A Consideration of the Single Release Location for the Multi-Unit Accidents

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Abstract: The objective of this study is to find a single release location that can represent multi units for the level 3 multi-unit PSA, based on the current limitations of computational codes. For this purpose, the method of using the weighted average of units' locations was proposed. Thus, the elements that can be considered as the weighting factors were classified, selected, applied to the reference plants. Also, MSPAR-SITE, the program to create site information by using this method and to visualize the results, were developed. Then, the concentration of the radionuclide and the early health effect were evaluated based on the derived locations. Through the results, it was confirmed that there was no significant difference in the all of the considered weighted single locations. In the area close to the site, the results of the single locations were not consistent with those of the multiple locations well. It may cause the under- or overestimation of the early fatality risk. However, in the case that the distance between the units is relatively very close, it is expected that the use of the single location will not substantially impact.

Keywords: Multi-Unit PSA, Release Location, Level 3 PSA, MSPAR-SITE

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1. INTRODUCTION

After the Fukushima accident, the Multi-Unit Probabilistic Safety Assessment (MU-PSA), which evaluates comprehensive risks considering the sharing and the linkage characteristics among the nuclear power plant units in a site, has gained attention around the world. Especially in Korea, due to the narrow territory, more than 5 units are constructed on all sites. Therefore, MU-PSA is regarded as a very important issue in Korea and many related studies are being conducted.

The level 3 (L3) PSA is the final step of estimating the ultimate nuclear power plants' risk by analyzing the off-site consequences of the accidents from the radiation releases which resulted of the level 1 & 2 PSA and predicting the residents' doses, health risks, and economic risks. There are several computational codes for the L3 PSA such as MELCORE Accident Consequence Code System (MACCS) developed by US Sandia National Laboratory (SNL), Code SYstem from MAria (COSYMA) from EU and Off-Site Consequence Analysis code for Atmospheric Releases in reactor accident (OSCAAR) from Japan. Among them, MACCS is widely used in the US, Korea, and other countries.

All calculations in MACCS, including the transportation and dispersion of radioactive plume segments by the Gaussian plume model, mitigative actions, early and latent health effects risks, and so on, are implemented and saved in the spatial grid elements divided by the specified radius and directions on the polar coordination whose center is a release location. With the most recent update, the ability to reflect multiple source terms whose release time are various was added in MACCS. However, the function to perform the multi-source term calculation considering the positional difference is not provided yet.

For the realistic simulation of the multi-unit accidents in L3 PSA, it is necessary to analyze off-site behaviors when the radioactive materials are released from the locations of each unit [1]. However, due to the limitation from the calculation structure of the computational codes, the currently available method is to select the single release location which represents the multiple units, considering the locations of each unit, the scale and probability of the accident, the characteristics of the site, and so forth.

Thus, in this study, the weighted average was considered as a method to determine an appropriate single release location. Also, the elements in the characteristics of site and units and results of the level 1, 2 PSA that could be used as the weighting factor were distinguished and selected for the preliminary evaluation. Then, the distribution of radioactive material concentration and the health risk of the residents for each selected location for the reference units were evaluated and compared. In addition, MSPAR-SITE, a computational code for supporting MACCS, was developed to create site information as the input and to visualize output results.

2. WEIGHTING FACTOR

2.1. Classification of the Elements

The triplets of the risk consist of the event scenario, the probability, and the consequence. It can be expressed mathematically as equation (1). They can be considered similarly for determining the single release location. Therefore, the characteristics of the site and units and the results of level 1, 2 PSA are classified according to the event identification, the probability, and the consequence respectively, shown in Table 1.

$$\mathrm{R} = < S_i, P_i, C_i > = \sum P_i \times C_i \quad (i = 1,2,3 \cdots, n) \tag{1}$$

S_i, : Accident Scenario of the Event *i* for the Defined Risk
P_i : Probability of the Event *i*
C_i : Consequence of the Event *i*

