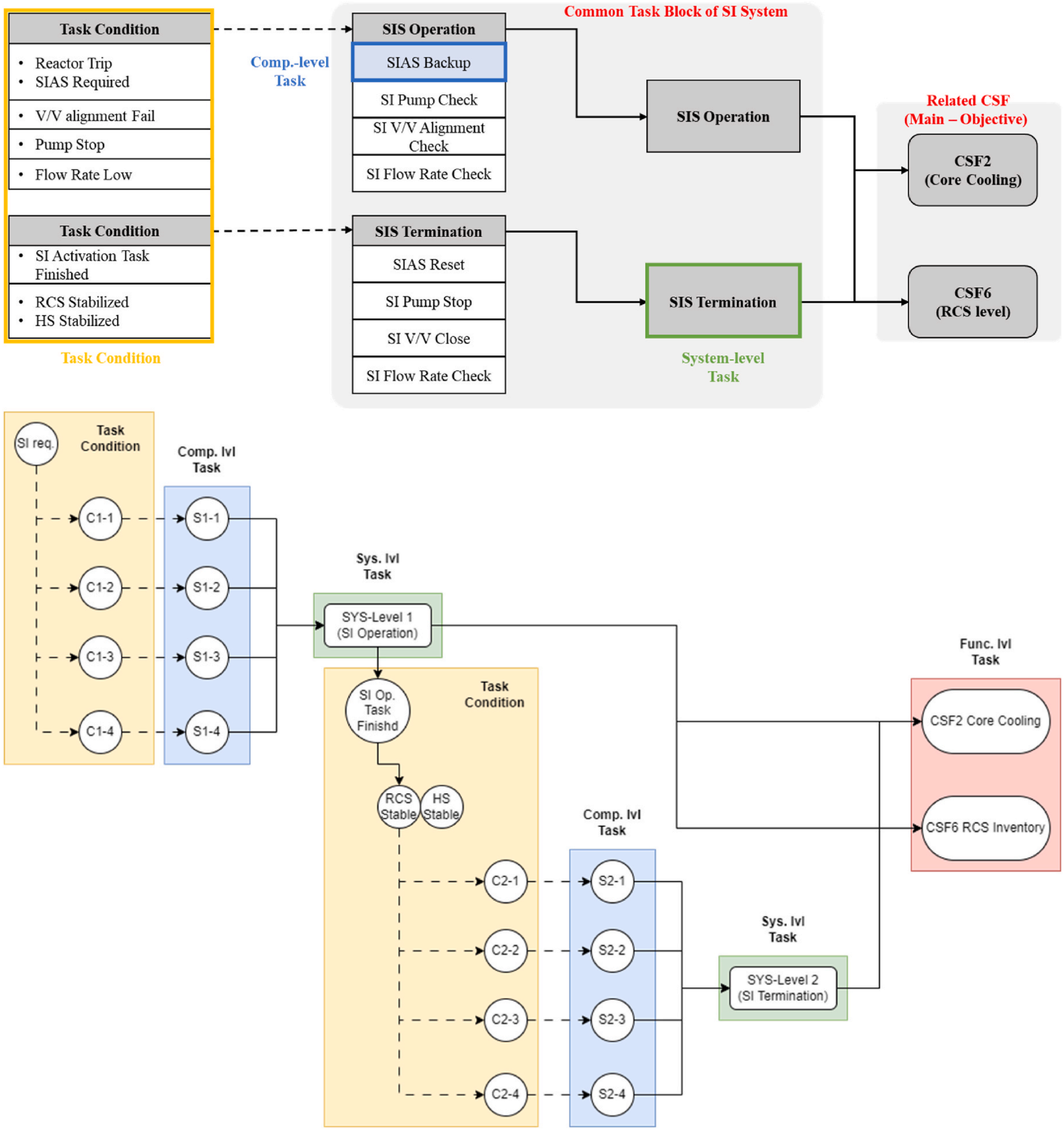

Fig. 6. Common task block grouping example – condition-task relation tree.

three main steps:

- **Defining the Highest-Level Objectives (Goals):** The process began by defining the highest-level goals of the plant during an emergency, which are the six CSFs shown at the top of Fig. 8: Subcriticality, Core Cooling, Heat Sink, RCS Integrity, Containment Integrity, and RCS Inventory. These represent the fundamental safety objectives that must be maintained to prevent core damage and ensure plant stability.
- **Functional Decomposition into Means-End Hierarchy:** Next, each CSF goal was decomposed into the necessary sub-functions and the physical systems that act as the means to achieve these ends. This creates the hierarchical structure visible in Fig. 8. For instance, to achieve the 'Heat Sink' goal (CSF3), the model identifies the functions of the Main Steam (MS), Feedwater (FW), and Auxiliary Feedwater (AFW) systems as the primary means. Similarly, the 'Core Cooling' goal (CSF2) is supported by the functions of the Reactor Coolant System (RCS) and the Safety Injection (SI) system. This step establishes a clear causal link, showing how specific plant systems directly contribute to achieving overall safety objectives.
- **Modeling Mass-Energy Flows and Component Functions:** Finally, the mass and energy flows within these physical systems were modeled at the most granular level. In MFM, a flow structure consists of functions like source (providing mass/energy), transport (moving it), storage, and sink. Individual components were represented by the functional roles they play in these flows. For example, within the Safety Injection system, the Refueling Water Storage Tank (RWST) is modeled as a source function, the SI pumps are modeled as a transport function that provides motive force, and the associated pipes and valves also contribute to the transport function. By modeling these functional relationships for all relevant systems, a comprehensive network was created that represents the plant's operational logic, not just its physical layout. The overall structure of this interconnected model is presented in Fig. 8.

