Development of Common Cause Failures (CCF) Multiplier Calculation Program for PSA

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1. Introduction

The Common Cause Failures (CCF) in Nuclear Power Plants (NPP) are one of the significant factors to affect Core Damage Frequency (CDF). The CCF analysis, therefore, should be applied to Probabilistic Safety Assessment (PSA). Due to the fact that the CCF events rarely occur, the other NPPs' CCF events data are inevitably used for PSA. In order to perform PSA of the Korean NPPs, most of CCF data provided by U.S NRC (United States Nuclear Regulatory commission) have been employed.

However, the CCF data provided by U.S NRC is just CCF parameter values not the CCF raw data which are restricted by individual U.S NPPs. Therefore, the CCF Multipliers calculated by the provided CCF parameters have to be used to perform PSA for Korean NPPs. In this work, we developed the CCF multiplier calculation program which can not only provide the ease calculation of CCF Multiplier but also improve CCF modeling efficiency for PSA.

2. Methods and Results

2.1 CCF Models

There are three CCF models commonly used: Basic Parameter Model (BPM), Multiple Greek Letter Model (MGL), and Alpha-Factor Model (AFM) as shown in table 1.

Table 1: Estimation for CCF parameters

Models	Non-Staggered	Staggered
BPM	$Q_k^{NS} = n_k / N_k^{NS}$	$Q_k^{S} = n_k / N_k^{S}$
	$k = 1, \ldots, m$	$k = 1, \ldots, m$
MGL	$\rho_k^{NS} = \sum_{i=k}^{m} i \cdot n_i \Big/ \sum_{i=k-1}^{m} i \cdot n_i$	$\rho_k^{S} = \sum_{i=k}^{m} n_i \Big/ \sum_{i=k-1}^{m} n_i$
	$(2 \le k \le m)$ $(\rho_1 = 1, \rho_2 = \beta, \rho_3 = \gamma, \rho_4 = \delta, \ldots, \rho_{m+1} = 0)$	
AFM	$\alpha_k = n_k \Big/ \sum_{k=1}^{m} n_k$	
	$k = 1, \ldots, m$ $\alpha_1 + \alpha_2 + \ldots + \alpha_m = 1$	

Table 2: CCF parameters to BPM conversion formula

Models	Non-Staggered (NS)	Staggered (S)
MGL to BPM	$Q_k^{NS} = \dfrac{\left(\prod_{i=1}^{k} \rho_i^{NS}\right) \cdot (1 - \rho_{k+1}^{NS})}{{}_{m-1}C_{k-1}} \cdot Q_t^{NS}$	$Q_k^{S} = \dfrac{\left(\prod_{i=1}^{k} \rho_i^{S}\right) \cdot (1 - \rho_{k+1}^{S})}{{}_{m-1}C_{k-1}} \cdot Q_t^{S}$
	$(2 \le k \le m)$ $(\rho_1 = 1, \rho_2 = \beta, \rho_3 = \gamma, \rho_4 = \delta, \ldots, \rho_{m+1} = 0)$	
AFM to BPM	$Q_k^{NS} = \dfrac{k}{{}_{m-1}C_{k-1}} \cdot \dfrac{\alpha_k}{\alpha_t} \cdot Q_t^{NS}$	$Q_k^{S} = \dfrac{\alpha_k}{{}_{m-1}C_{k-1}} \cdot Q_t^{S}$
	$k = 1, \ldots, m$ $\alpha_1 + \alpha_2 + \ldots + \alpha_m = 1$ $\alpha_t = \sum_{k=1}^{m} k \cdot \alpha_k$	

The MGL and AFM models can be converted to BMP model following the conversion formulas described in table 2.

2.2 CCF Multipliers

The conversion formulas, however, cannot be practically used due to fact that the total failure probability of each component (Q_t) is unavailable generally. Therefore, the conversion formulas are converted to the approximated equations to be practically used as shown in table 3. In these equations, M_k and Q_1 are CCF multiplier and single failure probability, respectively. The CCF multiplier calculation program developed in this study was designed to easily calculate CCF multipliers for both MGL and AFM models.

