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Design of Human-System Interface for Severe Accident Management Support System based on Human Factors Engineering Program

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중대사고관리 지원시스템을 위한 인간공학 프로그램 기반
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원자력발전소는 설계 당시 정의된 설계기준 사고에 대해서도 안전하게 전력생산을 할 수 있도록 안전계통과 운전 절차서, 그리고 훈련 절차 등이 구비되어있다. 하지만, 운전원에 대한 교육 및 훈련에도 불구하고 사고에 사건이나 사고 상황을 적절히 대처하지 못하게 되면, 핵연료에 있는 방사성물질이 원자로 용기를 거쳐 격납건물 내로 퍼질 수 있게 된다. 만약 이 당시에 노심 냉각 및 격납건물 건전성을 확보하지 못하게 되면 환경으로 누출될 수 있는 것을 고려해야 한다. 이렇게, 노심의 손상과 관계없이 방사성물질이 외부로 누출 가능한 사고를 중대사고라고 하며, 중대사고를 완화 및 관리하기 위한 전략으로 중대사고 관리지침서를 사용한다. 하지만, 중대사고 관리지침서에는 비상 운전 절차서처럼 세세한 절차를 운전원에게 제공하여 운전원이 수행해야하는 내용을 포함하지 않으며, 오직 발전소 상태 완화를 위한 방법만이 제시되어 있다. 실제 상황에서 사고관리를 담당해야 할 기관들이 급박하고 긴장된 순간에 의사결정을 하는 과정에 큰 어려움이 있을 것으로 예상되어왔다.

위와 같은 이유를 포함하여, 중대사고와 중대사고 관리지침서의 몇 가지 이슈를 보완하고자 전 세계적으로 중대사고관리 지원시스템에 대한 연구가 활발히 진행되어왔다. 본 연구도 중대사고 상황에서 운전원에게 정보를 제공하여 적절한 의사결정을 할 수 있도록 도와주는 중대사고관리 지원시스템에 대한 인간-시스템 연계를 개발을 목적으로 한다.

원자력발전소에서 절차서, 디스플레이, 훈련 프로그램 개발을 수행할 때는 NUREG-0711에서 제안하는 인간공학 프로그램을 이용 할 수 있다. 이 연구 역시 디스플레이를 개발하기 위한 연구이기 때문에, 인간공학 프로그램을 이용하여 연구를 수행하였다. 본 연구에서는 인간공학 프로그램 중 1) 운전 경험 검토, 2) 기능요건분석 및 기능할당, 3) 직무분석, 4) 운전조분석, 5) 인간-시스템 연계 개발과 같이 총 5가지의 활동을 수행하였다.

운전 경험 검토는 이전의 운전 경험을 검토하여 개발될 시스템의 설계요건을 도출하는 목적이다. 운전경험검토에서는 두 가지 활동 1) 9개의 원자력발전소에서 발생한 중대사고 검토, 2) 국·내외에서 개발된 중대사고 지원시스템에 대한 검토를 수행하였다. 각 활동을 통해 도출된 16개의 설계요건은 개발될 지원시스템의 설계요건으로 사용되었다. 기능요건분석 및 기능할당은 중대사고관리에 최종 목적을 달성하기 위해, 필요한 안전기능과 안전기능을 만족하기 위한 성공경로를 계층적 구조 방법을 이용하여 도출하고, 도출된 안전기능과 성공경로에 대한 자동화 수준 할당과 모델링을 수행하였으며, 모델링은 Multilevel Flow Modeling (MFM)을 이용하였다. 또한, 도출된 안전기능에 대한 자동화 수준을 선정하였다. 기능요건분석의 결과는 개발될 지원시스템에서 기능-디스플레이에 표시하였다. 직무분석은 운전원이 직무를 수행할 때 반드시 수행되어야 하는 직무를 식별하고, 그 직무를 수행하는데 필요한 정보 등을 도출하는 목적으로 수행하였으며, 계층적 직무분석을 통해 지침서 전이에 대해 나타내었으며, 직무 분해 방법을 통해 상세 분석을 수행하였다. 직무분석의 결과는 개발될 지원시스템에서 직무-디스플레이에 표시될 예정이며, 이 디스플레이는 운전원이 직무를 수행하는데 필요한 모든 정보(기기, 시스템 및 변수들)를 한 화면에서 확인할 수 있도록 디자인하였다.

본 연구의 결과인 중대사고관리 지원시스템 인간-기계연계는 중대사고 대응거점에 설치되어 불확실성이 높은 중대사고 상황에서 필요한 정보를 적절히 전달하고, 의사결정에 도움을 줄 수 있을 것으로 기대된다. 또한, 중대사고 대응조직의 인적오류의 가능성을 줄여 최종적으로 원전의 위험도를 감소시키는데 기여할수 있을 것으로 기대된다. 추가로, 인간공학 프로그램을 적용한 중대사고관리 지원시스템의 개발은 현재 연구수준의 시스템 기능 개발을 넘어, 실제 적용 가능한 기술 수준으로 끌어올리는 기회가 될 수 있을 것으로 사료된다.

I. Introduction

At Korea nuclear power plants (NPPs), when the core exit temperature (CET) exceeds 649 degrees of Celsius, the operators in main control room (MCR) exit ongoing procedure(s). This may be the emergency operating procedure (EOP). Immediately after, the operators enter the severe accident management guidelines (SAMGs). The SAMG was developed for mitigation, handling, and management of severe accidents (SAs) in the NPPs. The SAMG is designed to 1) prevent and mitigate the core damage, and 2) maintain containment integrity. During the change from the EOP to the SAMG, the plant control authority shifts from the MCR to the technical support center (TSC). This shift is recommended because a group (TSC) is regarded as having more effective decision-making than an individual in the highly uncertain condition of a SA. The decision-making regarding the SAMG is performed by the TSC and corresponding actions are mostly performed by MCR operators [1].

However, currently, there are several issues in SAMG and severe accident management (SAM) in the nuclear domain and some of them are explained this paper. First, the SAMG is described only for the NPP systems or key strategies required for mitigating SA, rather than directing any specific actions of operators, as can be found in the EOP. For example, the EOP describes opening the valve and starting the pump, but the SAMG describes just purpose and method for performing of the strategy [2]. Second, the SAMG contains only strategies to mitigate NPP accidents according to the symptoms of an accident. At that time, there is little information about the performance and accident scenarios of the NPPs, such as the diagnosis, prediction, and evaluation of the SA assessment. Therefore, the operator in MCR or TSC who are in charge of managing SA may have difficulty in decision-making [3]. Third, The SAMG developers can not anticipate all possible accident scenarios, which may lead to gaps in SAMG coverage in terms of both scenario coverage and phenomena detail [4]. Fourth, the current SAMG requires the TSC to evaluate the positive and negative impacts of performing selected strategies and make decisions based on insufficient information [1].

For this reason, the severe accident management support system (SAMSS) has been developed to help operator’s decision-making and SAM for improved safety of NPPs. Until now, SAMSSs have been developed so far, globally and among them, reviews have been conducted on 1) Computerized Accident Management Support (CAMS) [5], 2) Computerized Severe Accident Management Operator Support (SAMOS) [6], 3) Severe Accident Management and Training Simulator (SAMAT) [7], 4) Severe Accident Management EXpert System (SAMEX) [3,8] and 5) Accident Management Support Tool (AMST) [9] in this study. A description of it is shown in section 2.A.2.

However, the above systems were not successfully applied to actual NPPs. One of the reasons for the failure of actual implementation is lack of consideration into human-system interaction and human factors engineering (HFE) program following NUREG-0711 [10]. For the successful deployment of SAMSS, sufficient consideration of human-system interaction should be performed. Failure of earlier operator support systems indicates that human-system interaction, as well as functional capabilities (i.e., accuracy and coverage), are a key element of operator support systems.

This study used the HFE program proposed by NUREG-0711, to properly consider human-system interaction. Therefore, this study presents results from five elements of HFE program following NUREG-0711 for the design of SAMSS, i.e., operating experience review (OER), functional requirement analysis & function allocation (FRA&FA) task analysis (TA), staffing analysis, and human-system interface (HSI) design.

II. Analysis for Severe Accident Management Support Systems based on Human Factors Engineering Program in NUREG-0711

The OER, FRA&FA, TA, and staffing analysis for the SAMSS have been performed by the following elements suggested by the NUREG-0711 HFE program. The objective of the HFE element is to verify that the license applicant for NPPs has an HFE design team with the responsibility, authority, placement within the organization, and composition to reasonably assure that the plant design meets the commitment to HFE. Further, a plan should guide the team to ensure that the HFE program is properly developed, executed, overseen, and documented [10]. A total of 12 elements exist in the HFE program, and some of them were selected and performed in this study. In Fig. 1 represents the overall elements proposed by the HFE program in NUREG-0711.

In addition, the total HFE program elements that have been or will be performed for this study is shown in Fig. 2. In this study, as a part of the analysis and design part in Fig. 2, the OER, FRA&FA, TA, and staffing analysis were performed.

Through OER, a review of the SA and the SAMSS developed was conducted, and the result of that, which is the design requirements were identified. The FRA&FA was performed to identify the safety functions and their success paths of SAMSS to be developed. In addition, the automation level was allocated through function allocation. The TA was performed to identify the specific task that personnel performs in order to accomplish identified safety functions. Last, the staffing analysis was performed using a review on the radiation emergency plant in Korea Hydro & Nuclear Power (KHNP).

The sub-sections of this chapter describes the contents of OER, FRA&FA, TA, and staffing analysis with the result from each element.

