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Conceptual Operator Support System Interface Design for Early Emergency Responses in Nuclear Power Plants

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1. Introduction

Nuclear power plant operators perform their tasks by exchanging numerous information with plant systems, and implementing action or obtaining information is conducted through visual information displays. The use of visual information displays is a critical part of the operation of nuclear power plants and is an essential part of the support system. Traditional visual information displays in the past focus on providing physical information about the status of the subsystem or subcomponent of the workspace. Therefore, it is possible to give workers a lot of cognitive workload while exploring, integrating, and inferring information. As can be seen in the Three-Mile Island Accident (TMI-2), improperly designed displays can seriously compromise nuclear safety [1]. On the other hand, a properly designed display can help reduce the workload of the operator and ease the complexity of the system [2].

Currently, nuclear power plants are applying digitalized main control rooms from analog main control rooms due to advances in technology [3]. As the main control room and the instrumentation control system became digitized, the operation procedures were also changed from the existing paper-based procedures (PBP) to the computer-based procedures (CBP). PBP has been applied to real nuclear power plant operations for a long time and the safety of PBP is proved. While PBP is proved as a safety operation support system, human error is still identified as a potential cause of nuclear power plant accident risk. [4]. PBP is a static system and is designed with major scenarios predicted by experts in advance. PBP was unable to accommodate excessive data because of its physical limitations in the amount of information. As the form of the procedure was converted to CBP, the physical limitation on the information amount was eliminated. However, the information acceptance quantity to the operator is limited. Therefore, an appropriate amount of data should be provided in consideration of the operator's workload. In other words, an appropriate amount of information and an efficient information delivery system are required to secure the nuclear power plant safety. This paper presents an interface system of an operation support system that replaces the contents of the early emergency response procedure and provides them to the operator in an appropriate form. The purpose of this system is to reduce the workload by providing the contents of the existing procedures in a hierarchical structure, and to help the operator's situation awareness by reflecting the dynamic situation of the plant and providing the necessary tasks in appropriate form.

2. The Concept of Operator Support System

This section describes the procedures that the proposed system targets, the system framework and interface developments.

2.1 Emergency Operating Procedure

The operating procedures for nuclear power plants are classified into three categories: general operating procedure (GOP), abnormal operating procedure (AOP), and emergency operating procedure (EOP). Normally, operators conduct the GOP and if a problem occurs, they enter the AOP. If the event is serious, EOP is entered when automatically trip is occurred or it is deemed necessary to trip. A Korean standard nuclear power plant, APR1400, will carry out Standard Post Trip Action (SPTA) when it enters EOP. SPTA is a kind of initial response procedure for the emergency accident. SPTA focuses on critical safety functions (CSFs), which are the most important for securing plant safety. After SPTA is complete, enter diagnosis action (DA) to check that there is an optimized recovery procedure (ORP) that matches the symptoms. If the symptoms match the event, enter OPR, and if not, perform functional recovery procedures based on the degraded CSF. The targets of the proposed systems in this paper are SPTA and DA. To verify the applicability of the support system, the relevant procedures consisting of relatively simple tasks were selected.

