An Emergency Response Study during Multi-Unit Accidents

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Abstract: Interests in multi-unit PSA have been increased after the Fukushima nuclear power plant accident. According to this situation, there has been growing necessity for multi-unit PSA as well as single-unit PSA performed mainly. Proper level 3 PSA performance is essential because total results derived from PSA are ultimately integrated in level 3 PSA. Establishment of emergency response plans is required for realistic level 3 PSA. Off-site resident protective actions consist of evacuation, sheltering, and relocation. Therefore, it is necessary to derive appropriate alternative protective actions for multi-unit level 3 PSA. Many off-site consequence assessments considering various protective alternative recommendations for multi-unit accidents were performed using MACCS in this study. Appropriate conditions for alternative protective actions in multi-unit accidents were found based on the results of this study.

Keywords: PSA, Protective Action Recommendations, Multi-unit accident, MACCS

1. INTRODUCTION

A lot of researches have been conducted on how to estimate multi-unit site risk in many countries including Republic of Korea. A lot of multi-unit Probabilistic Safety Assessment(PSA) methodologies have been proposed because multi-unit PSA must be performed to estimate site risk. Specifically, researches on multi-unit PSA are being actively carried out in Korea with high density of nuclear power plants(NPPs). Most of the above researches on the proposed multi-unit PSA methodology are about multi-unit level 1 PSA [1,2,3]. However, level 3 PSA should be performed to ultimately estimate site risk. There are also several papers considering results of level 3 PSA for multi-unit accidents [4,5].

Protective actions for emergency response in NPP accidents are very effective in dose and risk reduction. Therefore, it may be most effective to evacuate off-site residents as soon as radiation emergency is issued. However, evacuation is a very difficult protective action to be properly performed. It may be more protective to plan sheltering depending on an accident. These emergency response plans should be planned considering each site characteristic.

There have been many studies on emergency response to single-unit accidents until now. NUREG-0654 (Sup.3) related to this is broadly referred. However, this document only includes the contents related to single-unit accidents. In the current situation where the importance of multi-unit PSA increases, it is needed to study emergency response plans for multi-unit accidents.

In this study, it was tried to extend the scope of reference [6] and [7] to multi-unit accidents in the Kori site of Korea. Various protective alternative recommendations were assumed and a lot of off-site consequence assessments were performed using MACCS in order to derive the conditions of effective alternative protective actions by selecting the most existing OPR1000 reactor type in Korea. The results of this study on the reference site with two OPR1000 units will contribute significantly to establishing an effective emergency response plans for multi-unit accidents.

2. METHODOLOGY

This study was carried out in accordance with ‘Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants – Guidance for Protective Action Strategies’ (NUREG-0654, Sup.3) and ‘Review of NUREG-0654, Supplement 3, “Criteria for Protective Action Recommendations for Severe Accident” – Technical Basis for Protective Action Strategies’ (NUREG/CR-6953, Vol.3) [7,8]. The scope of analysis was extended to multi-unit accident based on these reports. Source term categories(STCs) were firstly selected. Emergency response scenarios were secondly selected. Finally, input parameters reflecting the general characteristics of Korea were set for MACCS simulations.

2.1. Source Term Categories and Release Category Combinations

The biggest difference between single-unit accidents and multi-unit accidents is that there are several source terms with time differences. Therefore, multi-unit accident STC combinations was derived based on the STCs considered in single-unit level 3 PSA [9]. The start times of each release were sorted in ascending order to obtain values corresponding to about 33 and 66 percentiles for the 17 STCs of the reference reactor. As a result, approximately 6,000 and 10,000 seconds were estimated and each STC were categorized into early release(ER), intermediate release(IR), and late release(LR). The STC with the largest release fraction of Cs group was set as the representative STC of each category. However, the STC 19 was selected because the timing of release of STC 15 was too late for the LR category. These results are shown in Table 1. Each unit can have the different release category in the reference site. Therefore, combinations of release category for two units were set as shown in Table 2. Each unit can have a different timing of accident initiation. For simplicity, only common-cause initiator(CCI) was considered in this study. Each unit ultimately had same timing of accident initiation. However, this does not mean that each unit released radioactive materials at the same time. Criteria for categorizing the STCs or the criteria for setting the representative STC may vary depending on analysts. Therefore, the criteria used in this study could be an example.

