Application of Off-site Consequence Calculation Method for Multi-Unit Nuclear Power Plants

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1. Introduction

In Level 3 Probabilistic Safety Assessment (PSA), evaluating the risk of a multi-unit site with Single Location (Center Of Mass, COM) method which integrates all the nuclear power plants (NPPs) into one virtual point has a high uncertainty. Since COM method doesn't properly describe the realistic dispersion figures of radioactive materials released from the several NPPs, it is inappropriate to apply this calculation method into a multi-unit accident.

Generally, there are at least 2 NPPs in each of nuclear sites and more than 6 NPPs in every domestic site are in operation. In particular, most of the domestic nuclear sites are surrounded by densely populated areas, a new off-site consequence calculation method reflecting the realistic conditions and circumstances is required.

Several studies have been emphasizing the importance of risk assessment and severe accident management in multi-unit site[1]. One study considers unit-to-unit interaction and dependency in terms of multi-unit PSA[2]. Six essential factors (initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies) were mentioned to be considered in multi-unit PSA[3]. Another study[4] suggests multi-unit PSA methodology with the consideration of 3 factors (propagation of initial events, common cause failure and human error). Multi-unit PSA based on external events was explained in another study[5]. In this study, the fragility of the site was quantified and correlation between NPPs was considered to core damage frequency. These studies show the necessity of new off-site consequence calculation method for multi-unit accident since the off-site consequence calculation method for single-unit cannot be directly applied to the multi-unit accident.

Since COM method doesn't take consideration of overlap of plumes released from the actual locations of NPPs, applying it into a multi-unit accident results in either overestimate or underestimate depends on the area.

In this study, Multi-Unit (ML) method was applied in the case of multi-unit accident under several weather conditions and each result was compared with another result using COM method.

2. Methods

2.1 Calculation of two dimensional radioactive nuclide on ground level.

MACCS2[6] calculates the concentration of released radioactive nuclides using Gaussian Plume Equation[7].

$$\chi(x, y, 0) = \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (1)$$

Air and ground concentrations for all of the 60 nuclides as well as horizontal and vertical atmosphere diffusion coefficient, σ_y and σ_z on the centerline are calculated in discrete values at regular intervals by ATMOS output of MACCS2. The radioactive nuclide concentrations on the centerline at ground level ($y = 0, z = 0$) can be calculated as

$$\chi(x) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (2)$$

Air concentrations at ground level ($z = 0$) can be calculated as

$$\chi(x, y) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (3)$$

To obtain continuous nuclide concentrations and atmospheric diffusion coefficients, discrete values at regular intervals are interpolated.

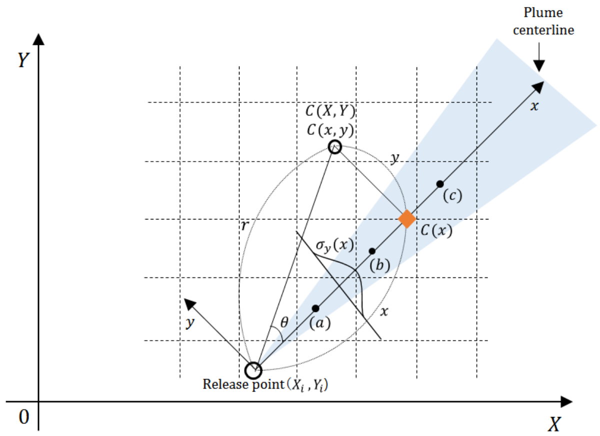


Fig. 2. x, y coordinates in local and global coordinate system

Fig. 2 represents the global coordinate (X, Y) and local coordinate (x, y). $C(X, Y)$ and $C(x, y)$ represent the radioactive nuclide concentration at (X, Y) and (x, y). $C(x)$ and σ_y on the diamond spot are calculated by the interpolation of points (b) and (C). y is the distance from the centerline to the (X, Y). $\chi(x, y)$ can be calculated by Eq. 3 when $\chi(x)$, σ_y and y are defined.

