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Development of Integrated Dynamic Emergency Operating Procedure with Hierarchical Structure

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1. Introduction

The operation of a nuclear power plant is divided into three categories: normal, abnormal, and emergency operation [1]. During emergency operation, emergency operating procedures (EOPs) are employed to prevent operator errors. In an emergency accident, the situation can rapidly change, triggering numerous alarms in various ways. It is therefore essential to have well-designed EOPs in place to prevent operator error. Initially, EOPs took the form of paper-based procedures (PBPs). While PBPs were effective in maintaining safe plant operation for many years, they were also recognized as a potential source of human error [2].

PBP is a static system, but a power plant is a dynamic system. Due to this difference in characteristics, PBP is designed to respond to various situations. This requires the operator to filter out irrelevant information in order to find the part related to the current work, which can lead to incorrect responses and wasted time. Therefore, operators must use external information sources such as drawings or expertise in addition to procedures to ensure accurate understanding of the current plant [2].

The advancement of technology is resulting in a transition from traditional analog Main Control Rooms (MCRs) [3, 4] to digitalized MCRs, accompanied by a shift from paper-based procedures (PBP) to computer-based procedures (CBP). Emergency Operating Procedures (EOPs) have also evolved into CBPs to better reflect the actual conditions of power plants. However, due to difficulties in regulation and safety verification, CBP implementation in actual power plants remains limited to the use of CBPs that utilize dynamic information in a restricted manner.

With the development of AI technology, various power plant prediction methods are being proposed [5, 6]. These prediction methods enable the rearrangement of procedural structures based on priority that reflects real-time power plant information instead of the traditional fixed sequence of procedures. This paper proposes a dynamic procedural framework that utilizes real-time power plant information to respond to emergencies, assuming that priority information is provided through prediction. The proposed framework analyzes and dismantles the traditional fixed sequence EOPs structure and rearranges the procedure sequence based on priority information. Hierarchical Petri Nets (HPNs) are used to visually model the procedure to prioritize critical safety functions (CSFs).

2. Methods and Results

This paragraph proposes a framework for a new procedure based on the analysis of the existing procedural structure, the modified process, and the newly introduced procedural framework.

2.1 Emergency Operating Procedure (EOP) Structure

The main aim of Emergency Operating Procedures (EOPs) is to respond effectively to emergency situations and ensure safety functions are secured to prevent damage to the core. EOPs consist of four primary procedures [1]: *immediate actions and diagnostic procedures, event-related symptom-based optimal recovery guidelines (ORGs), CSF restoration guidelines, and CSF status trees*.

The immediate actions and diagnostic procedures are critical for promptly responding to significant anomalies and determining the plant's status. Operators use the diagnosis results to identify the most suitable procedure to mitigate the accident. If the ORGs correspond with the diagnosis results, the corresponding ORG is followed; otherwise, a CSF restoration guideline is chosen based on the level of safety function degradation. Figure 1 illustrates this process.

The system proposed in this paper aims to create an integrated procedure instead of the conventional procedural structure, which includes initial response, diagnosis, and entry into a specific procedure. This new approach independently performs initial response and diagnosis and seamlessly enters into a dynamic procedure, regardless of the accident scenario. The dynamic procedure receives real-time status information about the power plant and reallocates task priorities accordingly.