Table 1: Release Categorization of 17 STCs

Release Category	STC	Type of Containment Failure	Timing of Release [sec]	Rank of Cs Group Release
ER (Early Release)	2	RPV failure / Containment intact	3,573	6
	4	Early containment rupture	3,634	5
	13	Basemat Melt-Through	5,779	2
	14*	***Alpha mode failure***	***1,550***	***1***
	16	Containment isolation failure	5,889	4
	18	ISLOCA	4,275	3
IR (Intermediate Release)	3	Early containment leak	8,485	5
	7	Late containment leak	7,034	4
	8	Late containment leak	8,485	6
	10	Late containment rupture	8,485	3
	11	Late containment rupture	7,034	7
	12*	***Late containment rupture***	***8,485***	***1***
	17	Containment isolation failure	6,296	2
LR (Late Release)	1	Corium cooled before RPV failure	15,562	4
	6	Late containment leak	81,208	3
	15	Containment failure before reactor breach	199,976	1
	19*	***SGTR***	***11,252***	***2***

*: Representative STC of each Release Category

Table 2: Release Category Combinations

Case 1	Case 2	Case 3
ER + IR	ER + LR	IR + LR

2.2. Protective Alternative Recommendations for Each Cohort

Evacuation is the most effective protective actions for residents from NPP accidents. However, shelter-in-place(SIP) may be more protective under certain conditions (e.g. when radioactive plumes pass, it may be safer to be sheltered in building). Protective alternative recommendations considered in this study were described below.

i. Immediate evacuation: Residents evacuate immediately after some delays including delay to emergency notification, delay to homecoming, and delay to evacuate
ii. SIP then evacuate: Residents evacuate after some delays including delay to emergency notification, delay to shelter, and period of sheltering

Delay to emergency notification means the delay time until residents are notified of emergency response actions instruction. Input values related to each period are described in 2.3.2.
Three regions of 0~2, 2~5, and 5~10 mile were considered with 10-mile emergency planning zone(EPZ) in NUREG-0654 (Sup.3). However, concept of EPZ in Korea was changed in 2016 with the revision of the Nuclear Safety Act. EPZ consists of precaution action zone(PAZ, 3~5 km) and urgent protective action planning zone(UPZ, 20~30 km) in Korea [11]. It was needed to set boundary for setting cohort which means a population with similar behavior. Therefore, the distance of 16 km was referred as plume exposure pathway [8]. The equivalent area within the UPZ boundary was calculated with considering the approximate UPZ map and the administrative districts involved of the reference site. The calculated distance of 26 km was also considered. Additionally, the distance of 10 km was considered for segmentation of evacuation zone (0~16 km). Therefor, 0~5, 5~10, and 10~16 km regions were considered for evacuation zone. All evacuees were instructed to exit the equivalent UPZ boundary (26 km).
For the 'Immediate evacuation' protective alternative recommendation, information of evacuation time estimation(ETE) was needed to set evacuation speed. The ETE information was approximately referred by the reference [10]. The cohort relatively close to NPP was assumed that had a longer ETE. Three ETE were assumed for each cohort for finding proper protective alternative recommendations. These results are shown in Table 3.

Table 3: ETE Values Assumed for Each Cohort

Category	Cohort 1 (0~5 km)	Cohort 2 (5~10 km)	Cohort 3 (10~16 km)
ETE Values	3 / 4 / 5 [hr]	2 / 3 / 4 [hr]	1 / 2 / 3 [hr]

For the 'SIP then evacuate' protective alternative recommendation, three sheltering periods were considered. Three sheltering periods were same for all cohorts. All evacuees of each cohort were instructed to evacuate with middle value of the ETE values after the SIP. These results are shown in Table 4.

