Functional Requirement Analysis for Severe Accident Management Support System Using Multilevel Flow Modeling

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Abstract: This study aims at developing a functional requirement analysis (FRA) for severe accident management support system using Multilevel Flow Modeling (MFM) in Nuclear Power Plants (NPPs). FRA defines high-level functions that have to be accomplished to meet the goal of NPP. This includes the identification of functions that have to be performed to satisfy the overall NPP goal. FRA also provides a framework for determining the roles and responsibilities of personnel and automation through Functional Allocation (FA). MFM uses means-end and whole-part decomposition concept, which helps systems engineers and plant operators to cope with complexity because they facilitate reasoning on different levels of abstraction. MFM has been used to model complex processes such as NPPs. In this study, the safety goal of NPPs is divided into prevention of core damage and prevention of radiation release outside containment. Then, functions and systems to satisfy these safety goals in a reference plants are also defined. Those functions and systems are modeled using the MFM to show physical and functional relations between functions, between functions and systems, and between systems.

Keywords: Severe Accident, Support system, FRA, SAMG, and MFM

1. INTRODUCTION

At the present Nuclear Power Plants (NPPs), when Severe Accident (SA) occurs, the operators exit the ongoing procedures and enter the Severe Accident Management Guidelines (SAMGs) for safety of NPPs [1]. The SAMGs are procedures developed for the purpose of mitigation and management SA in NPPs. However, the current SAMGs contain only strategies to mitigate NPP accidents according to the symptoms of SA. There is little information about the performance and SA scenarios of the NPPs, such as the diagnosis, prediction, and evaluation of the SA assessment. Operator in Main Control Room (MCR) and Technical Support Center (TSC) who are in charge of managing SA may have difficulty in decision making [2]. The lessons learned after the Three Mile Island (TMI), Chernobyl and Fukushima accidents are that the operator could not clearly distinguish a SA. One of many reasons is that operator were not educated about SA, many alarms occurred, and the situations were complicated, so operators could not know exactly what was going on at the NPPs [3]. For this reason, the necessity of Severe Accident Management Support System (SAMSS) has been raised to help operator’s decision making and Severe Accident Management (SAM) for safety of NPPs.

After the Fukushima Daiichi accident, global interest in SAM, SAMSS and mitigation of SA has increased. In such situations, it becomes increasingly difficult for operators to carry out the correct actions and human error is more likely. Therefore, it is necessary to develop a SAMSS that can help operators in complex process situation. Since TMI accident, some SAMSSs have been developed to support the mitigation of severe accident by operators.

Some of the SAMSSs that have been developed so far are as follows. The Severe Accident Management Expert System (SAMEX) was developed by Korea Atomic Energy Research Institute (KAERI) and has functions to predict major safety function behavior of NPPs. Accident Diagnostic, Analysis and Management (ADAM) has been developed in Energy Research Institute (ERI). It applies the information generated by on-line as well as SA code simulation to use for accident management and training. Severe Accident Management System Online Network (SAMSON) developed in ARD Corporation has the function of predicting occurrence time of major events such as Loss of Coolant Accident (LOCA), Steam Generator Tube Rupture (SGTR). The Severe Accident Management