This MFM model provides two main types of information to

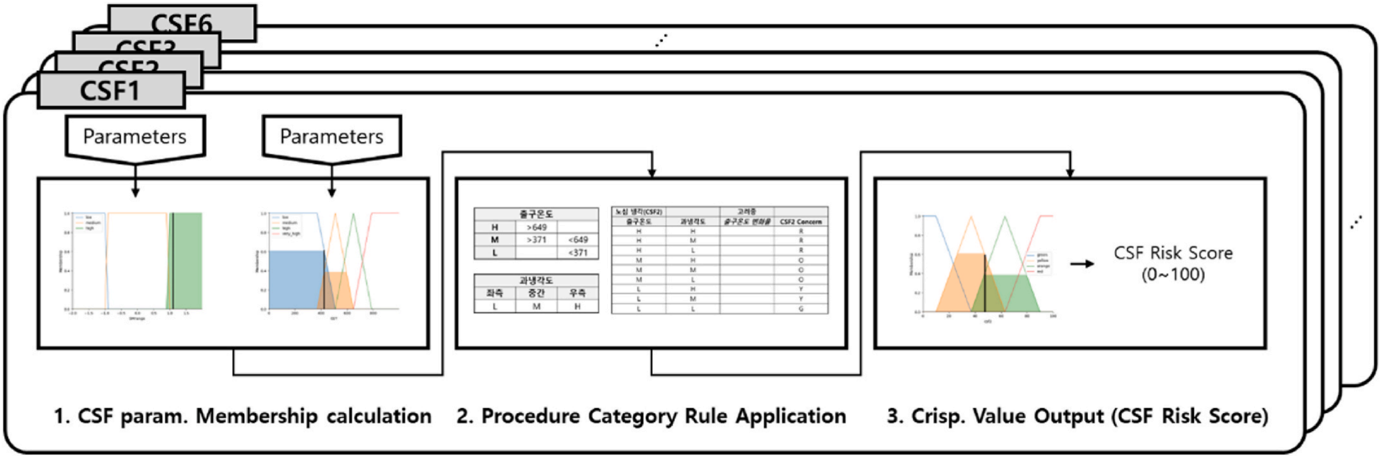

Fig. 7. CSF score evaluation process.

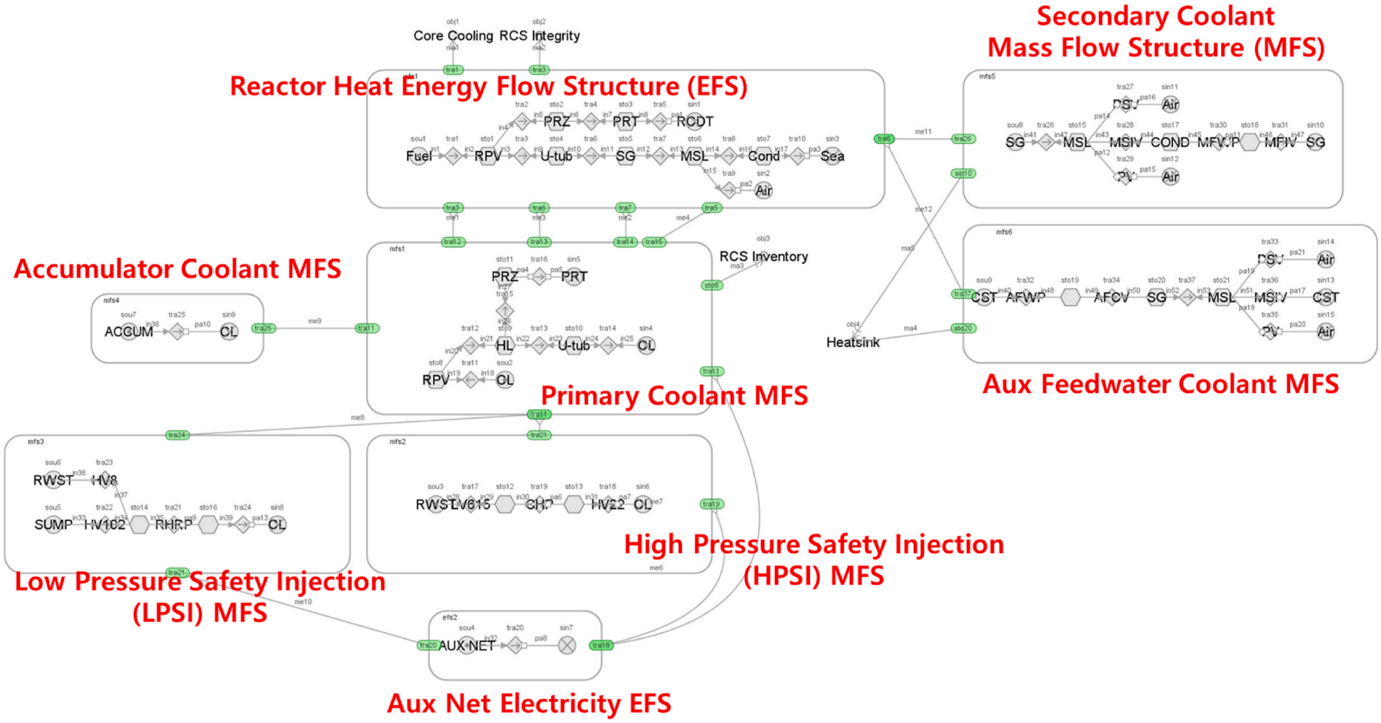

Fig. 8. Overall MFM model for NSSS in CSF Emergency Operation.