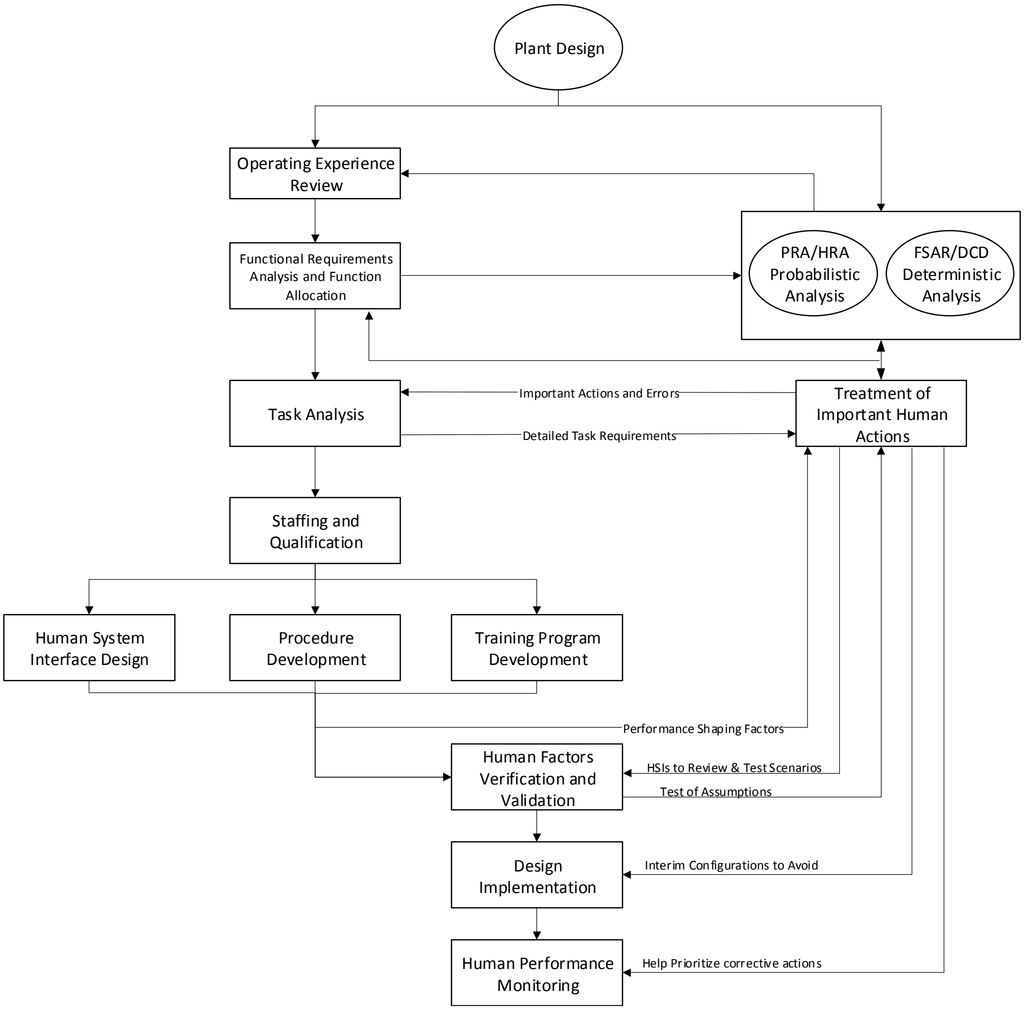

Fig. 1. All Elements in Human Factors Engineering Program Following NUREG-0711 [10]

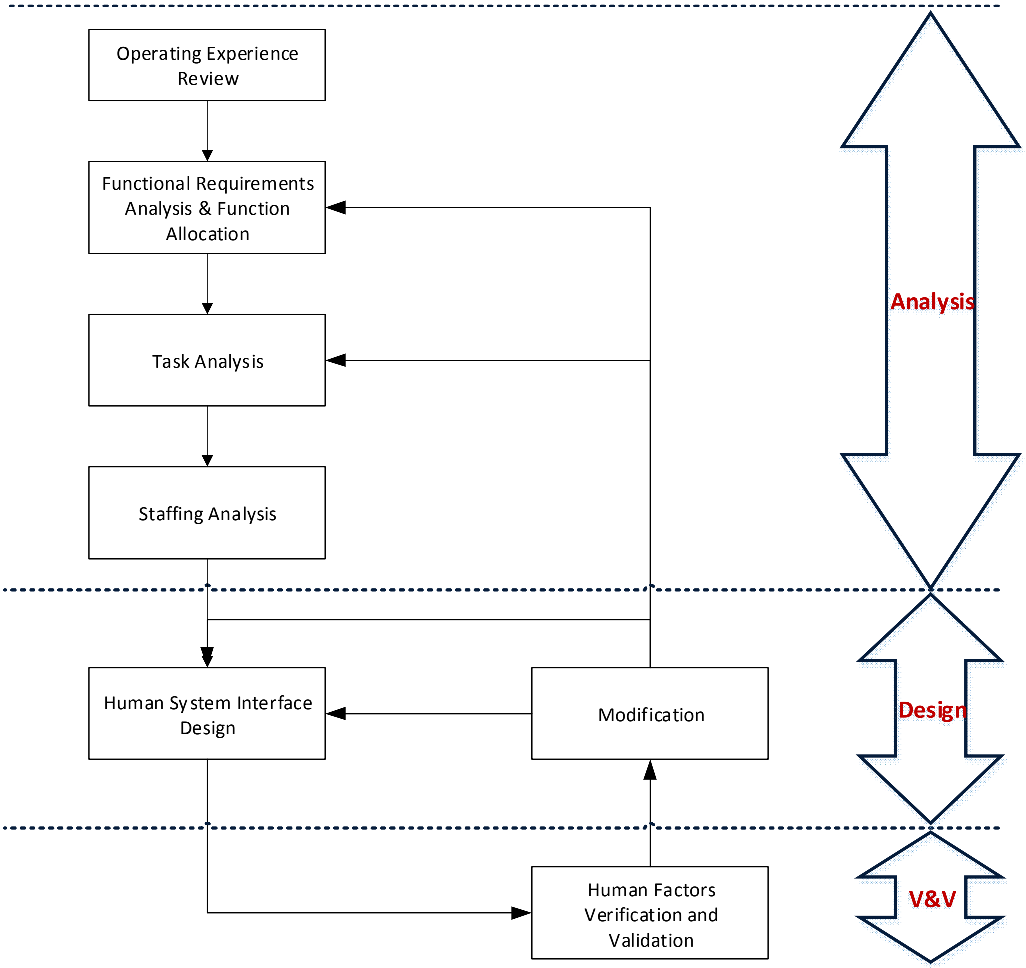

Fig. 2. Elements for Human-System Interface of Severe Accident Management Support System [10]

A. Operating Experience Review

The purpose of the OER is to identify the safety issues that are HFE-related in the nuclear field. The OER provides information on the performance of the former design. The issues and lessons learned from operating experience provide a basis for improving the design of NPPs, at the start of the design process in NPPs. The objective of OER is to verify that the applicant for a design review has identified and analyzed HFE-related issues in previous designs similar to the current one under review [10]. In this way, the negative system of previous designs may be avoided in the current one, while retaining the positive system. The OER has to consider the previous systems upon which the design is based, the technological approaches selected, and the HFE issues of the NPPs.

Through the OER activities, this study carried out a review of nine previous SA that occurred in the nuclear field (TMI, Chernobyl, Fukushima, etc,) and reviewed the purpose, system, and functions of SAMSSs that have been developed so far. From those two activities, sixteen (16) design requirements were identified for the new SAMSS to be developed.

1. Review on the 9-Severe Accidents in the Nuclear Field

For this paper, as mentioned above, a total of nine (9) SAs were reviewed, i.e., 1) TMI, 2) Chernobyl, 3) Fukushima, 4) Jaslovske Bohunice KS 150, 5) Chapelcross Reactor 2, 6) Saint Laurent Unit A1, 7) Lucens, 8) Fermi 1, and 9) SL-1. From that review, several human and organizational issues in responding to SA in the nuclear field were identified [12-17]. The issues of HFE in terms of some typical issues and SA response include the following.

Some of the above mentioned accidents reported that operator training for SAM was not appropriate. As a typical example, it was reported that the operator had never been trained to open some valves (isolation condenser valve) and, therefore, the operator could not open the valves in actual SA situations.

The reliability of the power supply system should be supplemented. The Fukushima NPP SA was recorded as the worst SA in the nuclear domain ever caused by natural disasters. During the loss of power, the operators can not check the exactly actual parameter for NPP. So the operator relied on portable lights such as flash and mobile phones and then could access very limited information and plant variables. If there was an emergency power source available for the operator or worker, or if power could be recovered quickly, the consequences of the SA would be far less serious.

The operator shall be provided with only the key information at the time of the accident. More than 100 alarms were turned on at the same time when the accident occurred at TMI, so it was difficult for operators to take action for the accident because various information such as power-operated relief valve (PORV) Stuck open and reactor drain tank (RDT) level was not readily available.

NPP monitoring including instruments critical to accident response should be reinforced: In the SA of Fukushima NPP, the lack of direct information on the plant condition, especially, the state of the reactor, caused great difficulties in accident handling and mitigation. Loss of power is one of the major causes, but the instrument itself has lost its function due to the failure. The failure of the reactor water level sensor misled the operators to think that the core does not a meltdown. Therefore, the performance of important sensors and instruments need to be guaranteed even in extreme condition.

As a result of these reviews, human and organizational factors were identified in terms of each SA response. A summary of that is shown in Table 1 below.

Table 1. Identified Issues of Human Factors and Organizational Factors

SA \ Error	Human Factors	Organizational Factors
TMI	• Did not accurately check the condition of the valve • PORV stuck open was not recognized • Due to the many alarms did not easily check the required alarm • Lack of training for SA by operators	• Poor information transfer by regulatory agencies • Poor man-machine interface design
Chernobyl	• Lack of accurate verification of the condition of the plant • Did not a suitable act according to the procedure. • Lack of training for SA by operators	• Poor awareness of safety culture • Lack of training facility
Fukushima	• Lack of training for SA and natural disaster by operators • Failure to execute procedure quickly	• Lack of imagination and response to natural disasters • Lack of independence of regulatory agencies • Lack of responsibility and infrastructure reinforcement by operating institutions • Lack of infrastructure for safety • Lack of reliability of the power supply system • Lack of practical ability to cope with SA • Lack of procedures • Lack of action in the absence of a manual • Lack of communication between institutions • Lack of information and impact assessment on neighboring countries
Jaslovské Bohunice KS 150	• Lack of training on gel packet rupture	• Lack of procedures related to gel packet rupture

Chapelcross Reactor 2	• -	• Lack of procedures
Saint Laurent Unit A1	• Lack of training for manual power generation of the charger	• Lack of training on manual power generation of chargers
Lucens	• Lack of knowledge of single fan operation	• Lack of training
Fermi 1	• Unable to identify the condition of the NPP	• Lack of equipment for operators to check the conditions of the plant • Poor man-machine interface design
SL-1	• Technical supervisor's non-attendance during a night shift • Lack of training on performing procedures	• Lack of training on procedures

2. Review on the Severe Accident Management Support System

The review of the status of technology has been performed to identify the design requirements for the SAMSS that will be developed. In this chapter, a total of five SAMSSs that have been developed so far are introduced.