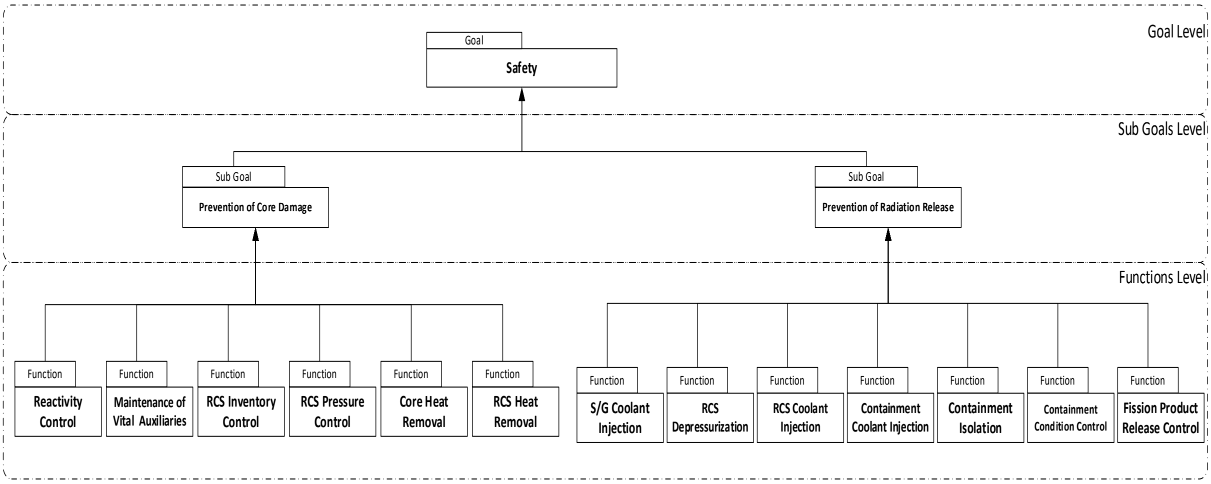
Operator Support (SAMOS) developed by US-NRC has the function of major NPPs event variable behavior predictions and major event distinction [2].

As a part of a project to develop a SAMSS, this study aims to perform an FRA for prevention of core damage and prevention of radiation release using MFM. Section 2 introduces the nine-safety functions in NPPs and the derived functions from SAMGs. Then, systems to achieve the functions are identified through a hierarchical method. Section 3 presents the modeling of functions and systems using MFM. In this paper, Reactor Coolant System (RCS) Inventory Control, RCS Coolant Injection, and Steam Generator (SG) Coolant Injection were modeled as an example.

2. Identification of Safety Functions for Severe Accident Management

The FRA was carried out following the human factors engineering process in NUREG-0711 [4]. Total thirteen safety functions have been identified from emergency operating procedures (EOPs) and SAMGs. The EOPs are also considered in this study because the safety functions and systems are shared by EOPs and SAMGs and the information about how EOPs were conducted is important in conducting the SAMG. The purposes of those functions are divided into the prevention of core damage and the prevention of radiation release. Those functions are presented in a hierarchical structure as shown in Figure 1.

Figure 1: Safety functions for severe accident management



2.1 Safety functions to prevent core damage

The purpose of EOPs is primarily the prevention core damage. This study identified six safety functions to prevent core damage for the OPR1000 [5]. The functions are as follows:

- Reactivity Control: shutting reactor down to bring the reactor to a subcritical state and reduce decay heat production
- Maintenance of Vital Auxiliaries: maintaining of systems needed to support safety systems (e.g., electric power and component cooling)
- RCS Inventory Control: maintaining a coolant medium around core
- RCS Pressure Control: maintaining coolant medium in proper state
- Core Heat Removal: transferring heat out of core system medium
- RCS Heat Removal: transferring heat out of coolant system medium

2.2 Safety functions to prevent radiation release

The functions to prevent radiation release can be divided into two folds: 1) cooling down and depressurization of reactor and vessel, and 2) maintaining the integrity of containment. Four safety functions are identified with relation to the cooling down and depressurization of reactor from the OPR1000 SAMG [2,6,7].

- SG Coolant Injection: injection of cooling water into the SG for RCS heat removal and SG tube breakage prevention
- RCS Depressurization: enabling RCS replenishment using Low Pressure Safety Injection (LPSI) and protect the Shutdown Cooling System (SCS) that is in use
- RCS Coolant Injection: cooling the core and ensuring reactor vessel protection
- Containment Coolant Injection: prevention and delay of reactor vessel damage (it also has a function of removing radioactive material in containment)

Three safety functions are identified for maintaining the integrity of containment as follows [2,6,7].