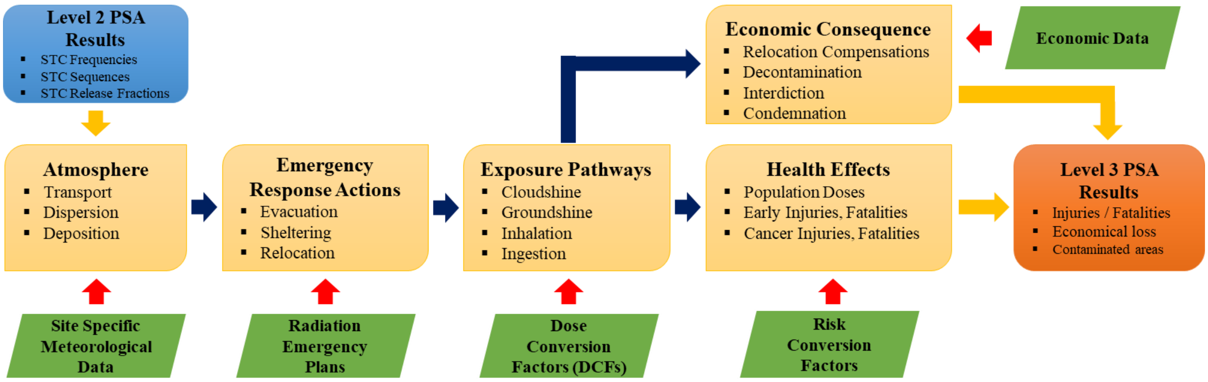
Table 4: Sheltering Periods Assumed for Each Cohort

Category	Cohort 1 (0~5 km)	Cohort 2 (5~10 km)	Cohort 3 (10~16 km)
Sheltering Periods	4 / 5 / 6 [hr]		

2.3. MACCS Input Parameters

A lot of input parameters are required to perform off-site consequence assessments using MACCS. Therefore, investigations for input parameters were performed. ATMOS and EARLY module were considered because lone term effects were not the scope of this study. Descriptions of each input parameters in ATMOS and EARLY module are in the following paragraphs. Overall flow of MACCS simulation is shown in Fig. 1.

Figure 1: Overall flow in the MACCS



2.3.1. ATMOS module

ATMOS module contains input parameters about atmosphere dispersion/advection and source terms. Input parameters for atmosphere dispersion/advection and dry/wet deposition were referred from the State-Of-the-Art Reactor Consequence Analyses(SOARCA) study reports [13,14]. Additionally, statistical data of Korea were investigated to reflect domestic terrain characteristics as much as possible and weather data were also investigated from meteorological observatory near the reference site in 2016 [15]. Reference [9] was used to assign input parameters of the representative STCs in Table 1. Several input parameters were assumed because the MELCOR result files(PTF file) for each representative STC were not available. Each STC has not one plume segment but several plume segments. To consider this in a more realistic way, it was assumed that each STC had several plume segments (2 ~4 segments). It was also assumed that a segment released earlier had large release fraction. Additionally, off-site resident notification timings(alarm timing) were assumed to be the core uncover times by referring to the thermal/hydraulic analyses for each representative STC. These results are shown in Table 5. Finally, 'Multi Source Term' function updated from MACCS 3.10 version was utilized to simulate multi-unit accidents.

Table 5: Input Parameters for Each Representative STC

<table>
<tr><th>Representative STC</th><th>Segment</th><th>Release Duration [sec] (PLUDUR)</th><th>Delay to Release [sec] (PDELAY)</th><th>Notification Timings [sec] (OALARM)</th><th>Heat Contents [W] (PLHEAT)</th><th>Release Height [m] (PLHITE)</th><th>Release Fraction* [%] (RELFRC)</th></tr>
<tr><td rowspan="2">STC 14 (ER)</td><td>1st</td><td rowspan="9">3,600</td><td>1,550</td><td rowspan="2">1,000</td><td rowspan="9">0</td><td rowspan="9">40</td><td>90</td></tr>
<tr><td>2nd</td><td>5,150</td><td>10</td></tr>
<tr><td rowspan="3">STC 12 (IR)</td><td>1st</td><td>8,485</td><td rowspan="3">6,707</td><td>70</td></tr>
<tr><td>2nd</td><td>12,085</td><td>20</td></tr>
<tr><td>3rd</td><td>15,685</td><td>10</td></tr>
<tr><td rowspan="4">STC 19 (LR)</td><td>1st</td><td>11,252</td><td rowspan="4">9,359</td><td>50</td></tr>
<tr><td>2nd</td><td>14,852</td><td>25</td></tr>
<tr><td>3rd</td><td>18,452</td><td>15</td></tr>
<tr><td>4rd</td><td>22,052</td><td>10</td></tr>
</table>