Table 1: Classification of the Weighting Elements

	Characteristics of Site and Units	Results of Level 1	Results of Level 2
Event Identification	Location, Wind Speed and Direction, Population, Structure of In-site Facilities		
Probability		Core Damage Frequency	Large Early Release Frequency, Containment Failure Frequency
Consequence	Power (Electric, Thermal), Core Inventory,		Release Fraction

2.2. Selection of Weighting Factors

Among classified elements, the weighting factors were selected mainly for the values that are relatively simple or often used in PSA. The wind speed, wind direction, and the structure of in-site facilities were judged to be difficult to be set as the weighting factor because they require in-depth research on building effects and weather data, which were excluded in this study.

Also, it should be noted that the most of currently available data classified as the probability elements are for the single unit accident. However, in order to use the probability to select the single release location that represents the multiple units, it should be derived from multi-unit accident scenarios. So, the elements regarded to the probability were excluded too.

The core inventory and the release fraction were used to calculate the released inventory, the product of two. For the population, it was judged difficult to assign a weight to each unit. Therefore, a unit which is closest to the area with the dense population was taken as the representative location.

To sum up, the method of weighted single location is organized into 5 options: 1. Simple location average, 2. Electric power weighted location average, 3. Thermal power weighted location average, 4. Released inventory weighted location average, 5. Location of the unit with dense population. The classified elements not considered as the weighting factor in this study may be studied in the future if necessary.

3. APPLICATION AND RESULTS

3.1. Application to the Reference Plants

As the reference plants, one WH600 type plant and two OPR1000 type plants from Kori site in Korea were selected. The electric and thermal power of the WH600 and OPR1000 are 650 MW_e, 1882MW_{th} and 1000MW_e, 2825MW_{th}, respectively [2]. The closest densely populated area to the Kori site is Busan, located in the southwest of the site. Among the reference plants, WH600 is closest to Busan.

In the case of the released inventory, the data of core inventory and release fraction are required. For the core inventory, the core burnup calculation was conducted using FISPACT-Ⅱ code and the results were applied to each reactor type. To obtain the release fraction data, the Source Term Category (STC) and the representative accident scenario should be determined. In this study, The Steam Generator Tube Rupture accident (SGTR) was selected as the representative scenario because the health effects risk of it was expected to be high. The release fraction for the SGTR referred to the results of the existing thermal hydraulic analysis for each reactor type [3].

Through the preliminary evaluation using MACCS with these core inventory and release fraction, the released inventory of each reactor for the 69 nuclides considered in the US State-of-the-Art Reactor Consequence Analyses (SOARCA) project was figured out [4]. Among 69 nuclides, only 10 nuclides matched the nuclides mentioned in the radiological equivalence to I-131 for releases to the atmosphere provided by IAEA [5]. The released inventory of 10 nuclides was multiplied by the corresponding multiplication factor, and the sum of them was taken as the weighting factor.

Therefore, the weighting factors of each reference plant for the selected options are summarized in Table 2.

Table 2: Weighting Factors for Reference Plants

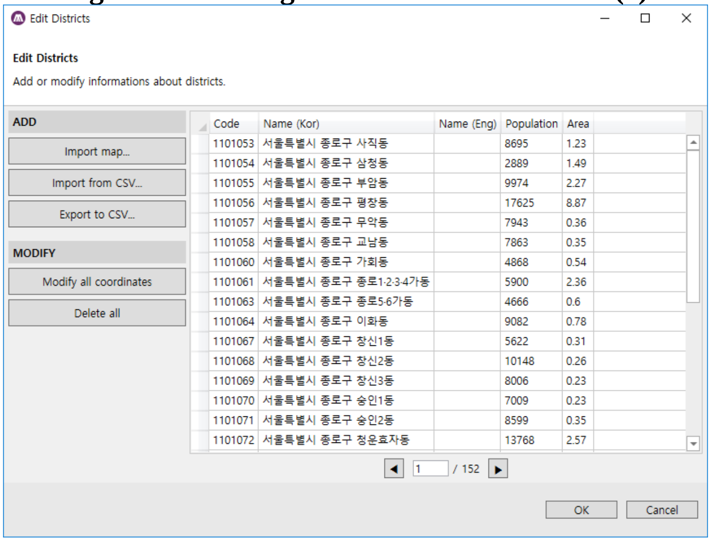
	Simple Average	Electric Power	Thermal Power	Released Inventory	Population
K2 (WH600)	1	650	1882	1.25E+18	1
SK1 (OPR1000)	1	1000	2825	2.23E+18	0
SK2 (OPR1000)	1	1000	2825	2.23E+18	0

