Accident Sequence Precursor Analysis for SGTR by Using Dynamic PSA Approach

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1. Introduction

The research introduced how to apply Dynamic Probabilistic Safety Assessment (DPSA) methodology based on Steam Generator Tube Rupture (SGTR) scenario occurred in an operating nuclear power plant (NPP). Conventional Probabilistic Safety Assessment (PSA) methodology is commonly used for Accident Sequence Precursor (ASP) quantification. It quantifies Conditional Core Damage Probability (CCDP) by using general data instead of operational data for a specific accident. It also brings in conservative assumption to simplify conventional PSA model, therefore there are greater risk to have different result because they do not consider dynamic interaction between plant process variables and operator action under accident condition. Whereas DPSA methodology can apply dynamic response of plant/operating crew system to CCDP calculation as the accident happens. [1] It minimizes the conservative assumption for the simplification, which results in more realistic CCDP calculation than conventional PSA methodology. we create the system that can be reflect the dynamic response of plant/operating crew system by building Thermal hydraulic model by using MARS (Multi-dimensional Analysis of Reactor Safety) code, [2] and constructing Operating crew state model by using MOSAIQUE (MOdule for SAmpling Input and QUantifying Estimator) code. They were used to be example of SGTR accident.

2. Methods and Results

2.1 ASP Analysis

The analysis of ASP initiated to evaluate the potential safety significance of the occurred accident during the operation or which may cause severe accident quantitatively. Conventional Probability Safety Assessment (PSA) used widely for ASP quantification. [3] As the result of the Conventional PSA model's quantification if the case satisfies CCDP >1.0e-6, it is selected to be a precursor. Selected precursor reviewed by regulators and operators for the establishment of accident prevention plan an-d nuclear safety improvement plan. The US Nuclear Regulatory Commission (NRC) first started ASP analysis, and since 1986 they publish 'NUREG/CR-4674, Precursor to Potential Severe Core Damage Accidents' series every year. [4]

2.2 SGTR Accident Scenario

We selected SGTR accident scenario provided by Operational Performance Information System for Nuclear Power Plant (OPIS). The selected SGTR accident scenario is as follow.

Table 1.Selected SGTR accident scenario [5]

Time of the event	The main event
17:50	Start of cooling operation on steam circuit cont rol channel
18:33 (+0min)	Sudden drop of water level in the pressurizer (Assumed as SGTR accident)
18:38 (+5min)	High pressure safety injection reset
18:42 (+11min)	Reached to the threshold level of pressurizer
18:46 (+13min)	Steam generator #2 isolated
18:49 (+16min)	Passive high pressure safety injection
19:00 (+27min)	Cooling operation of steam isolated valve by ci rcuit valve
19:59 (+89min)	Reached to the pressure equilibrium of primary and secondary system

After reactor shutdown for preventative maintenance, during the cooling operation by steam bypass control system, SGTR accident occurred at hot standby condition. The operator had reset the related operating in order to prevent the safety injection system on the accordance with the pressure drop in the pressurizer during the cooling operation of steam circuit control channel, and thereby, the water level of pressurizer was suddenly decreased. The operator had verified the steam generator tube rupture from the alert of radiation observer (RE-152) and thus, isolated the tube ruptured steam generator(#2) in order to repress the release of radioactive material to the outside of containment building. Then, the water level of pressurizer was recovered by passive operation of high pressure safety injection and reached to pressure equilibrium by performing the cooling and de-pressurizing operation of primary and secondary system with steam circuit control channel and the main, sub sprinkle of pressurizer. [5]

2.3 Application Procedure of DPSA for ASP Analysis

Application procedure of DPSA is described in this section. The first step is accident selection. Accident must be met screening criteria (e.g., component failure with loss of redundancy) for ASP analysis. The second step is to build the thermal hydraulic model. Thermal hydraulic model be used for simulation. Through simulation, we determine whether the core damage or not. The third step is to build the operator action crew model. Operator action crew model be used for sample data generation. Operator action crew state model is described in section 2.4 in detail. The final step is to CCDP calculation. CCDP calculation is described in section 2.6 in detail.