operators through two sub-monitors: the Function Status Monitor and the System Status Monitor.

Function Status Monitor.

The Function Status Monitor aims to analyze the impact of failures or anomalies during procedural tasks on plant systems and safety functions. It uses abnormal states as input triggers to update the statuses of MFM sub-functions, perform predictive analyses, and generate a Consequence Tree. To ensure intuitive understanding, the system converts this tree into a Master Logic Diagram (MLD), which presents a simplified and hierarchical relationship, following the implementation approach of the existing research of Risk Evaluator [38].

For instance, in a simulation of Charging Pump (CHP) flow reduction, an emergency triggers the Safety Injection Actuation Signal (SIAS), and the CHP assumes the role of the Safety Injection Pump (SIP). During this process, the original Volume Control Tank (VCT) path is closed, and the Refueling Water Storage Tank (RWST) path is opened to perform safety injection. A diagram illustrating this anomaly propagation (Fig. 9) clearly shows the impact on major safety functions, particularly CSF2 (Core Cooling) and CSF6 (RCS Inventory).

System Status Monitor.

The System Status Monitor focuses on summarizing and visualizing the current system status to enhance operator situation awareness. Based on MFM, it verifies whether flow structures, including Source, Transport, Storage, Balance, and Sink, are functioning correctly. If any sub-function is unavailable, the information is propagated to the higher-level flow to provide a comprehensive overview of the system status.

For example, the Low-Pressure Safety Injection (LPSI) system flow involves water supplied from the RWST and the sump inside the containment building, passing through isolation valves and the Residual Heat Removal Pump (RHRP) to the RCS cold leg. The system checks five key elements—signal activation, valve alignment, pump condition, tank status, and flow generation. If all elements are verified and the flow is