2.2 Calculation of radioactive nuclide concentration for multi- unit accident

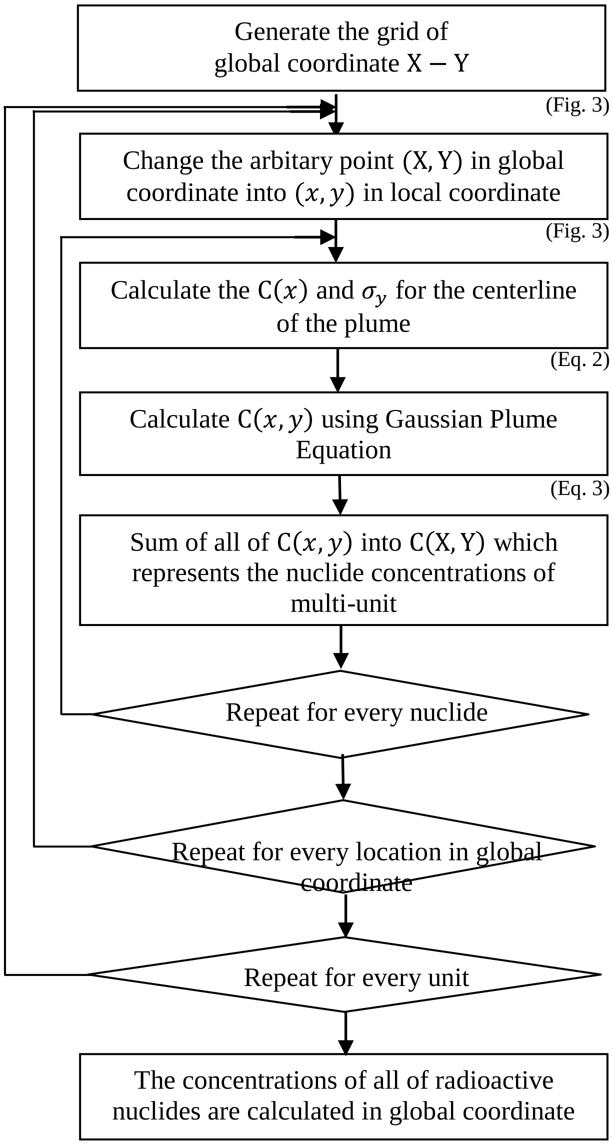


Fig. 3. Flow chart of radioactive nuclide concentration calculation for multi-unit

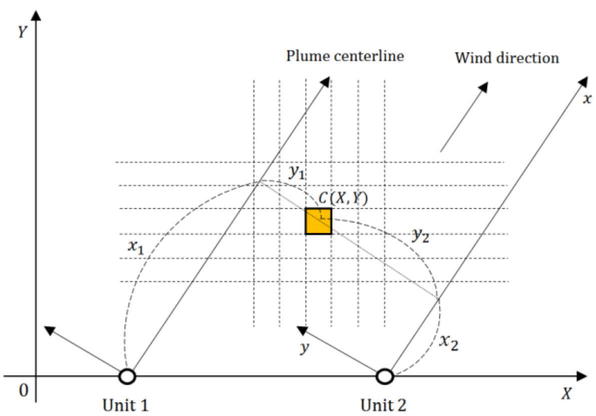


Fig. 4. Calculation of radioactive nuclide concentration at (X, Y)

Fig. 4 shows the radioactive nuclide concentration calculation for two virtual NPPs. In global coordinates, the radioactive nuclide concentration at arbitrary point (X, Y) is the sum of those from each release. Summation can be demonstrated as

$$C(X,Y) = \sum_{i=1}^{2} C_i(x_i \to X, y_i \to Y)$$
$$D(X,Y) = \sum_{i=1}^{2} D_i(x_i \to X, y_i \to Y) \quad (4)$$

$C(X,Y)$ and $D(X,Y)$ respectively represent the concentration of radioactive nuclide C and D for unit i.

Since the multi-unit site has several release points for each unit, the origins for each plume and the directions of the centerline are different. To combine the radioactive nuclide concentrations for each plume, coordinate transformation is required.

3. Application

3.1 Benchmarking

Fig. 5 shows each location of NPP units, center of mass, and population.