CAMS was developed as a support system proposed by the Organization for Economic Cooperation and Development (OECD) Halden Reactor Project (HRP). The major functions of CAMS are signal validation, tracking simulator, predictive simulator, strategy generator, critical function monitoring, and man-machine interface (MMI) [5].

SAMOS is a SA support system developed by the NSC of the Netherlands. SAMOS intended to utilize the CAMS system, Westinghouse Owner Group (WOG) SAMG, and MAAP4 based simulator developed as part of the OECD HRP as an element technology and to be used in VVER NPPs. SAMOS has diagnostic function by Logic diagram and prediction function by MAAP iterative calculation [6].

SAMAT was developed by Korea Atomic Energy Research Institute (KAERI). SAMAT is a system to systematically provide functions such as 1) provide all available information to eliminate uncertainties in the SA as much as possible, 2) provide information about NPP conditions such as major variables for the SAs, 3) show SAMG-related information, 4) verify which strategies can be used to proactively predict NPP behavior, and 5) select the best strategy for mitigating and management of the current accidents. SAMAT is based on the SAMG for Korea Standard Nuclear Power (KSNP), now called optimized power reactor 1000 (OPR1000). It consists of four parts: 1) a training simulator, 2) a variable safety parameter display system (SPDS), 3) a handbook, and 4) a knowledge base. The training simulator module can virtually perform a strategy; the SA SPDS module identifies the status of the NPP, and the knowledge-based module contains critical accident scenarios to enable operators to utilize a variety of information when carrying out SAMGs [7].

SAMEX is used when the design basis accident (DBA) of NPP develops into a SA, but even before that (maybe in the emergency situation), it can be used as a support system to predict and respond to the progress of the accident in advance. It can be also used for the purpose of training the TSC staff for situations related to SA. Although the existing SAMG mitigation strategies only provide guidance regarding the coolant injection (for example, temperature, pressure, hydrogen concentration, and fission product control) for the required systems, , SAMEX can be used as a support system of supplementing them [3,8].

AMST is an accident support system developed for the WWER-1000 plant at the Sharif University of Technology in IRAN. AMST is an accident support system consisting of a tracker to diagnose an accident, a predictor to predict the progress of an accident, and a decision support function [1,7].

3. Design Requirements from Operating Experience Review

As a result of the OER, the design requirements were identified through the review of the nine (9) SAs and the review of the developed SAMSSs so far. The Table 2 below shows the design requirements with their source. This design requirements will be used as an inputs for the HSI design.

Table 2. Design Requirements for the Severe Accident Management Support System

No.	Design requirements	Ref. No.
1	The alarm should be required to notify the operator of the occurrence of a SA.	[14,17,18]
2	Support functions (systems) should be required to enable response organizations to perform the procedures or guidelines quickly and accurately.	[14,15,17]
3	Even in vulnerable environments such as loss of power, the system should be provided with information to operators.	[19,20]
4	Functions should be required to enable operators to respond creatively to accidents in situations that differ from procedures or guidelines.	[14,19]
5	The ability to support collaboration should be required when multiple organizations participate in the SA response.	[14,18]
6	In the event of a SA, functions should be required to predict the behavior of the NPP, the progress of SA, and the release of radiation.	[3,8,9]
7	Functions should be required to support operator decision-making in the event of a SA.	[9,21]
8	Functions should be required to diagnose the cause of a SA.	[3,8,9]
9	Functions should be required that support the accident management strategies of response organizations.	[3,17,19]
10	Functions should be required to monitor the major safety functions in the NPPs.	[14,15]
11	The capability to collect the information and to assess the state of NPP should be required.	[15,17]
12	Functions should be required to inform the operator of the possibility of core damage in advance.	[3,4,17,19]
13	Functions should be required to provide the operator with information about the coolant inventory of the reactor core.	[3,4,17]
14	If there is a need to switch from EOP to SAMG a function to inform the operator is required.	[17,19]
15	Functions should be required to monitor the condition of the containment and the core.	[17,19]
16	Functions should be required to inform that the plant has reached a controlled, stable state.	[17,19]

B. Functional Requirement Analysis

The FRA identifies the operation and safety objectives of the NPP and the functions of the NPP that must be performed to meet them. Prevent or mitigate the consequences of postulated accidents to ensure the health and safety of the people. The purpose of FRA is to provide a set of high-level functions that should be accomplished to meet the goals of plants. FRA also functions to look forward to performance delineate the relationships between high-level functions and the NPP systems (e.g., plant arrangement or success paths) responsible for performing the functions. FRA can provide a framework for determining the roles and responsibilities of personnel and automation [10]

In this study, for the FRA, the safety functions and their success paths were derived from SAMG in KSNP for management and mitigation of SA using a hierarchical structure. Then those safety functions and success paths were modeled through the MFM.

1. Identify the Safety Function from SAMG in Korea NPP through Hierarchical Structure

As a result of the FRA, a total of seven safety functions were identified on the basis of the SAMG developed by KAERI [22, 23, 24]. The identification methodology used was as a hierarchical structure as mentioned previously. The hierarchical structure of SAMG safety functions is presented in Fig. 3 below.

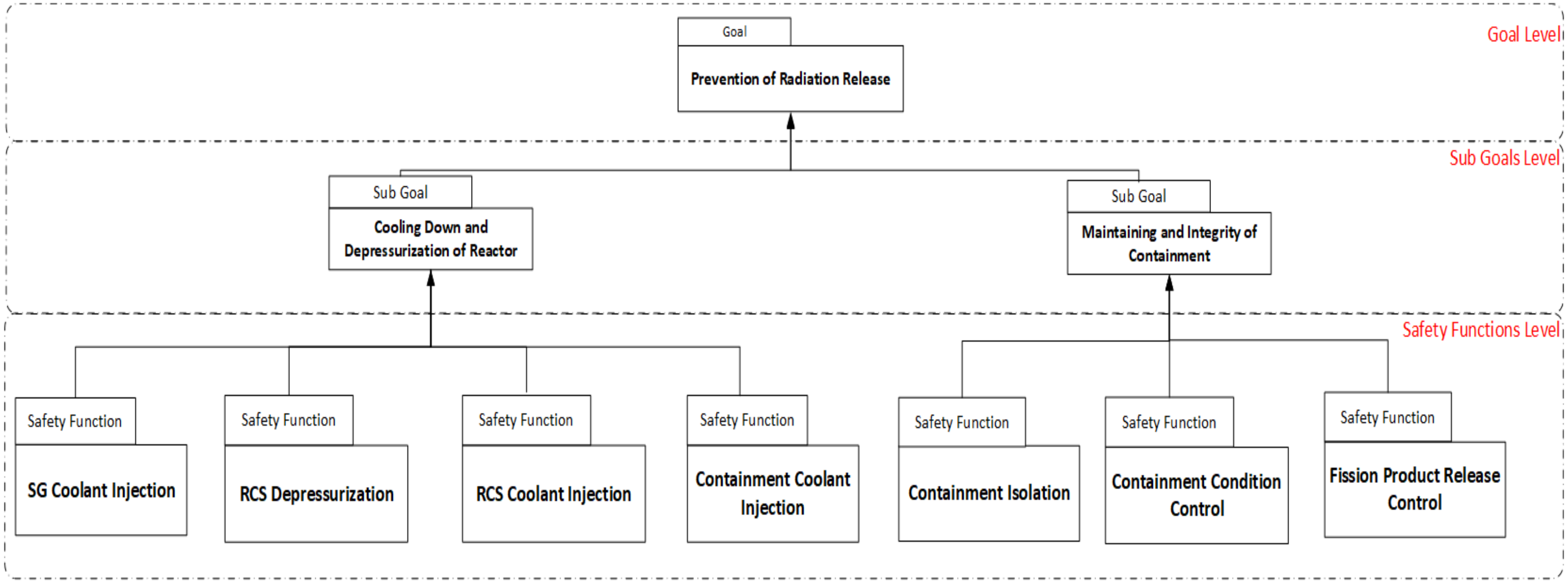

Fig. 3. Identified Safety Functions for Prevention of Radiation Release Through Hierarchical Structure

The goal of identified safety functions is the prevention of radiation release. Then, it can be divided into two sub-goals: 1) cooling down and depressurization of reactor and 2) maintaining the integrity of the containment. To achieve sub-goal and goal, the identified safety functions and their success paths should be satisfied.

Four identified safety functions with relation to the cooling down and depressurization of the reactor core are: 1) Steam Generator (SG) coolant injection: coolant injection into the SG secondary side for reactor coolant system (RCS) heat removal with SG, and SG tube leakage prevention. 2) RCS depressurization: through the depressurization of RCS, enabling the replenishment in RCS using low-pressure safety injection (LPSI), and protection of the shutdown cooling system (SCS) in current use. 3) RCS coolant injection: through coolant injection into the RCS, cooling the core and RCS and ensuring reactor vessel protection. 4) containment coolant injection: through the coolant injection in the containment, preventing and delay of reactor vessel damage (it related also with maintaining the integrity of containment).

In addition, three identified safety functions with relation to the maintaining the integrity of containment are: 1) fission product release control: to reduce the risk of exposure (radiation, hydrogen, etc.) to the people near the NPP, during a SA from the in-containment. 2) containment condition control: to control the containment condition, such as temperature, pressure, hydrogen, and fission product concentration in the containment. 3) containment hydrogen control: to prevent and control the hydrogen explosion in the containment.