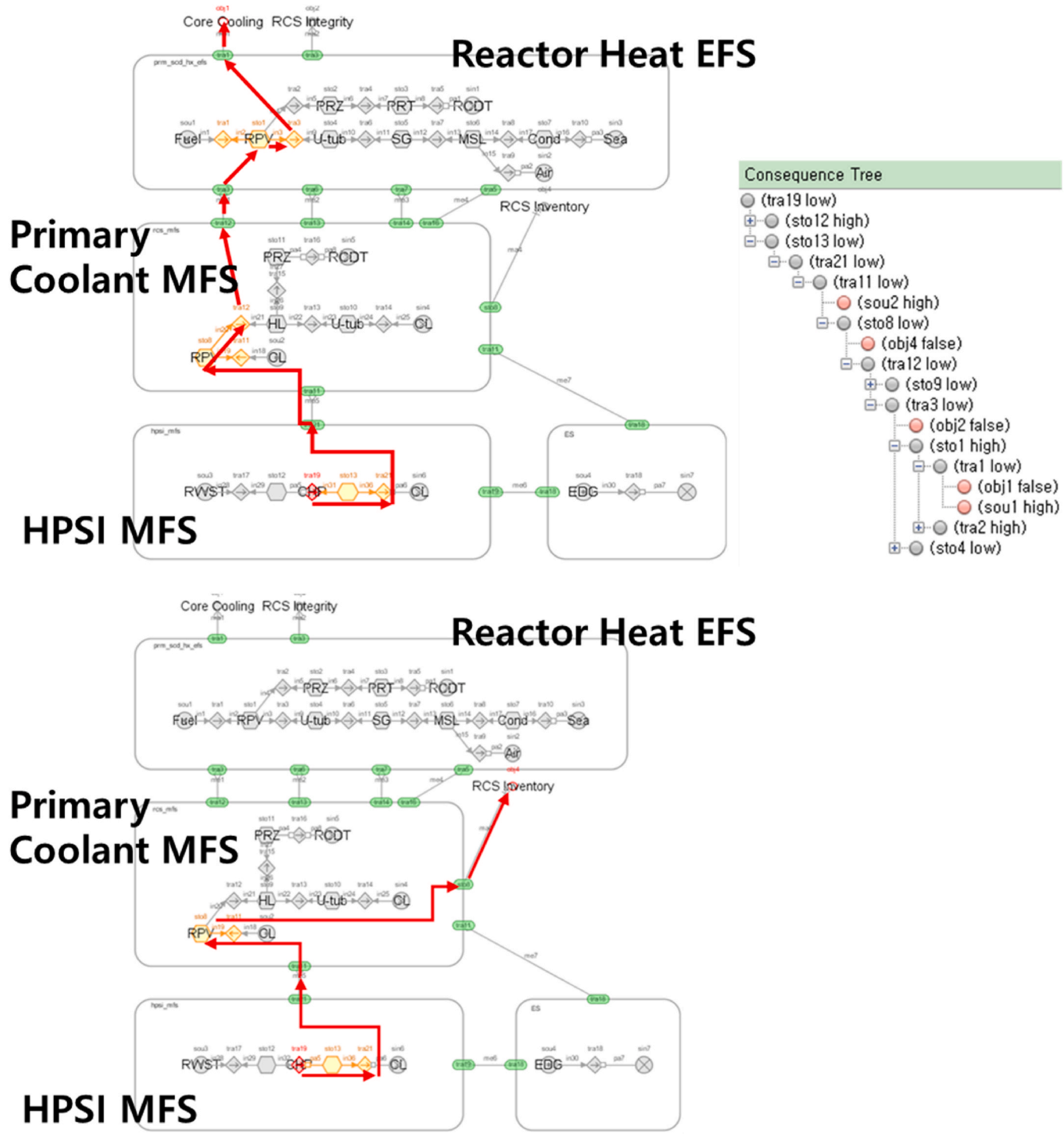

Fig. 9. Function status monitor MFM model consequence tree example (CHP anomaly).

successfully formed, the interface indicates Operation (Flow Generation) status with color coding. Conversely, if the flow is not formed, the system displays Stop, or Unavailable if the system is inoperable (see Fig. 10).

Both monitors provide essential insights—predictive scenarios and real-time system statuses—that improve operational efficiency and safety in the plant.

3.5. Interface integration development

The interface integration phase focused on combining information from all three components (Task Block Browser, CSF Score Evaluator, and Plant Status Monitor) into a unified display system. The interface layout was designed based on operators' natural visual workflow, positioning critical information for immediate recognition while maintaining access to detailed data when needed. (see Fig. 11).

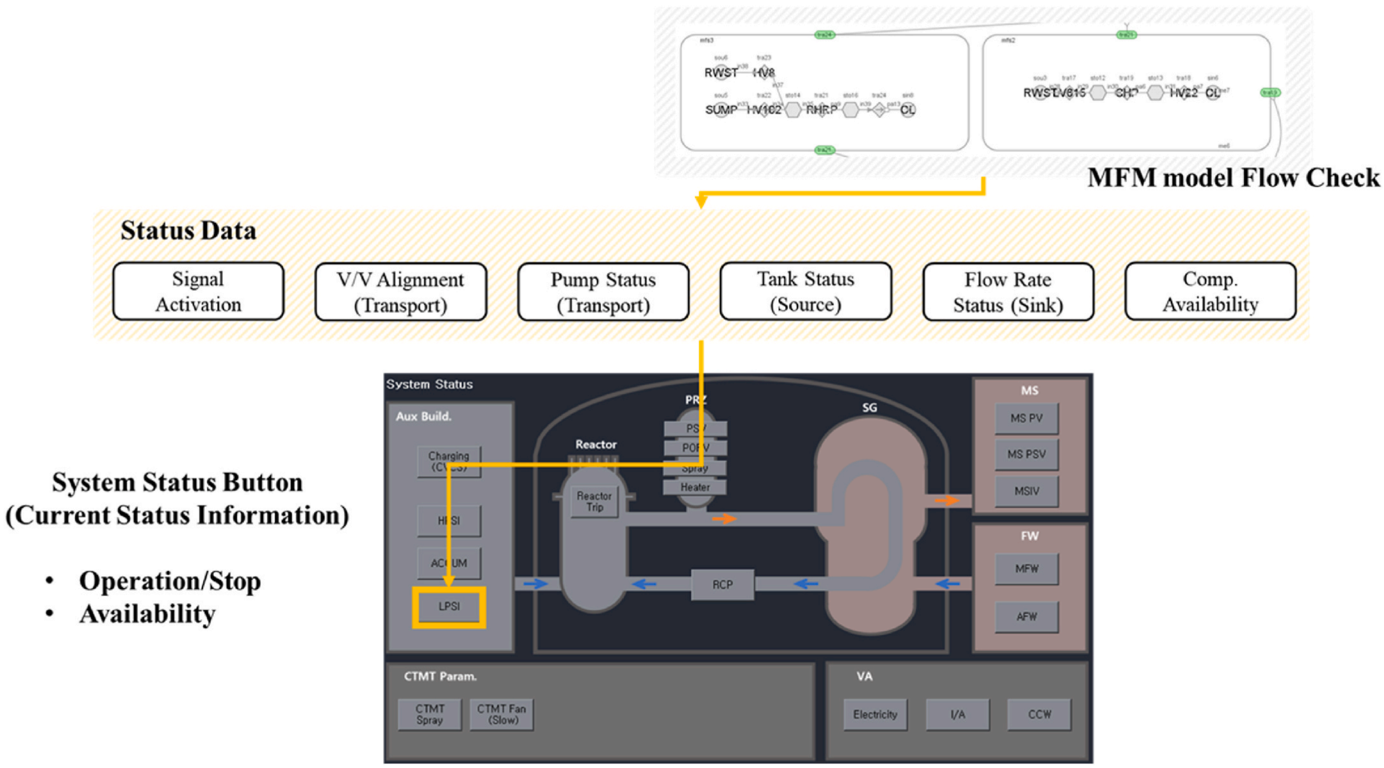

Fig. 10. CNS MFM model example for system status monitor.