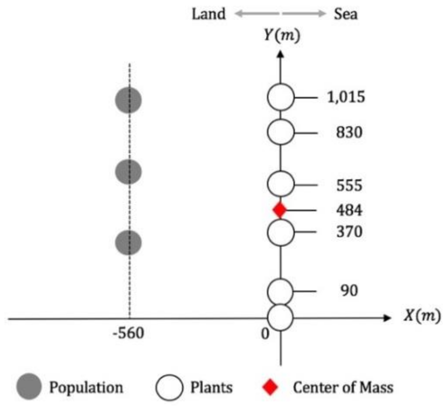


Fig. 5. Site layout

The population distribution is located along the Exclusive Area Boundary (EAB)[8]. NPPs are listed in the positive direction of the y-axis from the origin. Each location and the information of virtual NPPs are listed below.

Table 1. Locations and Power levels

Location	$X_i\ (m)$	$Y_i\ (m)$	$P_i\ (Power)$ (b)
Unit 1	0	0	0.95
Unit 2	0	90	0.95
Unit 3	0	370	1.00
Unit 4	0	555	1.00
Unit 5	0	830	1.00
Unit 6	0	1015	1.00
EAB	-560		
Center Of Mass (a)	0	484	

(a) $Y_{COM} = \frac{\sum_{i=1}^{6} P_i Y_i}{\sum_{i=1}^{6} P_i}$

(b) Values are normalized by 2,825 MWt

3.2 Weather data

Radioactive nuclide concentration distribution varies with the weather condition. Annual weather data were applied to each of COM and ML method. For annual weather, 1460 data sets are generated when sampling each four data set out of 24 hourly weather data sets for 365days (Use 8760(24*365) data set for precise calculation). 1460 results can be obtained for each unit in both of COM and ML method and results of 6 NPP units are overlapped at center of mass in COM method. Based on the sampled weather data, windrose can be drawn as Fig. 6.

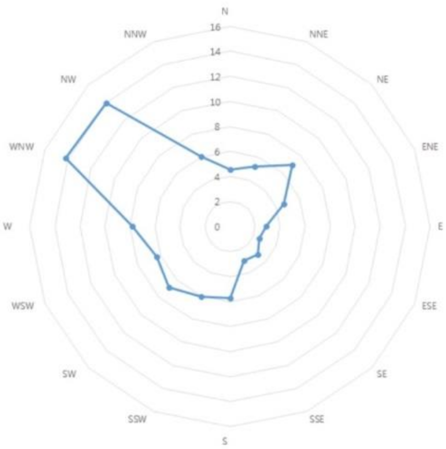


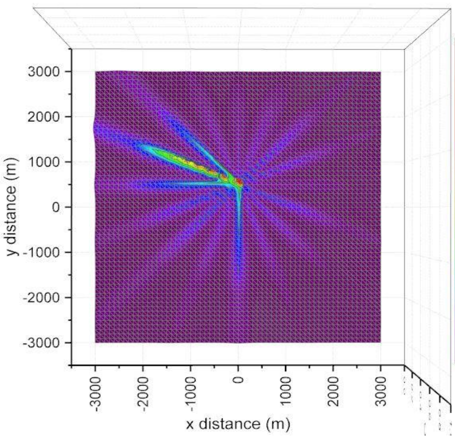
Fig. 6. Annual weather windrose

Fig. 6 shows the irregularity of the wind influences in the area in one year. NW and WNW direction tends to be much influenced by the weather.

4. Results

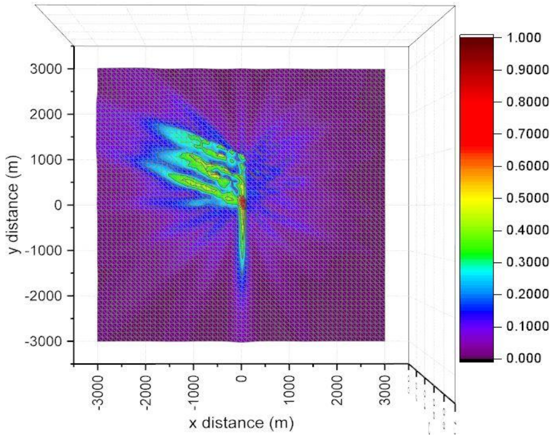
In this study, the air and ground concentrations of Cs-137 were compared in COM and ML method under annual weather condition. Each case is normalized with the maximum value of whole cases.

