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Development of A Methodology for Analyzing Multi-Unit Source Terms using WinMACCS

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1. Introduction

In Korea, probabilistic safety assessment (PSA) was legislated to improve safety of nuclear power plants in 2016. The Korea Hydro Nuclear Power Co. (KHNP) performed level 3 PSA for the Shin Kori unit 3 and 4 among many nuclear power plants for a first time. The level 3 PSA is specifically performed to calculate off-site consequences. The performance of the KHNP was based on a single unit, and the level 3 PSA for multi-unit accidents would be needed in Korea with a high nuclear power plant density.

Until now, a lot of level 3 PSA for a single unit has been researched using MACCS2 1.12 recommended by the Nuclear Regulatory Commission (NRC). MACCS2 1.12 can specify multiple source terms and calculate risks for each source term respectively. Also, MACCS2 1.12 can release multiple plume segments up to 4 [1]. However, these characteristics are not enough to assess the off-site consequences of the multi-unit accident because simply adding the risks for each source term is likely to overestimate fatalities and injuries.

In this study, an adequate methodology for analyzing multi-unit source terms was researched to calculate the off-site consequences of the multi-unit accident. The Kori site in Korea was chosen for reference site and WinMACCS 3.10 (MACCS 3.10) was used.

2. Methods and Results

The important points in simulating the multi-unit accident are temporal and spatial consideration. Therefore, two analyses were performed considering the temporal difference of release times in case of multi-unit accident using WinMACCS 3.10. And, it was assumed that all units were in the same spatial position. Emergency actions, such as sheltering and evacuation, were not considered except for dose dependent relocations.

2.1 Reference Reactor and Input Values

APR1400 was chosen as a reference reactor by referring to the Kori site. Therefore, the situations in which several APR1400 type reactors release radioactive materials simultaneously or at different time due to common initiation event were simulated.

It was assumed that loss of off-site power (LOOP) event which could be a common initiation event occurs in the two units. If all emergency diesel generators fail, the LOOP event is transferred to station blackout (SBO) event. Therefore, source term categories (STCs) initiated from the SBO event were considered among the all STCs. There were 8 STCs initiated from the SBO event. Among them, STC12 was chosen as a reference STC. The representative accident sequence of the STC12 is sequence 51 of containment event tree (CET) 131 for the SBO event. The severe accident sequence of the STC12 proceeds through failure of hot leg (HLFAIL), reactor vessel rupture (RVRUPTURE), no dynamical containment failure (NODCF), early containment failure (ECF-RUPTURE), and failure of containment spray system (NOCS). The release input values of the STC12 are showed in Table I. In simulations, heat content of the plume was assumed to be zero because the PSA reports made it difficult to know about that. The duration of the plume was assumed to be 1 hour (pop release) for conservative calculations.

WinMACCS 3.10 was used to simulate the multi-unit source term. Input values such as core inventories, release fractions (for 72 hours), building height, population, and meteorology data of the Kori site were used and only early health effects were considered. Rest of the input values in ATMOS and EARLY module were substituted by reference data which was used for the Surry plant in the State-of-the-Art Reactor Consequence Analyses (SOARCA) report [2].

Table I: Input values of the STC12 in WinMACCS 3.10

PDELAY	PLUDUR	PLHITE	PLHEAT	
44,408 sec	3,600 sec	20.58 m	0 watt	
RELFRC (Release Fraction)				
Noble Gas	Cs Group	Ba Group	I Group	
1.00E+00	1.20E-01	9.63E-03	2.56E-01	
Te Group	Ru Group	Mo Group	Ce Group	La Group
5.79E-02	1.94E-02	1.94E-02	1.57E-04	8.35E-05

2.2 Simultaneous Releases for Multi-Units (up to 6)

The analysis was performed in which up to six units of the same APR1400 type had accident simultaneously. In this analysis, two methods were used to simulate the multi-unit source terms. The first method was to linearly increase the core inventories to the number of units. Therefore, only one radioactive plume was released for each simulation. The input variable called 'CORSCA' was used to perform the first method. The second method was to create source term files for each unit and set all time offsets to 0 in WinMACCS 3.10. Therefore, the number of radioactive plumes which was equal to the number of units were released simultaneously for each simulation. The function called 'Multi Source Term File Set' (CombineSource.exe) was used to do the second method [3].