This study also identified the systems that can be applied to achieve the safety functions and goals of a plant, also called success paths. The success paths have been identified by the review of the SAMG and piping and instrumentation diagram (P&ID) of KSNP. Table 3 below shows the identified safety functions and success paths [22, 23, 24]. In addition, as mentioned previously, the modeling of identified safety functions and success paths was also performed through MFM.

Table 3. Identified Safety Functions and their Success Paths

Ultimate Goal	Sub Goals	Safety Functions	Success paths
Prevention of Radiation Release	Cooling and Depressurization of the Reactor	SG coolant injection	● Auxiliary Feed-water System ● Main Feed-water System ● External Injection System ● SG Steaming
		RCS depressurization	● Reactor Coolant Gas Vent System ● Safety Depressurization System ● Pressurizer Pressure Control System ● SG Steaming
		RCS coolant injection	● Safety Injection System ● Containment Spray Pump ● Chemical & Volume Control System ● External Injection System
		Containment coolant injection	● Containment Spray System ● RWT Gravity Drain System
	Maintaining the Integrity of the Containment	Containment isolation	● Containment Isolation System
		Containment condition control	● Containment Cooling System ● Containment Spray System ● Combustible Gas Control System ● Passive Autocatalytic Recombiner (Non-Power)
		Fission product release control	● Containment Fan Cooler ● Containment Isolation System ● Containment Spray System

2. Multilevel Flow Modeling

MFM is a modeling method proposed by Morten Lind that can easily model complex industrial processes, e.g., NPPs. MFM is a useful method to deduce systems into multiple stages by applying the concepts of means-end and whole-part decomposition. The MFM model can divide the goals and functions of the system into Mass, Energy and Information structures, and represents the relationship between the functions associated with its flow. Through the cause-consequence or goal-means modeling of the system, it is possible to identify the cause of the system failure and the consequences of the system failure [25, 26, 27, 28].

This study presents an example of MFM modelling for SG coolant injection safety function. This is decsribed in the following section.

3. Modeling of Identified Safety Functions Through Multilevel Flow Modeling

Before the design of an MFM model, a process model for SG coolant injection was developed. The process model of SG coolant injection includes the auxiliary feed-water system (AFWS) , main feed-water system (MFWS) and external injection system (EIS) . Fig. 4 shows a simplified success paths diagram for SG coolant injection safety function using the process modeling tool of an MFM program.

Based on the process model in Fig. 4, an MFM model has been designed as shown in Fig. 5. The MFM model for the SG coolant injection safety function consists of three levels. The first level (the highest level) shows the goal structure (red rectangle) in Fig. 5. It can use the cold-leg and hot-leg temperatures to ensure that the RCS heat is being removed. The second level shows the energy flow structure (green rectangle) that represents the heat exchange between nuclear steam supply system (NSSS), i.e., hot side and success paths, i.e., cold side. The third level shows the mass flow structure (blue rectangle). It represents the components and mass flow path in the success paths i.e., AFWS, MFWS, EIS of SG coolant injection safety function as well as in the NSSS. The FRA results (MFM) will be used as a display in the HSI design.

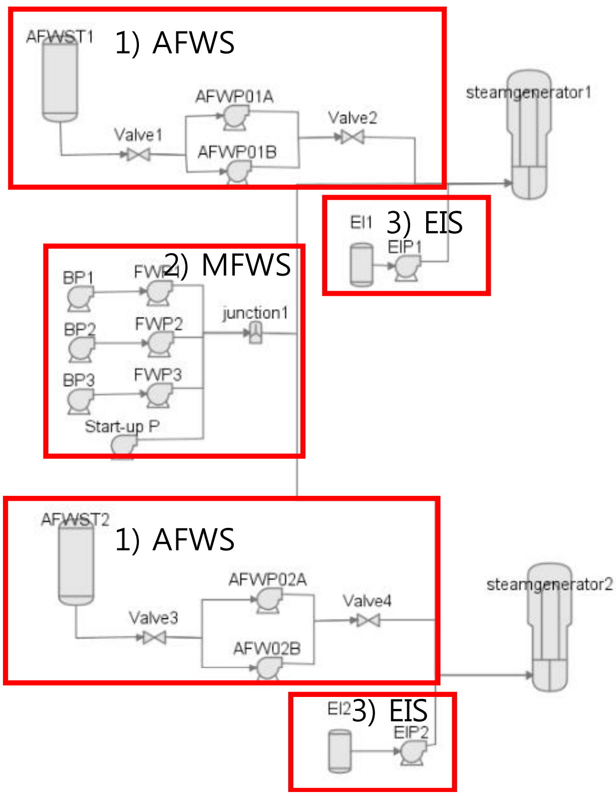

Fig. 4. Steam Generator Coolant Injection Modeling using the Process Model of MFM

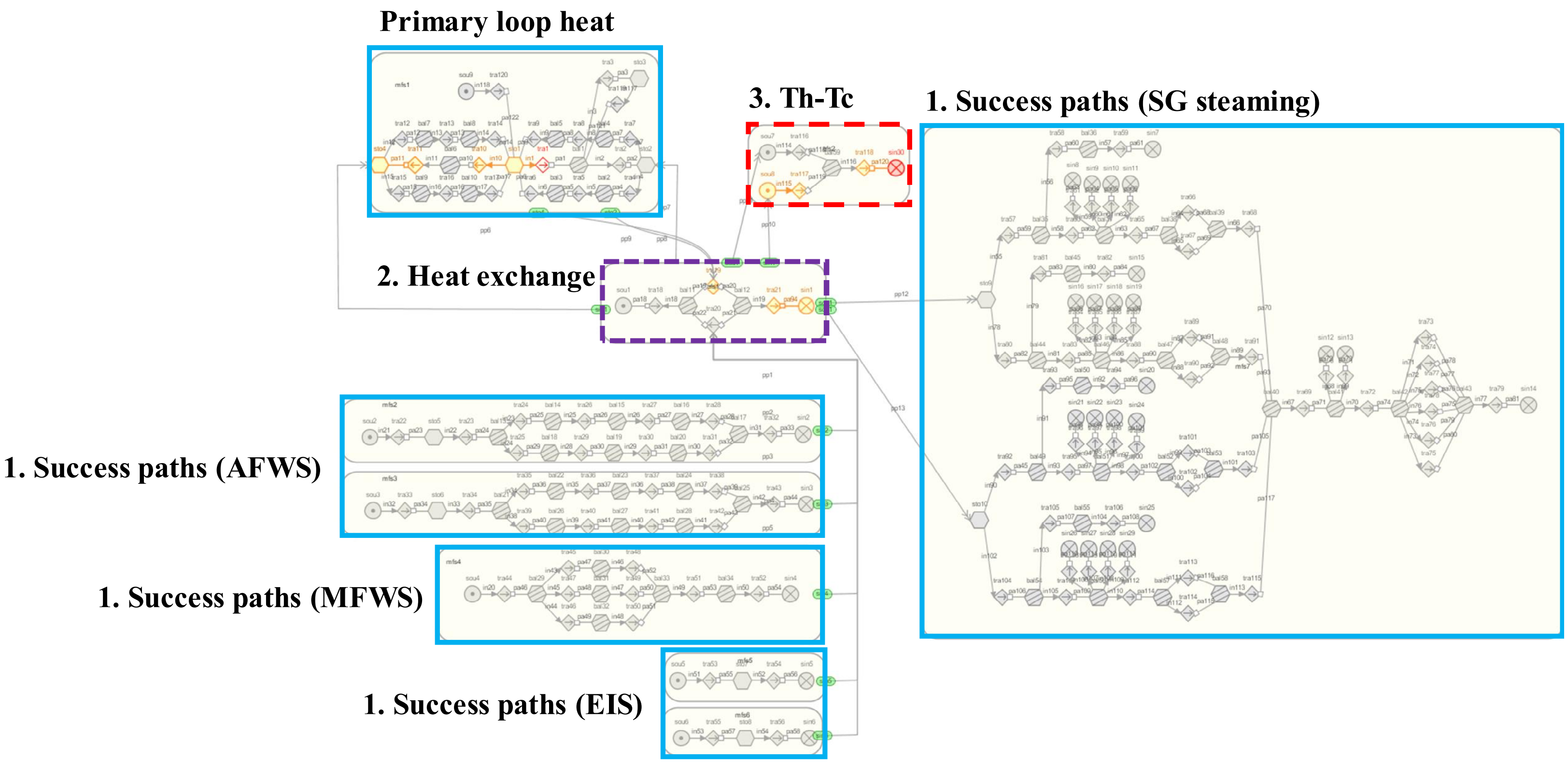

Fig. 5. Steam Generator Coolant Injection Modeling using MFM Model

C. Function Allocation

Functional allocation (FA) is to determine the level of automation of safety functions derived from the FRA and to define the functions that the operator shall perform [10]. In this study, it was assumed that automatic operation was unreliable because a SA meant that safety equipment (or systems) installed in an NPP did not perform the required functions properly. Indeed, when the guidance on SAMG for the reference plant is reviewed, it is stated that the availability of all equipment should be re-evaluated. Therefore, the assumption is that all of the safety functions required for the allocation of functions of the SAMSS to be developed require manual operation.

D. Task Analysis

The definition of TA is a set of human actions that absolutely contribute to the goals of a particular function and the goals of the systems. As an element in NUREG-0711, TA identifies the specific tasks that are required for an operator to perform an action and the information, control, and task support needed to complete a given task [10].

In this study, two TA methods were used to analyze the identified safety function of SG coolant injection. One is the hierarchical task analysis (HTA) and the other is the decomposition method. Each of these methods will be explained in the following sub-sections.

1. Results Through Hierarchical Task Analysis

HTA is the most widely used method for TA. It was originally developed for the purpose of understanding cognitive task analysis (CTA). HTA hierarchically lists and analyzes tasks in the order of goals, sub-goals, operations, and plans. HTA results can be used as inputs to many human factor analyses such as allocation of function, workload assessment, and interface design [10, 29]. The HTA is used for analyzing the CTA of SAMGs in this study.

