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Functional Requirement Analysis and Task Analysis for Severe Accident Management Support System

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1. Introduction

The severe accident management guidelines (SAMGs) are guidelines developed for the purpose of mitigation and management of severe accident (SA) in NPPs. When SA occurs in nuclear power plants (NPPs), the operators in main control room (MCR) exit all procedures and enter the SAMGs for mitigation of SA for the safety of NPPs.

However, current SAMGs have some issues when operators follow them. In the case of accidents in Three Mile Island (TMI), Chernobyl, and Fukushima, the problem of decision making, communication and inability of knowing the exact current state of NPPs were common [1]. Due to these issues, the necessity of developing severe accident management support system (SAMSS) has been raised. The SAMSS aims to support the mitigation of SA by an operator in MCR or technical support center (TSC).

There are two examples of SAMSSs developed in Korea [1,2]. Korea Atomic Energy Research Institute (KAERI) developed severe accident management and training support system (SAMAT) and severe accident management expert system (SAMEX) for mitigation and proper management of SAs. SAMAT includes displays for the SA training simulator, computerization of SAMGs, and current NPP variable and status. SAMEX has the functions of predicting the main safety functions behavior of NPPs and emission and behavior of radiation source.

As a part of a project to develop a SAMSS, this study aims to perform functional requirement analysis (FRA) for SAMGs using multilevel flow modeling (MFM) and task analysis (TA) for SAMGs using hierarchy task analysis (HTA) and decomposition method. Section 2 introduces the identification of functions from SAMGs and modeling of safety functions and systems using MFM. Section 3 presents the TA for SAMGs using HTA and decomposition method. This paper shows the analysis of Mitigation-01 (i.e., Steam Generator Coolant Injection) as an example.

2. Identification of Safety Functions

FRA is a part of the human factors engineering process recommended in NUREG-0711. FRA is to find out which safety functions must be accomplished for NPPs safety [4].

In this study, a total of seven safety functions have been identified from SAMGs. The purpose of those safety functions is the prevention of radiation release after SA.

The safety functions to prevent radiation release are divided into two goals. First is cool-down depressurization of reactor and primary side, and second is maintaining the integrity of reactor building.

2.1 Cool-down and depressurization of reactor and primary side

The functions to achieve the cool-down and depressurization of the reactor and primary side are as follows [5]:

- Steam generator coolant injection: Injection of coolant into the steam generator for Reactor Coolant System (RCS) heat removal, RCS depressurization, and steam generator tube breakage prevention
- RCS depressurization: Low pressure safety injection (LPSI) to supply coolant to the RCS and protects the working shutdown cooling system (SCS)
- RCS coolant injection: core cooling and the reactor vessel protection using the injection of coolant to RCS
- Containment coolant injection: Prevention of reactor vessel damage or delay through cooling of the outer wall of the reactor vessel. Removal of radioactive material in containment

2.2 Maintaining the integrity of reactor building

The functions to achieve the maintaining the integrity of reactor building are as follows:

- Fission product release control: Reducing the risk of exposure to people near NPPs during an in-containment SA
- Containment condition control: Ensuring the integrity of the building by reducing the high temperature, high pressure, and fission product concentration in the containment.
- Containment hydrogen control: Preventing hydrogen explosion by controlling hydrogen in reactor building [5].

2.3 Success path of the safety function

This study also identifies systems that can be applied to accomplish the safety functions, which are called success paths. The success paths have been identified from SAMGs and divided into safety and non-safety systems.

As an example, this paper presents the analysis of Mitigation-01, i.e., steam generator coolant injection. The steam generator coolant injection has the following success path.

- Safety system
  - Auxiliary feed water system
- Non-safety system
  - Main feed water system
  - External Injection system

The external injection system is a portable equipment introduced after the Fukushima accident.