3.2. Development of MSPAR-SITE

To find a simple or weighted average of the various locations and make site information into an input file for MACCS, Multi-unit Standardized Plant Analysis Risk-SITE (MSPAR-SITE) code was developed. Also, it has a function to visualize the concentration of the radionuclide or the dose distribution, ones of the output of MACCS, on the map.

MSPAR-SITE was made using WPF and Javascript-based Google Map APIs. The input data using KML format should contain name, population, and area of the administrative districts as shown in Figure 1. And it draws a polar coordinated grid around a specified release location. The population of each grid element is provided by applying divided and conquer. If one sector contains different administrative districts, the sector will be divided into four small sectors. Then, if one sector is within just one administrative district, there is no need to be divided more and the population of the sector will be calculated using the population density of the district given by input and the area of the sector.

Figure 1: Running Screen of MSPAR-SITE (1)



Edit Districts

Add or modify informations about districts.

Code	Name (Kor)	Name (Eng)	Population	Area
1101053	서울특별시 종로구 사직동		8695	1.23
1101054	서울특별시 종로구 삼청동		2889	1.49
1101055	서울특별시 종로구 부암동		9974	2.27
1101056	서울특별시 종로구 평창동		17625	8.87
1101057	서울특별시 종로구 무악동		7943	0.36
1101058	서울특별시 종로구 교남동		7863	0.35
1101060	서울특별시 종로구 가회동		4868	0.54
1101061	서울특별시 종로구 종로1·2·3·4가동		5900	2.36
1101063	서울특별시 종로구 종로5·6가동		4666	0.6
1101064	서울특별시 종로구 이화동		9082	0.78
1101067	서울특별시 종로구 창신1동		5622	0.31
1101068	서울특별시 종로구 창신2동		10148	0.26
1101069	서울특별시 종로구 창신3동		8006	0.23
1101070	서울특별시 종로구 숭인1동		7009	0.23
1101071	서울특별시 종로구 숭인2동		8599	0.35
1101072	서울특별시 종로구 청운효자동		13768	2.57

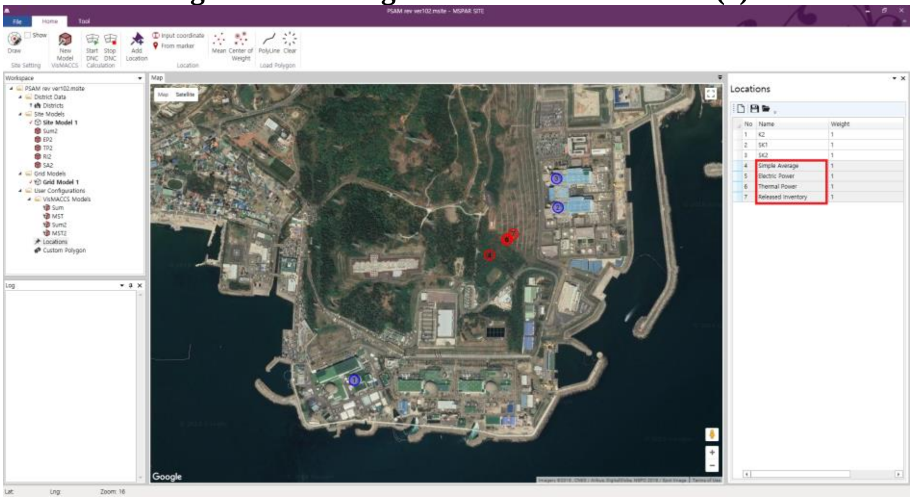
For the multiple units, several locations are able to be registered and from them, a new weighted location will be found out using the center of mass formula, equation (2).