The HTA for the SG coolant injection was performed in four steps as shown in Fig. 6 . The goal of HTA is SG coolant injection. To satisfy this strategy, the following nine steps should be performed by the operator:

1) Purpose: confirm the purpose of the strategy execution
2) Check the performing condition: determine if the operator needs to perform the current strategy
3) Expected plant behavior: determine the expected plant behaviour
4) Related with EOP: check the relationship of goal with existing EOP
5) Check the available means: identify the available equipment for feed-water injection into the SG and identify the available equipment for depressurization for RCS or SG if necessary
6) Determine whether to carry out a strategy:identify the negative impact of the performing of the strategy and determine whether to carry out the strategy accordingly
7) Determine how to carry out a strategy: determine which means to carry out the strategy if operator decides to carry out the strategy in “Determine whether to carry out a strategy” (examples are coolant injection path, depressurization path, coolant injection equipment, depressurization equipment, etc.)
8) Perform Strategy: pass the information selected by the TSC (decision-making from the previous step) to the MCR (who actually carries out the strategy).
9) End Strategy: identifying the long-term interest in coolant injection and end the strategy under certain conditions.

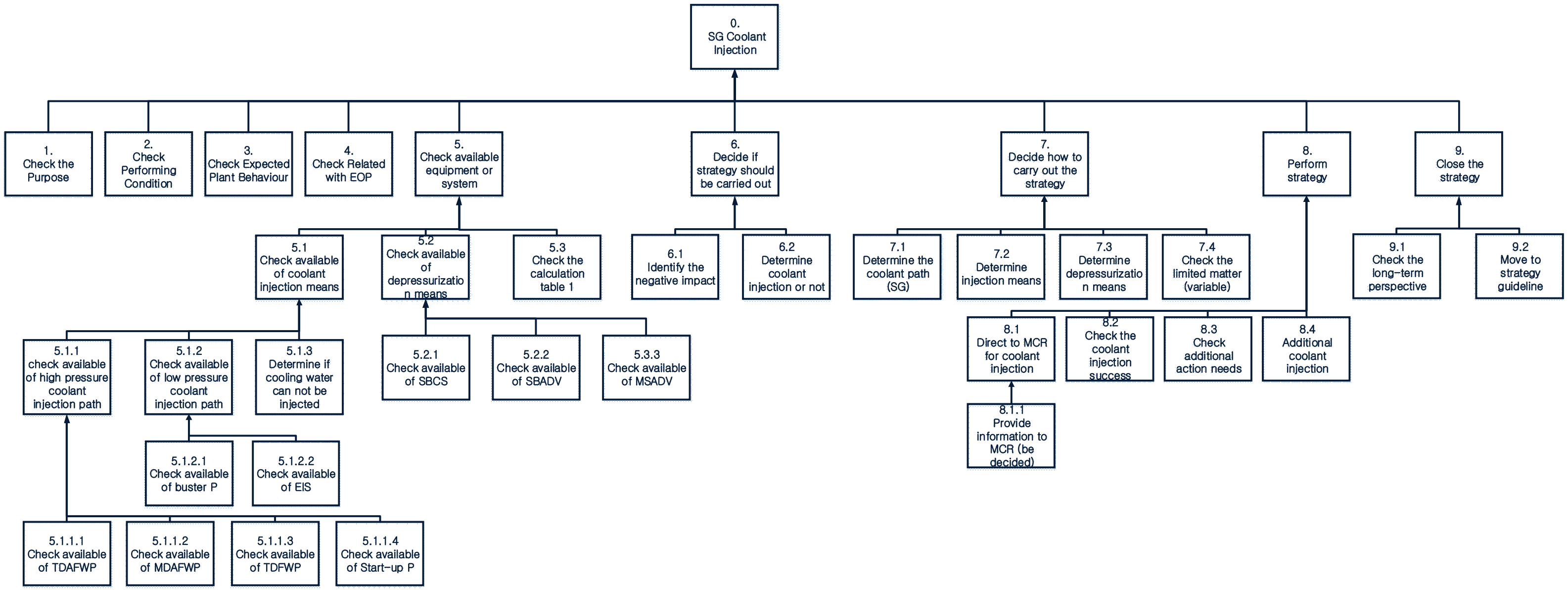

Fig. 6. Example of Hierarchical Task Analysis for Steam Generator Coolant Injection

2. Results Through Task Decomposition Method

The task decomposition method is a method of collecting detailed information about a particular task or scenario, describing the task or activity under analysis, and then decomposing the task using information about a particular task [29].

In this study, the operator actions were derived from SAMGs and the detailed analysis of each operator's actions was applied through the task decomposition method. As for the TA applying the task decomposition method, the characteristics of each task were defined (task verbs), necessary information, control actions performed as a result, and intrinsic actions (calculations, comparisons, memories, trends, and results). In addition, the "description area" indicates the difficulty for operators performing such tasks by indicating that no criteria or specific information exists for performing the tasks, and the description of all categories and descriptions used in task decomposition is shown in Table 4.

Table 4. Category and Description for Task Decomposition Method

category	detailed category	Description (Example)
Task	Task Step	A basic representation of the steps in the guideline and additional numbering if necessary. (1.1.a, 1.2, 1.2.a, etc.)
	Task Description	Write down the task to perform task analysis (check the steam generator pressure, etc.)
	Caution	If required by the guideline, write down the caution to be checked in the task performance.
	Task Verb	Write down the verb form of the task (check, perform, etc.)
	Task Type	Write down the form of the task. (checking, performing, etc.)
Information	Task Information	Write down the information(s) necessary to perform the task. (State of the pump, electric power, RCS pressure, etc.)
	Information Characteristic	Write down which type of information is required. (State, Parameter, Trend, Procedure, etc.)
	Standard Value	Write down the standard values required to perform the task. (Availability of system, pressure is lower than

		113.5kg/cm2a, etc.)
	System	Write down the systems required to perform the tasks. (SBCS, MFWS, etc.)
	Component	Write down the equipment required to perform the tasks. (SI-V637, SI-636, etc.)
Control	Control Type	Write down the required control type for the task that requires control. (Discrete, Continuous, Dynamic)
	System	Write down the required system for tasks that require control. (SI, SDS, etc.)
	Component	Write down the required equipment for tasks that require control. (SI-PP02A, 827-MC05A-F2, etc.)
Inherence action	Calculation	Write TRUE for tasks that require calculation, and FALSE for tasks that do not require calculation.
	Memory	Write TRUE for tasks that require memory of operator, and FALSE for tasks that do not require memory of the operator.
	Comparison	Write TRUE for tasks that require comparison, and FALSE for tasks that do not require comparison.
	Trend	Write TRUE for tasks that require trend analysis, and FALSE for tasks that do not require trend analysis.
Result	Result	Write down the results from the performance of the task.
Description	Description	Write down the lack of information (information uncertainty) required to perform the task.

A detailed analysis of the total 11 SAMGs was performed using the task decomposition method. The following example shows the analysis results of the SG coolant injection. A total of 81 tasks were derived from the strategy of SG coolant injection. Fig. 7 below shows some of the task analysis results in "check the available means" from the results of the analyses using the task decomposition method.