4.1 Application of annual weather



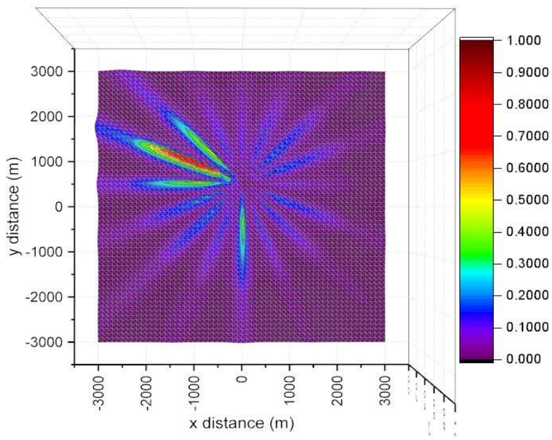
* Normalized by the maximum value

Fig. 7. Air Concentration of Cs-137 on annual weather using COM method



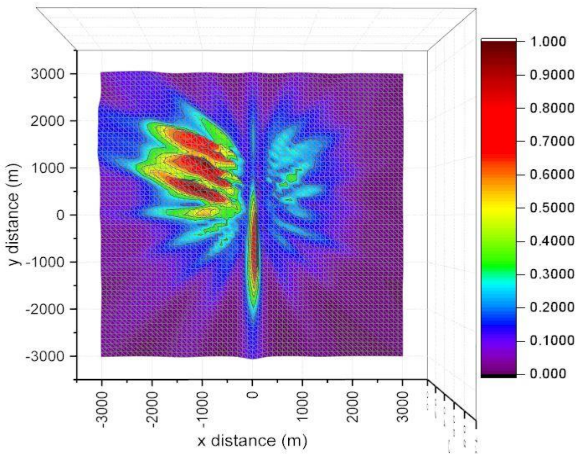
* Normalized by the maximum value

Fig. 8. Air Concentration of Cs-137 on annual weather using ML method



* Normalized by the maximum value

Fig. 9. Ground Concentration of Cs-137 on annual weather using COM method



* Normalized by the maximum value

Fig. 10. Ground Concentration of Cs-137 on annual weather using ML method

Fig. 7 to 10 shows the air and ground concentrations of Cs-137 calculated by COM and ML method under annual weather condition. There is a stark difference between the results of two methods. The concentration distribution of Cs-137 spreads out narrow from the center of mass and shows relatively high values along the centerline of the plume in COM method. ML method shows a broad and even distribution of Cs-137 throughout the multi-unit site. Since all of the release points are piled up into the center of mass in COM method, the concentration of Cs-137 is relatively high. The annual wind rose is fully reflected in ML method, however, only part of it is appeared in COM method. Consequently, the graph of the Cs-137 concentration distribution has a radial shape considering only one release point. ML method, on the other hand, shows more wide shape with the consideration of all of release points.

5. Conclusions

In this study, methods to calculate the off-site consequence for multi-unit site are suggested. Applying COM method into the multi-unit accident increases the uncertainty of the result. In COM method, all of the release points of each NPP unit overlap at the center of mass so that the radioactive materials released from each NPP are piled up one on another. Consequently, it leads to unrealistic results of either overestimated or underestimated radioactive nuclide concentrations depending on the locations. COM method can be suggested only for few cases when population distribution and NPP units are collinear. When the both of NPP units and population lie on the same line and the wind blows towards the population across the NPP units, the radioactive nuclide concentrations can be both reinforced and offset. To be specific, the influence of the close NPP units on the population is offset by one of the distant NPP units which has relatively low radioactive nuclide concentration. Thus, overall radioactive nuclide concentration calculated by COM method is nearly equal to one calculated by ML method.

In this study, 16 wind direction was considered in annual weather condition. The difference of results between COM and ML method applying each of 16 and 64 wind direction will be compared in further research.

ML method proposes more sophisticated calculation of multi-unit accident by reflecting the real locations of NPP units. By applying annual weather data into ML method, more realistic result is carried out according to the annual weather. Furthermore, more accurate and efficient evacuation plan can be established.

This study is summarized as

1. ML method precisely calculates the superposition of the plumes in the multi-unit accident, so that raises the accuracy of the calculation.
2. ML method drives out more precise radioactive nuclide concentration calculation and shows realistic distribution of radioactive nuclide when the annual weather data are applied in the calculation.

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