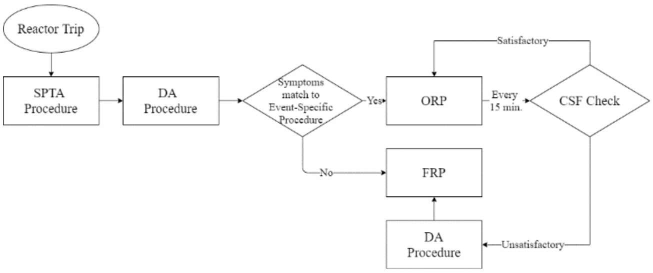

Fig. 1. General Structure of the EOP system in APR1400

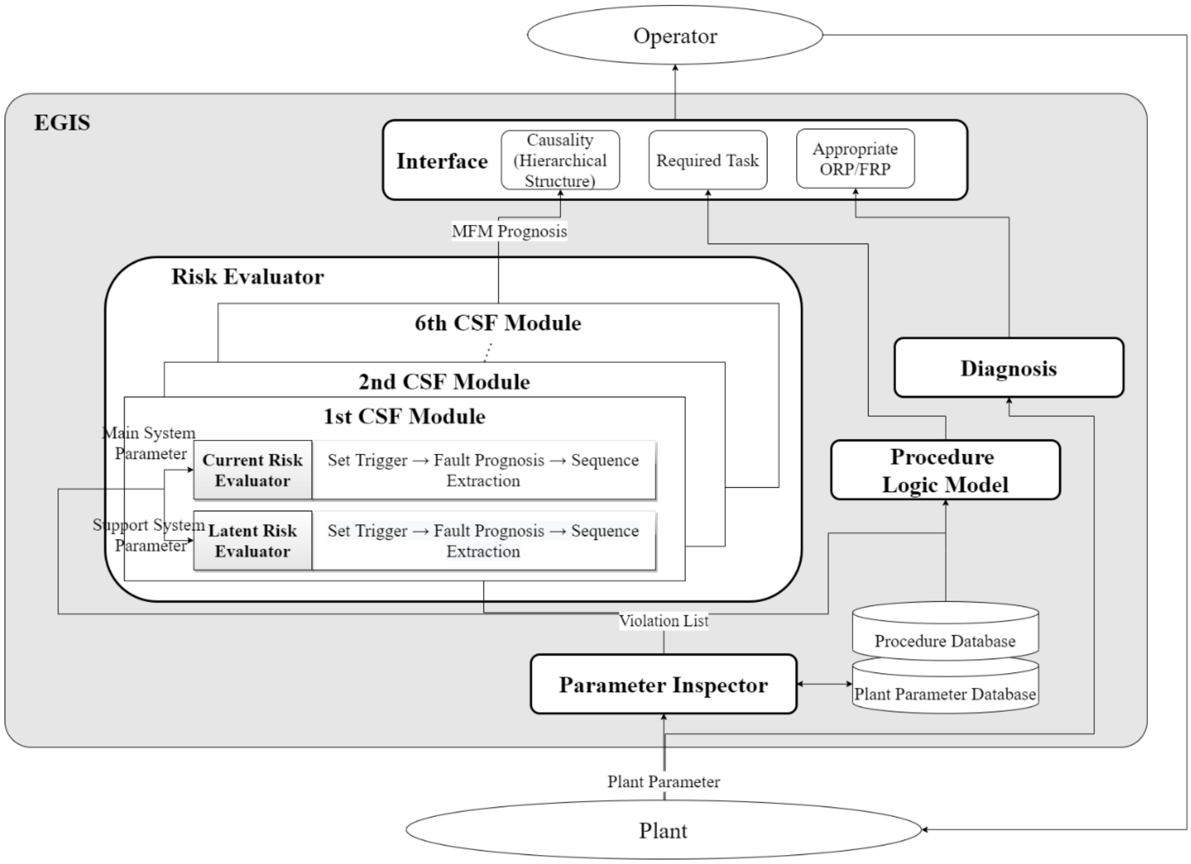

Fig. 2. EGIS Framework

2.2 Emergency Guidance Intelligent System

The proposed system is named with EGIS (Emergency Guidance Intelligent System). The purpose of this system is substitute SPTA and DA and provide information more effectively. For this purpose, EGIS is composed with 5 modules

- Parameter Inspector
- Procedure Logic Model
- Diagnosis
- Risk Evaluator

The parameter inspector surveils the key parameters in the procedures. The module judges the parameters get out of allowable limits. A violated parameter list is delivered to the procedure logic model and risk evaluator.

The procedure logic model is developed to alternate SPTA procedure tasks. If the condition is satisfied, the appropriate required tasks are transferred with a rule-based logic. The logic of SPTA procedures is simple and can be implemented with the rule-based logic. The risk evaluators are used to analyze defects that the procedure logic model cannot cope with the procedure logic model.

The risk evaluator consists of a current risk evaluator that analyzes the causality of frontline systems and a late risk evaluator that analyzes the causality of secondary systems. Risk evaluators were developed using multilevel flow modeling (MFM), one of the means-end methodologies. Risk evaluators are modeled based on each of the essential safety functions. The 6 CSFs were considered: subcriticality, core cooling, heat sink, reactor coolant system (RCS) integrity, containment integrity, RCS inventory.