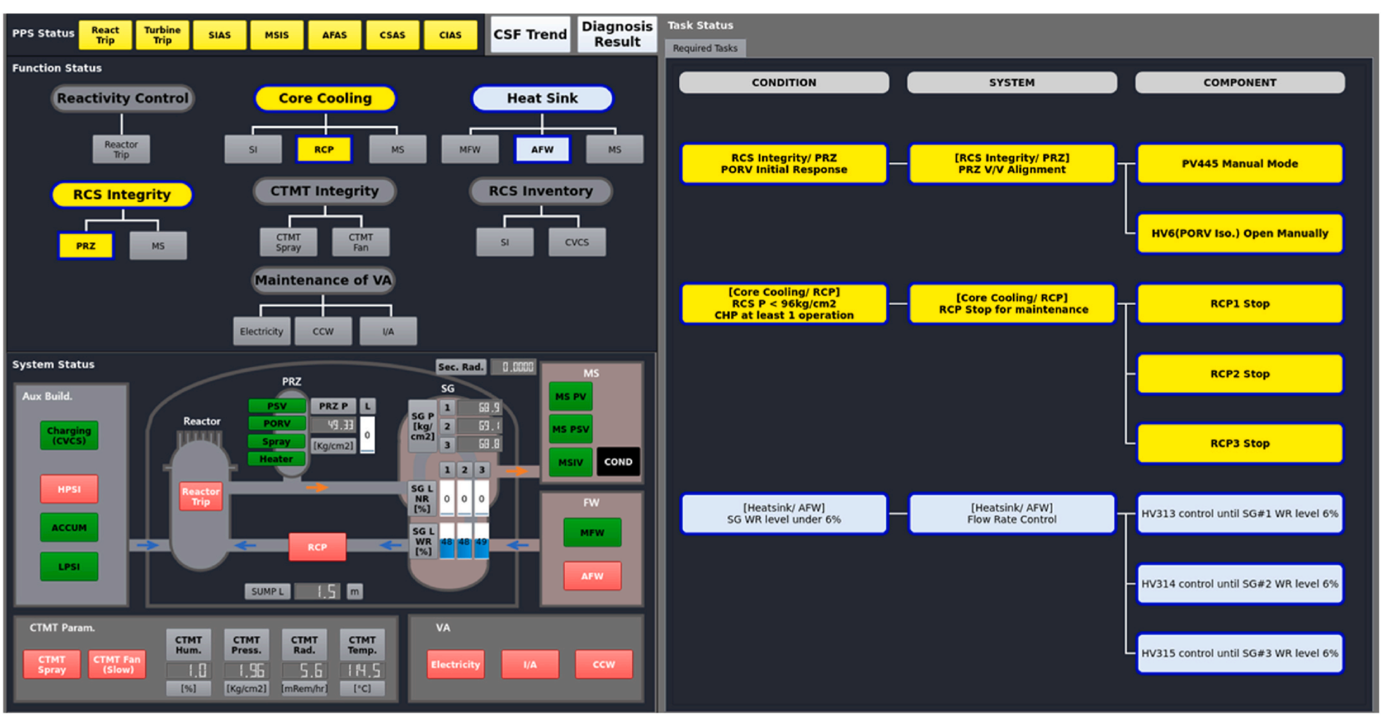

Fig. 11. EGIS interface overview.

The integrated interface consists of 6 main display areas (see Table 1). The interface layout can be broadly divided into left and right sections. At the top left are the PPS Status, CSF Trend button, and Diagnosis Result button. Among these, the PPS (Plant Protection Signal) Status area, located at the very top left, displays critical PPS information essential for emergency operation in nuclear power plants. When a corresponding signal is triggered, a yellow alarm is displayed. To the right of this area are the CSF Trend and Diagnosis Result buttons. Clicking the CSF Trend button brings up the CSF Trend Window Interface shown in the figure below. The Diagnosis Result button, although supplementary, provides operators with AI-generated diagnostic results to enhance their awareness of emergency plant conditions. The middle

Table 1
EGIS interface section mapping: Functions and roles.

Interface Section	Related Function	Description
PPS Status Window	N/A	Displays critical signal alarm buttons associated with the highest-priority tasks in the EOP
CSF Trend Button	CSF Score Evaluator	Displays safety function scores and trends
Diagnosis Button	Diagnosis Module (Assumption)	Displays diagnosis result
Function Status Window	Plant Status Monitor (Function Status Monitor)	Shows functional consequences using simplified Master Logic Diagrams
System Status Window	Plant Status Monitor (System Status Monitor)	Presents system status using flow-based visualization
Task Status Window	Task Block Browser	Displays task blocks in a hierarchical structure, with expandable details and context menus for manual status control

left contains the Function Status Window, while the bottom left houses the System Status Window. These displays allow operators to quickly identify which systems and safety functions are affected by current tasks, as well as assess the current status of those systems. Finally, on the right side is the Task Status Window. Based on system analysis, this window selectively presents only the necessary actions that operators need to take.