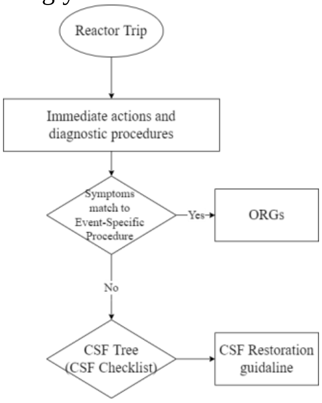

Fig. 1. Conventional EOP Progress

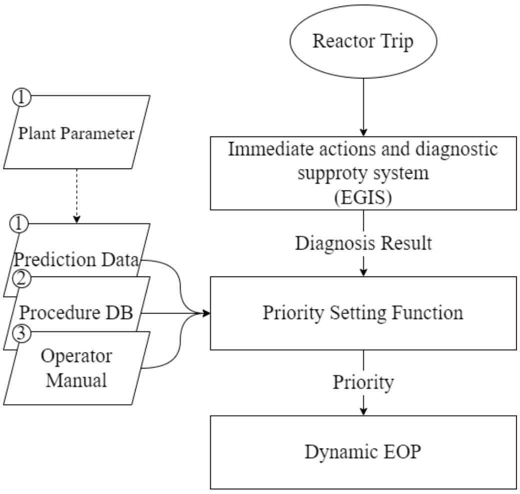

Fig. 2. Dynamic EOP Progress

As shown in Figure 2, During emergency operations, the initial response is handled by the Emergency Guidance Intelligent System (EGIS), an intelligent system designed for emergency operations [7]. After completing initial response and diagnosis using EGIS, the system enters the priority setting function in Dynamic EOP. the priority setting function can change priorities based on the selection. In Case 1, real-time data from the power plant is received and inserted into the priority setting function, allowing for real-time priority determination. In Case 2, diagnostic results and the existing procedure database are loaded, allowing for priority output in the existing procedure sequence. In Case 3, priorities can be changed based on the operator's decision, resulting in the printing of the procedure with the adjusted priorities.

2.2 EOP Task Analysis

The analysis of the EOPs revealed that the ORGs and CSF restoration guidelines shared many common tasks, which were organized to efficiently respond to typical accident scenarios based on the general progression of accidents in the procedures. Additionally, the analysis identified four main differences: (1) the task prioritization for each CSF based on accident scenarios, (2) differences in the Reactor Coolant Pump (RCP) status and timing of shutdown depending on the plant status, (3) differences in the isolation status and timing during the rupture accidents, and (4) the formation of bubbles in the Reactor Coolant System (RCS). A dynamic procedure framework was developed, taking into account these four factors.

2.3 Dynamic EOP Framework

In the process of converting the traditional procedure into a dynamic procedure, Petri nets were used as the engineering model. Petri nets were chosen due to their ability to simulate states and events, as well as their visual representation of a system's structure as a graph model. However, as the complexity of the model increases with scale, building the model becomes more challenging. Therefore, the hierarchical Petri net (HPN) was utilized to simplify the model. By using the Petri net model, the logic of the procedure was modeled according to various factors, such as precedence, assignment operation, multiple tasks operation, multiple resources operation, multiple tasks and an assignment operation, multiple precedence constraints, and priorities [8].