2.4 Multilevel flow modeling for safety functions in Mitigation-01

MFM is applied for the modeling of function identified in the earlier section. The basic MFM concept can be represented through a flowchart in which the symbols represented in the structure (mass, flow, and control) are influenced. MFM uses means-end and whole-part concept [6,7]. MFM is used to represent the final goal (safety of NPPs or power generation) of the NPPs and the function to achieve it. MFM uses several symbols. Table I shows the MFM symbols used in this study.

Table I: Symbol and description of MFM [6]

Symbol	Description
source	The source symbol means the function of the system, which serves to store infinite mass or energy.
sink	The sink symbol means the function of a system that absorbs mass or energy indefinitely.
transport	The transport symbol means the ability of a system to transfer mass or energy between two systems or locations. Transport can be connected to other symbols via relations symbols like influencers or participants.
storage	A storage symbol means a system that acts as an accumulator of mass or energy. The storage symbol has no limit on the number of connections and the number of operating conditions.
balance	The balance symbol means the function of the system, which provides a balance between the total proportion of in-flow and out-flow. Balance symbol also has no limit on the number of connections.
influencer	The influencer symbol means to help flow functions connect through transport if transport plays a role in influencing the amount of material transported.
participant	The participant symbol has almost the same meaning as influencer, but the difference is that it is used to passively receive mass or energy.
producer-product	A producer-product symbol means acts to connect each structure when the function in one structure results in a transformation that serves as a function in the other structure.

2.4.1 Process modeling model using MFM for steam generator coolant injection

In this paper, the steam generator coolant injection was modeled using MFM. In order to build an MFM model, success paths with the process model of MFM have been identified. Those contain auxiliary feed water system train 1 (AFWS 1), AFWS 2, main feed water system (MFWS), external injection train 1 (EI 1), EI 2 and main steam system.

Fig. 1 below shows a success path diagram of steam generator coolant injection using a process model tool of MFM.

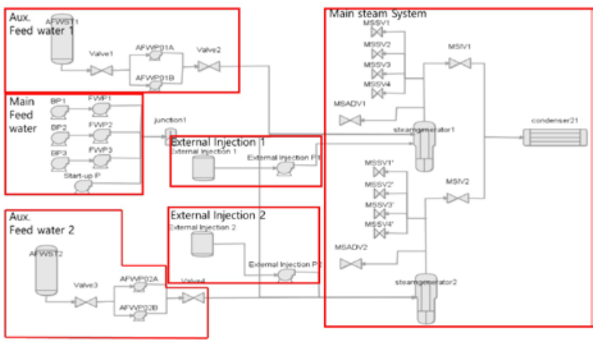

Fig. 1. Steam generator coolant injection model using the process diagram of MFM.

2.4.2 MFM model for steam generator coolant injection

Based on the success path model shown in Fig. 1, an MFM model was implemented. Fig. 2 below shows the MFM model for the steam generator coolant injection.

The model consists of three levels. The first level shows the goal structure (red rectangle). It represents the cold-leg and hot-leg temperatures to ensure that the RCS heat is being removed.

Then, the second level (green) represents a heat exchanger. The heat exchanger structure is an energy flow structure that shows the heat transfer in the third level structure.

The third level (blue) shows the success path of steam generator coolant injection. It contains the mass flow structure of the nuclear steam supply system (NSSS), AFWS 1, AFWS 2, MFWS, EI 1, EI 2 and main steam system.

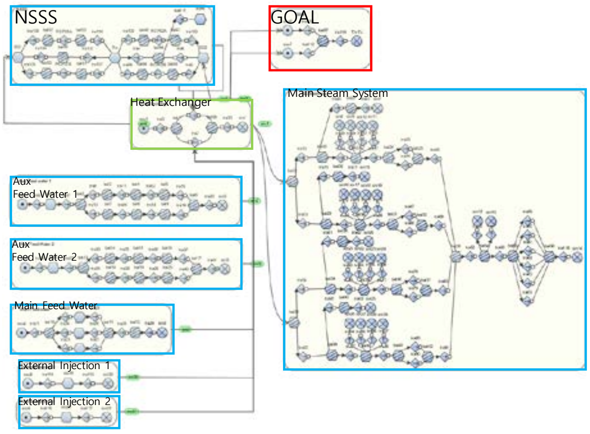

Fig. 2. Steam generator coolant injection modeling using multilevel flow model of MFM.