*: Percentage of 72-hour release fraction calculated from environmental release

2.3.2. EARLY module

Input parameters of each cohort were almost same except for the ETE values in this study. However, characteristic input parameters for each cohort should be assigned for more realistic and site-specific analysis. In case of 'Immediate evacuate', the period of 'delay to shelter' and 'delay to evacuate' were assumed to be as 20 and 40 minutes, respectively. In case of 'SIP then evacuate', the period of 'delay to shelter' was assumed to be as 20 minutes. The off-site resident notification timing of STC firstly released was applied for all cohorts in each release category combinations. All evacuees of each cohort were instructed to move radial direction because the evacuation type was selected ‘Radial’ in MACCS. Based on these assumption, the travel distances of each cohort were estimated by considering the length from the innermost radius of each cohort to the equivalent UPZ (26 km). Effect of moving in azimuthal direction in actual situations was considered by multiplying the travel distances by 1.3. Calculation of a site-specific ETE values should be performed since ETE values are very important input parameters from the viewpoint of risk. Additionally, network evacuation type should be considered rather than radial evacuation for more realistic simulations. Input parameters of each cohort are shown in Table 6. FGR-13 dose conversion factor(DCF) file recommended by the U.S. Nuclear Regulatory Commission(USNRC) was used. Site file reflecting the population of the reference site was produced by using the ‘MSPAR-SITE’ code developed in our laboratory [16].

Table 6: EARLY Module Input Parameters of Each Cohort

Protective Alternative Recommendation	**Input Parameter**	**Cohort 1 (0~5 km)**			**Cohort 2 (5~10 km)**			**Cohort 3 (10~16 km)**		
Common*	Travel distance [km]	26×1.3 = 33.8			21×1.3 = 27.3			16×1.3 = 20.8		
Immediate Evacuate	ETE value [hr]	3	4	5	2	3	4	1	2	3
	Evacuation speed (ESPEED) [km/hr]	11.3	8.5	6.8	13.7	9.1	6.8	20.8	10.4	6.9
	Delay to shelter (DLTSHL) [min]	20								
	Delay to evacuate (DLTEVA) [min]	40								
SIP then Evacuate	ETE value [hr]	4			3			2		
	Evacuation speed (ESPEED) [km/hr]	8.5			9.1			10.4		
	Delay to shelter (DLTSHL) [min]	20								
	Delay to evacuate (DLTEVA) [**hr**]	4	5	6	4	5	6	4	5	6

*: Travel distance is applied to both ‘Immediate Evacuate’ and ‘SIP then Evacuate’

3. RESULTS AND DISCUSSIONS

A lot of off-site consequence assessments were performed for each cohort using MACCS, and early fatalities and latent cancer fatalities were estimated. The results were normalized to present a common platform for analysis of early fatality and latent cancer fatality case. Normalizing the results required dividing all fatality values by the summation of fatality values for each protective alternative recommendation case. In the following paragraphs, the result analyses were presented by consequence types and cohorts.

3.1. Early Fatality

3.1.1. Cohort 1

‘Immediate evacuate’ action had lower consequence for all combination cases for the cohort 1. This result was clear when the LR category was included. The shorter the ETE values, the less consequence was estimated when the ER category was included. The consequence difference between 5-hr ETE and 4-hr SIP cases was very small. Therefore, if it is expected that it will take a long time (longer than 5 hours) to perform the evacuation, it may be recommended to perform the ‘SIP then evacuate’ action. However, this tendency decreased when the IR or LR STC was included. Total early health effect results for the cohort 1 are shown in Table 7.

Table 7: Total Early Health Effect Results of the Cohort 1

Combination Case	'Immediate Evacuate' Action ETE Values [hr]			'SIP then evacuate' Action SIP Periods [hr]		
	3	4	5	4	5	6
Case 1 (ER+IR)	12.94 %	14.96 %	16.95 %	17.77 %	18.36 %	19.02 %
Case 2 (ER+LR)	12.91 %	14.80 %	16.61 %	17.90 %	18.54 %	19.25 %
Case 3 (IR+LR)	15.08 %	15.08 %	15.19 %	17.67 %	18.18 %	18.80 %

3.1.2. Cohort 2

'Immediate evacuate' action had lower consequence for all combination cases for the cohort 2. The consequence differences between 'Immediate evacuate' and 'SIP then evacuate' actions were very large. This tendency was larger as the combination cases included the LR category. The likelihood of encountering radioactive plumes was dependent on the period of the SIP. It was judged that 'Immediate evacuate' action was recommended because it is far from NPP relative the cohort 1. Total early health effect results for the cohort 2 are shown in Table 8.