The Task Status Window receives information from the Task Block Browser and provides operators with necessary task information. It is composed of three columns: Condition, System, and Component. Each column represents task conditions, system-level tasks, and component-level tasks, respectively, and intuitively displays the interrelationships between tasks. Task statuses are categorized as Needed, In Progress, Unavailable, or Completed, and their priority determines the propagated color status for higher-level task blocks. Tasks are automatically removed upon completion, and operators can manually adjust task statuses if needed.

The Function Status Window visually conveys task statuses and anomaly information provided by the Function Status Monitor. It utilizes Multilevel Flow Modeling (MFM) to generate Consequence Trees, which are then converted into Master Logic Diagram (MLD) format for display. This allows operators to clearly understand the impacts of tasks on systems and safety functions while tracking them in real time. The Function Status Window intuitively shows task interdependencies and system status changes, enabling operators to respond swiftly and effectively during emergency situations.

The System Status Window provides a visual representation of system flow integrity based on information from the System Status Monitor within the Plant Status Monitor. It verifies key elements such as signal activation, valve alignment, pump condition, tank status, and flow generation, presenting the results using graphics and color coding. The window clearly displays the operational status of the system (e.g., Operating, Stopped, or Unavailable), allowing operators to quickly grasp critical procedural information. This visual tool ensures operators can efficiently assess system functionality and take appropriate actions when necessary.

The CSF Trend Window displays the real-time results calculated by the CSF Score Evaluator, categorizing CSF scores with color-coded ranges. This enables operators to evaluate the overall plant status without needing to review individual variables. If necessary, the Detail Window provides trend information for variables associated with specific CSFs, allowing operators to predict state changes and take proactive measures.

Table 2
Color symbol logic definition in MLD.

Category	Color Symbol	Meaning
System Status Window	System (red)	Stop/Close/Break
	System (green)	Operation/Open/Energizing
	System (black)	Unavailable
PPS Window	System (yellow)	Signal/Alarm Activated
Task Status Window	Task (green border)	Task finished
	Task (blue border)	Continuous Task
	Task (yellow, blue border)	Task need to conduct (Blink)

EGIS integrates task status information, plant status monitoring, and CSF trend analysis to enhance operator situation awareness and support rapid and efficient decision-making during emergencies.

The EGIS interface applies Color Symbol Logic to provide operators with intuitive information (see Table 2). The status of valves or equipment is displayed as follows: green indicates a closed or stopped state, red indicates an open or operating state, black background represents an Unavailable status, and yellow background highlights alarms or critical signals. For task blocks, additional information is conveyed through border colors. A green border signifies that the task has been successfully completed, while a blue border indicates tasks requiring continuous execution. Tasks requiring immediate operator action are displayed with a yellow background and a blinking blue border, effectively drawing attention. This Color Symbol Logic enables operators to intuitively understand the overall plant status and the state of individual tasks, serving as a highly effective visual tool for supporting prompt and effective responses during emergency situations.

The CSF Trend Window displays the real-time results calculated by the CSF Score Evaluator, categorizing CSF scores within a range of 0–100 and presenting them in a graphical format (see Fig. 12). Scores are color-coded as Green (0–25), Yellow (25–50), Orange (50–75), and Red (75–100), allowing operators to quickly grasp the status of key variables. Unlike traditional CSF trees, this system enables real-time status tracking. CSF scores are arranged in a 2-row by 3-column format in the order of Subcriticality, Core Cooling, Heatsink, RCS Integrity, Containment Integrity, and RCS Inventory, providing operators with a comprehensive overview of critical variable states without the need to check individual variables. For additional details, the Detail Window allows operators to view trends for variables associated with specific CSFs. For instance, in the case of CSF2 (Core Cooling), operators can analyze the trends of Core Exit Temperature (CET) and Subcooled Margin (SM) to assess whether they fall within the safe range. This trend analysis helps identify the causes of CSF score changes and anticipate state shifts before scores reach critical levels, enabling proactive stabilization measures. The CSF Trend Window serves as a vital tool for reducing the workload associated with situation awareness by providing high-level trend information and supporting efficient operator responses.