2.3 Time Different Releases for Two Units

In this analysis, the calculations that two units released radioactive plumes at different times were performed. The time differences were set to 4-hour interval from 4 hours to 24 hours. By these time differences, the situations of the second unit accident within one day after the first unit accident were simulated. Also, the time differences were set to 1-day interval from 1 day to 5 days, and the situations of the second unit accident within one week after the first unit accident were simulated.

2.4 Results of the Simultaneous Releases

In both the first (using CORSCA) and second (using Multi Source Term File Set) method, the population weighted risks tended to increase as the number of units increased. However, the risk of early fatalities did not exactly increase in proportion to the number of units in 1 mile (1.6 km). This was because the population within 1 mile was not large enough. Also, the risk of cancer fatalities did not exactly increase in proportion to the number of units in the same radius. This was because the amount of dose exposed increased and the number of early fatalities increased. The results of population weighted risk for both methods are shown in Table II.

The results between the first and second method were almost identical. This was because simultaneous multi-unit accidents were considered and MACCS 3.10 allowed overlapping of the radioactive plumes. The results of dividing the risk of first method by that of second method are shown in Fig. 1 (for early fatalities) and 2 (for cancer fatalities). At very slightly, the first method assessed more conservatively for cancer fatalities, and the second method assessed more conservatively for early fatalities.

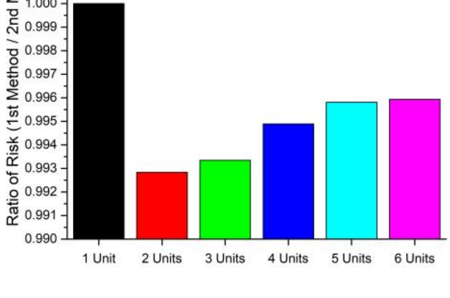

Fig. 1. Ratio of risk for early fatalities within 8 km

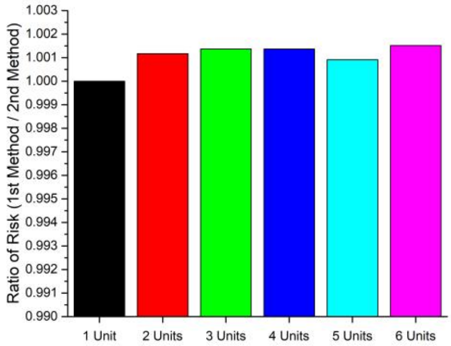

Fig. 2. Ratio of risk for cancer fatalities within 32 km

2.5 Results of the Time Different Releases

The risks of early and cancer fatalities tended to decrease as the time difference longer, and then to converge, when compared to the simultaneous two-unit accident. These results are shown in Table III.

In the calculation of early fatalities, the threshold dose is considered in the risk calculations. Therefore, if the dose exposed decreased, the probability of exceeding the threshold dose was reduced, so that the longer time difference, the less the risk of early fatalities. In the case of cancer fatalities, there was no threshold dose, but since the risks were calculated by the LNT (Linear No Threshold) model, the longer the time difference, the less the risk of cancer fatalities. This was because the longer the time difference, the shorter the total time that was affected by the radioactive plumes due to relocations. This tendency was more evident through a significant reduction in the risk of cancer fatalities when the time difference was 1 day because the relocations were occurred after one day (TIMHOT = 1 day). These results are shown in Fig. 3.