- Fission Product Release Control: reducing the risk of exposure to people during an accident from the in-containment
- Containment Condition Control: controlling containment temperature, pressure and reduction of fission product concentration
- Containment Hydrogen Control: preventing hydrogen explosion in the containment

Table 1: Success paths for the safety function

Purpose	Function	Safety System	Non-Safety System
Prevention of Core Damage	Reactivity Control	Reactor Trip (Reactor Protection System) Safety Injection (HPSI)	Rod Control (Diverse Protection System) Chemical Volume & Control System
	Maintenance of Vital Auxiliaries	Emergency Diesel Station batteries	1MW Mobile Generator 3.2MW Mobile Generator Alternative AC Diesel Generator
	RCS Inventory Control	Safety Injection	CVCS Charging & Let down External Injection
	RCS Pressure Control	Safety Injection	Pressurizer Pressure Control Chemical Volume & Control System SG Steaming
	Core Heat Removal	Natural Circulation	Forced Circulation
	RCS Heat Removal	Auxiliary Feedwater Shutdown Cooling Feed and Bleed	Main Feedwater External Injection SG Steaming
Prevention of Radiation Release	SG Coolant Injection	Auxiliary Feedwater	Main feedwater External Injection
	RCS Depressurization	Reactor Coolant Gas Vent Safety Depressurization	Pressurizer Auxiliary Spray SG Steaming
	RCS Coolant Injection	Safety Injection	Chemical Volume & Control System External Injection
	Containment Coolant Injection	Containment Spray	-
	Containment Isolation	Containment Isolation	-
	Containment Condition Control	Containment Cooling Containment Spray Combustible Gas Control	Passive Autocatalytic Recombiner (Non-Power PAR)
	Fission Product Release Control	Containment Fan Cooler Containment Isolation Containment Spray	-

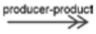
2.3 Success path for the safety functions

This study also identified systems that can be applied to achieve the safety function, called success path. The success path has been identified from EOPs and SAMG and classified into safety and non-safety systems. Table 1 shows the success paths for the thirteen safety functions.

3. Multilevel Flow Modeling

MFM is a method for functional modeling of complicated industrial processes and belong therefore in its thinking and methodology to the branch of Artificial Intelligence called qualitative reasoning. MFM has a primary objective on representation of NPP goals and functions and provide a ethodological way of using those concepts to represent complex industrial process. The fundamental MFM modeling concepts comprise objectives, flow structures, a set of functional primitives (flow functions and control functions), a set of means-end and influence relations representing purpose related dependencies between functions and objectives and among the functions themselves [8]. MFM uses means-end and whole-part decomposition concept, which helps systems engineers and plant operators to cope with complexity because they facilitate reasoning on different levels of abstraction [9]. Some of researchers proposed that MFM could model accident information monitoring system and alarm design, which can help operators decision making in case of an accident [10]. Therefore, MFM is a modeling technique that shows how a function affects subsequent functions. For example, when the function low is input, we can see what function the next function receives [11]. There are many symbols in MFM. The symbol used in this study and their descriptions are shown in Table 2 below.

Table 2: Symbol of MFM concept and their description [8]

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

4. Modeling safety functions Using MFM

This section introduces two examples of MFM modeling for the RCS Inventory Control/RCS Coolant Injection and SG Coolant Injection.

4.1 RCS Inventory Control and RCS Coolant Injection

This section introduces the MFM model for the RCS Inventory Control and RCS Coolant Injection. Even though these functions have different purposes, they share the same success paths and then the goal of the functions, i.e., injecting water to the RCS. Figure 2 shows a simplified schematic of RCS Inventory Control and RCS Coolant Injection. As shown in Table 1, three systems, i.e., safety injection (SI), Chemical & Volume Control System (CVCS), and external injection (EI), are available to supply water in the reference plant. Safety injection and external injection can be divided into two divisions, respectively, i.e. SIS1/SIS2 and EI1/EI2.