$$p_{new} = \frac{\sum_i p_i w_i}{\sum_i w_i} \tag{2}$$

p_{new} : The coordinates (x,y) of the new location
p_i : The coordinates (x,y) of the location *i*
w_i : the weight of the location *i*

The weighted average locations that are derived from MSPAR-SITE when applying the weighting factors for each option in Table 2 are shown in Figure 2. As shown, the positional difference in the single release locations for each option is relatively small. The distance to the release inventory weighted location which is the farthest from the simple average location, is about 130 meters. Therefore, the effects of the choice among them is not expected to be significant.

Figure 2: Running Screen of MSPAR-SITE (2)



No	Name	Weight
1	K2	1
2	SK1	1
3	SK2	1
4	Simple Average	1
5	Electric Power	1
6	Thermal Power	1
7	Released Inventory	1

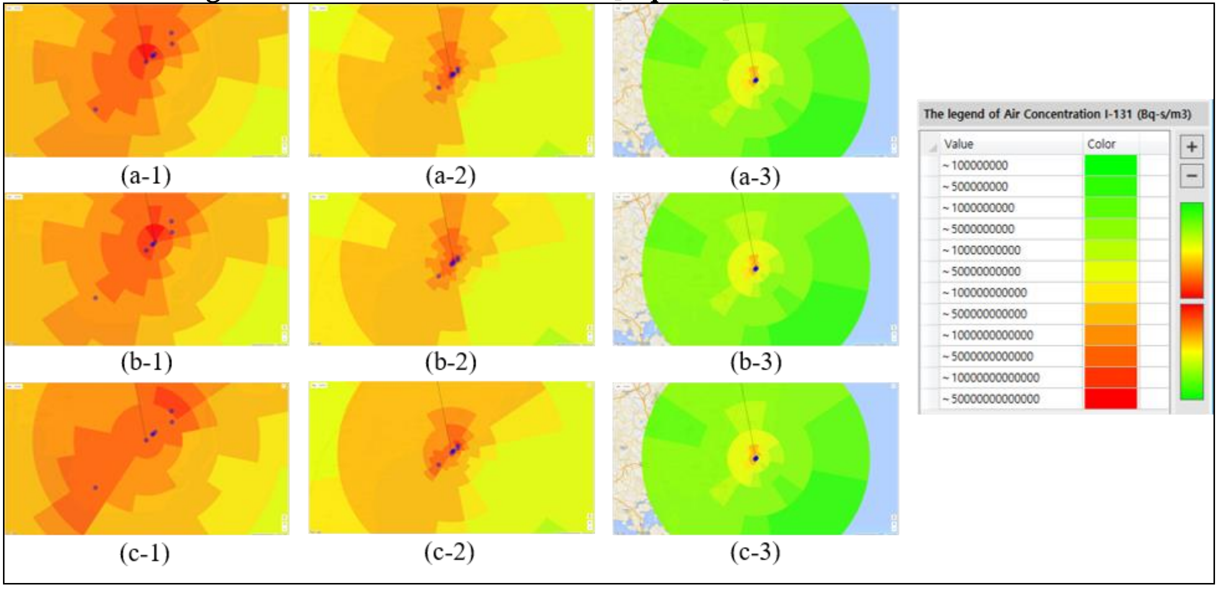
3.3. Evaluation of Radionuclide Concentration

Although the choice between the weighting factor options is expected to have little impact, in order to decide which single location most appropriately represents the multiple units, it is necessary to compare results of the transportation and the dispersion of the released radioactive materials from the weighted single for each option with those of multiple locations for every considered units.