Procedure	Task Step	Task	Warning for Task	Task Verb	Information					Control			Internal act				Task type	Output	description
Procedure	Step	Task	Warning for Task	Verb	Information	Information characteristics	Base Value	System	Component	Control Act	System	Component	Calculation	Remember	Comparison	Trend	Task type	Output	description
Mit-01	1	Check the available means		Check						NA	NA	NA	F	F	F	F	Check		
	1.1	Identify useful means of coolant injection into the steam generator.		Identify															
	1.1.A	Check the availability of the high-pressure coolant injection path of the steam generator.		Check						NA	NA	NA	F	F	F	F	Check		
	1.1.A.1	Check the availability of the high-pressure coolant injection path of the steam generator. (Turbine Driven Auxiliary Feedwater Pump)		Check	Damage status	state	Undamaged	AFWS	AF-PP01A AF-PP01B	NA	NA	NA	F	F	F	F	Check	The availability of turbine-driven auxiliary feedwater pump has been identified.	No criteria for the Damage status
					Steam Generator Pressure	parameter	5.3 kg/cm2g	MSS	MS-PI-1013A, MS-PI-1013B, MS-PI-1013C, MS-PI-1013D MS-PI-1023A, MS-PI-1023B, MS-PI-1023C, MS-PI-1023D	NA	NA	NA	F	F	T	T	Check		
					Auxiliary Feedwater Stroage Tank	parameter	77.60%	AFWS	AFWST	NA	NA	NA	F	F	T	T	Check		
					Condensate storage tank	parameter	78.80%	CS	Condensate storage tank	NA	NA	NA	F	F	T	T	Check		
					desalted water storage tank	parameter	5%	CS	desalted water storage tank	NA	NA	NA	F	F	T	T	Check		
					Raw water storage tank	parameter	10%	CS	Raw water storage tank	NA	NA	NA	F	F	T	T	Check		
					Procedure-3542	Procedure	Reference			NA	NA	NA	F	F	T	F	Check		
	1.1.A.2	Check the availability of the high-pressure coolant injection path of the steam generator. (Moter Driven Auxiliary Feedwater Pump)		Check	Damage status	stete	Undamaged	AFWS	AF-PP02A AF-PP02B	NA	NA	NA	F	F	T	F	Check	The availability of moter-driven auxiliary feedwater pump has been identified.	No criteria for the Damage status
					AC power	state		Electric	4.16Kv 823-SW01A-G2/ SW1-BG2	NA	NA	NA	F	F	T	F	Check		
					Control power	state		Electric	841-MC01A/01B	NA	NA	NA	F	F	T	F	Check		
					Auxiliary Feedwater Stroage Tank	parameter	77.60%	AFWS	AFWST	NA	NA	NA	F	F	T	T	Check		
					Condensate storage tank	parameter	78.80%	CS	Condensate storage tank	NA	NA	NA	F	F	T	T	Check		
					desalted water storage tank	parameter	5%	CS	desalted water storage tank	NA	NA	NA	F	F	T	T	Check		
					Raw water storage tank	parameter	10%	CS	Raw water storage tank	NA	NA	NA	F	F	T	T	Check		
					Procedure-3542	Procedure	Reference			NA	NA	NA	F	F	T	F	Check		
	1.1.A.3	Check the availability of the high-pressure coolant injection path of the steam generator. (Turbine Driven Feedwater Pump)		Check	Damage status	state	Undamaged	MFWS	FW-PP01 FW-PP02	NA	NA	NA	F	F	F	F	Check	The availability of turbine-driven feedwater pump has been identified.	No criteria for the Damage status
					Steam Generator Pressure	parameter	7.9 kg/cm2g	MSS	MS-PI-1013A, MS-PI-1013B, MS-PI-1013C, MS-PI-1013D MS-PI-1023A, MS-PI-1023B, MS-PI-1023C, MS-PI-1023D	NA	NA	NA	F	F	T	F	Check		
					Seal cooling state (Condensate pump operation)	state				NA	NA	NA	F	F	F	F	Check		
					TGBCCW	state				NA	NA	NA	F	F	F	F	Check		
					deaerater storage tank	parameter	26%	CS	deaerater storage tank	NA	NA	NA	F	F	T	F	Check		
					Procedure-3541-A	Procedure				NA	NA	NA	F	F	F	F	Check		
	1.1.A.4	Check the availability of the high-pressure coolant injection path of the steam generator.		Check	Damage status	state	Undamaged	MFSW	FW-PP03	NA	NA	NA	F	F	T	F	Check	The availability of moter-driven auxiliary pump has been identified.	
					AC power	state	Available			NA	NA	NA	F	F	T	F	Check		
	1.1.A.5	Check the availability of the high-pressure coolant injection path of the steam generator. (Start-up Pump)		Check	Damage status	state	Undamaged	FWS	FW-PP07	NA	NA	NA	F	F	F	F	Check	The availability of start up pump has been identified.	
					AC power	state		Electric	13.8Kv 821-SW02N-J2	NA	NA	NA	F	F	F	F	Check		
					Control power	state		Electric	841-DP01N/02N	NA	NA	NA	F	F	F	F	Check		
					Seal cooling state (Condensate pump operation)	state				NA	NA	NA	F	F	F	F	Check		
					TGBCCW	state				NA	NA	NA	F	F	F	F	Check		
					deaerater storage tank	parameter	26%	CS	deaerater storage tank	NA	NA	NA	F	F	T	F	Check		
					Procedure-3541-A	Procedure				NA	NA	NA	F	F	F	F	Check		
	1.1.A.6	If the level of the auxiliary feedwater storage tank is not sufficient, fill the auxiliary feedwater storage tank level with the fire pump.		Perform	Auxiliary Feedwater Stroage Tank	Parameter		AFWS	AFWST	Dynamic	EIS	Fire Engine	F	F	T	F	Perform	fill	No criteria for the level of coolant
	1.1.A.7	If the level of the deaerator storage tank is not sufficient, use condensate pumps to fill the level of the deaerator storage tank.		Perform	deaerater storage tank	Parameter		CS	deaerater storage tank	Dynamic	CS	CSP	F	F	T	F	Perform	fill	No criteria for the level of coolant
	1.1.B	If the injection means of high-pressure coolant is available, go to step 3.		Decide	Available TDAFWP	state	Available	AFWS	AF-PP01A AF-PP01B	NA	NA	NA	F	T	F	F	Decide	The basis of judgment on the quantity of feedwater injection can be provided in Step 3.	
					Available MDAFWP	state	Available	AFWS	AF-PP02A AF-PP02B	NA	NA	NA	F	T	F	F	Decide		
					Available TDFWP	state	Available	FWS	FW-PP01 FW-PP02	NA	NA	NA	F	T	F	F	Decide		
					Available MDFWP	state	Available	FWS	FW-PP03	NA	NA	NA	F	T	F	F	Decide		
					Available Start-up P	state	Available	FWS	FW-PP07	NA	NA	NA	F	T	F	F	Decide		
	1.1.C.1	Check the availability of the low-pressure coolant injection path of the steam generator. (Booster Pump)		Check	Damage status	state	Undamaged	MFWS	FW-PP04 FW-PP05 FW-PP06	NA	NA	NA	F	F	F	F	Check	The availability of booster pump has been identified.	No criteria for the Damage status
					AC power	state		Electric	821-SW02N-F1/13.8kV SW02N	NA	NA	NA	F	F	F	F	Check		
	1.1.C.2	Check the availability of the low-pressure coolant injection path of the steam generator. (External Injection Pump or Fire Engine)		Check	Damage status	state		EIS		NA	NA	NA	F	F	F	F	Check	The availability of External Injection pump has been identified.	1. The emergency cooling water injection flow path on the secondary system must be checked for availability, but the SAMGs do not have the proper information. 2. There is no accurate information about
					External Injection pump	state		EIS	Fire Engine	NA	NA	NA	F	F	F	F	Check	The availability of fire engine has been identified.	
	1.1.D	If there is no feedwater injection method, perform the following:		Perform	Coolant injection path is not available	state				NA	NA	NA	F	T	F	F	Perform		
	1.1.D.1	Identify the cause of the inability to inject water		Identify	Coolant injection path is not available	state				NA	NA	NA	F	F	F	F	Perform	Identifying the cause of non-coolant injection	
	1.1.D.2	Prioritize actions to restore the means of coolant injection and instruct OSC or MCR to initiate appropriate recovery actions		Decide						NA	NA	NA	F	F	F	F	Decide	Means Recovery and Availability	

Fig. 7. Example of Task Decomposition Method for Steam Generator Coolant Injection Strategy

E. Staffing Analysis

The purpose of the staffing analysis is to analyze the response organization and personnel in the SA for the development of the HSI. It also analyzes the organization's license, knowledge, and experience level for the SA response tasks and identifies design requirements for the SAMSS [4].

For this study, the radiation emergency plan of the operator in the domestic NPP was reviewed to analyze the necessary organization and personnel in the event of a SA [13]. The domestic NPP operators' approximate SA response organization includes "MCR", "emergency offsite facility", "TSC", "operation support center“, "severe accident support organization", and Fig. 8 below shows the schematic SA response structure of the operator of the domestic NPP [14]. The numbers in the brackets indicate the number of personnel in each organization. In addition, each organization is described below .

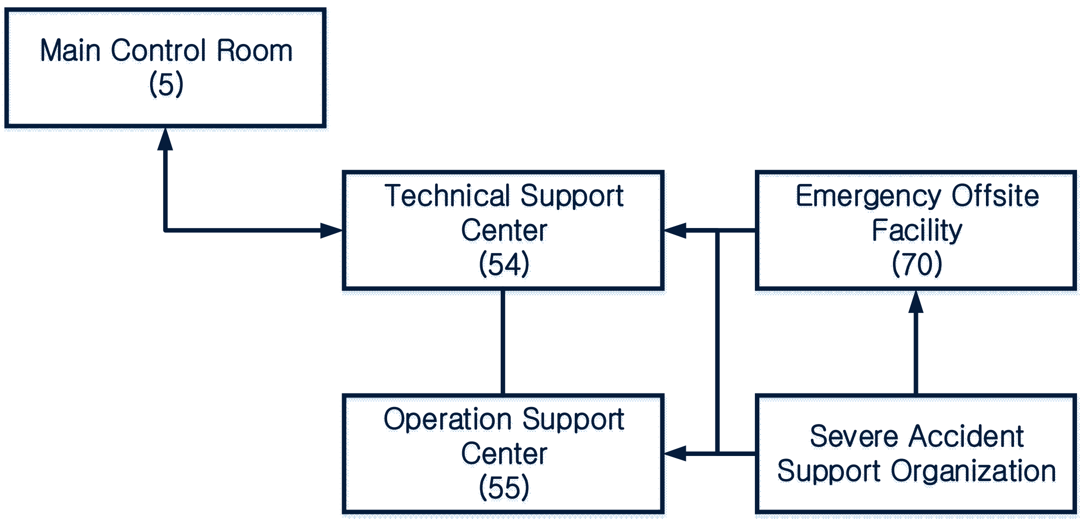

Fig. 8. Schematic Organization for the Response of KHNP to Severe Accidents

1. Technical Support Center

The TSC is an organization that carries out the SAMG in the SA and makes the final decision on the overal SAM strategy. It is also an organization that reports the results of the analysis and countermeasures of the current emergency situation and radioactive sample analysis of the plant to the head of the emergency headquarters. The TSC includes the technical support team, the radiation countermeasures team, and the emergency operation team.

2. Operations Support Center

The operation support center is an organization that consults with the TSC for emergency maintenance and performs the role of maintaining the cooperative system with the relevant agencies related to fire station and medical care. The operation support center includes the maintenance plan team, the mechanical team, the electric team, the instrumentation and control team, and the maintenance support team.

3. Emergency Offsite Facility

The emergency offsite facility maintains a cooperative system with the disaster countermeasures organization, identifies emergency situations and establishes countermeasures accordingly. It is also an organization that performs the role of reviewing and reporting on residents' protection measures to the head of the emergency headquarters. Emergency offsite facility departments include the center of administrative support, announcement support center, etc.

In addition, KHNP is planning a new organizational chart to manage SA more efficiently. Fundamentally, the current structure will remain thesame. The organizations to be included are the disaster response safety center, and the STAG and SAFE-T belonging to the KHNP central research institute (CRI). Accordingly, the direction of improvement of the organization for responding to SA of KHNP is shown in Fig. 9 [14].