Figure 2: RCS Inventory Control and RCS Coolant Injection modeling using process model of MFM

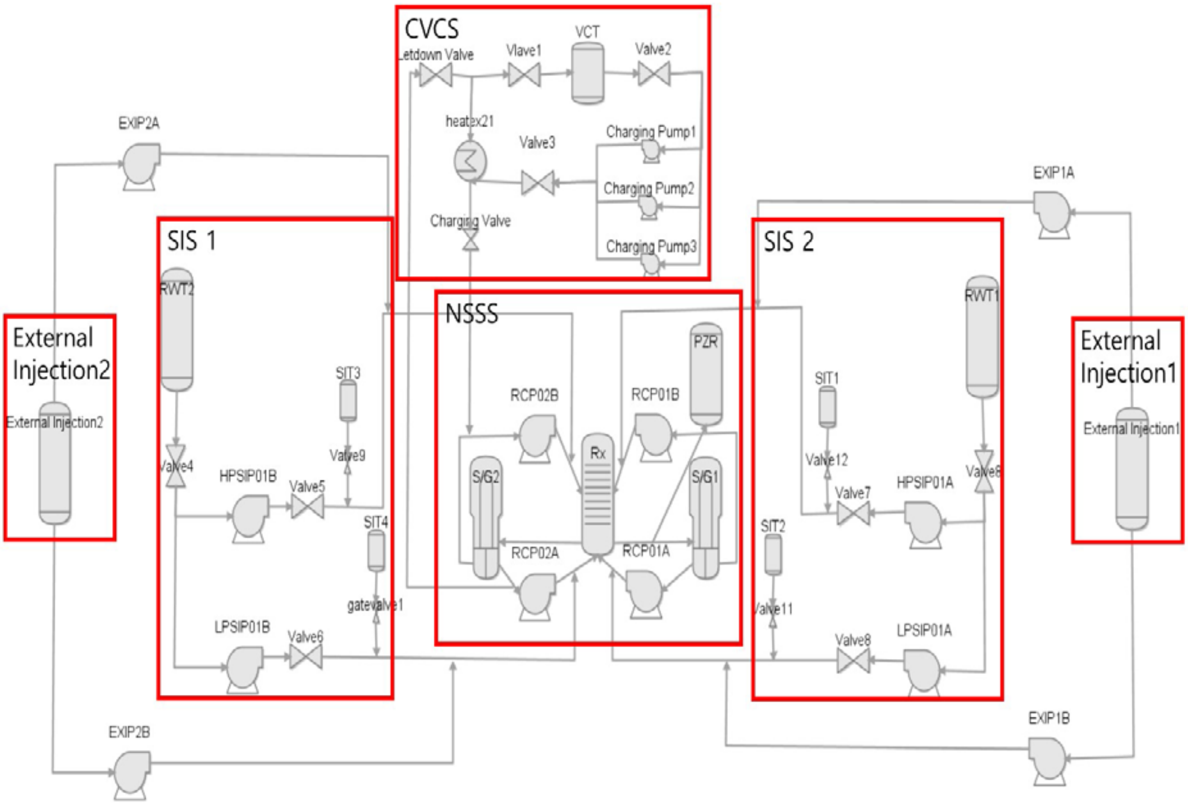
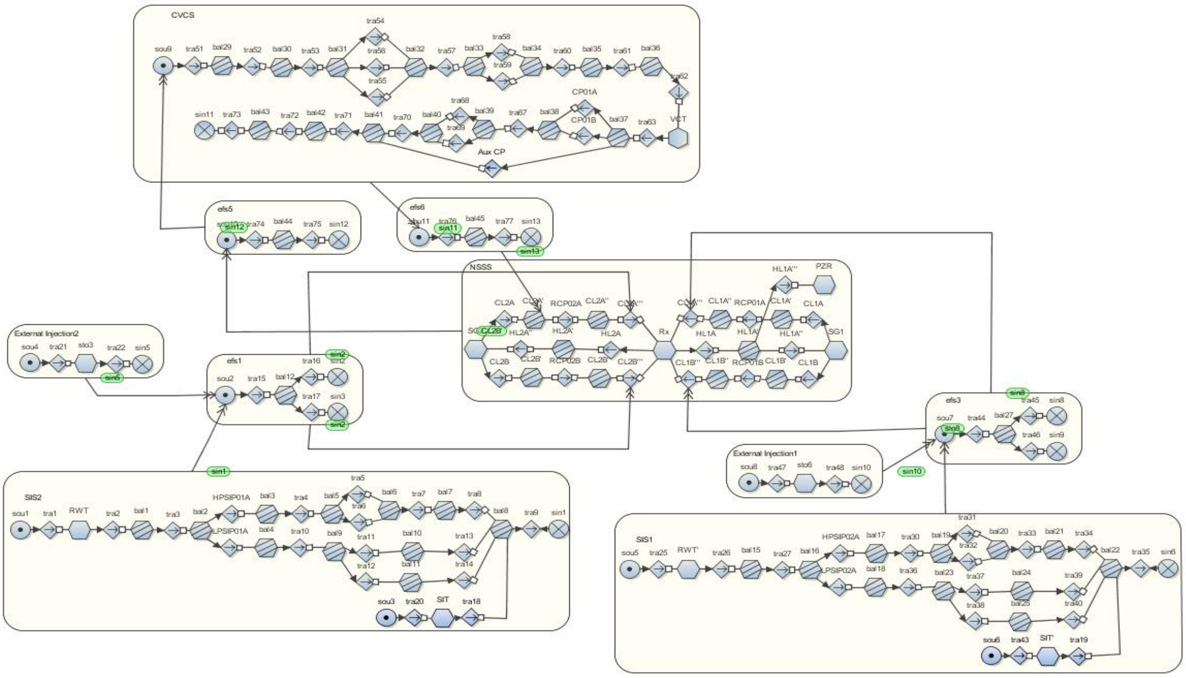