As mentioned above, in this study, SGTR was considered as the representative accident scenario. And it was assumed that the accidents occurred simultaneously in the 3 reference plants. One-year data from the reference site in 2009 were used as the meteorological data. The characteristics of the plants and the site were reflected as much as possible to assign the factors associated with the transportation and the dispersion of the radionuclide in MACCS. If the data on the Korean situation were scarce or underdeveloped, the values of the US SOARCA project were used [3, 4]. For the weighted single location cases, the multi-source term function of WinMACCS was used.

The distribution of the radionuclide concentration for each grid element is provided in the form of the text file by MACCS. MSPAR-SITE can import it, draw the grid again for the selected location, color the grid elements according to the specified color legend, and visualize it. This process was implemented for the air and ground concentration of Cs-137 and I-131, respectively. However, the difference between radionuclide or between air and ground concentration affected only the magnitude of the value, and the distribution is almost similar. So, the results only for the air concentration of I-131 were interpreted, shown in the Figure 3.

Figure 3: I-131 Air Concentration [Bq-s/m^3] from Various Locations



(a-1) (a-2) (a-3)

(b-1) (b-2) (b-3)

(c-1) (c-2) (c-3)

The legend of Air Concentration I-131 (Bq-s/m3)

Value	Color
~ 100000000	🟩
~ 500000000	🟩
~ 1000000000	🟩
~ 5000000000	🟩
~ 10000000000	🟩
~ 50000000000	🟨
~ 100000000000	🟨
~ 500000000000	🟧
~ 1000000000000	🟧
~ 5000000000000	🟧
~ 10000000000000	🟥
~ 50000000000000	🟥

* a: Simple Average Location, b: Release Inventory Location, c: Multiple Locations
1: Zoom 16, 2: Zoom 14, 3: Zoom 16

The results of the radionuclide concentration among single location cases were very similar, with only slight positional differences due to the parallel translation. And the patterns of the concentration distribution are same one another regardless of the cases. Thus, only the cases for the simple average and release inventory were included in Figure 3. The resemblance between single release location cases leads the difficulty to judge which of them is most similar to the case of multiple locations.

Comparing the results of the weighted single location with those of the multiple locations, the concentration distributions in the area outside 5km from the release location showed similarity. However, in the area inside 5km, close to the site, they were significantly different. In the multiple locations case, there were two areas with the relatively high concentration compared to surroundings.

One was around WH600 unit and the other was around two OPR1000 units. On the other hand, there was only one area with a relatively high concentration around the specified release location in the single location cases. And the maximum degree of the concentration of that area in the single location cases was much higher than that in the multiple locations case. But, in the multiple locations cases, the concentration degree was more even and higher in a wider area within 5km. It is caused that despite the effect of the entire meteorological data which makes the radioactive materials head to the north and southwest is same, it affects at one point for the single location cases and at multiple points for multiple locations case. These differences in the concentration distribution near the site can lead to significant over- or underestimation of the early fatality risk, generally evaluated in 1 mile from a site boundary.

Also, it is expected that selecting the area with higher power and more number of units as the representative single location is meaningful although there is little difference between the results of the weighting factor options. In the multiple locations case, the radionuclides concentrations from two OPR1000 units were overlapped. It means that, for the units with very close distance, assessment using the single location will not be significantly different from that using the multiple locations.

3.4. Evaluation of Early Fatality Consequence

As mentioned above, the choice of the single release location can affect the early fatality risk significantly. Thus, the early fatality consequence of the reference scenario was analyzed, reflecting the population distribution of the reference site calculated by MSPAR-SITE. In the model to calculate the early fatality consequence, only the emergency phase for 7 days was considered. Also, it is assumed that there is no emergency response. The values for the factors related to the health effects were referred to US SOARCA Project [4]. The fatality risk for the multiple locations case cannot be evaluated by MACCS. So, the case of the multiple locations was excluded.

The change between the options in the population weighted risk from the specified location to the certain radius is shown in Table 3.