3. Task Analysis for Safety Functions

The definition of a task is a set of human actions that absolutely contribute to the goals of a particular function and the goals of the system. 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 [4]. In this study, two TA methods were used to analyze the function of steam generator 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 section.

3.1 Hierarchical task analysis of steam generator coolant injection

HTA is one of the most widely used methods for TAs. 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 [8,9]. The HTA is used for analyzing the CTA of SAMGs in this study.

The HTA for the steam generator coolant injection was performed in four steps as shown in Fig. 3. The final goal is steam generator coolant injection, the sub-goal is checking the injection channel, and operating high pressure coolant injection and low pressure coolant injection, and related systems. For the high pressure coolant injection, there are turbine driven aux feed water pump (TDAFWP), motor driven aux feed water pump (MDAFWP), turbine driven feed water pump (TDFWP) and start-up pump (SP). For low pressure coolant injection, there are buster pump (BP) and external injection pump (EIP).

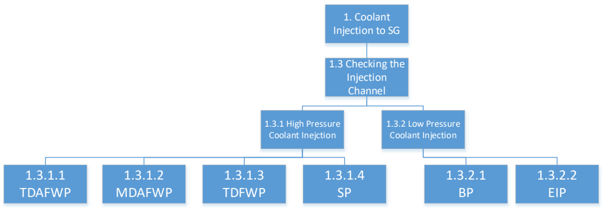

Fig. 3.Brief hierarchical task analysis of steam generator coolant injection.

3.2 Decomposition method of steam generator coolant injection

The decomposition method expands the task description into a series of statements for the task. Initially, a short set of explanations for all work elements is generated and additional information is derived using a predetermined set of subtrees. This subheading is chosen by the analyst to obtain the information needed to deal with the particular problem under consideration (e.g. signal to initiate behavior, control, decision, error, response, feedback, etc.) [8,9]. Decomposition method can use the results of HTA. Table II shows the categories of task decomposition and their corresponding decomposition description.

Table II: An example of task decomposition.

Description of task: 1.3.2.2 Check availability of external injection system (pump).	Task difficulty: Low, it is not necessary to check the damage states of the equipment, AC power, seal cooling, lubricant cooling and deaerator storage tank level.
Purpose of task: Primary cooling by coolant injection.	Requirements for undertaking task: Used when the steam generator pressure is less than 1.41 bar. To meet the design flow (780lpm), the steam generator secondary (out of U-tube) should be depressurized to 0.11bar.
Sequence of activity: Check the steam generator pressure and temperature and perform action if the condition is satisfied.	Information: The water level can be checked through the steam generator water level detector.
Required speed: Limit to 6.3l/s for 10 minutes if the SG level is less than 1%	Outputs from the task: It is possible to raise the water level and to remove the heat from the NSSS through the steam generator.
Communications : Since external injection is a mobile equipment, communication with the on-site operator is important.	Task complexity: Medium. After confirming the pressure in the steam generator, it can be performed if the pressure condition is satisfied.

Critical values: Steam generator level, and flow rate of the external injection system.	Error consequence: The tube of the unbroken steam generator may be broken and the radiation may leak to the secondary side.
Adverse hazards: Steam generator tube damage	

4. Conclusion

This study carried out for FRA and TA as a part of the process of NUREG-0711 for the SAMSS development. In FRA, the identification of safety functions from SAMGs and success paths of safety functions, and their modeling using MFM were performed. TA was also conducted using both the HTA and decomposition methods.

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