Figure 3 shows the MFM model for the RCS Inventory Control and RCS Coolant Injection. The model consists of three levels. The top level shows the nuclear steam supply system (NSSS). The success of this function can be verified through the levels of pressurizer (PZR) or reactor (RX). The top level shows whether the safety function is satisfied. In the NSSS structure, RX, PZR, SG, and Reactor Coolant Pumps (RCP) are modeled. Rx, PZR, and SG are represented by tanks to show the water level. The RCP is modeled as a transport to describe the flow of fluid. The pipes connecting components were modeled as the balance.

Then, the second is the energy flow structure. The energy flow structure (efs) models the energy transfer from the system to the NSSS. Because the volume of water is the primary concern for the RCS Inventory Control and RCS Coolant Injection, the efs just illustrates the flow from the system to the NSSS.

The third level models the success paths to supply water, called the mass flow structure (mfs). Total five mfs are modeled, i.e., SIS1, SIS2, CVCS, EI1, and EI2. Each SIS consists one high pressure safety injection (HPSI), one low pressure safety injection (LPSI), and safety injection tank (SIT). One SIS injection is connected into one cold-leg in the NSSS. The CVCS consists of charging and letdown. The CVCS receives the flow from the NSSS (i.e., letdown) as well as supplies the flow to the NSSS (i.e., charging). Thus, the letdown and charging flows were modeled as the efs5 and efs6, respectively. The EI means the water supply to the NSSS from the mobile equipment or fire trucks. The EI injection is connected to the end of SIS flow line. Two EIs were modeled in the third level.