The diagnosis module is developed to substitute the DA procedure. The module is developed with one of the artificial neural network method, gate recurrent unit.

Eventually, the interface receives causal relationships, necessary tasks, and diagnostic results from each module. The module provides the information to the operator in the hierarchical form of the CSF.

2.3 Interface Development

The interface system is developed with a master logic diagram (MLD) which is based on MFM. MFM is one of the methodologies of quantitative reasoning, which is convenient for analyzing complex plant systems in the form of means-end. The conventional interface method consists of a collection of subsystems and sub-component, but MFM consists of a collection of sub-functions. The sub-function group is linked to the parent function and the parent function is also linked to the final goal, which can be expressed as meaning-end flow. For example, the conventional method states a pump as a pump, but the MFM sees the pump as a transport function and assumes the unit of function that carries the flow rate or energy. This can finally be connected to essential safety functions. Through this structure, it is possible to construct an interface form that considers more ecological characteristics than existing interfaces. The symbols of each function are summarized in figure 3.

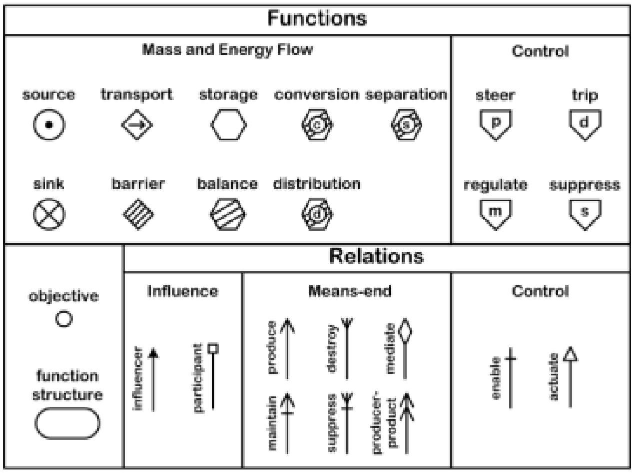

Fig. 3. The basic MFM symbols [5].

Based on this, the MFM model for the RCS inventory is shown in figure 3. Each pump and valve flow path is implemented as a function and these functions belong to the system and are eventually connected to the CSFs.

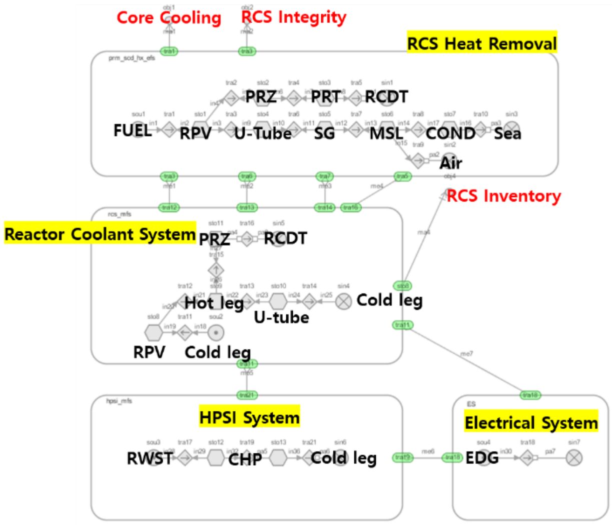

Fig. 4. The basic MFM symbols

In Fig 5, it is an MFM model that mimics when charging pump (CHP) No. 1, which acts as a high-pressure safety injection (HPSI) pump, is broken. It can be seen that the transport function corresponding to CHP1 acts as a trigger and eventually affects core cooling. Based on this, Figure 6 shows that it consists of a simple form of MLD shown on the actual interface screen.