However, the above results were shown at relatively longer distance (more than 1.6 km), and slightly different tendency was shown at relatively shorter distance (less than 1.6 km). When the time difference was longer, the risk of early and cancer fatalities increased and then decreased in the Table III. This tendency was presumed to be the application of the shielding factor of evacuation rather than the that of normal activity from the start of the relocations. The shielding factor of evacuation is set larger than the that of normal activity in general, and thus the dose received is larger in application of shielding factor of evacuation [2]. Therefore, it was predicted that migrants of innermost region were exposed to the second radioactive plume during the relocations. This tendency was shown for longer time differences in the risk of cancer fatalities which had no threshold dose.

Table II: Risks of early and cancer fatalities for two methods (up to 6 units)

Method	Risk Type	Radius [km]	1 Unit	2 Units	3 Units	4 Units	5 Units	6 Units
CORSCA (Method 1)	ERL FAT/TOTAL	0 ~ 1.6	3.64E-02	5.91E-02	7.25E-02	8.21E-02	8.91E-02	9.46E-02
	ERL FAT/TOTAL	0 ~ 8	3.39E-03	7.07E-03	1.05E-02	1.36E-02	1.66E-02	1.96E-02
	ERL FAT/TOTAL	0 ~ 16	3.83E-04	7.99E-04	1.18E-03	1.58E-03	2.08E-03	2.84E-03
	ERL FAT/TOTAL	0 ~ 80	1.35E-05	2.83E-05	4.18E-05	5.57E-05	7.34E-05	1.01E-04
	CAN FAT/TOTAL	0 ~ 1.6	7.03E-02	7.56E-02	7.74E-02	7.52E-02	7.27E-02	7.02E-02
	CAN FAT/TOTAL	0 ~ 16	9.87E-03	1.86E-02	2.69E-02	3.47E-02	4.23E-02	4.93E-02
	CAN FAT/TOTAL	0 ~ 32	1.90E-03	4.28E-03	6.60E-03	8.81E-03	1.10E-02	1.32E-02
	CAN FAT/TOTAL	0 ~ 80	1.11E-03	2.50E-03	3.87E-03	5.20E-03	6.54E-03	7.85E-03
Multi Source Term File Set (Method 2)	ERL FAT/TOTAL	0 ~ 1.6	3.64E-02	5.95E-02	7.29E-02	8.24E-02	8.94E-02	9.49E-02
	ERL FAT/TOTAL	0 ~ 8	3.39E-03	7.12E-03	1.05E-02	1.37E-02	1.67E-02	1.97E-02
	ERL FAT/TOTAL	0 ~ 16	3.83E-04	8.05E-04	1.19E-03	1.58E-03	2.08E-03	2.85E-03
	ERL FAT/TOTAL	0 ~ 80	1.35E-05	2.85E-05	4.20E-05	5.59E-05	7.37E-05	1.01E-04
	CAN FAT/TOTAL	0 ~ 1.6	7.03E-02	7.56E-02	7.73E-02	7.50E-02	7.24E-02	7.00E-02
	CAN FAT/TOTAL	0 ~ 16	9.87E-03	1.86E-02	2.69E-02	3.47E-02	4.23E-02	4.93E-02
	CAN FAT/TOTAL	0 ~ 32	1.90E-03	4.28E-03	6.59E-03	8.80E-03	1.10E-02	1.32E-02
	CAN FAT/TOTAL	0 ~ 80	1.11E-03	2.50E-03	3.87E-03	5.19E-03	6.53E-03	7.84E-03

Table III: Risks of early and cancer fatalities for several time differences (for 2 units)