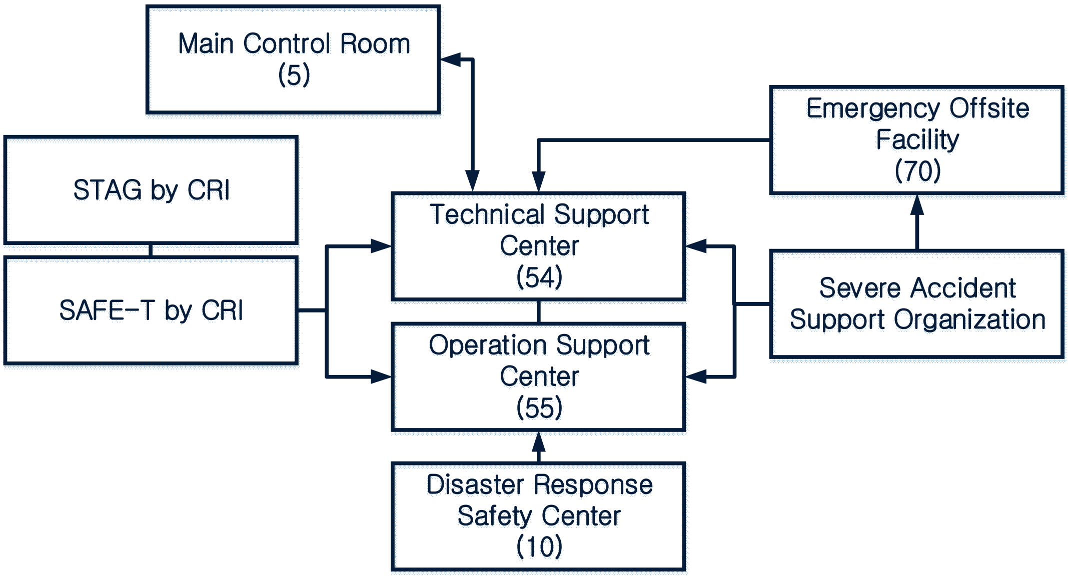

Fig. 9. Improvement of the Organization for Responding to Severe Accidents of KHNP

Ⅲ. Design of a Human-System Interface for Severe Accident Management Support System

The HSI is defined as the technology through which personnel interacts with plant systems to perform their functions and tasks. The HSI design process represents the translation of identified safety functions and task requirements into HSI characteristics and functions [11].

In this chapter, HSI is designed for SAMSS. For the HSI design, 16 design requirements derived from the OER, the HFE analysis (FRA&FA, TA, and SA), and the Human-System Interface Design Guidelines Rev.2 (NUREG-0700) [30] were considered. The result of the HSI design is the HSI design document and an example of the design. Fig. 10 shows the design process in this study.

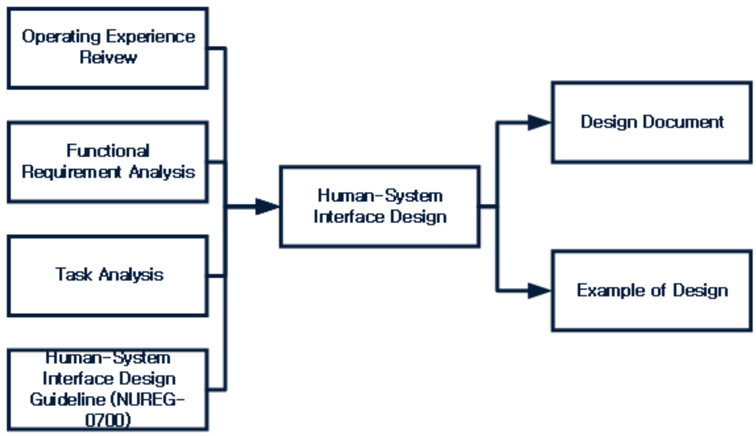

Fig. 10. Human-System Interface Design Process

Fig. 11 shows the overview of the HSI of the SAMSS proposed in this study. The HSI of the SAMSS has divided into 1) information display area, 2) guideline display area, 3) function display area, and 4) task display area. The information display area provides the basic information related to SAMG performance, and guideline display area provides the contents of SAMG systematically. The function display area and task display area provide the necessary information to perform the SAMGs. The HSI composition of the SAMSS is proposed based on the higher level requirements derived from the OER. The explanation for each area is as follows.

The purpose of the guideline display area is to support the performance of SAMGs, which are guidelines that must be followed by operators in SA situation (5, 7, 9 in Table 2). The function display area is configured to monitor the safety functions required by the SAMG at one screen (10, 13, 15 in Table 2). The task display area was proposed to collect the information required by the SAMG and to assist in the assessment of the plant's condition (11 in Table 2).

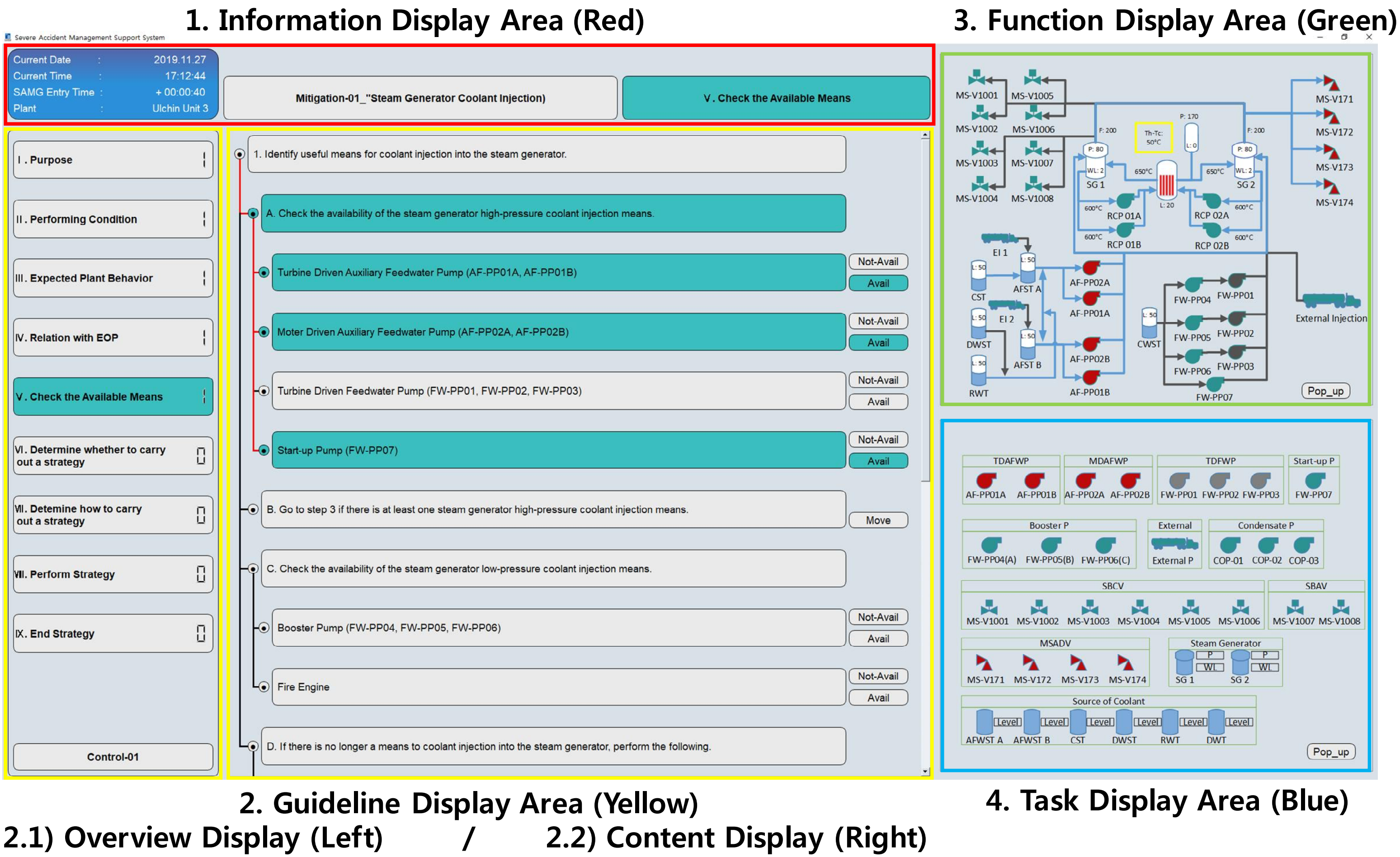

Fig. 11. Overall of Human-System Interface for Severe Accident Management Support System

A. Information Display Area

The Information Display Area is an area that provides the basic information necessary to perform SAMGs. This area shows the current time and date, the elapsed time after entering the SAMG, the plant, the SAMGs being performed, and the steps being performed. Fig. 12 below, shows the information display area.

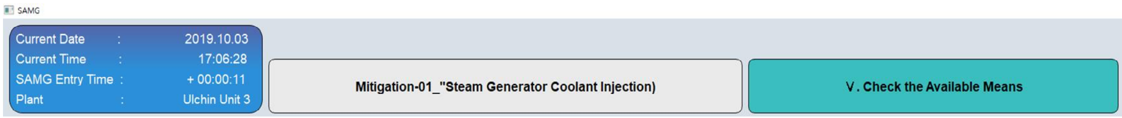

Fig. 12. Information Display Area

B. Guideline Display Area

The main purpose of the guideline display area is to show the overview and content of SAMG and help the person perform the SAMG. It is divided into two displays; the overview display and the content display.

1. Overview Display

Overview display is a display that provides the operator with a higher level configuration corresponding to the step in the SAMG. The overview display allows users to move easily in order to understand the configuration of the instructions and to understand the content of the steps. The overview display includes the following functions:

- Display number of performance: Indicates the number of times the operator has performed the step. SAMGs require the same action to be carried out continuously
- Place-Keeping: Indicating the completed steps, the in-complete steps, and the current performance steps

- Move the detailed steps: Select the steps to be displayed on the content display
- Move to the control-01 guideline: Used by the operator to move to the previous or current guideline of the SAMG.

The architecture of the overview display is written to reflect the results of the HTA. The overview display was designed based on the second level actions to achieve a higher purpose (safety function) of the HTA results. Fig. 13 shows the relationship between HTA results and the overview display.