Figure 3: Model of RCS Inventory Control & RCS Coolant Injection using MFM



4.2 SG Coolant Injection

This Section introduces the MFM model for the SG Coolant Injection. The purpose of function is to supply water to SG to remove the heat from the RCS. Figure 4 shows a simplified schematic of SG Coolant Injection. As shown in Table 1, three systems, i.e., Auxiliary Feedwater (AFW), Main Feedwater (MFW), and EI, are available to supply water. AFW can be divided into two division, respectively, i.e. Aux. Feedwater1/Aux. Feedwater2.

Figure 4: Model of SG Coolant Injection using process model built-in MFM

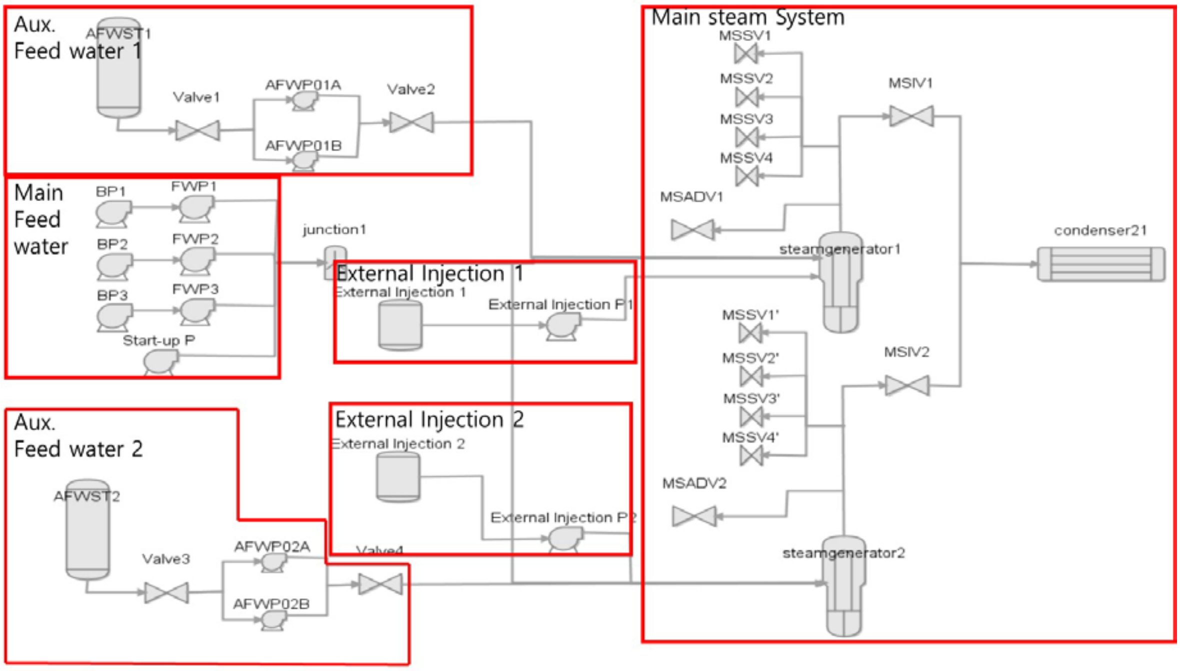
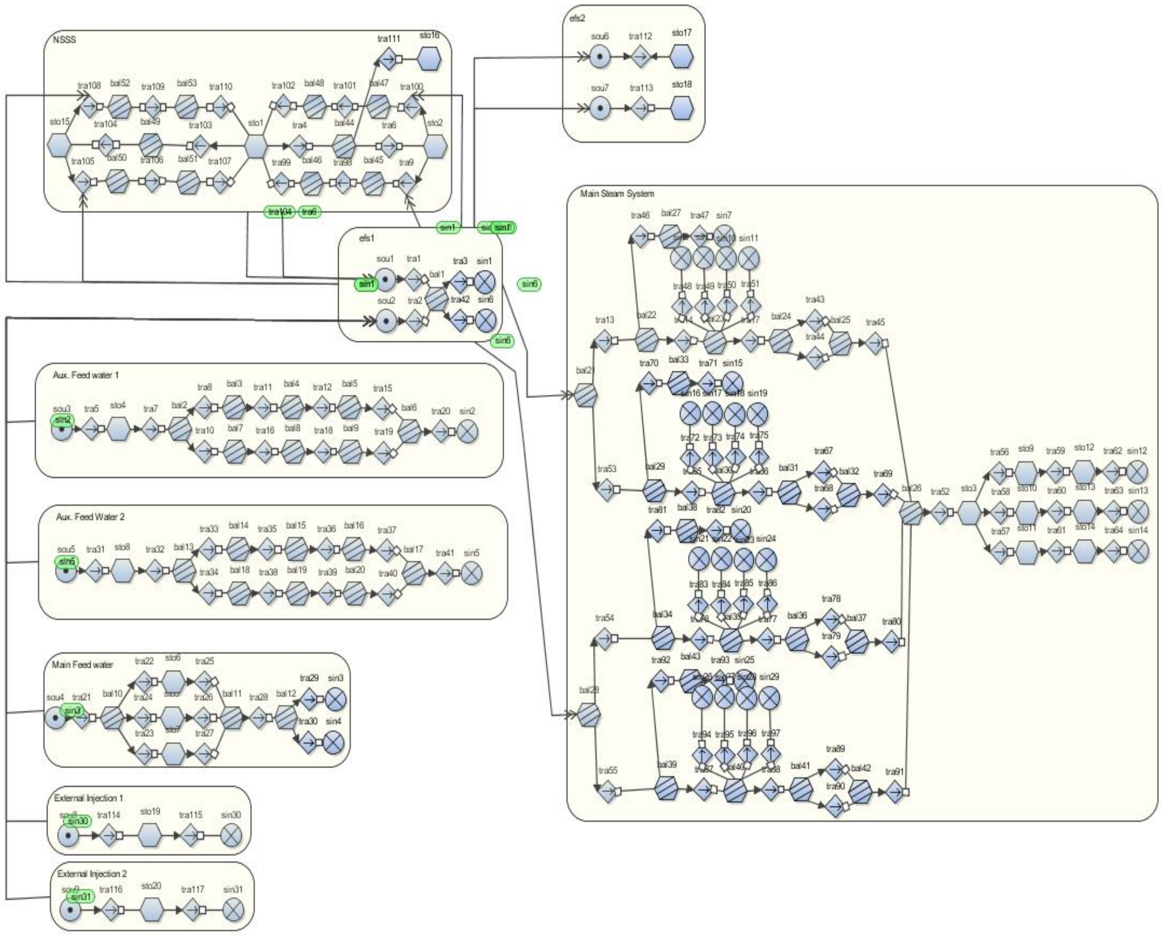


Figure 5 shows the MFM model for the SG Coolant Injection. The model also consists of three levels. At the top level, the efs2 represents the coldleg and hotleg temperatures ensure that the RCS heat is being removed.

Then, the second level, i.e., efs1, shows the heat transfer from the primary loop to the second loop. The sin6 represents the steam generated in the SG after obtaining the heat from the RCS in efs1.

The third level models the success paths to supply water to the SG and to remove steam from the SG, called the mfs. Total six mfs are modeled, i.e., AFW1, AFW2, MFW, EI1, EI2, and Main Steam (MS). The five modeled structures, i.e., AFW1, AFW2, MFW, EI1, and EI2, are connected to sou2 for the heat exchange in efs1. The MS is connected to the sin6 to show the removed steam from the SG.

Figure 5: Model of SG Coolant Injection using MFM



4. Conclusion

This study attempted to perform a FRA for the SAM in NPPs. Functions and systems to prevent core damage and radiation release were identified for the reference plant. Then, the relation between/among functions and systems has been modeled using the MFM. This study is being conducted as a part of project to develop a human-system interface for the SAMSS. After carrying out the task analysis, the design of human-system interface will be performed in the near future.

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