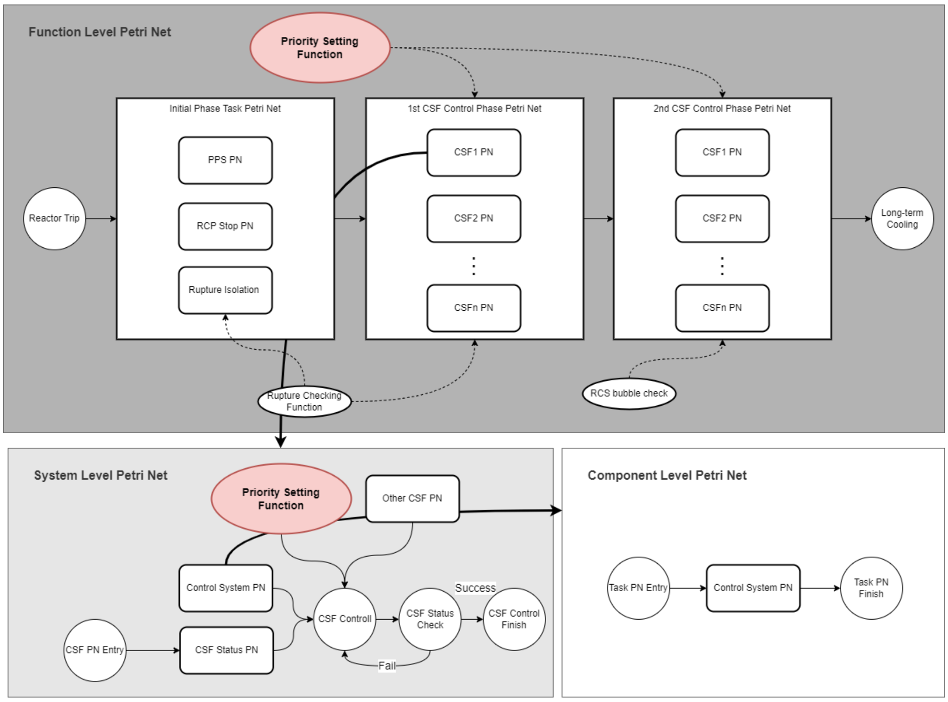

Fig. 3. Dynamic EOP Framework

The structure of the Dynamic EOP is composed of a 3x3 matrix, consisting of three levels in the function, system, and component domains, and three levels in the time domain: initial phase, first CSF control phase, and second CSF control phase. In the function domain, the overall progress of the EOP is modeled for each CSF, while in the system domain, the system structure corresponding to a specific CSF is simulated. In the component level, specific tasks corresponding to a particular system are modeled. In the time domain, the initial phase is made up of tasks performed in the early stages of the procedure, such as PPS, RCP stop, isolation rupture, etc. The first CSF control phase is composed of tasks corresponding to the damaged CSF, and the second CSF control phase is divided into a stabilization phase before entering long-term cooling. In the second control phase, the system is more precisely stabilized, so conditions such as bubble formation are checked.

To achieve this, the linear procedure structure was dismantled and the tasks were classified by system and CSF. These classified tasks were then connected in parallel to create the procedure modeling. The priority setting function, which allows operators to rearrange the procedure based on power plant information, is a key feature of the Dynamic EOP. As shown in Figures 3 and 4, the priority setting function is connected to each CSF, system, and inhibitor. The priority is set by reconstructing the inhibitor combination with prediction result data from other systems.

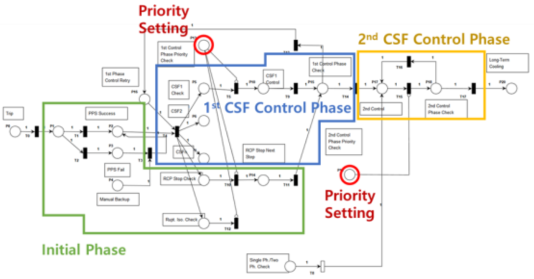

Fig. 4. Dynamic EOP Petri Net (Function Scale)

The priority setting function can be used not only with prediction results but also by arranging tasks in the order of the existing procedure. By inputting diagnostic results, tasks can be rearranged according to the order of the existing procedure based on the procedure database. In addition, tasks can also be rearranged by changing the priority level based on the judgment of the operator.

3. Summary and Conclusions

The current nuclear power plants are undergoing a transition from PBP to CBP, but CBP still has many static characteristics of PBP. As a result, unnecessary information is provided to workers due to differences between dynamic plant information and CBP, leading to an increase in workload and potentially lowering the quality of human performance. To address this issue, this study proposes a dynamic EOP that reflects the dynamic characteristics of the power plant. To develop the dynamic EOP, procedure analysis was performed, and a 3x3 time-step and structural domain was developed using HPN. The most important aspect of this model is the ability to select a priority setting function to construct procedures. The priority setting function can be chosen in various forms, such as a power plant behavior prediction model, an existing procedure model, or an operator manual setting model, enabling the creation of diverse procedural structures. In the initial stage, this study plans to perform accuracy verification by inserting the existing procedure database into the priority setting function, and also to develop a prediction model suitable for application to the model. Ultimately, case studies will be performed by combining prediction models to show appropriate procedural outputs.

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