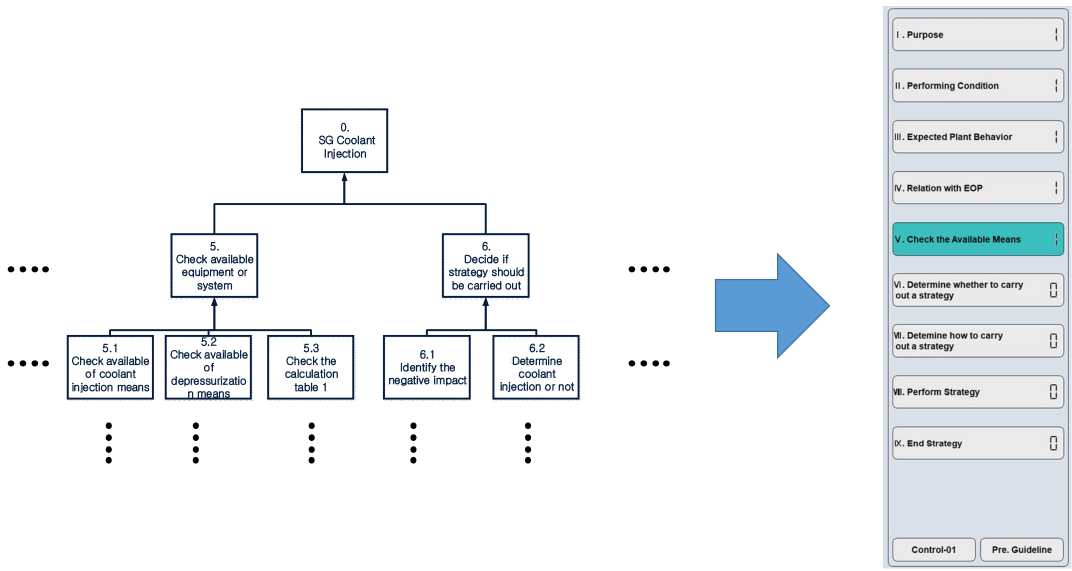

Fig. 13. The Relation between HTA Results and the Overview Display

2. Contents Display

The content display is a display that displays detailed instructions for the selected step. The display contains information such as steps, tasks, and task verbs from the task decomposition method. The content display includes the following functions:

- Carrying out the instructions: Entering the instructions using the relevant performing button.
- Place-Keeping: Completed steps, incomplete steps, are marked to guide performance
- Folding: The ability to fold instructions that the operator currently performs, has not yet performed, or does not need to perform.

In the "Task" area, the sequence of contents was listed based on the step items derived in the task decomposition method. In addition, buttons for performing each content were named using the results of the task verbs. Fig. 14 below shows the relationship between the results of the task decomposition method and the content display configuration.

Procedure	Task Step	Task	Warring for Task	Task Verb
Procedure	**Step**	**Task**	**Warring for Task**	**Verb**
Mit-01	5	Check the available means		Check
	5.1	Identify useful means of coolant injection into the steam generator.		Identify
	5.1.A	Check the availability of the high-pressure coolant injection path of the steam generator.		Check
	5.1.A.1	Check the availability of the high-pressure coolant injection path of the steam generator. (Turbine Driven Auxiliary Feedwater Pump)		Check

Fig. 14. The Relation between the Task Decomposition Method and Content Display

C. Function Display Area

The function display area is a display area that provides the satisfaction of safety functions, the possible success paths, and the operation of success paths that need to be satisfied with the selected instructions. This area is provided by converting the MFM models derived from the FRA into a more familiar Piping & Instrument Diagram (P&ID) format for the operator or TSC agent. The Function Display Area includes the following key functions:

- Providing the goal of safety function: Indicating the plant process variables that can indicate the goal of the safety function
- Providing the plant variables: Providing the plant current values related to safety functions
- Providing a success path for safety functions: Providing a success path for safety functions as a result of FRA
- Providing success path status: Providing information on the status of success paths (operable / non-operable) to satisfy safety functions
- Providing information on equipment availability: Providing the current condition of the equipment to the operator (Green: Inoperable), Red: In operation, gray: Not operable due to failure or maintenance lights)
- Pop-up: The function display area is expanded in a separate window.

Fig 15 below shows the relationship between the MFM model and the function display area.

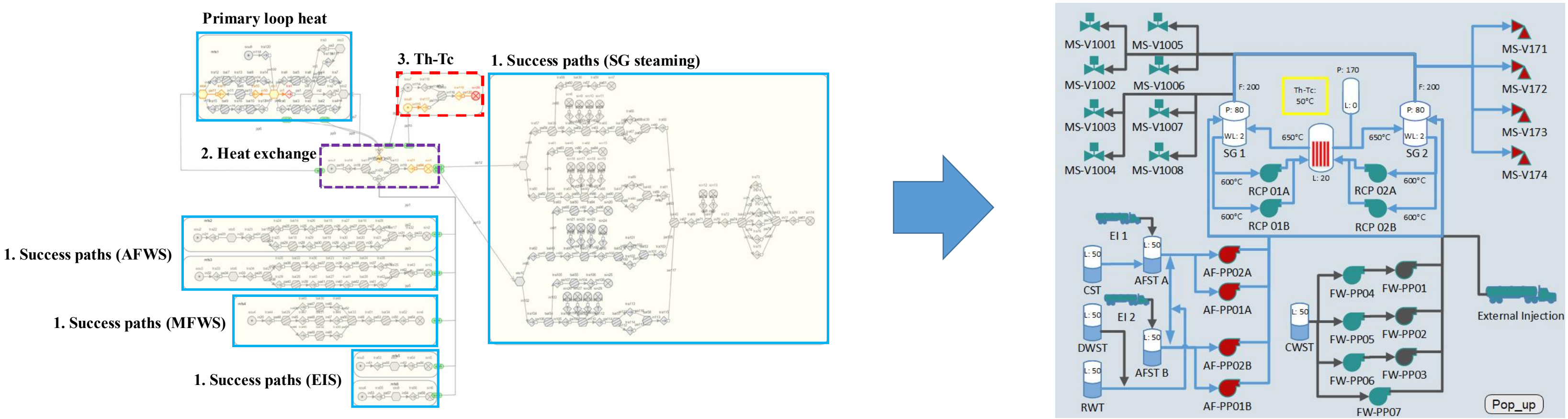

Fig. 15. The Relation between the Multilevel Flow Modeling and Function Display Area

D. Task Display Area

The purpose of the task display area is to collectively show the necessary information for performing the selected step to support the decision making of the operator. This area groups and displays the information needed to perform the steps resulting from the task decomposition method on a single display. The sequence of the presentation of each information is consistent with the order of the SAMG's instructions to minimize unnecessary cognitive activity by the operators. The task display area includes the following functions:

- Providing plant variables: Plant current variables (SG level, pressurizer pressure, etc) values are provided.
- Providing information on equipment availability: Providing the current condition of the equipment to the operator (Green: Inoperable), Red: In operation, gray: Not operable due to failure or maintenance)
- Pop-up: The function display area is expanded in a separate window.

The task decomposition method lists all the information required to perform the step (equipment and system, information characteristics, plant variables, reference values) based on the "information" item. Fig 16 shows the relationship between the task decomposition method results and the task display area.

Task	Warring for Task	Verb	Information	Information characteristics	Base Value	System	Component
Check the availability of the high-pressure coolant injection path of the steam generator. (Turbine Driven Auxiliary Feedwater Pump)		Check	Damage status	state	Undamaged	AFWS	AF-PP01A AF-PP01B
			Steam Generator Pressure	parameter	5.3 kg/cm2g	MSS	MS-PI-1013A, MS-PI-1013B, MS-PI-1013C, MS-PI-1013D MS-PI-1023A, MS-PI-1023B, MS-PI-1023C, MS-PI-1023D
			Auxiliary Feedwater Stroage Tank	parameter	77.60%	AFWS	AFWST
			Condensate storage tank	parameter	78.80%	CS	Condensate storage tank
			desalted water storage tank	parameter	5%	CS	desalted water storage tank
			Raw water storage tank	parameter	10%	CS	Raw water storage tank
			Procedure-3542	Procedure	Reference		

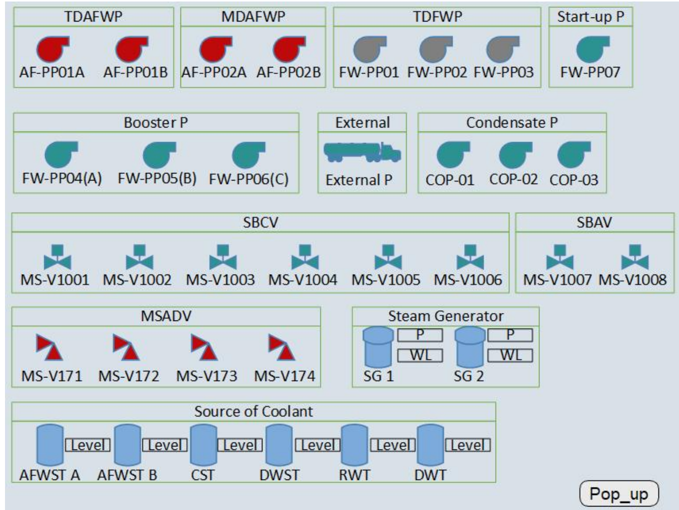

Fig. 16. The Relation between the Task Decomposition Method and the Task Display Area

Ⅳ.Conclusion

This study aims at designing the HSI for SAMSS that can help operators in providing information and decision-making in SA situations. The SAMSS has been developed so far. However, due to difficulties in implementing the human-system interaction and HFE application, this research has been designed using HFE program in NUREG-0711. As a prior study, the OER, FRA&FA, TA, and staffing analysis were carried out and the HSI was designed based on those results.

As a result of the OER, 16 design requirements were derived from reviews of the SAs that occurred in the past and SAMSSs that have been developed so far. HSI has been designed based on these requirements. In FRA&FA, the 7-safety functions and their success paths for SAM were identified using a hierarchical structure and modelling of identified safety functions and their success paths were performed through MFM. In addition, the automation level of function was allocated through FA. This result was used in the function display area. In TA, the tasks that the operator of each identified safety function must perform were analyzed using HTA and task decomposition method. These results were used in task display area and guideline display area respectively in the HSI design. Finally, the review of SA response organization was conducted through staffing analysis.

Based on the results of the above analyses (OER, FRA&FA, TA, and staffing analysis), the HSI design of SAMSS was performed. The displays are divided into “information display area”, “guideline display area”, “function display area”, and “task display area” for each purpose. The display uses "function display", and "task display" concepts, which collectively indicates the information to perform the selected guideline. This is expected to be easier for operators to obtain information from an area when carrying out actual guidelines, thus making it easier to perform the selected guideline and decision-making because the information appears collectively. In addition, if the system is installed in the response organization and the response organization uses the system in response to SA, it is expected to reduce the possibility of human error and thus contribute to reducing the risk of NPPs.

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