Step 1: Select the accident - Occurred accident under operation - Unexpected core damage initiators (LOOP, SGTR, and SBLOCA) - All events in which a reactor trip was demanded and safety-related component failed
Step 2: Build the thermal hydraulic model - For the simulation - Full-scale plant model at steady state (Including related reactor protection system) - transient input file (Including operator action)
Step 3: Build the operator action crew state model - For sample data generation - set distribution of operator action - Select sampling method
Step 4: CCDP calculation

Fig. 1. Application procedure of DPSA

2.4 Operating Crew State Model

We selected operator actions in the previously described SGTR accident scenario for generating the samples, and set the distribution of operator action by using MOSAIQUE code. [6] In this study, log-normal distribution is used for modeling operator action, because it has been used the most in human reliability analysis field. We performed operator action time sampling by using log discretization approach in set the distribution. The tail section of distribution is set a distribution for discretization in detail because most operator action failure is appeared in tail section. Then sampling was performed. Using the log discretization approach is to avoid disadvantages of Monte-Carlo sampling method. Each operator action was assumed as an independent trial.

Table 2. Discretization strategies for operator action time

	Branches
Operator action time	5%, 50%, 90%, 99%, 99.9%, 99.99%tiles, skip
Branch probability	0.05, 0.45, 0.4, 9e-2, 9e-3, 9e-4, 1e-4

We selected the 5%tile, 50%tile, 90%tile, 95%tile, 99%tile, 99.9%tile, 99.99%tile in cumulated distribution of operator action time, and applied the probability of each section as Table 3. 7 kinds of sample data sets were generated by arranging selected samples randomly. Samples can be randomly arranged because each operator action was assumed as an independent trial. Generated sample data sets are considered to accident sequence, and we decided to as whether core damage occurred by using previously constructed thermal hydraulic model.

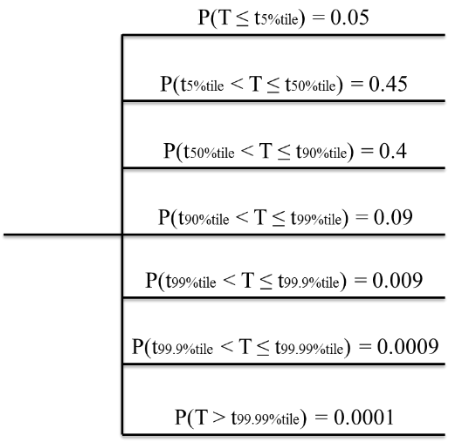

Fig. 2. Log discretization approach (7 Branches)

Figure 2 shows branches of the log discretization approach and probability of each branch. [7] Generated sample data has branch probability in their range, and the assigned branch probabilities are used for CCDP calculation.

2.5 Thermal Hydraulic Model

Thermal hydraulic model was built by using MARS code. Figure 1 shows original nodalization diagram of OPR-1000 for build the thermal hydraulic model. We are not describing the results of simulation by using thermal hydraulic model in this paper, but we describe overall issues thermal hydraulic model to help understand for procedure of DPSA and modeling method of SGTR hydraulic model.

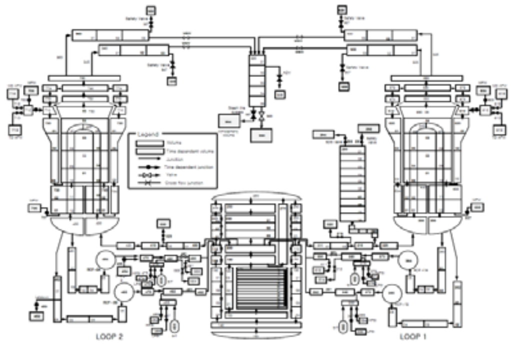

Fig. 3. Nodalization diagram of the MARS model for the SGTR in the OPR-1000 [8]

Table 3 shows designed data of main parameters of primary and secondary system and calculation data by using MARS. The calculated parameters by MARS are used as the initial condition of thermal hydraulic model at steady state condition.

Table 3. Comparison of design values and calculated results under steady-state conditions for the OPR-1000 [8]

System types	Parameters	OPR-1000 (Design)	MARS
Primary cooling system	Core power(MWt)	2815	2815
	Hot leg flow rate (kg/s)	7700	7717
	Hot leg temperature (K)	600.3	600.5
	Cold leg temperature (K)	569.2	569.0
	Pressurizer pressure (kg/s)	15.51	15.51
Secondary cooling system	Feedwater mass flow rate (kg/s)	721.02	721.13
	Steam generator pressure (MPa)	7.38	7.38

After the SGTR occurred, cooling water in primary system flow from primary side to secondary side. The start point of tube rupture is when valve described in figure 2 opens on normal condition. We assumed that if pressure of primary and secondary system is reached to pressure equilibrium state, simulation is terminated. [9]