Table 3: Population Weighted Risk Ratio to Simple Average Location Case

Radius from 0 km (km)	Simple Average	Electric Power	Thermal Power	Released Inventory	Population
1	1.00	1.05	1.06	1.05	1.48
2	1.00	0.98	0.98	0.97	1.36
3	1.00	1.00	1.00	1.00	0.98
5	1.00	1.00	1.00	1.00	0.98
10	1.00	1.00	1.00	1.00	0.98
20	1.00	1.00	1.00	1.00	0.98
80	1.00	1.00	1.00	1.00	0.98

Table 4: Comparison of the Results between Simple Average and Population Options

Radius from 0 km (km)	Population Weighted Risk		Health Effects Cases		Total Number of Population	
	Simple Average	Population	Simple Average	Population	Simple Average	Population
1	1.00	1.48	1.00	1.00	1.00	0.68
2	0.88	1.20	1.36	1.35	2.68	2.15
3	0.41	0.40	32.69	33.54	5.51	5.12
5	0.41	0.40	32.69	33.54	16.20	16.75

The results of all cases except the population weighted option showed a variation within 5%. It indicates that even considering the population, there is no significant difference in the weighted single location options because the locations are very close to each other.On the other hand, the results of population option had distinct differences with those of the simple average option. In the population weighted risk ratio, to the 2km radius, the results of the population option were about 35 to 48% higher. From the 5km radius, the results of the population were about 2% smaller. It implies that the choice of the population option can have a significant effect on the results in the area where the early fatality risk is generally evaluated in.

To analyze it in more detail, in the simple average and population options, the results of the population weighted risk, the number of the early health effects, and the total number of the population from the release location to certain radius were summarized as the ratio to the results to the 1km of the simple average option in Table 4. First, the total number of the population of the population case was less until 3km radius though the total number of population in 80km of this case was larger. Also, in the health effects cases results, little differences between both options were shown and there was no change between radius further than 3km. In other words, within 2km, the results of the population option showed a similar number of cases, even though the total number of the population is smaller. It can explain the results of the population weighted risk well. It is expected to be due to the interaction between the population distribution by directions and the entire meteorological information. In short, it would be necessary to analyze the population distribution in the radius of the early fatality evaluation and the entire meteorological information, rather than a simple method to set the release location as the unit closest to the city, when population element is reflected in the weighting factor.

4. CONCLUSION

The objective of this study is to consider a single release location that can represent multiple units for the level 3 multi-unit PSA, based on the current limitation of computational codes. For this purpose, the method of using the weighted average of units' locations was proposed. Thus, the elements that can be considered as the weighting factors were classified, selected, applied to the reference plants. Also, MSPAR-SITE, the program to create site information by using this method and to visualize the results were developed. Finally, the concentration of the radionuclide and the early health effect were evaluated based on the derived locations for comparison.

Through the results, it was confirmed that there was no significant difference in the all of the weighted single locations. So, it is recommended that a simple option should be selected, considering the number of units and the power. In the area close to the site, the results of the single location cases were not consistent with those of the multiple locations well. And it may lead the under- or overestimation of the early fatality risk. However, in the case that the distance between the units is relatively very close, it is expected that the use of the single location will not substantially impact.

In order to analyze the differences between the weighted single locations in the area close to a site more realistically, it is necessary to consider the elements such as wind speed, direction, and the position of the on-site facilities for the further works. Also, in this study, the elements related to the probability were not used for the weighting factors and the accident scenario was assumed that the SGTR occurred in the 3 units at the same time. To consider the probability and reflect more valid multi-unit accident scenarios, a lot of efforts for the level 1 and 2 multi-unit PSA will be necessary. And the reconsideration of the weight in the population element is necessary, including the entire meteorological information and the population distribution by the directions. However, like other elements, it is expected that it will not have much effect on the results to consider the probability and more detailed population information as the weighting factor. In addition, only 3 units in the reference site were considered in this study. Therefore, further study on the entire reference site will be needed from the viewpoint of comprehensive site risk. Finally, it will be noted that weighted single location method considered in this study is only for the situation that the multiple release locations are not able to be used.

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