Table 3: Estimators for the CCF Multipliers

Models	Non-Staggered (NS)	Staggered (S)
MGL	$Q_k^{NS} \approx M_k^{NS} \cdot Q_1^{NS}$	$Q_k^{S} \approx M_k^{S} \cdot Q_1^{S}$
	$M_k^{NS} = \dfrac{\left(\prod_{i=1}^{k} \rho_i^{NS}\right) \cdot (1 - \rho_{k+1}^{NS})}{{}_{m-1}C_{k-1}}$	$M_k^{S} = \dfrac{\left(\prod_{i=1}^{k} \rho_i^{S}\right) \cdot (1 - \rho_{k+1}^{S})}{{}_{m-1}C_{k-1}}$
AFM	$Q_k^{NS} \approx M_k^{NS} \cdot Q_1^{NS}$	$Q_k^{S} \approx M_k^{S} \cdot Q_1^{S}$
	$M_k^{NS} = \dfrac{k}{{}_{m-1}C_{k-1}} \times \dfrac{\alpha_k}{\alpha_t}$	$M_k^{S} = \dfrac{\alpha_k}{{}_{m-1}C_{k-1}}$

2.3 CCF Multiplier Calculation Program

The developed CCF multiplier calculation program is composed of four main functions: input data, conversion of AFM to MGL, CCF Multiplier, and Bayesian analysis as shown in table 4. Input data can deal with the CCF parameters of AFM in NUREG/CR-5497 (2007) in which users can select appropriate CCF parameters considering System, Failure mode, type of Component, and system size. Conversion function can convert from AFM parameters to MGL parameters. The CCF multiplier function can automatically calculate the CCF multiplier values from CCF parameters selected for user. In addition, the function can connect calculated CCF multiplier values with Basic Event of Fault Tree (BEFT) information when user input the BEFT information. Bayesian analysis function can perform Bayesian-updating for the CCF parameter using the number of the CCF events.

Table 4: Main functions of the CCF multipliers program

Main function	Description
Input data	Select of AFM parameter data
Conversion	AFM to MGL conversion (parameter)
CCF multiplier	AFM/MGL multiplier calculation
	Connect AFM /MGL multiplier and BE
Bayesian analysis	Bayesian analysis of AFM/MGL parameter
	AFM/MGL multiplier calculation (posterior)
	Connect AFM/MGL multiplier and BE (posterior)

2.4 Calculation of the CCF multiplier

Table 5 shows the CCF parameter values given by NUREG/CR-5497(2007). For verification of the developed CCF multiplier calculation program, the other CCF parameters were calculated by the developed program using only the beta distribution parameters A. And then, the calculated CCF parameters were compared with original CCF parameters.

Table 6 shows the CCF parameters values calculated by the program, resulting that the calculated values were exactly matched to original values in table 5.

Table 5: The AFM parameter values of Auxiliary Feedwater system Motor Driven Pumps-FS-m=2 in NUREG/CR-5497(2007)

	Fail mode	Alpha-Factor		Alpha 1	Alpha 2
CCF component group Size m =2	Fail to Start (FS)	Distributions Parameters	A	1.14E+02	6.64E+00
			B	6.64E+00	1.14E+02
		Percentiles	5%	9.07E-01	2.57E-02
			50%	9.48E-01	5.25E-02
			95%	9.74E-01	9.27E-02
		Mean		9.45E-01	5.50E-02

Table 6: Estimation of AFM parameter using this program

Alpha Factor	Alpha 1	Alpha 2
A	1.14E+02	6.64E+00
B	6.64E+00	1.14E+02
5%	9.07E-01	2.57E-02
50%	9.48E-01	5.25E-02
95%	9.74E-01	9.27E-02
Mean	9.45E-01	5.50E-02

The CCF multipliers of MGL and AFM were also calculated using the program with the CCF parameters in table 5. Table 7 compares the calculated CCF multiplier values, showing that the calculated values for both models were exactly matched each other. Following the results, it was verified that the developed program works well without any problems.

Table 7: The CCF multiplier calculated by the developed program

CCF Multiplier (Non-Staggered)		
M_k^{NS}	M_1^{NS}	M_2^{NS}
MGL	8.958E-01	1.042E-01
AFM	8.958E-01	1.042E-01
CCF Multiplier (Staggered)		
M_k^{S}	M_1^{S}	M_2^{S}
MGL	9.450E-01	5.498E-02
AFM	9.450E-01	5.498E-02

3. Conclusions

The present study developed the CCF multiplier calculation program which provides the functions of CCF multiplier calculation and Bayesian-based CCF parameters estimation. The CCF multiplier calculation program was verified without any problems. The developed program can not only provide the ease calculation of CCF multiplier but also improve CCF modeling efficiency for PSA, expecting that this program could have contribution to the CCF analysis for PSA in the future.

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