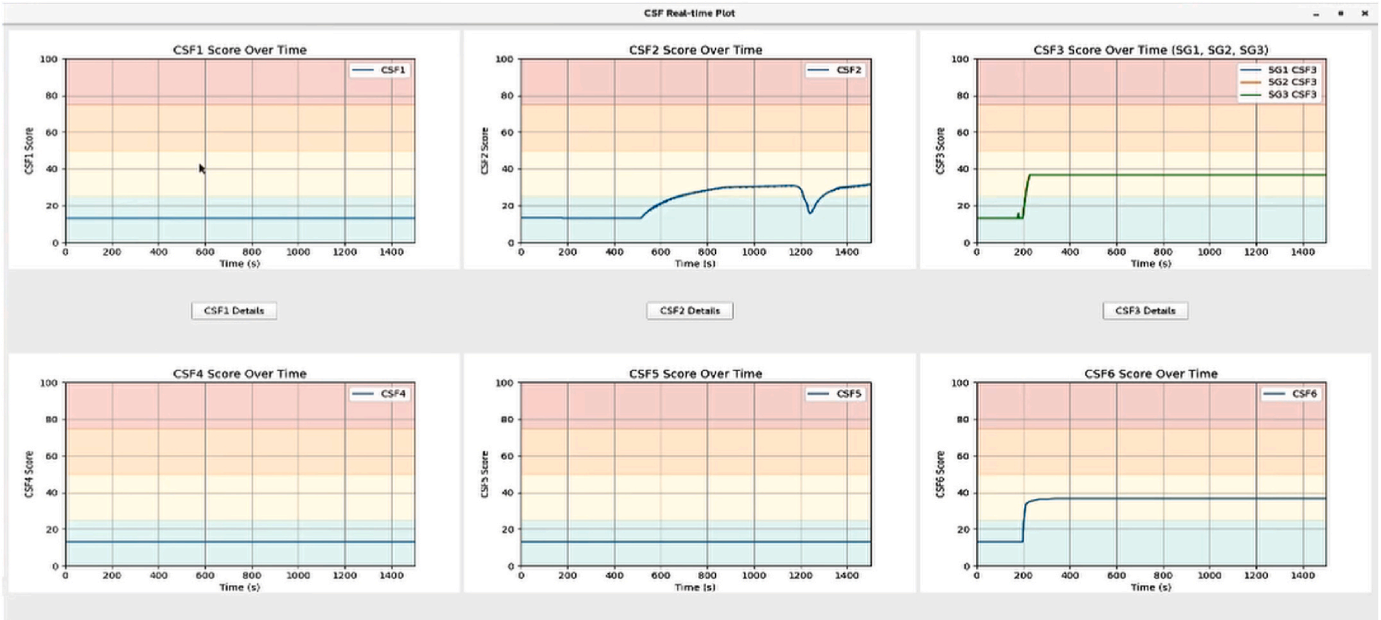

Fig. 12. CSF trend window interface.

4. Case study

4.1. Implementation overview

This study conducted a pilot study to verify the functionality of the developed system and design experimental scenarios for subsequent evaluation. The Compact Nuclear Simulator (CNS) of the Westinghouse 960 MW model, developed by the Korea Atomic Energy Research Institute (KAERI) [39,40], was utilized for this purpose. CNS is a tool capable of simulating various nuclear power plant accident scenarios, providing a suitable environment for system performance evaluation and experimental scenario design.

Analysis of the accident scenarios provided by CNS and Emergency Operating Procedures (EOPs) identified the Loss of Coolant Accident (LOCA) as the most appropriate scenario for verifying system performance. This scenario involves a pipe break of 20 cm^2 and was designed to evaluate whether the interface system outputs procedures correctly and whether each interface window functions properly under emergency conditions. In this scenario, operators follow paper-based EOPs starting with steps 1 to 21 of the E−00 procedure before transitioning through a diagnostic process to the E−01 procedure. They then perform steps 1 to 11 of the E−01 procedure until meeting the entry conditions for the S-1.2 procedure (cooling and depressurization following a loss of reactor coolant). Subsequently, operators transition to S-1.2 and proceed to step 4, which involves cooling the reactor to a cold shutdown state. Considering the characteristics of the CNS environment and experimental time constraints, the depressurization target was set at 45 kg/cm^2, as determined by pilot testing.

The paper-based EOP consisted of 36 high-level tasks, including 3 diagnostic tasks. The developed system was designed to replace 33 of these tasks, and the pilot study identified that operators needed to manually perform 6 tasks using the EGIS and PBP systems. Additionally, the study verified the functionality of the CSF Trend Window in accurately displaying plant status. This evaluation confirmed that the system provides intuitive information on plant status during emergencies, enabling operators to quickly assess key variable states.

The pilot study served to validate the system's core functionalities and identify areas requiring evaluation in the main experiment. A structured observation sheet was used to document experimental findings systematically. This process confirmed the interface's effectiveness in delivering appropriate information to operators, contributing to reduced task completion times and minimized human error.

4.2. System performance analysis

The case study focused on evaluating three key aspects of EGIS: Task Provision Performance:

- The Task Block Browser successfully identified and presented only the necessary tasks from the 36 high-level tasks in the paper-based EOP
- Automated verification of plant parameters reduced the number of manual verification tasks
- The hierarchical task structure effectively communicated both immediate actions and their safety implications

Safety Function Monitoring:

- The CSF Score Evaluator provided continuous tracking of safety parameters
- Early detection of parameter trends enabled proactive operator response
- Integration of multiple parameters into normalized scores simplified system status assessment

Plant Status Visualization:

- The Plant Status Monitor displayed system relationships and potential consequences
- Color coding and graphical representations displayed plant status
- Real-time updates of system conditions supported operator situation awareness

The pilot test was conducted with seven graduate students in nuclear engineering, all of whom had over 10 h of experience operating the CNS or had completed at least one semester of a CNS operation course. Each participant performed one scenario in the PBP environment and another in the EGIS environment, resulting in a total of 14 test cases. The tests were based on the same scenario and focused on comparing task performance and error rates between the two environments.

Table 3
Human error result in PBP.

Subject	PBP Key Task Error (Step Demand: 6)	PBP Remain Task Error (Step Demand: 27)	Diagnosis Error (Step Demand: 3)
1	0	0	0
2	1	3	1
3	0	0	0
4	0	0	0
5	0	0	0
6	0	2	0
7	1	0	0
Total	2	5	1

Table 4
Human error rate.