Table 8: Total Early Health Effect Results of the Cohort 2

Combination Case	'Immediate Evacuate' Action ETE Values [hr]			'SIP then evacuate' Action SIP Periods [hr]		
	3	4	5	4	5	6
Case 1 (ER+IR)	0.42 %	4.18 %	17.48 %	26.99 %	25.56 %	25.36 %
Case 2 (ER+LR)	0.40 %	3.96 %	16.96 %	26.62 %	25.84 %	26.23 %
Case 3 (IR+LR)	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	100.00 %

3.1.3. Cohort 3

The tendency for the cohort 3 was almost identical to the cohort 2. This tendency was larger because the cohort 3 was relatively so far from NPP relative to the cohort 2. In case of the case 3 combination, there was no early health effect. If 'SIP then evacuate' action is to be instructed in a specific circumstance, it is necessary to consider the likelihood of encountering radioactive plumes in setting sheltering period. Therefore, 'Immediate evacuate' action should be recommended for the cohort 3. Total early health effect results for the cohort 3 are shown in Table 9.

Table 9: Total Early Health Effect Results of the Cohort 3

Combination Case	'Immediate Evacuate' Action ETE Values [hr]			'SIP then evacuate' Action SIP Periods [hr]		
	3	4	5	4	5	6
Case 1 (ER+IR)	0.00 %	0.00 %	10.83 %	27.77 %	30.83 %	30.57 %
Case 2 (ER+LR)	0.00 %	0.00 %	10.55 %	27.11 %	30.80 %	31.54 %
Case 3 (IR+LR)	-	-	-	-	-	-

3.2. Latent Cancer Fatality

3.2.1. Cohort 1, 2, and 3

The tendencies for latent cancer health effect of each cohort were almost identical. Therefore, the results of each cohort were presented at once. Latent cancer health effects decreased with shorter ETE values. However, is did not have a certain tendency according to the SIP periods. Doses are commonly increased during sheltering period because people are continually exposed through groundshine exposure pathway. However, if people terminate SIP and go outside while radioactive plumes are passing, they will be more exposed. It was possible by this reason to explain the case in which the consequences were reduced even if the SIP period was long. Total latent cancer health effect results for each cohort are shown in Table 10, 11, and 12.

Table 10: Total Latent Cancer Health Effect Results of the Cohort 1

Combination Case	'Immediate Evacuate' Action			'SIP then evacuate' Action		
	ETE Values [hr]			SIP Periods [hr]		
	3	4	5	4	5	6
Case 1 (ER+IR)	12.64 %	13.22 %	13.93 %	20.42 %	20.03 %	19.76 %
Case 2 (ER+LR)	9.28 %	9.63 %	10.06 %	21.42 %	24.20 %	25.41 %
Case 3 (IR+LR)	3.08 %	3.38 %	4.06 %	28.94 %	30.66 %	29.88 %

Table 11: Total Latent Cancer Health Effect Results of the Cohort 2

Combination Case	'Immediate Evacuate' Action			'SIP then evacuate' Action		
	ETE Values [hr]			SIP Periods [hr]		
	3	4	5	4	5	6
Case 1 (ER+IR)	3.63 %	7.78 %	13.27 %	27.24 %	24.87 %	23.21 %
Case 2 (ER+LR)	2.48 %	5.33 %	9.13 %	25.20 %	28.39 %	29.48 %
Case 3 (IR+LR)	0.06 %	0.36 %	1.12 %	31.85 %	33.98 %	32.63 %

Table 12: Total Latent Cancer Health Effect Results of the Cohort 3

Combination Case	'Immediate Evacuate' Action			'SIP then evacuate' Action		
	ETE Values [hr]			SIP Periods [hr]		
	3	4	5	4	5	6
Case 1 (ER+IR)	0.50 %	3.08 %	8.78 %	31.32 %	29.09 %	27.22 %
Case 2 (ER+LR)	0.35 %	2.15 %	6.15 %	25.52 %	31.90 %	33.94 %
Case 3 (IR+LR)	0.00 %	0.14 %	0.89 %	31.10 %	33.77 %	34.10 %