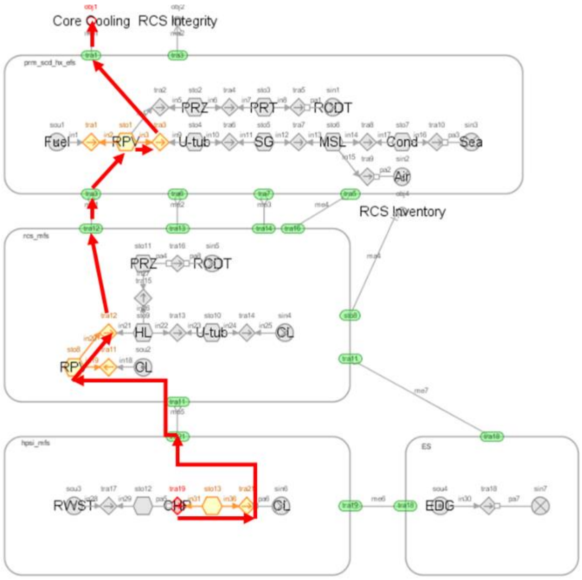

Fig. 5. MFM Fault Propagation

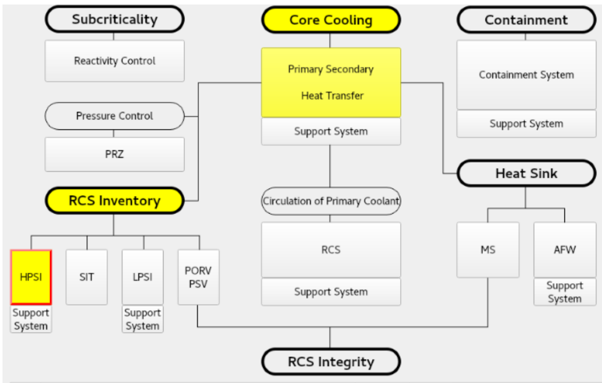

Fig. 6. Fault Propagation Interface

As can be seen at Figure 6, the operator will be informed that the HPSI, a system that corresponds to CHP1, is lit in yellow and the red border flashes which means there is a necessary job. The RCS Inventory (CSF6), primary secondary heat transfer (CSF6), and Core cooling (CSF2), which are connected to HPSI, are linked together to indicate an yellow light.

Finally, the system works in conjunction with the compact nuclear simulator [6] developed by the Korea atomic energy research installation.

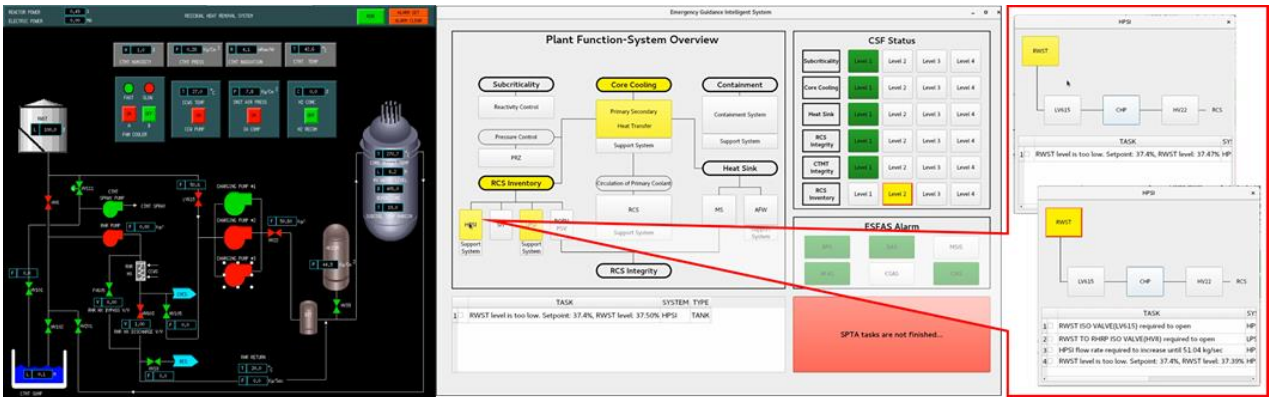

Fig. 7. Realtime EGIS Interface (CHP1 Failure + LOCA)

3. Summary and Conclusions

This paper describes the process of developing an efficient interface of the operation support system to replace SPTA and DA, which are emergency initial procedures. Through MLD using MFM, we developed the hierarchical structure and interface form using meaning-end logic. The goal is to provide a more intuitive interface by configuring the flow logic of the lower and higher functions rather than the lower system configuration. It is configured based on CSF. It is expected that this interface will reduce the workload of operators and improve the situation compared to existing procedures. Future research will design and conduct ergonomic experiments to verify the effectiveness.

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