Risk Type	Radius [km]	0 Hour	4 Hours	8 Hours	12 Hours	16 Hours	20 Hours	1 Day	2 Days	3 Days	4 Days	5 Days
ERL FAT/TOTAL	0 ~ 1.6	5.95E-02	6.57E-02	5.82E-02	5.13E-02	4.67E-02	4.26E-02	3.68E-02	3.68E-02	3.68E-02	3.68E-02	3.68E-02
ERL FAT/TOTAL	0 ~ 8	7.12E-03	6.12E-03	5.28E-03	4.58E-03	4.17E-03	3.86E-03	3.42E-03	3.42E-03	3.42E-03	3.42E-03	3.42E-03
ERL FAT/TOTAL	0 ~ 16	8.05E-04	6.93E-04	5.97E-04	5.18E-04	4.71E-04	4.36E-04	3.87E-04	3.87E-04	3.87E-04	3.87E-04	3.87E-04
ERL FAT/TOTAL	0 ~ 80	2.85E-05	2.45E-05	2.11E-05	1.83E-05	1.67E-05	1.54E-05	1.37E-05	1.37E-05	1.37E-05	1.37E-05	1.37E-05
CAN FAT/TOTAL	0 ~ 1.6	7.56E-02	1.16E-01	1.30E-01	1.37E-01	1.38E-01	1.39E-01	7.46E-02	7.03E-02	7.03E-02	7.03E-02	7.03E-02
CAN FAT/TOTAL	0 ~ 16	1.86E-02	1.74E-02	1.63E-02	1.56E-02	1.52E-02	1.47E-02	1.06E-02	9.87E-03	9.87E-03	9.87E-03	9.87E-03
CAN FAT/TOTAL	0 ~ 32	4.28E-03	3.52E-03	3.16E-03	2.93E-03	2.80E-03	2.67E-03	2.01E-03	1.90E-03	1.90E-03	1.90E-03	1.90E-03
CAN FAT/TOTAL	0 ~ 80	2.50E-03	2.06E-03	1.85E-03	1.72E-03	1.64E-03	1.56E-03	1.18E-03	1.11E-03	1.11E-03	1.11E-03	1.11E-03

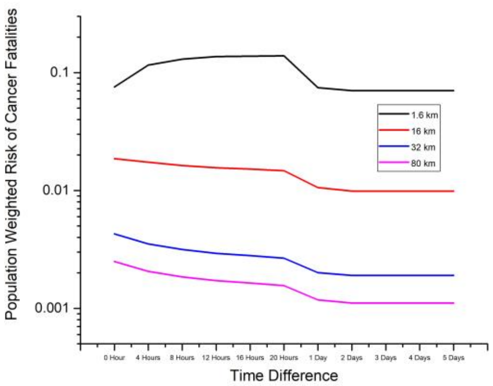

Fig. 3. 'Time difference vs Population weighted risk of cancer fatalities' curves for several radius

3. Conclusions

In this study, it was researched how to simulate multi-unit source terms in simultaneous or time different multi-unit accident. The first analysis simulated the simultaneous multi-unit accident. Next, the second analysis simulated the time different two-unit accident.

It was confirmed that there was almost no difference between 'CORSCA' and 'Multi Source Term File Set' function from the results of the first analysis.

Also, it was confirmed that the longer the time difference, the more the risks decreased from the results of the second analysis (more than 1.6 km). In addition, it was confirmed that the relocations had a large effect on the risk of cancer fatalities in the time difference of one day. However, the risks within 1.6 km tended to increase as the time difference increased. The reason for this tendency was presumably due to the application of shielding factor of evacuation and meeting with the second radioactive plume.

It was suggested that the simultaneous multi-unit accident could be simulated by simply increasing the core inventories for same reactor types. However, it was convenient to use 'Multi Source Term File Set' in the time different multi-unit accident. Also, it was confirmed that the relocations and the shielding factors had a large effect on the time different multi-unit accident. Therefore, it was predicted that emergency response activities would have a large effect in the time different multi-unit accident although this study did not consider it. The results of this study will be helpful in researching an adequate methodology for analyzing multi-unit source terms.

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REFERENCES

[1] U.S. NRC, "Code Manual for MACCS2: Volume 1, User's Guide", NUREG/CR-6613, 1997.
[2] U.S. NRC, "MACCS Best Practices as Applied in the State of the Art Reactor Consequence Analysis (SOARCA) Project", NUREG/CR-7009, 2014
[3] U.S. NRC, "User's Guide and Reference Manual for WinMACCS Version 3", NUREG/CR-XXXX, 2009