Subject	PBP Key Task Error	PBP Remain Task Error	Diagnosis Error	Total
Human Error Rate (%)	4.762	2.646	4.762	3.175

In the EGIS test group, tasks that could be practically observed were defined as Key Tasks, with a total of six demands identified. Diagnostic tasks, on the other hand, were excluded from the evaluation since the EGIS system assumes these tasks are performed by an artificial intelligence model, leading to the exclusion of three demands. Additionally, 27 other demands were excluded because they could not be observed during the test. As a result, only six demands were observable in the EGIS test group, compared to 36 demands in the PBP test group.

An analysis of task performance revealed that human errors occurred exclusively in the PBP environment, while no errors were observed in the EGIS test group. This was attributed to the lower task demand in the EGIS system and the real-time reminders provided via the Task Status Window, which continuously displayed pending tasks until they were completed.

In the PBP test group, a total of eight human errors were observed across all subjects. As shown in Table 3, these consisted of two errors in the key task category (step demand: 6), five errors in the remaining task category (step demand: 27), and one diagnostic error (step demand: 3). This corresponds to error rates of 4.762 % for key tasks, 2.646 % for remaining tasks, and 4.762 % for diagnostics, resulting in an overall human error rate of 3.175 % for the PBP group (Table 4). In contrast, no human errors were observed in either EGIS condition (EGIS without UI and EGIS with UI), resulting in a 0 % error rate. These findings demonstrate that the EGIS system effectively eliminates observable human errors under experimental conditions, particularly for student-level operators.

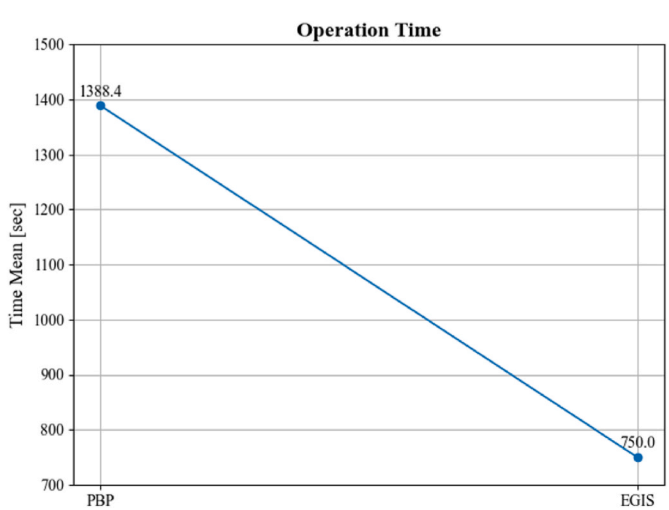

Fig. 13. Operation time result.

Task completion time was used to compare the procedure execution speed across test groups and analyze the impact of each system environment on operational efficiency. The results showed that the average task completion time was 24 min and 8 s in the PBP environment and 12 min and 30 s in the EGIS environment. Statistical analysis was conducted using the Tukey test, which yielded a p-value of 0.0017 and Cohen's d effect size, which yielded 2.1474, confirming statistical significance (see Fig. 13).

In conclusion, this study conducted a pilot study using scenarios within the EGIS environment to verify the implementation of system functionalities and to briefly analyze the impact on task errors and task performance. The results confirmed that the EGIS system was effective in reducing errors and achieving task goals more quickly when applied to student-level operators. These findings suggest that the EGIS system contributes to improving task efficiency and enhancing operator performance.

5. Conclusion

This study aimed to address the static limitations of traditional emergency operating procedures in nuclear power plants by developing EGIS, an integrated system designed to dynamically support operators during emergencies. EGIS provides task blocks based on real-time plant conditions, continuously evaluates CSF scores, and intuitively visualizes plant system status. These features were developed to enhance operator performance and reduce human errors in high-stress scenarios.

The pilot study conducted using a Loss of Coolant Accident (LOCA) scenario in the Compact Nuclear Simulator demonstrated EGIS's potential effectiveness. Compared to paper-based procedures, EGIS reduced task completion time by approximately 48 %, highlighting its efficiency in emergency task management. Furthermore, while the paper-based procedure group exhibited a 3.175 % human error rate, the EGIS group experienced no observable errors during tests involving student operators. These findings emphasize the system's ability to minimize human errors through dynamic task provision, real-time status monitoring, and intuitive interfaces, thereby supporting more precise and effective operator responses.

Despite the promising results, this study remains an initial validation, limited to a pilot test environment. To achieve practical application in operational settings, further research is necessary. This includes expanding validation across a variety of accident scenarios to confirm EGIS's adaptability and reliability in diverse emergency conditions. In particular, systematic human factors experiments focusing on task performance, workload reduction, and situation awareness will be essential. Additionally, feedback from professional operators in actual plant environments must be incorporated to refine the system interface and enhance functionality, ensuring alignment with real-world requirements.

This research holds significance in proposing a dynamic and innovative approach to emergency operation support within digital main control room environments. By addressing the limitations of static procedures, EGIS represents a step forward in enhancing the safety and efficiency of nuclear power plant operations. Through continued validation and iterative improvement, EGIS has the potential to become a cornerstone technology for modernizing emergency response systems in the nuclear energy sector, ultimately contributing to greater operational resilience and safety.

CRediT authorship contribution statement

Jung Sung Kang: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Seung Jun Lee:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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