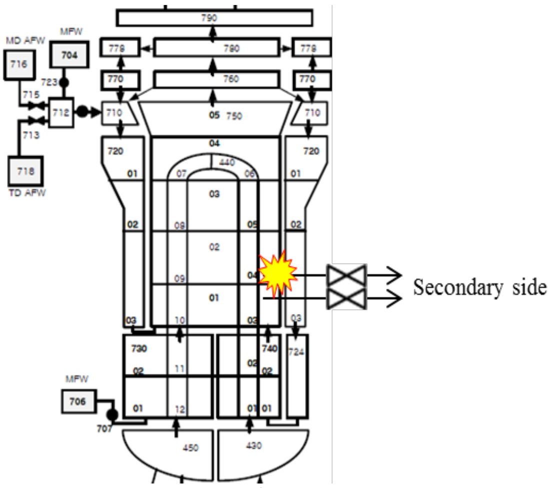

Fig. 4. Schematic diagram of SGTR model

2.6 CCDP Calculation

The following is the process of CCDP calculation. The calculation reflects the dynamic response of plant/operating crew system in accident using thermal hydraulic model and operating crew state model.

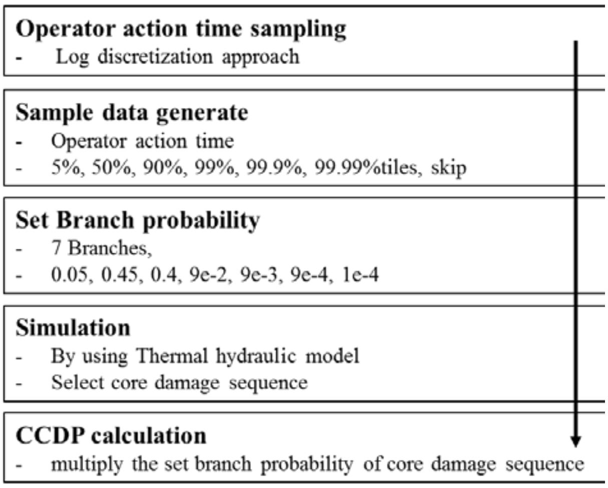

Fig. 5. CCDP calculation process

In the selected SGTR accident scenario, figure out the occurrence of core damage by using the thermal hydraulic model after sampling for operator actions. In this study, we provide not simulation results by using thermal hydraulic model, because the focus of this paper is introducing application procedures of DSPA methodology. So, we assumed only one virtual core damaged accident sequence as simply example. Figure 5 shows the virtual accident sequence with core damage occurred. We assumed only one virtual core damaged accident sequence. However, several core damaged accident sequences can be occurred through thermal hydraulic model. Calculation method in several core damaged accident sequence cases has been described in the following paragraphs.

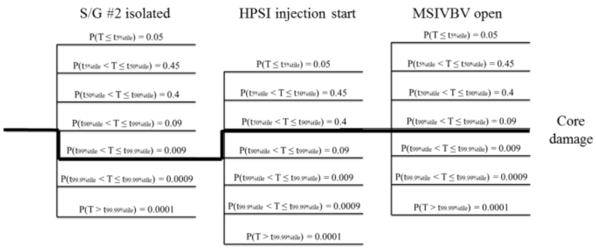

Fig. 5. Virtual core damaged accident sequence

In the SGTR accident, we selected 3 operator actions options-SG #2 isolated, HPSI injection start and MSIVBV open. Additionally, we set a distribution for discretization into 7 branches. We assumed each operator actions as an independent trial and 7 kinds of accident sequences occurred, and we also assumed core damage occurred in one out of 7 accidents. CCDP of SGTR accident is calculated by multiplying the probability of each core damage occurred branches. If several core damage sequences occurred, add each CCDP. Its calculation method is similar to total CCDP calculation method of conventional PSA.

$$\text{CCDP} = Br_1 * Br_2 * Br_3 \text{ (core damage sequence)} \quad (1)$$

Where
Br_1 = S/G#2 isolated 99.9%tile branch probability
Br_2 = HPSI injection start 90%tile branch probability
Br_3 = MSIBV opens 99%tile branch probability

3. Conclusions

The study introduced how to quantify CCDP more realistically than conventional PSA methodology as they analyze ASP, and describe the specific process. DPSA methodology contributes the analysis of ASP by reflecting dynamic response of plant/operating crew system to power plant risk quantification calculation. It also minimizes conventional PSA model's conservative assumption for implication, which allows us to calculate power plant's risk more effectively. The study calculated CCDP of virtual by using DPSA methodology, and confirmed the applicability of DPSA methodology for the analysis of ASP.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No.1403003)

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