4. CONCLUSION

Alternative protective actions for multi-unit accidents were studied based on the NUREG/CR-6953 (Vol.3) considering those for single-unit accidents. The most significant difference was that multi-unit accidents had multiple source terms compared with single-unit accidents. It was ultimately found that emergency response plans should be established considering the following source terms even if one source term passed. In this study, off-site consequence assessments were performed by simulating multi-

unit accidents for the reference site with the two reference plants. Emergency response scenarios were set up in consideration of the protective alternative recommendations. Based on the results, it was confirmed that 'Immediate evacuate' action is more protective than 'SIP then evacuate' action.
However, the degree of shielding maybe continuously reduced during the SIP period in the real. It is necessary to select an appropriate shielding factor since a dynamic shielding factor could not be applied in MACCS. It is also necessary to use the MELCOR results(PTF files) to consider realistic source term characteristics. Additionally, sensitivity analyses considering effect of shadow evacuation and that of time difference in accident initiation should be performed.
It was revealed that appropriate emergency response plans should be established for single-unit PSA as well as multi-unit PSA according to release characteristics of STCs in this study. The results of this study would contribute to establishment of effective emergency response plans for multi-unit accidents.

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References

[1] Le Duy, Tu Duong, Dominique Vasseur, and Emmanuel Serdet. "Probabilistic Safety Assessment of twin-unit nuclear sites: Methodological elements." Reliability Engineering & System Safety 145 (2016): 250-261.
[2] Zhang, Sai, Jiejuan Tong, and Jun Zhao. "An integrated modeling approach for event sequence development in multi-unit probabilistic risk assessment." Reliability Engineering & System Safety 155 (2016): 147-159.
[3] Modarres, Mohammad, Taotao Zhou, and Mahmoud Massoud. "Advances in multi-unit nuclear power plant probabilistic risk assessment." Reliability Engineering & System Safety 157 (2017): 87-100.
[4] Hudson, Daniel Wayne. Multi-unit accident contributions to US Nuclear Regulatory Commission quantitative health objectives: A safety goal policy analysis using models from state-of-the-art reactor consequence analyses. Diss. University of Maryland, College Park, 2016.
[5] Hudson, Daniel W., and Mohammad Modarres. "Multiunit Accident Contributions to Quantitative Health Objectives: A Safety Goal Policy Analysis." Nuclear Technology 197.3 (2017): 227-247.
[6] US Nuclear Regulatory Commission. Review of NUREG-0654, Supplement 3 "Criteria for protective actions recommendations for severe accidents, Sandia National Laboratories. Vol. 1. NUREG/CR-6953, 2010.
[7] US Nuclear Regulatory Commission. Review of NUREG-0654, Supplement 3 "Criteria for protective actions recommendations for severe accidents, Sandia National Laboratories. Vol. 3. NUREG/CR-6953, 2010.
[8] US Nuclear Regulatory Commission. Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants – Guidance for Protective Action Strategies, FEMA-REP-1, Rev. 1., Supplement 3, NUREG/CR-0654.
[9] Korea Hydro & Nuclear Power Co.(KHNP Co.). Level 2 Probabilistic Safety Assessment Report for Shin-Kori unit 1 & 2.
[10] Korea Hydro & Nuclear Power Co.(KHNP Co.). Radiological Emergency Planning for Kori Site.
[11] Republic of Korea, "ACT ON MEASURES FOR THE PROTECTION OF NUCLEAR FACILITIES, ETC. AND PREVENTION OF RADIATION DISASTERS", Act No. 10074, 2010.
[12] US Nuclear Regulatory Commission. Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants, FEMA-REP-1, Rev. 1. NUREG/CR-0654.
[13] US Nuclear Regulatory Commission. "State-of-the-art reactor consequence analyses (SOARCA) report." Washington DC, US Government Printing Office, NUREG-1935 (2012).
[14] US Nuclear Regulatory Commission. MACCS Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project. NUREG/CR-7009, August, 2014.

[15] Korean Statistical Information System, http://kosis.kr/index/index.do
[16] B.M. Ahn, et al., Development of the MSPAR-SITE Code for Estimating Multi-Unit MACCS Site, Transactions of the Korea Nuclear Society Spring Meeting, Jeju, Korea(2018).